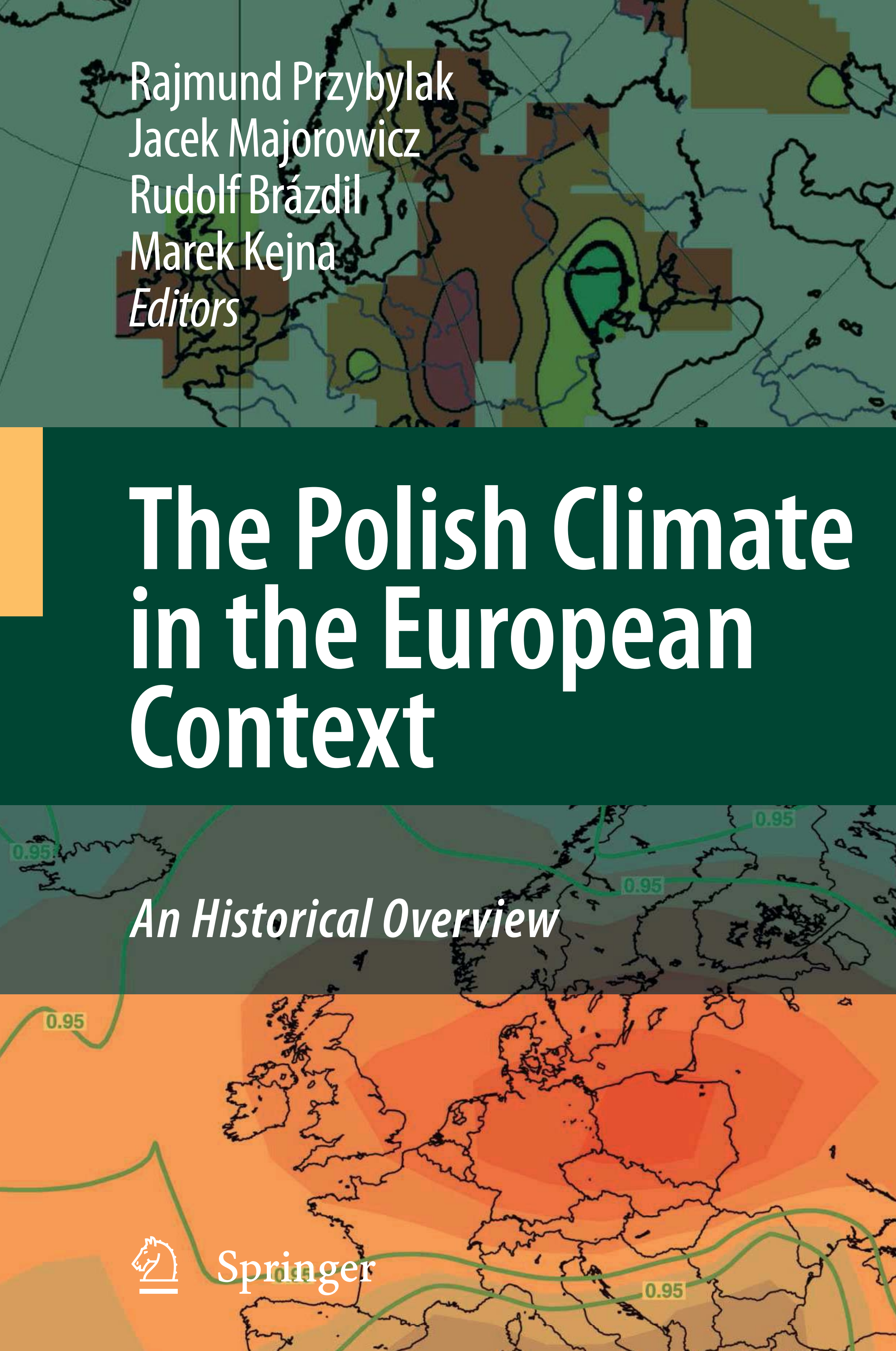

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The Polish Climate in the European Context

An Historical Overview

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Preface

How unusual was the climate of the twentieth century? This question has dominated research on climate variability in recent decades as scientists have tried to assess the role of increased concentrations of greenhouse gases on the global environment. From our understanding of the physics of the atmosphere, we expect that the net effect will be warming, and this is confirmed by model simulations of the climate system. But another line of evidence is to examine early instrumental records, historical documents and proxy records of climate from natural archives, to extend the overall record of climate further back in time. In this way, recent observations can be placed in a long-term perspective, providing a third approach to evaluating the nature and significance of recent climate changes.

For many regions of the world, instrumental records were obtained at the same time that anthropogenic effects on the atmosphere were increasing, so "natural" and human-induced factors affecting the climate system became progressively more intertwined. Thus, distinguishing anthropogenic from natural climate variability is often problematical in recent decades. Long-term records, which extend back before the industrial revolution, provide a picture of climate variability at a time when greenhouse gases were much closer to their long-term background level (~280 ppmv, versus 385 ppmv today). Europe has a wealth of such records. Not only are there many long-term instrumental records, but also meticulously kept written records from many locations that document past weather conditions. Collectively, these invaluable sources enable a detailed picture of past climatic conditions to be constructed, not just of average conditions, but also of the frequency of extremes. In addition, many "natural archives" – physical or biological phenomena that have in some way registered the climate in times past – are available to extend the paleoclimate perspective, both in time and space. This includes tree rings, lake sediments, stalagmites and borehole temperatures. Poland is particularly rich in such paleoclimatic resources, but too often the barrier of language has limited the wider dissemination of information about such records. This volume seeks to address that problem by making information about the long-term climate of Poland and adjacent regions available to a larger audience. It begins with a broad European perspective on climate variability, then focuses on records from Poland and other eastern European countries over recent centuries. It is clear that such records can help us respond to the initial question posed above. However, the answers are not always straightforward, revealing a complexity in climate variability that will require much additional research before it can be fully understood.

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Contents

Part III The Climate of Poland and Europe in Recent Centuries: New Findings Results

Editors' Introduction

The study of the climate history of the past millennium is based on a variety of instrumental, documentary and natural proxy data. These data have already been used in numerous studies for climate reconstructions in different parts of the world, and for the world as a whole. This has not only helped to advance our understanding of long-term natural climate variability, but has also improved our ability to evaluate the extent of climate warming well into the future. Such information allows us to assess the potential contribution of natural forcings in these processes in contrast to that of anthropogenic factors related mainly to an enhanced greenhouse effect due to the emission of greenhouse gases to the atmosphere. Knowledge of the range of natural climate variability is very important and it can be obtained only through the analysis of information concerning the weather and climate from the pre-industrial period.

The past is the key to the future. This is particularly true in climatology because knowledge of past climates is important in the prediction of future climate scenarios. Although such scenarios are based mainly on the projections of climate models, empirical studies based on instrumental, documentary and natural proxy data cannot be neglected. Moreover, a broader knowledge of climates of the past may help to better validate climatic models. If they simulate past climates well, it is safer to assume that simulations of future climates will also be more credible. On the other hand, the climate, particularly in its extreme manifestations, exerts a considerable influence on changes in both the natural and man-made environments (as recent examples, one may recall the floods of July 1997 and August 2002 in Central Europe or the extent of damage caused by tropical cyclones in New Orleans and Florida in August 2005).

In recent decades our knowledge of the climate histories of several European countries (including Poland) has increased considerably. This is also observable for the pre-instrumental period, though very seldom does this knowledge go back further than the past 500 years. With a view to encouraging Polish and international researchers to undertake more investigations into this period, an international conference *The Climate of Poland in Historical Times in Relation to the Climate of Europe* was organised in Toruń (Poland) from 11 to 13 October 2007. At present, the international community of climatologists only have limited access to studies on long-term climate changes in Poland owing to the language barrier, with most of the research in this area being available only in Polish. Moreover, no synthesis exists of climate changes in Poland in recent centuries, either in Polish or in any other language. Taking these facts into account, the organisers of the conference decided to prepare the present monograph to synthesise our current knowledge on the history of Poland's climate in past centuries, in the context of broader research efforts directed towards providing a more general climate history of Europe.

The present monograph entitled *The Polish Climate in the European Context: An Historical Overview* is a result of work undertaken by an international team of scientists. Part 1 provides the background to climate change in the European context and a summary of our knowledge of climate change and variability in Europe mainly in the past 500 years. Different aspects of climate changes (including extremes) are described for the whole of the continent, as well as in a more detailed way for Central and Eastern Europe.

Part 2 describes the present state of knowledge concerning the history of Poland's climate in recent centuries. In the first Chapter, a synthesis of climate variability during the instrumental period is given. We provide a short history of observations of basic meteorological variables (temperature, precipitation, cloudiness, humidity, etc.) as well as their long-term changes. In the following sections, syntheses of current climate change histories in Poland based on three kinsds of proxy data (documentary, dendrochronological and borehole data) are presented Chapters.

Part 3 presents new findings on different aspects of climate change and variability on both continental and regional scales (i.e. for both Europe in general and Poland in particular). The majority of the papers feature analyses of long-term changes in selected meteorological variables (mainly air temperature and precipitation) for individual sites or areas located in different regions of Poland or Central Europe.

The Editors would like to thank all the contributing authors for their papers, as well as the reviewers for their critical comments and suggestions which significantly improved the quality of all contributions presented in this monograph. We hope that this book will prove to be of value to everyone studying climate change and variability during historical times.

The Editors
Toruń, Poland, April 2009

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Part I
The European Background

Chapter 1

Climate Change in Poland in the Past Centuries and its Relationship to European Climate: Evidence from Reconstructions and Coupled Climate Models

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Abbreviations

AD	Anno Domini
AOGCM	Atmosphere-Ocean General Circulation Model
CCA	Canonical Correlation Analysis
Cc	Centre of Low Pressure
CPC	Climate Prediction Center
CRU	Climatic Research Unit
Bc	Cyclonic Trough
DJF	December January February
EA/WRUS-I	East Atlantic/West Russia Index
EA/WRUS	East Atlantic/West Russia pattern
EOF	Empirical Orthogonal Function
EU2	Eurasia-2 pattern
GCM	Global Circulation Model
ECHAM4	Model name composed from ECMWF and Hamburg
ECHO-G	Model name composed from ECHAM4 and HOPE-G
HadCM3	Hadley Centre Coupled Model, version 3
HOPE-G	Hamburg Ocean Primitive Equation model
IPCC	Intergovernmental Panel on Climate Change
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NAO	North Atlantic Oscillation
NAOI	North Atlantic Oscillation Index
Nc	North Cyclonic Situation
NEc	Northeastern Cyclonic Situation
OASIS	Ocean Atmosphere Sea Ice Soil (model coupling software)
OCCR	Oeschger Centre for Climate Change Research
PC	Principal Component
RR	Precipitation
SCAND	Scandinavian pattern
SCAND-I	Scandinavian Index
SLP	Sea Level Pressure
TT	Temperature
UKMO	United Kingdom Meteorological Office

1.1 Introduction

The knowledge of climate and its variability during the past centuries can improve our understanding of natural climate variability and also help to address the question of whether modern climate change is unprecedented in a long-term context (Folland et al. 2001; Jansen et al. 2007; Hegerl et al. 2007; Mann et al. 2008 and references therein). The lack of widespread instrumental climate records introduces the need for the use of natural climate archives from 'proxy' data such as tree-rings, corals, speleothems and ice cores, as well as documentary evidence to reconstruct climate in past centuries (see Jones et al. 2009 for a review). The focus of many previous proxy data studies has been hemispheric or global mean temperature (see Jansen et al. 2007; Mann et al. 2008 and references therein), although some studies have also attempted to reconstruct the underlying large-scale spatial patterns of past surface temperature and precipitation changes at continental scales. The principal region where this has been analysed is Europe (e.g. Küttel et al. 2007; Mann et al. 2000; Luterbacher et al. 2004, 2007; Xoplaki et al. 2005; Guiot et al. 2005; Pauling et al. 2006; Riedwyl et al. 2008). Studies indicate that the late twentieth century European climate is very likely warmer than that of any time during the past 500 years. This agrees with findings for the entire Northern Hemisphere. Hemispheric temperature reconstructions do not provide information about regional-scale temperature and precipitation variability such as the intrinsic seasonal patterns of climate change as they have occurred in Europe during the past centuries. High-resolution reconstructions also illuminate key climatic features, such as regionally very mild/cold or wet/dry winters that may be masked in a hemispheric reconstruction. Klimenko and Solomina (2009, this book) present a compilation of climatic variations in the east European plain during the last millennium using different climate proxies. Therefore, regional studies and reconstructions of climate change are critically important when climate impacts are evaluated.

In October 2007 an international conference entitled *The Climate of Poland in Historical Times in Relation to the Climate of Europe* was held in Toruń (Poland). The main aim was to mobilise Polish and international researchers to undertake investigations to improve knowledge about the history of climate in Poland during the past centuries. The outcomes of other results from the conference are published in Parts 2 and 3.

The climate history of Poland is rich and knowledge has increased considerably over the last decades. Information about past weather conditions is found in the collection of more or less systematically written notes about atmospheric phenomena. Weather chronicles in Poland are original notes which have been kept by a number of professors at Cracow University in the second half of the fifteenth century and first half of the sixteenth century (Limanówka 1996). They present visual meteorological observations, performed in most cases sporadically and regularly only in short periods of 1527–1551 (Limanówka 2000) and 1502–1540 (Limanówka 2001). The majority of notes concern the city of Cracow and places with high political, economical, scientific or cultural importance. Bujak (1932) initiated studies related to this topic. The first volume was published by Walawender (1932) and covered the 1450–1586 period. The successive studies of Walawender's team focused on the periods 1587–1647 (Werchracki 1938), 1648–1696 (Namaczyńska 1937) and 1772–1848 (Szewczuk 1939). Publication of the volume covering 1697–1750 prepared by Jukniewicz (1937) was interrupted by the war. As a result, part of the volumes prepared by Werchracki (1938) and Jukniewicz (1937) remained only in the form of short reports and the original volumes were not preserved. The fifteenth and sixteenth centuries are rich with chronicles; in turn the seventeenth century is full of diaries and letters (Limanówka 2001). The different works contain many gaps, which were partially completed by Rojecki (1965). The amount of meteorological information increases by the end of the seventeenth century, when first instrumental observations became available (Hanik 1972). Long-term climate (mainly temperature and precipitation) reconstructions for the last centuries were presented by Sadowski (1991), Limanówka (1996, 2000, 2001), Trepińska (1997), Bokwa et al. (2001), Majorowicz et al. (2001, 2004), Niedźwiedź (2004), Przybylak et al. (2004, 2005), Büntgen et al. (2007), Šafanda and Majorowicz (2009, this issue) and Majorowicz (2009, this issue). For more details, see Przybylak (2007) and Part 2.

Poland lies in the center of Europe and its climate represents roughly an average climate of Europe (continental climate dominating in eastern Europe and maritime climate occurring in western Europe). Winter temperature in Poland correlates very well with most of Europe as the atmospheric circulation is a main factor influencing climate variations in Poland (see results). The local modifications are rather small because the country is relatively flat. Less than 1% of the Polish area is above 1,000 m and the climatic impact of the Baltic Sea is restricted to a relatively thin belt stretching 50 km along the coast (Woś 1999).

Trenberth (1990) points to the fact that the atmospheric circulation is the main forcing factor for the regional variability of temperature and precipitation. Advective processes exerted by the atmospheric circulation are a crucial factor controlling regional changes of temperature and precipitation. This influence is stronger during winter due to the heat capacity of the underlying surface. Low- and high-frequency variations in air temperatures (year-to-year, decade-to-decade) are far from uniform but occur in distinctive large-scale patterns (Trenberth 1995). Regional or local climate is generally much more variable than climate on a hemispheric or global scale because variations in one region are partially balanced by opposite variations elsewhere (e.g. Mann et al. 2000; Jones and Mann 2004). Indeed a closer inspection of the spatial structure of climate variability, in particular on seasonal and longer time scales, shows that it occurs predominantly in preferred large-scale and geographically anchored spatial patterns (e.g. Baldini et al. 2008). Such patterns result from interactions between the atmospheric circulation and the land and ocean surfaces.

In the context of future climate change one question that is often not considered is the amplitude of regional deviations from the global warming trend, which can be caused by particular sensitivity of the region to external forcing or to internal dynamics, and which can be seasonally dependent. In particular the comparison of regional climate reconstructions and model simulations at regional scales can shed light on the skill of the models to represent realistically the regional variability, and therefore to estimate the amplitude of possible regional multidecadal deviations against the backdrop of a global warming trend (see also Luterbacher et al. 2009; Zorita et al. 2009).

This work attempts to better understand the interannual-to-interdecadal Polish winter precipitation and temperature variability within the reconstruction/observation period in comparison with continental European climate variations covering the last centuries. We will compare the findings with outputs of two GCMs (ECHO-G and HadCM3) and discuss the physical processes behind those variations. The role of the large-scale atmospheric circulation dynamics/forcing connected with the observed winter temperature and precipitation changes over Poland will be investigated both in the reconstructions and in the model world.

Sections 1.2 and 1.3 briefly describe the datasets (instrumental, reconstructions, GCMs) and the multivariate methods used for this study. The results Section 1.4.1 shows the winter temperature and precipitation evolution over Poland in comparison to Europe back to 1500 within the reconstructions and the ECHO-G and HadCM3 simulations. Further, the relationship between important atmospheric teleconnection patterns and the winter air temperature and precipitation variability over Poland within the last approximately 60 years is investigated in Section 1.4.2. This will provide a first impression on the role of simple circulation indices in driving climate variability over Poland and how the influence changes in space and time. Section 1.4.3 expands on Section 1.4.2 and performs a canonical correlation analysis (CCA) between a new gridded North Atlantic European sea level pressure dataset and Polish winter temperature and precipitation over the 1750–1990 period both using reconstruction/instrumental and model data (ECHO-G and HadCM3). Thus, this part assesses the driving atmospheric large-scale patterns behind recent and past climate anomalies in Poland. The conclusions are presented in Section 1.5.

1.2 Data

1.2.1 Instrumental and Reconstructed Data

Rather than using station data from Poland, we restricted our analysis to gridded high spatial resolution data as this allows us for a better comparison with outputs of GCMs. We used the European mean winter (DJF) surface air temperature reconstructions over land on a 0.5° × 0.5° grid by Luterbacher et al. (2004, updated using only long temperature series and temperature indices as predictors; Xoplaki et al. 2005; Luterbacher et al. 2007), which are calibrated against the CRU TS2.1 (Mitchell and Jones 2005). The reconstructions are seasonally resolved from 1500 to 1658, when only proxy data (tree-rings, ice cores, documentary-based temperature indices, sea ice information) are available. Thereafter, early instrumental data are also used in the reconstruction approach and the fields are available on a monthly resolution. After around 1760, the main information in these reconstructions comes from early instrumental data (see also Brázdil and Dobrovolný 2009, this issue; Dobrovolný et al. 2009). The reconstructions were used until 1900 and substituted with observation-based data (Mitchell and Jones 2005) thereafter.

Similar as for temperature, seasonal European precipitation was reconstructed by Pauling et al. (2006) back to 1500. Reconstructions are based on a large variety of long instrumental precipitation series, precipitation indices based on documentary evidence (e.g. Brázdil et al. 2005 for a review) and natural proxies that are sensitive to precipitation signals. The Mitchell and Jones (2005) data were used for calibration and to extend the reconstructions from 1901 to 2002. For more information related to the reconstruction technique and the data used, the reader is referred to the corresponding literature (Luterbacher et al. 2002, 2004; Pauling et al. 2006).

For our purposes we extracted temperature and precipitation for Poland (14.25°E–24.25°E; 49.25°N–54.75°N) consisting of 252 grid points. The area of Poland thus accounts to approximately 4% of all the grid cells of European land areas. The reconstruction method is designed to capture continental-scale temperature and precipitation fields (Luterbacher et al. 2004, 2007; Xoplaki et al. 2005; Pauling et al. 2006). Small-scale variations are not resolved by definition. Therefore, care should be given in the interpretation if a selection of grid points is used.

We used the new gridded 5° × 5° resolved seasonal sea level pressure (SLP) data produced by Küttel et al. (2009). For the first time terrestrial, instrumental station pressure series and maritime wind information derived from ship log data were combined and statistically extrapolated to a regular grid covering the North Atlantic, Europe and the Mediterranean. This dataset proved to more adequately capture the SLP variability over the North Atlantic than existing sea level pressure reconstructions (e.g. Luterbacher et al. 2002) before the first instrumental SLP measurements in Iceland (Reykjavík in 1821) and Madeira (Funchal in 1850) became available. Furthermore, the new SLP reconstruction does not share any common predictors with reconstructed European temperature (Luterbacher et al. 2004, 2007; Xoplaki et al. 2005) and precipitation reconstructions (Pauling et al. 2006), thus it can be used independently to assess the driving atmospheric patterns behind recent and past climate anomalies. In our analysis we relate this new SLP dataset (40°W–50°E; 20°N–70°N; total consisting of 209 grid points) to winter temperature and precipitation over Poland for the last approximately 250 years using Canonical Correlation Analysis (CCA).

In order to get a first insight on the connection between the atmospheric circulation and the winter (DJF) air temperature and precipitation variability over Poland (using CRU TS3.0 which is an updated version of Mitchell and Jones 2005), a simple correlation (Spearman) analysis of important teleconnection patterns of the Northern Hemisphere is performed. Three anomaly patterns were considered, namely the North Atlantic Oscillation (NAO; Barnston and Livezey 1987), the East Atlantic/Western Russia pattern (EA/WRUS referred to as the Eurasia-2, EU2, pattern by Barnston and Livezey 1987) and the Scandinavian pattern (SCAND; Barnston and Livezey 1987), which are expected to exert an influence on Polish climate.

1.2.1.1 North Atlantic Oscillation (NAO)

The North Atlantic Oscillation (NAO) is the most important large-scale mode of climate variability in the Northern Hemisphere. The NAO describes a large-scale meridional vacillation in atmospheric mass between the North Atlantic regions of the subtropical anticyclone near the Azores and the subpolar low pressure system near Iceland (e.g. Wanner et al. 2001 and references therein). Synchronous strengthening (positive NAO phase) and weakening (negative NAO phase) have been shown to result in distinct, dipole-like climate anomaly patterns between western Greenland/Mediterranean and northern Europe/northeast US/Scandinavia. The monthly derived index (NAOI) is taken from the Climate Prediction Center (CPC) at: http:/www.cpc.ncep.noaa.gov/data/teledoc/telecontents.html.

1.2.1.2 East Atlantic/Western Russia Pattern (EA/WRUS)

The East Atlantic/Western Russia (EA/WRUS) pattern is one of the two prominent patterns that affect Eurasia during most of the year. This pattern is prominent in all months except June–August, and has been referred to as the Eurasia-2 (EU2) pattern by Barnston and Livezey (1987). In winter, two main anomaly centres, located over the Caspian Sea and western Europe, comprise the EA/WRUS pattern. A three-celled pattern is then evident in the spring and autumn seasons, with two main anomaly centres of opposite sign located over western-northwestern Russia and over northwestern Europe. The third centre, having the same sign as the Russia centre, is located off the Portuguese coast in spring. The monthly derived index (EA/WRUS-I) is taken from the Climate Prediction Center (CPC) at: http:/www.cpc.ncep.noaa.gov/data/teledoc/telecontents.html.

1.2.1.3 Scandinavian Pattern (SCAND)

The Scandinavian (SCAND) pattern consists of a primary circulation centre, which spans Scandinavia and large portions of the Arctic Ocean north of Siberia. Two additional weaker centres with opposite sign to the Scandinavia centre are located over western Europe and over the Mongolia/western China sector. The SCAND pattern is a prominent mode in all months except June and July and has been previously referred to as the Eurasia-1 pattern by Barnston and Livezey (1987). The positive phase of this pattern is associated with positive height anomalies, sometimes reflecting major blocking anticyclones, over Scandinavia and western Russia, and negative anomalies over the Iberian Peninsula and northwestern Africa. The SCAND pattern plays a considerable role in precipitation variability over Europe (Wibig 1999). The corresponding monthly index (SCAND-I) stems from the CPC at: http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.html.

1.2.2 Model Data

1.2.2.1 ECHO-G Temperature and Precipitation Data

ECHO-G is a coupled atmosphere-ocean general circulation model (AOGCM), consisting of the ECHAM4 atmospheric general circulation model and the Hamburg Ocean Primitive Equation model HOPE-G, which includes a dynamic-thermodynamic sea-ice model with snow cover. Both components were developed at the Max-Planck

Institute for Meteorology in Hamburg and coupled with the OASIS-Software. The atmospheric component ECHAM4 has a horizontal resolution of T30 (approx. 3.75° × 3.75° longitude/latitude) and 19 levels along the vertical direction, five of them located above 200 hPa, the highest being 10 hPa, thus having a rather coarse resolution of the stratosphere. The oceanic component HOPE-G has a resolution of approx. 2.8° × 2.8° longitude/latitude, with a decrease in meridional grid point separation towards the equator to a value of 0.5°. This enables a more realistic representation of equatorial ocean currents. HOPE-G has 20 levels along the vertical direction. Due to the interactive coupling between ocean and atmosphere and the coarse model resolution, ECHO-G needs a constant mean flux adjustment to avoid a significant climate drift. Thus additional fluxes of heat and freshwater are applied to the ocean. This flux adjustment is constant in time and its global integral vanishes. In this comparison, the 'Erik-the-Red' run of ECHO-G is used (von Storch et al. 2004; González-Rouco et al. 2006). This simulation includes natural (solar irradiance and the radiative effect of volcanic eruptions) and anthropogenic (greenhouse gases) forcing over the period 1000–1990.

For the CCA (see below) between the large-scale winter atmospheric circulation and Polish winter temperature and precipitation variability back to 1750 we used the same spatial area as for the reconstructions/instrumental data set. For SLP we selected 350 grid points representing the area 40°W–50°E; 25°N–70°N while for temperature and precipitation only six grid points representing Poland were chosen.

1.2.2.2 HadCM3 Temperature and Precipitation Data

As ECHO-G, HadCM3 is a state-of-the-art AOGCM. Unlike ECHO-G, no flux adjustment to prevent large climate drifts is applied in the model HadCM3. However, a small long-term climate drift is still present, the magnitude of which is estimated from a long control run. This drift is then corrected from the temperature data of the present simulation (Tett et al. 2007). The atmospheric component HadAM3 is a version of the United Kingdom Meteorological Office (UKMO) unified forecast and climate model with a horizontal grid spacing of 2.5° (latitude) × 3.75° (longitude) [the T-resolutions apply only to spectral models]. HadAM3 is a finite-difference model and has 19 levels along the vertical direction. The ocean component has 20 levels with a spatial resolution of 1.25° × 1.25° degrees thus resulting in six ocean grid cells to one atmosphere grid cell. The resolution is higher near the ocean surface, making it therefore possible to represent important details in oceanic current structures. The sea ice model uses a simple thermodynamic scheme including leads and snow-cover. In this study, two HadCM3 runs were merged: a natural-forcings run from 1500 to 1749 and an all-forcings run spanning the period 1750–1999. The natural-forcings run is driven by prescribed changes in volcanic forcing, solar irradiance and orbital forcing, while anthropogenic forcing factors were fixed at estimated pre-industrial values. The all-forcings run on the other hand is driven by prescribed changes in volcanic forcing, solar irradiance, orbital forcing, greenhouse gases, tropospheric sulphate aerosol, stratospheric ozone and land-use/land-cover.

For the CCA between the large-scale winter atmospheric circulation and Polish winter temperature and precipitation variability back to 1750 we used the same spatial area as for the reconstructions/instrumental data set. For SLP we selected 525 grid points whereas for temperature and precipitation nine grid points representing Poland were extracted.

There are relevant differences in the implementation of some of the external forcings in both models. The most important comprise the volcanic forcing. Whereas in ECHO-G the overall radiative effects of the volcanic aerosols on the radiation balance is implemented as a global change in the effective solar constant, in HadCM3 the prescribed radiative properties of the volcanic aerosols are explicitly represented for several latitudinal bands. Also, in HadCM3 the effect of aerosols in the short-wave and infrared spectral bands is treated separately, whereas in ECHO-G only the integrated change in the radiative forcing is parameterised within the solar forcing. The amplitude of the past changes of solar irradiance is also slightly different in both model simulations. In the ECHO-G simulation the changes between present and the Late Maunder Minimum amount to 0.3% of the total solar constant, whereas in the HadCM3 simulation the solar irradiance is assumed to have changed by 0.25% (Tett et al. 2007) between these two periods.

Another difference is that the HadCM3 simulation is also driven by tropospheric aerosols in the twentieth century. Its radiative forcing is most strongly felt in Northern summer in the twentieth century. The ECHO-G simulation does not include tropospheric aerosols.

Finally, the forcings in the HadCM3 simulation include changes in the land-use, which in Europe have been especially large in the past centuries. The increasing surface albedo associated with deforestation and expanding agricultural lands leads to more shortwave radiation being reflected back to space and, other factors remaining unchanged, to lower surface temperatures. This effect is missing in the ECHO-G simulation, which does not consider past land-use changes.

In general, the implementation of some of the forcings in the HadCM3 runs, specially volcanic and tropospheric aerosols, is a priori more realistic than in the ECHO-G runs.

1.3 Methods

1.3.1 Canonical Correlation Analysis (CCA)

To assess the connection between the new gridded large-scale SLP data of Küttel et al. (2009) and Polish winter temperature and precipitation both in the reconstruction/instrumental and model world, we calibrated a downscaling model using CCA in the empirical orthogonal function (EOF) space and subsequently validated this model by means of cross-validation (e.g. Michaelson 1987). To be consistent with the length of the three different data sets, we applied CCA over the common period 1750–1990. Only a short overview of the methods used is provided here, for a detailed description of the methodology the reader is referred to Barnett and Preisendorfer (1987), Wilks (1995) and von Storch and Zwiers (1999). Before performing the CCA, the original data were projected onto their EOFs retaining only a limited number of them, accounting for most of the total variance in the datasets. As a preliminary step to the calculation of EOFs, the annual cycle was removed from all station and grid point time series by subtracting from each winter value the 1750–1990 long-term mean. The gridded predictor data were then weighted by multiplying with the square root of the cosine of latitude to account for the latitudinal variation of the grid area (North et al. 1982; Livezey and Smith 1999). A further step to ensure the stationarity of the variables needed for the calculation of EOFs and CCA was to detrend the time series. A standard linear least square fit method has been used as described for example by Edwards (1984). After the diagonalisation of the covariance and cross-correlation matrices during the EOF and CCA processes, the long-term trends were recovered by regressing the original datasets onto their EOFs or canonical vectors as in Busuioc and von Storch (1996). This provides estimations of the principal components and canonical series with long-term variability and trends. We have used five EOFs of Polish temperature and Polish precipitation as well as of large-scale SLP for the reconstructions and the model data. To calculate the statistical models during cross-validation in all exercises we used all five canonical vectors. The cross-validation was applied by discarding one winter from the data set in each step and then predicting them, based on the remaining data. This process was repeated for each winter in the 1750–1990 record (e.g. von Storch and Zwiers 1999). The performance of the statistical model was evaluated by calculating the correlation between the predicted and the raw data. The correlation provides a measure of time concordance in the series.

1.4 Results and Discussions

1.4.1 Comparing Winter Temperature and Precipitation Over Poland and European Land Areas in Reconstructions and in the Model World

This section characterises the seasonal temperature and precipitation evolution of Poland extracted from Luterbacher et al. (2004) and Pauling et al. (2006) covering the past 500 years. It highlights the relation between the temperature/precipitation evolution over Poland compared to the European average. This will shed light on the importance of that part of Europe in explaining seasonal temperature and precipitation changes at continental scales and how stable those connections are through time. Apart from multiproxy temperature and precipitation reconstructions updated with new gridded instrumental data (Mitchell and Jones 2005), we also use simulation data from the coupled global climate models ECHO-G (von Storch et al. 2004; González-Rouco et al. 2006) and HadCM3 (Tett et al. 2007). The rationale behind this comparison is on the one hand to test the realism of the models in simulating the subcontinental regional variability at multidecadal time scales. On the other hand, this analysis will help to support specific aspects of the reconstructions with model results that may possibly be uncertain, as for instance the robustness of the large- to regional-scale links found in the instrumental period and their stability with time in a multicentennial context.

Figure 1.1 shows the standardized winter (DJF) temperature evolution of Poland and European land areas (excluding Poland) over the past 500 years presented by Luterbacher et al. (2004) and as simulated by the ECHO-G and HadCM3 models.

The correlation (at interannual and multidecadal time scales) between reconstructed Poland and European mean temperatures (excluding the grid points representing Poland) over the full 500 year period is 0.96 (Fig. 1.1 top row). Similar high values are found if only twentieth century instrumental data are used. It shows the generally below normal winter conditions through a large part of the so-called 'Little Ice Age' with lowest values within the Late Maunder Minimum period (late seventeenth/early eighteenth century), a short warming period until the late 1730s (see Luterbacher et al. 2004, 2007; Jones and Briffa 2006), followed by colder conditions again. The twentieth century instrumental period is characterised by a temperature increase with the very likely highest values at the turn of the twenty first century (see also Luterbacher et al. 2004, 2007 for details). The very strong relationship between Polish winter and European temperatures both at interannual and interdecadal time scale is of major interest since some of the longest temperature proxy information stem from Poland (e.g. Sadowski 1991; Trepińska 1997; Bokwa et al. 2001; Majorowicz et al. 2004; Przybylak et al. 2005; Büntgen et al. 2007; Šafanda and Majorowicz 2009; Majorowicz 2009; see also Parts 2 and 3 of this book) which can improve European seasonal mean temperature reconstructions significantly.

Figure 1.2 presents decadally averaged winter (DJF) air temperature anomalies for the last 500 years for Poland with respect to the 1901–1960 reference period (Przybylak et al. 2005). Reconstructed 10-year mean winter air temperatures for parts of Poland based on documentary sources (that have not been used by Luterbacher et al. 2004, thus can be considered as independent) covering the period from 1501 to 1840 (Przybylak et al. 2005) were generally lower than the air temperatures occurring in the twentieth century (see detailed description and presentation of available long-term climate time series from Poland presented in Part 2 on Chapter 5, Przybylak 2009). The coldest winters, on average, occurred in the decade 1741–1750 (anomaly −3.7°C with respect to the 1901–1960 reference period). The warm period in the 1730s shown in Fig. 1.1 (see also Jones and Briffa 2006) is not present in Poland's temperature reconstruction (Fig. 1.2). According to Przybylak et al. (2005), winters in this decade were colder by about 2°C. In Czech Lands (Brázdil 1996) they were near the long-term average.

Large negative anomalies were observed in the following decades: 1541–1550, 1571–1580, 1591–1600, 1641–1650, 1651–1660 and 1771–1780. On the other hand, warm winters, on average, occurred in the first and third decades of the sixteenth century, and in the seventeenth century, except for the periods from 1630 to 1660 and from 1680 to 1700. A visual comparison of these results with the Luterbacher et al. (2004) European mean reconstruction (see Fig. 1.1, top panel) indicates that there is generally good agreement mainly for the first approximately 200 years with

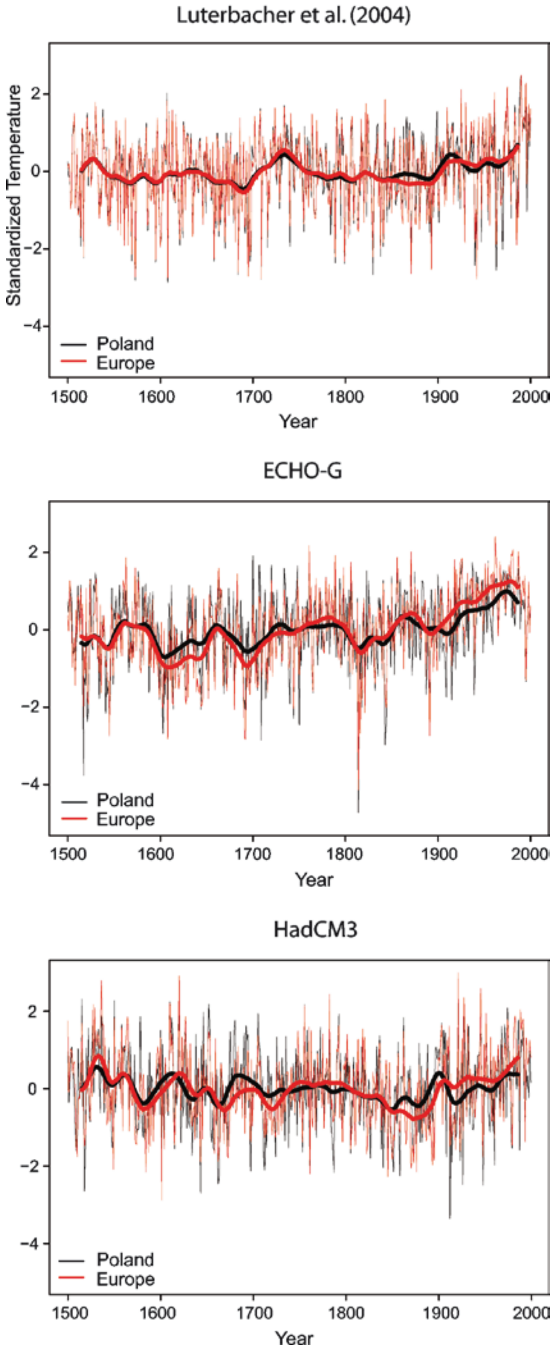

Fig. 1.1 Standardized winter mean temperatures of Poland (black line) and European land areas (excluding Poland, red line) 1500–2000 as reconstructed by Luterbacher et al. (2004, top panel), simulated by ECHO-G (von Storch et al. 2004; González-Rouco et al. 2006, middle panel) and HadCM3 (Tett et al. 2007, bottom panel). The thick lines denote the 30-yr running means

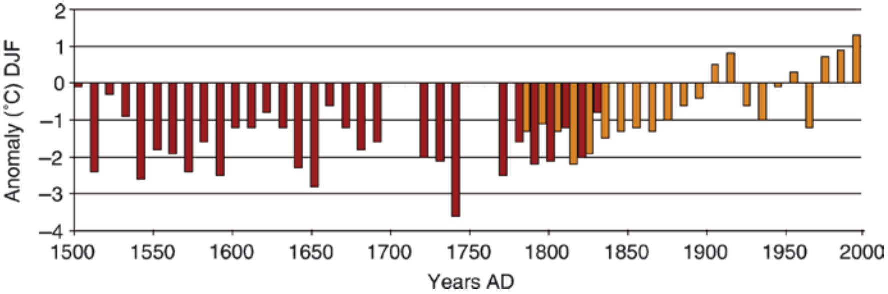

Fig. 1.2 Decadally averaged winter (DJF) air temperature anomalies for Poland with respect to the 1901–1960 reference period. *Dark red bars* present reconstructions based on documentary evidence (Przybylak et al. 2005), *Orange bars* (observation from Warsaw) are taken from Lorenc (2000)

below normal conditions. However, differences are found for instance at times when the lowest and highest winter temperatures occurred: documentary evidence from Poland indicates that in the seventeenth century the coldest winters occurred rather in the first half of the Late Maunder Minimum (Przybylak et al. 2005). A major difference is also the European winter warming trend starting in the late seventeenth century until the first decades of the eighteenth century (Fig. 1.1, top panel) (Luterbacher et al. 2004, 2007) which is not supported by the study of Przybylak et al. (2005) which either has gaps in the series or points to colder conditions. Despite these differences the estimated winter temperatures lay both within the uncertainty ranges of each other (not shown).

The match between the grid points representing Poland and Europe mean winter temperature in the model (in the corresponding model grid-cells) is similar to the reconstructions (Fig. 1.1). The correlations at interannual to multidecadal time scales are highly significant for ECHO-G and HadCM3, indicating that the correlation across space is in agreement in the models and the reconstructions. The ECHO-G winter temperature for Europe and Poland points to a slight overall warming from 1500 to the late 20th century, with minima around the end of the seventeenth and the beginning of the nineteenth centuries. There is a discernible acceleration of the warming trend within the twentieth century that leads to the highest temperatures at the end of the century. The overall long-term trend appears somewhat larger than in the reconstructions. The European/Poland winter temperature evolution within the HadCM3 model does not indicate an overall trend within the last half millennium and the warming in the twentieth century seems to be smaller than in ECHO-G and in the reconstruction/observations. The HadCM3 simulation does not display distinctive minima around the Late Maunder Minimum period. Concerning the interannual variability, the reconstructions display larger variations than in both simulations, in particular for the European average temperatures.

One reason for the stronger coherency in the reconstructions/instrumental data could be the inclusion of land and ocean grid points in the model simulations. Considering Fig. 1.3 (see below), both models and the instrumental data yield a very similar spatial correlation pattern between Polish mean temperature and the European field, whereas the reconstructions display longer spatial coherence, in particular in the zonal direction (in the meridional direction all four data sets seem quite similar). One speculation could be that in the reconstructions the variations in the zonal circulation have been more effective in modulating the winter temperature over the continent, whereas in the model it seems not to be so much the case. Possibly, this is linked with the inability of both models to produce warm episodes such as in 1730 (Jones and Briffa 2006; Zorita et al. 2009), and with the inability of models in general to reproduce the low-frequency variability of the NAO in the twentieth century (Osborn 2004). In summary the model swings of the NAO would be too short-lived and too weak, and this reflects in lower spatial temperature coherence, in particular in the zonal direction. It might be worth exploring this in more detail in future studies.

In general the HadCM3 simulation displays less long-term variability than the ECHO-G simulation, but there are also clear differences between both simulations and the reconstructions. The differences between model simulations can be due to the different magnitude of the changes in past solar forcing that are smaller in the HadCM3 simulations than in the ECHO-G simulation. However, it is difficult to explain some of these differences by invoking the external forcing alone. In the case of ECHO-G the total external forcing may be overestimated, due to the missing cooling effect of tropospheric aerosols in the twentieth century and the coarse representation of the volcanic forcing (in the model it can only induce cooling, whereas in reality tropical volcanic eruptions may induce a transient winter warming at middle and high latitudes due to atmospheric circulation anomalies, (Stenchikov et al. 2006). Also the magnitude of the long-term past solar changes is uncertain. One difference between the simulations and the reconstruction that is not likely to be dependent on the prescribed forcing is the level of interannual variability, which is larger in the reconstructions. A possible reason is that the reconstructed data are basically the result of a linear combination of a limited number of local proxy and documentary records, whereas in the models, the grid-cell values represent spatial averages over the whole grid-cell. This sampling effect alone would cause higher interannual variations in the reconstructions, although it is difficult to quantify whether or not it can completely explain the gap between simulations and reconstructions.

Figure 1.3 presents the spatial Pearson correlation maps between the average winter temperature of Poland (14.25°E–24.25°E; 49.25°N–54.75°N) and European land areas for the past 500 years (400 years reconstructions, the last 100 years gridded CRU data) and for the two GCMs. Approximately, 20 Polish station series are included in the gridded CRU TS3.0 dataset.

Except for the Icelandic area and the very southeast, the correlation between Poland winter temperature and European grid cells is highly significant. Thus, Fig. 1.3 underlines the strong connection between the area of Poland and most European areas (Poland excluded, Fig. 1.1) and the strong consistency between reconstructions/instrumental and model data.

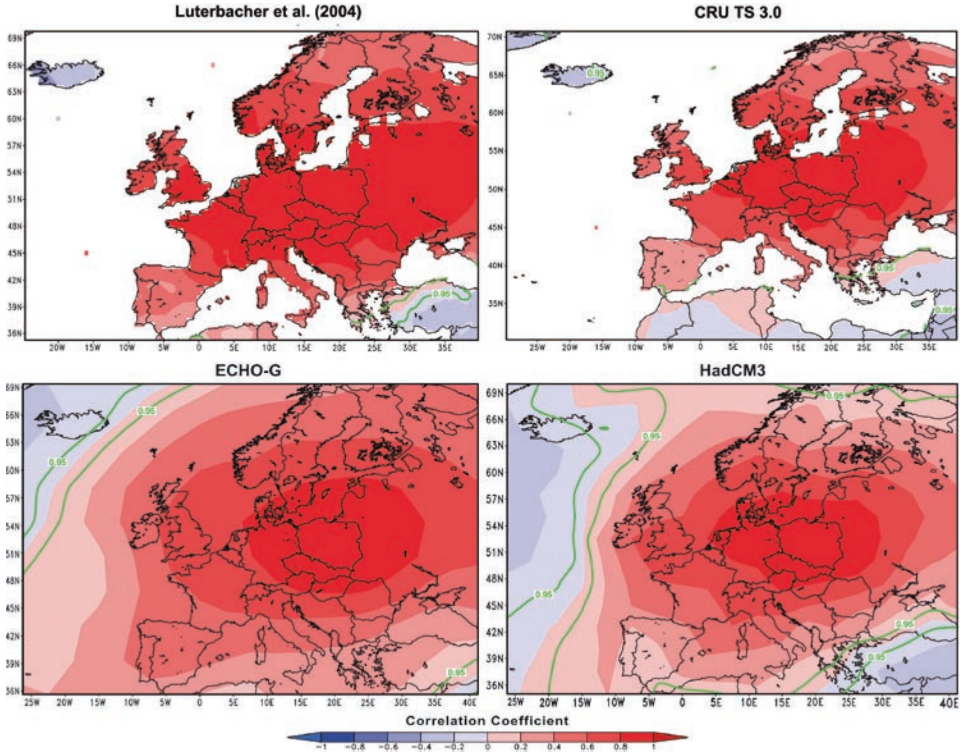

Fig. 1.3 (*top left*) Spatial correlation maps between winter temperature averaged over Poland (14.25°E–24.25°E; 49.25°N–54.75°N) and European land areas over the past 500 years (Luterbacher et al. 2004), (*top right*), as top left but for the instrumental period 1901–2006 (using CRU TS3.0); (*bottom left*) Spatial correlation maps between winter temperature averaged over Poland (15°E–22.5°E; 50.625°N–54.375°N) and Europe for the period 1500–1990 within the ECHO-G model (von Storch et al. 2004; González-Rouco et al. 2006); (*bottom right*) as bottom left but for 15°E–22.5°E; 50°N–55°N, the period 1500–1999 and the HadCM3 model (Tett et al. 2006). The significant areas (95% level) are marked in green contours

This result supports the ability of models to represent the regional climate variations in the frame of the European scale. The similar correlation patterns obtained from model and reconstructed and instrumental data indicates that the spatial correlation structure of the temperature field is well captured by the models. In addition, some minor features found in the reconstruction and in observations such as the smaller areas of negative correlations over Iceland and the eastern Mediterranean are also supported by both models at multicentennial time scales.

Precipitation is spatially and temporally more variable than temperature. However, the reconstructed winter precipitation over Poland (Pauling et al. 2006) also agrees very well with the entirety of Europe (Poland excluded; Fig. 1.4, top panel). The correlation at interannual and multidecadal time scales accounts for 70% of the total variance. The agreement is smaller in the model world (ECHO-G: interannual winter 0.19; multidecadal 0.41; HadCM3 interannual winter 0.04; multidecadal 0.39). One reason for the differences between reconstructions and models may be that in the mean model precipitation the whole Mediterranean Sea is included that returns negative correlations with Polish precipitation, whereas the average mean in the reconstruction only includes land areas. Another reason might be due to the reduced number of PCs reconstructed. The principal component regression used for the reconstructions may impose a spatial homogeneity upon the reconstructed data that is not so strongly present in the instrumental data. Very likely this effect is stronger for precipitation where the EOF filtering would be relatively stronger because of the noisy character of precipitation.

There is no overall trend visible in the precipitation reconstructions (Fig. 1.4). The discrepancies between Poland and Europe (excluding Poland) can be found in the early twentieth century with wetter (drier) conditions in Poland (Europe). The end of the twentieth century is characterised by wetter overall European winter conditions but lower values in Poland.

The model simulations do not display clear long-term trends for winter precipitation either. Only the ECHO-G simulation shows a small non-significant trend along the 500 year period towards wetter conditions. The low-frequency variability in the model simulations is comparable to the one in the reconstructions, but the interannual variability is larger in both simulations, in particular in the early two centuries. The reconstructed interannual variability increases along the 500 year period, but this could be due to missing information in the proxy and documentary records in the early period. In general, the model simulation indicates quite stable precipitation conditions over the full half millennium. Precipitation is known to be a variable with a high level of internal variations, and more so at regional scales, and it is more difficult to detect the influence of external forcing. This happens also in simulations for future climate with larger variations in the external forcing than in the past millennium (Barnett et al. 2004).

Figure 1.5 presents the spatial Spearman correlation maps between the average winter precipitation of Poland and European land areas for the past 500 years (Pauling et al. 2006), the last 100 years of gridded CRU TS3.0 data and within the two GCMs. The spatial correlation patterns are less homogenous compared to winter temperature conditions (Fig. 1.3) but generally indicate similar results. As in the

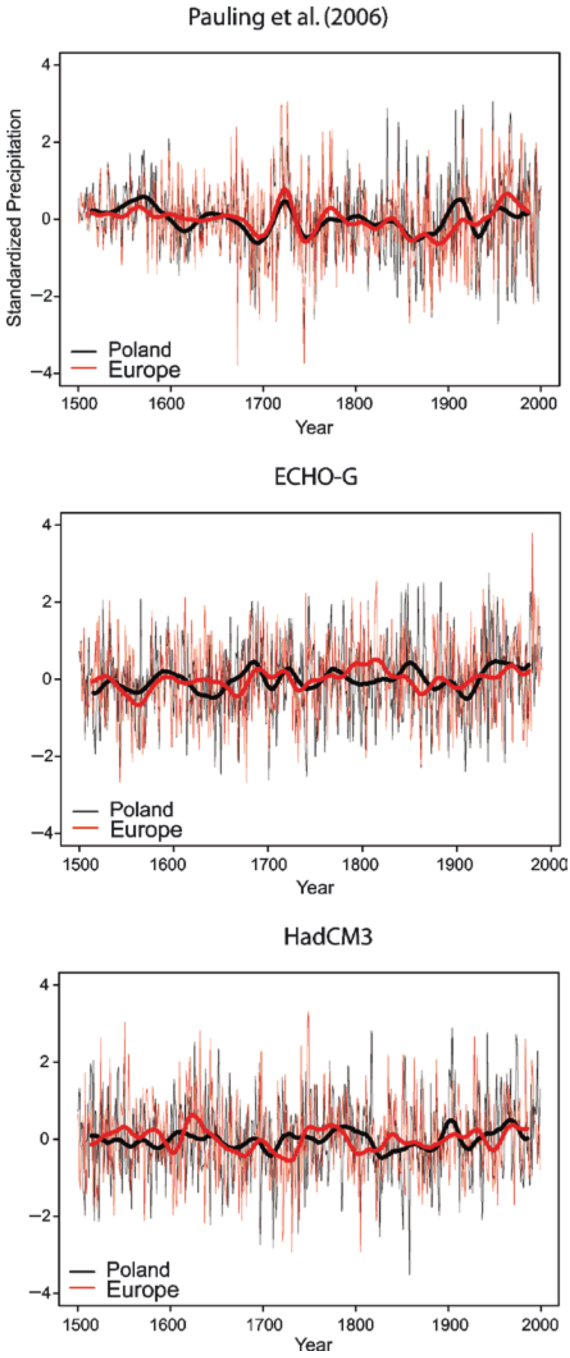

Fig. 1.4 As Fig. 1.1, but for precipitation

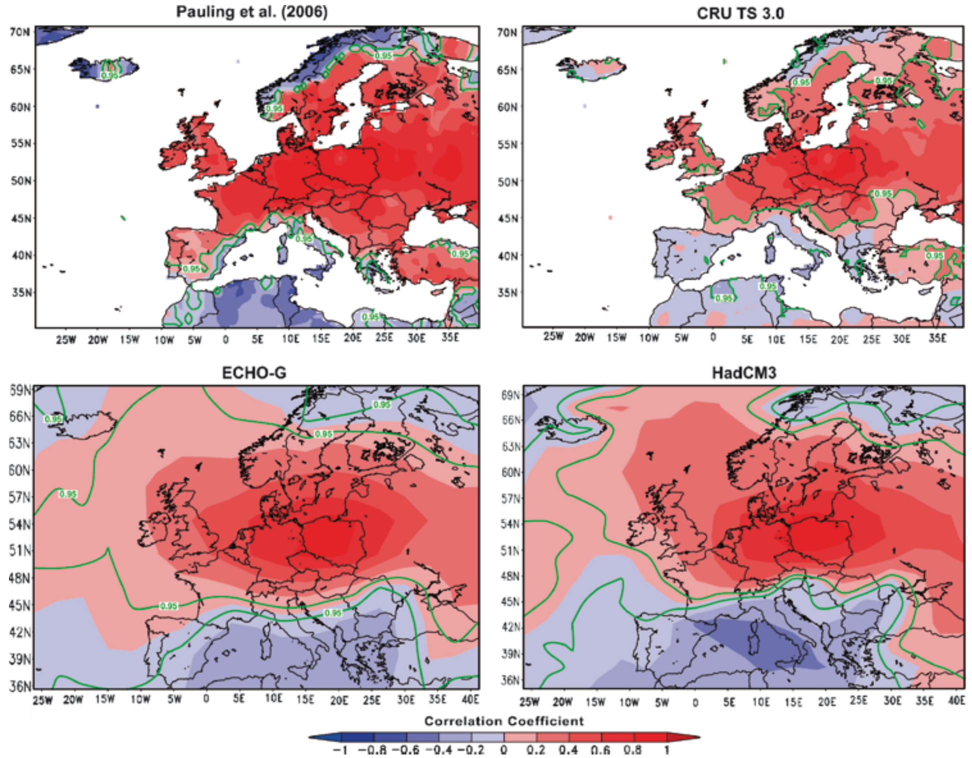

Fig. 1.5 (*top left*) Spatial correlation maps between winter precipitation averaged over Poland (14.25°E–24.25°E; 49.25°N–54.75°N) and European land areas over the past 500 years (Pauling et al. 2006), (*top right*), as top left but for the instrumental period 1901–2006 (using CRU TS3.0); (*bottom left*) Spatial correlation maps between winter precipitation averaged over Poland (15°E–22.5°E; 50.625°N–54.375°N) and Europe for the period 1500–1990 within the ECHO-G model (von Storch et al. 2004; González-Rouco et al. 2006); (*bottom right*) as bottom left but for 15°E–22.5°E; 50°N–55°N, the period 1500–1999 and the HadCM3 model (Tett et al. 2006). The significant areas (95% level) are marked in green contours

case of winter temperature the spatial patterns of the reconstructions/last 100 year instrumental data and GCMs are consistent with significant positive correlations generally over northern and eastern Europe and negative correlations in the Mediterranean area. The signal is weaker than temperature but still large parts of Europe show coherence with mean Polish winter precipitation.

The spatial coherency of precipitation in the models seems more similar to the observations, whereas the reconstructions display high correlations over longer distances. This could be due to the PC basis of the reconstructions (see above).

The next section sheds some light on the relation between selected atmospheric teleconnection indices and Polish winter temperature and precipitation.

1.4.2 Spatial Correlation Analysis Between Polish Winter Precipitation and Temperature with Teleconnection Indices

For the period 1950–2006 correlations between the Polish winter temperature and precipitation (using CRU TS 3.0, of gridded CRU TS3.0 data) and the NAOI (e.g. Barnston and Livezey 1987), SCAND-I (Barnston and Livezey 1987) and the EA/WRUS-I (Barnston and Livezey 1987) were calculated (Fig. 1.6).

The spatial correlation pattern demonstrates that winter temperature over Poland is significantly positively correlated with the North Atlantic Oscillation Index (NAOI, $p<0.05$). More than 50% of the winter temperature variations can be accounted for by the influence of this index. For the longer period (1780–1990) Przybylak et al. (2003) found approximately a twice as small influence of the NAO on winter temperature in Warsaw. The spatial correlation map between the winter NAO and winter precipitation over Poland reveals a dipole pattern with positive (negative) correlations in the north (south). The NAO explains approximately 25–30% of the winter precipitation variations in the northwest and southeast of Poland (Fig. 1.5 bottom). Winter precipitation in Poland was also analysed in relation to circulation patterns at 500 hPa level by Wibig (1999). Monthly precipitation totals from 12 Polish stations from the period 1951–1990 were correlated with circulation patterns defined as rotated principal components of the 500 hPa geopotential heights in the Euro-Atlantic sector and generally agree with the findings in Fig. 1.6.

The spatial correlation can be explained by typical and dominant winter circulation patterns in Europe. The highly correlated areas (see also Figs. 1.3 and 1.5) indicate a clear influence of zonal circulation conditions, either through a westerly component related to mild and wet air masses from the Atlantic or through cold and mostly dry continental air from east (negative phase of the NAO or strong western Russian or Baltic high pressure system). This zonal pattern indicates a strong influence of the NAO (see also Fig. 1.6) on the European continent in winter with above normal precipitation between the British Isles and eastern Europe in positive phases (e.g. Hurrell 1995; Jones et al. 2003; Baldini et al. 2008). In periods of a negative

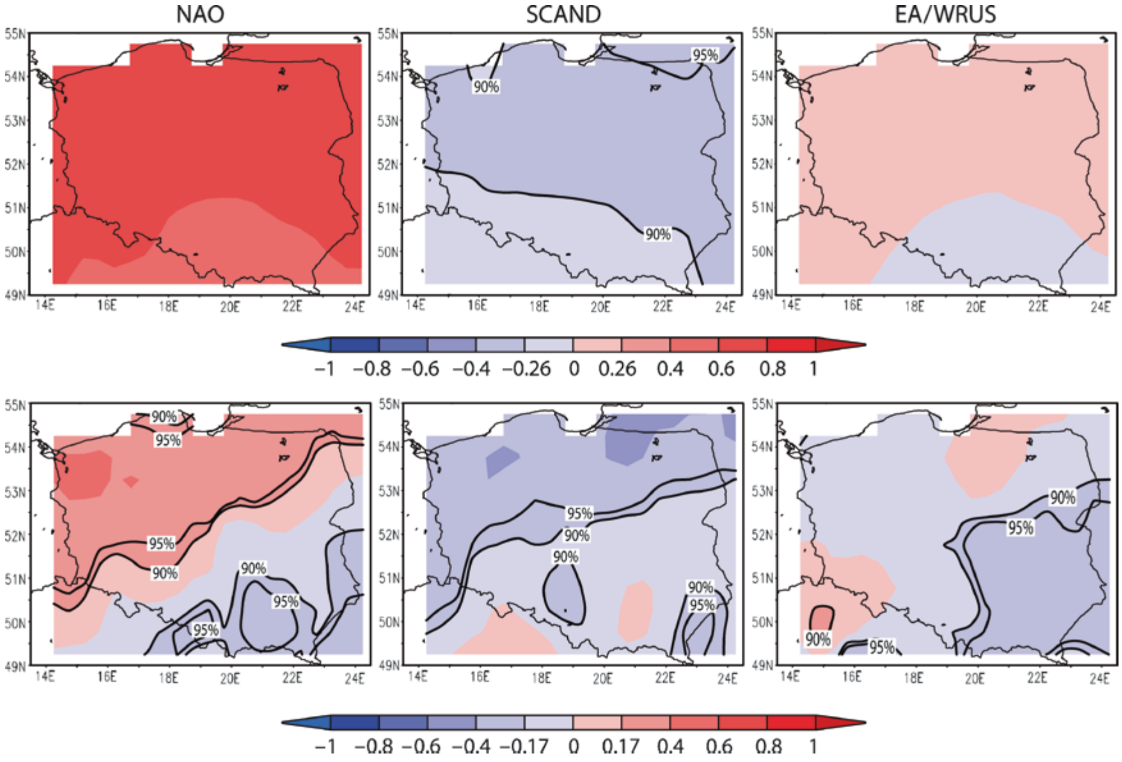

Fig. 1.6 Spatial correlation between NAO (*left*), SCAND (*middle*) and EA/WRUS (*right*) teleconnection indices and the 0.5° × 0.5° gridded CRU TS 3.0 surface air temperature (*top row*) and precipitation (using CRU TS3.0 *bottom row*) over the period 1950–2006 (indices downloaded from http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml, accessed July 12th 2008). For temperature the Pearson product-moment and for precipitation the Spearman rank correlation coefficient (e.g. Wilks 1995) was applied. Significant areas at the 90% and 95% significance levels are indicated. Note, in the NAO/temperature panel all areas are statistically significant at the 95% level

NAOI, more moisture is conveyed to the western Mediterranean whereas weaker westerly winds allow a stronger influence of cold and dry continental air masses in central and eastern Europe, including Poland. The congruence of precipitation amounts between Poland and the area between the English Channel and Russia could also be demonstrated in Stössel (2008), where the area between France and the Baltic Sea was calculated to be the most representative for explaining European winter precipitation.

The correlation between SCAND-I and Polish temperature in winter is generally negative, though significant ($p<0.1$) only in the central and northern parts. In case of a positive SCAND-I, a strong positive pressure anomaly is centred over Scandinavia and western Russia and negative anomalies over the Iberian Peninsula connected with anomalous easterlies and thus cold and dry airflow over the area of interest. Positive (negative) SCAND-I go along with negative (positive) winter precipitation anomalies in the northern parts of the country. SCAND explains around 25–30% of the winter precipitation variations in the northern parts of the country, while only 5–10% of winter temperature variations can be related to the SCAND pattern. The mountainous southern part returns mostly non-significant results.

The EA/WRUS pattern does not seem to exert any significant influence on Polish winter temperature (Fig. 1.6 top). Concerning precipitation, a significant contribution of the EA/WRUS influence on Polish winter precipitation can be found in the southeastern parts of the country (Fig. 1.6 bottom).

Wibig (2009) has shown that mean winter minimum, maximum and average daily temperature calculated from of station data (23 stations from Poland) as well as numbers of frost days in winter (days with minimum temperature equal or below 0°C) and ice days (days with maximum temperature equal or below 0°C) correlate positively with the NAO and EA indices and negatively with the SCAND-I.

Differences of sea level pressure (based on CRU grid point pressure data) and 500 hPa levels (taken from NCEP/NCAR dataset) between the 10 wettest and the 10 driest, as well as between the 10 hottest and the 10 coldest months were also analysed (Wibig 2004). During wet periods the pressure gradient over Europe was stronger and the storm tracks over the North Sea and northern Scandinavia were more frequent than during the dry ones, when the blocking situations over central Europe occurred more often. The deep Icelandic Low accompanied the inflow of warm air from the west during warmer winters. Degirmendžić et al. (2004) analyzed the sensitivity of air temperature and precipitation variations to circulation variations described by sea-level pressure in the centre of Poland (52.5°N, 20°E) and geostrophic wind calculated from meridians 45°N and 65°N and the latitudes at 10°E and 30°E. By using multiple regression it was shown that these three factors (SLP at selected grid point and both components of geostrophic wind) explain up to 77% and 44% of temperature and precipitation variability respectively. Twardosz and Niedźwiedź (2001) have shown that high precipitation events in Poland are most frequent during the northeastern cyclonic situation (NEc), north cyclonic situation (Nc), cyclonic trough (Bc) and centre of low pressure (Cc) according to typology by Niedźwiedź (1992, 2004).

Rosenzweig et al. (2008) showed that changes in biological and physical systems consistently occur in regions of observed temperature increase that itself cannot be explained by natural climate variations alone. Long-term, regional-scale dynamical analyses of temperature and precipitation variability are essential for the detection of impacts and adaption of ecosystems (Ahas et al. 2002; Menzel et al. 2006; Rutishauser et al. 2008). Often the regional impacts are related to atmospheric circulation patterns such as the NAO (Scheifinger et al. 2002; Aasa et al. 2004; Bednorz 2004; Menzel et al. 2005; Sinelschikova et al. 2007). In years with strong positive NAOI in both winter and spring, the latitudinal gradients of spring phases are smaller making the spatial pattern more uniform (Menzel et al. 2005). There is a large body of evidence that changes in general circulation impact regional temperature patterns in Poland and this, in turn, will induce changes in the timing of ecosystem processes (Bednorz 2004; Aasa et al. 2004; Menzel et al. 2005, 2006). Changes in snow cover, plant vegetation activity onset and changes in bird migration and pollen season are a few indications of climate change impact evidence. Fourteen out of 16 migratory bird species in western Poland tend to arrive earlier in the 1990s than in the 1910s (Tryjanowski et al. 2002). Tryjanowski and Sparks (2008) showed that the arrival time of white stork (*Ciconia ciconia*) in Poland during the period 1983–2003 had an impact on the duration of occupied nests and thus greater productivity. Stach et al. (2008) suggest that the severity of the birch pollen season in Poland is related to the NAOI for the period 1995–2005. However, the more remote site from the Baltic Sea, Cracow, showed only a very limited correlation with the NAO. These examples show the overall impact of climate change on regional ecosystems and human health (Stach et al. 2008) but also highlight the strong local modifications by causes not related to climate.

1.4.3 CCA Between Winter Large-Scale Atmospheric Circulation and Winter Climate Variability in Poland Back to 1750 Using Reconstructions/Instrumental Data and GCMs

1.4.3.1 CCA SLP-Polish Winter Temperature

The interannual to interdecadal covariability between Polish winter temperature and large-scale atmospheric circulation during the period 1750–1990 is presented using canonical patterns for the reconstructions/instrumental data and for the two GCMs. The results focus on the first CCA mode, since it captures most of the Polish temperature variability. Spatial patterns and expansion coefficients of the modes are presented in Figs. 1.7, 1.8 and 1.9. The variance that is explained by the first CCA pattern (Fig. 1.7) is approximately 35% for SLP and 89% of Polish winter temperature. This pair exhibits a canonical correlation of 0.79 for the unfiltered data.

The first canonical map of SLP shows the well-known dipole pattern with positive values (related to positive normalised time components in Fig. 1.7 bottom left) south of approximately 50°N and negative SLP anomalies north of it.

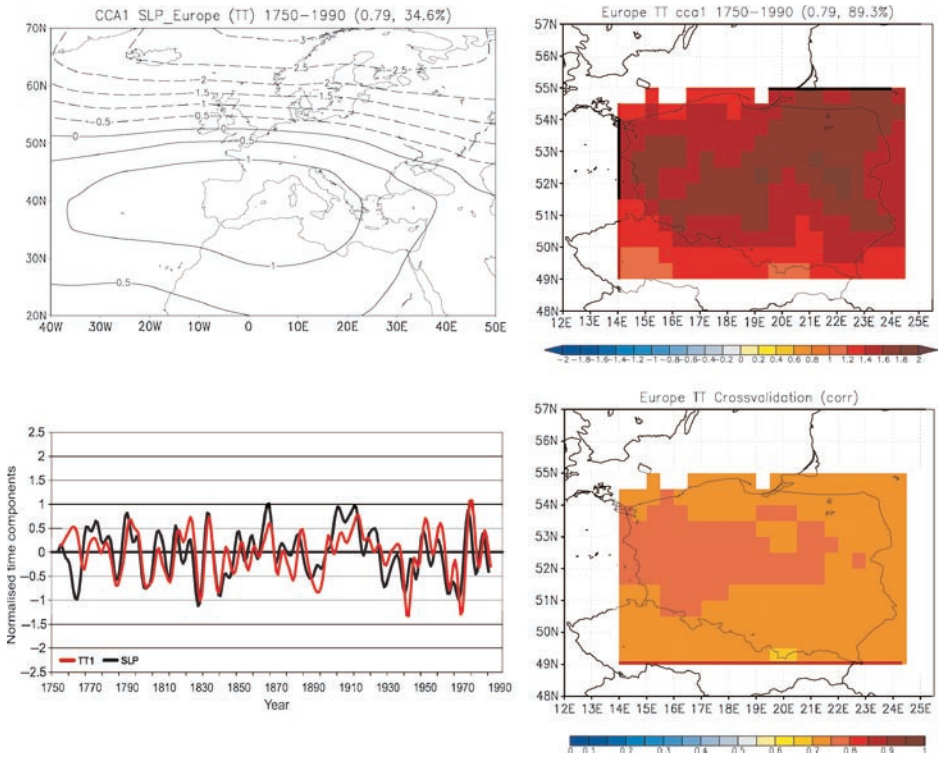

Fig. 1.7 Canonical spatial patterns of the first CCA between winter SLP (*top left*) and winter gridded temperature over Poland 1750–1990 (*top right*). The canonical correlation patterns depict typical anomalies in the variables, that is hPa for SLP and °C for temperature. They explain 35% (SLP) and 89% (Polish winter temperature) of the total variance in the CCA space; (*bottom left*): normalised time components (10 year Gaussian filtered) of the first CCA patterns of SLP anomalies (*black line*) and Polish winter temperature anomalies (*red line*). The correlation between the two unfiltered winter curves is 0.79; (*bottom right*) spatial distribution of correlation obtained from cross-validation for the model using SLP as single predictor

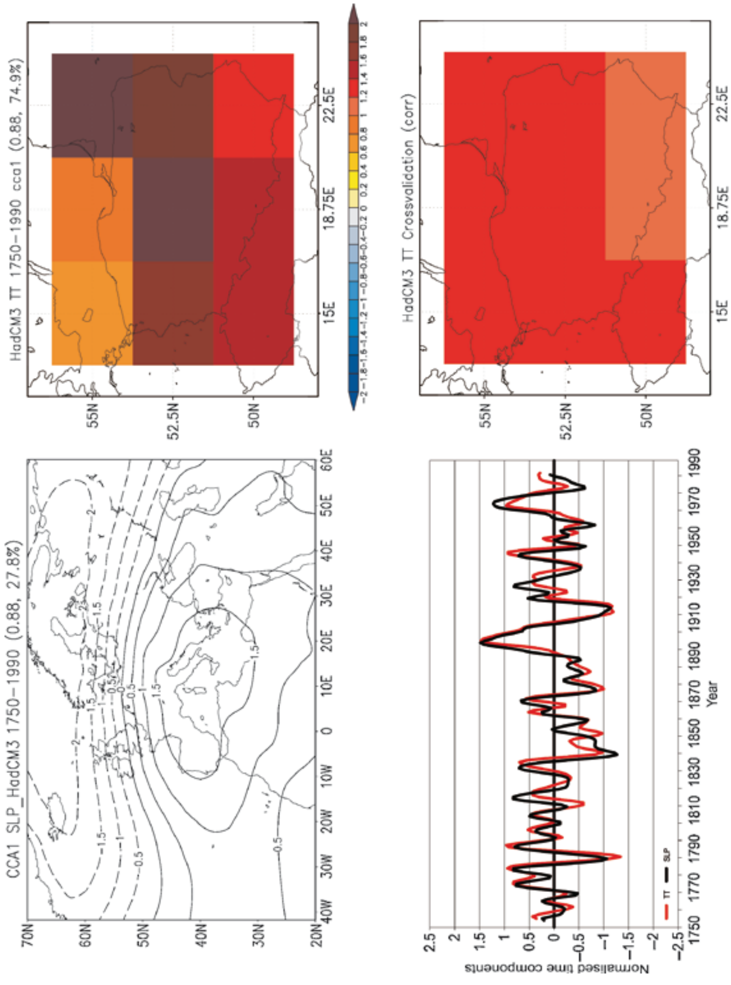

Fig. 1.8 Same as Fig. 1.7 but for the HadCM3 model. The canonical correlation patterns account for 28% (SLP) and 75% (Polish winter temperature) of the total variance in the CCA space; (bottom left): normalised time components. The correlation between the two unfiltered winter curves is 0.88

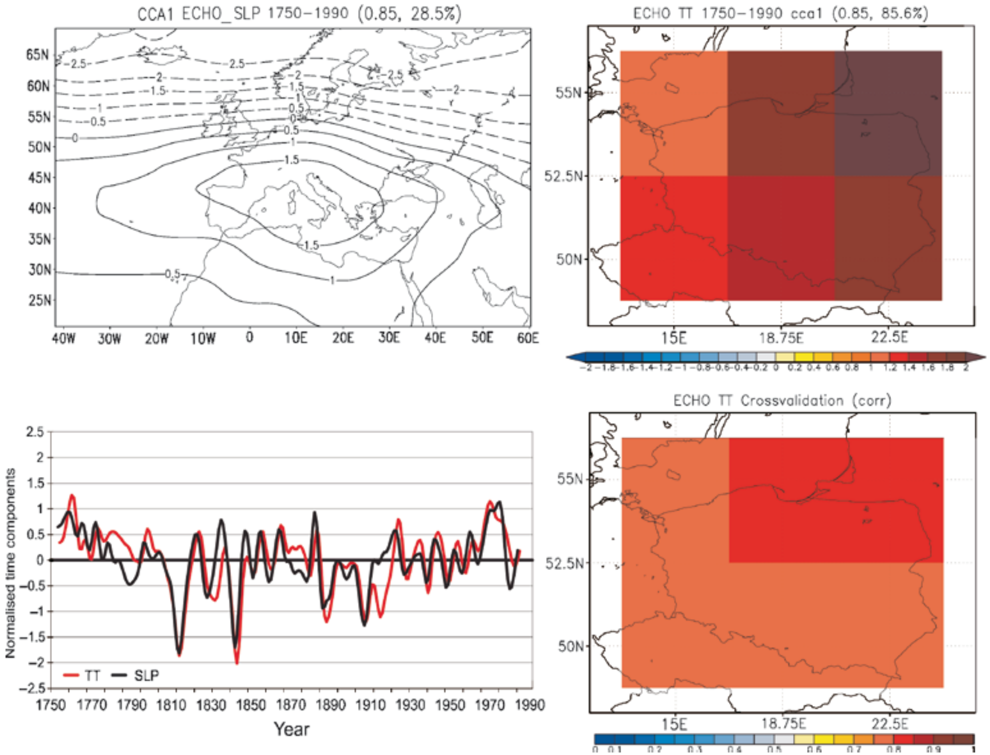

Fig. 1.9 Same as Fig. 1.7 but for the ECHO-G model. The canonical correlation patterns account for 29% (SLP) and 86% (Polish winter temperature) of the total variance in the CCA space; (bottom left): normalised time components. The correlation between the two unfiltered winter curves is 0.85

The anomalous strong westerly flow is responsible for the positive temperature anomalies all over Poland. The normalised time components in Fig. 1.7 (bottom left) do not give any indication about long-term trends. However, distinctive decadal to interdecadal variations are visible. Figure 1.7 (bottom right) shows the spatial distribution of skill (spatial correlation) using SLP as predictor for Polish winter temperature over the last 241 years. The correlations indicate a uniform spatial structure with high values all over the country, thus the statistical downscaling model performs very well all over the grid.

Figure 1.8 shows the first CCA pattern for the HadCM3 model. The SLP anomaly plot is very similar to the one presented in Fig. 1.7 for the reconstructions/instrumental period, both in terms of location of the anomalies as well as the pressure gradients. The corresponding anomalous temperature pattern over Poland represented by only nine grid cells support the findings from the reconstruction period with distinctly overall positive anomalies. The explained variances in the SLP and temperature fields are comparable with Fig. 1.7, though slightly lower. As for the reconstructions/instrumental CCA, there is no evidence of any trends in the normalised time components. The cross-validation results clearly indicate that the statistical downscaling model performs very well over the nine grid points.

Figure 1.9 shows the first CCA pattern for the ECHO-G model. The SLP anomaly map reveals strong resemblance to the one presented in Fig. 1.8 for the HadCM3 model and thus also for the reconstruction/instrumental period. Four out of six grid points show above normal temperature conditions. The explained variances in the SLP and temperature fields are comparable with findings from the HadCM3 and also for the reconstructions/instrumental period. As for HadCM3, there is no overall trend detectable in the normalised time components and the cross-validation results indicate very good performance over the six grid points.

Figures 1.7–1.9 reveal consistency in identifying both in the reconstructions and in the simulations the most important driving pattern of atmospheric circulation accounting for winter temperature variability over Poland. The simple mechanism behind this link highlights advection of moist mild air masses that induce higher temperatures over the study area. This atmospheric structure of low pressures over Poland also causes cloudier skies and hinders the drop of temperature that would be caused by radiative loss at night times, thus contributing to warmer winter months. The opposite can be said if the reversed sign of the pattern is considered, thus favouring continental cold air over Poland, clear skies and nocturnal radiative loss in winter.

1.4.3.2 CCA SLP-Polish Winter Precipitation

The first CCA mode (Fig. 1.10, 0.66 correlation) between observed and reconstructed Polish winter precipitation and SLP (Küttel et al. 2009) during the period 1750–1990 explains around 17% of the SLP variance and more than half of the Polish winter precipitation variability. The pattern of the SLP field indicates a half-meridional positive anomaly covering large parts of the continent with the centre

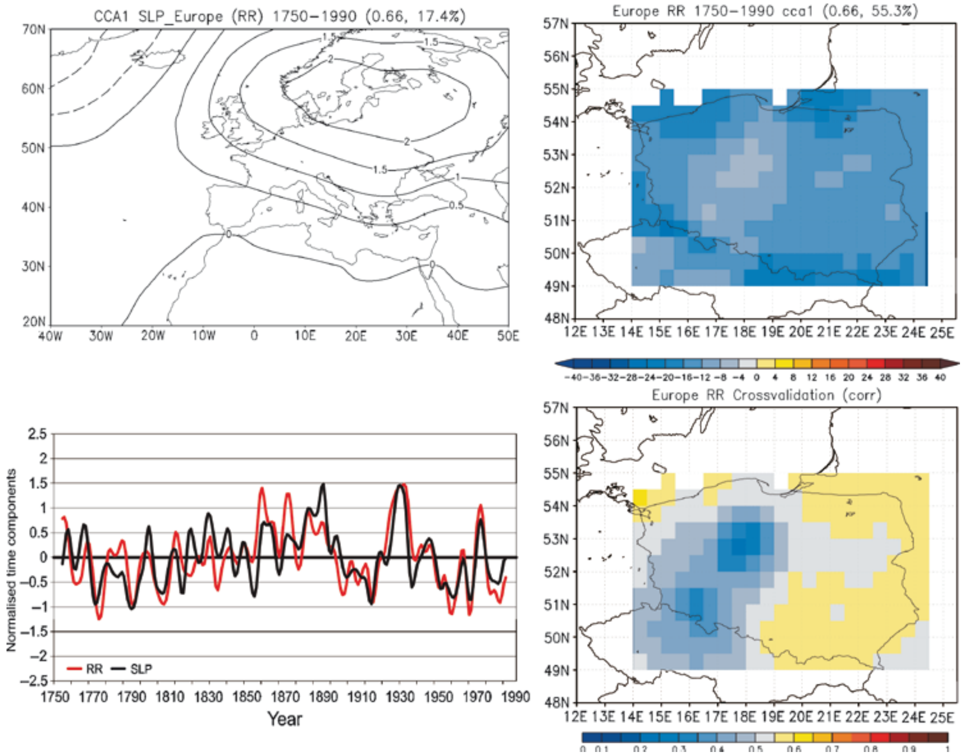

Fig. 1.10 Canonical spatial patterns of the first CCA between winter SLP (*top left*) and winter gridded precipitation over Poland 1750–1990 (*top right*). The canonical correlation patterns depict typical anomalies in the variables, that is hPa for SLP and mm for precipitation. They explain 17% (SLP) and 55% (Polish winter precipitation) of the total variance in the CCA space; (*bottom left*): normalised time components (10 year Gaussian filtered) of the first CCA patterns of SLP anomalies (*black line*) and Polish winter precipitation anomalies (*red line*). The correlation between the two unfiltered winter curves is 0.66; (*bottom right*) spatial distribution of correlation obtained from cross-validation for the model using SLP as single predictor

over southern Scandinavia. The corresponding anomalous precipitation pattern shows a monopole pattern with negative anomalies all over the country. In winters with positive normalised time components, anomalous dry air is advected from an easterly direction towards Poland. This joint pattern shows a positive trend from 1750 to the late nineteenth century (Fig. 1.10 bottom left). Within the twentieth century, the normalised time components show strong interdecadal variability with a tendency towards more anomalous low pressure conditions over northeastern Europe connected with anomalous advection of wetter conditions from the west/northwest towards Poland, in agreement with findings from Fig. 1.4. A similar analysis to that of Fig. 1.10 applied only to the 1900–1990 period leads to virtually identical results (not shown), thus suggesting that this large- to regional-scale link is stable in time.

The correlation skill score (Fig. 1.10 bottom right) generally shows higher values in the eastern part of Poland. The downscaling model performs less well in the western and southern areas.

Figure 1.11 shows the first CCA pattern between winter SLP and winter precipitation for the HadCM3 model. The SLP anomaly plot is similar to the one presented in Fig. 1.10, though with a stronger negative anomaly shifted towards the northeast. The explained variance in terms of SLP is higher than for the reconstructions/instrumental data but is smaller for the precipitation anomalies. The precipitation pattern over Poland represented by only nine grid cells connected with the dipole SLP pattern also reveals overall drier conditions (in case of positive normalised time components). No statistical long-term trend is discernible in the normalised time components, in agreement with Fig. 1.4. The cross-validation results (Fig. 1.11 bottom right) show an overall good performance of the statistical downscaling model.

Figure 1.12 presents the first CCA pattern between winter SLP and winter precipitation for the ECHO-G model. Compared to Figs. 1.10 and 1.11, the SLP anomaly pattern is more zonal with positive anomalies in the north and negative anomalies in the south (in case of positive normalised time components). The explained variances are comparable to the reconstructions/instrumental CCA (Fig. 1.10). The anomalous easterly flow connected to the positive anomaly in the north is connected with below normal precipitation over the area of Poland (Fig. 1.12 top right). There is resemblance with the overall trend of the SLP and precipitation normalised time components in Fig. 1.10, indicating an upward trend within the first 150 years approximately followed by a negative trend towards more anomalous cyclonic conditions and thus more precipitation over Poland in recent decades. The cross-validation results (Fig. 1.12 bottom right) indicate overall good performance of the statistical downscaling model.

Thus, both models show an anomalous low over the Iberian Peninsula and a relative high over Scandinavia. The impact of these simulated large-scale patterns is comparable to that found in the reconstruction where the large-scale anomaly pattern provided deficit of precipitation in the area of interest. However, the structure of the large-scale SLP pattern is somewhat different in the models and the reconstruction.

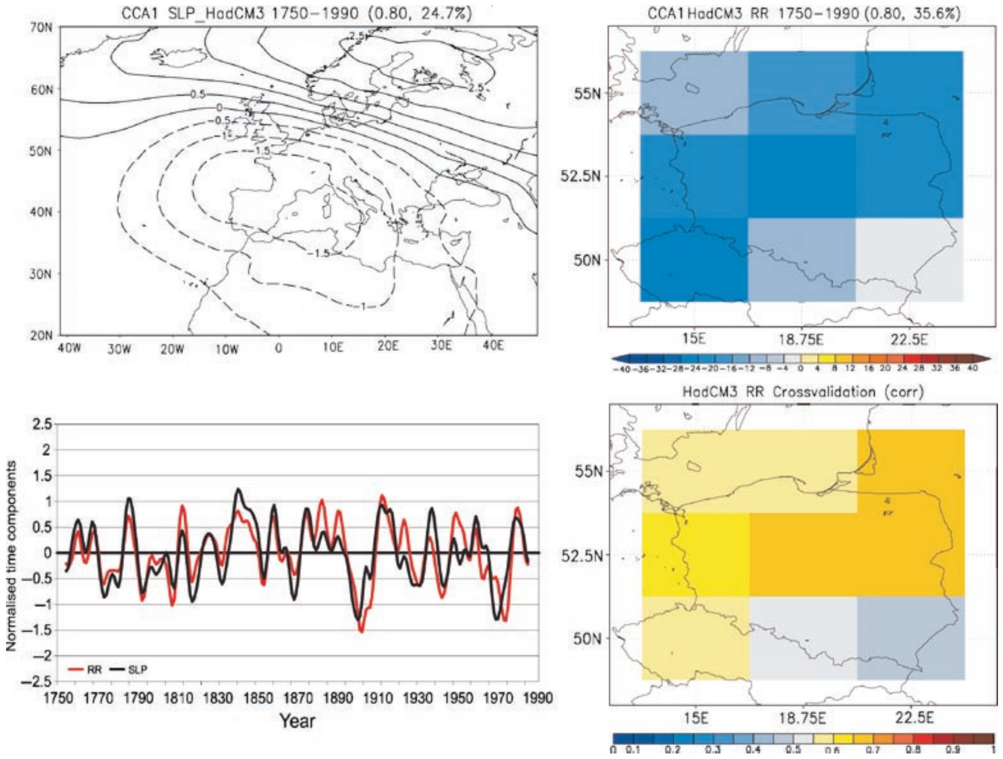

Fig. 1.11 Same as Fig. 1.10 but for the HadCM3 model. They explain 25% (SLP) and 36% (Polish winter precipitation) of the total variance in the CCA space. The correlation between the two winter curves is 0.80

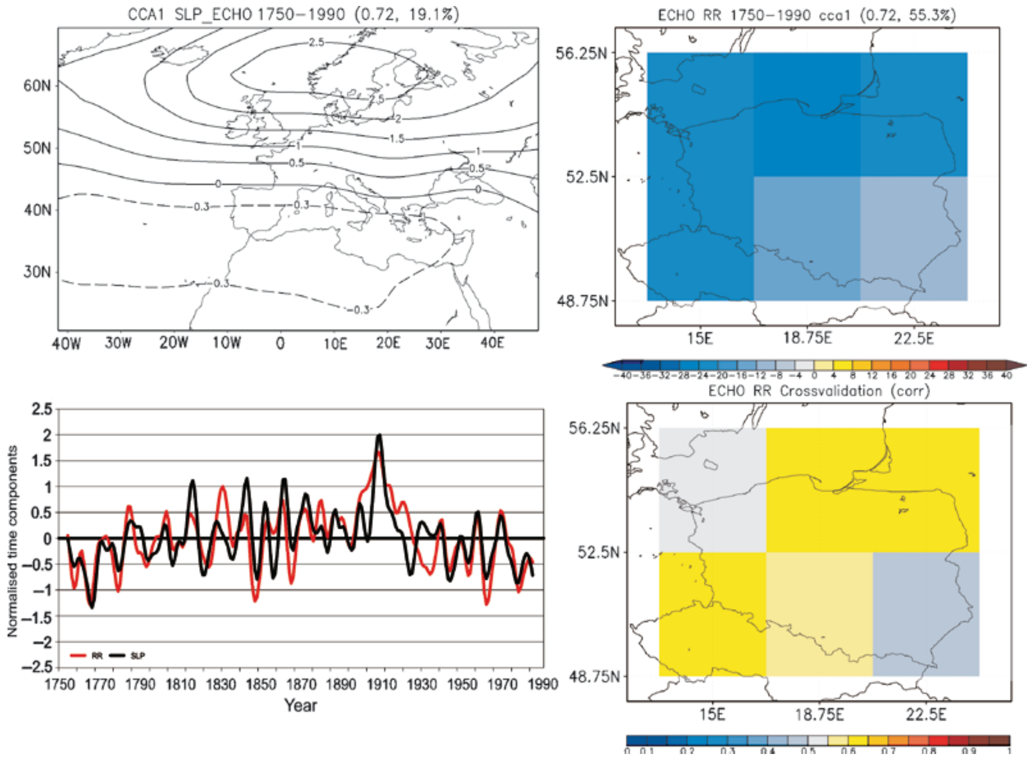

Fig. 1.12 Same as Fig. 1.10 but for the ECHO-G model. They explain 19% (SLP) and 55% (Polish winter precipitation) of the total variance in the CCA space. The correlation between the two winter curves is 0.72

1.5 Discussions and Conclusions

We investigated the winter temperature and precipitation evolution over Poland over the last 500 years in comparison with the European average (excluding Poland) both in reconstructions/instrumental data and in the ECHO-G and HadCM3 models. Results indicate very good agreement between European land and Polish winter temperatures (at interannual and interdecadal time scales) both in reconstructions and in the models. In Poland, generally colder winter conditions were found within the 'Little Ice Age' and temperature values at the turn of the twenty first century are very likely the warmest in the context of the past half millennium. The strong agreement between Polish winter temperature and European average conditions is of major interest since some of the longest temperature proxy information stems from Poland and therefore can improve European temperature reconstructions significantly.

Precipitation is spatially and temporally more variable than temperature. However, results indicate that reconstructed winter precipitation over Poland agrees well with those of the rest of Europe. The agreement is smaller between the reconstruction and the two models. Neither the reconstructions nor the models point to significant long-term trends within the last half millennium. The low-frequency variability in the model simulations is comparable to the reconstructions, though the interannual variability is larger in both models.

The most important atmospheric circulation pattern for Polish winter temperature variability is the NAO. SCAND and to a lesser degree also the NAO and EA/WRUS are of relevance accounting for a significant amount of winter precipitation variations in Poland.

Finally, the role of the large-scale atmospheric circulation dynamics/forcing back to 1750 in explaining Polish winter temperature and precipitation variations was investigated both in the reconstructions and in the model world. CCA results show that the leading SLP modes responsible for dry/wet Polish winter conditions are in good agreement in the reconstructions and model world.

One aspect of the climate model simulations that has not received much attention so far is the amplitude of regional variations and its connections with the large-scale climate. The future global warming trend will be superimposed on multidecadal regional variability, which may be itself caused by a response to the external forcing or by the internal dynamics. An example of the first case can be illustrated by certain atmospheric circulation patterns that change with increasing concentrations of atmospheric greenhouse gases. The analyses of the model simulations indicate that the models are able to produce a quite realistic picture of the regional variability of temperature and precipitation and its connection to the continental-scale variability in this region of the midlatitudes, despite their relatively coarse resolution. The modes of atmospheric circulation relevant for regional temperature and precipitation variability are to some extent well represented in the model simulations. A stricter test on regions with more complex topography would probably be more demanding for the models, but future, higher resolutions models should be increasingly capable of producing realistic simulations of regional climate variability.

Another issue that is worth highlighting is the agreement among the CCA results between the SLP field and Polish temperature in the model simulations and in the reconstruction with those of the instrumental dataset in the twentieth century (not shown). These results suggest both that the model is able to reproduce the links observed in instrumental and proxy data and also that the large- to regional-scale relationships found in the instrumental data are robust during the last centuries of both reconstructed and simulated climate. The stability of the large- to regional-scale links is relevant not only in the context of downscaling approaches but also regarding the large-scale palaeoclimate reconstruction exercises, where the robustness of the link between a local proxy and large-scale climate is a conditional hypothesis for the reconstruction. It could be argued that since the reconstruction used herein includes the information of several modes of variability that are found in the instrumental period and used in the application of the principal component regression approach to reconstruct European past climate (e.g. Luterbacher et al. 2004; Xoplaki et al. 2005; Pauling et al. 2006), it is not surprising that the CCA analysis delivers this stable behaviour along the period of study. However, the good match with the model simulations within the multicentennial period studied suggests that the dominant mode found in the twentieth century data and in the reconstruction is also stable in the model world over the simulated period and produces similar impacts in Polish temperature.

In the case of precipitation this agreement also holds in the analysis performed on the reconstruction and on the instrumental data. As for the model, the large-scale structure found to be relevant for Polish precipitation exhibits positive pressure anomalies over Poland associated to a deficit of precipitation, as in the case of reconstruction; over southern Europe however the model suggests negative SLP anomalies, the reasons for this different behaviour remaining so far unknown.

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Chapter 2
Historical Climate in Central Europe During the Last 500 Years

Rudolf Brázdil and Petr Dobrovolný

2.1 Introduction

The climate of the past millennium is usually divided into the Medieval Warm Period (MWP; recently termed the Medieval Climate Anomaly – MCA), the 'Little Ice Age' (LIA) and subsequent Recent Global Warming (RGW) (Bradley 2000; Bradley et al. 2003b). This division has its roots in papers by the English climatologist Hubert H. Lamb (1965, 1984). Lamb, analysing data mainly derived from Western Europe and northern parts of the Atlantic, placed the MWP within the period AD 950–1200 (AD 1150–1300 in the greater part of Europe) and the LIA between the years 1550 and 1850, with its most pronounced features in AD 1550–1700. Lamb denoted the time interval between MWP and LIA as a period of gradual climate deterioration. Jones and Mann (2004) discuss the limited utility of MWP (MCA) and LIA in describing the climate of the past millennium arising out of dramatic differences between past regional and hemispheric/global trends as well as distinguishing between changes in surface temperature and precipitation/drought fields. Similarly, Bradley et al. (2003a) drew attention to non-synchronous warmest Medieval temperatures around the globe.

In terms of the concept described above, the period of the last 500 years, on which this study for Central Europe concentrates, belongs in the greater part to the LIA and from the end of the nineteenth century to the present to the RGW. The term 'Little Ice Age' was originally used to describe glacier behaviour (Matthes 1939, 1940), not for climate. Generally, it was the most recent period in which glaciers advanced to expanded positions and fluctuated around them in the greater part of the globe (for more details of the LIA see e.g. Grove 1988, 2004; Bradley and Jones 1992; Ogilvie and Jónsson 2001; Matthews and Briffa 2005). Although glacial advances and retreats are most frequently related to temperature, other meteorological elements, such as precipitation, are also important (Nesje and Dahl 2003; Steiner et al. 2008).

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While it is generally accepted that the LIA ended around the mid-nineteenth century (e.g. with reference to the nineteenth-century central and western European Alps, Zumbühl et al. (2008) mention one maximum extent around 1820 and a second around 1855), its beginning is more subject to debate. Different proposals have been made, varying according to available data, time resolution and geographical region. For example, Pfister et al. (1996, 1998) placed the start of the LIA after AD 1300, as confirmed by the three maximum advances of the Great Aletsch glacier in the Alps around AD 1350, 1650 and 1850 (Holzhauser 1997; Holzhauser and Zumbühl 1999). A period of similar synchronous glacier advances in 1300–1860 was also confirmed by Holzhauser et al. (2005) for the Great Aletsch, the Gorner and the Lower Grindelwald glaciers in the Alps. Grove (2004) moved the beginning of the LIA to the thirteenth or fourteenth century and its culmination between the mid-sixteenth and mid-nineteenth centuries. In contrast, Jones and Bradley (1992) simply opined that universal delimitation of a beginning and an end to such a period is very difficult.

The period of the last part of the past millennium, the Recent Global Warming period, is established by global/hemispheric temperature series starting in 1850 (Brohan et al. 2006). Over the past 100 years (1906–2005), the global temperature rise has reached a value of 0.74°C (Solomon et al. 2007). Contrary to the preceding IPCC report (Houghton et al. 2001), this means an intensification of the warming trend by 0.14°C, because the temperature rise in the period 1901–2000 reached a value of 0.60°C. Recent global warming is very likely to have been caused by anthropogenic activity (Solomon et al. 2007).

The climate paradigm under discussion is reflected in a different way through reconstructed temperature series based on various proxy and instrumental data covering the past millennium in the Northern Hemisphere (e.g. Mann et al. 1999; Jones et al. 2001; Esper et al. 2002; Moberg et al. 2005; for an evaluation of various millennial reconstruction methods see Lee and Zwiers 2008). Similar series have also been calculated for the whole of Europe (Luterbacher et al. 2004, 2007; Xoplaki et al. 2005), for Western Europe (Guiot et al. 2005) and for the greater Alpine area (Casty et al. 2005). The question remains as to whether the features typical of temperature fluctuations in the above series are also expressed in temperature series for Central Europe or its individual parts.

Central Europe is defined, for the purposes of this article, as the territory consisting of Germany, Switzerland, Austria, the Czech Republic, Poland, Slovakia and Hungary. With the intention of characterising climate fluctuations in this part of Europe for the last 500 years, this paper starts from a description of available climatological data, with particular attention to documentary evidence, and methods of analyzing it, together with climate reconstruction, then continues by listing available temperature and precipitation series for Central Europe with analysis of the variability of climatic patterns over the past 500 years discussed in the broader European context. Finally, perspectives on further research are formulated. This paper concentrates largely on temperature changes but also addresses issues related to precipitation.

2.2 Instrumental and Proxy Climatological Data

Central Europe is a region with a long tradition of instrumental meteorological observations (for example, Warsaw in Poland started in December 1654 – see Przybylak this volume). In 1717, the Breslau (now Wrocław, Poland) physician, Johan Kanold organised an international meteorological network of observers and correspondents and published quarterly results for 1717–1726 in *Sammlung von Natur- und Medicin-, wie auch hierzu gehörigen Kunst- und Literatur-Geschichten* in the years 1718–1727 (Fig. 2.1). This network also continued in the years 1727–1730, thanks to Andreas Elias Büchner, a professor of medicine at Erfurt (for more details see Brázdil and Valášek 2002). For several countries, this network published the very first instrumental observations on their territory, such as the measurements taken by Johann Carl Rost in Zákupy in northern Bohemia (Brázdil and Valášek 2002) and those of Johann Adam Reimann in Prešov in eastern Slovakia (Brázdil et al. 2008b). The most continuous observations from the whole period of the existence of this network come from the stations in Wroclaw (Poland; for more details of this station see Przybylak 2009), Löbau, Nürnberg (both Germany) and Zürich (Switzerland).

Another network of meteorological stations known as the *Societas Meteorologica Palatina* was established by Karl Theodor, Elector of the Palatinate, in 1780. At its maximum extension, this network comprised 39 stations, including several from Central Europe. All the stations used standardised instruments and made their observations according to regulations issued by the Society (e.g. observing times at 07.00, 14.00 and 21.00 h mean local time). The results of the observations were published for the years 1780–1792 in the *Ephemerides Societatis Meteorologicae Palatinae* in Mannheim (see e.g. Traumüller 1885; Kington 1974). Some stations were also included in a local meteorological network of 21 stations in Bavaria, operated by the Bavarian Academy of Science in Munich under the direction of Jesuit Franz Xaver Epp (Lüdecke 1997).

Further to this international effort, the development of meteorological observations was also taken up by a number of individuals who started making meteorological observations out of their own interest, mainly as part of the activities of scientific and economic societies (for example, the Meteorological Section of the Moravian-Silesian Economic Society in Moravia and Silesia – see Brázdil et al. 2005b). However, systematically organised networks of meteorological stations evolved out of the establishment of national meteorological institutes. For example, in the former Austrian empire such an institute, known as the "Imperial-Royal Central Institute for Meteorology and Earth Magnetism" (*K. k. Central-Anstalt für Meteorologie und Erdmagnetismus*) in Vienna was created at the request of the Academy of Sciences through Emperor Franz Joseph I on 23 July 1851. Its aim was to coordinate and check the work of meteorological stations, collect the results of their observations and evaluate them (Hammerl et al. 2001).

It is clear that the collection of consistent meteorological data from the eighteenth century onwards was hindered by many factors, such as changes of observation point,

Sammlung
Von
Natur- und Medicin-
Wie auch
hierzu gehörigen Kunſt- und Literatur-.
Geſchichten,
So ſich
An. 1717. in den 3. Sommer-Monaten
In Schleſien und andern Ländern begeben.
Welcher Geſtalt nemlich:
1) Die Veränderung des Gewitters von Tage zu Tage und von Zeit zu Zeit. 2) Land- und Witterungs-Seuchen, von Monat zu Monat, nach dem Einfluß Lufft und Wetters. 3) Zu- und Mißwachs von Feld- Wald- und Garten-Früchten, auch allerhand animaliſchem Proventu, in allerley Ländern Europens von einer Jahrs-Zeit zur andern bemercket worden: Wie nicht weniger 4) was vor eintzelne eclatante natürliche Begebenheiten am Firmament, in der Lufft, auf und unter der Erde, im Waſſer, an Menſchen und Vieh: auch 5) was vor neue phyſicaliſche und mediciniſche Erfindungen dieſe Zeit über hervorgebracht und bekañt worden: und denn 6) was in re literaria Phyſico-Medica veränderliches vorgefallen.
Alles in ordentlicher Connexion und mit allerley Reflexions
Aus vielfältiger Correſpondenz, und andern Relationibus, ſo wie groſſen
Theils aus eigener Erfahrung zuſammen geleſen;
Und
Als ein Verſuch ans Licht geſtellet
Von
Einigen Breßlauiſchen Medicis.
Sommer-Quartal 1717.

Breßlau,
Bey Michael Hubert, M DCC XVIII.

Fig. 2.1 Title page of the first volume of Kanold's *Sammlung von Natur- und Medicin-, wie auch hierzu gehörigen Kunst- und Literatur-Geschichten* with the results of meteorological observations for the summer quarter (July–September) of 1717 different observers, and a variety of instruments, observing times and procedures, as well as by changes in the station surroundings, all of which could give rise to inhomogeneities in long-term series. Great efforts must be made to detect possible artificial breaks in series and adjust them in such a way as to obtain relatively homogeneous series, concentrating not only on methods of detection and adjustment (see e.g. Peterson et al. 1998 for an overview), but also on the homogenisation proper of long-term station datasets (see e.g. HISTALP in Austria – Auer et al. 2005, 2007). Only homogenised series are useful for the study of long-term climate variability, while series consisting of only raw, measured data may produce controversial low-frequency fluctuations.

The study of climate variability in the pre-instrumental period is limited to various forms of proxy intrinsic to natural phenomena and man-made archives (Bradley 1999). The current paper concentrates mainly on the man-made proxies that are available in the form of documentary evidence. Documentary evidence is used in historical climatology, which focuses mainly on the reconstruction of temporal and spatial patterns of weather and climate, as well as climate-related natural disasters, for the period prior to the creation of national meteorological networks, that is mainly for the last millennium (see Brázdil et al. 2005a for more details and more references therein).

Basic sources of documentary data worthy of note for the past 500 years in Central Europe include (e.g. Pfister 1984, 1999; Pfister et al. 1999; Glaser 2001, 2008; Brázdil et al. 2005a):

1. *Annals, chronicles, memory books and memories* may all include information about the weather and related phenomena. To varying degrees of detail, they often describe the course of extreme weather events, material damage and even human casualties. The quality and accuracy of any given record depends on the intellectual level of the writer and particularly whether s/he was an eye-witness. Deriving reports from other, indirect, sources or from hearsay may well give rise to mistakes in dating and description of phenomena.
2. *Visual daily weather observations* were recorded by their authors more or less regularly for ephemerids, calendars and personal diaries. As well as descriptions of daily weather, they also include information about weather-related extremes and their impacts. Contemporary expressions have to be converted into current meteorological terminology (Fig. 2.2).
3. *Correspondence (letters)* contains information about weather and related extremes if the situation concerned the author of the letter in some way. Official letters sent by estate administrators to the owners of the estates, in which they often described serious weather events occurring on the estate and affecting its operation, form a special sub-category.
4. *Special broadsheets* were often printed and distributed on the occasion of disastrous or remarkable weather-related events (such as floods or windstorms). These circulars (the forerunners of today's newspapers) were intended either to impart information about these extremes or to promote some religio-political agenda that might be derived from them.

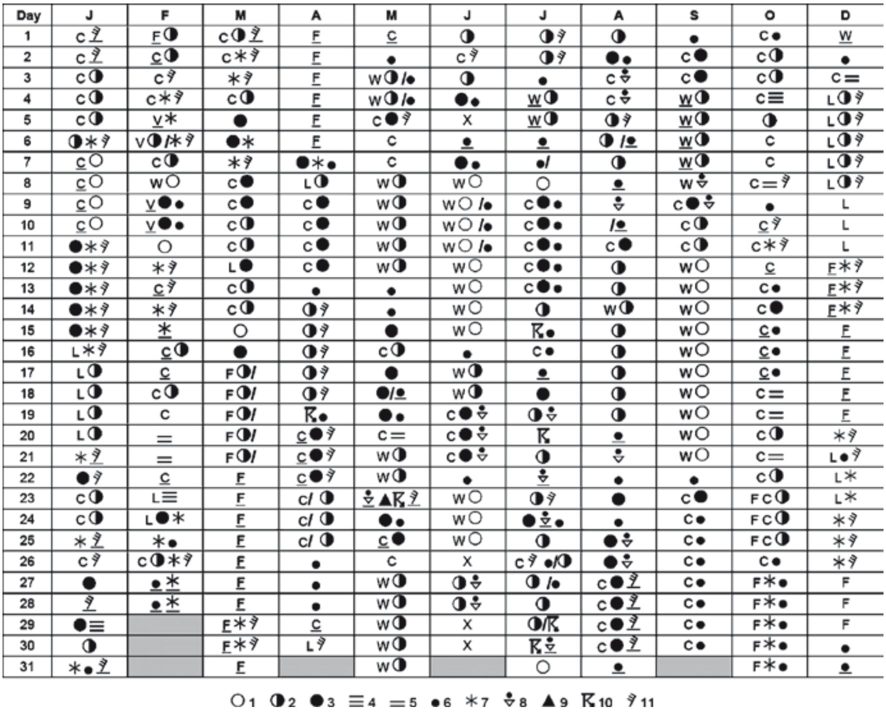

Fig. 2.2 Example of interpretation of visual daily weather records: Jan Nádherný, Bohemia, 1805 (missing November) (Brázdil et al. 2007). Key: H – hot, W – warm, L – mild, C – cold, F – frost, V – variable, X – missing record, 1 – clear sky, 2 – half-covered sky, 3 – overcast, 4 – fog, 5 – misty, 6 – rain, 7 – snow, 8 – shower, torrential rain, 9 – hail, 10 – thunderstorm, 11 – wind. Underlined symbols express strong intensity of phenomenon. A slash (/) distinguishes night and morning from afternoon and evening occurrences of the phenomenon

5. *Economic records* include the data collected in association with any economic activity or procedure influenced by weather or weather-related extremes, for example, the dates of grape-harvest, wine quality and quantity, yields and prices of agricultural crops, wages paid for various kinds of work (e.g. cutting ice at water mills, clearing snow, repair of property damaged by weather extremes), etc. Particularly valuable are reports linked to the collection of taxes and applications for rebates on the grounds of weather-related damage (due to, for example, hail, flood, torrential rain or windstorm), preserved at different levels of state administration (Brázdil et al. 2006).
6. *Newspapers and journals* usually concentrate on descriptions of unusual weather or on weather-related extremes. They frequently contain information about the causes, the course and the impacts of extremes, sometimes with appeals for solidarity and help for the afflicted.
7. *Pictorial evidence* in the form of paintings or photos, created at various levels of technical expertise, records weather-related phenomena (e.g. glacier position) and

largely weather-related extremes and their consequences (e.g. after flood or windstorm). However, paintings are often reflections of the author's imagination rather than a real representation of events. They often fulfilled the task of generating historical "memory" to make people recall the horrors of destructive extremes and thus conveyed moral warnings of God's punishment for sins committed, thus evoking respect for such events.

8. *Stall-keepers' and market songs* often describe an extreme (e.g. a flash flood after thunderstorm and torrential rain) as a spectacular and dramatic topic, largely inspired by sudden and unexpected onset, high death toll and severe damage on a local or regional scale. Although they may describe the event, its occurrence and impacts, critical evaluation of the possible distortion of reality in the information presented (*licentia poetica*) is essential.
9. *Early scientific papers and communications* often contain information about weather and related extremes, their occurrence, causes and impacts. However, care must be exercised in relation to what are known as weather compilations (e.g. Weikinn 1958–2002), which may contain a mixture of different reports that are in some cases far from exact or even credible (for a critique of such sources see e.g. Bell and Ogilvie 1978; Brázdil et al. 2005a).
10. *Epigraphic sources* usually consist of marks or short remarks chiselled into stone or marked on houses, bridges, gates, or ancient trees. They often show the level of extremely high (or low) water or recall some extreme event (e.g. someone's death by lightning or flash flood). Water-marks, in particular, should be assessed for originality, particularly with respect to the age of the object on which they are recorded, because they may be transferring information from other places.
11. *Early instrumental meteorological observations* started in some places much before the establishment of national meteorological services (for the seventeenth–eighteenth centuries, see e.g. Kanold's Breslau network – Brázdil and Valášek 2002). They usually contain data about air pressure and temperature, wind direction, cloudiness and the occurrence of meteorological phenomena, but technical detail vital to their homogenisation (position, instruments, terms, etc.) is often absent.

In the course of primary extraction of data from documentary evidence, it is essential that further methodological work follows key requirements in handling this type of evidence (Brázdil et al. 2005a):

- Primary sources must be favoured (secondary sources may be used only after thorough checking)
- Formal errors in typing and dating must be avoided
- Descriptive information must be interpreted using recent meteorological terminology
- A knowledge of the historical context in which this data originated is essential

If documentary data makes up a continuous series (e.g. dates of grape harvests, start dates for other agricultural harvest, spring opening of harbours), they may worked up for a standard palaeoclimatological reconstruction of temperature series (see e.g. Jevrejeva 2001; Tarand and Nordli 2001; Chuine et al. 2004; Meier et al. 2007; Leijonhufvud et al. 2008, 2009). Spatially and temporally discontinuous series of temperature/precipitation indices usually have to be created from documentary data of a qualitative and descriptive character; these can be subsequently used for further analyses and reconstructions.

Depending on the density and quality of the basic information, a graded scaling into ordinal numbers may be used. Simple indices employing a three-term classification are very often applied: months are classified as index −1 (cold or dry), 0 (normal) and 1 (warm or wet). Weighted indices use a seven-term classification for months (temperature: −3 extremely cold, −2 very cold, −1 cold, 0 normal, 1 warm, 2 very warm, 3 extremely warm; and for precipitation: −3 extremely dry, −2 very dry, −1 dry, 0 normal, 1 wet, 2 very wet, 3 extremely wet). Seasonal or annual indices may be obtained by summation of monthly values (i.e. the seasonal values can fluctuate from −9 to 9 and annual values from −36 to 36) (Pfister 1984, 1992). A different scaling into ordinal numbers has occasionally been used in certain papers. For example, Koslowski and Glaser (1999) developed a winter ice severity index from ice volume along the German Baltic coast with a gradation of weak (index 0), strong (1), very strong (2) and extreme (3) winter severity. Van Engelen et al. (2001) used an ordinal scale from 1 to 9 for reconstruction of winter (from 1 – extremely mild to 9 – extremely severe) and summer (from 1 – extremely cool to 9 – extremely warm) temperatures in the Low Countries.

2.3 Methods of Climate Reconstruction

While long-term homogenised series may be used directly for statistical analyses (see e.g. von Storch and Zwiers 1999), index temperature/precipitation series must first be converted into recent meteorological units by a reconstruction procedure. The standard scheme of palaeoclimatological reconstruction (Fig. 2.3) assumes that such an index series may be calibrated and verified against instrumental observations for an overlapping period. The aim of the calibration is to determine the transfer function between the indices and the real climate variable. Prior to being used for a reconstruction, the transfer functions need to be verified for an independent period; or at least a cross-validation procedure has to be carried out if the data series is short. The relationship obtained for a calibration period and evaluated by various statistical measures (e.g. squared correlation r^2, standard error of estimate *SE* and the Durbin-Watson test for autocorrelation in residuals) is subsequently applied to a verification period for which the climate values have been estimated from the documentary data. These estimations are then compared with the measured values and evaluated again using various statistical measures (e.g. r^2, reduction of error *RE*, coefficient of efficiency CE). If the transfer function obtained expresses the variability of the climate factor under consideration

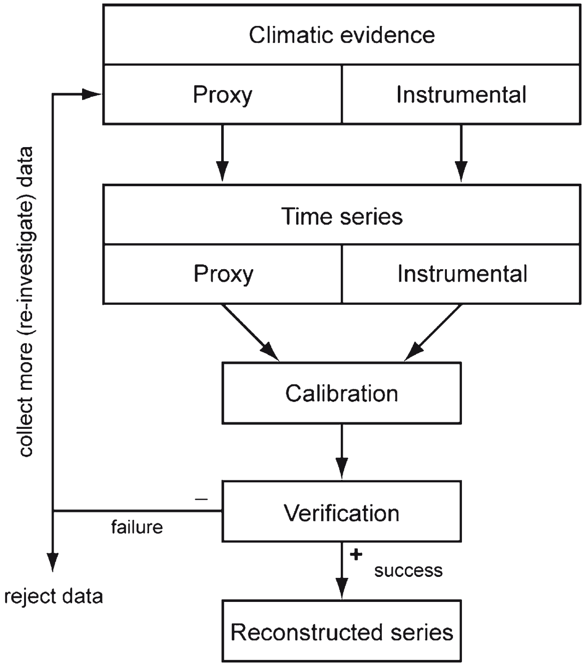

Fig. 2.3 Scheme of a standard palaeoclimatological reconstruction (modified after Brázdil 2002)

with satisfactory accuracy, the chronology of the proxy can be used for climate reconstruction. The transfer functions, usually derived from relatively modern periods, may however be non-stationary (e.g. when phenological series have been affected by changes in crop mix, the introduction of new varieties of crops or the introduction of different harvest technology – see e.g. Meier et al. 2007). This problem can, to some extent, be ameliorated by considering a sufficiently long calibration period.

Detail of a scheme of reconstruction using documentary evidence-based temperature indices is shown in Fig. 2.4. The series of temperature indices created is calibrated and verified with instrumental (measured) temperatures in the overlapping period by linear regression. This exercise allows estimation of explained variance in the reconstruction. In the final stage, the reconstructed part is joined to the instrumental part of the series and error bars for the expression of reconstruction uncertainty are determined. This approach has already been applied in calculation of the Prague temperature series for 1718–2007 (Dobrovolný et al. 2009a) and of the Central European temperature series for 1500–2007 (Dobrovolný et al. 2009b – see following section).

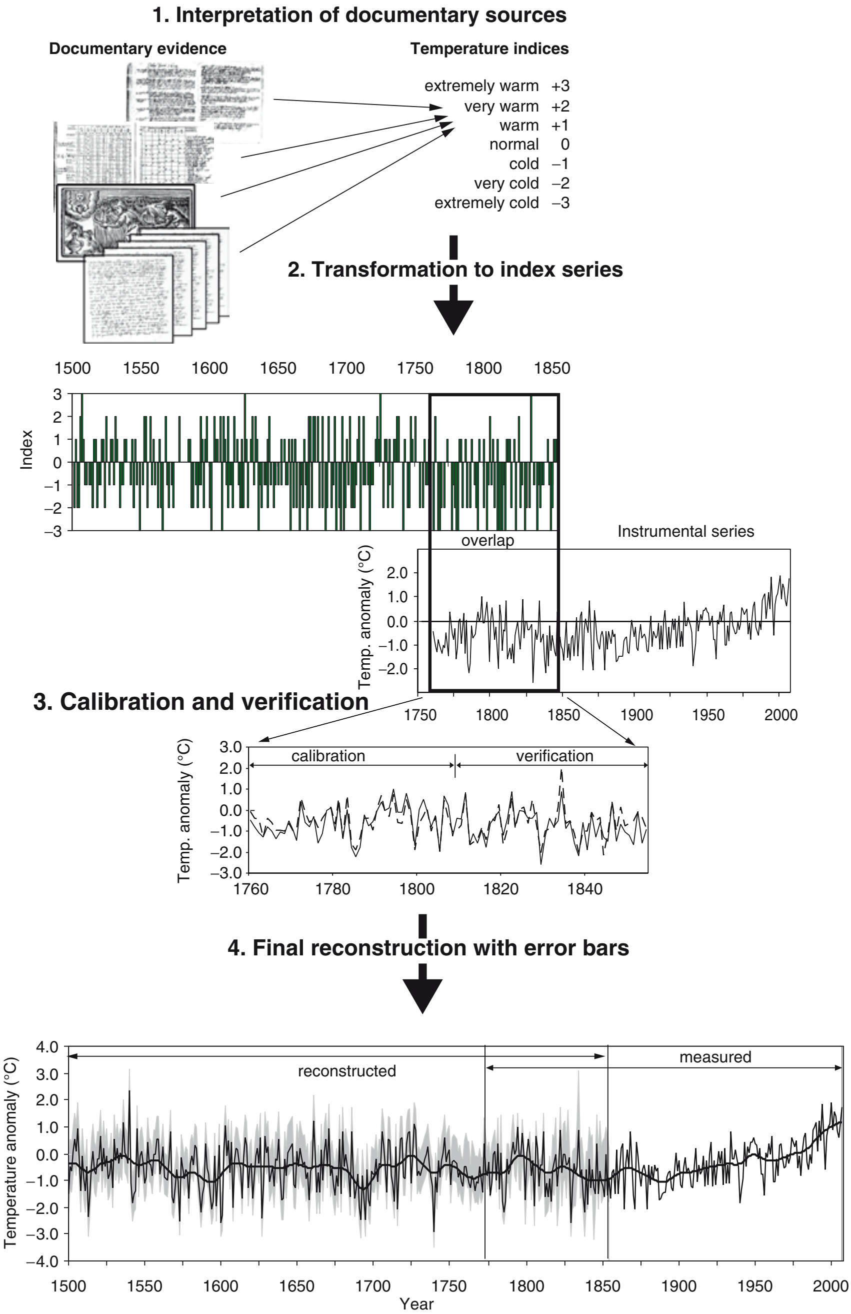

Fig. 2.4 Scheme of temperature reconstruction procedure using documentary evidence-based temperature series

2.4 Temperature and Precipitation Series Based on Documentary Evidence in Central Europe for the Last 500 Years

Temperature/precipitation series for the past 500 years may be obtained only by combining temperature/precipitation reconstructions (from related man-made or natural proxy series) and corresponding long-term instrumental series. Series of temperature or precipitation indices derived mainly from documentary evidence, as well as reconstructions based on them, have been published since the 1980s for several Central European countries or regions, as follows from the overview below (T – temperature, R – precipitation, m – monthly, s – seasonal, a – annual):

1. Austria: eastern Austria, 1700–1830, summer T/R – combined documentary and tree-ring data (Strömmer 2003)
2. Czech Republic: Prague-Klementinum, from the thirteenth century, decadal sT, aT, sR, aR reconstructions (Brázdil 1996); Olomouc 1693–1783, mT, mR indices (with gaps) (Brázdil et al. 2008a); Prague-Klementinum 1718–2007, sT, aT reconstructions (Dobrovolný et al. 2009a)
3. Germany: past millennium, decadal sT, sR indices; from AD 1500, sT, aT, sR, aR reconstructions (Glaser 2001, 2009a)
4. Historical Hungary: from the sixteenth century, mT, mR indices (with gaps) (Rácz 1999); AD 1650–1900, aT indices (Bartholy et al. 2004)
5. Poland: AD 1501–1840, decadal sT (DJF, JJA) indices (with gaps) (Przybylak et al. 2005); for the same period, decadal DJF and JJA temperatures and incomplete DJF and JJA precipitation indices (Przybylak et al. 2004)
6. Slovakia: eastern Slovakia, AD 1717–1730, mT, mR indices (Brázdil et al. 2008b)
7. Switzerland: from AD 1525, mT, mR indices and reconstructions (Pfister 1984 – indices re-worked several times later, e.g. Pfister 1999)
8. Regions: Central Europe as an average of the Czech Republic, Germany and Switzerland, sixteenth century, sT, aT, sR, aR reconstructions (Pfister and Brázdil 1999); the Swiss Alpine region (43.25°–48.25°N, 4.25°–16.25°E), aT, sT (DJF, JJA), aR, sR (DJF, JJA) from AD 1500 based on long instrumental series and documentary proxies, worked up by principal component regression analysis (Casty et al. 2005)

More recently, combined efforts within the EU Millennium project (Gagen et al. 2006) have resulted in the calculation of new monthly, seasonal and annual Central European temperature (CEuT) series combining documentary and instrumental data (Dobrovolný et al. 2009b). In applying a standard palaeoclimatological approach (Fig. 2.4; for more details see also Dobrovolný et al. 2009a), linear regression was used for calibration and verification of index temperature series and instrumental temperature series for the period 1771–1854. An index temperature series was created from corresponding series from Germany, Switzerland and the Czech Republic, derived from documentary evidence for the period 1500–1854.

The instrumental temperature series for 1760–2007 was taken as an average of 11 homogenised series from Austria (Kremsmünster, Vienna, Innsbruck), Switzerland (Basle, Geneva, Bern), Germany (Regensburg, Karlsruhe, Munich, Hohenpeissenberg) and the Czech Republic (Prague-Klementinum). These were further corrected for the insufficient radiation protection for early thermometers (see Böhm et al. 2009) and the growth of the urban heat island effect. The index series correlate well with the instrumental temperatures; the explained variance in the overlapping period is thus 83% for winter, 80% for spring, 77% for summer, 73% for autumn and finally 81% for annual mean temperatures. Verification statistics indicated high reconstruction skill for all seasons and the year.

Fluctuations in seasonal and annual CEuT series in the period 1500–2007 are shown in Fig. 2.5. These series display well-expressed inter-annual and decadal variability but, with the exception of the period of recent global warming with the highest values in all series in the most recent years, it is difficult to derive any long-term tendencies. In contrast, the coldest periods occurred mainly in the pre-instrumental period: DJF in the 1510s and 1690s, MAM in the 1740s, JJA in the 1590s, SON in the 1760s and annual values in the 1690s.

2.5 Temperature and Precipitation in Central Europe Since AD 1500 – Discussion

2.5.1 Air Temperature

Fluctuations in CEuT series can be compared with some other existing temperature reconstructions in Europe:

1. Seasonal Central European temperature series (further LUT), 1500–2004, calculated from gridded temperature data at latitudes 45°–53°N and longitudes 5°–18°E from Luterbacher et al. (2004, 2007) and Xoplaki et al. (2005); these series were created entirely from documentary and natural proxies for 1500–1658, from a mix of documentary data, natural proxies and early instrumental records for 1659–1750 and from instrumental temperature series from then onwards
2. DJF, JJA and annual temperature series for the Low Countries, 764–1998, calculated from documentary evidence (before 1706) and instrumental data by van Engelen et al. (2001) and Shabalova and van Engelen (2003)
3. JFMA Stockholm temperature series, 1502–2008, calculated from dates of the spring opening of Stockholm harbour (1502–1892) and instrumental records starting in 1893 by Leijonhufvud et al. (2009)
4. DJFM Tallin temperature series, 1500–1997, calculated from the first day of ice-break up in the port of Tallin and on the rivers in northern Estonia by Tarand and Nordli (2001)
5. Central England Temperature (CET) series, 1659–2005, compiled up to 1720 from "the results of readings of highly imperfect instruments in uncertain expo-

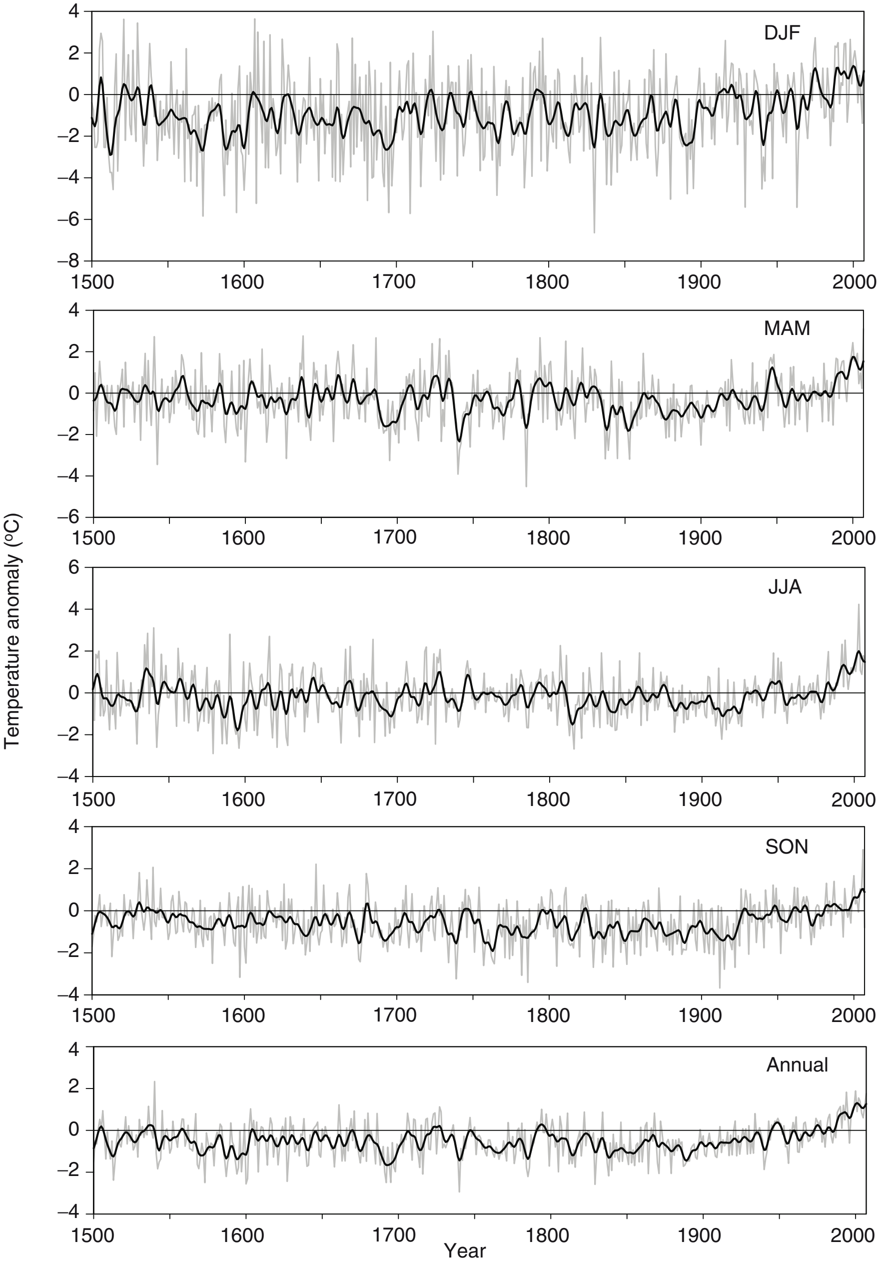

Fig. 2.5 Fluctuations of anomalies (with respect to 1961–1990) of seasonal and annual Central European temperature series for the period AD 1500–2007, smoothed by 10-year Gaussian filter (data: Dobrovolný et al. 2009)

sures at a considerable distance … or on estimates based on interpretation of daily observations of wind and weather" (Manley 1974) and followed by instrumental temperature records afterwards (Parker et al. 1992)

6. April–September Western Europe temperature series, 1068–1987, for latitudes 35°–55°N and longitudes 10°W–20°E based on tree-ring widths, grape harvest dates, Greenland ice oxygen isotope series and temperature indices derived from documentary data by Guiot et al. (2005)
7. June–July Bavarian Forest/Austrian Alps temperature series, before 1500–1997, created as composite chronology from tree-ring widths in stringed instruments and since 1800 from spruce *Picea abies* (Wilson and Topham 2004)
8. June–September temperatures of European Alps, 755–2004, reconstructed from larch *Larix decidua* Mill. tree-ring density series by Büntgen et al. (2006)
9. Summer temperatures in the Hala Gąsienicowa (Tatra Mountains), 1550–2007, reconstructed from tree-rings from the Tatras and the eastern Alps and compiled instrumental series since 1791 by Niedźwiedź (2004)
10. Spring–summer Burgundy temperatures series, 1370–2003, reconstructed from records of grape-harvest dates in the French region of Burgundy by Chuine et al. (2004)
11. April–August Swiss temperature series, 1480–2006, based on grape-harvest dates from the Swiss Plateau region and north-western Switzerland by Meier et al. (2007)

The ice winter severity index for the western Baltic, 1500–1997, derived from classified values of accumulated areal ice volume along the German Baltic coast by Koslowski and Glaser (1999), was also used for comparison.

To estimate spatial relations between CEuT series and other parts of Europe, the instrumental part of CEuT was correlated with 5° × 5° gridded temperatures of HadCRUT3 (Brohan et al. 2006) for the period 1850–2007. Figure 2.6 demonstrates spatial correlations for the four seasons of the year. As expected, the highest correlations are obtained for the Central European grids and decrease with increasing distance from this core region. Correlations are better expressed in the winter, with its strong circulation patterns, than in the summer when temperatures are strongly influenced by local solar radiation and clouds. Moreover, the instrumental part of the CEuT series since 1760 is further correlated with corresponding instrumental parts of other reconstructions (such as LUT, the Low Countries or CET).

Comparison of CEuT series with Central European LUT series (Luterbacher et al. 2004, 2007; Xoplaki et al. 2005) and with the Low Countries series (Shabalova and van Engelen 2003) has already been discussed in detail by Dobrovolný et al. (2009b). High 31-year running correlations (Fig. 2.7) between CEuT and LUT series before 1650 and after 1800 indicate the similar data sets used in both reconstructions (temperature indices for Germany and Switzerland and instrumental records, respectively) while weaker correlations between 1650 and 1800 show up the wider variety of original datasets used. The most dramatic drop in correlations occurs in JJA temperatures during the 1750s (consequently in annual series as well), in similar fashion to the correlations between the Low Countries and CET series, in which correlation coefficients even fade to the statistically insignificant. However, similar sudden drops in the 31-year running correlations may also be observed in other cases (e.g. the 1890s in CET series for JJA). Because both CET and the Low Countries series have been utilised in the LUT European gridded temperature reconstruction, all three series are not fully independent. Possible reasons for the lost coherency in JJA temperatures around the 1750s must therefore be further investigated.

The "winter" CEuT series shows weaker coherency in its fluctuations when compared with series farther north or north-east of Central Europe (Fig. 2.8a). While its correlations with the ice winter severity index of the western Baltic (Koslowski and Glaser 1999) are statistically significant, with lowest values during the second half of the nineteenth century, for both remaining reconstructions – Stockholm (Leijonhufvud et al. 2009) and Tallin (Tarand and Nordli 2001) – the correlations are often insignificant, and even negative before AD 1650. These

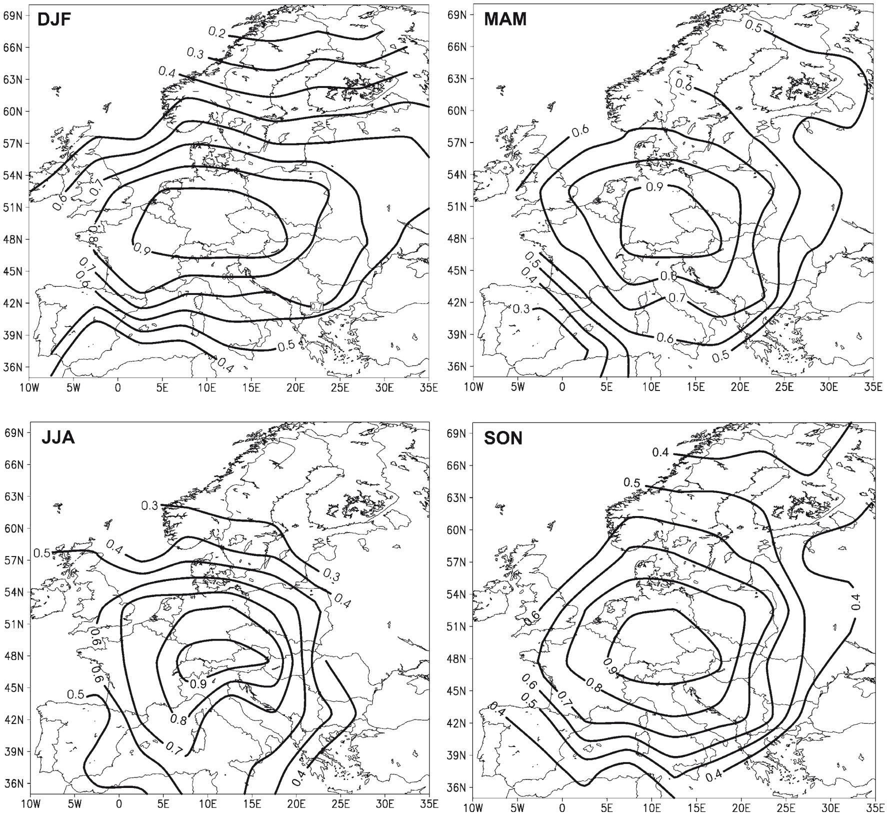

Fig. 2.6 Spatial correlations between seasonal CEuT series (the instrumental part) and HadCRUT3 5° × 5° gridded temperatures (Brohan et al. 2006) for 1850–2007

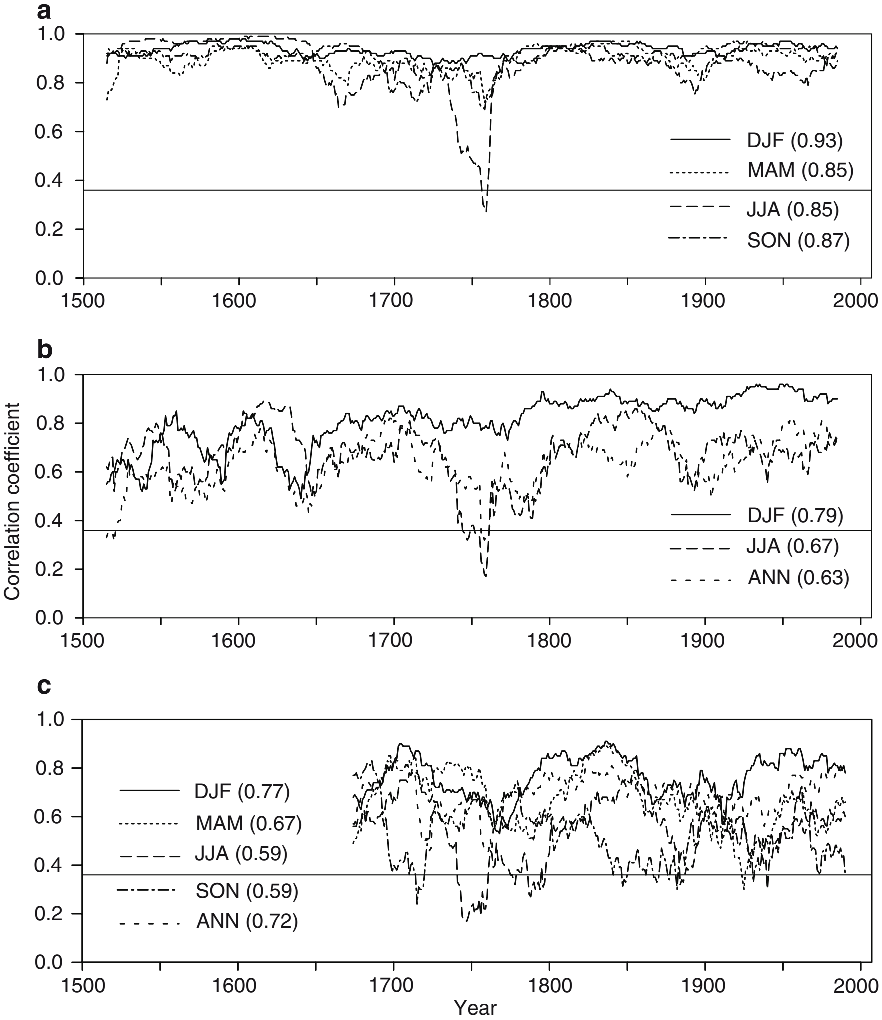

Fig. 2.7 Running 31-year correlation coefficients of seasonal and annual CEuT series with (**a**) Central European LUT series (data: Luterbacher et al. 2004; Xoplaki et al. 2005), (**b**) the Low Countries series (Shabalova and van Engelen 2003) and (**c**) CET series (Manley 1974). Correlation coefficients with CEuT series for the whole length of the three series used are indicated in brackets. Horizontal line – critical value of correlation coefficients for α = 0.05 according to *t*-test

discrepancies cannot be explained only by decreasing temperature correlations with increasing distance (compare Fig. 2.6) between studied regions/stations; they are probably related to weaknesses in the actual reconstructions. The highest long-term correlation coefficient is shown by the winter CEuT series with the Central Europe LUT series (0.93), while the lowest are shown with the Tallin and Stockholm series (0.36 and 0.45, respectively).

Similar correlations are also obtained in comparison of "summer-half" CEuT series with reconstructions based on tree-rings (Wilson and Topham 2004; Niedźwiedź 2004; Büntgen et al. 2006) (Fig. 2.8b) and much higher ones for reconstructions using wine harvest data (Chuine et al. 2004; Meier et al. 2007), or rather multi-proxy reconstruction combining various proxies (Guiot et al. 2005) (Fig. 2.8c). The coherency between CEuT and vintage-based series is much higher compared to correlations between CEuT and tree-ring-based series. The 31-year running correlations between CEuT and tree-ring-based series are mostly insignificant before 1800 and show much higher variability throughout the period. An important decrease in correlations with April–August Swiss series occurs around 1750 and 1890 (similar to the April–September series for Western Europe). It reflects the higher coherency of summer temperature patterns in Western and Central Europe as well as the territorial overlap of the CEuT series with the reconstruction for Western Europe. Some differences in the series compared can perhaps be attributed to individual extreme years/seasons. However, it is difficult to establish the extent to which some of the longer-term losses of coherency (e.g. in the eighteenth century when CEuT is compared with tree-ring-based series, Fig. 2.8b) are related to natural climate variability or to the homogeneity and quality of proxy series.

The summer CEuT series shows the highest long-term correlation coefficient with the Central European LUT series (0.85); notably high are the overall correlations with wine-harvest dates series, which achieve 0.64 to 0.70 (Fig. 2.8c). Three of the tree-ring series employed show relatively lower correlations, between 0.41 and 0.46 (Fig. 2.8b).

2.5.2 Precipitation

Reconstruction of precipitation generally presents greater problems than that of temperatures, due to the large spatial and temporal variability involved. Even instrumental precipitation measurements are biased by significant systematic errors and by the different types of the rain-gauges used for measurements in individual countries (see e.g. Sevruk 2004). Despite these facts, Pauling et al. (2006) applied principal component regression technique to reconstruct seasonal gridded European precipitation series spanning AD 1500–2000, combining instrumental precipitation records, precipitation indices derived from documentary data and several natural proxies (tree-rings, ice cores, corals and speleothems). Although the highest reconstruction skill was found for winter over Central Europe, the reconstruction method was designed to capture continental-scale precipitation fields while small-scale variations are not resolved, by definition. Therefore care should be exercised in the interpretation of comparison based on selected grid points.

Taking these limitations into account, Central European seasonal precipitation series were calculated from 0.5° × 0.5° resolved grids by Pauling et al. (2006) for latitudes 45°–53°N and longitudes 5°–18°E (Fig. 2.9). These series mainly show inter-annual and decadal fluctuations, without long-term trends. With respect to the

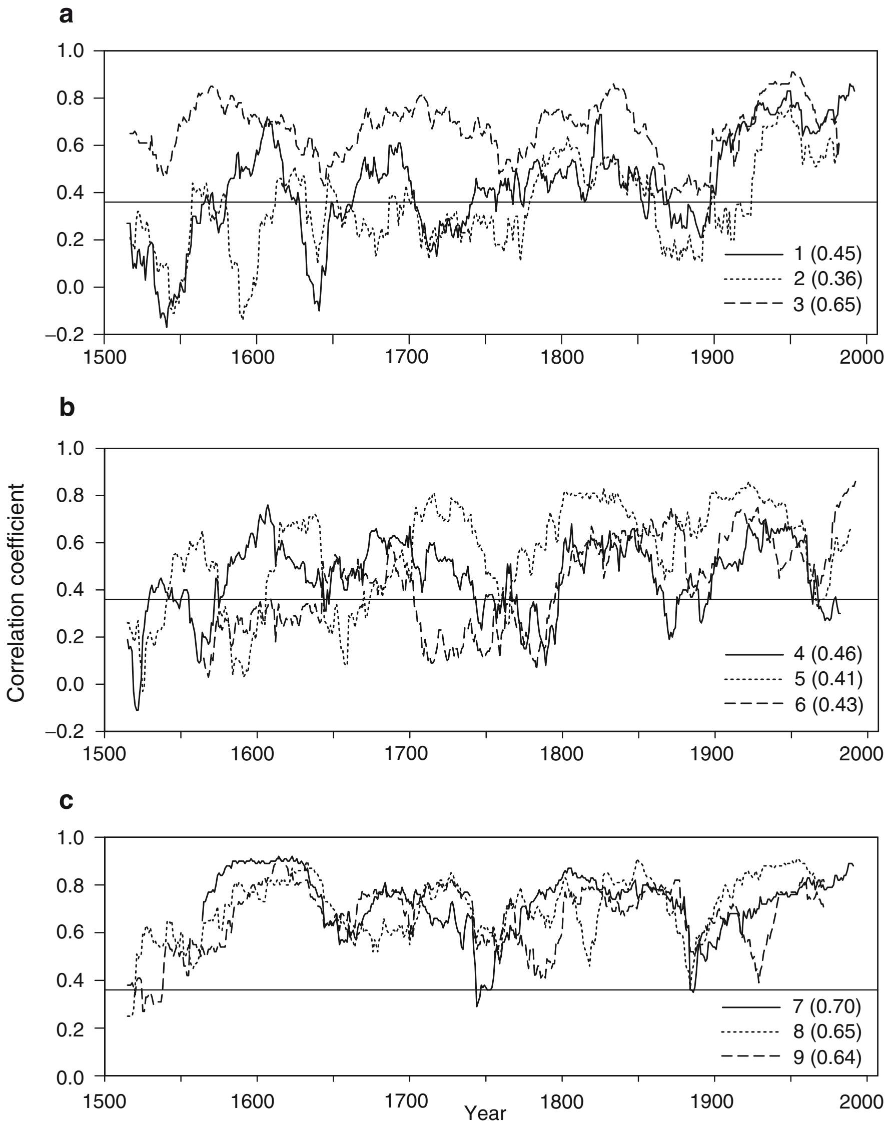

Fig. 2.8 Running 31-year correlation coefficients of (**a**) "winter" CEuT series with (1) JFMA Stockholm series (Leijonhufvud et al. 2009), (2) DJFM Tallin series (Tarand and Nordli 2001), (3) ice winter severity index (Koslowski and Glaser 1999) and (**b**, **c**) "summer-half" CEuT series with (4) June–July Bavarian Forest/Austrian Alps series (Wilson and Topham 2004), (5) June–September Alpine series (Büntgen et al. 2006), (6) JJA Hala Gąsienicowa (Tatra Mountains) series (Niedźwiedź 2004), (7) April–August Swiss series (Meier et al. 2007), (8) April–September Western Europe series (Guiot et al. 2005), (9) April–August Burgundy series (Chuine et al. 2004). CEuT series are always calculated for the same months as corresponding series (1)–(9) used for comparisons. Correlation coefficients with CEuT series for the whole length of series used are indicated in brackets. Horizontal line – critical value of correlation coefficients for α = 0.05 according to *t*-test

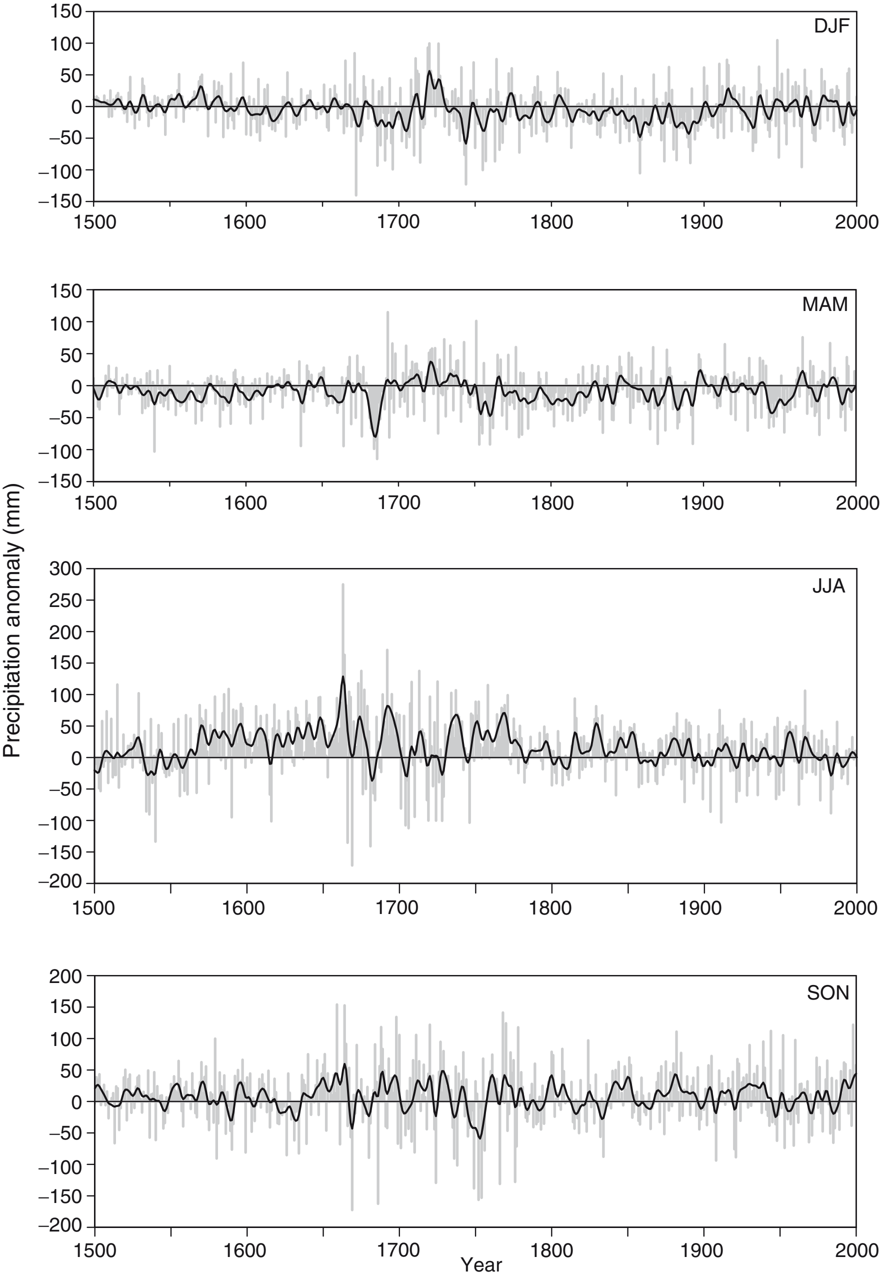

Fig. 2.9 Fluctuations of anomalies (with respect to 1961–1990) of seasonal Central European precipitation series (calculated from grids at latitudes 45–53°N and longitudes 5–18°E from data by Pauling et al. 2006) for the period AD 1500–2000, smoothed by 10-year Gaussian filter

reference period 1961–1990, different periods of above- or below-mean precipitation totals may be identified. The most spectacular is the prevailing higher summer precipitation from the 1560s to the 1770s. An increasing trend can be observed in the sixteenth–seventeenth centuries, while a general decrease in summer precipitation appears afterwards. Remarkably dry were the precipitation patterns of MAM in the 1680s and SON around 1750. On the other hand, the highest winter precipitation occurred around the 1720s and summer precipitation around the 1660s.

Because series of precipitation indices for Switzerland (Pfister 1984, 1999) and Germany (Glaser 2001) are not fully independent of the reconstruction by Pauling et al. (2006), series based on tree-ring reconstructions may be used for comparison with the calculated Central European series. Using fir *Abies alba* tree-rings, Brázdil et al. (2002) reconstructed series of March–July precipitation for southern Moravia AD 1376–1996, explaining 38% of tree-ring width variability. Wilson et al. (2005) used tree-ring width series of Norway spruce for March–August precipitation reconstruction in the Bavarian Forest region AD 1480–2000, explaining 40% of tree-ring width variability (cubic smoothing spline chronology). Comparison of all series on a decadal scale (Fig. 2.10) shows good agreement in some time intervals but even contradictory fluctuations in others. Moreover, large fluctuations in the southern Moravian series after 1950 are related to the destruction of relationships between fir growth and precipitation, as discussed in a more detail by Brázdil et al. (2002).

The 500-year correlations between all three series are rather weak (Central Europe with southern Moravia 0.27 and the Bavarian Forest region 0.45, between the latter two series 0.36). Running correlations are highest for the first part of the seventeenth century. However March–July precipitation totals from southern Moravia do not show significant correlations with Central European gridded reconstructions for the majority of the 500-year chronology (Fig. 2.11). Differences among the three precipitation series may be related to uncertainties in corresponding reconstructions as well as to greater spatial variability of precipitation patterns in Central Europe.

2.5.3 Caveats for Temperature/Precipitation Reconstruction

Temperature/precipitation reconstructions based on documentary evidence are biased by several factors, among which the creation of index series, the reconstruction methods used and expression of the low-frequency signal should be mentioned (see also Dobrovolný et al. 2009a for more details).

2.5.3.1 Deriving Index Series

The key factor in temperature/precipitation reconstructions based on index series is the quality and completeness of monthly indices derived from documentary evidence. This is a great challenge, requiring a broad statistical and dynamic understanding.

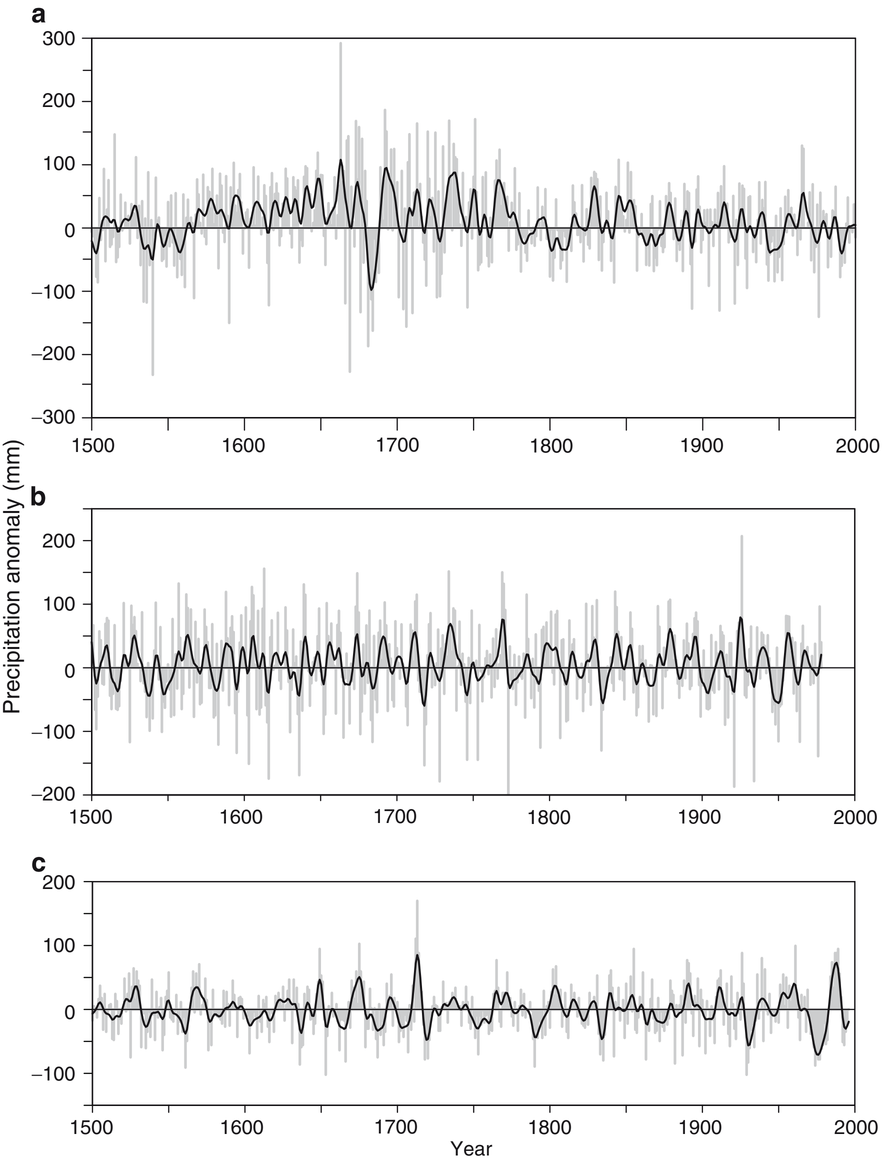

Fig. 2.10 Fluctuations of precipitation anomalies (with respect to 1961–1990) smoothed by 10-year Gaussian filter for precipitation series of (**a**) Central Europe (March–August) calculated from data by Pauling et al. (2006), (**b**) the Bavarian Forest region (March–August) (Wilson et al. 2005) and (**c**) southern Moravia (March–July) (Brázdil et al. 2002)

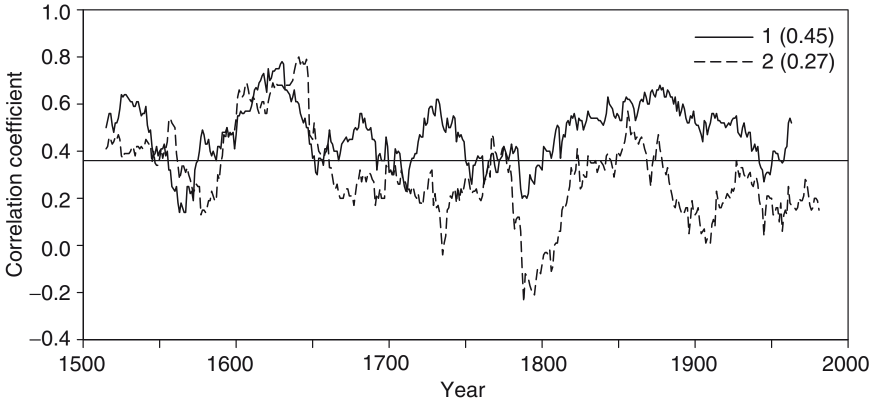

Fig. 2.11 Running 31-year correlation coefficients of Central European "summer-half" precipitation anomalies (with respect to 1961–1990) calculated from data by Pauling et al. (2006) with reconstructed precipitation series of (1) the Bavarian Forest region (March–August) (Wilson et al. 2005) and (2) southern Moravia (March–July) (Brázdil et al. 2002). Central European series is calculated as the sum of MAM and JJA series. Correlation coefficients with Central European series for the whole 500-year period are indicated in brackets. Horizontal line – critical value of correlation coefficients for $\alpha = 0.05$ according to *t*-test

High application and expertise of any given researcher is essential to minimise the degree of subjectivity in this process. However, some more or less objective facts complicate the procedure:

- Missing monthly indices: documentary data for some months may be missing or the character of the information does not allow interpretation in terms of temperature and precipitation (months without written records cannot then be taken correctly as "normal")
- Changes in observer focus on the weather over the course of the year: observers tended to pay greater attention to more strongly expressed weather contrasts or indicators (e.g. heavy frosts, severe heat-waves) and to periods which were economically important for agriculture or other human activities
- Extreme values: the selection of any ordinal scale does not allow the expression of real extremes typified by very high deviations from normal weather patterns
- Non-climatic signal: changes related to other non-climatic causes may be wrongly interpreted as climatologically forced (e.g. arising out of changes in variety of plants, land-use, agricultural practices, etc.)

Some of these problems can be alleviated by further archive research, looking for additional documentary data, combining different data sources and comparing index series from different regions (more useful for temperature than for precipitation because of diminishing decrease in correlations with increasing distance between stations/regions).

2.5.3.2 Reconstruction Methods

Most of the reconstructions mentioned in the current paper are based on a linear regression model (LRM) constructed between the proxy data as an independent variable and temperature/precipitation instrumental measurements. Critical to documentary-based reconstructions is the establishment of a period with sufficiently long overlap to instrumental series. With the onset of the first instrumental measurements, mostly during the eighteenth century in Europe, some traditional documentary sources gradually fade and are replaced with only instrumental data. It is often difficult, therefore, to assemble a sufficiently long calibration/verification period. Even though some calibration approaches can be based on pseudo-proxies (Mann and Rutherford 2002) or on recent measurements (Pfister 1992), independent comparison of proxy series with target measurements is the crucial point for a standard palaeoclimatological approach (Cook et al. 1994). Such an approach permits the use of generally accepted statistics and objectively evaluates the reconstruction skill of documentary proxies.

Linear regression is relatively simple in application. However, the regression line is "averaging" a possibly existing trend into one "mean line" valid for the calibration period. This means that any long-term trend can be obtained only for a case in which certain positive (negative) indices appear more frequently in one period in comparison with prevailing negative (positive) indices in another period.

However, the values of independent variables (proxies) are not gathered without error and, considering the general rules of LRM applicability (see e.g. von Storch and Zwiers 1999), reconstruction results should be interpreted with care. Reconstructed series should be accompanied by uncertainty estimates, usually expressed as standard error and its multiples. However, it is sometimes necessary to inflate the value of standard error with some factors that consider, for example, the number of replicated series used for construction of a proxy series or mutual correlations between individual proxy series. Moreover, there are various uncertainties specific to individual proxy types, as well as those typical of documentary evidence, as discussed in Dobrovolný et al. (2009b). Methods of estimating error are particularly well developed in dendroclimatology (Esper et al. 2005).

Compared to other proxies such as tree-ring data, documentary evidence is often extreme-oriented. This means that outliers and extreme values are mostly well characterised, while descriptions of less significant departures from "normal" conditions are sometimes missing from man-made archives. This feature can further complicate the establishment of a relatively long and homogeneous overlapping period. On the other hand, information on frequency and intensity of extreme events may be utilized for reconstruction in the way suggested by Rodrigo (2008). Bürger (2007) gives an overview of several methods used for temperature reconstruction from various proxies. Although originally related to Northern Hemisphere field reconstructions, possible approaches can be roughly divided into two main groups. The first includes construction of a transfer function between predictor and predictant(s). Regression-based methods may be mentioned at this point. The second group encompasses iterative techniques, for example the RegEM algorithm (see Mann et al. 2005). Although Pfister (1999) characterised documentary evidence as a proxy type that can be used for climate reconstruction with the help of relatively simple and robust methods, as has been demonstrated by several recent papers (Leijonhufvud et al. 2008, 2009; Dobrovolný et al. 2009a, 2009b), the statistical techniques above can be successfully used in reconstructions based on documentary data.

2.5.3.3 High- and Low-Frequency Signals

Zorita et al. (2009) compared seasonal and annual CEuT series with the outputs of two temperature simulations modelled by ECHO-G. This series, in contrast to the JFMA temperatures in Stockholm (Leijonhufvud et al. 2009) and CET series (Manley 1974), shows weaker agreement with model simulations at selected grid points, mainly in expression of the low-frequency signal. Similarly, von Storch et al. (2004) mentioned underestimation of low-frequency variability in Northern Hemisphere temperature reconstructions based on regression methods, something that is reflected in stronger decadal fluctuations. However, several other papers (e.g. Mann et al. 2005; Goosse et al. 2005) have suggested that these results are overstated.

The weak low-frequency signal in CEuT reconstruction may be explained by the application of LRM to temperature indices derived from documentary data. This, in turn, is related to the fact that the authors of documentary records described the weather with respect to their own perception, in terms appropriate to the weather patterns prevailing in the contemporaneous period. This means that every one of them had a different concept of what constituted “normal”, something that obviously cannot be reflected in the interpretation of indices. Rather, the index series created express deviations from normal patterns typical of the selected recent reference period (e.g. 1901–1960 or 1961–1990). Thus temperature reconstructions based on the creation of temperature indices are less able to express the low-frequency signal. This situation may be partly improved if we can combine a particular reconstruction with other proxies expressing certain long-term trends (e.g. series of phenophases, freezing of rivers and lakes, start of agricultural and viticultural harvests, etc.). On the other hand, reconstructions based on such long-term bio-physically-based proxies might lack this bias (e.g. Chuine et al. 2004; Meier et al. 2007; Leijonhufvud et al. 2008, 2009).

2.6 Perspectives on Further Research in Central Europe

In Central Europe, a long tradition of meteorological observation and a relatively rich body of documentary evidence come together to create a good background for further investigations into the climate variability of the area over the past 500 years. Any corresponding climatic time series covering this long time interval may be obtained only as a combination of reconstruction based on proxy data and instrumental records. Reconstructions based on documentary evidence are capable of providing monthly, seasonal and annual temperature/precipitation series, that is there are no time constraints, while many natural proxies such as tree-rings, ice cores, lake sediments, etc. (e.g. Bradley 1999; Jones and Mann 2004; Jones et al. 2009) can be used for climate reconstructions only for periods in terms of a combination of a number of months, a season or the whole year.

It follows from this article that a great deal of effort has been devoted to the study of the last 500 years of Central European climate. Despite this, there still exists a largely unfulfilled potential for further research, mainly on:

- Homogenisation of long-term temperature and precipitation series (outside HISTALP – Auer et al. 2005, 2007), including utilisation of early instrumental meteorological measurements
- Revision of existing weather compilations, documentary datasets and their completion by other new archival sources
- Creation of new temperature/precipitation index series based on documentary evidence and filling of existing gaps in available series
- Further collection of documentary data for the overlapping period with instrumental records for correct calibration/verification using the standard palaeoclimatological method
- Development and application of new methods of temperature/precipitation reconstruction and calculation of error bars
- Cross-checking of documentary data, temperature/precipitation reconstructions and results of model runs
- Deepening of co-operation between environmental historians and climatologists, as well as with climate modellers
- Cross-checking and combining of reconstructions based on man-made and natural climate proxies.

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Chapter 3
Climatic Variations in the East European Plain During the Last Millennium: State of the Art

Vladimir Klimenko and Olga Solomina

3.1 Introduction: Climate of the East European Plain

East European (Russian) Plain is located in the high to mid latitudes between the Arctic Ocean in the north, Black and Caspian Seas in the south, and from the Polish/Ukraine frontier in the west and the western slope of to the Urals Mountains in the east (Fig. 3.1). The radiation balance in winter is negative at the whole East European Plain except for the most southern territories, while in summer it is positive everywhere. The climate is mostly influenced by the Westerlies. The air masses from the Atlantic in winter bring warmth and precipitation, in summer they are responsible for the cool and wet weather conditions. Moving to the east the air masses become drier – warmer in summer and colder in winter (Shahgedanova 2002).

Because the warm weather in winter is caused by the Atlantic cyclones coming from the west, the spatial contrasts in winter climate is smaller in the north-south comparatively to the east-west direction. In the northern part of the East European Plain the mean January temperature varies from −10°C to −20°C from west to east, in the southern part – from +5°C to −15°C changing in the same direction. The summer temperature depends mainly on solar radiation, therefore the summer isotherms almost correspond to the parallels. Mean July temperature is +8°C at the far north and +24°C in near Caspian region.

Precipitation distribution depends mainly on the atmospheric circulation patterns. The Westerlies bringing high cloudiness and precipitation are complimented by the high frequency of cyclones of the Arctic and the Polar Fronts. The cyclones are most frequent between 55°N and 60°N where the annual precipitation is up to 600–700 mm in the west and 500–600 mm in the east of the Plain. To the east the frequency of anticyclones increases. The air masses are loosing their humidity here

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Fig. 3.1 East European Plain. The sites indicated are mentioned in the text. The numbers are: (1) Polovetsko-Kupanskoye peat bog, Yaroslavskaya oblast'; (2) Polistovo, Pskovskaya oblast'; (3) Panfilovo, Vladimirskaya oblast'; (4) Karelia; (5) Belorus'; (6) Nigula, SW Estonia; (7) Usviatsky Mokh, Tverskaya oblast'; (8) Saki Lake, Crimea; (9) Pertozero, S. Karelia

and the precipitation in the southern part of the East European Plain is lower (500–300 mm, down to 200 mm per year). Precipitation in summer is caused by the circulation at the Arctic and temperate fronts while only 10% of precipitation are associated with the inner mass processes. The precipitation/evaporation ratio is positive (+200 mm) in the north, close to zero in the area of the issues of the Don and Dniester rivers, and negative to the south (the deficit is up to 700 mm).

Alisov (1969) subdivided the territory of the East European Plain into three climatic areas. This division is still valid despite of the half century time passed since Alisov's work. The regions are: (1) Northern Atlantic-Arctic area (southern boundary located between the Ladoga and Pechora river issues). (2) Middle Atlantic-continental area (southern boundary from the mid flow of the Dniester to the mid Volga) (3) Southern continental area. The areas are also subdivided into the western and eastern sub-areas with the boundary running from the Severnaya Dvina to the Volga issues and Dnieper mouth. The climate is mirrored by the vegetation and soil zones. The major zones represented at the East European Plain are tundra, forest-tundra, forest, forest-steppe, semi desert and desert.

In this paper we briefly overview the data on long instrumental series of meteorological records, historical, tree ring, palynological records and the results of multi proxy reconstructions of the mean annual, summer, winter temperatures and annual precipitation in the European Plain for the last millennium published in the scientific literature both international and Russian.

3.2 Materials and Methods

The details on the methodology of proxy-based reconstructions can be find elsewhere (e.g. Bradley 1999; Jones and Mann 2004), therefore we do not describe it here unless these details are necessary to explain the discrepancies between the results obtained by different researchers or the methodology of the reconstructions substantially differs from the standard one.

Longest instrumental records in the Eastern Europe go back to the mid eighteenth century (Table 3.1). The long instrumental meteorological series provided here are from the data bank VNIIGMI-MTSD (http://www.meteo.ru/data/mdata.htm) as well as from the earlier records revised and summarized by Gazina and Klimenko (2008). The long term trends of temperature and precipitation variations in the East European Plain were revised from time to time (e.g. Voyeikov 1892, 1907; Gruza et al. 1977; Gazina and Klimenko 2008) using the long instrumental time series and taking into account the new portions of records. In the most recent comprehensive summary of climatic variations in the Russian Federation the basic period used is 1936–2006 (Meleshko 2008).

Various types of historical records are available in the East European Plain for the last millennium, including historical chronicles, letters, notes of travelers, merchants etc. The oldest historical chronicle was initiated during the time of Prince Yaroslav the Wise in Kiev in AD 1037–1038 (Likhachev 1947) though the earliest record of unusual climatic events dates back to the earlier time (year AD 867) (Rybakov 1963). The registration of climatic events in the Russian Plain became systematic from the fourteenth century. Climatically significant data was extracted from these records and analysed by a number of researchers such as Bogolepov (1907, 1912), Berg (1911), Buchinsky (1957), Betin and Preobrazhensky (1962) and many others. The most comprehensive compilations belong to Borisenkov

Table 3.1 List of the longest meteorological records (stations) at the East European Plain

No	Meteorological station	Latitude (N)	Longitude (E)	Beginning of records
1	St-Petersburg	59.97	30.30	1743
2	Vilnius	54.63	25.28	1777
3	Moscow	55.75	37.57	1779
4	Riga	56.97	24.70	1795
5	Tallinn	59.42	24.80	1811
6	Kiev	50.40	30.45	1811
7	Kazan	55.78	49.18	1812
8	Arkhangel’sk	64.58	40.50	1813
9	Petrozavodsk	61.82	34.27	1816
10	Syktyvkar	61.67	50.85	1817
11	Odessa	46.48	30.63	1821
12	Simferopol’	45.02	33.98	1821
13	L’vov	49.82	23.95	1824
14	Kishinev	47.02	28.87	1825
15	Orenburg	51.75	55.10	1832
16	Saratov	51.57	46.03	1836
17	Astrakhan’	46.27	48.03	1837
18	Tambov	52.73	41.47	1845
19	Fort Shevchenko	44.55	50.25	1848
20	Minsk	53.87	27.53	1849
21	Kaliningrad	54.70	20.62	1851

and Pasetsky (1988, 2003). They are based on the 37 volumes of “Complete Selection of Russian Chronicles” and also include the data from other historical sources. In Section 3.4 we summarize the results of these studies.

Several researchers attempted to quantify the historical information on climatic changes in the East European Plain in the last millennium (Lyakhov 1984; Zolotokrilin et al. 1986; Zolotokrilin and Popova 1988; Voronov 1992; Klige et al. 1993; Krenke and Chernavskaya 1998). Lyakhov (1984) qualified as temperature and precipitation anomalies as those which exceed the half of the amplitude of the observed fluctuations. The correlation of the number of these cases and the mean values of temperature averaged for 30 years periods allowed the quantification of the historical records for 30-years mean periods.

Voronov (1992) and Klige et al. (1993) used a similar approach. However instead of the absolute numbers of anomalies these authors used their normalized values (i.e. the number of extreme events divided to the total number of the recorded events). They also made corrections for the decrease of the density of historical data back in time suggesting that the total number of events should be constant through the time. According to Klige et al. (1993) the coefficients of correlation of the 30-year averaged extremes with the mean monthly temperatures and sum of precipitation for the longest meteorological records (Sankt-Petersburg, Moscow, Kiev, Riga) for four regions (respectively NW, Central, SW, W) are high enough ($r = 0.80–0.85$) to allow the reconstructions. The mean statistical error of the reconstructions is estimated as ±0.2°C for the temperature and ±20 mm for precipitation. However Klige et al. (1993) warned that a degree of uncertainty of these reconstructions related to the specific data source as well as to the approach itself based on several assumptions is still rather high.

High resolution reconstructions based on the tree-ring data are not sufficiently long in the East European Plain to cover the whole millennium. Most tree-ring time series constructed for the East European Plain before 1990s were not quality controlled. The common practice to apply the running means for the detrending eliminating the long-term trends does not allow the use of most of old series for the climatic analyses. The archeological wood covering the last millennium in the Arkhangelskaya, Tverskaya, Novgorodskaya oblast' and some other regions although successfully cross-dated within individual archeological sites (basing on the historical dates of churches) was not aggregated into chronologies and used for the climatic reconstructions except for some rare cases (Chernikh 1996; Pushin et al. 2004).

In the last decades new high quality tree-ring based reconstructions 300–400 years long for the East European Plain were published (Schweingruber and Briffa 1996; Vaganov et al. 1996; Briffa et al. 2001) Schweingruber and Briffa (1996) analysed the coherency of ring width and density records along the northern tree line and found out that the spruce and larch chronologies in the Sub-Arctic of North Eurasia react similarly to the environmental factors. Both ring width and maximum density chronologies represent well the fluctuations of several decades, but the density chronologies show better the high frequency fluctuations. There is a clear coherency between all chronologies from 42°E to 152°E, although a certain growth (density) patterns vary in different regions. The general coherency of the records allowed Briffa et al. (2001) to average the individual chronologies in three sectors in the Northern Eurasia North of Europe (NEUR), North of Siberia and East of Siberia. All these series were correlated against the instrumental data (mean monthly temperature for April–September, anomalies from 1961–1990) produced from the grid box instrumental surface anomalies. The correlation of the series with the temperature is generally very high ($r = 0.76$ for the NEUR series). However the Northern European regional chronology includes as well the chronologies from Sweden, Finland and other northern territories outside the East European Plain, therefore it is not fully applicable here. In general tree-ring based reconstructions represent one of the best source of climatic information at the northern tree line of the East European Plain for the last four to five centuries due to their high resolution, good replication of chronologies, and high correlation of tree-ring parameters to the climatic variations. The records are available at http://www.ncdc.noaa.gov/paleo/treering.html.

Longer chronologies exist only in the mountain areas surrounding the East European Plain. Those from the Polar Urals and Khibiny Mts are temperature sensitive. For the Polar Urals Mountains Shiyatov (1986) reconstructed the May–September temperature from AD 914 to 1990. The reconstruction accounts for 66–70% of summer temperature variance (Briffa et al. 1995). The millennium long reconstructions based on ring width, density and stable isotopes in the Khibiny Mts are under way (Boettger et al. 2004). MacDonald et al. (2007) used tree rings chronologies and Palmer Drought Sensitivity Index for the river discharge reconstructions for the period

AD 1800–1990 for the S.Dvina, Pechora, Ob', Yenisey, Lena and Kolyma Rivers. The dendrohydrologic models explain up to 55% (the Pechora) of the observed variability of flow. The drought sensitive chronology in the Crimea was used for the reconstruction of the spring-early summer precipitation by Solomina et al. (2005).

The wood macrofossils can be useful to estimate the long-term temperature trends, which are not preserved in the ring properties alone. This kind of data is available for the Polar Urals (Shiyatov 2000) and the Khibiny Mountains (Hiller et al. 2001).

Another way to estimate the low frequency temperature variability is the borehole temperature measurements. More than 1,400 sites of heat flux measurements in the Former Soviet Union were catalogued, although most of the sites are located in the Urals and Siberia. After a quality control of these data Pollack et al. (2003) included only four sites from the European Russia in their reconstruction of the surface temperature trends based on borehole data http://www.ncdc.noaa.gov/paleo/borehole/core.html. The Urals' data set is much more comprehensive and suitable for the regional reconstructions (Demezhko et al. 2003).

Palynological records are numerous in the Russian Plain, though they normally are poorly constrained by the radiocarbon dates, which precludes the possibility of high resolution reconstructions. However they are suitable to estimate the multidecadal variations of the last one to two millennia. Detailed palynological reconstructions in the East European Plain used in this paper are listed in Table 3.2.

In palynological reconstructions, cited in this paper, a statistical approach, which allows the transformation of the palynological parameters into the numerical climatological format developed by Klimanov (1989) was used. This approach takes into account the relation between subfossil spectra and modern climatic conditions. The resolution of these reconstructions is limited by the accuracy of the radiocarbon dates and is sometimes less than a century. However in case of high and regular peat accumulation the reconstructions can reach a multidecadal resolution and therefore these reconstructions can be compatible with the long instrumental data (Klimanov and Nikiforova 1982; Klimenko et al. 2001). Summer, annual and winter temperature and annual precipitation can be reconstructed this way though with different degree of reliability which is higher in case of parameters related to the growth season. The mean error estimate for the mean annual temperature reconstruction and for the mean July temperature is ±0.6°C, for mean January temperature is ±1°C, and for annual precipitation is ±25 mm (Klimanov 1989).

One of the most detailed palaeoclimatic reconstruction is based on the Usviatsky Mokh (UM) site (Klimenko et al. 2001) (see Fig. 3.1). The peat sediments were recovered from the section up to 80 cm depth with the resolution of 1 cm, and further down to 2 m depth cored using a TBO borer and sampled each 2.5 cm. Thus 128 samples in total were collected and palynologically analysed. The age of sediments was constrained by 20 radiocarbon dates (from 170 to 4630 ^{14}C years). Due to the detailed sampling Klimenko et al. (2001) were able to distinguish in these records 35 periods of warming/cooling during the last ca 600 years. The high resolution of the palynological records in the last 600 years and very high rate of peat accumulation (1.3 mm per year) in UM allows a direct comparison and calibration of palynological data with temperature records which are more than 200 years long in this area. The deeper layers (older than 600 years) allow only a lower resolution (see Section 3.7).

Table 3.2 Most detailed palynological records in the European part of the FSU

Region	Period	Climatic parameter reconstructed	Reference
NW of Russia (Leningradskaya and Novgorodskaya oblast' (58–61°N, 30–31°E)	Last 13,000 years	Mean annual temperature	Arslanov et al. (1999)
Polovetsko-Kupanskoye peat bog,Yaroslavskaya oblast' (57°N, 39°E)	AD 250–1950	Mean annual, summer, winter temperatures and mean annual precipitation	Klimanov et al. (1995)
Polistovo (Pskovskaya oblast') (56.8° N, 30.1°E)	AD 500–1950	Mean annual temperature	Chernavskaya (1995)
Panfilovo (Vladimirskaya oblast') (55.7°N, 40.5°E)	AD 500–1950	Mean annual temperature	Chernavskaya (1995)
Karelia (63°N, 34°E)	Last 11,000 years	Mean annual, summer, winter temperatures and mean annual precipitation	Klimanov (1994)
Belorus' (54°N, 27°E)	Last 13,000 years	Mean annual, summer, winter temperatures and mean annual precipitation	Klimanov (1994)
Nigula, SW Estonia, юго-запад (59°N, 26°E)	Last 2,000 years	Mean annual and summer temperatures and mean annual precipitation	Klimanov et al. (1985)
Northern Near Black Sea Region	Last 8,000 years	Temperature of January, July and annual precipitation	Kremenetsky (1991)

There were several attempts to compare the results of different proxies, but most of them were qualitative and descriptive (e.g. Krenke 1995). Sleptsov (2002) and Klimenko and Sleptsov (2003) produced the first quantitative multi-proxy temperature and precipitation reconstructions for the East European Plain for the last one to two millennia. The temperature reconstruction is based on eleven time series of palynological, historical and dendrochronological data mostly from the central and northern parts of the East European Plain (Table 3.3). As soon as the borehole data are of too low resolution this type of records was not included in the reconstruction. In total for the annual temperature reconstruction Klimenko and Sleptsov (2003) possess a data set consisting of 374 points unevenly distributed in time from AD 15 to 1995. For the mean annual precipitation reconstruction they selected six most relevant sources (284 points for the period from AD 305 to 1995 (Table 3.4). Data sets for summer and winter temperatures consist of 388 and 293 points respectively from AD 350 to 1995.

The authors of this reconstruction used two approaches to deal with the initial data sets (see details in Klimenko et al. 2001): (1) Methods of correlations and spectral analyses and the algorithm of numerical filtration, taking into account the stochastic

Table 3.3 Time series used for the multi-proxy mean annual temperature reconstruction

№	Site	Type of data	Weight	Reference
1	Usviatsky Mokh, Tverskaya oblast' (56°N, 32°E)	Palynology	1.0	Klimenko et al. (2001)
2	NW of Russia (58–61°N, 30–31°E)	Palynology	1.0	Arslanov et al. (1999)
3	Polovetsko-Kupanskoye, Yaroslavskaya Oblast' (57°N, 39°E)	Palynology	0.5	Klimanov et al. (1995)
4	Panfilovo (55.7°N, 40.5°E)	Palynology	0.5	Chernavskaya (1995)
5	Polystovo (56.8°N, 30.1°E)	Palynology	0.5	Chernavskaya (1995)
6	Center of East European Plain	Historical	1.0	Klige et al. (1993)
7	Center of East European Plain	Historical	1.0	Lyakhov (1984)
8	NW of East European Plain	Historical	0.25	Klige et al. (1993)
9	W of East European Plain	Historical	0.25	Klige et al. (1993)
10	SW of East European Plain	Historical	0.25	Klige et al. (1993)
11	Northern Eurasia	Dendrochronology	0.5	Lovelius (1979)

Table 3.4 Time series used for the multi-proxy of annual precipitation reconstruction

No	Site	Type of data	Weight	Reference
1	Usviatsky Mokh (56°N, 32°E)	Palynology	1.0	Klimenko et al. (2001)
2	Polovetsko-Kupanskoye, Yaroslavskaya Oblast' (57°N, 39°E)	Palynology	0.5	Klimanov et al. (1995)
3	Center of East European Plain	Historical	1.0	Klige et al. (1993)
4	NW of East European Plain	Historical	0.25	Klige et al. (1993)
5	W of East European Plain	Historical	0.25	Klige et al. (1993)
6	Pertozero	Hydrological	0.5	Schostakovich (1934)

nature of discretisation. (2) The program of nonparametric regression using the expert estimates of the weight of each record. These estimates are based on the detalization, accuracy, potential biases of the series which were estimated by the disagreement of each record with other series. The series reconstructed using the two approaches agrees well and also are significantly correlated with the long instrumental data (average for Sankt-Petersburg, Moscow, Riga, and Vilnius) (r = 0.79). The method 1 is however resulted in a less detailed curve losing the high frequency variations. Therefore the final reconstruction is based on the method 2 (see also Section 3.9). The accuracy of the reconstruction is estimated as ±0.2°C. The same approach was used to reconstruct annual precipitation (see Table 3.4). The correlation coefficient between the instrumental data of precipitation and the reconstructed values is 0.57.

3.3 Instrumental Data

In this section we discuss the long-term trends of annual temperature and precipitation and their spatial coherency within the East European Plain recorded at the meteorological stations with the longest records.

3.3.1 *Mean Annual Temperature*

Gazina and Klimenko (2008) analysed the winter, summer and annual temperature variations (Fig. 3.2) at four longest meteorological stations in the Eastern Europe which possess minimum or no gaps (St-Petersburg, Vilnius, Moscow and Riga). The upward trend in the annual temperature can be seen in Moscow records since 1870s. At the three other stations the warming began much later – only in 1960s–1970s.

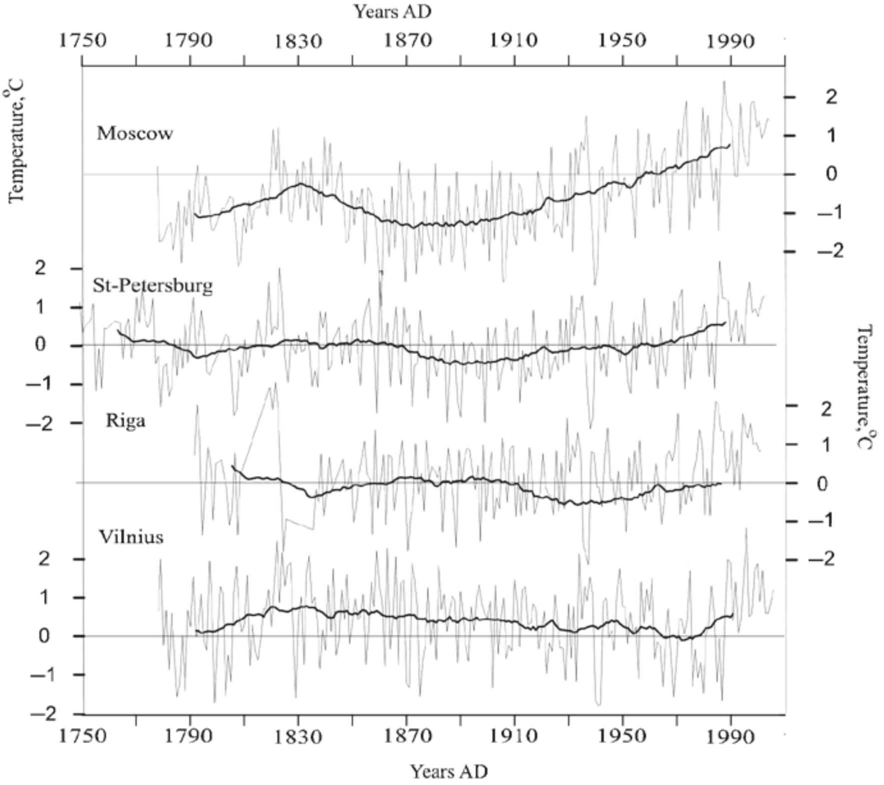

Fig. 3.2 Mean annual temperature anomalies from 1951 to 1980 mean at St-Petersburg, Moscow, Vilnius and Riga (annual and 30-year running means)

Gazina and Klimenko (2008) found out that during the last two centuries the winter temperature significantly increased (up to 3°C) at all four stations, while the summer temperature slightly decreased. This finding contrasts with the Western Europe, where the warming both in winter and summer are recorded (IPCC 2007).

The temperature records from all four meteorological stations are significantly correlated (r from 0.64 to 0.86). According to this data the major coolings in the northern and central regions of the East European Plain occurred in 1760s, 1780s, 1810s, 1940s; warmings date back to 1770s, 1820s, 1930s and 1990s. The mean annual temperature in the 1990s and 2000s only slightly exceeded the thermal maximum of the 1820s.

A century long records (1890–1990) provide an opportunity to assess the agreement between the temperature changes in the different regions of the East European Plain (Fig. 3.3). Generally interannual to decadal variations occur simultaneously in these regions, though the similarity of the southern curve with the two others is lower (r = 0.66). Gruza et al. (1977) analysed the spatial variability of temperature and precipitation in the Former Soviet Union and concluded that the temperature anomalies in the center and the periphery of the East European Plain correlate for all months. Instrumental data show that in general the temperature variations in the East European Plain are similar to those in Central Europe (Gazina and Klimenko 2008).

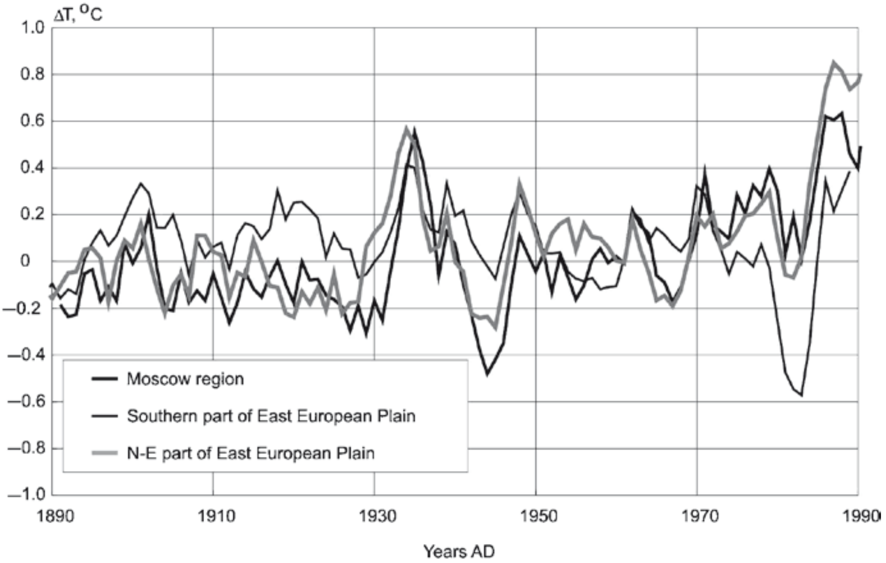

Fig. 3.3 11-years running mean of instrumental annual temperature anomalies from 1951 to 1980 mean for Moscow, NW part of the East European Plain (St-Petersburg, Riga, Vilnius), and SW part of the East European Plain (Kiev, Simferopol’, Odessa)

3.3.2 Annual Precipitation

In general precipitation is much more variable in different regions in the East European Plain, however some anomalies occur simultaneously in the whole region. The annual precipitation in northern (St-Petersburg) and central (Moscow) parts of the Plain on one hand and southern stations (Kiev and Odessa) on the other are poorly correlated (r = 0.21). The difference between the north and south is quite large for both interannual variability and long-term trends. The increase in annual precipitation over the last 150 years is significant both in Moscow and St-Petersburg, but the trend is insignificant in the southern regions. The most prominent increase of annual precipitation in the East European Plain begun in the last decades (1976–2006) (Meleshko 2008).

3.4 Historical Data

3.4.1 Documentary Evidence of Climate Changes in the East European Plain

Figure 3.4 compiled by Shahgedanova (2002) from the data of Borisenkov and Pasetsky (1988) presents the occurrence of extreme droughts, outbreaks of crop-eating insects, wet summers and autumns, frosts in the early and late summers, unusually wet and dry winters, cold springs, floods, heavy storms and famines. The number of extremes is gradually increased from the second half of twelfth century. The tendency continued into the early thirteenth century: in 1200–1220s the highest number (seven) of cold winters were recorded, whereas in the next 20 years, in contrast, the unusually warm winters (five) prevailed. Such conditions led to the severe famine recorded in the chronicles (Bozheryanov 1907; Likhachev 1947). In AD 1230 there was a total crop failure at the whole Russian territory – one of about ten events of the same magnitude recorded in the whole historical period (Slovtsov 1858).

The decades of the 1230s and 1240s were mild and no extreme weather events were recorded. In the last quarter of the thirteenth and the early fourteenth centuries the chronicles mention more often the “great storms” and unusual floods, dry summers would follow the rainy warm seasons. The decades of the 1340s and 1350s were relatively stable in terms of climate: except for four “great storms” no other extreme are mentioned at that time. The last 40 years of this century were very dry: 11 dry years were recorded which resulted in the fully dried rivers, forest and peat bogs fires. At the same time the number of cold winters, early frosts and late springs increased. In total in the fourteenth century the chronicles recorded more than 100 extreme events and 30 years of famine.

In the fifteenth century the number of extremes further increased up to 150 events, though most of them were regional. Heavy rains and severe droughts, cold winters and cool summers resulted in more than 40 years of famine, 15 of them were

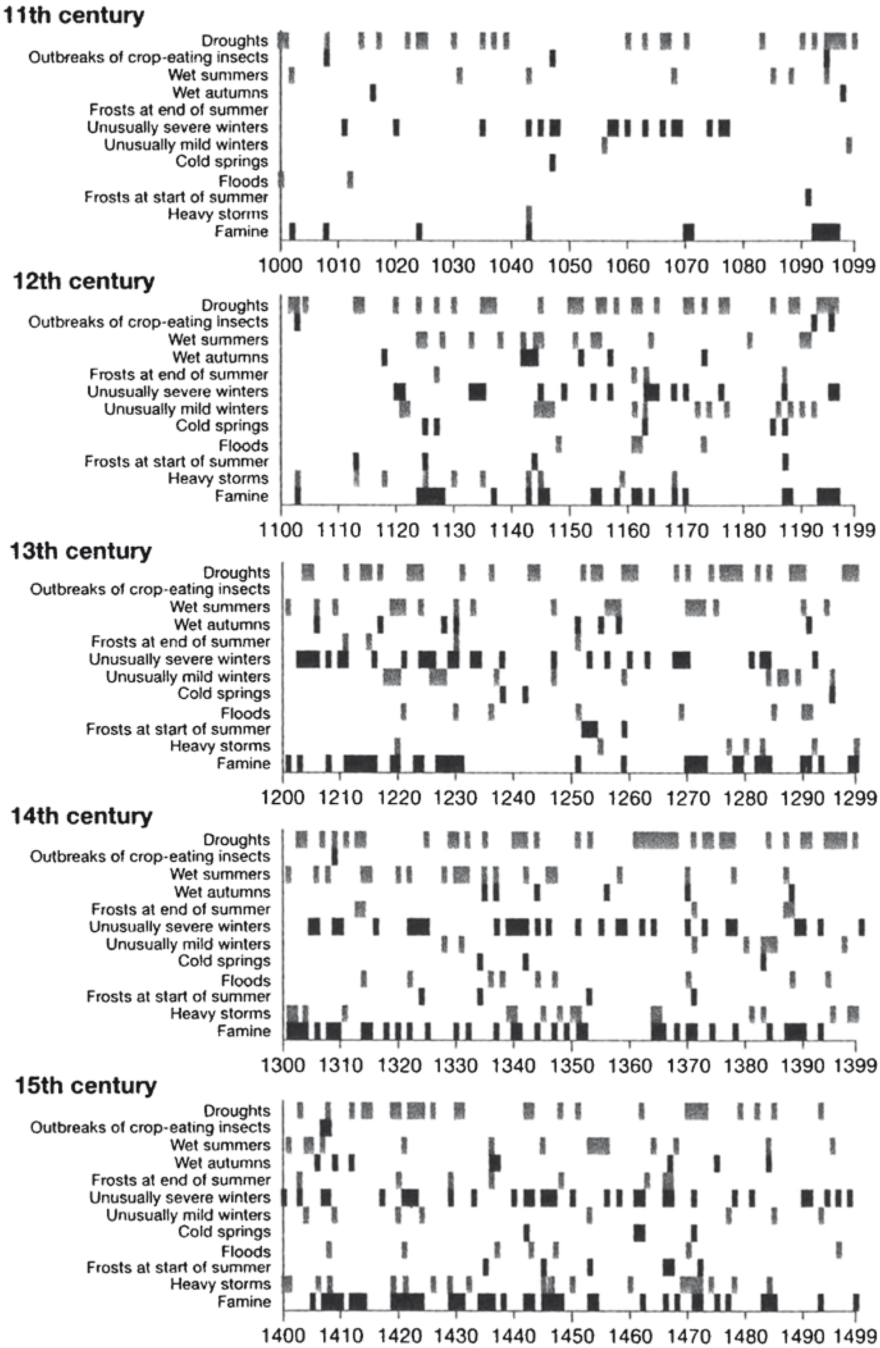

Fig. 3.4 Number of climatic extremes (occurrence of extreme droughts, outbreaks of crop-eating insects, wet summers and autumns, frosts at the beginning and ends of summers, unusually wet and dry winters, cold springs, floods, heavy storms and famines) in the East European Plain compiled by Shahgedanova using the data of Borisenkov and Pasetsky (1988, 2003) (From Shahgedanova 2002)

extremely hard. The decades of the 1440s and 1450s were extreme in terms of frequency of severe winters.

In the second half of the sixteenth century and in the early seventeenth century the climate in the East European Plain was very variable: the number of severe winters increased as well as the occurrence of cold summers. The frosts and long heavy rains in summer 1601 in combination with the winter conditions unfavorable for agriculture resulted in a very severe famine in 1601–1603. The early eighteenth century in general was rather mild – the extremes were not numerous. This information agrees with the data on favorable conditions for the marine travels in the Arctic seas. In the second quarter of the seventeenth century the Russian seafarers reached Chukotka and passed through Bering Strait.

The climate in the second half of the seventeenth century was very variable. Between years 1640 and 1659 eleven summers were extremely dry. On the other hand the anomalously rainy summers with frosts in the early and late summers were also recorded.

In the eighteenth century 39 years were extremely dry, 19 years extremely rainy, 36 had very severe winters, 22 – mild winters, 33 – high floods and 22 – “great storms”; more often than before the frosts were recorded in the late summers and cold springs. These climatic conditions led to 68 extremely famine years in the eighteenth century (including those of the very poor crops in the whole Russia in 1716 and 1722).

In the beginning of the nineteenth century the severity of winters was still high and mild winters were rare. The droughts were still often, but they occurred mostly locally. The lowest number of extremes were recorded between 1800 and 1820 and between 1860 and 1900.

3.4.2 Quantitative Estimate of Climate Changes in the East European Plain Using Historical Data

Figures 3.5, 3.6, 3.7, and 3.8 display the results of the reconstructions of 30-years anomalies of annual, summer, winter temperatures and annual precipitation for various regions of the East European Plain from Voronov (1992), Klige et al. (1993), and Lyakhov (1984). According to historical data (Borisenkov and Pasetsky 1988; Voronov 1992; Klige et al. 1993) the annual temperature was changing relatively synchronously in the western, south-western, north-western and central regions of the East European Plain (see Fig. 3.5). This conclusion corresponds to the results obtained from the long instrumental records in the nineteenth to twentieth centuries (see Section 3.3, Fig. 3.3). The late twelfth and late fourteenth centuries were the warmest within the twelfth to nineteenth century period, whereas the early fifteenth and the whole nineteenth centuries were the coldest. The precipitation variations are more regionally variable with the most humid conditions in all regions in the fifteenth to the early sixteenth centuries (see Fig. 3.6). Some discrepancies noticeable in different reconstructions are discussed in Section 3.10.

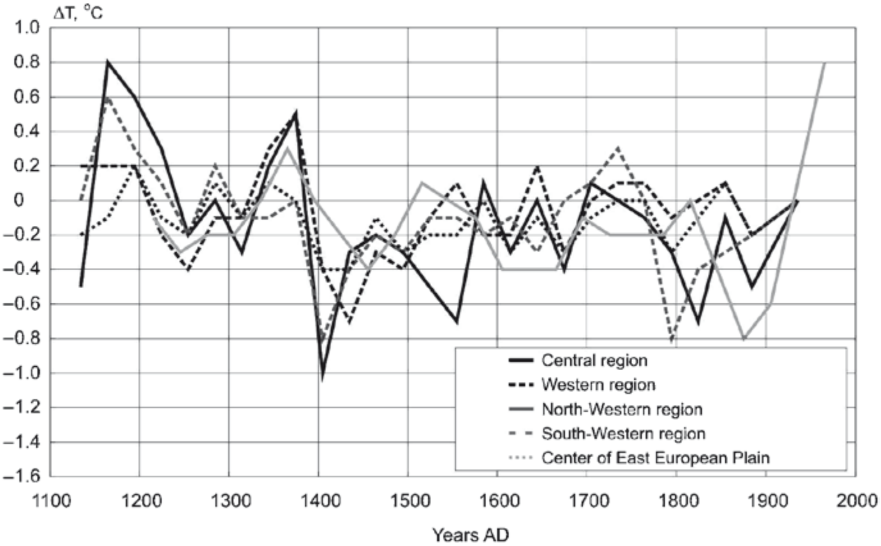

Fig. 3.5 Mean annual temperature anomalies in the center of the East European Plain (deviations from 1890 to 1950 mean) based on historical records (Lyakhov 1984; Klige et al. 1993)

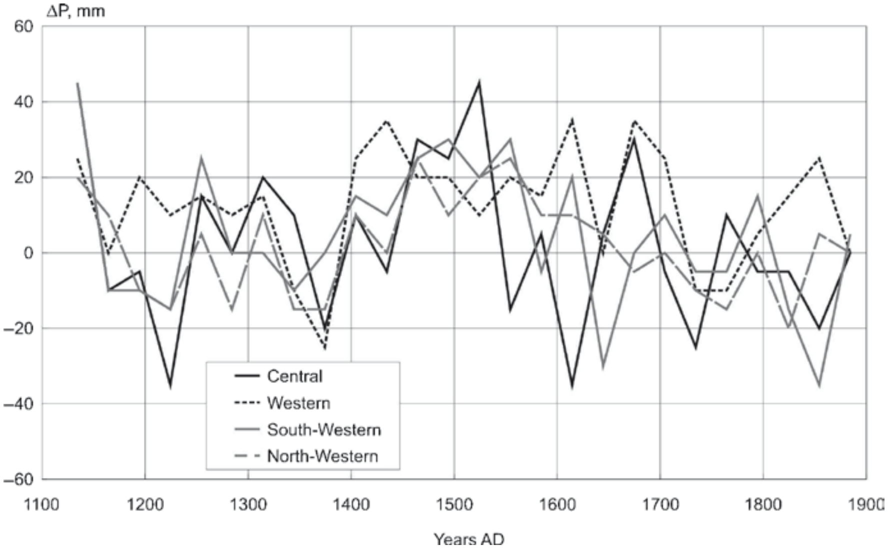

Fig. 3.6 Mean annual precipitation anomalies (deviations from 1890–1950 mean) based on historical records (Klige et al. 1993)

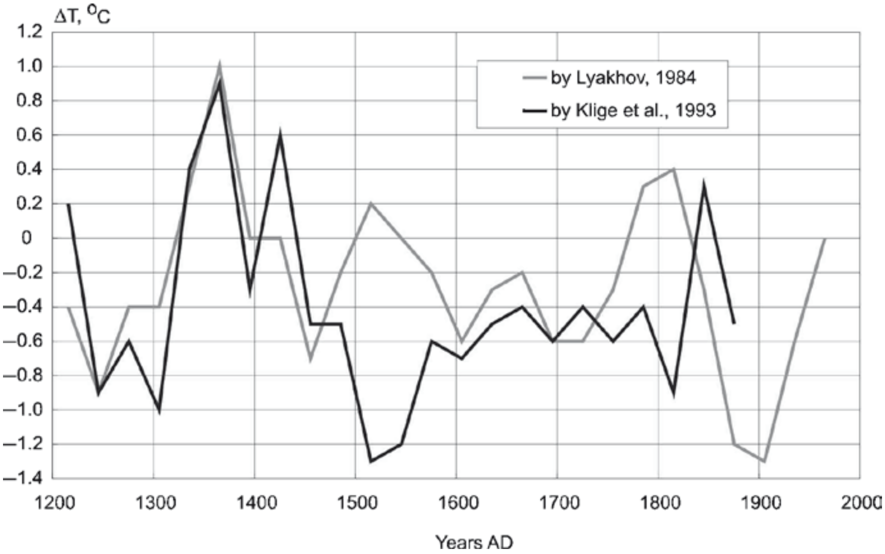

Fig. 3.7 Summer temperature anomalies in the center of the East European Plain (deviations from 1890 to 1950 mean) based on historical records (Lyakhov 1984; Klige et al. 1993)

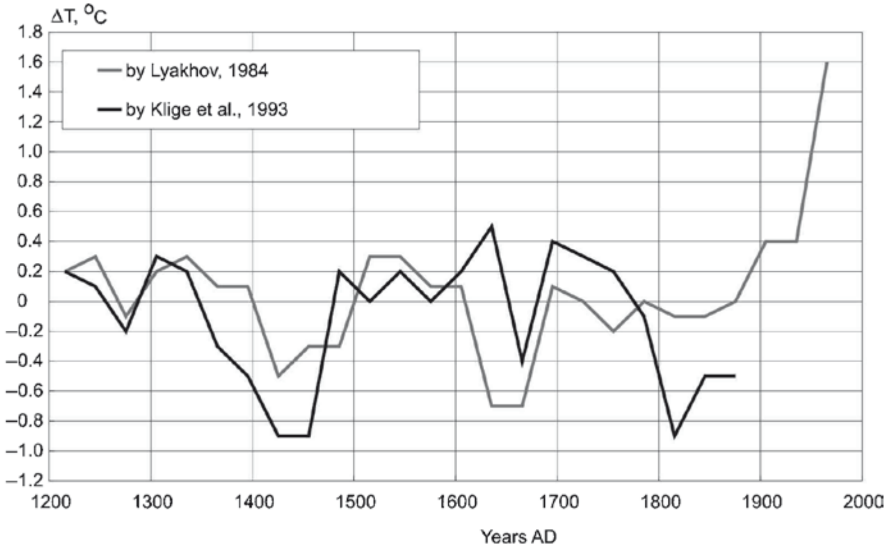

Fig. 3.8 Winter temperature anomalies (deviations from 1890 to 1950 mean) based on historical records (Lyakhov 1984; Klige et al. 1993)

3.5 Tree-Ring Data

3.5.1 Summer Temperature Reconstructions

In the Fig. 3.9 the spatial pattern of maximum density in the Northern part of East European Plain (smoothed by decades) is displayed (Schweingruber and Briffa 1996). Two major large-scale events are evident over the whole profile – the twentieth century warming and extremely cold period in the first half of the seventeenth century. The second decade and the mid nineteenth century were also very cold in the north of the Russian Plain, whereas in the eighteenth century the climate was, on the contrary, rather warm. The short-term coolings in the chronologies – sharp decrease of ring width/density for one to three years (not shown in the Fig. 3.9, where smoothed values are presented) are normally forced by climatically effective volcanic eruptions and they occur simultaneously along the whole profile at the northern tree line (Briffa et al. 2004).

In the mountains of the Urals and Kola Peninsula the reconstructions based on the ring width agrees reasonably well with the upper timberline variations. Both types of records in the Urals show the warming from the ninth to thirteenth centuries (Shiyatov 1986, 2000). At the end of the thirteenth century the degradation of larch forests has begun: this climate deterioration lasted until the early twentieth century. In the Kola Peninsula the warming from ca AD 600 to 1200 was documented by wood macrofossils found beyond the present upper tree limit (Hiller et al. 2001).

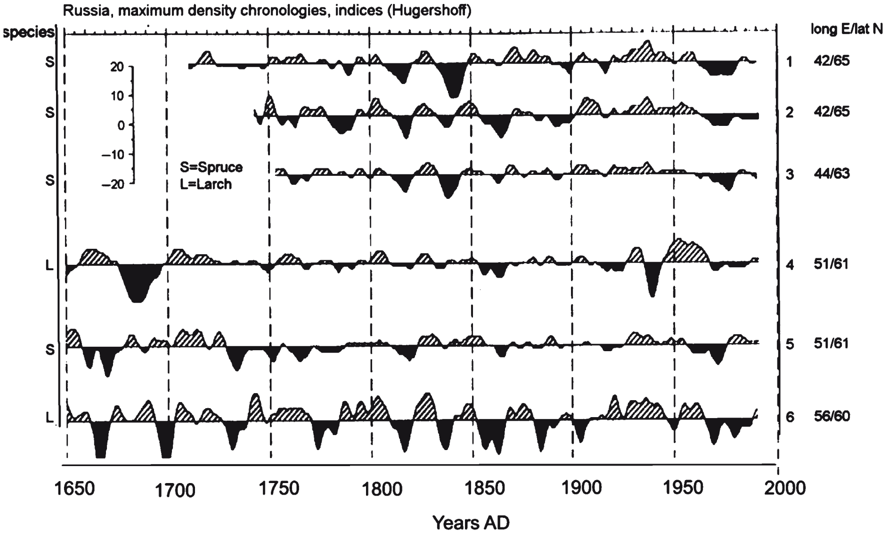

Fig. 3.9 Tree ring maximum density chronologies at the Northern tree line in the East European Plain and adjacent regions (Schweingruber and Briffa 1996). Species: S – spruce, L – larch

3.5.2 Precipitation and Runoff Reconstructions

Due to rare occurence of trees sensitive to humidity suitable for reconstructions we are not aware of any quantitative tree-ring based reconstructions in the East European Plain. Solomina et al. (2005) reconstructed April–July precipitation using *Pinus hamata* ring width (1620–2002) in the Crimea (Fig. 3.10). Most droughts recorded in historical documents in the seventeenth to nineteenth centuries in the Crimea and Southern Russia (e.g. in 1687, 1833–1834, 1845, 1881–1882) coincide with below-average reconstructed precipitation in the concurrent or following year, however the extremely wet summers recorded in the historical documents are not as well captured by the reconstruction. The reconstruction captures two periods of large variability in April-July precipitation: in the 1650s–1720s and 1820–1920s. The earlier period coincides with the Maunder Minimum period, which was cold over much of Europe (Luterbacher et al. 2001; Luterbacher et al. 2004; Xoplaki et al. 2005). The reconstruction also shows two periods of moderate values during much of the eighteenth and the twentieth centuries (after the 1920s).

Tree-ring based discharge reconstructions of the Northern Dvina and the Pechora Rivers for the period AD 1800–1990 indicate that there is no long-term monotonic trend toward higher discharge over the past 200 years. Reconstructed annual discharge for the individual rivers and the total discharge from all the rivers experienced in the twentieth century are within the bounds of natural variability experienced over the past 200 years. The Northern Dvina and the Pechora reconstructions display significant multidecadal variability in discharge (30–60 years) similar to that observed in the North Atlantic, North Pacific, and Northern Hemisphere climatic parameters (MacDonald et al. 2007).

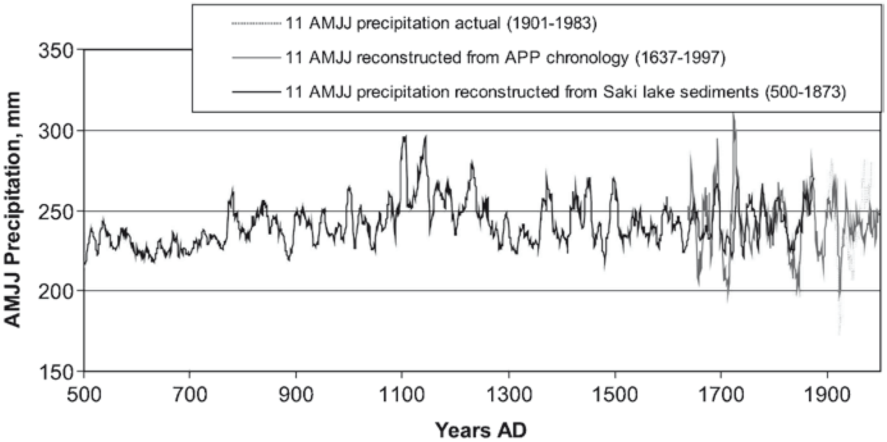

Fig. 3.10 Sum of AMJJ precipitation measured at Aj-Petri meteorological station (a), AMJJ precipitation reconstructed from tree rings (b). Eleven-year running mean of the Saki Lake chronology for the last 1,500 years (c) (Solomina et al. 2005)

3.6 Borehole Temperatures

Most borehole temperature reconstructions of the last millennia in the European Russia come from the Northern and Central Urals (Demezhko and Golovanova 2007). According to this reconstruction the ground surface temperatures in the Medieval Warm Period (approximately between AD 1100 and 1200) were 0.4 K higher than in 1900s–1960s. During the Little Ice Age culmination (approximately AD 1720s) it was 1.6 K cooler than in the twentieth century. The overall pattern of temperature changes in the last millennium reconstructed by borehole data are similar in the Urals and Belgorodskaya oblast', however in the center of the East European Plain the twentieth century mean annual temperature is 0.4 K higher than it was in the warmest period in the first half of the millennium (Duchkov and Sokolova 2000),

3.7 Palynological Data

Chernavskaya (1996) used eleven chronologically controlled sections and calibrated this data with more than 100 recent spectra all over the East European Plain. Chernavskaya (1995) analysed more than a hundred recent pollen spectra and found out that the pollens of broad-live trees are the best indicators of the warming/cooling trends in the East European Plain. According to this study the maximum warming occurred in the ninth to tenth centuries in the west of the plain and in the tenth to eleventh centuries – in the east. Some spectra display a cooling in the middle of the twelfth century and especially in the late twelfth to early fifteenth centuries, when the temperature decreased by 2–3°C. Coolings also occurred in the late seventeenth and eighteenth centuries and two warmings are recorded in the sixteenth and second half of eighteenth centuries.

Sleptsov (2002) selected four best constrained palynological series and adjusted these reconstructions to the common reference period (1951–1980) (Fig. 3.11). In all records one can see the absence of the long term trend in the first millennium, the thermal maximum around the turn of the millennium and the clear cooling trend in the last 1,000 years. However the multidecadal variations often differ for individual reconstructions both in terms of timing and amplitude.

Klimanov et al. (1995) provided a quantitative reconstruction of several climatic parameters basing on detailed pollen data of Polovetsko-Kupanskoye peat bog in the center of the East European Plain (see map at Fig. 3.1). They noticed that the negative trends in summer and winter temperature begun in the twelfth century and continued up to the mid twentieth century, while the whole first millennium and the earlier part of the second millennium AD were relatively warm both in summer and in winter. No long term trends are observed in the annual precipitation.

The same approach as used in Klimanov et al. (1995) was applied to reconstruct the temperature and precipitation of the UM pollen site. A very good agreement

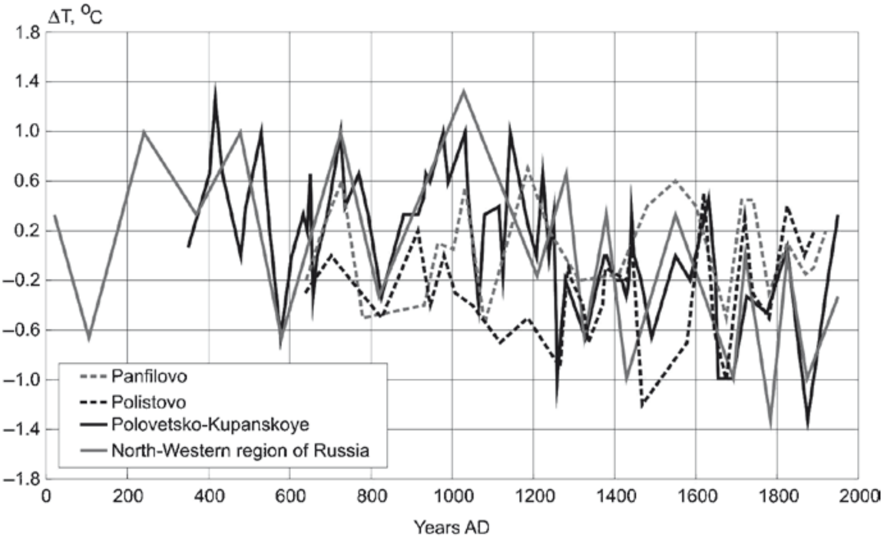

Fig. 3.11 Mean annual temperature anomalies (from 1951 to 1980 mean) according to various palynological reconstructions in the East European Plain

exists between the recorded meteorological parameters (e.g. annual temperature) and the UM pollen-based reconstruction (Fig. 3.12). According to this reconstruction the coldest periods occurred in the first quarter of the fifteenth, end of seventeenth and eighteenth centuries. The warmest periods after the MWP at the decadal and miltidecadal levels occurred in the 1820s and in the end of the twelfth century. The coolings were more pronounced than the warmings: the cooling anomalies (from the 1951–1980 mean) were up to 1°C, while the warmest anomalies did not exceed 0.7°C. One can see two thermal maxima when the annual temperature increased by 1°C around AD 2000 and 1100. The first warming was similar to modern conditions in terms of precipitation, while during the MWP the precipitation exceeded the modern values by 25–50 mm. Major coolings date back to around 1700 BP, 1200 BP, 1000 BP, 650 BP, 500 BP. The amplitudes of January temperature fluctuations exceed those in July. No clear relationship between temperature and precipitation is established. A cooling trend is evident in the last millennium, while the annual temperature variations in the first millennium do not show any clear tendency (Klimenko et al. 2001). According to the UM reconstruction the most humid periods occurred in the early fourteenth, end of the fifteenth early sixteenth, mid seventeenth, last quarter of the eighteenth centuries and driest periods in the end of the fourteenth – early fifteenth, last third of the sixteenth, end of seventeenth to early eighteenth, mid nineteenth centuries. There is no clear millennium-long trend in the annual precipitation.

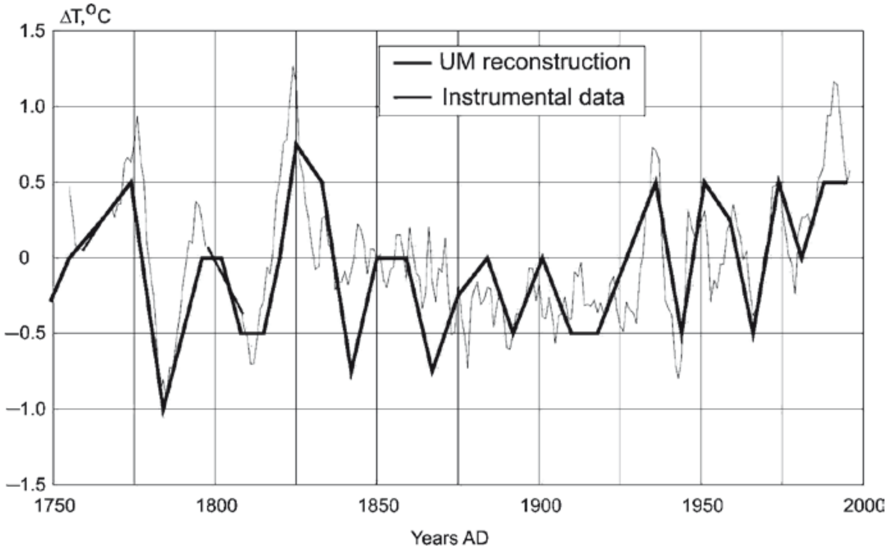

Fig. 3.12 Mean annual temperature anomalies reconstructed by palynological data at Usviatsky Mokh peat bog and average mean annual temperature for meteorological stations Riga, St-Petersburg, Moscow and Vilnius, 7 years running mean (Klimenko et al. 2001)

3.8 Hydrological Data

Schostakovich (1934, 1936) reconstructed mean annual precipitation rate using the thickness of annually laminated sediments in the Saki Lake the Crimea and Pertozero (Karelia) (see Fig. 3.1 and Table 3.5). The sediment layer thickness (mean for 10 and 30 years intervals) were calibrated against the meteorological data, though the Crimean meteorological records at that time were too short to be sure about the relationship between the sediment layers thickness and climatic parameters. Solomina et al. (2005) later on demonstrated that indeed the Saki Lake sediments correlate with spring to early summer precipitation (see Fig. 3.10). An 11-year filtered version of the reconstruction correlates with an annually-laminated sediment-thickness record from the Saki Lake, once this record is shifted backward by 15 years. The offset may be explained by anthropogenic changes at the lake in the late nineteenth century. The correlation allows the extension of the precipitation reconstruction further back in time. The Saki Lake chronology shows that the period between the 1050s and 1250s was extremely wet. The overall humidity level of the region appears higher than at any time of the instrumental records. This interval partly coincides with the MWP (e.g. ~AD 900–1240; Grove and Switzur 1994). Schwets (1978) reconstructed the Dnieper runoff basing on several proxies (see Table 3.5). Rauner (1981) used empirical equation relating the mean precipitation in the Dnieper region and the runoff. This reconstruction explains no more than 50% of variation of precipitation. The three reconstructions of precipitation show that precipitation variations in all three regions were quasi-stationary. In the northern part of the East European Plain (to the North of

Table 3.5 Palaeohydrological series in the East European Plain

Period	Reconstructed parameter	Resolution (years)	Region	Reference
AD 761–1900	Mean annual precipitation	30	Pertozero, South Karelia	Schostakovich (1934)
AD 761–1900	Mean annual precipitation,April-July precipitation	30-years running mean	Saki Lake	Schostakovich (1934)
AD 761–1960	Mean annual precipitation	30	Dnieper basin	Schwets (1978)

55°N) the century-long variations dominate, while in the southern part those of higher frequency (decadal) are more prominent. According to the proxy data the variability of precipitation in the North (60–100 mm) is generally higher than those in the South (30–40 mm). The variations of precipitation in the North and South are not correlated (Klimenko and Sleptsov 2003).

3.9 Multi-proxy Reconstruction

The results of Klimenko and Sleptsov (2003) and Sleptsov (2002) quantitative multi-proxy temperature and precipitation reconstructions are presented in Figs. 3.13, 3.14, 3.15, and 3.16. For all reconstructed parameters the correlation of the proxy time series and the instrumental records (250 years long averaged for decades) are significant at the 95% level.

The reconstruction shows that the tenth century was the warmest in the East European Plain in the last 2000 years. After the tenth century a clear cooling trend is evident up to the early twentieth century. During this period an overall rate of cooling was about an order of magnitude lower than the rate of the recent warming in the course of the twentieth century. On the whole during the past millennium the fifteenth century was the coolest one, while the most pronounced decadal cooling occurred in the late seventeenth century. The winter temperature amplitude of variations is twice as large as those of summer.

Long-term summer coolings are mostly associated with dry periods in the northern regions (to the north of Vilnius-Saratov line, see Fig. 3.1) (The coefficient of correlation between the smoothed summer temperature and precipitation is r = 0.33), while in the southern regions the correspondence is opposite (Klimenko 2001). Annual precipitation variations do not show any long-term trend during the last two millennia.

It is of interest that during the last millennium all even centuries were relatively warm, while the odd ones – were cold (Table 3.6). Similar sequence (though with the opposite sign) is evident for the first to seventh centuries AD. This is probably related to the 200-years climatic cycle triggered by solar activity (Mikushina et al. 1997). The reverse of the millennium-long cooling trend in the twentieth century may be caused by anthropogenic influence, but the peak temperature of the tenth century is still to be

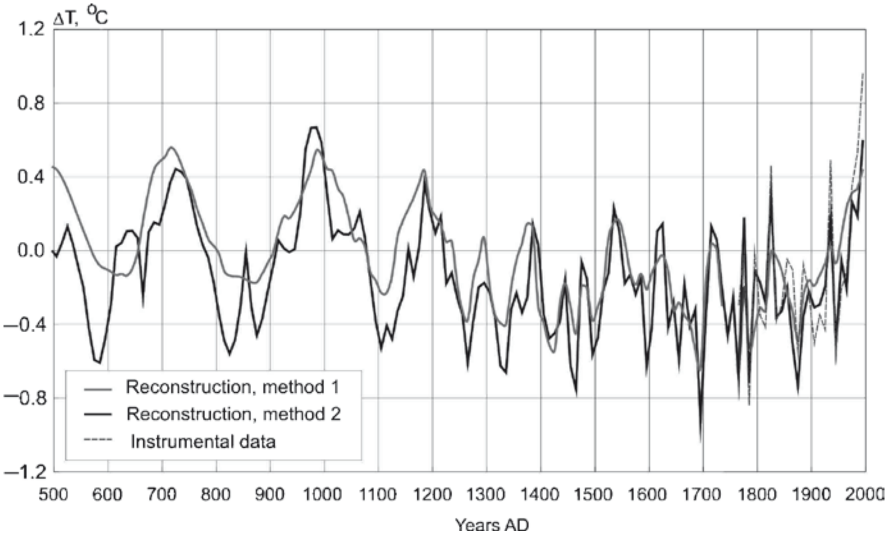

Fig. 3.13 Reconstructed mean annual temperature deviations from 1951 to 1980 mean averaged for decades reconstructed in comparison with the instrumental records (average for St Petersburg, Moscow, Riga, Vilnius)

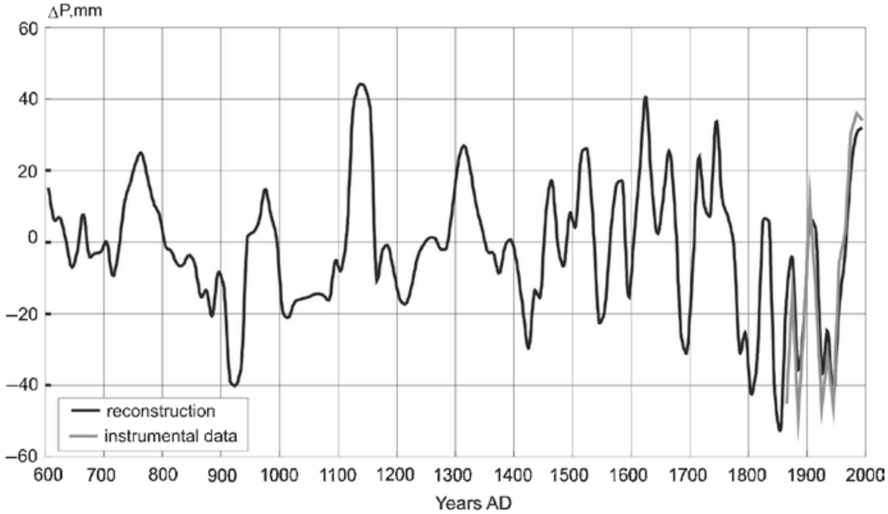

Fig. 3.14 Reconstructed mean annual precipitation deviations from 1951 to 1980 averaged for decades reconstructed in comparison with instrumental data (average for St Petersburg, Moscow, Riga, Vilnius)

reached. The global warming of anthropogenic origin is not manifested in the summer temperature while the winter temperature in the late twentieth century exceeded the peak values of the last two millennia, even those of the MWP.

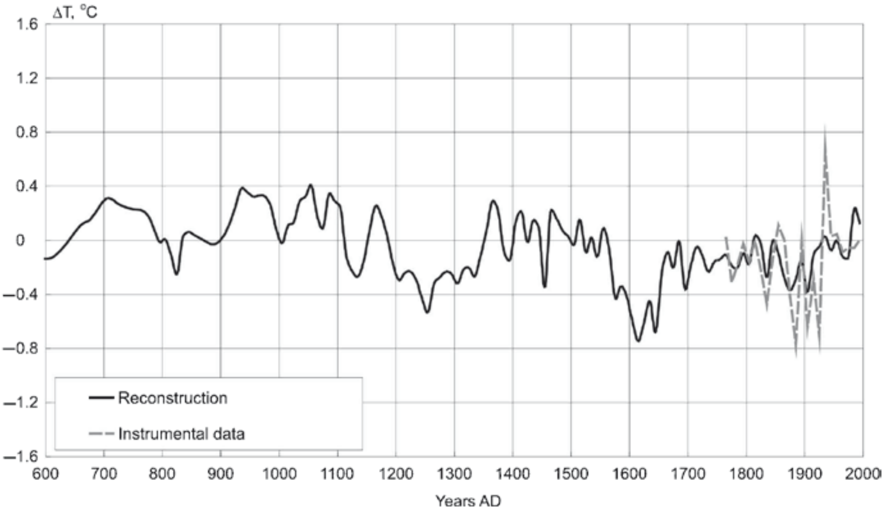

Fig. 3.15 Reconstructed mean summer temperature deviations from 1951 to 1980 averaged for decades in comparison with instrumental data (average for St Petersburg, Moscow, Riga, Vilnius)

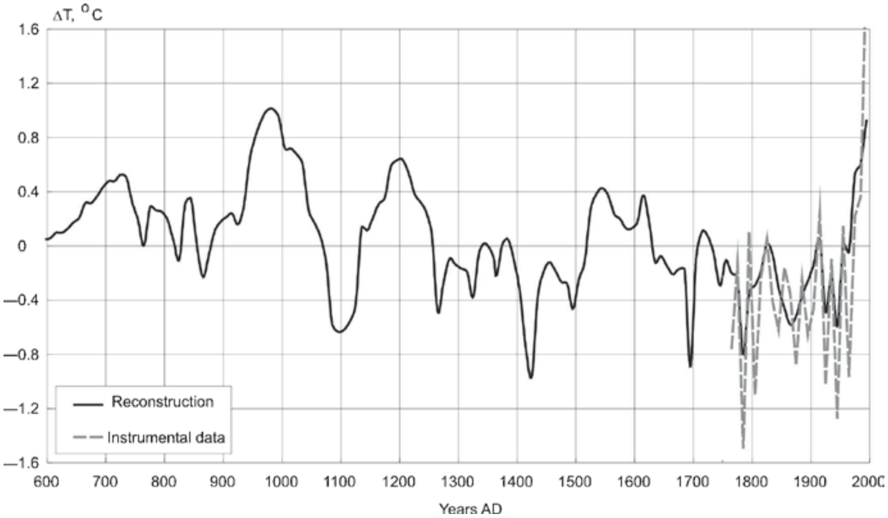

Fig. 3.16 Reconstructed mean winter temperature deviations from 1951 to 1980 averaged for decades in comparison with instrumental data (average for St Petersburg, Moscow, Riga, Vilnius)

Table 3.6 Centennial anomalies of the mean annual temperature (deviations from 1951 to 1980 mean)

Century	Temperature anomaly (°C)
09	–0.34
10	0.30
11	0.07
12	–0.15
13	–0.25
14	–0.20
15	–0.44
16	–0.16
17	–0.33
18	–0.23
19	–0.32
20	–0.02

3.10 Discussion

In this chapter we briefly discuss the possibilities and the gaps in the last millennium climate research in the East European Plain and potential biases and errors in the available reconstructions.

Our overview shows that there are great potentials for the climatic reconstructions in the East European Plain. The instrumental records up to three centuries long can be successfully used to estimate the long term trends in monthly and seasonal temperature and precipitation and to calibrate the proxy records. However the long meteorological records attracted surprisingly low attention of Russian climatologists up till very recent time when the problem of the potential anthropogenic warming had arisen. Still a lot can be and should be done to homogenize the data, fill the gaps in the records, use the historical documents to extend the series back in time and make it available to the public.

The historical information was successfully used by a number of researchers to create the numerical series of almost one millennium long. Still a lot of historical documents including private diaries, notes, documents in local archives etc. are not included in the study. More sophisticated techniques of reconstruction can be also applied in this field, e.g. to derive spatial charts of monthly and seasonal reconstructions of temperature, sea level pressure, 500-hPa geopotential height fields etc. (Brázdil et al. 2005).

There is a certain disagreement between the historical reconstructions of Lyakhov (1984) and Klige et al. (1993) (Figs. 3.7 and 3.8), especially dramatic for summer temperature in the sixteenth century and winter temperature in the late eighteenth century. The difference was never comprehensively discussed in the literature. It might be explained by some differences in methodology used by the two groups of researchers. Lyakhov and Voronov and Klige et al. used different periods of averaging the data. The documentary base used by Voronov (1992) and

Klige et al.(1993) is larger than the one used by Lyakhov; they also took into account the uneven distribution of the number of records in time. However the comparison of both reconstructions (summer temperature anomalies) with those from Europe (Brázdil et al. 2005) shows that Lyakhov's curve fits much better to the long Prague reconstruction, reproducing most long-term coolings and warmings. One can expect such a similarity, while Klimenko and Sleptsov (2003) demonstrated the close correspondence of the instrumental records of Prague and those of the north of East European Plain. Thus, the problem of reliability of the historical reconstructions of climate on the East European Plain still remains largely unresolved. More scrutinized analyses including the more transparent procedure of selection the data, calibration and verification of the models is necessary to increase the creditability of the reconstructions.

Tree-rings at the northern tree limit provided some well-replicated high quality summer temperature reconstructions up to five centuries long. There are however potentials to extend the series back in time and increase the density of the network using the archeological wood and the material from the wooden houses. Unfortunately no reliable tree-ring based precipitation reconstruction from the southern regions in the East European Plain is available due to the lack of old forests in these agricultural regions. It still might be possible to find some appropriate wood (e.g. oaks) for this purpose in the protected areas. Khasanov (2004) was able to cross-date the oaks buried at the bottom of small rivers in Tverskaya area and create the floating chronology covering the period from the mid tenth to the late thirteenth centuries and demonstrated the possibility to create a millennium-long chronology in the area.

The tree-ring reconstructions in the North of the East European Plain are based on the maximum density rather the ring width (Briffa et al. 2004) therefore the underepresentation of the long-term trend of the temperature is not critical in this case. However both density and ring width in this area showed a "divergence" problem from the 1960s, when the correlation between the ring width and density from one side, and the instrumental records of temperatures from the other side, weakened considerably. Briffa et al. (2004) cut the calibration series at that point and derived the temperature reconstructions from the shorter meteorological records, although the reason for this "divergence" phenomena, which also happened in many other places, is still unclear (see for details D'Arrigo et al. 2007).

The tree-ring and historical data are sharing to a certain extent their advantages (seasonal resolution, reliable chronologies) and disadvantages. Therefore the comparison of this data both at the annual and decadal (multidecadal) basis is natural. The detailed comparison of this kind was never made for this area and it is also not in the scope of this paper. We can just notice a few cases in this relation. The year 1601 was the coldest in the last 400 years in the Northern Hemisphere (high to mid latitudes) according to the tree-ring data (Briffa et al. 2004).The frosts and long heavy rains in summer 1601 in combination with the winter conditions unfavorable for agriculture resulted in a very severe famine in 1601–1603 and led to dramatic perturbations in the Russian history. The comparisons of the 15 years running means of Briffa et al. (2004) Northern European summer temperature reconstruction with the two historical reconstructions represented at Fig. 3.7 shows a very good visual agreement with the Klige et al. (1993) curve and much poorer correspondence with the Lyakhov's (1984) reconstruction. In these terms one may conclude that the Klige et al. (1993) reconstruction is more reliable. However this conclusion would contradict the results of our previous comparison of the two reconstructions with the historical data from Prague (see above). This kind of contradictions shows that the problem of the high resolution seasonal reconstructions on the East European Plain is still very far from the final solution.

The lower resolution records, such as borehole temperature and biostratigraphic analyses, can be useful to provide the longer term trends, which are often biased in historical and tree-ring series. Unfortunately most palynological reconstructions in the East European Plain have a very poor chronological control and the lack of the AMS dating facilities in Russia limit the possibilities to improve the reconstructions in terms of resolution and spatial coverage in the future. However Klimenko et al. (2001) showed that pollen reconstruction can also yield a much higher resolution and can be calibrated directly against the meteorological records smoothed by decades if it is well chronologically controlled. The UM reconstruction does not contradict to the earlier palynological reconstructions (see Table 3.3), although due to higher resolution the UM reconstruction provides more detailed chronological information. For instance according to this reconstruction the peak of MWP warming occurred around AD 970 while it was traditionally placed at AD 1000. Other proxies, such as historical data (Borisenkov and Pasetsky 1988) and the decrease of sea ice index in the Baltic support this conclusion (Koslowski and Glaser 1999; Tarand and Nordli 2001). A certain agreement exists between the UM reconstruction, historical (Klige et al. 1993) and hydrological data (Schostakovich 1934), though a very clear discrepancy between the records is evident for the periods of the 1450–1550s, the early seventeenth and early eighteenth centuries. The reasons of such disagreement can be related to various biases in proxy records (chronology, seasonality recorded, calibration etc.) as well as they can reflect the real regional variability in precipitation.

The first multi-proxy reconstructions in the East European Plain of the summer, winter, annual temperature and annual precipitation provided by Klimenko and Sleptsov (2003) agrees well with the instrumental data. As soon as almost all reliable millennium-long series were used in this reconstruction there are no many opportunities to check the consistency of these curves comparing them with other independent records in this area. The comparison of the Klimenko and Sleptsov (2003) annual temperature reconstruction with the two well-known reconstructions of the Northern Hemisphere (Fig. 3.17) shows that all three demonstrate a slight negative long-term trend which reverses in the last century (earlier in the case of Crowley and Lowery reconstruction). The amplitude of variations is greatest in the Russian Plain (1.5°C), while the two other curves are much flatter. The decadal variability agrees for some periods, but during the other periods (e.g. the eleventh, fourteenth, sixteenth, nineteenth centuries) there is almost no similarity. The details of this discussion can be found in Sleptsov (2002). It is clear that one cannot expect the identity of these reconstructions which represent different areas. In general it is

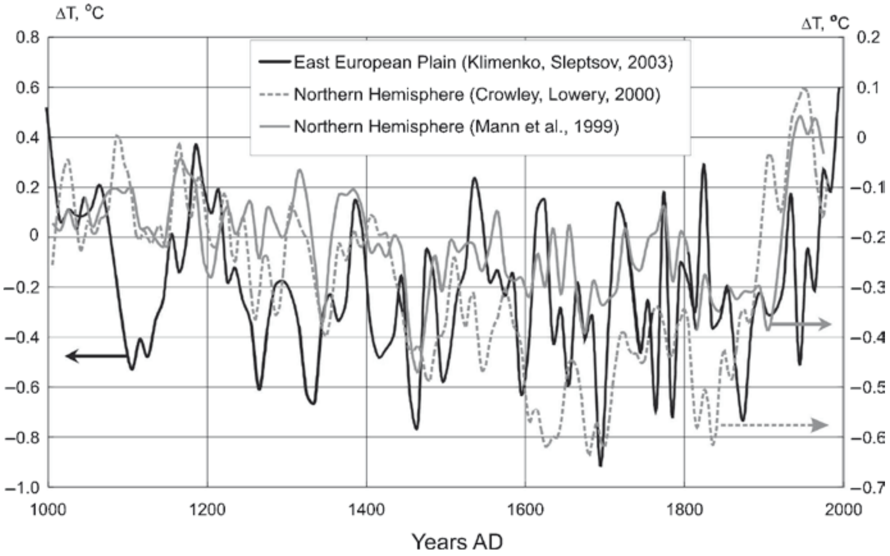

Fig. 3.17 Comparison of the Klimenko et al. (2003) annual temperature reconstruction for the East European Plain with the two Mann et al. (1999) and Crowley and Lowery (2000) annual temperature reconstructions for the Northern Hemisphere

getting more and more clear that reliable regional rather than hemispheric reconstructions for the last two millennia are necessary at the moment in order to increase our understanding of the spatial patterns of natural climatic variability (PAGES Science and Implementation Plan 2009). In case of the East European Plain it means that the north and south of the plain with largely different regimes of temperature and especially precipitation should be considered separately.

Precipitation and humidity reconstructions are generally less reliable in this area. In addition to historical records they are largely based on the Schostakovich (1934, 1936) studies on the lake sediment properties and are not quality controlled. Although Solomina et al. (2005) demonstrated that the thickness of annually laminated sediments in the Saki Lake correlates with the drought sensitive ring width chronology the problem still requires additional studies at the modern technological level.

3.11 Concluding Remarks

Meteorological, historical, tree-ring, palynological, lake sediments records and the first attempts of quantitative multi-proxy reconstructions of temperature and precipitation allow the estimation of major trends in these parameters in the East European Plain for the last millennium. The multi-proxy reconstruction provides most systematic and quantitative estimates. This reconstruction recorded the long-term negative trends in seasonal and annual temperature over the whole millennium with the exception of the last century. In the twentieth century the winter and annual temperature increased and the trend reversed. The winter temperature exceeded now the level of the peak of the Medieval Warm Period (a turn of the tenth–eleventh centuries), while those of the summer are still within the natural variability of the last millennium. No significant trends are identified in the annual precipitation of the last millennium. In the North of the East European Plain there is a tendency of anticorrelation of decadal variability of annual precipitation and temperature, which was described earlier (Zolotokrilin and Popova 1988). It was noticed that there was a 200-years natural variability in annual temperature during the last millennium (even centuries are relatively warm, while the odd ones were cold), which might be related to the cycles of solar activity (Wanner et al. 2008).

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Chapter 4
The Climate of Europe in Recent Centuries in the Context of the Climate of Mid to High Latitude Northern Hemisphere from Borehole Temperature Logs

Jacek Majorowicz

4.1 Introduction

In recent years, geothermal logs have been used to reconstruct ground surface temperature histories (GSTH). Information about past ground surface temperature (GST) can be derived from the vertical distribution of temperature of the underlying soil, rock, or ice substrate. A decades and longer persistent increase of GST will cause a wave of warming to propagate downward. In most cases, the GST and the climatic surface air temperatures at the borehole site are closely connected and temperature-depth (T-z) profiles measured in boreholes are used to generate reconstructions of near-surface air temperature (SAT). A large number of continental boreholes have provided GST reconstructions for up to the last 500 years (Lachenbruch and Marshall 1986; Wang et al. 1994; Huang and Pollack 1997; Pollack and Huang 2000; Harris and Chapman 2001; Majorowicz et al. 2004b; Bodri and Čermak 2007). GSTH are particularly valuable because temperature itself is being measured and not calibrated against the SAT instrumental record and are thus not a proxy for temperature.

An important benefit of borehole temperature-based reconstructions is also one of its limitations. The surface temperature signal is attenuated as it is transferred to depth and higher frequency noise, peripheral to the climate signal being sought, is eliminated. General trends in borehole temperature based SAT reconstructions for the past few 100 years are considered robust with the temporal resolution only a few decades at the beginning of the twentieth century, but decreasing with time prior to that period (National Academy of Sciences 2006). Reconstructions of climatic signals during earlier periods of the Holocene are less robust, even in cases of a purely conductive subsurface thermal regime because there is poor knowledge of thermal conductivity variations in many borehole records in the International

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Heat Flow Commission (IHFC) database (Huang et al. 2000). This presents an obstacle in the separation of steady-state and transient components of the temperature profile. In most well cases, only the average conductivity is available for the entire length of the temperature profile. In addition, lateral inhomogeneities of the surrounding geological media can not be easily recognized. Also, noise suppression techniques used by some inversion procedures create the risk of interpreting noise as climatic signal which can lead to loss of the GSTH resolution even in cases of high quality data with a real climatic signal.

Two separate and important quantitative uncertainties of borehole-based reconstructions have been mentioned (National Academy of Sciences 2006). Firstly, GST and the overlying SAT may vary differently over time, due to changes in snow cover and soil moisture. A close association has been found between measured ground temperatures and ground temperatures calculated using air temperatures suggesting the average bias must be small over mid-latitudes (Harris and Chapman 2001). A comparison of borehole-based and instrumental twentieth century warming trends for specific regions (Pollack and Smerdon 2004) shows no consistent offset related to precipitation. The effects of deforestation and urban expansion on subsurface temperature (see Majorowicz et al. 2004b; Bodri and Čermak 2007 for recent references) are also important. These are real changes to local climate but do not reflect larger spatial scale changes. The borehole temperature database has been screened to eliminate other sorts of groundwater influences that are more readily apparent as well as sites with urban influence.

Average regional borehole temperature reconstructions, including eastern and western North America, Europe, Australia, and South Africa, show warming over the past two to three centuries, the period referred to in this study as the Recent Warm Period (RWP), preceded by relatively cooler conditions of the Little Ice Age (LIA) for a few centuries. Estimates of the average magnitude of the Northern Hemisphere RWP warming signal from borehole temperatures from the mid-nineteenth to the late twentieth century range from approximately 0.7°C to 0.9°C (Huang et al. 2000; Harris and Chapman 2001). This is consistent or higher than the temperature increase estimated from the instrumental record (IPCC 2001).

Most previous studies for the global continental areas and in the northern hemisphere have focussed on average global, continental reconstruction of GST history (Pollack et al. 1998; Huang et al. 2000; Harris and Chapman 2001). While global, hemispheric and continental GST histories are useful, we need to remember that they are averages of hundreds of individual GSTH (Fig. 4.1). Usually standard error of estimate is given as shown in the comparison made between the average reconstruction of Pollack et al. (1998), and the individual GSTH histories for wells as in the 1998 International Heat Flow Commission world data base. Some recent studies were emphasizing combined spatial and temporal variations (Majorowicz et al. 2002; Beltrami and Bourlon 2004). These suggest large spatial variability in the amplitude of warming or cooling in the recent centuries. This variability can explain to a large variability (noise like) shown in a stack of individual reconstructions used to derive global continental average GST history (GSTH) (Fig. 4.1).

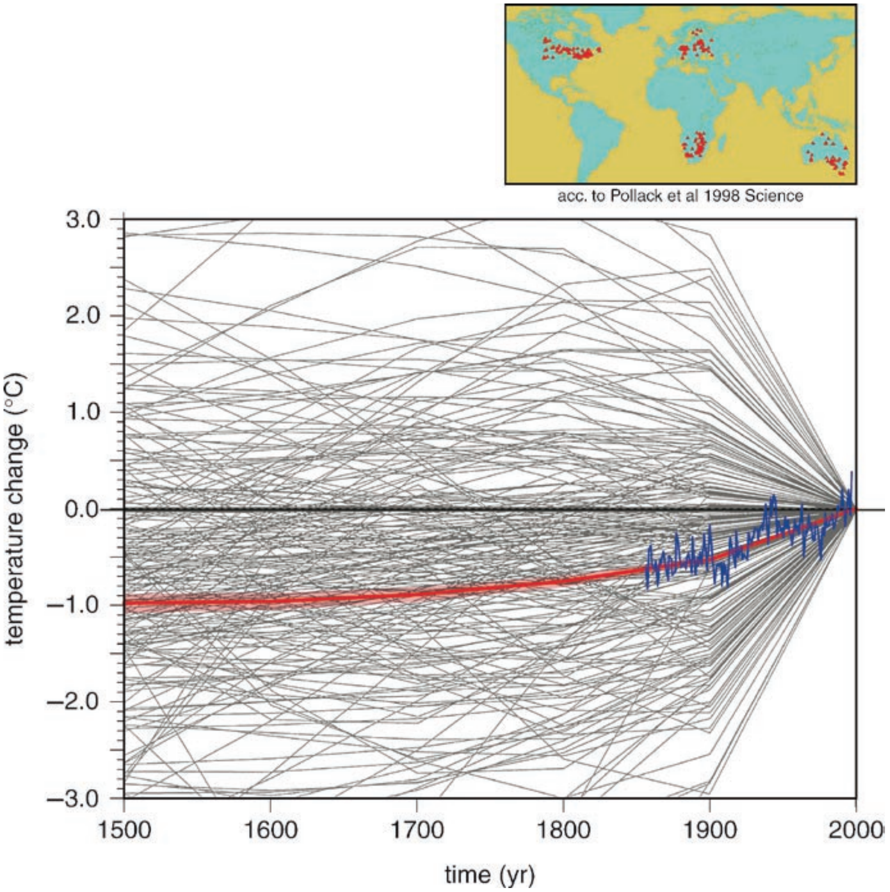


Fig. 4.1 Large-scale surface temperature reconstructions from well temperature logs for the global data set acc. to Pollack et al. (1998), (*red curve*) shown here against the stack of individual GST reconstructions from well temperature logs in the IHFC data base as of 1998 compared with global SAT average (*blue curve*)

Figure 4.2 shows a set of large-scale surface temperature reconstructions from different research groups, each using its own methodology and selection of climate proxies, including the record of mean GSTH (Huang et al. 2000), and the global mean SAT instrumental record beginning in the mid-nineteenth century (National Academy of Sciences 2006). Temperature records vary and are subject to different sets of uncertainties that generally increase going back in time. However, the reconstruction set conveys a qualitatively consistent picture of changes over the past 1,100 years, and especially since 1500. The warmer conditions centered around 1000 AD were known as the Medieval Warm Period (MWP). This was followed by a relatively colder period known as the LIA centered around 1700. The existence and extent of a LIA from roughly 1500 to 1850 is supported by a wide variety of

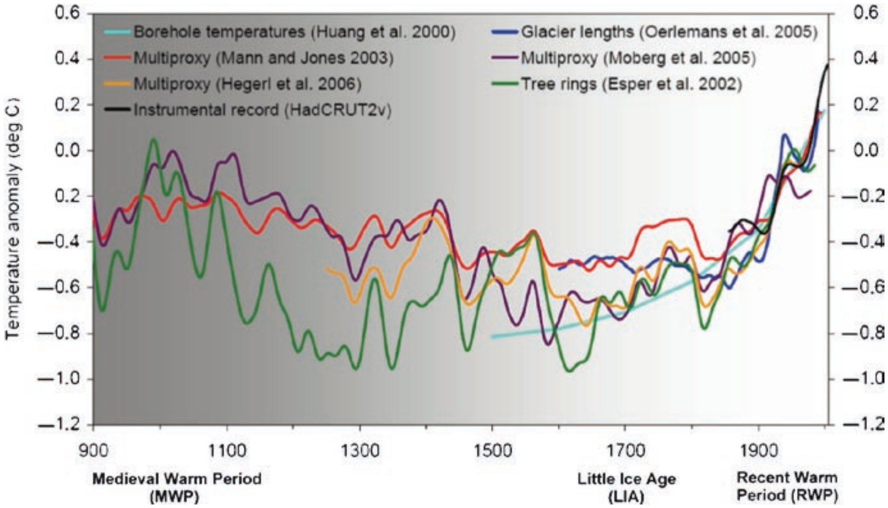


Fig. 4.2 Smoothed reconstructions of large-scale (Northern Hemisphere mean or global mean) surface air temperature variations from different research teams and the instrumental record of global mean surface air temperature. Notice large warming magnitude from borehole temperatures. (Adapted from Figure S-1 National Academy of Sciences 2006)

evidence including ice cores, tree rings, glacier length records, historical documents, and borehole temperatures. The LIA was characterized by harsh winters, shorter growing seasons, and a drier climate with a decline in global and hemispheric temperatures up to 1.0°C from peak MWP conditions. The effects were more pronounced in higher latitudes where there was a 1.0°–2.0°C cooling.

The onset of warming resulting in the RWP (Fig. 4.2), on hemispheric and global scales, was between 1,600 and 1,850. However, current evidence does not support globally synchronous periods of anomalous cold, or warmth, over this timeframe, and the conventional terms "LIA" and "MWP" have limited utility in describing trends in hemispheric or global mean temperature changes in past centuries (IPCC 2001). By the mid-twentieth century, the RWP had attained levels higher than those at any time during the MWP. Most of the LIA occurred prior to the industrial age and the widespread burning of fossil fuels. Causes of the LIA are attributed primarily to natural solar and volcanic forcings (IPCC 2001). Current evidence does not support globally synchronous periods of anomalous cold over the LIA timeframe. It is thus reasonable to expect that the spatial signature of the RWP onset, as well as its magnitude, would also be variable. Recovery from the LIA is generally coincident with the beginning of the industrial age and elevated fossil fuel burning, as well as with widespread landscape alterations in low and middle latitudes.

This study analyzes borehole temperature-depth (temperature logs) data in the IHFC/NOAA International Heat Flow Commission data base plus additional data from boreholes in northern Canada and Alaska (Lachenbruch and Marshall 1986; Lachenbruch et al. 1988; Majorowicz et al. 2005) together with new Polish data in

Europe not contained in the IHFC data base (Majorowicz et al. 2004a; 2008; Šafanda et al. 2004) to study spatial variability of the large northern part of the northern hemisphere. The study is to standardize all available temperature-depth profiles of comparable sampling and depth range from across high latitude Northern Hemisphere including European and Polish data being a focus of this work, by inverting them with the same parameterization for spatial analysis. A simple ramp function model (Lachenbruch and Marshall 1986; Lachenbruch et al. 1988) is applied to allow for estimates of spatial variability, on a continental scale, in the timing of the onset of the RWP and the relative magnitude of that warming to the present day. It is consistent , though this simplified approach does not guarantee an unbiased estimate of the RWP because a real RWP might not take the form of a simple ramp. However, it is well known experience that the recent warming event can be reasonably approximated by a ramp model as shown later in Fig. 4.7. Ramp model error estimates for the timing of warming onset are lower than those for other model estimates, thus it more closly approximates the change-point from the previous colder climatic regime as well as the magnitude of that change over the past few 100 years.

The borehole temperature logs are influenced by the surface temperature forcing histories in different time scales (Čermak 1971). Other than influence of the RWP preceded by the LIA, Poland and surrounding territory of Northern and Central Europe were exposed to a harsh periglacial climate in the forefront of the Fennoscandian ice sheet during the last glacial. Deep European borehole temperature logs done in equilibrium conditions reveal that positive temperature gradients gradually increase with depth to the values undisturbed by the glacial cycles (Clauser et al. 1997; Šafanda and Rajver 2001; Kukkonen and Joeleht 2003; Demezhko et al. 2006). In NE Poland, instead, the gradient was found to be negative in the upper 400 m in the Udryn -Sidorowka wells. There, ice in the ice bearing permafrost zone existed only few 1,000 years ago (Šafanda et al. 2004). Low paleosurface temperatures of the last glaciation – postglacial temperature recovery (Holocene) influence heat flow variation with depth. The recent study in Europe (Clauser et al. 1997; Šafanda and Rajver 2001; Kukkonen and Joeleht 2003; Šafanda et al. 2004) showed that heat flow is increasing with depth in several deep wells in thermal equilibrium. It was suggested that some of the world's heat flow determination may be underestimated if they come from wells shallower than 1–2 km. Gosnold et al. (2005) showed using statistical approach to the data from the International Heat Flow data base that heat flow is increasing with depth in the Northern Hemisphere.

In Poland, the mean glacial-interglacial surface temperature difference derived from the deep borehole temperature log of Udryn–Sidorowka is 18°C (Šafanda et al. 2004). Present ground surface temperature in Poland is 8°–10°C. The combination of low paleo-surface temperatures and low heat flow created the condition for existence of more than 500 m thick permafrost in the upper 800–900 m sedimentary part of the Precambrian platform (Šafanda et al. 2004). Sidorowka temperature-depth log was made in 492 m well in full equilibrium state as the well was resting since 1970th. The deeper part of the profile was added using log of Udryn – 8 done in Sidorowka 311-9 vicinity (3 km). Udryn well had continuous commercial T-z log done in 1970th to a depth of 2,300 m. The well was close to equilibrium as the temperature log was done some two weeks after the drilling operations ceased and low temperature well with low geothermal gradient conditions were close in temperature to circulation fluid temperature varying in 20°–30°C range. Deep heat flow 40 mW/m^2 (Šafanda et al. 2004) is typical for this well in a low heat generation anorthozite intrusion within the western part of the Precambrian craton. The other great opportunity to measure equilibrium temperature in the Polish area occurred in late November 2005 in the well Torun-1 drilled originally in 1979 to a depth of 5.5 km is still accessible for logging to a depth of 2930 m. Torun-1 (Majorowicz et al. 2008). The well was logged under the initiative of the Torun-1 Geothermal Working Group. Majorowicz et al. (2008) used this rare deep equilibrium log to estimate paleo - temperature history of the surface in the context of glacial-postglacial change and its influence on the heat flow- depth variations. Heat flow variations with depth can be explained by a model of surface temperature changes >10°C from glacial –interglacial events including latest interglacial/Holocen history. Additional interpretations of such history of climate change from glacial to Holocene in Poland are given in Part 3 by Mottaghy et al. (2009). Mottaghy et al. (2009) find from the analysis of the new data from Czeszewo well, located in western Poland, about 400 km from Udryn about 10 K lower temperatures at the LGM than today. This is considerably less than in Udryn and confirmed by recently published results of the 2.9 km deep temperature log in the Toruń borehole (130 km NE of Czeszewo) (Majorowicz et al. 2008). The possible reasons for this large difference of the temperatures during the LGM within a few 100 km seems to be the different position with respect to the time-dependent rim of the Eurasian ice sheet as discussed later in this volume byMottaghy et al. (2009).

Analysis of these recent deep equilibrium borehole temperatures shows that RWP was 1°–1.5°C and RWP temperature level slightly lower than Holocene Optimum.

4.2 Method

The application of the method of inversion of the borehole temperature profiles in the context of the recent global warming debate has been in use only for some two decades (Lachenbruch and Marshall 1986). The borehole climate method is unique as it is based on the direct physical link between the measured borehole temperature-depth profile and the reconstructed parameter of the past climate, the GST change. For typical values of the thermal diffusivity of rocks, i.e., about 10^{-6} m^{2}s^{-1} the temperature profile measured in a borehole a few hundred meters deep may contain information about GST changes in the last millennium. The signal underground is, however, attenuated considerably through heat diffusion and decreases with depth .The degradation of the signal imposes a physical limit on the information on surface temperature history potentially retrieved by using inversion technique from the observed subsurface temperature anomalies. This is to be shown in this paper to be evident when inversion history based on synthetic temperature log from model forcing is compared with that forcing history. The reconstruct GSTH has proved to be quite successful in reconstructing two robust signals, (a) the amplitude of the last glacial/interglacial temperature difference, and (b) the surface temperature trend of the last 100–150 years and eventually, when combined with the surface air temperature series, in estimating their pre-observational mean.

4.2.1 Ramp Model

A decades and longer persistent increase of GST will cause a temperature wave to diffuse by conduction into the subsurface and imposes a transient "climate" signal on the steady-state geothermal gradient. The interpretation of a GSTH as a SATH is usually based on two basic assumptions: (1) The GST systematically couples with the SAT, (2) there is a constant offset between GST and SAT at each well site.

Time changes of the subsurface temperature can be solved using the transient heat conduction equation:

$$C_v \, \partial T/\partial t = \partial[k(\partial T/\partial z)]/\partial z + A \tag{4.1}$$

where T is the temperature, k is the thermal conductivity, C_v is the volumetric heat capacity, A is the rate of heat generation per unit volume, z is the depth, and t is the time, in a one-dimensional geothermal model.

The solution of (1) for t = t* and the initial condition t(z,t) = 0 according to Lachenbruch et al. (1988) is:

$$T(z) = D\, 2^n\, \Gamma\, (0.5\, n + 1)\, i^n\, \mathrm{erfc}\, (z/(4\alpha\, t^*)^{-0.5}) \tag{4.2}$$

where i^n erfc (β) is the nth integral of the error function of β and Γ(β) is the gamma function of argument β and D is surface temperature increase α is diffusivity.

The above solution gives the ground temperature after a warming event of duration t* with surface temperature change D. The model can be changed with adjustment of n. These functions control the model of GST change as follows; a step increase for n = 0, a parabolic increase for n = 1, and a linear change for n = 2.

The previously described problems with subsurface temperature data held in the IHFC database and limited knowledge of conductivity variation with depth suggest use of a simple linear increase temperature–time model (Lachenbruch et al., 1988). The pre-observational mean (POM) of SAT prior to the RWP, and the slope of the linear temperature increase with time, are used to search for the best-fit with measured temperature-depth transient. The timing of the warming onset and the linear change with time are the variables to be solved. As shown by most of the Functional Space Inversion (FSI) generated GSTH's, such as for the Northern Hemisphere model of Harris and Chapman (2001), the recent warming/cooling signal can be best characterized by a ramp function model (n = 2) of linear increase after a constant POM.

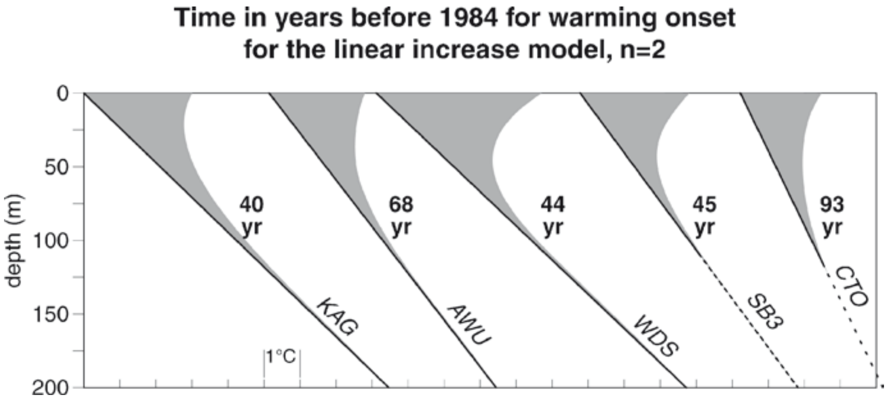


Fig. 4.3 Time (in years) before 1984 of the recent warming onset for the selected deep Alaska well temperature logs based on forward model (constant pre-observational mean POM temperature level followed by the linear increase of temperature – ramp function) (Modified from Lachenbruch and Marschall 1986)

Several analytical and numerical methods have been used for the derivation of GSTH from well temperature logs in North America (Canada and USA). Figure 4.3 shows an example from Alaskan data (Lachenbruch and Marshall 1986) and explains the use of temperature-depth profiles in determining the time of the warming onset.

The a priori model of GST change (a linear change of SAT with time) was used in Fig. 4.3. The above solutions are used to get a best-fit to the temperature anomaly with depth data. Extrapolation of the linear portion of the thermal profile, which is controlled by deep heat flow and thermal conductivity K to the surface z_o yields the intercept temperature $T(z_o)$. The deviation of the measured temperature profile T(z) from the extrapolated linear profile, results in temperature anomaly dT(z, t) which in the simplest interpretation represents the response of the ground to recent rise of the mean annual SAT from a previous long-term value, or recent cooling in case of negative anomaly. The combination of subsequent warming, or cooling, events complicates the disturbing signal with depth for simple models (Fig. 4.4).

Figure 4.5 demonstrates the differences between synthetic temperature–depth transients, as calculated for several model cases (linear, parabolic, exponential), and different times of warming onset. The temperature signal onset can be related to time at depth. Thus, the temperature–depth signal carries significant information about the timing of warming onset which can vary slightly with different a priori models assumed (i.e. step, linear, parabolic and exponential). This principle was first used by Lachenbruch and Marshall 1986 in a study of northern Alaska wells.

Data errors related to limited conductivity resolution and measurement, and the over-simplification assumptions made (homogenous 1-dimensional media) limit more detailed characterization of the GSTH prior to the RWP. Thus, a simple uniform model is necessary in order to include as many Northern Hemisphere (these come mostly from the high latitudes) borehole temperature logs as possible.

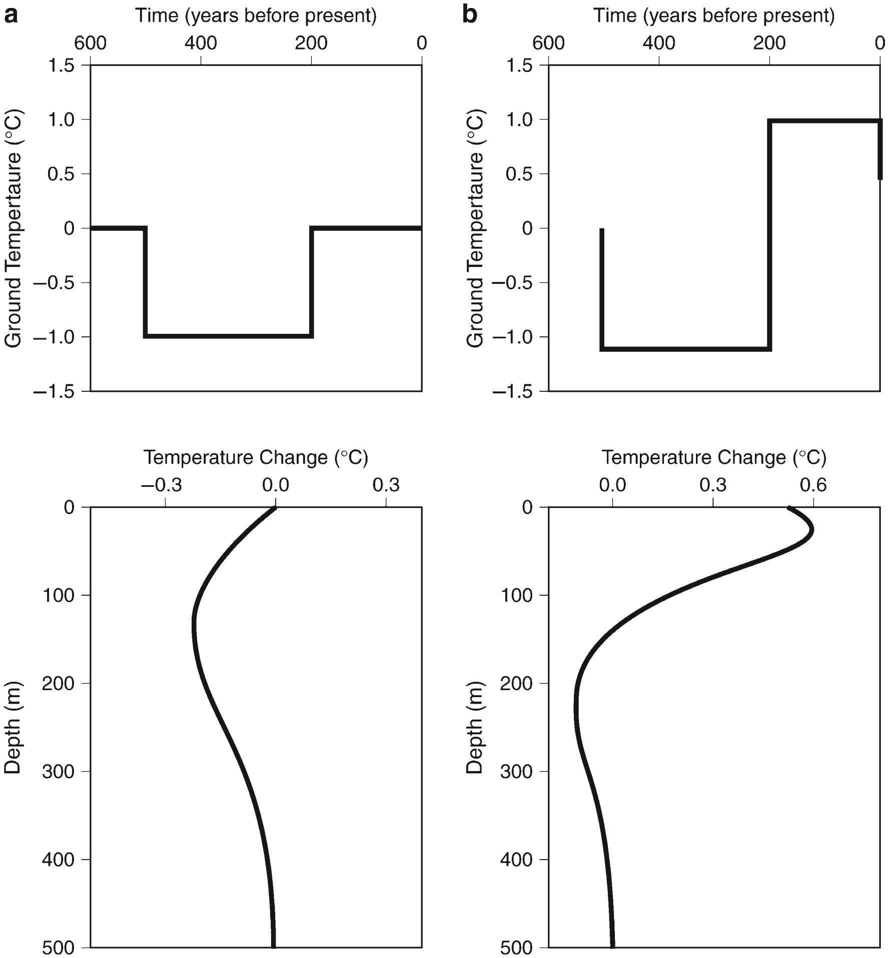


Fig. 4.4 The combination of subsequent warming/cooling, events (*upper two pannels*) and corresponding response of temperature with depth (*lower pannels* respectively).

This approach was used by Wang et al. (1994) to characterize recent ground warming in areas of eastern and western Canada.

The GST value reconstructed for time t = τ before logging represents an average over the time interval, the width of which is proportional to τ (Clow 1992), due to the diffusive character of heat conduction. The diffusivity is an important parameter in the calculation of GSTH from temperature–depth data. The value used here (0.8–1.2 × 10^{-6} m^2/s) is commonly used for model calculations in North American GSTH reconstructions (Jessop 1990). The rate at which the averaging interval increases with τ depends directly on the level of noise inevitably present in each temperature log and on the temperature sampling density. For a typical log with a 5m sampling step and a level of noise of the order of hundredths of a degree Kelvin

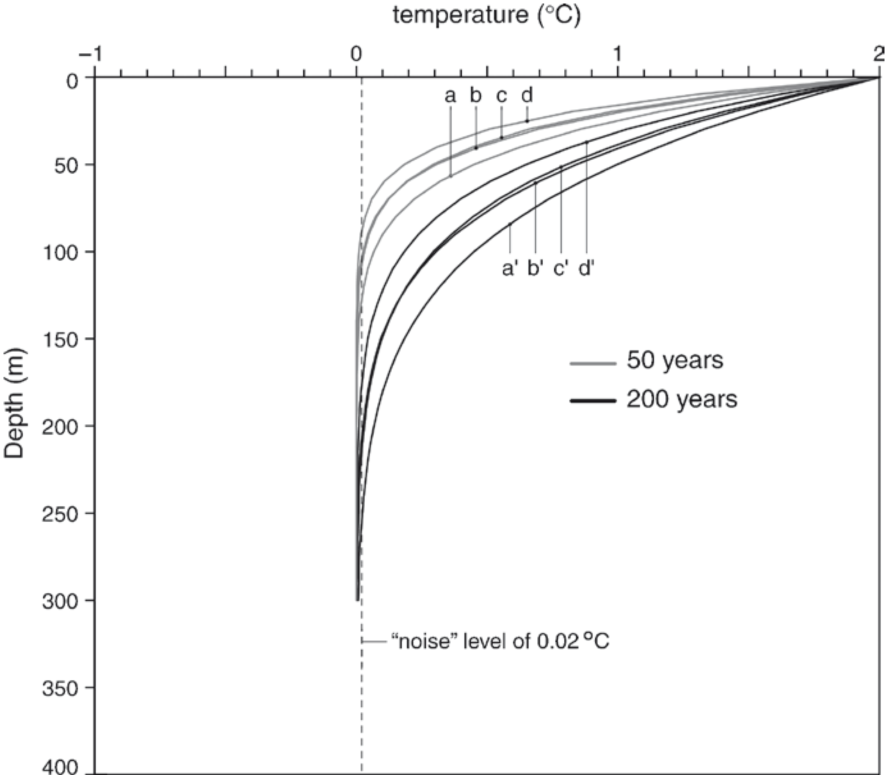


Fig. 4.5 Response to a parabolic and linear increase of surface temperature (2°C) in homogeneous medium for a time of warming onset of 50 years and 200 years. Noise level of 0.02°C is a likely minimum to see (measure) low level signals at depth. Modelling was done for common diffusivities (Jessop 1990) of 0.8E^{-6}m^2/s and 1.2E^{-6}m^2/s (a, a′ and b, b′) and (c, c′ and ,d, d′) for 50 years and 200 years respectively

(0.01 K), GST is estimated as an average greater than 0.5*τ. Ramp model error estimates (standard deviation) for the timing of warming onset are lower than those for synthetic inversions. They range from 5 years at 50 years, 10 years at 100 years, 24 years at 200 years, and 38 years at 300 years.

4.2.2 Inversion Methods

GST reconstruction from subsurface temperature profiles presents an inverse problem. Due to its complexity, all existing techniques for systematic inversion it is assumed that heat transfer is by conduction only through a one-dimensional heterogeneous medium. This assumption excludes the advective component of heat transfer due to subsurface fluids or convective disturbances within the fluid-filled borehole, as well as lateral heterogeneity in thermo physical parameters of rocks, uneven surface relief or space variations of the surface temperature from the account as they may bias the reconstruction (Shen et al. 1995). These effects and processes can be considered in „non-systematic" or random inversion approaches like the Monte Carlo method.

At present, the most frequently used systematic inversion methods are functional space inversion technique (FSI), (Shen and Beck 1991; Shen et al. 1995) and the singular value decomposition (SVD). In both methods, the mathematical representation of the physical processes relating the GST changes and the subsurface temperatures is reduced to the one-dimensional heat conduction problem. Different comparisons have shown similar results in most of the cases considered. The basic features of the GST history reconstruction will be demonstrated here using the FSI algorithm.

The FSI method is basically the generalized least-squares inversion method. It uses the so called Bayesian approach, when both the measured temperature profile, the parameters of the physical model and the sought history of the surface temperature are treated as random quantities in the probabilistic model defined by a priori estimates of these quantities and their standard deviations (SDs). The a priori values are modified during the inversion in order to reach the a posteriori configuration with maximum probability.

The inversion scheme is usually framed very conservatively in terms of a null hypothesis, i.e. with an a priori assumption that there is no climate signal present in the inverted borehole temperature profiles. It renders the analysis independent of any other proxy interpretations. A priori SD of GST variations, usually 0.5–2 K, permits a deviation from the null hypothesis if the data push in that direction. This approach can be combined with the known GST history, for instance from the meteorological observations, as an a priori estimate for the recent part of the reconstructed period. A further statistical property of the sought GST history, which must be fixed prior to the inversion, is the characteristic time of correlation of the GST variations. In order to stabilize the solution in accordance with the decreasing resolution of the method for the more remote variations a linear decrease of the characteristic time from the most remote to the most recent period considered in the inversion is recommended (Shen and Beck 1991; Shen et al. 1995). For instance, in reconstructing the last millennium it is 500 – 100 years, in reconstructing the last 50,000 years it is about 10,000 – 100 years.

The thermo-physical parameters, whose a priori values and SDs must be defined at the beginning of the inversion, are: thermal conductivity, heat sources and specific heat of rocks encountered within the borehole together with an estimate of the surface temperature T_o at time t_0 and the heat flow C_b at the bottom at depth z_b. It stems from the character of the problem that a posteriori values of T_o and C_b are well resolved and are close to the correct values even when their a priori estimates are incorrect, provided their SDs are big enough to render the inversion a freedom to push the estimates in the proper direction. On the other hand, values of specific heat and of heat production are practically unresolved by the data, but because of their small influence on the subsurface temperature field a qualified a priori estimate of their mean values is sufficient. A very important parameter of the inversion is the thermal conductivity. It controls the temperature gradient and hence its variations with depth and determines the shape of the steady-state part of the measured temperature profile. If the conductivity depth profile of the inverted borehole is not known, all variations of the positive temperature gradient can be theoretically explained as a consequence of the depth variations of the thermal conductivity. Uncertainty in this parameter, expressed by its a priori SD, plays a critical role in the inversion. The choices of a priori SDs of conductivity and/or measured temperature data provides also a method for suppressing undesired effects of noise in the input data on the resulting GST history.

The measured temperature profile is an a priori estimate of the random quantity, which can be changed during the inversion within a frame given by the probabilistic model based on a priori SDs. In the course of inversion, the T-z profile is decomposed into a posteriori steady-state and transient components. As a rule, the shortwave variations of the temperature gradient are compensated for by variations in the conductivity profile and thus incorporated into the steady-state component of the temperature.

Because the amplitude of the GST changes propagating downward attenuates exponentially, the magnitude of the present subsurface response to variations over the last millennium is, with the exception of the quite recent changes, of the order of hundredths of degrees. Many factors can produce non-climatic vertical variations of temperature of a similar magnitude to climatic factors. The typical source of these variations are unrecognized vertical and/or lateral variations of thermal conductivity. Vertical variations, if recognized, may be considered in the inversion. Lateral variations cannot be taken into account due to one-dimensional representation of the problem. T-z profiles, when inverted with typical values of a priori SDs of conductivity observed in lithologically uniform units, about few tenths of W/m K, and of temperature measurements, first hundredths of Kelvin, produce spurious GST history based on the amplification of this kind of noise (Shen et al. 1995). As numerical experiments have shown (Shen et al. 1995), suppression of the noise can be achieved by increasing the SD of the a priori thermal conductivity model and of the measured temperatures to values about 1 – 2 W/m K and 0.05–0.2 K. Larger a priori SDs of the conductivity and the temperature data mean that an increasing relative weight is given on the a priori GST history, whereas a priori conductivity and temperature data can be adjusted in the course of the inversion. Consequently, a posteriori GST histories for larger SDs are closer to a priori GST hypothesis and the risk of interpreting the noise as the climatic signal is attenuated. Such a kind of inversion is referred to as "loose" inversion in contrast to "tight" inversion carried out with smaller a priori SDs. The potential disadvantage of the loose inversion – the loss of the GST history resolution in case of high quality data with a real climatic signal – is evident (Fig. 4.6).

The above described method's assumption excludes the advective component of heat transfer due to subsurface fluids or convective disturbances within the fluid-filled borehole, as well as lateral heterogeneity in thermophysical parameters of rocks, uneven surface relief or space variations of the surface temperature from the account.

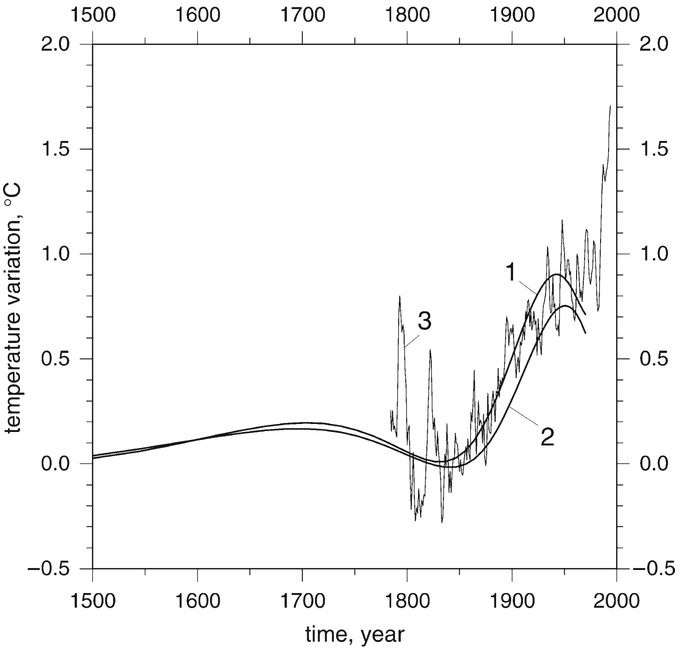


Fig. 4.6 Example of FSI reconstruction of ground surface temperature (°C) history from Polish borehole temperature logs. Curve 1: reconstruction from the continuous borehole temperature logs (from wells deeper than 450 m) which indicate large ground surface temperature warming; Curve 2: average based on all deep borehole temperature logs shown in Majorowicz et al. (2004a; Przybylak et al. 2005); Curve 3: homogeneous air temperature series from Warsaw (11-year running average) (Lorenc 2000)

4.2.3 Comparison with Temperature Variations from GCM

Figure 4.7 shows the Echo-G SAT simulation for the Northern Hemisphere for the last 1,000 years (von Storch et al. 2004; Gonzales-Rauco et al. 2003, González-Rouco et al. 2006; Zorita and von Storch 2005). The ECHO-G SAT and the assumed POM level are used as forcing to illustrate the decrease in time resolution using an inversion of the synthetic temperature–depth profile derived from the conductive 1-dimensional model. The method used is similar to that of González-Rouco et al. (2006). The model parameters are, an assumed diffusivity 1×10^{-6} m^2/s, heat production 0, an a priori SD (1 W/(m K), 0.05 K), the correlation time linearly decreasing from 500 to 100 years between 1000 and 2000 AD and an a priori SD of the ground temperature linearly increasing from 0.5 to 2 K between 1000 and 2000 AD, and a POM SAT that is assumed equal to the temperature level for the time before initiation of the ECHO-G SAT. The synthetic inversion (FSI) temperature–depth (T-z) profile calculated from Echo-G model and obtained smoothed ground surface temperature history is also shown in Fig. 4.7.

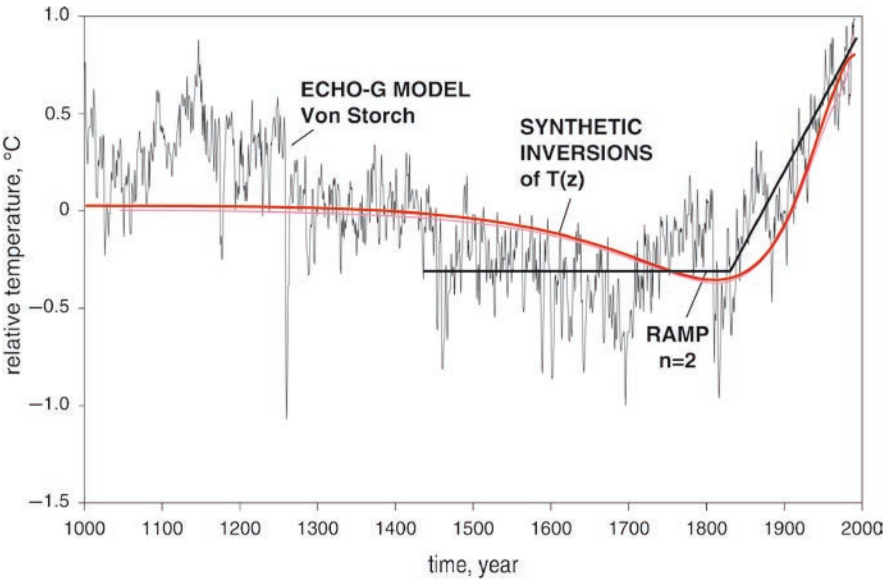


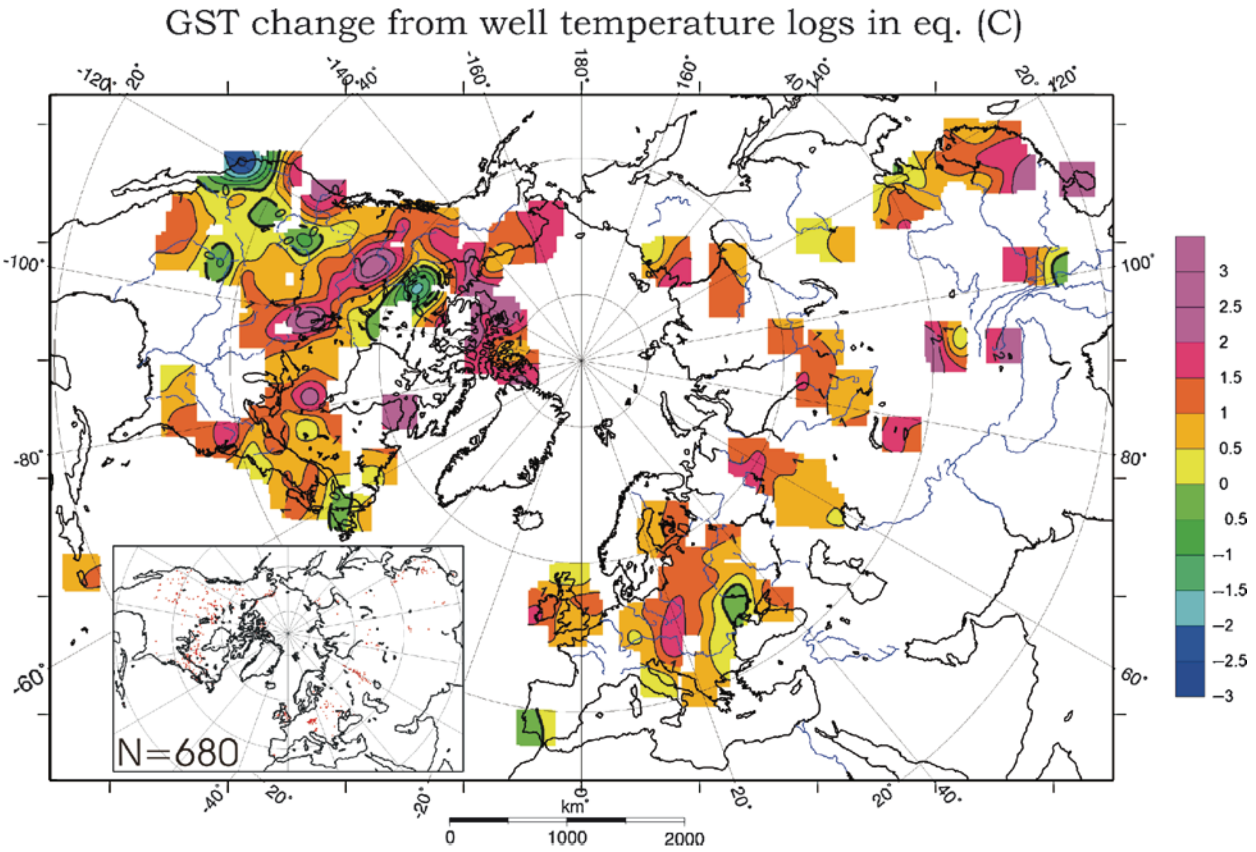
Fig. 4.7 Comparison of ECHO-G model Northern Hemisphere reconstruction of surface temperature history for the last 1,000 years with the performance of FSI inversion of the temperature –depth based on ECHO-G derived surface temperature forcing in replicating temperature-time variability (*red curves*). A simple model used in this paper (RAMP n = 2) is also shown

The forcing function consists of a series of N jumps of amplitude $\Delta T_i = T_i - T_{i-1}$ at times t_i. The subsurface temperature response T to SAT forcing at depth is calculated according to equation (4.1) Carslaw and Jaeger (1959). The ramp model depends on one free parameter, the mean long-term temperature T_o before the first change at time t_1. T_o is the pre-observational mean (POM). The thermal diffusivity governs the transient–state heat conduction.

It is apparent from Fig. 4.7 that the ramp model inversion of the temperature-depth signal is smooth prior to the onset of the RWP. The ramp model more closely approximates the onset of the RWP (the change-point from a previously colder climatic regime) and the major temperature changes of the past few 100 years. Major climatic events, such as the LIA and the RWP are not identifiable as they would be if the synthetic inversion technique were used. However, the ramp model for temperature inversion yields the best results in identifying both the timing of onset of the RWP and the magnitude of warming to the present day. This method is applied to all well temperature data used in this study.

4.3 Variability of GST Warming

Figure 4.8 shows the warming magnitude of GST across North part of the northern hemisphere including Eurasia and Northern America since 1800 AD. Average warming derived from temperature data is 0.947°C with large standard deviation of



GST change from well temperature logs in eq. (C)

Fig. 4.8 GST warming magnitude (°C) since 1800 derived from well temperature profiles

1.05°C which shows large variability of the warming amplitude across the continental areas (see also Fig. 4.1). This estimate is greater than that provided by other proxy data sources, mainly tree-ring, for the Northern Hemisphere (Mann et al. 1998; see also Mann et al. 2003 for the possible reasons in difference between GST warming from 'boreholes' and SAT warming from instrumental plus other proxy; mainly tree rings), however is close to reconstructions of Esper et al. (2002). It is higher than the estimate for northern North America (Cook et al. 2004). These GST warming results for the high latitude's Northern Hemisphere are supported globally (Huang et al. 2000) and for the Northern Hemisphere (Harris and Chapman 2001).

An estimate of the timing of the onset of warming can be made based on the derived GSTH model, or directly from the depth of the onset of the deviation of temperature from long-range deep geothermal gradient. The temporal resolution decreases at times greater than 200 years even at low noise level (see Fig. 4.5). At greater depth, the amplitude of the temperature signal is low and smaller uncertainties in model parameters (conductivity, diffusivity, etc.) can have increasing influence. Figure 4.9 shows the timing of the onset of the RWP. It is understood that it is not equivalent with the termination of the LIA, for Northern part of the northern hemisphere. The onset of RWP would be earlier than the termination of LIA because in a simple ramp model RWP would include small part of LIA (see Fig. 4.7).

The mean onset of GST warming is two centuries. The timing of the onset of the RWP varies considerably, from 50–150 years in much of western and central Canada, Alaska and Europe, to 100–200 years in northern Canada,central USA Great Plains and Asia , to greater than 200 years in eastern Canada and much of the conterminous USA The map pattern clearly has a latitudinal component with much of the 50°–60°N band, as well as in northern Alaska, recovering from the colder conditions of the LIA relatively recently in the late-nineteenth and early twentieth centuries. It is also nineteenth to early twentieth century from the European GSTH. To the south, GST warming in eastern North America and much of the conterminous USA began earlier, perhaps as early as the seventeenth and eighteenth centuries. These results are confirmed by previous independent regional studies (Lachenbruch and Marshall 1986; Deming 1995; Majorowicz et al. 2002). LIA signal was much weaker in the Eastern US, Canada and Asia than it was in western Canada, Alaska and parts of Europe. Data from a large number of wells over vast regions are in general agreement.

The global and hemispheric averages of SAT and GST (Fig. 4.1) suggest that the observed warming of the twentieth century (the RWP) was preceded by an extended cold period (the LIA) that persisted for several centuries and attained a minimum between 1500 and 1850. GSTH results for the North America and Eurasia fit the temporal parameters shown in Fig. 4.1. Such corroborating evidence strongly suggests a large spatial decade-to-century-scale variability is common to widely separated and diverse climate regions. For North America as a whole, the recovery from the LIA coincides in a large part with the onset of the anthropogenic land cover changes, which began in the early to mid-nineteenth century in eastern Canada and USA, during the nineteenth century in the remainder of the conterminous USA, and early twentieth century in western Canada (Skinner and Majorowicz 1999).

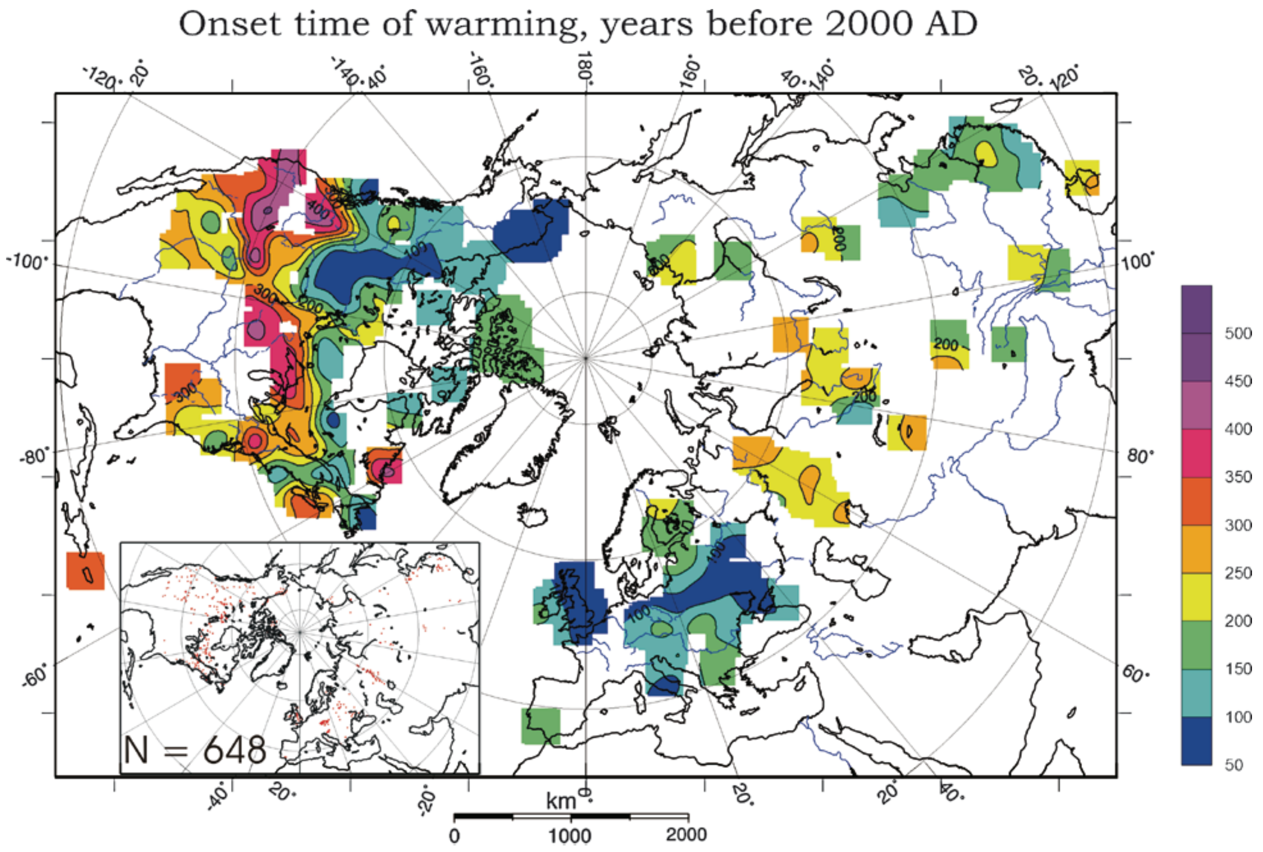


Fig. 4.9 RWP onset time (years before 2000 AD)

These changes, when superimposed upon larger-scale climate warming, are the probable cause of the excessively large magnitudes of GST warming in northwestern North America from northern Ontario to Alaska some regions, as illustrated in Fig. 4.8. Decadal-to-century-scale GST variability in this region is similar to that of the Northern Hemisphere. These findings strongly suggest that the similar, but enhanced, temperature signal identified by a large number of GSTH's make this a robust indicator region of global change. Large regional GSTH's are a direct measure of the warming/cooling magnitude and have proved extremely useful in cross-checking the credibility of century-scale proxy reconstructions and providing inference of past climate variations in a region with sparse proxy climate data coverage.

The spatial variation in warming and cooling over the instrumental record around the Northern Hemisphere and globally (IPCC 2001) is also evident in pre-instrumental times, as identified from inversions of temperature logs from all continents (Pollack et al. 1998; Huang et al. 2000) and northern N. Hemisphere (this work). The timing of the onset of warming in the conterminous USA (sixteenth to seventeenth centuries), east-central Canada (eighteenth and nineteenth centuries), western Canada (nineteenth century), the Canadian Arctic (eighteenth to nineteenth centuries), Alaska (twentieth century), Central Europe (nineteenth to twentieth centuries), Western Asia (eighteenth to nineteenth centuries) as well as the regional variations in warming magnitudes, are recognizably different. The relatively cooler conditions of the LIA and the subsequent warming of the RWP are common in all regions; however, their timing and magnitudes are significantly different. The onset of earlier warming in east-central Canada, the conterminous USA and Western Asia precedes that of the industrial age by at least a century. This is likely related to the asynchronous LIA signal across the continent.

An explanation of these differences is not within the scope of this paper, however, some suggestions explaining such differences can be made. Besides climatic warming due to anthropogenic green house factor effecting to a larger extend northern parts of the N. Hemisphere an additional factor contributing to the observed large scale regional differences can be the anthropogenic warming related to land use change. Settlement and land clearing began in western Canada in the early twentieth century and progressed northward throughout the century. Settlement in eastern Canada and USA was much earlier, in the mid- to late nineteenth century. These were even earlier in Europe where the clear –cutting effect upon GST change is likely to old to be noticed on borehole temperature logs as significant temperature anomaly. Therefore, it is likely that the European borehole temperature data unlike NW American data contain climatic warming signal only. This can explain difference in GST warming magnitude derived from borehole temperatures. It is unlikely however, that this effect alone could explain east–west and south-north differences observed in the northern N. Hemisphere (Fig. 4.8). While the main forcing is likely due to climatic warming, land cover changes due to deforestation and conversion of grassland to agricultural land can also dramatically alter surface temperature and the subsurface temperature field (Skinner and Majorowicz 1999).

4.4 Polish and European Recent GST Warming

Warming signals from borehole temperatures in northern North America are larger than those registered in northern Europe and northern Eurasia which is evident from comparison of temperature depth transients from borehole logs (Fig. 4.10). This confirms the results of the review of the data from Europe and other continents by Bodri and Čermak (2007). It reveals that more rapid GST warming has occurred in the northern parts of N. America and Asia than in Europe or Australia (Bodri and Čermak 2007; their Table 8). Part of very high ground warming derived from borehole temperature profiles in NW part of North America could be recent land clearing and clear-cutting (Skinner and Majorowicz 1999; Majorowicz and Skinner 2001) which is superimposed on the climatic forcing signal.

RWP patterns of the amplitude and time of the warming onset (Figs. 4.11 and 4.12) respectively are based on the 'ramp model' GSTH reconstructions from the

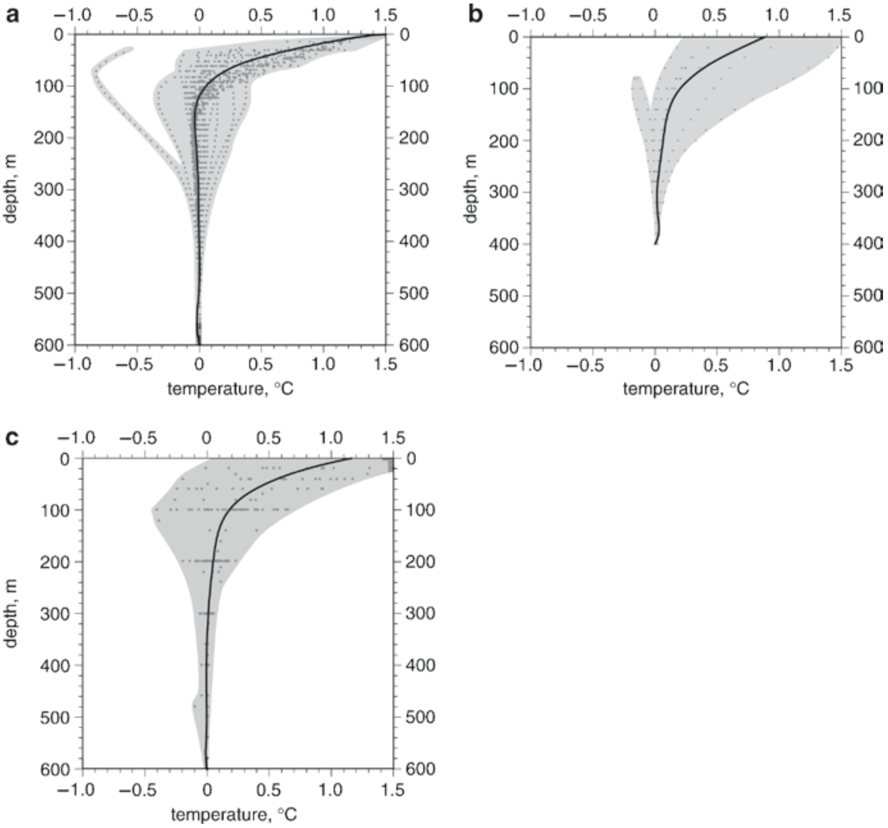


Fig. 4.10 Temperature – depth anomalies (transients) from temperature depth logs in N. America (**a**), N, Europe (**b**) N, Asia (**c**)

available Europe's well temperature logs data available from IHFC/NOAA data base plus additional highest quality precision temperature log data for NE Poland from Šafanda et al. (2004) and Majorowicz et al. (2008) and SW Poland (Majorowicz et al. 2004a). The distribution of the data points shown in the insert maps (Figs. 4.11 and 4.12) is uneven. We have from Albania (2 data points), Belarus (12), Czech Republic and Slovakia (39); Germany (5), Spain and Portugal (4), Finland (4), Ireland (4), Italy (2), Poland (14), Romania (5), Slovenia (8), Ukraine (14), and UK (20 data points). The data from Ural (Russia) are at the eastern border of Europe. Averaging and grid procedures allowed reconstruction of the RWP pattern (Fig. 4.11) and time of the RWP warming onset after LIA (Fig. 4.12).

RWP pattern agrees in general with findings of Luterbacher et al. (2004) based on multiproxy reconstructions of monthly and seasonal surface temperature fields for Europe back to 1500. Luterbacher et al. (2004; 2007) and Xoplaki et al. (2005) shows that late twentieth- and early twenty-first century European climate is very likely (95% confidence level) warmer than that during the past 500 years. This agrees with

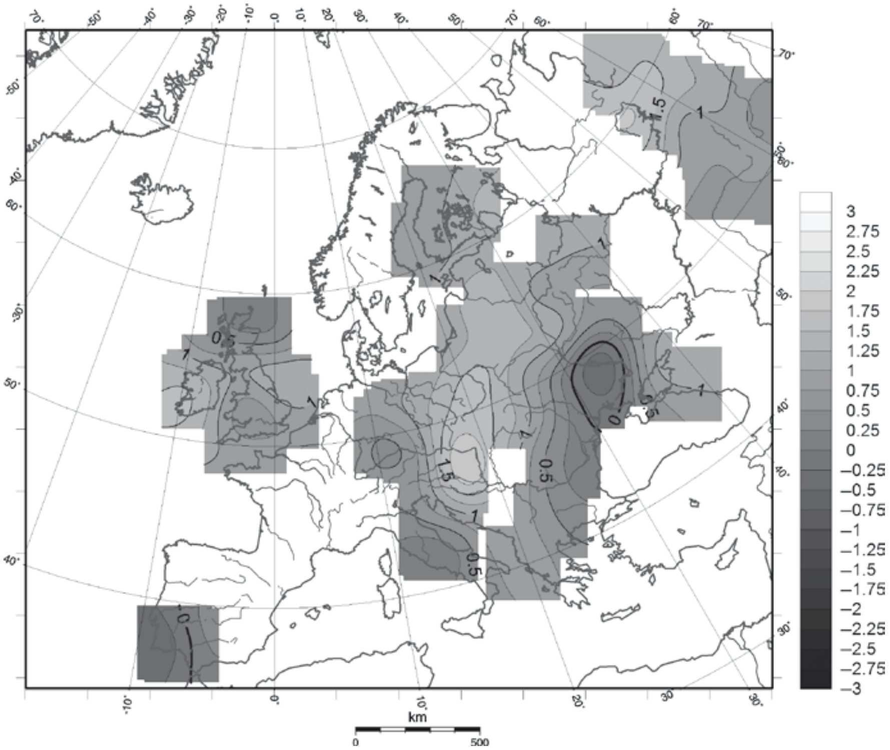


Fig. 4.11 European GST warming magnitude (°C) since 1800 AD derived from well temperature profiles

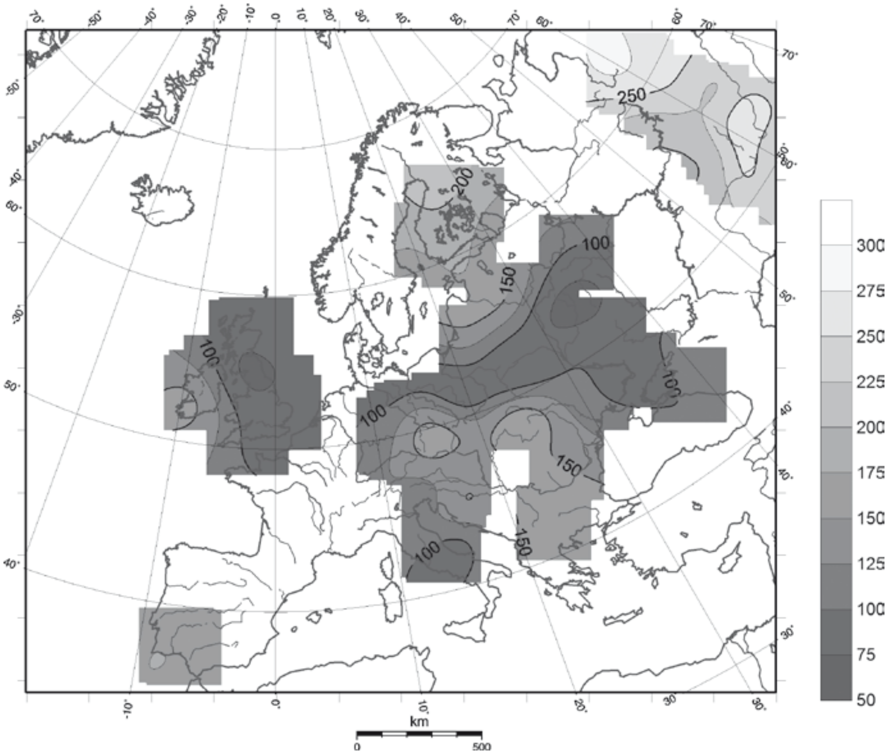


Fig. 4.12 Onset of the Recent Warm period (RWP) derived from temperature well logs (years before 2000 AD)

findings for the entire Northern Hemisphere. European winter average temperatures during the period 1500 to 1900 were reduced by 0.5°C (0.25°C for annual mean temperatures) compared to the twentieth century. Summer temperatures did not experience systematic century-scale cooling relative to present conditions. The coldest European winter was 1708/1709; 2003 was by far the hottest summer.

GST reconstructions from Poland's deep borehole temperature profiles using continuous wireline log technology show that its average pre-instrumental level (1500–1778) is about 0.9°–1.5°C lower than the mean air temperature for the period 1951–1981 (Majorowicz et al. 2004a; Przybylak et al. 2005). We can use the above reconstruction as a guide though it was not used in mapping of the contours of GST warming here as the data quality is much lower than those of the precise borehole temperature logs in equilibrium wells rest years to decades after the drilling disturbance. Such data has been published (Majorowicz et al. 2004a, 2008; Šafanda et al. 2004; Šafanda and Majorowicz 2009, this volume). The interpretation of these shows that GST warming is 1.0°–1.5°C as derived from the individual and simultaneous inversions of well temperature data using the FSI method. A very good correspondence of the results has been found between series of annual mean GSTs from the FSI method and mean seasonal air temperatures reconstructed using documentary evidence (Przybylak et al. 2005; Šafanda and Majorowicz 2009, this volume).

Acknowledgments I would like to thank Stanislaw Wybraniec for help with graphics which went into maps (Figs. 4.8, 4.9, 4.11, 4.12). Jan Šafanda is thanked for inverting synthetic profiles. Helpful comments of Shaopeng Huang and Rajmund Przybylak helped to improve the manuscript. The research presented in this section was partly funded by a grant obtained from the State Committee for Scientific Research 2007–2010 (grant no. N306 018 32/1027) and partly by support from Environment Canada (Walter Skinner, EC, Downsview, Scientific Authority).

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Part II
The Climate of Poland in Recent Centuries: A Synthesis of Current Knowledge

Chapter 5
Instrumental Observations

Rajmund Przybylak

5.1 History of Early-Instrumental Observations

The region of Poland in both its historical and present boundaries has, in international terms, one of the longest histories of instrumental meteorological observations (e.g. Gorczyński 1934; Rojecki 1956, 1968; Marciniak 1990; Trepińska 1993; Lorenc 2000; see also Table 5.1). The first observations were made in Warsaw in either December 1654 or at the beginning of 1655 (Rojecki 1956, 1966, 1968). Warsaw was one of 11 European stations which were included in the first network of meteorological stations (the so-called 'Rete medicea') organised by Ferdinand II, Grand Duke of Tuscany, and his brother Prince Leopold de Medici (Camuffo 2002). It is known that meteorological observations within this network began on 15 December 1654 and continued until 1667. In Warsaw, meteorological measurements included air temperature records (using the 50° Florentine thermometer) and visual observations of states of the sky. These were recorded either once or three times a day. There is, however, no information available about the precise location of these observations, nor do we know who made them or the precise periods during which they were made. The very eventful history of Poland (involving partitions, wars etc.) is the main reason why much of the valuable meteorological and documentary data concerning weather and climate have been lost. Only a small number of the reported series of observations now survive, covering a period of 7 days (10–16 May 1655), and these are available in the Biblioteca Nationale Centrale in Florence, Italy (Table 5.1). It is notable, however, that these instrumental meteorological observations from Warsaw are the oldest extant instrumental observations (outside Italy) in the world.

The second oldest instrumental observations in Poland were recorded between April 1710 and December 1721 in Wrocław (south-west Poland) by physician David von Grebner (Hellmann 1883, 1914; Landsberg 1983). Observations were

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Table 5.1 Isolated early-instrumental series of meteorological observations in Poland in the seventeenth and eighteenth centuries

L.p.	Site	Period	Observer(s)	Variables measured	Resolution of observations	Source of data	Availability of data/ Electronic form
1	Warsaw	12.1654–1667	unknown	T, SoS	three times a day	Biblioteca Nationale Centrale, Florence, Italy	10–16.05.1655/not available
2	Gubin	01.1697–06.1697	Maria Małgorzata Kirch	T	unknown	Miętus et al. (1999)	?
3	Wrocław	04.1710–1721, gaps for 10.1712–09.1713 and 08.1717	David von Grebner	T, AP	one to three times a day	Library of Wrocław University	WP/DC-NCU
4	Wrocław	1717–1726, 1727–1730	Johann Kanold/A.E. Büchner	T, AP, WD, GWD	three times a day	*Breslauer Sammlung* (Wrocław Collection)	WP/not available
5	Legnica	10.1717–12.1719	unknown	T, AP, H****	unknown	Miętus et al. (2001)	?
6	Kurów-Oława	02.1718–06.1719	unknown	P	three times a day	Miętus et al. (2000a)	?
7	Warsaw	1725–1728	Christian Heinrich Erndtel/G. Rautenberg	AP, WD, SoS, P	twice a day	Erndtel (1730), Warsavia, Physice Illustrata…. For more details see references	WP/DC-NCU
8	Gdańsk	1739–1772	Michael Christoph Hanow	T, AP, H, WD, WS, P, MP	four times a day	Hanow's manuscript Wetterbeobachtungen, von aus Jahren 1739–1772	WP/DMK-GU

9	Toruń	1740–10.06.1767	Samuel Theodor Schönwald	T, AP, WD, SoS, P	twice a day	journal Thornische Wöchentliche, Nachrichten und Anzeigen nebst einem Abhange von Gelehrten Sachen	1760–1767/DC-NCU
10	Gdańsk	1744–1784	Carl Gottfried Minior	T, WD, AP***, MP	twice a day	Minior's manuscript of meteorological records kept, in the Main Library of the Technical University in Gdańsk	WP/DMK-GU
11	Gdańsk	1752–1789	Johann Eilhard Reinick	T, AP, WD, MP	twice a day	Reinick's manuscript of meteorological records kept, in the Main Library of the Technical University in Gdańsk	WP/DMK-GU
12	Warsaw	07.1760–05.1762, 05.1762–03.1763	J. E. Guettard, Rev. J. Delsuc	T, AP, C, P, MP	three times a day, twice a day	Guettard (1768), see references, http://imgbase-scd-ulp.u-strasbg.fr/ displayimage.php?pos=-25308	WP/DC-NCU
13	Gdańsk	1764–1790	Johann Konrad Eichhorn	AP, T#, WD#	two to four times a day	Eichhorn's manuscript of meteorological records kept, in the Main Library of the Technical University in Gdańsk	WP/DMK-GU

(continued)

Table 5.1 (continued)

L.p.	Site	Period	Observer(s)	Variables measured	Resolution of observations	Source of data	Availability of data/ Electronic form
14	Warsaw	1779–1799	Rev. Jowin Fryderyk Bończa-Bystrzycki	T, AP, SoS*, WD**	three times a day	Bończa-Bystrzycki's manuscript of meteorological, records kept in the Archive of the Institute of Meteorology and Water Management in Warsaw	WP/not available
15	Żagań	1781–1792##	Preus?	T, AP, H, P, WD, WS, MP	three times a day	Ephemerides Societatis Meteorologicae Palatinae, 1783–1795, Volumines II–XIII, Mannheimii	WP/DC-NCU
16	Gdańsk	1783–1806, gaps for 1783–84 and 1795	Fülbach	T, AP, WD, H, MP	twice a day, from 1787 3 times a day	Fülbach's manuscript of meteorological records kept, in the Main Library of the Technical University in Gdańsk	WP/DMK-GU
17	Mogiła near Cracow	1783	Filip Carosi	unknown	unknown	Hanik (1972)	probably lost
18	Szczecin	1783–1784.02	unknown	T, AP	three times a day	Miętus et al. (1994); Miętus (1997)	?

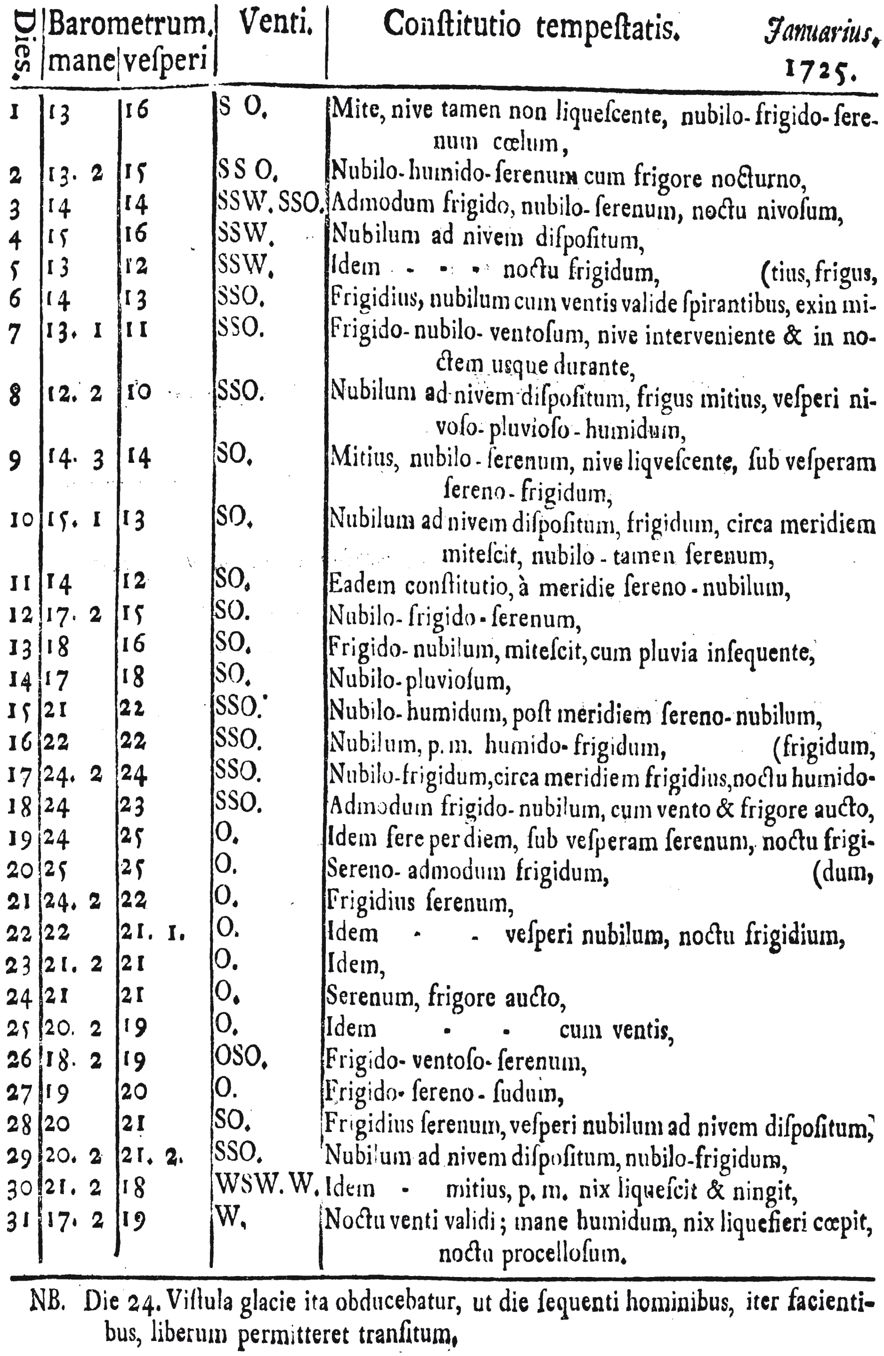
19	Twardogóra	1783–1785	Brockshammer	T, AP	unknown	Miętus (2000c)	?
20	Oleśnica	12.1783–1789	unknown	T, AP, WS	six times a day	Miętus (2000b)	?
21	Legnica	10.1783–06.1785	unknown	T	unknown	Miętus (1997); Miętus and Chwalczewska (2001)	?
22	Jasło	1785–1808	Józef Hibl	unknown	unknown	Hanik (1972)	probably lost
23	Gdańsk	1788–1812 some gaps in 1788–89 and 1811	R. Sturke	T, AP, WD, MP	twice a day	Sturke's manuscript of meteorological records kept, in the Main Library of the Technical University in Gdańsk	WP/DMK-GU
24	Cracow	05.1792–05.1794	Jan Śniadecki and others	T, AP, SoS, WD, P, H, MP	three times a day	meteorological records kept in the Department of Climatology, Jagiellonian University	WP/DC-JU

Explanations: T – air temperature, AP – atmospheric pressure, SoS – state of sky, WD – wind direction, WS – wind speed, C – cloudiness, P – precipitation, H – humidity, MP – meteorological phenomena, GDW – general weather description, WP – Whole period, DC-NCU – Department of Climatology Nicolaus Copernicus University in Toruń, DMK-GU – Department of Meteorology and Climatology of Gdańsk University, DC-JU – Department of Climatology, Jagiellonian University, * – from June 1779, ** – from 1784,*** – without 1744–1754 and 1761–1763, **** – from 1st March 1718, # – measurements taken sporadically, ## – for 1787 only observations of WD, WS and MP are available limited to measurements of air temperature and atmospheric pressure (Pyka 2003). Yet von Grebner had begun recording non-instrumental observations of different weather characteristics as early as 1692. Similar to the Warsaw observations, there is no information about the precise location of these measurements. Von Grebner also used the Florentine thermometer, which had a brass scale with a star in the middle, above which were 80° and below which were 100° (Landsberg 1983). The results of these observations are available in unpublished form in the Library of Wrocław University. For purposes of comparison, another Wrocław physician – Johann Kanold (1679–1729) – began meteorological measurements in Silesia (e.g. Wrocław, Oława, and Legnica) and in other European countries in 1717. He recorded measurements in Wrocław up to 1726, and then from 1727 to 1730 they were continued by Andreas Elias Büchner (1701–1769), professor of medicine at Wrocław University (Brázdil and Valášek 2002; Munzar 2003; Brázdil et al. 2008). They included measurements of air temperature, air pressure, wind direction and general descriptions of weather. Measurements were taken three times a day and the results were published in an encyclopaedic series *Sammlung Von Natur- und Medicin-, Wie auch hierzu gehörigen Kunst- und Literatur-Geschichten* (the so-called *Breslauer Sammlung* – Wrocław Collection).

The next extant isolated series of meteorological measurements (1725–1728) comes from Warsaw and mainly concerns atmospheric pressure. Measurements of this variable were recorded by Christian Heinrich Erndtel (1670–1734), with the help of G. Rautenberg, twice a day (in the morning and evening), using a barometer constructed by Jacob Leupold. The barometer had a relative scale of probably 30° or 32° (Rojecki 1968). The meteorological results were published *in extenso* by Erndtel (1730) in a work entitled *Warsavia Physice Illustrata…*. In this publication, aside from atmospheric pressure, details are also given of average wind direction, the state of the sky, kinds of precipitation and thermal perception (Fig. 5.1).

Gdańsk is the third place in Poland to have a very rich history of instrumental observations (see Filipiak 2007a, b; Miętus 2007), and documentary evidence is also available for long periods before the start of instrumental observations in 1739. Two such records are especially valuable for climate reconstructions. The first is a publication written by Wilhelm Misocacus entitled *Prognosticum oder Practica auffs Jahr 1577…1595*, giving a description of the weather for each season for the period 1577–1593. The second is *Calendars* written by Fryderyk Büthner between the years 1655 and 1696 and contains mainly astronomical information, but also a daily description of the weather conditions (Miętus 2007).

According to Miętus (2007) for the eighteenth century we know of six isolated series of meteorological measurements made in Gdańsk. The observers and periods of observations are as follows: Michael Christoph Hanow (1739–1772), Carl Gottfried Minior (1744–1784), Johann Eilhard Reinick (1752–1789), Johann Konrad Eichhorn (1764–1790), Fülbach (1783–1806), and R. Skurke (1788–1812). The most complete weather information is given by Hanow in the three volumes of his manuscripts (*Wetterbeobachtungen von aus Jahren 1739–1772*). This work presents the results of measurements of air temperature, atmospheric pressure, amount of precipitation, air humidity, and wind direction taken four times a day



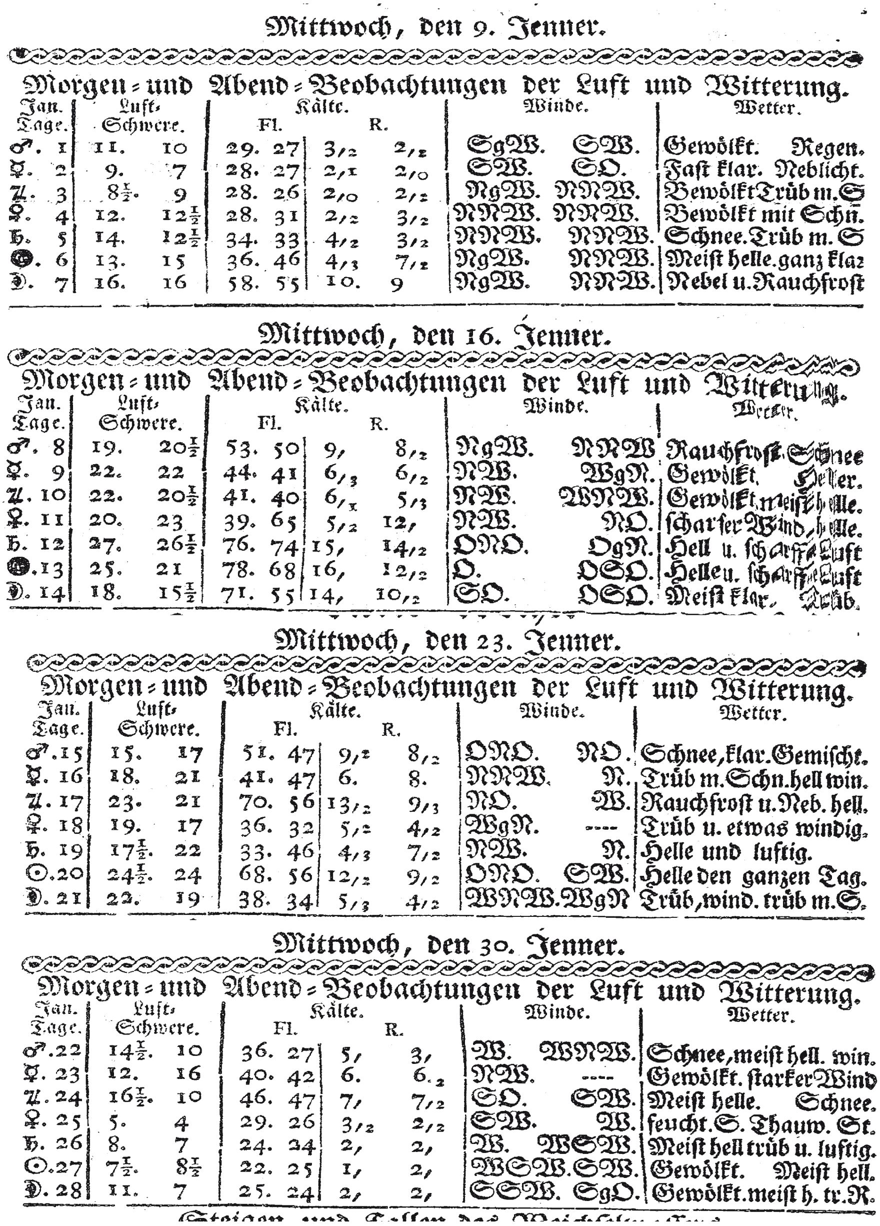
Dies.	Barometrum.		Venti.	Conſtitutio tempeſtatis. *Januarius.* 1725.
	mane	veſperi		
1	13	16	S O.	Mite, nive tamen non liqueſcente, nubilo-frigido-ſerenum cœlum,
2	13. 2	15	S S O.	Nubilo-humido-ſerenum cum frigore nocturno,
3	14	14	SSW. SSO.	Admodum frigido, nubilo-ſerenum, noctu nivoſum,
4	15	16	SSW.	Nubilum ad nivem diſpoſitum,
5	13	12	SSW.	Idem - - - noctu frigidum, (tius, frigus,
6	14	13	SSO.	Frigidius, nubilum cum ventis valide ſpirantibus, exin mi-
7	13. 1	11	SSO.	Frigido-nubilo-ventoſum, nive interveniente & in noctem usque durante,
8	12. 2	10	SSO.	Nubilum ad nivem diſpoſitum, frigus mitius, veſperi nivoſo-pluvioſo-humidum,
9	14. 3	14	SO.	Mitius, nubilo-ſerenum, nive liqveſcente, ſub veſperam ſereno-frigidum,
10	15. 1	13	SO.	Nubilum ad nivem diſpoſitum, frigidum, circa meridiem miteſcit, nubilo-tamen ſerenum,
11	14	12	SO.	Eadem conſtitutio, à meridie ſereno-nubilum,
12	17. 2	15	SO.	Nubilo-frigido-ſerenum,
13	18	16	SO.	Frigido-nubilum, miteſcit, cum pluvia inſequente,
14	17	18	SO.	Nubilo-pluvioſum,
15	21	22	SSO.	Nubilo-humidum, poſt meridiem ſereno-nubilum,
16	22	22	SSO.	Nubilum, p. m. humido-frigidum, (frigidum,
17	24. 2	24	SSO.	Nubilo-frigidum, circa meridiem frigidius, noctu humido-
18	24	23	SSO.	Admodum frigido-nubilum, cum vento & frigore aucto,
19	24	25	O.	Idem fere per diem, ſub veſperam ſerenum, noctu frigi-
20	25	25	O.	Sereno-admodum frigidum, (dum,
21	24. 2	22	O.	Frigidius ſerenum,
22	22	21. 1.	O.	Idem - - veſperi nubilum, noctu frigidium,
23	21. 2	21	O.	Idem,
24	21	21	O.	Serenum, frigore aucto,
25	20. 2	19	O.	Idem - - cum ventis,
26	18. 2	19	OSO.	Frigido-ventoſo-ſerenum,
27	19	20	O.	Frigido-ſereno-ſudum,
28	20	21	SO.	Frigidius ſerenum, veſperi nubilum ad nivem diſpoſitum,
29	20. 2	21. 2.	SSO.	Nubilum ad nivem diſpoſitum, nubilo-frigidum,
30	21. 2	18	WSW. W.	Idem - mitius, p. m. nix liqueſcit & ningit,
31	17. 2	19	W.	Noctu venti validi; mane humidum, nix liquefieri cœpit, noctu procelloſum.

NB. Die 24. Viſtula glacie ita obducebatur, ut die ſequenti hominibus, iter facientibus, liberum permitteret tranſitum,

Fig. 5.1 Facsimile of a page of the published records of meteorological observations made in Warsaw in 1725–1728 by C.H. Erndtel (1730) from 1 January 1739 to 30 September 1772 (Filipiak 2007a). The measurements were taken in the centre of Gdańsk, but there is no information given about the exposition of the meteorological instruments. The other series give daily data (usually two or four measurements a day) mainly limited to air temperature, atmospheric pressure and wind direction. For more details see Filipiak and Miętus (2009, this volume).

Instrumental observations began in Toruń in 1740, just 1 year after Gdańsk (Rojecki 1965). Daily observations in the morning and evening hours (precise times are unknown) were conducted up to 10 June 1767, probably in the centre of Toruń in the area of the local *Gymnasium*. Unfortunately, the original observation data for years before 1760 are missing, and thus it is now impossible to know exactly which meteorological observations were made during this period. From the journal *Thornische Wöchentliche Nachrichten und Anzeigen nebst einem Abhange von Gelehrten Sachen* it is known that at least temperature measurements were taken. The second issue of the journal, from 1760, gives a list of the lowest winter temperatures from 1740 to 1759. The journal featured meteorological observations from Toruń from 1760 onwards, and thus they are available up to 10 June 1767. Elements measured included air temperature, atmospheric pressure, wind direction, states of the sky, precipitation, and some other hydrometeors (Fig. 5.2). The observations were probably made by Samuel Theodor Schönwald, a professor of mathematics in the local *Gymnasium*. Air temperature was measured up to January 1 1758 with a Florentine thermometer and from 1758 onwards a second thermometer with a Réaumur scale was also used. The two thermometers were installed outside the building. Air pressure measurements were taken using a glass tube 86.4 cm in length, the open end of which was immersed in a wooden container. The next isolated series of meteorological variables in Toruń are known for the periods 1821–1825 (Hellmann 1883) and 1842–1858 (Rojecki 1965). For the first period we have no information about the elements measured. On the other hand, during the second period, measurements of air temperature and atmospheric pressure were recorded once a day at 8 am. Air temperature data averaged monthly are given in Table II (Rojecki 1965).

The next important series of instrumental meteorological observations in Warsaw was done by two Frenchmen – J.E. Guettard (1715–1786), a naturalist and member of the Royal Academy of Sciences in Paris, and the Rev. J. Delsuc, secretary to the French ambassador to the King of Poland. Guettard made his observations from July 1 1760 to May 5 1762, while Delsuc made his from May 6 1762 to March 31 1763 (Rojecki 1968). Measurements include air temperature and atmospheric pressure, while cloud cover, kinds of precipitation and other atmospheric phenomena were visually observed (Fig. 5.3). Guettard made observations three times a day (in the morning, mainly between 6 am and 7 am, at 3 pm and at midnight), while Delsuc recorded them only twice a day at 3 pm and 10 pm. There is no information available about the detailed location and exposition of the meteorological instruments. For temperature measurements, mercury and alcohol thermometers with the Réaumur scale were used, produced by Cappy, a French technician. For atmospheric pressure, a mercury barometer produced in Warsaw was used, with a scale



Mittwoch, den 9. Jenner.

Morgen- und Abend-Beobachtungen der Luft und Witterung.

Jan. Tage.	Luft-Schwere.		Kälte. Fl.		Kälte. R.		Winde.		Wetter.
♂. 1	11.	10	29.	27	3/2	2/2	SgW.	SW.	Gewölkt. Regen.
☿. 2	9.	7	28.	27	2/1	2/0	SW.	SO.	Faſt klar. Neblicht.
♃. 3	8½.	9	28.	26	2/0	2/2	NgW.	NNW.	Bewölkt Trüb m. S
♀. 4	12.	12½	28.	31	2/2	3/2	NNW.	NNW.	Bewölkt mit Schn.
♄. 5	14.	12½	34.	33	4/2	3/2	NNW.	NNW.	Schnee. Trüb m. S
☉. 6	13.	15	36.	46	4/3	7/2	NgW.	NNW.	Meiſt helle. ganz klar
☽. 7	16.	16	58.	55	10.	9	NgW.	NNW.	Nebel u. Rauchfroſt

Mittwoch, den 16. Jenner.

Morgen- und Abend-Beobachtungen der Luft und Witterung.

Jan. Tage.	Luft-Schwere.		Kälte. Fl.		Kälte. R.		Winde.		Wetter.
♂. 8	19.	20½	53.	50	9/	8/2	NgW.	NNW	Rauchfroſt. Schnee
☿. 9	22.	22	44.	41	6/3	6/2	NW.	WgN.	Gewölkt. Heller.
♃. 10	22.	20½	41.	40	6/1	5/3	NW.	WNW.	Gewölkt. meiſt helle.
♀. 11	20.	23	39.	65	5/2	12/	NW.	NO.	ſcharfer Wind, helle.
♄. 12	27.	26½	76.	74	15/	14/2	ONO.	OgN.	Hell u. ſcharffe Luft
☉. 13	25.	21	78.	68	16/	12/2	O.	OSO.	Helle u. ſcharffe Luft
☽. 14	18.	15½	71.	55	14/	10/2	SO.	OSO.	Meiſt klar. Trüb.

Mittwoch, den 23. Jenner.

Morgen- und Abend-Beobachtungen der Luft und Witterung.

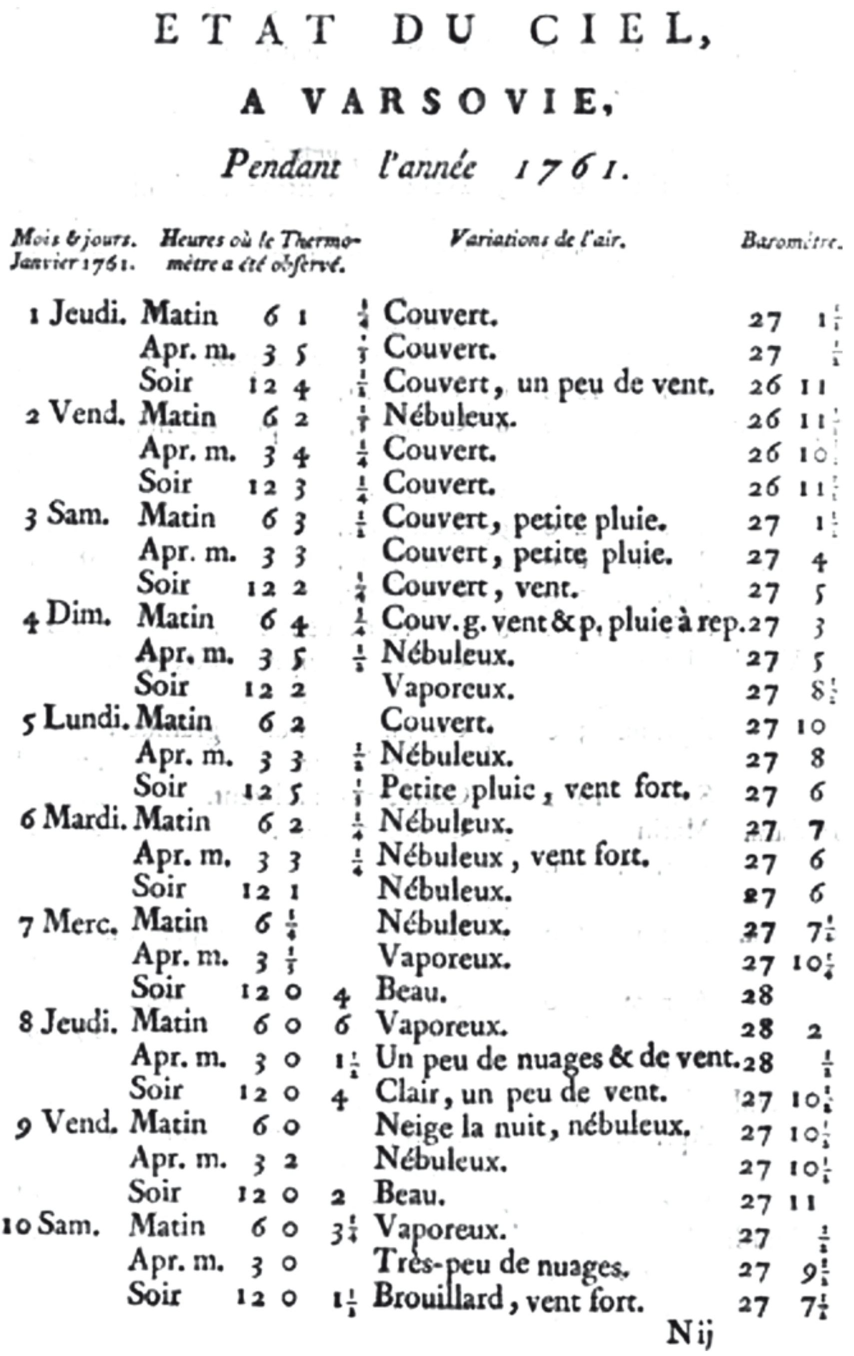
Jan. Tage.	Luft-Schwere.		Kälte. Fl.		Kälte. R.		Winde.		Wetter.
♂. 15	15.	17	51.	47	9/2	8/2	ONO.	NO.	Schnee, klar. Gemiſcht.
☿. 16	18.	21	41.	47	6.	8.	NNW.	N.	Trüb m. Schn. hell win.
♃. 17	23.	21	70.	56	13/2	9/3	NO.	W.	Rauchfroſt u. Neb. hell.
♀. 18	19.	17	36.	32	5/2	4/2	WgN.	----	Trüb u. etwas windig.
♄. 19	17½.	22	33.	46	4/3	7/2	NW.	N.	Helle und luſtig.
☉. 20	24½.	24	68.	56	12/2	9/2	ONO.	SW.	Helle den ganzen Tag.
☽. 21	22.	19	38.	34	5/3	4/2	WNW.	WgN	Trüb, wind. trüb m. S.

Mittwoch, den 30. Jenner.

Morgen- und Abend-Beobachtungen der Luft und Witterung.

Jan. Tage.	Luft-Schwere.		Kälte. Fl.		Kälte. R.		Winde.		Wetter.
♂. 22	14½.	10	36.	27	5/	3/	W.	WNW.	Schnee, meiſt hell. win.
☿. 23	12.	16	40.	42	6.	6.2	NW.	----	Gewölkt. ſtarker Wind
♃. 24	16½.	10	46.	47	7/	7/2	SO.	SW.	Meiſt helle. Schnee.
♀. 25	5.	4	29.	26	3/2	2/2	SW.	W.	feucht. S. Thauw. St.
♄. 26	8.	7	24.	24	2/	2/	W.	WSW.	Meiſt hell trüb u. luſtig.
☉. 27	7½.	8½	22.	25	1/	2/	WSW.	SW.	Gewölkt. Meiſt hell.
☽. 28	11.	7	25.	24	2/	2/	SSW.	SgO.	Gewölkt. meiſt h. tr. R.

Fig. 5.2 Facsimile of a page presenting tables with meteorological observations made in Toruń in 1760–1767 published in the journal *Thornische Wöchentliche Nachrichten und Anzeigen nebst einem Abhange von Gelehrten Sachen*



ETAT DU CIEL,

A VARSOVIE,

Pendant l'année 1761.

Mois & jours. Janvier 1761.	*Heures où le Thermomètre a été observé.*				*Variations de l'air.*	*Baromètre.*	
1 Jeudi.	Matin	6	1	¼	Couvert.	27	1½
	Apr. m.	3	5	⅓	Couvert.	27	½
	Soir	12	4	½	Couvert, un peu de vent.	26	11
2 Vend.	Matin	6	2	⅓	Nébuleux.	26	11½
	Apr. m.	3	4	¼	Couvert.	26	10½
	Soir	12	3	¼	Couvert.	26	11½
3 Sam.	Matin	6	3	½	Couvert, petite pluie.	27	1½
	Apr. m.	3	3		Couvert, petite pluie.	27	4
	Soir	12	2	¼	Couvert, vent.	27	5
4 Dim.	Matin	6	4	¼	Couv. g. vent & p. pluie à rep.	27	3
	Apr. m.	3	5	½	Nébuleux.	27	5
	Soir	12	2		Vaporeux.	27	8½
5 Lundi.	Matin	6	2		Couvert.	27	10
	Apr. m.	3	3	½	Nébuleux.	27	8
	Soir	12	5	⅓	Petite pluie, vent fort.	27	6
6 Mardi.	Matin	6	2	¼	Nébuleux.	27	7
	Apr. m.	3	3	¼	Nébuleux, vent fort.	27	6
	Soir	12	1		Nébuleux.	27	6
7 Merc.	Matin	6	¼		Nébuleux.	27	7½
	Apr. m.	3	⅓		Vaporeux.	27	10¼
	Soir	12	0	4	Beau.	28	
8 Jeudi.	Matin	6	0	6	Vaporeux.	28	2
	Apr. m.	3	0	1½	Un peu de nuages & de vent.	28	½
	Soir	12	0	4	Clair, un peu de vent.	27	10½
9 Vend.	Matin	6	0		Neige la nuit, nébuleux.	27	10½
	Apr. m.	3	2		Nébuleux.	27	10½
	Soir	12	0	2	Beau.	27	11
10 Sam.	Matin	6	0	3¼	Vaporeux.	27	½
	Apr. m.	3	0		Très-peu de nuages.	27	9½
	Soir	12	0	1½	Brouillard, vent fort.	27	7½

N ij

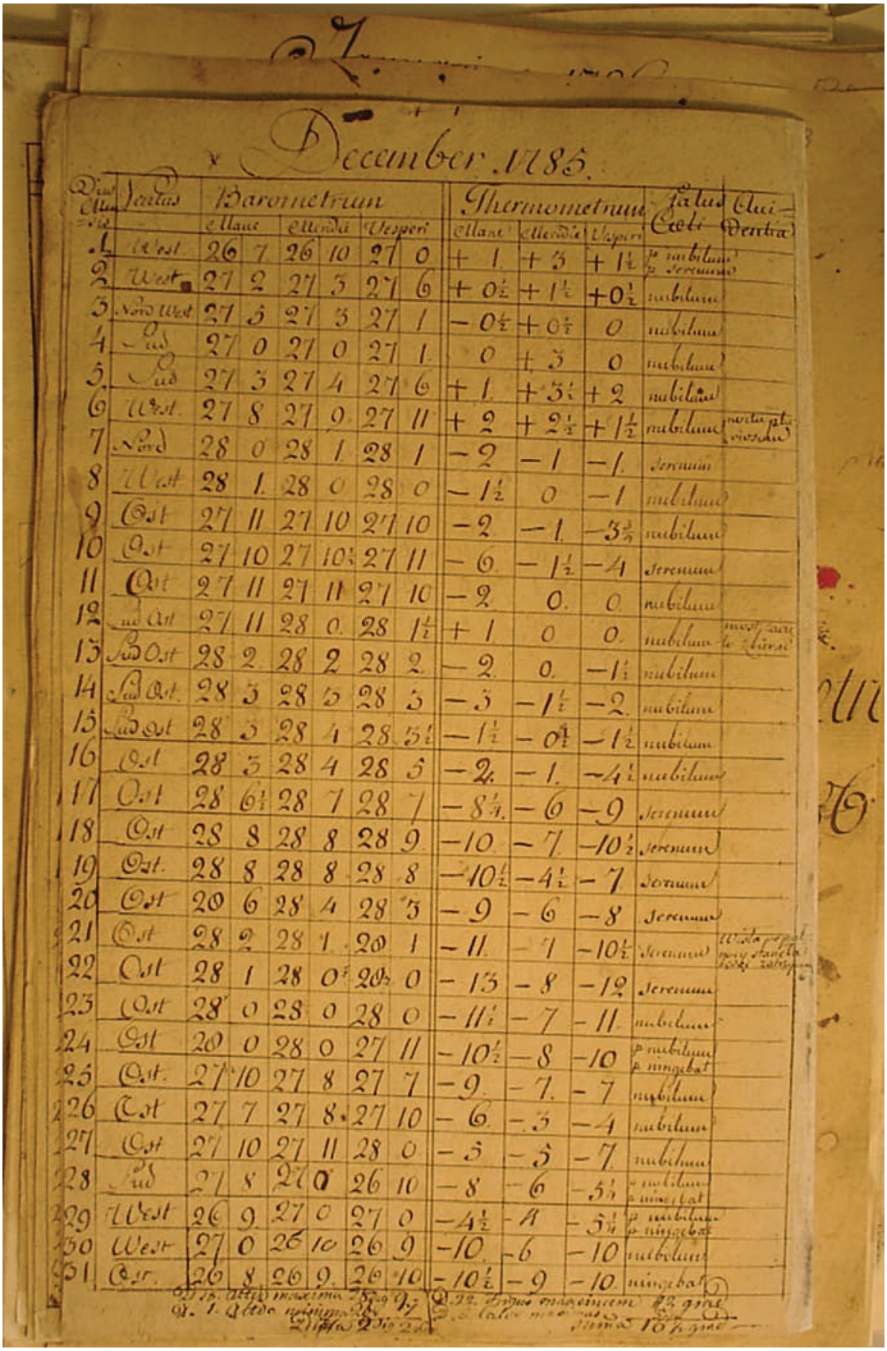
Fig. 5.3 Facsimile of a page of the published records of meteorological observations made in Warsaw in 1760–1762 by J.E. Guettard (1768) in French inches (1 French inch = 27.07 mm). All the results of meteorological measurements were published in a book written by Guettard (1768) and are available at http://imgbase-scd-ulp.u-strasbg.fr/displayimage.php?pos=-25308. Michalczewski (1988), using the regression method and a set of contemporary data from Warsaw, established some statistical relationships which allowed him to homogenise the original air temperature data and to calculate daily means (see Table 2 in Michalczewski 1988).

The last isolated series of instrumental observations in Warsaw in the 18th century was recorded by the Rev. Jowin Fryderyk Bończa-Bystrzycki from 1 January 1779 to 31 December 1799 with two long breaks from 18 September to 25 November 1787 and from 15 September to 14 December 1790. In these periods he conducted observations in Stężyca near Dęblin, not far from Warsaw. In case of air temperature measurements from 1 January 1779 onwards there is an almost continuous record, with a break only from 1 January 1800 to 30 September 1803. There are some indications that Rev. Bończa-Bystrzycki may have started these observations as early as in 1775. In the *Gazeta Warszawska* from 5 March 1785 it is noted that severe frost had been recorded at the Castle Observatory in Warsaw in 1776, and 1777, that is earlier than 1 January 1779. Unfortunately, source data have not survived from this time. Meteorological observations were carried out at the top of the tower of the Astronomical Observatory in the Royal Castle. Temperature observations using a Réaumur scale thermometer, positioned on the east side of the tower, were recorded three times a day: during sunrise, 1 h after midday and in the evening after sunset (Rojecki 1968). Atmospheric pressure was also recorded thrice daily, probably at the same times as for temperature, and using an English barometer. From June 1779 the state of sky was noted (probably its average state during the day), while from the beginning of 1784 daily records of wind direction were measured in the morning, using an eight-direction wind rose (Fig. 5.4).

Rojecki (1968) noted that Löve and Riem (1785) provide a list of absolute minimum temperatures for Warsaw from 1709 to 1785. From this he suggests that air temperature measurements in Warsaw were recorded more or less systematically from this period onwards.

In Vilnius (now the capital of Lithuania) isolated series of instrumental observations were recorded in the 1770s at the Astronomical Observatory founded in 1753. While some of them are missing between 1773 and 1776, there is a continuous series of air temperatures from 1777 onwards (Gorczyński and Kosińska 1916; Gorczyński 1934; Bukantis and Rimkus 2005).

The first instrumental meteorological observations in south-eastern Poland were carried out in 1783 by Filip Carosi in Mogiła near Cracow (Hanik 1972). However, there is no information about the variables measured, the location and exposition of instruments etc. It is also known that between 1785 and 1808 measurements of air temperature and wind direction were recorded in Jasło by the physician Józef Hibl. In both cases there are probably no preserved data. However, the best known meteorological observations come from Cracow, where they were conducted irregularly from 1 May 1792 to 15 July 1825 (for details see Trepińska 1997a). The measurements were made in the Astronomical Observatory founded in 1791 by Jan



December 1785.

Dies Mensis	Ventus	Barometrum Mane		Meridie		Vesperi		Thermometrum Mane	Meridie	Vesperi	Status Coeli	Accidentia
1	West	26	7	26	10	27	0	+ 1	+ 3	+ 1½	½ nubilum ½ serenum	
2	West	27	2	27	3	27	6	+ 0½	+ 1½	+ 0½	nubilum	
3	Nord West	27	3	27	3	27	1	− 0½	+ 0½	0	nubilum	
4	Sud	27	0	27	0	27	1	0	+ 3	0	nubilum	
5	Sud	27	3	27	4	27	6	+ 1	+ 3½	+ 2	nubilum	
6	West	27	8	27	9	27	11	+ 2	+ 2½	+ 1½	nubilum	[illegible]
7	Nord	28	0	28	1	28	1	− 2	− 1	− 1	serenum	
8	West	28	1	28	0	28	0	− 1½	0	− 1	nubilum	
9	Ost	27	11	27	10	27	10	− 2	− 1	− 3¾	nubilum	
10	Ost	27	10	27	10½	27	11	− 6	− 1½	− 4	serenum	
11	Ost	27	11	27	11	27	10	− 2	0	0	nubilum	
12	Sud Ost	27	11	28	0	28	1½	+ 1	0	0	nubilum	[illegible]
13	Sud Ost	28	2	28	2	28	2	− 2	0	− 1½	nubilum	
14	Sud Ost	28	3	28	3	28	3	− 3	− 1½	− 2	nubilum	
15	Sud Ost	28	3	28	4	28	3½	− 1½	− 0½	− 1½	nubilum	
16	Ost	28	3	28	4	28	3	− 2	− 1	− 4½	nubilum	
17	Ost	28	6½	28	7	28	7	− 8¼	− 6	− 9	serenum	
18	Ost	28	8	28	8	28	9	− 10	− 7	− 10½	serenum	
19	Ost	28	8	28	8	28	8	− 10½	− 4½	− 7	serenum	
20	Ost	28	6	28	4	28	3	− 9	− 6	− 8	serenum	
21	Ost	28	2	28	1	28	1	− 11	− 7	− 10½	serenum	[illegible]
22	Ost	28	1	28	0½	28	0	− 13	− 8	− 12	serenum	
23	Ost	28	0	28	0	28	0	− 11½	− 7	− 11	nubilum	
24	Ost	28	0	28	0	27	11	− 10½	− 8	− 10	½ nubilum ½ ningebat	
25	Ost	27	10	27	8	27	7	− 9	− 7	− 7	nubilum	
26	Ost	27	7	27	8	27	10	− 6	− 3	− 4	nubilum	
27	Ost	27	10	27	11	28	0	− 3	− 3	− 7	nubilum	
28	Sud	27	8	27	0	26	10	− 8	− 6	− 5½	½ nubilum ½ ningebat	
29	West	26	9	27	0	27	0	− 4½	− 4	− 5¾	½ nubilum ½ ningebat	
30	West	27	0	26	10	26	9	− 10	− 6	− 10	nubilum	
31	Ost	26	8	26	9	26	10	− 10½	− 9	− 10	ningebat	

Fig. 5.4 Facsimile of a one page presenting records of meteorological observations (December 1785) made in the years 1779–1799 by Rev. J.F. Bończa-Bystrzycki at the Royal Castle in Warsaw (original documents are available in the archive of the Institute of Meteorology and Water Management in Warsaw)

Śniadecki (1756–1830), who also gave instructions describing the basic rules for taking measurements. The meteorological station was set up with four meteorological instruments: two Réaumur scale thermometers (located both within and outside the building), a mercury barometer in Paris inches, and a hair hygrometer (Trepińska 1993, 1997b). Observations were recorded by three observers (including Śniadecki) three times a day between 6 am and 7 am, 2 pm and 3 pm, and at around 9 pm the local time. Aside from instrumental measurements, visual observations of the state of the sky, the occurrence of precipitation and other atmospheric phenomena, and wind direction were also recorded (for more details see Trepińska 1993).

It should also be mentioned that the earliest Polish daily non-instrumental weather observations were made at Olkusz (near Cracow) by the Rev. Marcin Biem from 1490 onwards, sporadically at first and then later more systematically between 1502 and 1517 and then again between 1525 and 1540 (for details see the chapter 6 in this volume or Limanówka 2001). Indeed, in international terms these are the oldest non-instrumental meteorological observations in the world, being pre-dated probably only by the meteorological observations from 1269–1270 in a volume of works of Roger Bacon (Long 1974) and kept by the Rev. William Merle at Oxford Driby, in Lincolnshire, England between 1337–1344 (Lawrence 1972).

Hanik (1960, 1972) notes that meteorological observations started in Lviv (now in the Ukraine) at the end of the eighteenth century. However as these data have not survived, it is not possible to specify precisely when these observations began. The earliest extant meteorological data were published in the *Gazeta Lwowska* in October 1811 by a physician called Van Roy. He made observations of atmospheric pressure (using a Heber barometer), temperature (using a wall-mounted thermometer facing north-west), humidity (initially using a Buissart hygrometer in 1815, then later a Saussure hygrometer and, from 1837, an August psychrometer), wind directions and, from 1812, precipitation (Hanik 1972).

In north-west Poland the first instrumental observations of air temperature, atmospheric pressure, and precipitation were recorded for Szczecin in the period from 1 January 1783 to 28 February 1784 (Miętus et al. 1994; Miętus 1997). While we know neither who recorded the observations nor the recording locations, we do know that measurements were made using a barometer scaled in Paris lines (1 Paris line = 2.26 mm), and two thermometers (one with a Réaumur scale and the second with a Rosenthal scale) hanging outside a window on the north side of the building. Temperature measurements were recorded three times a day at 8 am, midday and 8 pm. Miętus et al. (1994) after Klemm (1976) also note that non-instrumental weather observations were recorded in Nowogard from 1561 to 1564 by Abraham Rockenbachs, and in Szczecin from 1635 to 1638 by Wawrzyniec Eichstadt.

In south-west Poland best-known early-instrumental meteorological observations were carried out in Żagań within the network of meteorological stations called the "Societas Meteorologica Palatina" which was established by Charles Theodore, Duke of Bavaria, in 1780. The station used standardised instruments and observations were made up to 1792 according to the regulations established by the Society (e.g. observing times at 0700, 1400 and 2100 h mean local time, see Table 5.1). The results of the observations were published *in extenso* between 1783 and 1795 in volumes II–XIII of the *Ephemerides Societatis Meteorologicae Palatinae* in Mannheim. It is also thought that between 1783 and 1785 (1783–1789 for Oleśnica) instrumental meteorological measurements of atmospheric pressure (Twardogóra and Oleśnica) and air temperature (Legnica, Twardogóra and Oleśnica) were recorded in this part of Poland (Miętus 1997; Miętus et al. 2000b, c; see also Table 5.1).

As the nineteenth century progressed, throughout the territory of Poland there was a growth in the number of stations measuring air temperature, atmospheric pressure, wind direction, the state of the sky and precipitation (see e.g. Gorczyński 1934; Hanik 1960, 1972; Kaczorowska 1962; Miętus 1997). A detailed review of their activities is beyond the scope of the present study. On the other hand, we shall provide a brief summary of the history of measurements of some other meteorological variables (e.g. solar radiation, sunshine duration, humidity, and extreme temperatures) for which measurement instruments were constructed throughout the nineteenth century and even as early as the end of the eighteenth century.

The first measurements of solar radiation in Poland were probably recorded in Puławy (Nowa Aleksandria) in 1894 or earlier (Kolomijcov 1894, after Górski and Górska 2000). Measurements were irregular and their results have been lost. The next known measurements of (direct) solar radiation began in 1900 at the Museum of Industry and Agriculture in Warsaw. The measurements were taken by Władysław Gorczyński, director of the Meteorological Office at the museum. Slightly older are measurements of sunshine duration. The first were recorded on the roof of the Śniadecki College building in the Astronomical Observatory in Cracow in June 1883 using a Campbell-Stokes heliograph (Morawska 1963), which was constructed by John Francis Campbell in 1854 and improved by George Gabriel Stokes in 1879. These Cracow sunshine data records are among the oldest in Europe with measurements beginning at a few sites as early as 1882 (Morawska-Horawska 1985). Later in the 1880s, sunshine duration measurements began to be recorded elsewhere in Poland, for example in Wrocław (from 1 July 1889) as well as in Olecko, Tczew, Szamotuły and Kołobrzeg (1890) (see Table 1 in Wójcik and Marciniak 1993). At the turn of the nineteenth and twentieth centuries measurements were also begun in Warszów-Świnoujście, Poradz, Bydgoszcz, Gorzów Wielkopolski, Zielona Góra, Głubczyce, and Warsaw. These measurements were the basis for the 40-year (1891–1930) mean sunshine duration values published in *Klimakunde des Deutschen Reiches, Band II – Tabellen* (1939), Stenz (1930, data for period 1891–1910) as well as from Table 1 in Wójcik and Marciniak (1993) referred to earlier.

The first measurements of air humidity in Poland started in the Astronomical Observatory in Cracow on 19 May 1792 (at noon) or in the same year in the Astronomical Observatory in Wrocław. Galle (1879) only quotes 1792 as being the first year of such observations in Wrocław. In this work he included tables containing average monthly and annual values of water vapour pressure and relative humidity for the period 1850–1875. In the first decades, probably up to 1850, the measurements were done using a hair hygrometer and later using an August psychrometer. The history of observations of this variable, as far as location and time are concerned, is probably the same as in the case of air temperature, described earlier. We have more details for measurements from Cracow. Again early measurements used a hair hygrometer developed by Horace-Bénédict de Saussure (1740–1799), the Swiss physicist, geologist and early Alpine explorer (MSc A Wypych, 2008, personal communication). From 20 May 1792 the measurements were recorded three times a day, between 6 am and 7 am, 2 pm and 3 pm, and at around 9 pm the local time. Using this instrument relative humidity measurements were carried out here until 1830. From 1 January 1831 to 1 July 1834 Körner's hygrometer was used, which was then replaced by the August psychrometer (Kowanetz 1997; Wypych 2007). Up to December 1862 there are some small gaps in the observations, but subsequently a continuous data series is available. The third oldest series of air humidity measurements comes from Warsaw. Observations began on 1 January 1806 by Antoni Szeliga-Magier (1762–1837), who continued the meteorological observations which had earlier been initiated by Rev. Bończa-Bystrzycki. For measurements, the same instruments were used as in Cracow. Observations were recorded three times a day – in the morning, afternoon, and evening. The afternoon measurements were taken between noon and 1 pm (in winter), 1 pm and 2 pm (in spring and autumn), and 2 pm and 3 pm (in summer); morning and evening observations were recorded 8 h earlier/later, respectively (Jastrzębowski 1841, after Rojecki 1968). A very long series of air humidity measurements is also available from 1 October 1811 for Lviv. In the first half of the nineteenth century these four measurement stations – Puławy, Cracow, Warsaw, and Lviv – were probably the only ones recording humidity. On the other hand, in the second half of the century (though mainly before 1881) humidity observations were recorded in many places (e.g. Szczecin, Świnoujście, Hel, Gdańsk, Koszalin, Bydgoszcz, Toruń, and Poznań. See, for example, *Klimakunde des Deutschen Reiches, Band II – Tabellen* 1939, which lists long-term monthly and annual means [for 2 pm] for the period 1881–1930).

Extreme maximum and minimum temperature measurements began for the first time in the territory of Poland in the Astronomical Observatory in Warsaw in either November 1825 or January 1826 (Lorenc 2007). Two extreme thermometers were located in a small box made from zinc and fastened to the inside side of the northern wall (9.5 m above ground) in an unheated staircase (Gorczyński 1913). This box was exposed at the northern and southern sides and was contained within a larger wooden holder of similar construction. For temperature measurements a Rutherford thermometrograph made by Kappeller in Vienna was used. Unfortunately, data for the period 1826–1914 as well as for some other periods listed in Lorenc (2007) have been lost, at least in Poland. However, Lorenc (2007) suggests that some data may be available in Russian archives. Continuous series of extreme temperatures exist from 1897, when measurements of these temperature parameters started in the Warsaw Museum station, where they were conducted until 1915 (for more details see Lorenc 2007). The next place for which long-term data of extreme temperatures are available (from 1 June 1837) is the Astronomical Observatory of the Jagiellonian University in Cracow. Measurements were taken using a metallic thermometer made by Jürgensen from Copenhagen. It had a round dial with three scales in Réaumur, Celsius, and Fahrenheit degrees (Kowanetz 1997). Thermometers were fixed to a meteorological screen fastened to the wall near the window facing north-northwest. The screen hung at a height of 12 m above the ground (Piotrowicz 2007). The series from Cracow for the period 1836–2007 is presented by Piotrowicz (2009, this volume) and is homogenised and extended to the beginning of 1836 using air temperature readings from four times: 7 am, noon, 3 pm and 9 pm local mean time. Prof. J. Trepińska (2008, personal communication) extended this series to 1826 using the same method.

5.2 History of Some Long-Term Continuous Meteorological Series

5.2.1 Air Temperature

The longest series of continuous air temperature data for the historical area of Poland started on 17 January 1777 in Vilnius. On the other hand, for the area of present-day Poland, the longest extant air temperature series is for Warsaw (from 1 January 1779), only 2 years shorter than the Vilnius series. This series (i.e. mean monthly and annual values) was recently homogenised by Lorenc (2000), using original observations made by the Rev. Bończa-Bystrzycki (1779–1799) mentioned earlier, by Antoni Szeliga-Magier (1803–1828), and by the staff of the Astronomical Observatory (including its first director J. Baranowski) founded in Warsaw in 1826, along with other different sets of data which Lorenc describes in detail. Three of these deserve to be mentioned in particular: Kowalczyk 1881; Gorczyński and Kosińska 1916; Michalczewski 1985. The history of temperature measurements in Warsaw and the methods used to fill gaps in the data and to check for homogeneity are presented in Rojecki (1968); Michalczewski (1985); Lorenc (2000). As noted earlier, for extreme temperatures an homogenised series is available from 1897 (for more details see Lorenc 2007, where monthly and annual mean values are published for the period 1897–2002).

The next long-term air temperature series (from February 1791) is for Wrocław (south-west Poland). The temperature measurements were made continuously at the Astronomical Observatory of Wrocław University up to 1930, and then in a station working within a network organised by the State Meteorological Institute. For the first 10 years measurements were made in the observatory room; then, owing to the bad health of Anton Jungnitz (1764–1831), the first director of the Astronomical Observatory and meteorological observer, they were recorded in his apartment on the second floor of the main university building, in the wing neighbouring the church (Pyka 2003). In 1825 the place of observation moved to the physics laboratory on the third floor, and from 1832 observations returned to the Astronomical Observatory. Two pairs of thermometers were installed in the windows facing north-northeast and east-northeast. Meteorological measurements were carried out regularly three times a day at 6 am, 2 pm and 10 pm until 1837, and then five times a day (6 am, 9 am, noon, 3 pm and 9 pm) until 1845. In 1846 there was a return to thrice-daily measurements, but from 1851 to 1875 two additional measurement times were added (at 10 am and 6 pm). However, the daily mean temperatures from the beginning of observations until 1886 (with the exception of the period 1837–1845) were calculated using only data from the three original observation times. For more details about temperature data, their quality and changes in time, as well as measurement techniques see Galle (1879), Pyka (2003).

Continuous air temperature measurements for Cracow are available from 16 August 1825 (Trepińska 1997a), though as noted earlier they began as early as 1 May 1792. Gaps in the oldest observations (1792–1825) were recently filled using observations from other long-term European stations (Ustrnul 1997). As a result, this series is now available for Cracow with monthly resolution from 1792.

A very long series of continuous temperature measurements is available for Gdańsk (from 1807). Mean monthly temperatures for the period from 1807 to 1910 were published by Momber (1906), while an homogenised series from 1851 onwards is available in Miętus (1998). In Lviv, temperature measurements began on 1 October 1811 (Hanik 1972) and these have generally continued up to the present day, with two main breaks from 1848 to 1850 and during World War II.

For some other stations data are also available from 1836 (Szczecin, see Kożuchowski and Miętus 1996; Wiśniewski et al. 1999), 1848 (Poznań, Koszalin), or from 1851 (for Hel and Bydgoszcz). Recently Kożuchowski and Żmudzka (2003) have calculated the areally averaged mean annual temperature for Poland for the years 1901–2000.

Long-term continuous and generally homogeneous series of average monthly extreme air temperatures (maximum and minimum) are available for Cracow (from 1836, Piotrowicz 2007), Warsaw (1897, Lorenc 2007), Śnieżka (1901, Wibig and Głowicki 2002), Zakopane (1906, Wibig 2000), and for Puławy (1918, for which some small gaps in data exist, Wibig and Głowicki 2002).

5.2.2 Atmospheric Precipitation

The longest series of instrumental observations of atmospheric precipitation is available from the Astronomical Observatory of Wrocław University from 1799 with only a few very short breaks (1–2 months) (Pyka 2003). The measurements were conducted first on the observatory terrace up to 1854, when they were transferred to the university courtyard. Pyka (2003) notes that this change of location of the rain-gauge resulted in a 28% increase in the amount of precipitation. In 1858 the rain-gauge was moved again, this time to the Botanical Garden. The monthly and annual totals of precipitation for the period 1851–1930 are published in *Klimakunde des Deutschen Reiches* (1939).

In Warsaw measurements of liquid precipitation began on 1 April 1803. From 1 January 1813 solid precipitation was also measured. Thus, continuous series of complete monthly totals (with the exception of January and February 1835) and annual totals (again excepting 1835) are available for the period 1813–1910 in

Gorczyński (1912). On the other hand, Marciniak and Kożuchowski (1990) have collected and published this series until 1980, without gaps. The homogenisation of both of these long-term series is currently being carried out (Tadeusz Bryś, 2008, personal communication, Halina Lorenc, 2008, personal communication).

Lviv is the third place in the former territory of Poland where measurements of precipitation started very early. Daily data are available from October 1811, though because they contain some gaps it has only been possible to calculate the monthly totals from 1824 (Niedźwiedź and Twardosz 2004). In this series there still exists one gap (from 1842 to 1851) which, in the opinion of the cited authors, it is possible to reconstruct.

In Cracow, instrumental measurements of this very important variable started relatively late, in August 1849 after the founding of the meteorological station in the Astronomical Observatory of the Jagiellonian University (Trepińska 1997a; Twardosz 1997a; Twardosz and Cebulska 2009, this volume). However, information on precipitation types is available from the beginning of observations in 1792, and from 1826 this was supplemented with information on times of occurrence and degrees of intensity. Using all of these data, Twardosz (1999) reconstructed monthly and annual precipitation totals from 1812 for all months and years, and also for some months and years for the period 1792–1811 (see his Table 5). The homogeneity of the series of monthly and annual totals of precipitation from 1850 onwards was checked by Twardosz (1997b). Precipitation measurements were taken on the terrace of Collegium Śniadecki. Rain-gauges were positioned on a corner pillar at a height of 13.6 m above ground at a distance of 4 m from the wall of the building. The measurements have been taken from 1849 to the present, three times a day, in the morning (mainly from 6 am to 7 am), afternoon (from 1 pm to 2 pm), and evening (from 7 pm to 10 pm), and these times were only changed on five occasions during the whole history of observations (for details see Twardosz 1997b).

Kożuchowski (1990, see his Table XVI) and Kożuchowski and Żmudzka (2003) have calculated the areally averaged mean annual precipitation totals for Poland for the years 1881–1980 (for their analysis see Brázdil and Kożuchowski 1986) and 1901–2000, respectively.

5.2.3 *Atmospheric Pressure*

The longest continuous series of measurements of atmospheric pressure is available from Warsaw from 1 January 1779. The history of these measurements is generally the same as that of air temperature measurements, with only one exception: in the case of temperature there was a break in observations from 1 January 1800 to 30 September 1803, while this is not the case for the atmospheric pressure. In this period this variable was measured by Karol Ludwik Kortum (1749–1808) in his flat three times a day, though no precise information is available on measurement times. He carried out the observations until the end of 1807 using a barometer scaled in Paris lines and located at a height of about 27 m above the average level of water in the river Vistula (Rojecki 1968). Antoni Szeliga-Magier began measurements of atmospheric pressure from 1 January 1803 and continued them until the end of 1828. For measurements he used a mercury barometer of his own construction scaled in Paris lines and located 8 m higher than Kortum's barometer. An homogenised series of monthly values of air pressure exists for the period from 1826 (Ustrnul and Czekierda 2000; Ustrnul and Feliks 2007).

The second longest series of continuous atmospheric pressure measurements is for the Astronomical Observatory of Wrocław University from February 1791 (Pyka 2003). As far as location and times are concerned, the situation is similar to that of air temperature measurements described earlier. Monthly and annual totals of atmospheric pressure for the period 1791–1854 and 1881–1930 are published in Galle (1857) and *Klimakunde des Deutschen Reiches* (1939), respectively.

The third longest series of continuous observations of atmospheric pressure probably comes from Lviv, where observations started on 1 October 1811.

The next continuous series after this is available for the historical meteorological station in Cracow from 16 August 1825. The first measurement was taken here on 1 May 1792 and data exist for the following isolated periods: 1 May 1792 to 18 May 1794; 1 September 1803 to 9 August 1804; 1 January 1805 to 5 October 1805; 1 October 1811 to 30 September 1823; and 1 January 1824 to 15 July 1825 (Trepińska 1997a). Recently, Ustrnul (1997) was able to fill the gaps for mean monthly and annual values using long-term data from the nearest European stations. Thus, at present the series is available from 1792 onwards (see Trepińska 1997c, 2007). It is also worth adding that in Cracow in 1848 the continuous recording of air pressure began. As a result, Cracow is one of only a small number of climatological stations in the world which have an unbroken series of hourly measurements (Obrębska-Starklowa 1993).

Gorczyński (1917) published tables containing mean monthly and annual values of air pressure for the oldest parts of these series, that is for the periods 1779–1910 (Warsaw), 1826–1910 (Cracow), and 1851–1910 (Lviv and Wrocław).

5.2.4 Other Meteorological Variables

Continuous series of other meteorological variables (solar radiation and sunshine duration, cloudiness, air humidity etc.) are markedly shorter and less reliable than described above three main variables. This may be the result of, for example, the late construction of measuring instruments and/or problems with the homogeneity of the obtained data.

Although solar radiation measurements started in Poland at the end of the 19th century, continuous series of, for example, monthly and annual totals of global and diffuse solar radiation are available only since the 1950s for a few stations (for details see Bogdańska et al. 2002). Recently however, Bryś and Bryś (2003, 2005, 2007) have presented analyses of changes of global solar radiation totals (for different periods of the year) in Wrocław for the periods 1901–2000, 1891–2003, and 1875–2004, respectively. Gaps in the measurement of global solar radiation, as well as data for period 1875–1890, were filled using reconstruction methods based on sunshine duration data. It should be added that these data for the period 1875–1890 were also reconstructed using the available measurement data of cloudiness, air temperature and humidity (for details see Bryś and Bryś 2007). Yet the situation for sunshine duration data is markedly better than it is for these other variables. The longest and the most reliable continuous series of monthly totals of sunshine duration is available for Cracow (from June 1883 onwards). Morawska (1963) using the close relationships noted between sunshine and cloudiness in Cracow, reconstructed monthly totals of sunshine duration for the years 1859–1883 for which observations of cloudiness had been made. Recently, Lewik et al. (2009, this volume) have reconstructed the mean monthly and annual values of sunshine duration for the years 1826–1883 on the basis of the number of clear and overcast days. The second longest continuous series of sunshine duration comes from Wrocław (from 1890 onwards, though reconstruction data exist from 1875). Homogenised series of this variable was recently presented by Dubicka and Pyka (2001) for the whole of the twentieth century, and by Bryś and Bryś (2005, 2007) for the periods 1891–2003 and 1875–2004, respectively. Long homogenised series of sunshine duration are also available for Warsaw (from 1903, see Podogrocki 2002) and for Puławy (from 1921, see Górski and Górska 2000).

One of the longest series of nephological observations in Europe (from 1792) is available for Cracow (the Meteorological Station of Department of Climatology at the Jagiellonian University). From 1792 to 1826 observations were irregular, but they are continuous from 1826 onwards. Up until 1853, cloudiness was measured on a 4-degree scale, and later on a 1–10 scale (e.g. Morawska 1963; Morawska-Horawska 1985; Matuszko 2001, 2003, 2007a, b; Lewik et al. 2009, this volume). Until recently, monthly and annual amounts of cloudiness were available from 1859 (e.g. Morawska 1963; Morawska-Horawska 1985; Matuszko 2001). In Chapter 15, Lewik et al. present a reconstruction of this variable to 1826 on the basis of the number of clear and overcast days available for the period 1826–1852 according to Wierzbicki (1873). On the other hand, for the period 1853–1862 mean monthly values of cloudiness were taken from a manuscript written by Franciszek Karliński (see Morawska 1963). Mean monthly and annual values of cloudiness in Cracow for the period 1901–2000 have been presented by Matuszko (2007b). For the whole period they are available in the Department of Climatology of the Jagiellonian University. According to Matuszko (2007b) that series is homogeneous, at least from 1863, and possibly from 1826 (Lewik et al. 2009, this volume). The next very long series comes from Wrocław. Information about the frequency of clear and cloudy days is available from 1791, while average monthly values of cloudiness are available from 1875 (MSc Tadeusz Bryś 2008, personal communication). Rojecki (1968) noted that Antoni Szeliga-Magier began observations of cloudiness in Warsaw in February 1808. The state of the sky was described in brief three times a day – in the morning, afternoon, and evening hours. It is quite probable that this kind of observation is continuous up to the present. Gorczyński and Wierzbicka (1915) and Gorczyński (1938) give long-term average values of cloudiness for Warsaw for the period 1886–1910. So far nobody has undertaken the process of homogenization of this series. The two publications mentioned also provide this kind of data for many other historical Polish stations (e.g. Hel, Poznań, Lviv, Puławy, Opole, Bydgoszcz, Koszalin, and Chojnice). A very long series of cloudiness observations is also available for Śnieżka (1602 m a.s.l.; Sudety Mountains) in south-west Poland and, from 1906, for Zakopane (Tatra Mountains) (Dubicka 1999; Limanówka and Ustrnul 2002). Dubicka (1999) has noted that there have been isolated series of observations at the Śnieżka station dating from 1824. On the other hand, continuous, regular observations (three times a day at 7 am, 1 pm and 9 pm) began in 1885. Using these data, series of monthly, seasonal and annual values of cloudiness have been calculated and homogenised for the period 1885–2007.

The history of measurements of air humidity in Poland was described briefly earlier and we know that the longest series are available for Cracow, Wrocław, Warsaw, and Lviv. However, continuous series of mean monthly values of this variable are only available for Wrocław and Cracow. For Wrocław, a continuous series of all humidity parameters (relative humidity, water vapour pressure and deficit of water vapour pressure) are available from 1850 (Tadeusz Bryś 2008, personal communication). On the other hand, for Cracow such a series is available in the archive of the Department of Climatology of the Jagiellonian University from 1863 (Wypych 2008, personal communication). Recently, Wypych (2007) published a series of mean monthly values of relative humidity for the period 1901–2000.

5.3 Climate Changes in the Instrumental Period

As we have seen from the history of instrumental meteorological observations presented in the previous section, there are quite a large number of long-term continuous and homogenised series of meteorological variables available for the area of Poland. The data available allow us to characterise reliably almost all aspects of the Polish climate and its changes over the last 100–200 years. The aim of this section is to give a brief summary of the characterisations of climate changes in the instrumental period, which have mainly been presented in the Polish literature on the subject. In some cases we have provided updates of these climatic studies.

The issue of climate changes in the area of Poland has been investigated very intensively, particularly since the 1980s, when evidence of global warming began to emerge. Around this time many conferences were organised, prompting Polish climatologists to investigate this issue in greater depth.[1] The majority of the papers presented during these conferences include analyses of different aspects of climate changes in Poland. The results of these investigations have been published in the

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[1] These conferences included 'Global Warming and Contemporary Climatic Changes in Poland' (University of Szczecin, 1993), 'Changes and Variability of Climate of Poland' (University of Łódź, 1999), 'Images and Reconstructions of Weather and Climate over the Last Millennium' (Jagiellonian University, 2000), 'Advances in Research on Climatic Change and its Importance for Human Life and Economic Activity' (Warsaw University, 2001), 'Man and Climate in the 20th Century' (Wrocław University, 2003), 'Extreme Hydrologic and Meteorological Phenomena' (Polish Geophysical Society and Institute of Meteorology and Water Management, 2003), 'Climate Variation in Various Scales of Time and Space' (Jagiellonian University, 2007), and 'The Climate of Poland in Historical Times in Relation to the European Climate' (Nicolaus Copernicus University, 2007).

following works: Kożuchowski 1993; Dubicki et al. 1999; Boryczka and Kossowska-Cezak 2001; Pyka et al. 2003; Piotrowicz and Twardosz 2007; Przybylak et al. 2009, this volume. Moreover, other volumes have also appeared mainly presenting different characteristics of long-term changes of individual meteorological variables, in particular air temperature, precipitation, and atmospheric pressure. The majority of studies limit the area of investigation to one site (e.g. Trepińska 1988; Trepińska 1997c; Lorenc 2000; Matuszko, 2007a,b,c), to certain parts of Poland (e.g. Miętus 1996; Wnęk 1999) or to the whole of Poland (e.g. Gorczyński and Kosińska 1916; Gorczyński 1917; Kaczorowska 1962; Kożuchowski 1985a; Boryczka et al. 1992). Moreover, many papers have been published in different journals and other conference proceedings, not listed here. A partial bibliography is provided in the references at the end of this chapter.

5.3.1 Air Temperature

As may be seen from our earlier discussion, our data concerning changes in air temperature in Poland date back to the eighteenth century. The mean annual temperatures for the periods 1779–1998 (Warsaw) and 1792–1995 (Cracow) show upward statistically significant linear trends reaching 0.55°C and 0.52°C per 100 years, respectively (Trepińska and Kowanetz 1997; Lorenc 2000). This means that the air temperature from the end of the eighteenth century to the present day has increased by more than 1°C (Fig. 5.5). Similarly Miętus (1996) has also detected a statistically significant rise in temperature for the period from 1836 to 1990 for the Baltic coast (see also Fig. 5.5). From this Figure it is evident that there is a good correspondence between the Warsaw and Baltic coast series. The areally averaged annual temperature for Poland as a

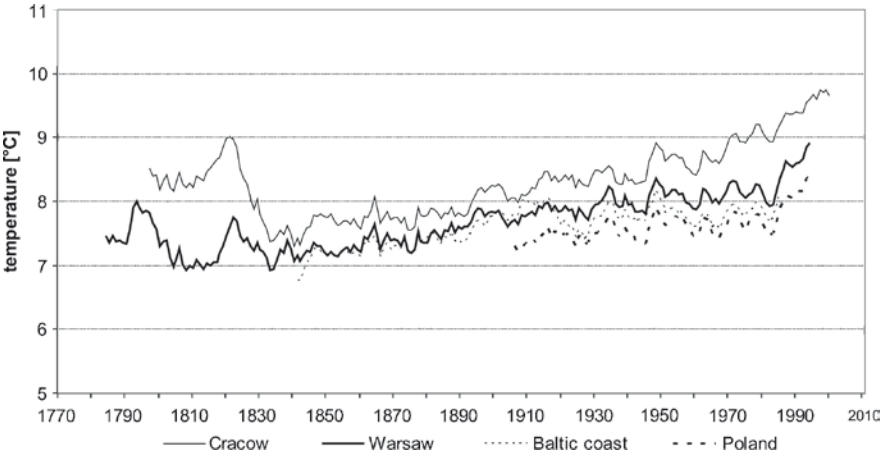

Fig. 5.5 Long-term courses of 11-year running mean annual air temperatures in Poland during a period of instrumental observations. Key: Data for Cracow after Trepińska (1971) and Matuszko (2007d, ed.), for Warsaw after Lorenc (2000), for the Baltic coast after Miętus (1996), and for Poland as a whole (after Żmudzka 2008)

whole reveals a similar statistically significant increase (by 0.89°C) from 1901 to 2000 (Kożuchowski and Żmudzka 2003). These authors calculated that the Warsaw and Cracow series are closely correlated with the areally averaged temperature for Poland (in both cases correlation coefficients for the period 1951–2000 amount to 0.99). Thus data from both of these stations reliably represent temperature changes in Poland (with the exception of the southern mountainous part of the country). The greatest rises in temperature in Warsaw and Cracow clearly occurred in winter (by more than 2°C) and in spring (by about 1.5°C). The Baltic coast shows a comparable temperature increase in winter, while in spring the rate of increase was about half of that for Warsaw and Cracow. On the other hand, out of all of the series analysed, the Baltic coast experienced the greatest increase in air temperature in autumn (Fig. 5.6). The rise in temperature slightly exceeds 2°C and was only a little smaller than in winter (Miętus 1996). Upward trends in areally averaged seasonal temperatures for the whole of Poland can also be clearly seen throughout the twentieth century (see Fig. 5.6). Seasonal trends for all of these sites are statistically significant, with the exception of summer in Warsaw, Cracow and the Baltic coast, and winter for the whole country. Thus, the climate in Poland in both the eighteenth and nineteenth centuries was more continental than it is today.

Lorenc (2000) distinguished four different periods in the Warsaw temperature series: 1779–1800, 1801–1889, 1890–1980 and 1981–1998 (certain thermal characteristics of the last period are still observable, see Figs. 5.5 and 5.6). The first period was very warm, with a maximum decade temperature of 7.8°C in the years 1791–1800. The second period was the coldest one in the history of temperature observations in Warsaw. The coldest decade was 1811–1820 (7.0°C). It was during this period that the coldest year – 1829 – was noted, with an average temperature of only 4.7°C. A downward trend in temperature was observed in Warsaw up to 1890, and since then an increase in air temperature has been evident (particularly in winter), with significant amplification after 1980.

Generally speaking, time changes of extreme temperatures in the period in question are similar to those noted for mean temperatures. However, because the homogenised series of extreme temperatures are shorter (e.g. from 1836 for Cracow and from 1897 for Warsaw) and because their starting points are in a cold period, their calculated trends are higher than for mean temperatures. For the common period of homogenised data available for Warsaw and Cracow (1897–2002), Lorenc (2007) has detected positive trends for all months, seasons and for the year as a whole (see also Figs. 5.7, 5.8, and 20.1 in Piotrowicz 2009, this volume). Annual average extreme temperatures increased during this period at a rate of 1.5°C/100 years (with the exception of the minimum temperature for Cracow, which rose by 1.7°C/100 years). In the case of the maximum temperature, the greatest increases occurred in spring (up to 2°C/100 years) and summer (1.6°C/100 years), while the lowest were in autumn (about 1°C/100 years). On the other hand, the greatest rise in minimum temperature was in autumn (in Warsaw and Cracow 1.6°C/100 years and 1.9°C/100 years, respectively) while the lowest was in summer (about 1.5°C/100 years in both cities). The two series, as Lorenc (2007) shows, are closely correlated. Correlation coefficients for all seasons (except summer for minimum temperature) and for the year as a whole even exceed 0.9. Thus, these two series reliably represent

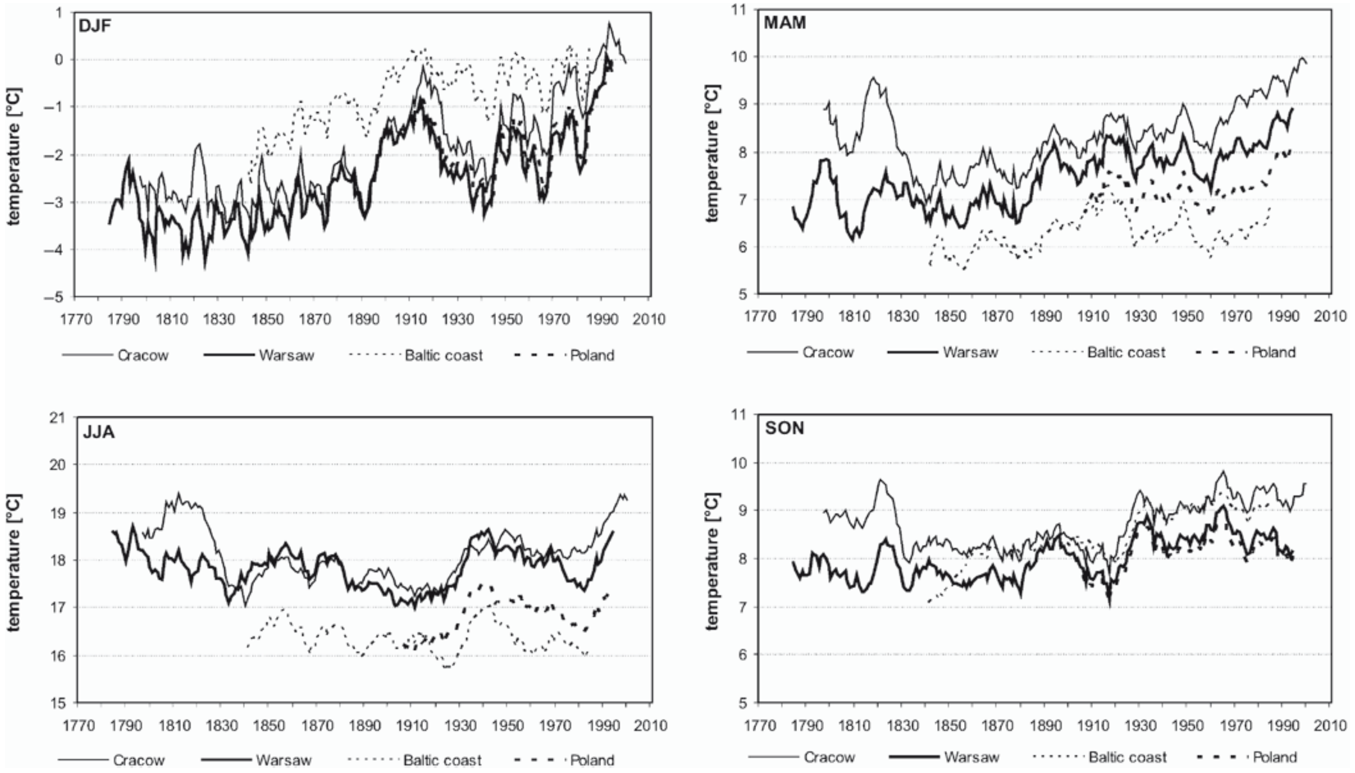

Fig. 5.6 Long-term courses of 11-year running mean seasonal air temperatures in Poland during a period of instrumental observations. Key: DJF – winter, MAM- spring, etc. Other explanations as in Fig. 5.5

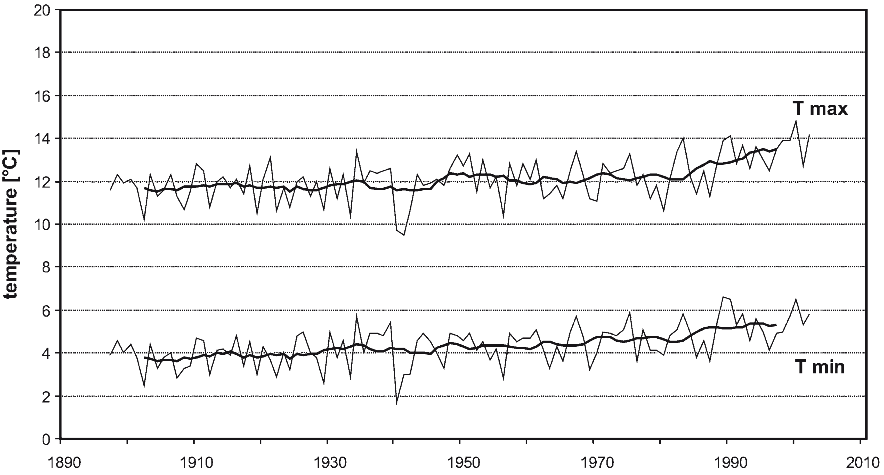

Fig. 5.7 Long-term courses of mean annual extreme air temperatures in Warsaw, 1893–2002 (based on data published in Lorenc 2007). Key: *solid line* – year-to-year courses, *bold line* – 11-year running mean

temperature changes at least for the central and southern parts of Poland. Piotrowicz (2009, this volume) analyses in detail the whole period of the Cracow series (1836–2007). Mainly due to the difference in the starting points (1897 and 1836) of both the analysed series, the trends calculated for the period 1836–2007 are smaller than for the period 1897–2002. For example, annual trends for maximum and minimum temperatures decreased to 1.0°C/100 years and 1.48°C/100 years respectively. Differences are also noted in the pattern of trend changes for the seasons. In the study period the greatest positive trends occurred in winter (1.79°C/100 years and 2.25°C/100 years for maximum and minimum temperatures respectively) and in spring (1.38°C/100 years and 1.48°C/100 years), while the lowest were for summer (0.17°C/100 years and 0.96°C/100 years). All trends are statistically significant at the level of 0.05 (except for the maximum temperature in summer). Wibig and Głowicki (2002) have analysed the problem for more stations, though these have shorter series of data limited to the twentieth century, and particularly from around 1950 onwards. The majority of the calculated trends are positive, and this feature is very well observed mainly in winter and spring and for the year as a whole. Minimum temperature clearly shows the greatest rise in comparison to maximum temperature. The latter even experienced a decrease in some of the sites analysed by the authors. As a result of this asymmetry, they found a statistically significant decrease in the mean annual diurnal temperature range for all the sites analysed, with a rate close to 0.06°C/decade. The strongest statistically significant decreases occurred in autumn and spring. They also found statistically significant decreases in the frequency of occurrence of cold days (minimum temperature below 0°C) and statistically significant increases in the frequency of occurrence of warm days (maximum temperature above 20°C) in the twentieth century. The rate of changes of the

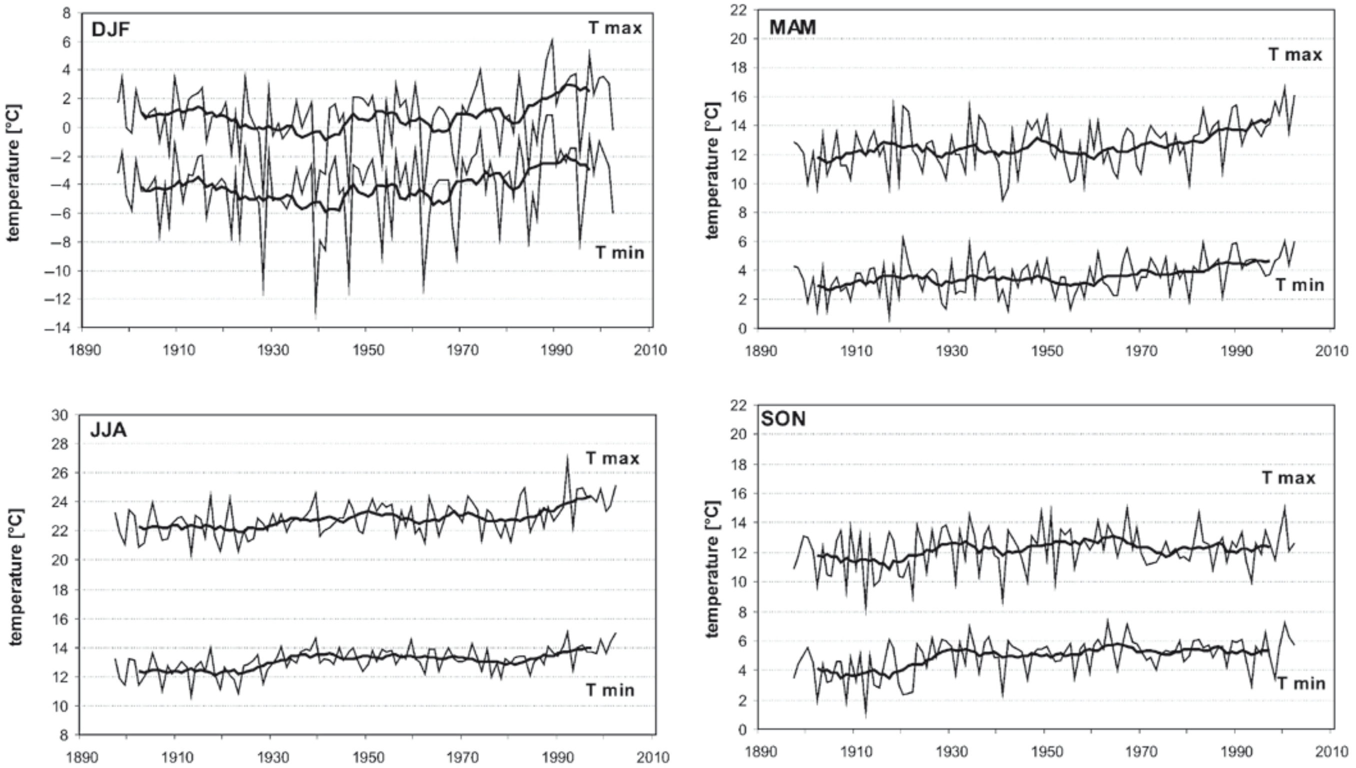

Fig. 5.8 Long-term courses of mean seasonal extreme air temperatures in Warsaw, 1893–2002 (based on data published in Lorenc 2007). Key: DJF – winter, MAM- spring, etc. Other explanations as in Fig. 5.7

temperature characteristics they investigated intensified markedly in the second half of the twentieth century, particularly after 1980.

5.3.2 Atmospheric Precipitation

Temporal and spatial changes of atmospheric precipitation are the greatest out of all the meteorological variables. Frequent fluctuations and abrupt changes in tendencies are common phenomena. As a result, the magnitude of the linear precipitation trends (and even their sign) strongly depends on the sites of the series as well as the starting and ending points. This fact should be taken into account when considering the results presented here. The majority of the papers which analyse the long-term changes in precipitation in Poland focus on small areas or even on one site in particular (e.g. Gorczyński 1912; Trepińska 1969; Hohendorf 1970; Kożuchowski 1985b; Twardosz 1999, 2007; Twardosz and Niedźwiedź 2001; Filipiak 2007b). However, there are also quite a large number of papers dealing with the whole of Poland or some of its regions (e.g. Kaczorowska 1962; Kożuchowski 1985a; Miętus 1996; Kożuchowski and Żmudzka 2003; Twardosz and Cebulska 2009, this volume).

The longest homogeneous series of precipitation from the area of Poland is available for Cracow. The seasonal and annual totals of precipitation for the period 1812–1900 are presented in Figs. 23.6 and 23.7 in Twardosz and Cebulska (2009, this volume), and a continuation of these series to 2007 is shown in Figs. 5.9 and 5.10. The first reconstructed part of series (up to the end of the 1820s), based on the available number of days with precipitation, does not seem to be entirely reliable. If we exclude

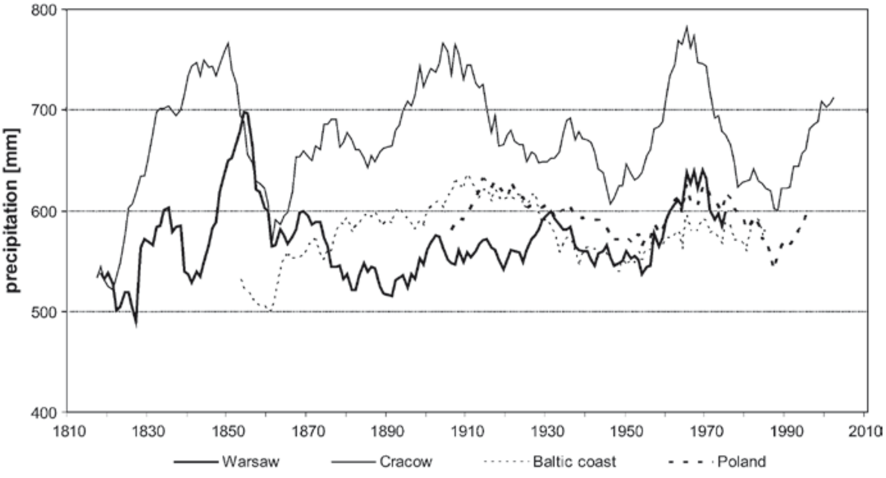

Fig. 5.9 Long-term courses of 11-year running mean annual precipitation in Poland during a period of instrumental observations. Key: Data for Warsaw after Kożuchowski (1990, ed.), for Cracow after Twardosz (1999, updated), for the Baltic coast after Miętus (1996), and for Poland (after Kożuchowski and Żmudzka 2003)

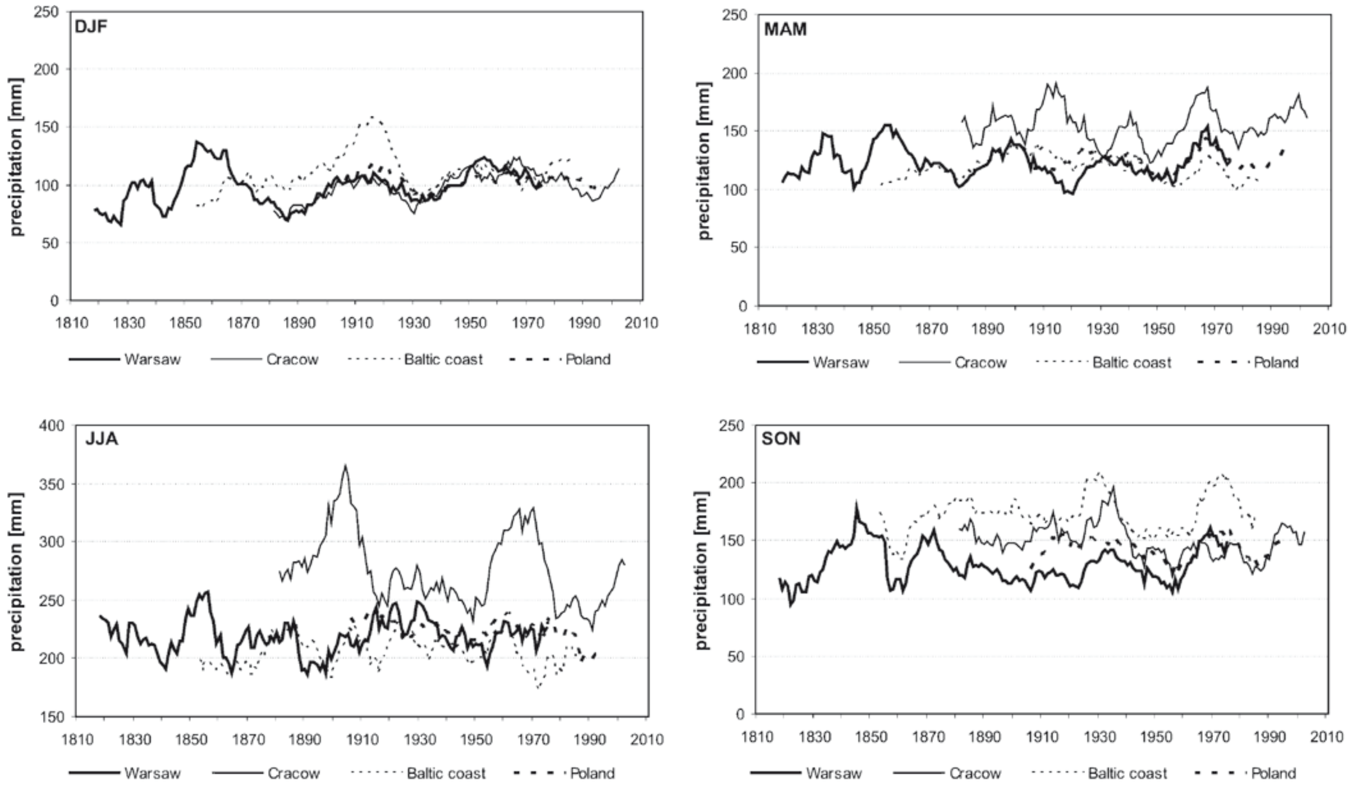

Fig. 5.10 Long-term courses of 11-year running mean seasonal precipitation in Poland during a period of instrumental observations. Key: DJF – winter, MAM- spring, etc. Other explanations as in Fig. 5.9, except for the Cracow station for which data were taken from Kożuchowski (1990, ed.) and Twardosz (2007, updated)

this part, then the annual precipitation totals in the nineteenth century show only small and insignificant changes. There was a wet period noted in all seasons from the 1830s to 1850s and then significantly lower precipitation amounts were recorded almost to the end of the century. At the turn of nineteenth and twentieth centuries there was another wet period ending in 1919 (Figs. 5.9 and 5.10). The next periods with above normal annual precipitation totals occurred from 1960 to 1972 and from 1996 onwards (Twardosz 2007; see also Fig. 5.9). The linear trends calculated for different sub-periods of the Cracow series are insignificant and unstable with respect to sign. For example, Kaczorowska (1962) obtained a positive trend in annual precipitation totals for the period 1851–1958 (20 mm/100 years), while Kożuchowski (1985a) noted a negative trend for the period 1881–1980 (−11 mm/100 years). For the whole series (1812–2007) the trend is slightly positive (23 mm/100 years) and is also statistically insignificant. Year-to-year (and long-term mean) changes in seasonal precipitation totals are markedly greatest in summer and lowest in winter (see Fig. 23.7 in Twardosz and Cebulska 2009, this volume, and Fig. 5.10). In the period 1876–2007 (Fig. 5.10), summer and autumn precipitation totals show downward trends, while trends are positive for winter and spring. However, all trends are small and, with the exception of winter, are not statistically significant.

Analysis of the other precipitation series presented in Figs. 5.9 and 5.10 reveals generally the same pattern of changes as in the Cracow series. This is particularly true for the series representing the Baltic coast and the whole of Poland. The correlation coefficients vary from 0.6 to 0.8 between the areally averaged precipitation series shown in Fig. 5.9 and the series from Polish stations calculated on the basis of data from the period 1951–2000 (see Fig. 3 in Kożuchowski and Żmudzka 2003). Seasonal and annual precipitation series in Poland are mainly characterised by short-term oscillations of between 2 and 4 years (Kożuchowski 1985a; Miętus 1996; Kożuchowski and Żmudzka 2003). The results presented in Figs. 5.9 and 5.10 and in the cited papers show that long-term trends in precipitation in Poland have so far been insignificant.

5.3.3 *Other Variables*

The long-term history of cloudiness changes in Poland can best be described using data from the Astronomical Observatory in Cracow. Żmudzka (2003) found that the series of areally averaged cloudiness for Poland in period 1951–2000 correlates strongly with data from particular stations located in lowland parts of the country (correlation coefficients vary from 0.7 in north-east Poland to more than 0.9 in central Poland). As was mentioned earlier, the Cracow series is the longest, and has recently been reconstructed and homogenised back to 1826 (Lewik et al. 2009, this volume). Many papers have provided various long-term analyses of different aspects of cloudiness in Cracow (e.g. Morawska 1963; Morawska-Horawska 1984, 1985, 2002; Matuszko 2001, 2003, 2007a, b; Lewik et al. 2009, this volume). The paper by Lewik et al. also provides a detailed description of the series and thus, only the main findings will be given here. The authors found a small increase in cloudiness for the entire series (see their Fig. 15.1), which, however, is statistically significant at a confidence level of 0.05. On the other hand, in the last 50 years there has been a dramatic statistically significant decrease in cloudiness. This decrease is also significant throughout the whole of the twentieth century (Matuszko 2007b). The highest values of cloudiness occurred in the periods 1826–1846 and 1926–1966, while the lowest were in the periods 1846–1858 and 1983–1995. The course of cloudiness in the twentieth century (and especially from around 1950 onwards) exhibits a significantly greater variability than in the nineteenth century. In two long-term observation sites located in mountainous areas of Poland (Śnieżka 1885–1995; Zakopane 1906–1990) the trends of both seasonal and annual values are upward and are statistically significant (Dubicka 1999; Limanówka and Ustrnul 2002). The greatest upward trends were noted in autumn in Śnieżka, and in summer in Zakopane. Recently, Żmudzka (2003) calculated monthly, seasonal, and annual areally averaged values of cloudiness for Poland (excluding mountainous regions) for the period 1951–2000. In all seasons (with the exception of autumn), and for the year as a whole, trends in cloudiness are downward and are not statistically significant. Positive trends, also not statistically significant, occurred only in three months: March, June, and September (see Table 1 in Żmudzka 2003). Thus, the Polish mountain areas reveal an opposite tendency in long-term cloudiness to that exhibited by lowland parts of Poland.

There are a few stations which have a long-term and homogeneous series of sunshine duration in Poland (Cracow, Wrocław, Warsaw, and Puławy). As was mentioned earlier, the longest series is available for Cracow, consisting of a reconstructed part (1826–1883) and of an observed part (1883-present). The changes in this variable for the period in question are described in detail in the paper referred to earlier by Lewik et al. (2009, this volume). From their Fig. 15.5 it is evident that in the nineteenth century the changes in sunshine duration were very small and there was no trend. On the other hand, in the twentieth century a downward trend is well expressed and is statistically significant at the level of 0.05 (Matuszko 2007c). The downward trend is also seen for the whole series, though it is not statistically significant. In the other stations discussed the trends are similar to those in Cracow. In each series a downward trend is observed up to about 1980 and then a small increase in sunshine duration is seen (Górski and Górska 2000; Podogrocki 2002; Bryś and Bryś 2007). There is only one long-term series of global solar radiation dating back to the nineteenth century (Wrocław) (Bryś and Bryś 2007). This series shows a statistically significant negative trend in the incoming solar radiation in the period 1875–2004. After 1980 an increased trend in global solar radiation is observable. For the period 1961–1995 similar tendencies were also observed in other Polish stations (Gdynia, Kołobrzeg, Suwałki, Mikołajki, Warsaw, Zakopane, and Kasprowy Wierch), that is decreasing to 1980 and then increasing (Bogdańska and Podogrocki 2000).

In addition to incoming solar radiation data, information about atmospheric pressure is also very important in climatic change research, particularly for the description of atmospheric circulation. While there are long series of observations of this variable available for Poland, the only homogeneous series available are for Warsaw (Ustrnul and Czekierda 2000) and Cracow (Trepińska 1988, 1997c, 2007). The Cracow series has been analysed in detail by Janina Trepińska in several papers. For example, figures presenting average monthly and annual changes in air pressure in the period 1792–1995 can be found in Trepińska (1997c), and for the period 1901–2000 in Trepińska (2007). For the earlier period, in all months (except June) and for the year as a whole, upward trends were observed, though they were not statistically significant. On the other hand, throughout the twentieth century a decreasing tendency was noted (except for March) (Trepińska 2007). According to Trepińska (2007), this means that in the nineteenth century anticyclones prevailed, while in the twentieth century cyclones were more frequent, although anticyclonic pressure patterns still dominated. In Polish conditions, such changes in circulation result in a decreasing degree of climatic continentality from the nineteenth century to the twentieth century. Ustrnul and Czekierda (2000) present an analysis of long-term air pressure series (1826–1999) for Warsaw. For the entire period, a slight positive trend in the mean annual values was observed (almost the same as for Cracow). The authors do not give information about monthly and seasonal changes but, based on the similarity of both of the described series (determination coefficients r^2 varying usually from 0.6 to 0.9, see Figs. 3–14 in Trepińska 1988), we can assume that in Warsaw changes were also insignificant in the majority of months and seasons.

For Poland we have two long-term continuous series of air humidity (for Wrocław and Cracow) dating back to the nineteenth century. However, at present the only reliable homogeneous series of this variable available is for Cracow for the period 1901–2000 (Wypych 2007). Three periods within the twentieth century can be distinguished in the series presenting average annual values of relative humidity (Fig. 5.11): 1901–1930 (slight rising tendency), 1931–1955 (no trend), and 1956–2000 (significant downward tendency). During the period as a whole a statistically significant downward trend is observed. Roughly speaking, seasonal patterns of changes are similar to those described for the annual values (Fig. 5.11). The negative trends in spring and summer are half those for autumn and winter. However, all these trends are statistically significant. On the other hand, saturation deficit shows a positive trend, in particular in the last four decades (Wypych 2007).

5.4 Conclusions

Results presented in this chapter show that the instrumental history of observations in Poland is one of the longest in the world and that some of the available sources of data have either not been analysed at all or only partially. Thus, the improvement of our knowledge about climate changes in Poland in recent centuries is still possible. The mean annual temperatures for the periods 1779–1998 (Warsaw) and 1792–1995 (Cracow) show upward statistically significant trends reaching 0.55°C and 0.52°C per 100 years, respectively. The areally averaged annual temperature for Poland as a whole reveals a statistically significant increase (by 0.89°C) from 1901 to 2000. On the other hand, long-term trends in precipitation and atmospheric pressure in Poland have been insignificant. In the twentieth century decreasing statistically significant trends were observed in Poland for relative air humidity, cloudiness, sunshine duration and incoming solar radiation.

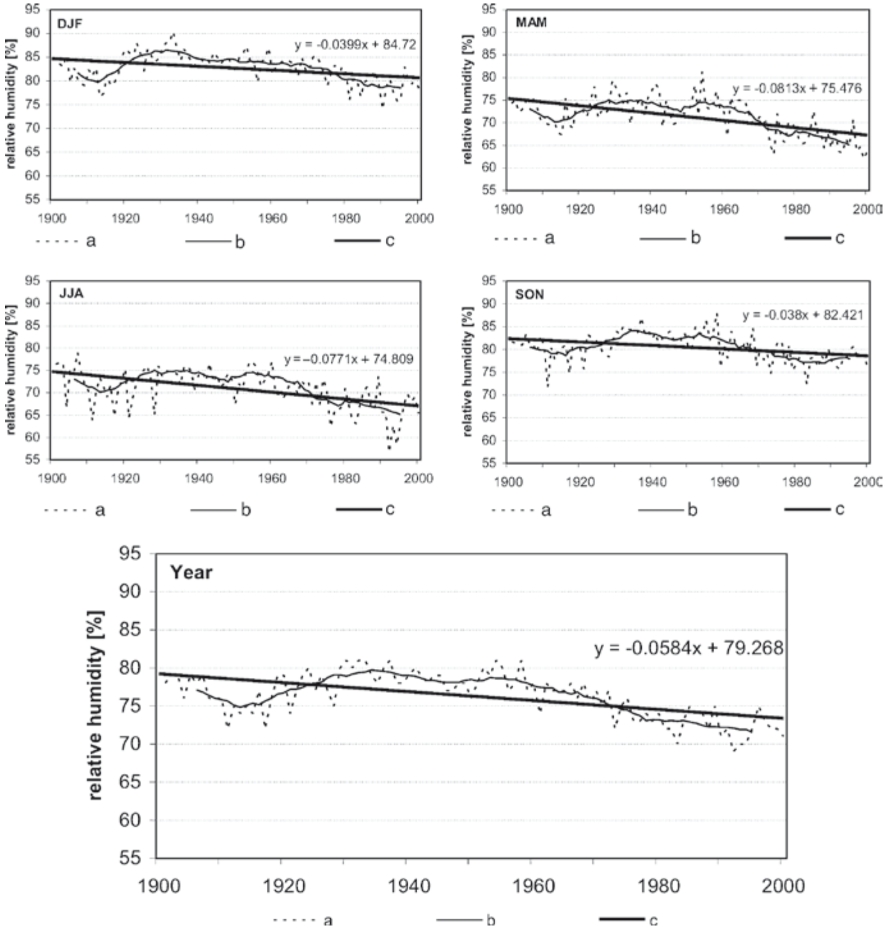

Fig. 5.11 Long-term courses of mean annual and seasonal relative air humidity in Cracow, 1901–2000 (based on data published in Wypych 2007). Key: DJF – winter, MAM- spring, etc.; a – year-to-year course, b – 11-year running mean, c – linear trend

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Chapter 6
Documentary Evidence

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6.1 Introduction

Historical climatology is a scientific discipline which has been developing rapidly in recent years (Brázdil et al. 2005). Learning about the climate's natural changeability is of key importance and it can be done in the most precise and reliable manner by analyzing the last millennium. At present we have many climate reconstructions based on documentary and natural proxy data for selected regions of the world (e.g. Pfister 1999; Rácz 1999; Proctor et al. 2000; Glaser 2001, 2008; Brázdil 2002; Briffa et al. 2002a, b; Luterbacher et al. 2004; Xoplaki et al. 2005; Büntgen et al. 2006; Pauling et al. 2006; Dobrovolný et al. 2008), as well as for the Northern Hemisphere and the earth as a whole (e.g. Mann et al. 1998, 1999; Jones et al. 2001; McIntyre and McKitrick 2003; Moberg et al. 2005; Juckes et al. 2007; Mann et al. 2008). Our knowledge of the climate of Poland in the last millennium has increased considerably (see for instance Michalczewski 1981; Maruszczak 1988, 1991; Sadowski 1991; Paczos 1993; Wójcik et al. 1999, 2000; Bokwa et al. 2001; Limanówka 2001; Majorowicz et al. 2001, 2004; Przybylak et al. 2001, 2003, 2004, 2005, 2008; Oliński 2002; Kotarba 2004; Nowosad et al. 2007).

The first study of the climatic conditions of Poland in the Middle Ages was conducted by Polaczkówna (1925). Unfortunately, the results of this work were affected by the fact that the sources used were not completely reliable. Another drawback was the uncritical acceptance of Brückner's theory of 35-year climatic cycles, which in the light of subsequent research proved to be false. Semkowicz (1922) pointed out the imperfections of the written sources used during the work on the reconstruction of the climate in the Middle Ages.

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Prior to the Second World War, apart from the research dealing directly with the climate there appeared studies concerning natural disasters, including various meteorological phenomena. Franciszek Bujak started research in this area in 1918, putting forward a research project in the area of economic history (Hoszowski 1960; Bujak 1976). The team he organised collected a considerable amount of data. This information was inconsistent, however, and the usefulness of some of it (for example, concerning famine, plagues, high prices and fires) is limited as far as research on climate change is concerned. Another drawback of this study was that the information about the weather was derived mainly from published sources. Excerpts were published for what was then the area of Poland from sources for the following years: 1450–1586 (Walawender 1932), 1648–1696 (Namaczyńska 1937) and (for Galicia) for the years 1772–1848 (Szewczuk 1937, 1939). The results of the research for the period 1587–1647 were shown only in Werchracki's preliminary report (1938). After the Second World War the material was analysed by Hoszowski, though he failed to publish his findings. The materials for the years 1697–1750 were destroyed during the war (Hoszowski 1960).

After 1945 research on the history of Poland's climate was begun again by both climatologists and historians. On the initiative of the State Institute of Hydrology and Meteorology a catalogue of weather records from the tenth to the sixteenth centuries was created on the basis of sources published and their translations into Polish (Rojecki 1965). Nevertheless, the translation is not perfect, and has recently been criticised by the historian Wnęk (1999). After a heavy drought in Silesia in 1959 an interdisciplinary team was established consisting of the staff of the Higher School of Agriculture in Wrocław and the Chair of Economic and Social History of the University of Wrocław. The team's supervisor was the historian Stefan Inglot and their main aim was to examine the effects of drought on agriculture in Poland. To this end, the historians collected not only materials connected with droughts in Silesia from the sixteenth to the mid-nineteenth centuries, but also all the available information about extreme hydrological and meteorological phenomena (such as rainy years and floods, severe winters, hot summers, etc.). The catalogue of weather information was not published, and the outcomes of the historians' work are known only from Inglot's short reports (Inglot 1962, 1966, 1968).

Malewicz's dissertation (1980) on natural phenomena in Polish medieval historiography is more comprehensive. It comprises not only information about the weather included in the sources analysed, but also questions from the history of science. In the appendix the author included source extracts on the subject of meteorological and astronomical phenomena. Malewicz's research was heavily criticised by the historian Derwich (1984), who reproached him for numerous mistakes in the chronology of records and the incompleteness of preliminary source research.

Within the scope of this brief review, it is worth mentioning the work of Górski (1965), who emphasised the usefulness of historical sources for examining climatic changes in Poland, and the study by Dunin-Wąsowicz (1974) which analysed the relationship between afforestation, water relations and settlements in the Middle Ages. There were also many studies devoted to the research into elemental disasters, in which the climate was not always present (see for example Stamirski 1962;

Kwak 1987; Ratajczak 1987, 1991; Motylewicz 1993). Yet all these studies referring to the reconstruction of Poland's climate on the basis of historical sources fail to include conclusions of a climatological nature or detailed analyses of climatic fluctuations.

This research direction becomes visible in the works of Maruszczak (1988, 1991), who presented a thorough description of temperature and humidity conditions in Poland in the last millennium. He estimated the average temperature of the subsequent 50-year periods on the basis of changes in temperature in the higher latitudes of the Northern Hemisphere and of palynological data, taking into account the correction resulting from the analysis of the prices of vegetable groceries. It must be noted however that in this hemisphere there was considerable regional diversity of tendencies relating to climate change in the periods from 50–100 years. Thus drawing conclusions about the value of elements of Poland's climate on the basis of data from places which are quite distant from each other (Great Britain, California, Greenland) may be misleading. One of the few Polish attempts to deal with the climatological interpretation of records exclusively from historical sources are studies by Sadowski (1986, 1991). They include among others the list of famine disasters in Poland in relation to climatic phenomena (rainy, dry and cold summers) from the period 1351–1750 as well as the frequency of severe winters and hot summers in individual decades starting from the thirteenth century.

At the end of this review one must mention the most recent research (Limanówka 2001; Bokwa et al. 2001; Nowosad et al. 2007; Przybylak et al. 2008), which analyzes climatic conditions in Poland in selected short periods from the sixteenth century (1502–1540) and seventeenth century (1656–1685) on the basis of records of weather conditions written by professors of the Academy of Cracow (in particular by Marcin Biem) and the voivode Jan Antoni Chrapowicki.

Studies describing the history of the development of meteorology, including the oldest meteorological observations in Poland, constitute a separate category (see for example Parczewski 1948a, b; Rojecki 1956, 1965; Staszewski 1966; Hanik 1972; Michalczewski 1979, 1988; Marciniak 1990; Miętus et al. 1994; Lorenc 1996, 2000; Wnęk 1999; Limanówka 2001).

As can be concluded from the survey, research on the modern climate in the historical area of Poland, based on documentary evidence, was not very common in the twentieth century, unlike in other parts of Europe and the world (for more details see Brázdil et al. 2005). Lack of interest in such research was the result of skepticism about the possibility of using historical sources in climate research, the final outcome of which, it was thought, should be clear-cut statistical results, enabling easy comparison between regions. This concerned mainly the Middle Ages and the early modern period (Semkowicz 1922). Undoubtedly, the skepticism was excessive, though its positive effect was that it showed limitations connected with obtaining data from historical sources.

It was not until the end of the twentieth century that research on the climate in Poland in the last millennium began to flourish. Earlier statements on this subject were quite general. Historians and geographers claimed that in from the medieval times on the climate was more humid and cooler on account of substantial forestation and a bigger amount of precipitation (Smolka 1881). There were opponents of this thesis who maintained that the humidity of the climate was rising as it had been much drier earlier, while others believed that the climate had not changed in Poland in historical times except some temporary fluctuations (Semkowicz 1922). Obviously statements of this kind were not based on extensive source research and analytical examination. The popularity of the research of Edward Brückner conducted at the beginning of the twentieth century and proving the existence of 35 year periods of climate fluctuations was continued in research on the Polish climate (Polaczkówna 1925).

The growing popularity of climate research in Poland is a reaction to the many gaps in our knowledge on the subject in this part of Europe, particularly with reference to the Middle Ages and modern times. Research is facilitated by methods which enable at least partial check of information included in historical sources. The check is possible thanks to the instrumental data provided by other fields of research, in particular in biology and geography, and better methods of evaluating the usefulness of historical sources in climate research. Also of major importance is the creation of various marking scales which enable comparison of data based on historical sources for different regions (Pfister 1999; Brázdil et al. 2005). Nevertheless, the basic problem was and is the precise transformation of source information into numerical data based on historical narratives. The methods used here are still not perfect, though they allow us to obtain relatively precise data and, more importantly, they help to define the existing research possibilities and limitations which cannot be ignored. A growing number of written sources, including both climate records as well as similar studies concerning other regions of Europe, facilitate climate research and enable us to make comparisons and to draw conclusions.

6.2 Documentary Sources – Kinds and Quality

Polish sources from the fifteenth century to the end of the eighteenth century are specific. Unlike in many other regions, data concerning the viticulture (such as in France, Guyot and Godet 1935; Lachiver 1991) did not survive. Economic data concerning corn crops are imperfect too. Taxes paid by villages and individual farms are recorded, though these reflect neither the time nor the amounts harvested – factors which in many regions enabled the examination of climatic fluctuations (see for example Pejml 1966; Pfister 1979; Brázdil and Kotyza 2000). Some information can be provided by data concerning fluctuations in the prices of corn in comparison with data referring to the amounts of corn which were harvested (e.g. for Gdańsk, the most important harbor for corn exports from Poland, see Pelc 1937). Changes in prices may result from different factors, not always connected with the amount of crop (e.g. Brázdil and Durďáková 2000). Hence, the price index cannot be conclusive for the evaluation of conditions of corn growth and weather conditions. While such research will certainly be useful in climate reconstruction, this field still requires much work in the future. At present, narrative sources prove to be the most useful, such as chronicles, diaries, individual records, records including daily comments on the weather, and correspondence. Their major drawback is their subjective character, which makes it more difficult to transform them into numerical data. Moreover, instrumental data based on permanent observations and expressed numerically were preserved for periods in the eighteenth century (cf. Chapter 5).

Sources including systematic information for longer chronological periods are particularly important. They allow us to learn more about the language employed by the author, to define the magnitude of the meteorological phenomena which they describe and to provide a comparative description of the weather during a longer period of time.

The following kinds of sources were analysed:

1. Narrative sources – yearbooks, chronicles (political, monastic, parish, home, and school chronicles), diaries and memoirs, descriptions of journeys and trips, military expeditions and diplomatic missions. Such sources frequently included general descriptions of seasons of the year and were quite reliable. They were created either directly after the events they described or some time later. In the second case they were written from memory or were based on earlier records. In each case, critical source research was conducted in order to specify such questions as the period of time which passed from a given weather phenomenon to the moment of recording it, the location of a given weather phenomenon in relation to the place where the phenomenon was recorded, the source of information of the author, the reliability of the source, etc.
2. Daily weather records. The overwhelming number of weather records in some sources allow us to regard them as "weather chronicles" (excerpts from historical sources). The best known source of this kind is the diary of the Voivode of Vitebsk Province Jan Antoni Chrapowicki written in the second half of the seventeenth century (Nowosad et al. 2007). Other examples are notes of professors from Cracow from the sixteenth century, particularly those of Marcin Biem (Limanówka 2001). Apart from diaries, calendars were also taken into consideration. Their owners used to write in empty spaces their comments about interesting events, many of which were meteorological. The value of sources of this type is high, provided the owner of the calendar or his address can be indisputably identified and that we have long and complete descriptions for one particular place.
3. Correspondence. The problem which the use of correspondence raises is the selection of collections of letters to research. Sensitivity to weather conditions was a personal feature of individual writers. Having found a writer who met the requirements, researchers began seeking out collections of his letters. Appropriate letter writers were found among numerous sources – agents of the royal courts and clients of powerful dignitaries, or co-workers of special agencies established in Europe with the aim of providing information. Another group constituted letters of farm officials to their superiors or farm owners. One example of correspondence which includes weather data are the letters of Michał Dorengowski to the Radziwiłł family kept in the Central Archives of Historical Records in Warsaw, or the letters of Anzelm-Piarist, officer of Sapieha, starost of Merkinė to his

principal in the Library of the Lithuanian Academy of Sciences in Vilnius. Longer series of correspondence can be found for the eighteenth century, when writing skills and, in particular, the habit of writing down one's emotions, stopped being the privilege of the rich.

4. Manuscript and printed materials recording meteorological phenomena in chronicles of events, where special coverage was given to extreme cases (for example data for the years 1760–1767 in *Thornische Wöchentliche Nachrichten* and separate articles about some meteorological phenomena in this magazine).
5. Official files: documents (for example tax exemptions due to floods), inspection and inventory protocols, tax registers, official books (informing for example the closing down of offices during a flood or plague, but also including testimonies of witnesses), resolutions of parliament and regional assemblies, reports and protocols from meetings of collegial bodies, official statistics, directives and official reports. These provide some data, though the information is scattered and scarce. Moreover, they inform us about events which took place in the time which is hard to define. In cases where the basic sources of information are derived from reports of eye-witnesses, it must also be remembered that these individuals' accounts should not necessarily be taken at face value; it is always possible that such reports may have exaggerated the magnitude of the phenomena for the personal ends of those reporting them. Research done by Fr. Józef Nowacki is of particular value. He collected historical records from the archives of the Poznań diocese, many of which are of considerable climatological interest.
6. Economic sources, particularly bills.
7. Epigraphic sources (for example records about the flooding of the river at the Bridge Gate (*Brama Mostowa*) of the Old Town in Toruń).

6.2.1 The Middle Ages

The medieval period seems the most difficult with regard to doing such research due to the smaller number of sources available. Estimates as to how many extant sources are available for climate reconstruction vary between 200 to nearly 300 (Walawender 1932, though only from the second half of the fifteenth century; Rojecki 1965; Malewicz 1980). Excerpts referring to weather in Poland, particularly Silesia, found in foreign literature, are not numerous (Alexander 1987). The number of references collected by Polish researchers is incomplete, and it remains highly probably that new sources of data from the Middle Ages and later periods will emerge (Derwich 1984). It seems that potentially there may be up to a 1,000 notes concerning the weather, covering 70–80% of the period of the Middle Ages. Needless to say, the quality and information value of the source data will vary. They are very often dependent on each other and represent different interpretations of the same event. The characteristic feature of medieval records is that they comment on weather phenomena as if these phenomena had concerned the whole kingdom.

As a result, it is hard to draw more precise conclusions about the weather conditions in different regions. On the other hand, individual regional records do not allow us to make generalizations on the subject of the weather over a larger area. Descriptions of individual extreme events such as storms or hails, which led to destruction, are less important – naturally they concentrate on the particular place where the record was being made.

Roczniki written by Jan Długosz must be considered one of the most essential sources. It was the subject of a study by Polaczkówna (1925), who used records for almost 200 individual years from the period from the tenth century to the end of the fifteenth century, which she presented statistically. However, the study was based on the theory of Brückner, accepted *a priori*, and referred to the cyclical repetition of climatic periods, which affected the results and conclusions (Polaczkówna 1925). Gaps in data for many years resulted in imprecise conclusions. Undoubtedly, the source data needs to be reinterpreted, taking into account information from other sources. More attention should be paid to the analysis of the sources of individual records (Semkowicz 1922). Długosz used many other sources, in particular with reference to earlier centuries and many of these sources have survived (Semkowicz 1887; Zonenberg 2000). Historians' efforts should now be directed at the critical evaluation of the information acquired. Meanwhile, Długosz's records should be interpreted taking into consideration events in his life. Perhaps it might be useful to consider some differences resulting from his age: at different stages in his life he displayed varying degrees of sensitivity to temperature and humidity. Nevertheless, research of this kind remains a task for the future.

6.2.2 The Sixteenth Century

The last two decades of the fifteenth century and the sixteenth century as a whole brought a change in the quality of the sources. Academics at the University of Cracow began to keep systematic records of general meteorological phenomena, (not only extreme events). The significance of this development is even greater when one takes into account the fact that the sixteenth century was a period of substantial climatic changes (Pfister and Brázdil 1999). The records are written very straightforwardly and can easily be transformed into numerical data. However, their drawback is their lack of accuracy. The observations made by Marcin Biem (died 1540) for the years 1499–1531 and 1534–1540, included in *Almanach nova* by Johannes Stöffler and *Ephemerides* by Lucas Gaurricus, are of major significance. A number of writers kept records of this kind for longer periods, including Bernard of Biskupie for the years 1515–1531, Mikołaj Sokolnicki for the years 1521–1531, Michał of Wiślica for the years 1534–1550, and many others. The records were made on pages of different copies of Stöffler's *Almanach nova*, and on pages of another book by the same author, *Ephemeridum opus*. These are very often daily records, and altogether there are almost 13,000 of them. They have been studied in detail by Limanówka (2001). Outside Cracow it is difficult to find such rich meteorological information for the sixteenth century. Records referring to the weather in the sixteenth century are included in chronicles of Miechowita, Wapowski, and the diaries of Heinrich Wolff (for the times of Henry of Valois). Later sources describing the sixteenth century also deserve to be mentioned, such as the chronicle of Łochowski Mayor of Bydgoszcz, which was written up to 1637, and the Lvov and Ostrów yearbooks covering the same period and describing the eastern part of Poland (Bewzo 1970). In total, apart from the Cracow sources approximately 800 other records have been found.

6.2.3 The Seventeenth Century

The first half of the seventeenth century was not as prolific in weather records as was the sixteenth century and the second half of the seventeenth century. Apart from the above mentioned chronicles of Łochowski and the Lvov and Ostrów yearbooks, the following constitute important sources: diaries of Albrycht Stanisław Radziwiłł from the years 1632–1656 (Przyboś and Żelewski 1980), the chronicle of Joachim Jerlicz from the years 1612–1668 (Wójcicki ed. 1853) and the diary of Stanisław Oświęcim from the years 1643–1651 (Czermak ed. 1907). The number of records included in those sources does not exceed several dozen. The remaining diaries from the first half of the seventeenth century included even less information. In the second half of the seventeenth century numerous records can be found in Chrapowicki's diaries, written in the period 1656–1685. These are daily records, sometimes made even a few times a day. Rarely did he give weather information for longer periods. Usually they refer to temperatures, precipitation and winds and, in total, there are about between ten and 20,000 of them. Their drawback is that they refer to different and sometimes remote areas which happened to be on the journeys made by Chrapowicki. The records deal with Polish regions – Masovia, the Białystok region, and Podlasie – as well as with Lithuania, Belarus and even Russian areas such as the regions of Vitebsk and Smolensk. Another problem is that the second part of Chrapowicki's original manuscript is missing, and the diary is known exclusively from copies. Transcriptions made in the eighteenth and nineteenth centuries were not precise as copyists tended to omit weather records or to reduce them, concentrating on other areas of life described by the author (Nowosad et al. 2007).

Besides Chrapowicki's diary other sources known for this period include the printed calendars of Fryderyk Buethner, professor of mathematics in the Gdańsk gymnasium. Despite the fact that they fail to provide actual weather information (they are a printed forecast of the weather for subsequent days of the year based on astronomical research) short notes about actual weather conditions are included in the marginalia (Miętus 2007). A modest complement to the notes of Chrapowicki are other memoirs and diaries from the second half of the seventeenth century written by Werdum (Liske 1876), Łoś (Śreniawa-Szypiowski 2000), Niezabitowski (Sajkowski 1998), and the collection of memoirs of Sarnecki from the end of the seventeenth century (Woliński 1958). The end of the seventeenth century and the first years of the eighteenth century were described thoroughly, on a daily basis, in relation to south-western areas of Poland and south-eastern parts of Germany for the years 1692–1712 by David von Grebner (Grebner 1714). Aside from memoirs, a range of other sources was used where several 100 references of various kinds were found. Some of them such as *The Pelplin Chronicle* or other monastery chronicles included relatively homogeneous data referring to the vegetation periods of plants, times of harvest and weather conditions. The kind of source determined the type and quality of the record. Memoirs, diaries and occasional correspondence provided daily records and were kept systematically. Chronicles recorded complete seasons or years, which might have generated a coincidental picture and led to faulty judgment.

The attempt to gather and compile information about natural disasters for the seventeenth century was undertaken before the Second World War as the continuation of Walawander's research (Namaczyńska 1937). The effect of the research was the compilation of a few hundred records from printed memoirs, taking into consideration information about fires and plagues. Still, there were relatively few weather records, and further verification of the sources used in the project showed that many had been omitted as they had not been in the scope of the project concerning weather disasters. As a result of the research of the last few years (aside from Chrapowicki's records) over 700 weather records of various significance and character have been found. It must be emphasised that their number in the first and second half of the seventeenth century was almost the same. More than 300 records were found for the period from 1600 to 1649, while almost 400 were found for the period 1650–1699. As a consequence of further research we can expect a considerable increase in the number of weather records for this period. As historical sources (including memoirs) have been published with greater intensity lately, there is some hope that access to new historical data will be easier. Nevertheless, sources such as correspondence, calendars or newspapers will not be printed in the immediate future. Consequently, further research in archives and libraries in Poland and elsewhere is indispensable.

6.2.4 The Eighteenth Century

In the eighteenth century instrumental observations were becoming more and more common, and thus this allows us to compare older non-instrumental data against the new more reliable data which allows us to check references to the weather of a non-instrumental nature. In the eighteenth century weather records appeared more and more frequently in memoirs and private chronicles. The sources are characterised by a greater degree of regionalization. References relate mainly to the town or region where a source was created. Two sources from Toruń are typical examples of this kind: the chronicles of Johann Richtsteig, referring to Toruń in the years 1704–1730, and the memoirs of Dawid Brauer for the years 1719–1750. The amount of weather information included in private and official correspondence rose considerably in comparison with earlier periods, though it is largely unpublished and thus mainly to be found in manuscripts. Examples of such sources are the letters of Dorengowski from the years 1740–1741, and the letters of Anzelm-Piarist from the years 1729–1738.

6.2.5 A Concise Typology of Sources for the Period from the Sixteenth to Eighteenth Centuries

In the case of collected sources the biggest problem was the evaluation of the usefulness of information for purposes of climate reconstruction. Reliability was not the only element taken into account. Sometimes, due to the omission of details of some periods or territories, the research was based on data of poorer quality. Data coming from neighboring countries was also used for comparative purposes (e.g. Brázdil and Kotyza 2000; Munzar 2004). Further research in libraries and archives will certainly allow us to check and correct the data for these periods and territories. As was noticed in relation to the Middle Ages, records concern either one-off events, limited to a small territory and a short time period, or descriptions of weather conditions for a larger area and a longer period (a month, season or year). In various periods the proportions between those two basic types of phenomena were different. The usefulness of sources recording one-off events depends on their quantity, while sources recording weather conditions more broadly over a longer period are valuable when there is a scarcity of other data.

Very often the historical records which were collected concerned extreme situations as it was these which diarists and letter-writers thought most worthy of comment. Weather conditions were described in relation to vegetation periods and the influence of the weather on harvests. If a particular meteorological phenomenon took place in a month when it did not affect the vegetation of plants and harvest, there was little chance of it being recorded. The incidental nature of records and the noting down of only extreme phenomena are two dominant features in the data taken from source materials. It also presents us with certain methodological difficulties. If we assume, on the basis of the content analysis of sources, that during periods when no regular weather observations were made only abnormal phenomena were recorded, can we assume that in times and periods not mentioned in a source the weather conditions were average? Such an assumption is justified only in the case of sources for which it is quite probable that extreme phenomena were recorded comprehensively. It reflects the view expressed in the literature that a successful harvest was not recorded as a normal phenomenon because it did not attract attention. A lack of data thus leads us to assume that there was a good or average harvest in a given year (Hoszowski 1960).

A major drawback of the Polish source base is the paucity of sources presenting long-term series for one place. Most of the information we have is scattered among other sources. Hence, the selection of research sources plays a major role. Our experience leads us to opt for collections of daily records (frequently updated diaries and calendars, which we have just started to explore), chronicles and sets of correspondence made by individuals particularly interested in natural phenomena.

6.2.6 Territorial Distribution of Records

As far as the territorial distribution of weather records is concerned, we have about 150 records which cover the whole country, over 1,300 records for Pomerania, 35 records for the Warmia, Masuria and Suwałki region, about 200 for Greater Poland, 5,430 for Masovia, about 500 for Silesia, about 350 for Lesser Poland, 30 for the neighboring countries from the West, and about 5,000 for territories situated beyond the eastern border of Poland (used mainly to reconstruct the weather conditions in Masovia). Chrapowicki's diary results in a disproportionately high number of records for Masovia (with Podlasie) and the regions adjacent to Poland in the vicinity of Podlasie.

6.2.7 Chronological Distribution of Records

Altogether about 13,000 records were collected from over 200 different sources. The chronological distribution of references which were collected is as follows: the sixteenth century – about 750 records (not including the study by Limanówka [2001] which was also used and which comprised over 12,000 pieces of data for Cracow), the seventeenth century – about 11,000 records; the eighteenth century – 1,200 records; the nineteenth century – 35 records. The disproportionately high number of records in the seventeenth century results from the wealth of references to the weather in the diary of Jan Antoni Chrapowicki. This source has already been the subject of climatological analyses, though these studies have only used those parts of the diary which have been published – about 40% of the diary as a whole. We are now also working on including data derived from the diary manuscript. The information was first taken into consideration during the reconstruction of the climate of modern Poland. Poorer quality research from the nineteenth century resulted from the fact that the range and number of sources had not at that stage been analysed. The material collected is of a synthesizing nature (i.e. concerning opinions about seasons of the year), which increases its value.

Almost 300 records refer to the year as a whole; winter and spring get about 3,400 records each; 3,100 records deal with summer; and about 2,800 are related to autumn. Thus a fair distribution of sources between seasons has been achieved.

6.3 History of Poland's Climate in the Last Millennium

Climatic conditions are usually characterised by the use of data from instrumental observations (during last 200–300 years) and from so-called proxy data, which exploit the dependence of various natural phenomena on the climate. For the pre-instrumental period of the last millennium the best sources of information (in terms of precision and trustworthiness) for area of Poland are dendrochronological, documentary and borehole data. The use of research results from other branches of science (e.g. geology, geomorphology, pedology, archaeology, botany etc.) is limited, mainly due to restricted time resolution.

Before discussing the characteristics of the climate of the past millennium, readers should be aware of the fact that proxy data do not enable the reconstruction of all the meteorological variables which are generally used to describe the climate of a given region. In principle, for the greater part of a particular period, only three variables can be reconstructed in a virtually continuous way, though luckily these are the three most important variables: air temperature, ground surface temperature and precipitation. Information about other elements (e.g. wind, cloud cover, atmospheric phenomena) is only contained in historical sources, usually only those that contain daily records. Sources of this type are scarce and cover only a small fragment of the past millennium.

The methods for the reconstruction of these variables are described in detail in a number of recent studies (Przybylak et al. 2001, 2004, 2005; Majorowicz et al. 2001, 2004), and thus they will not be discussed here.

6.3.1 Air Temperature

As was mentioned earlier, air temperature is the meteorological variable for which the most information on changes has been collected in the past several hundred years. It is a well-known fact that it is connected with the very tight interdependency of natural phenomena with air temperature in our geographical latitude. Moreover, there is no doubt that this variable is highly important to life and human activity. Therefore most documentary records which have survived feature examples of extreme air-temperature values. Nevertheless we lack a sufficient volume of information for the credible reconstruction of the air temperatures for the first half of the past millennium (see Rojecki 1965). Furthermore, the credibility of historical records from that period is limited, a problem which was raised as early as 1922 by Semkowicz and which has been confirmed by modern historians (P. Oliński 2008, personal communication). Dendrochronological data available go only as far back as the year 1170 (Zielski 1997; see also Chapter 7). Practically speaking there are virtually no proxy data available on the climate for the first two centuries of the last millennium. Certainly it is possible to attempt to reconstruct the history of air temperature changes for that period on the basis of the data available from other regions, as has been proposed by Maruszczak (1991). However the credibility of such reconstructions is very limited, particularly when data from distant regions such as Great Britain, Greenland and California, are taken into consideration, which, when compared to Poland, often show a different rhythm of air temperature changes (see for instance Fig. 34.2 in Bradley and Jones 1995, where air temperature reconstructions for Europe and North America are presented). The opposition of air temperatures in Europe (including in Poland) and in Greenland (Kosiba 1949) has been known for a long time, particularly for winter; this phenomenon can be very easily explained by the influence of atmospheric circulation described by means of the North Atlantic Oscillation (NAO) index (Hurrell 1995). Bearing these reservations in mind, one can mention that the eleventh century according to Maruszczak (1991) was probably warmer than the norm, and the twelfth century (particularly its last 50 years) was the warmest on record for the whole millennium. The reconstructed average temperature for the months from January to April in the years 1170–1200 was one of the highest, if not the highest (see Fig. 7.15 in Chapter 7). For the years 1201–1500 slightly more information is available, as there has also been a study by Sadowski (1991) that utilises a small number of not very credible historical sources. According to Maruszczak (1991) average annual air temperatures were above the norm in the thirteenth century and in the first half of the fourteenth century, then a cooling followed for about a 100 years and in the second half of the fifteenth century a warming occurred again. According to studies by Sadowski (1991) there were both fewer severe winters and hot summers in the thirteenth century than there were throughout his 800-year study period, which means that this century was characterised by the highest degree of oceanism on the climate (see his Fig. 6). The average temperatures for the January–April period (as seen in Fig. 7.15 in Chapter 7) were relatively high and changed little during this period. Similar temperatures may be noted in the fourteenth century, during which period Sadowski's research (1991) also does not indicate higher air temperature changes. Thus his work cannot confirm the occurrence of climate cooling in the second half of the fourteenth century, as was described by Maruszczak (1991). According to Sadowski, the fifteenth century was characterised by the highest degree of climatic continentality in the study period. In that period, a sudden rise is noted in the number of severe winters, including as many as six in the decade 1451 to 1460. There were also many hot summers (from two to five per decade). Taking into consideration the fact that it is the winter temperature which exerts the greatest influence on the mean annual temperature, it should be noted that the second half of the fifteenth century was cool. This result thus contradicts the evaluation presented by Maruszczak (1991): the reconstructed average air temperatures for the January–April period indicate a somewhat later occurrence of this cooling (by about 20 years) (Fig. 7.15 in Chapter 7).

In summing up the state of our knowledge of air temperature changes in the period from 1001 to 1500, we should note that it is generally very modest and the existing reconstructions are highly unreliable.

A radical improvement in this respect occurs from the sixteenth century onwards. For this period there exist a few successful attempts at reconstructing the air temperature by means of utilising documentary sources (Sadowski 1991; Maruszczak 1991; Przybylak et al. 2004, 2005). Also air temperature reconstructions were published that were based on historical sources with large resolution (daily), but for shorter periods of several years (e.g. Limanówka 2001; Bokwa et al. 2001; Nowosad et al. 2007).

The frequency of occurrence of all extreme events (Table 6.1) in the period 1501–1840 was greatest in the first 150 years. Later they were noted more rarely, especially in the first half of the eighteenth century. Very severe and severe winters (indices −3 and −2, respectively) in the 10-year periods were most frequent in the last decade of the sixteenth century (six winters) and in the decades 1641–1650 and 1731–1740 (five winters in both cases). The fewest such winters occurred in the

Table 6.1 Frequency of occurrence of exceptionally warm and cold winters (DJF) and summers (JJA) in Poland from 1501 to 1840 (after Przybylak et al. 2005)

Period	DJF		JJA		Extreme seasons	
	2 and 3	−2 and −3	2 and 3	−2 and −3	Total	%
1501–1550	**7**	12	2	0	21	15.9
1551–1600	1	**14**	7	0	22	16.7
1601–1650	0	11	**10**	0	21	15.9
1651–1700	4	11	3	1	19	14.4
1701–1750	2	12	1	**3**	18	13.6
1751–1800	1	10	2	0	13	9.9
1801–1840	0	9	7	2	18	13.6
1501–1840	15	79	32	6	132	
%	11.4	59.8	24.3	4.5		100.0

Explanations of the indices (+3, +2, −2, and −3) are given in the text
The highest frequencies of occurrence of the exceptionally warm and cold seasons in 50-year periods are shown in bold

decades 1621–1630, 1631–1640, 1751–1760, 1831–1840, and probably in the period 1701–1720. From the 50-year periods, the second half of the sixteenth century was the richest in very severe and severe winters (14). A large number of such winters (12) also occurred in the first halves of the sixteenth and eighteenth centuries. Sadowski (1991) also obtained quite similar results.

There are significantly fewer historical sources which describe extremely warm and very warm winters (indices +3 and +2, respectively) in comparison with severe winters. However, the results presented in Table 6.1 show that their maximum frequency was in the first half of the sixteenth century (seven) and in the second half of the seventeenth century (four).

Only a third as many notes have been found for summer thermal conditions in comparison with those for winter (Table 6.1). Significantly more excerpts (32) relate to hot (extremely warm) and very warm (indices +3 and +2, respectively) summers than those referring to extremely cold and very cold summers (indices −3 and −2, respectively). The first group of summers occurred with the greatest frequency in the period 1580–1640 and at the beginning of the nineteenth century. Information about the second group of summers has only been found after 1650, with the highest frequency in the first half of the eighteenth century (Table 6.1).

Average 10-year air temperature values in winter (December to February) in the period from 1501–1840 were in all instances lower than those occurring in the twentieth century, and this is also true in the period from 1851 to 1950 (Fig. 1.2 in Luterbacher et al. Chapter 1). On average, the coldest winters occurred in the decade from 1741 to 1750 (the anomaly was −3.6°C). Major anomalies (app. −2.5°C) were recorded in the following decades: 1541–1550, 1571–1580, 1591–1600, 1641–1650, 1651–1660 and 1771–1780. Within the whole study period two long sub-periods can be distinguished when low temperatures persisted in winter (generally with anomalies lower than −1.5°C): 1540–1600 and 1720–1820. Between those two periods, with the exception of the years from 1641 to 1660, winters were distinctly warmer.

The warmest winters were recorded in the first and third decades of the sixteenth century. Brázdil (1996) obtained roughly similar results for winter air temperature anomaly changes (mostly the same variation, but lower values) for the territory of the Czech Republic. The biggest differences between both reconstructions were recorded for the periods from 1641 to 1660 and from 1721 to 1750. A comparison of these quantitative reconstructions with the results of the frequency of occurrence of severe and very severe winters indicates the existence of considerable differences. For example, according to Sadowski's data (1991) the greatest number of severe winters was recorded in he second half of the sixteenth century and throughout the seventeenth century, while the smallest number were in the eighteenth century. A similar pattern of changes for average annual temperatures is quoted by Maruszczak (1991), who states that the culmination of cooling occurred in the mid-seventeenth century. According to him, this was the coldest period in the whole of the millennium. In Fig. 1.2 in Luterbacher et al. (Chapter 1) one can see that winters were in fact very severe, and summers (see Fig. 6.1) were close to the long-term norm. Yet in the Czech Republic winters (and summers) in that period were not similarly conspicuous Comparing the reconstruction of winter temperature (Fig. 1.2 in Luterbacher et al. Chapter 1) with the reconstruction of the temperature for the period January–April (Fig. 7.15, Chapter 7), the prevalence of their consistent courses (eighteenth–nineteenth centuries) or inconsistent courses (the sixteenth and seventeenth centuries) should be noted. According to Przybylak et al. (2004) probable causes of these discrepancies in the results may include: (1) the use of not fully comparable data (with average temperatures being obtained at various times in the year, only partly overlapping), (2) inaccuracies in the reconstructions which were devised.

The reconstruction of the air temperature for the summer season based on historical data is much less credible and complete than for the winter season as there is less information available. This is clearly visible in Fig. 6.1. Nevertheless the general outline of the changes is clear. There was a dominance of positive or zero anomalies in the whole period under study as compared to the period 1851–1950, with the exception of the eighteenth century, with the maximum reaching 0.5°C–0.6°C in the decades 1551–1560, 1581–1590, 1611–1620, 1631–1640, 1661–1670, 1801–1810 and 1811–1820. The cool summer seasons were recorded mainly in the first half of the eighteenth century with the maximum in the period 1721–1740. In comparison with the territory of the Czech Republic there exists quite a high consistency of anomalies (except for the eighteenth century) although much lower than in the case of winters. It should be noted that due to large deficiencies in the reconstruction of decadal average values for summer temperatures in Poland, a full comparison is not possible. The possibility of the occurrence of hot summer seasons in Poland in the eighteenth century cannot be excluded in the decades for which there is a lack of data, particularly in view of the fact that they were recorded in the Czech Republic (Fig. 6.1).

In conclusion it should be said that our knowledge about the climate of Poland in the past 500 years has increased considerably in the recent years. Nevertheless it is still limited, particularly in relation to the summer season. We may state with some confidence, however, that in the period 1501–1840 the climate of Poland was

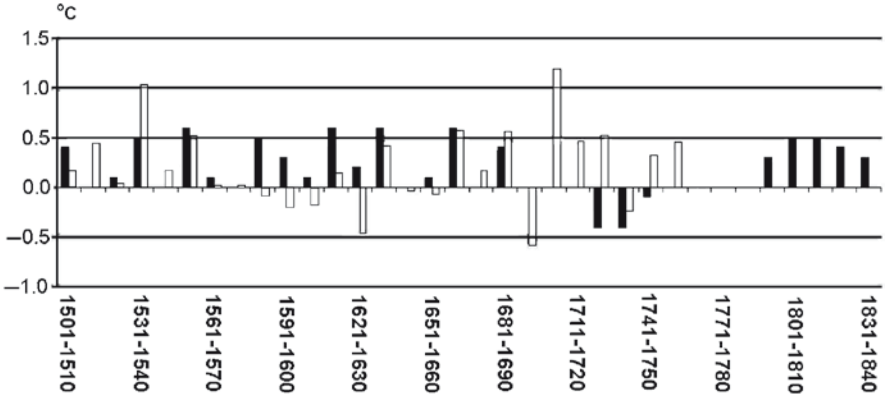

Fig. 6.1 Comparison of summer air temperature reconstructions for Poland (1501–1840, *black bars*) and the Czech Republic (1500–1769, *white bars*; after Brázdil 1996). Anomalies have been calculated relative to 1851–1950 means (modified after Przybylak et al. 2004)

characterised by a higher degree of thermal continentality than prevails at the moment. These results are consistent with the calculations of the values of the continentality index presented in the study by Sadowski (1991).

6.3.2 *Precipitation*

As was mentioned earlier, the reconstruction of precipitation faces much bigger challenges than the reconstruction of air temperature, mainly due to the lower influence of this variable on natural phenomena (e.g. annual growth of tree rings), and on human life and activity (with, consequently, fewer mentions of precipitation conditions in historical records in comparison with thermal conditions). It is for this reason that there are very few studies describing precipitation in Poland in the pre-instrumental period. Four studies (Maruszczak 1991; Przybylak et al. 2004, 2005; Kotarba 2004) discuss this problem for the period of several centuries, whereas another five (Bokwa et al. 2001; Limanówka 2001; Nowosad et al. 2007; Przybylak et al. 2008; Przybylak and Marciniak 2009, this volume) discuss it only for periods of several decades. Maruszczak (1991) provides very general information about mean annual humidity conditions (in the study the period is not specified), which should be understood as precipitation conditions. In the eleventh century they were average, though the twelfth century was the most humid in the whole millennium. The beginning of the thirteenth century was characterised by a decrease in precipitation, which was below the norm in the second half of the century. In the fourteenth century precipitation was on the increase and, from the second half of that century until the mid-fifteenth century, precipitation conditions were variable but close to the norm. Regarding the next 100 years, Maruszczak only mentions that considerable changes in humidity conditions took place and does not specify what kind of changes these were. It can be inferred, however, from the context that the climate became more humid, at least in the years 1480–1520. This hypothesis is confirmed by the data published by Przybylak et al. (2004) (see also Fig. 6.2). However Limanówka (2001) states, on the basis of a number of days with precipitation, that in the first half of the sixteenth century there was less precipitation than in the modern period. It seems, however, that the professors of the Wszechnica Krakowska (the precursor to today's Jagiellonian University in Cracow) tended to overlook low levels of precipitation, and these were consequently omitted from records. A similar problem with Chrapowicki's diary for the first 2 years (1656 and 1657) is confirmed by Nowosad et al. (2007). Therefore it seems that the value of the number of days with precipitation presented by Limanówka (2001) should be increased by this probable error. From the mid-sixteenth century to the mid-seventeenth century average precipitation conditions prevailed (Maruszczak 1991). Similar results were obtained by Przybylak et al. (2004) (see among others Fig. 6.2). The second half of the seventeenth century was, according

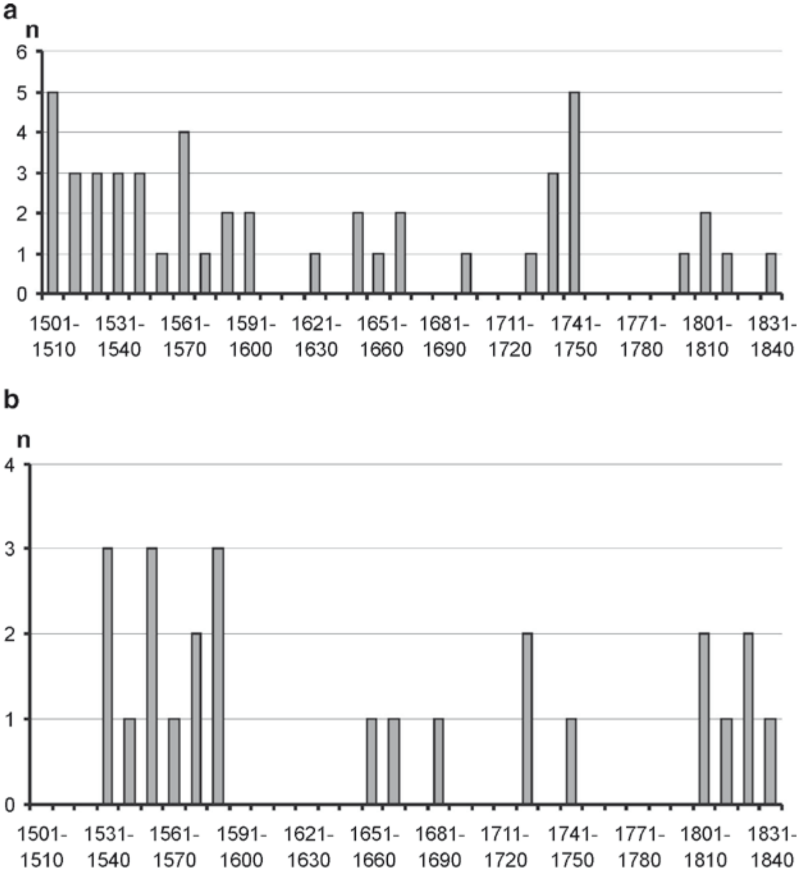

Fig. 6.2 Decadal frequencies (n) of occurrence of summers (Jun–Aug): (**a**) extreme wet and very wet and (**b**) extreme dry and very dry (after Przybylak et al. 2004)

to the reconstruction by Maruszczak (1991), poorer than average in terms of precipitation. However at least the first two decades of that period probably had standard annual precipitation, which was higher in summer and lower in winter than in the modern period (see Fig. 21.14 in Przybylak and Marciniak 2009, this volume). High values of precipitation in June and July in that period were discovered in the precipitation reconstruction carried out on the basis of dendrochronological data (see Fig. 2 in Przybylak et al. 2001). From the eighteenth century precipitation totals were near the norm, except for the turn of the eighteenth and nineteenth centuries, when there was less precipitation (Maruszczak 1991). The results obtained by Przybylak et al. (2004) confirm this in principle, with the exception of the period 1731–1750, which was most probably more wet than the norm (Fig. 6.2). Generally, similar results for the Tatra Mountains (in the southern part of Poland) were found by Kotarba (2004). Reconstructions of the sums of summer and winter precipitation for the Czech Republic (see for instance Fig. 2 in Brázdil 1994) are similar to those obtained for Poland (Table 1 and Fig. 4 in Przybylak et al. 2004).

6.4 Conclusions

1. The existing, incomplete and not fully credible reconstructions of the Polish climate in the last millennium indicate that the first 500 years (and particularly the first 300 years) were warmer than the latter 500 years. Mainly winters were warmer, whereas summers could be even cooler, if we assume the indicator to be the frequency of the occurrence of hot summers (see Fig. 1 in Sadowski 1991). Therefore the first 300–400 years of the millennium was a period of a high (indeed according to Sadowski [1991] the highest) degree of oceanism on the Polish climate. In Polish climate history we can therefore distinguish a so-called Medieval Warm Period, which most probably lasted until the beginning of the fourteenth century (according to Maruszczak 1991) or until the beginning of the fifteenth century (according to Sadowski 1991). Air temperature was then most probably higher on average by about 0.5°C–1.0°C.
2. Beginning from the fifteenth century the degree of continentality of the climate remains at a high level until the beginning of the nineteenth century. As a result winters were colder by about 1.5°C to 3.0°C in comparison with modern conditions, while summers were warmer by an average of about 0.5°C. Mean annual air and ground surface temperatures were probably lower than modern ones by about 0.9°C–1.5°C. A so-called Little Ice Age can be distinguished here, which clearly began around the mid-sixteenth century and probably ended in the second half of the nineteenth century.
3. The reconstruction of precipitation (the most variable meteorological element in time and space) is much more uncertain than is the reconstruction of air temperature. There was probably higher than average precipitation in the twelfth century (and particularly from 1151 to 1200), in the first half of the sixteenth century and also in the first half of the eighteenth century. The second half of thirteenth

century and the first half of nineteenth century were drier than average. In other periods precipitation conditions were close to average.

4. The above brief synthesis of information on the history of the climate of Poland in the last millennium confirms the veracity of the earlier thesis that, despite the advances in research which took place in the past 20 to 30 years, our knowledge of this subject remains both insufficient and uncertain.

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Fond 49,op.2, syg. 1961, 1890, 1891
National Museum in Cracow (Muzeum Narodowe w Krakowie)
Diaryusz Życia JWJmci Pana Jana Antoniego Chrapowickiego Wojewody Witebskiego [...] przekopiowany w roku 1786, T. 3 [1670–1673], T. 4 [1674–1676], T. 5 [1677–1679], T. 6 [1680–1682], T. 7 [1683-]), rps. MNKr. 169

Chapter 7
Dendrochronological Data

Andrzej Zielski, Marek Krąpiec, and Marcin Koprowski

7.1 Introduction

This chapter presents a summary of the results of climate reconstruction for Poland. For the first time in Poland, these results were investigated by an interdisciplinary team of scientists (geographers, dendrochronologists and mathematicians) along with historians and archivists. The group made, among other things, a reconstruction of climate based on a long Scots pine chronology. Historians collected a few thousand records of source materials related to climate. These data were collected and quantified in such a manner so as to make them comparable with the time scale made by the dendrochronologists (Przybylak et al. 2005). This study presents a background to Polish dendrochronology along with the dendrochronological proxy data derived by the paleoclimatological team, focusing on the dendroclimatological potential. The main dendrochronological data in Poland consist of the results of tree rings width measurements of native species, and a number of introduced species that have become naturalised, in Poland, and chronologies built from them. Some wood density measurements were also available for dendroclimatological analyses in the mountainous areas (Büntgen et al. 2007). Nearly all the studies looked at the relationships of growth with temperature and precipitation values, and occasionally other parameters were considered too (insect outbreaks, site characteristic etc.). In many of the dendroclimatological studies "moon rings", called also "included sapwood", a type of discoloration in the heartwood, (Krąpiec 1999) and "frost rings" were also investigated (Cedro 2004). Such anatomical anomalies are useful for recording of the occurrence and frequency of extreme weather phenomena.

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The climate of Poland is described as moderately warm, transient between Atlantic and continental. Mean summer temperature varies between 16.5°C and 20°C (except in the mountains), and mean sum of precipitation is about 600 mm per year. Relief plays a significant influence on the variation in climate; lower temperatures are characteristic of the mountainous area of the Sudety and the Carpathian Mountains. In the highlands the growth/climate relationship is quite specific. In the higher areas the influence of temperature increases and that of precipitation decreases. At elevations above 1,000 m a.s.l. the influence of sunshine as a growth-stimulating factor is higher in the summer, replacing the role of low temperatures limiting growth at such elevations.

Many other factors influence the climate-growth relationships in stands of trees, these include long-term trends connected with age, and both endo- and exogenous factors. Because of this, in dendroclimatological analysis, tree-ring data are transformed into residual chronologies, enhancing the low-frequency variance and greatly reducing any autocorrelation and thus emphasising the climate signal in the series. Dendroclimatological research has been carried out in Poland for over 60 years (Zinkiewicz 1946; Ermich 1953; Feliksik 1972; Bednarz 1976). As a result, there are numerous chronologies available for both native and naturalised species which form a basis for further research. These are summarised in Table 7.1.

Below we present the longest chronologies for each species, significant for wood dating. The longest chronologies have been constructed for:

1. Oak (*Quercus robur* L., *Q. petraea* LIEBL.)
   - Gdańsk Pomerania, 996–1985 AD (Ważny 1990)
   - Szczecin Pomerania 578–1393 AD and 1554–1994 AD (Ważny 1999), 553–1340 AD Zielski and Krąpiec 2004
   - Central Poland 593–965 AD (Ważny 1999)
   - Archaeological site in Biskupin 887–722 BC (Ważny 1993)
   - Warmia and Mazury 1093–1665 AD, 1695–2003 AD (Krąpiec et al. 2005)
   - Pułtusk region 1066–1462 AD (Krąpiec 1992)
   - Kalisz-Sieradz region 422–1027 AD, 1148–1316 AD (Zielski and Krąpiec 2004)
   - Lesser Poland 910–1997 AD (Krąpiec et al. 1998)
   - Low Silesia 780–1994 AD (Krąpiec et al. 1998)
   - Great Poland 449–1994 AD (Krąpiec et al. 1998)
   - Subfossil oaks in southern Poland 1795–612 BC, 474 BC–1555 AD (Krąpiec 1996, 2001)
   - Kuyavia and Pomerania region 1085–1584 AD (Zielski and Krąpiec 2004)
2. Scots pine wood (*Pinus sylvestris* L.)
   - Vistula valley – Pomerania region 1106–1994 AD (Zielski 1997)
   - Great Poland 1153–1700 AD and 1786–2001 AD (Zielski and Krąpiec 2004)
   - Suwałki Region 1582–2004 AD (Szychowska-Krapiec and Krąpiec 2005a)
   - Masovia 1176–1408 AD and 1652–1783 AD (Krąpiec et al. 2005)
   - North-eastern Poland 1110–1460 AD (Szychowska-Krapiec and Krąpiec 2005b)
   - Warmia and Mazury 1081–1408 and 1410–2003 (Krąpiec et al. 2005)

Table 7.1 Climatic signal in selected tree species in Poland

Reference	Species	Site	Age range	Method	Climatic signal
Bednarz and Ptak (1990)	*Quercus robur*	Niepołomice Forest (near Kraków)	1826–1980	Percentage of agreement and correlation	Precipitation in June–July
Bednarz et al. (1998–1999)	*Picea abies*	Babia Góra National Park	1636–1989 (longest)	Percentage of agreement and correlation	Positive dependence: temperature of June–July and precipitation of February–March
					Negative dependence: precipitation of June–July
Büntgen (2007)	*Picea abies*	Western Carpathian Tatra Mountains	1628–2004	Correlation	Reconstruction of temperature: June–July on the basis of tree rings width and April–September on the basis of maximum latewood density
	Larix decidua		1612–2004		
	Abies alba		1810–2004		
	Pinus mugo		1742–1969		
Cedro (2006)	*Pinus sylvestris*	Northwestern Poland	1886–2000	Response function (Respo, DPL), signature years analysis	Thermal conditions in February and in the beginning of spring, rainfall in the vegetation season
Cedro (2007)	*Quercus pubescens*	Bielinek Nature Reserve	1793–2004 (longest)	Response function (Respo, DPL), signature years analysis	Positive role of precipitation springx-summer
	Q. robur				Negative role of droughts in spring and summer, coupled with high air temperature
	Q. petraea				

(continued)

Table 7.1 (continued)

Reference	Species	Site	Age range	Method	Climatic signal
Cedro et al. (2007)	*Juniperus communis*	"Jałowce" reserve (Pomerania)	1903–2004	Response function (Respo, DPL), signature years analysis	Temperature in June, precipitation in February and May
Feliksik (1972)	*Pice abies*	Tatra Mountains	1810–1970	Correlation, Huber`s method	Positive effect of high temperature and low precipitation in summer
Feliksik (1988)	*Pinus sylvestris*	Dąbrowa Tarnowskar Forest Distinct	More than 100 yeras	Correlation, Huber`s method	Thermal condition from January to March, precipitation from April to August
Feliksik (1990)	*Abies alba*	Poland	1831–1977 (longest)	Correlation, Huber`s method	Winter temperature
Feliksik and Wilczyński (2000a)	*Picea abies*	the Ustroń Forest District	More than 100 years	Response function (Respo, DPL)	Low temperature of the end of the winter and of spring, dependably on site altitude (a.s.l.)
Feliksik and Wilczyński (2000b)	*Pinus sylvestris*	Dolny Śląsk	More than 100 years	Response function (Respo, DPL)	Positive influence of: previous cold autumn, warm February and March, cold and dry April, higher temperature of July, large amount of rainfall during the summer
Feliksik and Wilczyński (2001)	*Picea abies*	Istebna Forest District.	+/−100 years	Response function (Respo, DPL)	Temperature of winter and early spring, precipitation between spring and summer
Feliksik et al. (2000)	*Pinus sylvestris*	Świętokrzyski National Park	1931–1994	Response function (Respo, DPL)	Winter temperature
	Fagus sylvatica				June rainfalls
	Abies alba				Winter temperature
Feliksik et al. (1994)	*Picea abies*	Valley of Górna Wisła	More than 100 years	Correlation, Huber`s method	Temperature from December to March, rainfalls from June to July

Kaczka (2004)	*Picea abies*	Tatra Mountains	More than 300 years	Correlation and response function	Temperature in June and July
Krawczyk and Krąpiec (1999)	*Quercus* sp.	Niepołomice Forest		Response function	Temperature in February and May; precipitation: July previous year, June
Koprowski (2006)	*Fagus sylvatica*	Iława Forest District	1900–2002	Pointer years analysis (WEISER) Response function (PRECON)	May–June precipitation, July and September temperature (negative dependence) previous year
Koprowski and Gławenda (2007)	*Abies alba*	Olsztyńskie Lakeland (Wichrowo Forest District)	1902–2003	Response function (PRECON)	February–March temperature
Koprowski and Zielski (2002)	*Picea abies*	Olsztyńskie Lakeland	1840–1999	Pointer years analysis (WEISER)	Precipitation – end of spring beginning of summer, temperature – end of winter
Koprowski Zielski (2006, 2008)	*Picea abies*	Lowland Poland	Longest chronology 1785–1999	Response function (PRECON)	Boreal-baltic range – May–July precipitation Hercinian–Carpathian range – March temperature
Savva et al. (2006)	*Picea abie*	Tatra mountains	Longest chronology 1764–1993	Correlation	With increasing elevation, the strength of correlation declined for March–April and increased for June–July temperature

(continued)

Table 7.1 (continued)

Reference	Species	Site	Age range	Method	Climatic signal
Ufnalski (2001)	*Quercus robur*, *Q petraea*	Northern and central Poland	Oldest rings: *Q. robur* 1882; *Q. petraea* 1858	Pointer years analysis response function (Respo, DPL)	Rainfalls in June, temperature in previous August
Ważny and Eckstein (1991)	*Quercus* sp.		(Longest) 1554–1986	Response function (Respo, DPL)	Northern Poland; temperature in August (negative cor.), October, December previous year (negative cor.) and February and May. Precipitation: November previous year, June–September Eastern Poland temperature: February, May (negative corr). Precipitation: May, June Western Poland temperature: October previous year, January, September and April (negative corr)
Wilczyński (2004)	*Pinus sylvestris*	Szklarska Poręba Forest District	140 years	Pointer years analysis	Wide rings – warm and short winter, narrow rings – cold and long winter
Wilczyński and Feliksik (2004)	*Picea abies*	Western Beskid Mountains	More than 100 years	Convergence and Response function (Respo, DPL)	Temperature from February to April and summer period
Wilczyński and Gołąb (2001)	*Fagus sylvatica*	Beskid Wyspowy	More than 100 years	Response function (Respo, DPL)	Positive: previous year – wet July and warm and dry autumn; current year – warm winter and summer
Wilczyński and Skrzyszewski (2002)	*Pinus sylvestris*	Sudetic mountains	Almost 100 years	Correlation and Response function (Respo, DPL)	Positive high temperature during late winter months (February–March) and summer periods (July–August), and rainfalls from May to August

Zielski (1997)	*Pinus sylvestris*	Toruń region	1767–1983 (longest)	Response function (Respo, DPL)	February–March temperature, June–July precipitation
		Poznań region	1853–1983		February–April temperature; December previous year and January, June, July precipitation
		Olsztyn region	1853–1990		March, April and October, December prev. year -temperature
					June and December previous year-precipitation
		Augustów region	1857–1990		March, April temperature; June, July precipitation
Zielski and Koprowski (2001)	*Picea abies*	Olsztyńskie Lakeland	Longest chronology–1840–1999	Response function (Respo, DPL)	May–August precipitation. Negative dependence with temperature of November (previous year) and June. Positive dependence with March temperature
Zielski and Sygit (1998)	*Pinus sylvestris*	Poland	1907–1994	Response function (Respo – DPL)	February, March temperature
		λE19.3; φN 52.5 – λE20.3; φN 52.8 – λE21.3; φN52.7 – λE23.6; φN 52.9			
		Poland	1898–1994		February, March temperature

(continued)

Table 7.1 (continued)

Reference	Species	Site	Age range	Method	Climatic signal
\		λE22.3; φN52.5 – λE20.6; φN51.6			
		Poland	1913–1994		March temperature
		λE14.5; φN 52.7 – λE 15.7; φN 52.7 – λE16.4; φN52.8			
		Poland	1914–1994		February temperature
		λE 19,0; φN52,8			

  - Low Silesia 1062–1418 AD and 1648–1999 AD (Szychowska-Krapiec and Krąpiec 2001)
  - Lesser Poland 1091–2004 AD (Szychowska-Krąpiec 2009)
3. Fir wood (*Abies alba* Mill.)
  - In its natural range in Poland 1106–1998 AD (Szychowska-Krąpiec 2000)
  - Historical wood, Carpathian mountains 1406–1746 AD (Ważny 1999)
4. Norway spruce wood (*Picea abies* Mill.)
  - Beskid Żywiecki 1641–1995 AD (Szychowska-Krąpiec 1998)
  - Białowieża National Park 1785–1999 AD (Koprowski and Zielski 2006, 2008)
  - Babiogórski National Park 1650–1993 AD (Bednarz et al. 1998–1999)
  - Tatrzański National Park 1699–1978 AD (Feliksik and Schweingruber ITRDB)
  - Tatra region in Poland and Slovakia 1628–2004 AD (Büntgen et al. 2007).

Dated chronologies have therefore been made for most native coniferous and ring porous dicotyledonous trees in Poland, and these have proved to be very useful for dendroclimatological studies.

Dated wood has also been used for broader climatic studies. For example, similarities and differences between chronologies from living pine and spruce chronologies have been used to specify climatically different forestry regions (Zielski et al. 2001; Wilczyński et al. 2001; Koprowski and Zielski 2006). In recent studies, subfossil wood of *Taxodioxylon taxodii* from the Miocene period has also been used in paleoclimatological research in southern Poland (Kłusek 2006).

7.2 Material and Methods

This section presents the basic methodology used by the present authors. Other researchers may have used different methodologies, and these will be detailed in their publications.

7.2.1 Sampling

In most cases the material for dendroclimatological research is collected as cores from living trees. A basic tool for taking the samples is a Pressler borer. In some cases samples in the form of disks have been taken from the stem. Historical wood has either had cross-sectional disks removed, or cores extracted using a special drill for dry timber. A special technique is needed for taking research material from subfossil wood (for example so called black (bog) oaks) when a chainsaw is used, or from fossil (Miocene) wood where polished sections are used.

7.2.2 Material

For temperature reconstruction in Poland, a residual regional chronology of Scots pine tree-ring widths from the Lower Vistula region (Fig. 7.1) covering the period 1168–1994 has been used (Zielski 1997). The chronology included measurements of tree-ring widths in living trees (back to 1767) and historical timber (wooden frames and wooden roof constructions from old churches and buildings).

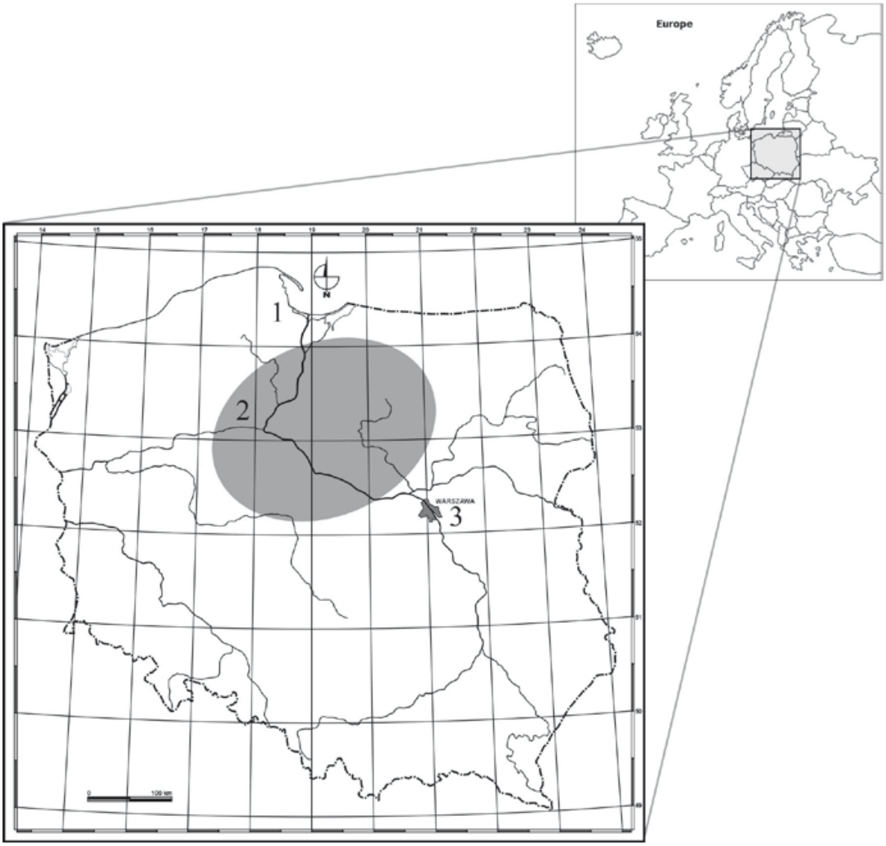

Fig. 7.1 Location of source data used to reconstruct temperature in Poland. Long-term series of air temperature; (1) Gdańsk; (2) Bydgoszcz; (3) Warsaw; circle: area for which tree-ring widths regional chronology of the Scots pine was constructed (Przybylak et al. 2005)

7.2.3 Methods

7.2.3.1 Measurement and Basic Statistical Methods

The samples were treated in the standard way and measured to the nearest of 0.01 mm by means of a mechanical instruments with a computer registering the ring width. A number of methods were used to assess the cross-matching between the samples:

Gleichläufigkeit (% GL) (Huber 1943)
The Student's t-test (Baillie and Pilcher 1973)
Program TREE-RINGS (Krawczyk and Krąpiec 1995)
Program CATRAS (Aniol 1983)
Program COFECHA (Holmes 1986; Grissino-Mayer 2001)
The skeleton plot method (Douglass 1939; Schweingruber et al., 1990; Zielski and Krąpiec 2004)

The residual chronologies for dendroclimatological analysis were built by program CRONOL (Holmes 1984). The climate-growth relationships were calculated by means of program RESPO (Holmes 1984) and program PRECON (Fritts 1996). This last program applies a bootstrap response function to estimate the error using random sampling for the data (Guiot 1993). The response function methods and program PRECON have been described in detail by Fritts (1976, 1996) and Briffa and Cook (1990). Hierarchical cluster analysis (HCA, program STATISTICA) was used to distinguish regions with similar increment pattern for Scots pine and Norway spruce.

Firstly, local chronologies were established. The correctness of the construction of those chronologies was checked using program COFECHA (Holmes 1986). In the next step, these chronologies were transformed using program CRONOL (Dendrochronology Program Library – DPL, routine CRN; Holmes 1984). The detrending procedure was applied to each of the examined series. Application of the autoregressive procedure to the detrended tree-ring series produced a residual version of the chronologies.

7.2.3.2 Signature Years

Cropper's (1979) algorithm was used in order to detect extreme wide and narrow rings, which identify extreme weather conditions. A five-year moving window was applied, according to formula:

$$z_i = \frac{x_i - mean[window]}{stdev[window]}$$

where:
z_i – index value in the year *i*

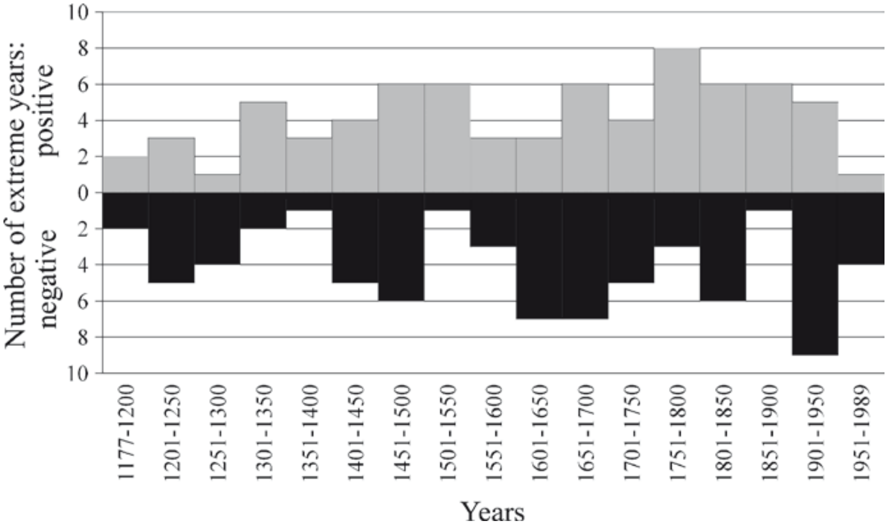

Fig. 7.2 Frequency of extreme years of Scots pine for 50 year periods (Wójcik et al. 2001)

x_i – original value in the year *i*
mean [window] – arithmetic mean of the ring width within window
$x_{i-2,}$ $x_{i-1,}$ $x_{i,}$ $x_{i+1,}$ x_{i+2}
stdev [window] – standard deviation of the ring width within the window $x_{i-2,}$ $x_{i-1,}$ $x_{i,}$ $x_{i+1.}$ x_{i+2}

The selection of extremely wide and narrow rings demands threshold values of z_i. For example all values $z_i < -1.25$ are defined as negative pointer years and all values of $z_i > 1.25$ are defined as positive pointer years (Meyer 1998–1999). Information about climate originating from historical (documentary) sources was used to explain the occurrence of extreme years in pre-instrumental times. The frequency of occurrence of pointer years were counted in the periods 1177–1994 for pine (Fig. 7.2) and 1843–1999 for spruce (Fig. 7.3) (Wójcik et al. 2001).

7.2.3.3 Reconstruction

Temperature and precipitation were reconstructed from pine ring-width curves through multiple regression analysis. These studies showed that there was a strong correlation between growth and climate in particular months (Fig. 7.4), and this varied between species as a result of their different genetic make-up. The conclusions are that reliable reconstructions can only be produced for the months where the relationships are seen to be statistically significant. Temperature and rainfall reconstructions from Scots pine tree-ring series were produced for the Kuyavia and Pomerania regions of Poland (Figs 7.5 and 7.6). The highest correlations between temperature and growth were found in February and March, and those for rainfall

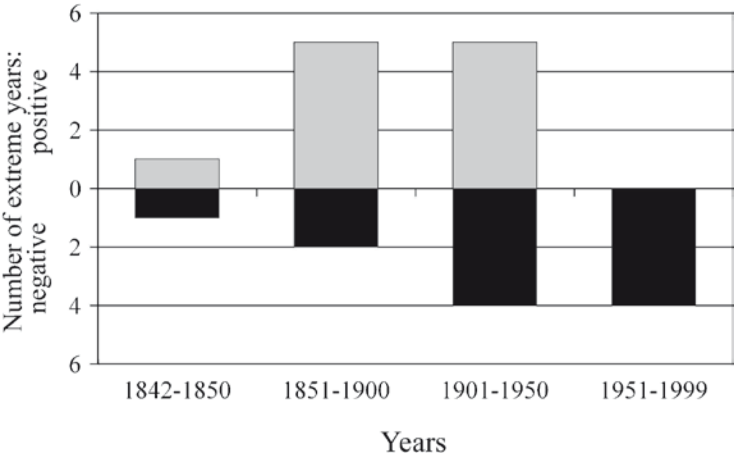

Fig. 7.3 Frequency of extreme years of Norway spruce for 50 year periods (Wójcik et al. 2001)

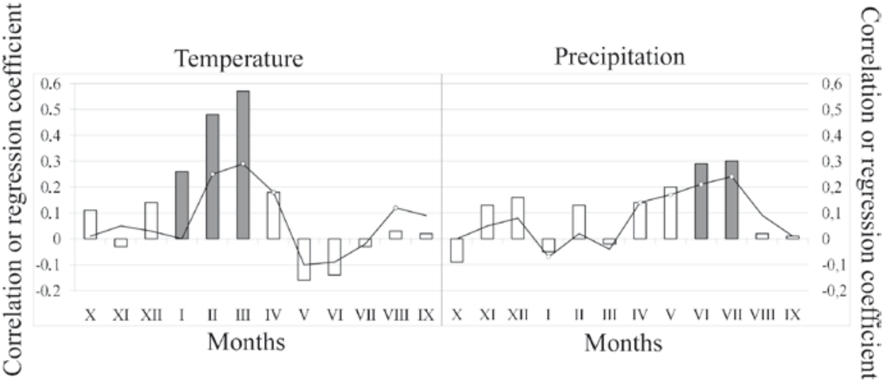

Fig. 7.4 Toruń region. Climate/growth dependence for tree rings of Scots pine, period 1891–1991. Line- multiple regression, columns-linear correlation. Marks on line or grey columns mean significant dependence between ring widths and selected months (counted by RESPO programme, DPL package) (Zielski and Krąpiec 2004)

occurred in June and July. The results of the reconstructions were smoothed using an 11-year moving window. The indexed chronology (with reduced long-term growth trends) POLSKANE (Zielski 1997) was used in these analyses. The model was calibrated using data for the period 1921–1970 and verification was carried out on data for the period 1871–1920. The temperature reconstruction was made on the basis of measurements from the meteorological station in Bydgoszcz along with series of mean values for the region, derived from four stations: Chojnice, Płock, Bydgoszcz and Toruń. The process resulted in the model between growth and climate being described by means of linear regression:

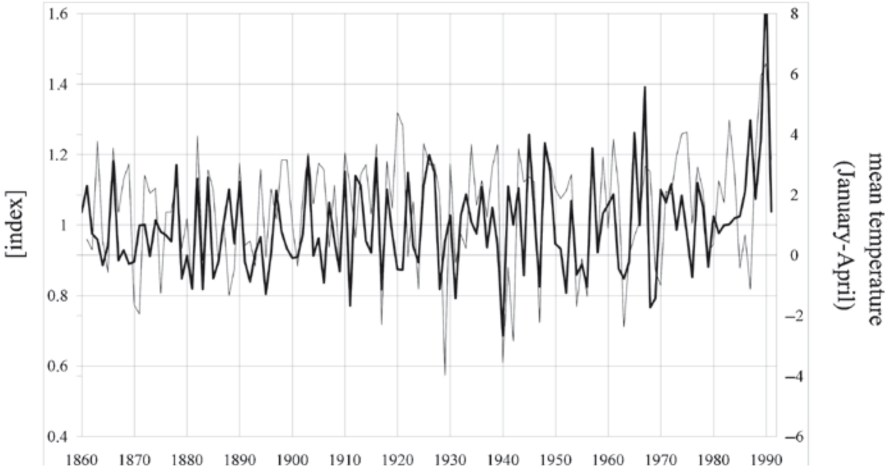

Fig. 7.5 Comparison mean monthly temperatures (from January to April in years 1861–1993) with pine residual chronology for Toruń region (Zielski and Krąpiec 2004)

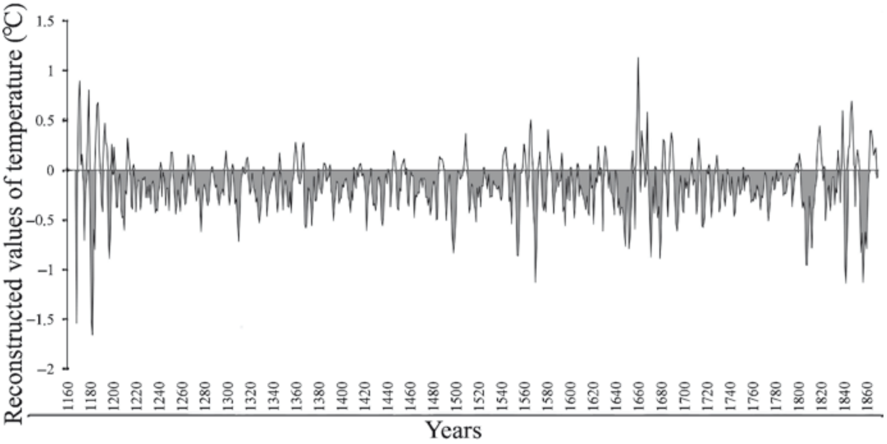

Fig. 7.6 Reconstructed and smoothed mean monthly temperatures from February to March in Kujawy and Pomorze region in years 1168–1870 (Zielski and Krąpiec 2004)

index temperature-precipitation =15.556*c + 0.278 (Zielski and Kamiński 2003).

In order to characterize the reconstructed climate and improve the comparison with historical data, categories of seasons were distinguished (cool, warm, normal, wet and dry);

– For mean regional air temperature

Criteria	Number of points	Characteristic of season
$x < m - 1\ SD$	1	Cool
$m - 1SD < x < m + 1SD$	2	Normal
$x > m + 1SD$	3	Warm

Explanations: x – mean air temperature of February and March in a given year, m – mean air temperature of February and March in the years 1861–1990, SD – standard deviation of mean air temperature of February and March in the years 1861–1990

– For precipitation (June and July) from Bydgoszcz

Criteria	Number of points	Characteristic of season
$y < m - 1\ SD$	1	Dry
$m - 1SD < y < m + 1SD$	2	Normal
$y > m + 1SD$	3	Wet

Explanations: y – mean total of precipitation from June to July in a given year, m – mean total of precipitation from June to July in the years 1861–1990, SD – standard deviation of precipitation total from June to July in the years 1861–1990.

In the next stage five categories of years were selected, each on the basis of temperature at the end of winter and the beginning of spring and precipitation levels at the end of spring and beginning of summer:

1. February–March cool and June–July dry
2. (a) February–March normal and June–July dry; or (b) February–March cool and June–July normal
3. (a) February–March normal and June–July normal; or (b) February–March warm and June–July dry; or (c) February–March cool and June–July wet
4. (a) February–March warm and June–July normal; or (b) February–March normal and June–July wet
5. February–March warm and June–July wet

The results from this analysis for the period 1861–1990 were entered into the calibration of the dendrochronological model in a similar way to those used previously for the temperature model alone. Like the results of the temperature analysis, the agreement of the reconstructed series produced by this means with the known meteorological data was very strong, with a coefficient of correlation of 0.702 in years 1921–1970 (Kamiński 2002; Zielski and Kamiński 2003).

7.2.3.4 Others

Other reconstructions from Polish pine chronologies have used the Principle Component Analysis (PCA) method and program CATRAS (Aniol 1983). Indexed chronologies were reduced to the form of a variance matrix of new variables, so-called eigenvalues. Finally, a new set of variables were obtained for each time series, the so-called principal components. The first two principal components were used for subsequent interpretation, as these contained a significant proportion of the overall variance.

7.3 Results and Discussion

The calculations of the statistical relationships from calibration period 1921–1970 proved that temperature in selected months explains slightly more than 50% of pine growth variation (correlation coefficient is 0.725). The verification process shows that temperature from 1871 to 1920 produced by means of the linear regression are rather very well correlated with the actual measured temperatures data (correlation coefficient is 0.49). The graph of reconstructed temperatures (Fig. 7.6) is therefore quite reliable. The *y* axis represents reconstructed temperatures values, and the *x* axis, calendar years. It is possible to read the reconstructed winter/spring temperature in degrees Celsius. This season is generally characterized by temperatures below 0 degrees. The graph highlights unusual growth periods, for example the end of the twelfth century, the sixteenth to the seventeenth centuries, and the nineteenth century.

Even during the not typical periods, some extreme years were also noted. Warmer periods (mean temperature > 0.5°C) and cooler periods (mean temperature ≦ -1°C) can be distinguished. The reconstruction data suggest periods when the winter/spring temperature was warmer than normal in 1180–1200, 1240–1270, 1340–1360, 1430–1490, 1530–1590, 1660–1680, 1820–1850, 1910–1940 and from 1985. In contrast, cooler winter/spring periods occurred in: 1290–1310, 1400–1420, 1500–1510, 1600–1650, 1750–1770, 1800–1810, 1880–1900, and 1900–1980. The coldest winter/spring periods were the first decade of the fourteenth century, the last decades of the fifteenth century and at the beginning of sixteenth century, as well as in the first decade of the nineteenth century.

Years, classified by index 4 and 5, on the graph are above value three (Fig. 7.7). Values below 3 represent time spans with prevailing indexes from 1 to 2. From the analysis of raw data results, that in years 1168–1870 point out prevailing of average years (Fig. 7.7).

For Scots pine (*Pinus sylvestris*), the most common tree species in Poland (about 70% of area of Polish forests), local chronologies were built covering the whole of Poland and from these it is possible to recognize spatial variance in the increment patterns, and hence suggest dendrochronological regions, in which the trees are responding in a similar way to environmental factors. Some 330,000 tree-ring widths were measured on 5,400 cores, representing 2,800 trees. Local chronologies were built for 136 sites distributed throughout Poland. Local chronologies (Fig. 7.8a) are characterized by many individual features resulting from differences in age and genetic features of the tree, soil conditions etc. Indexed chronologies (Fig. 7.8b) were constructed using program ARSTAN (Cook and Holmes 1996).

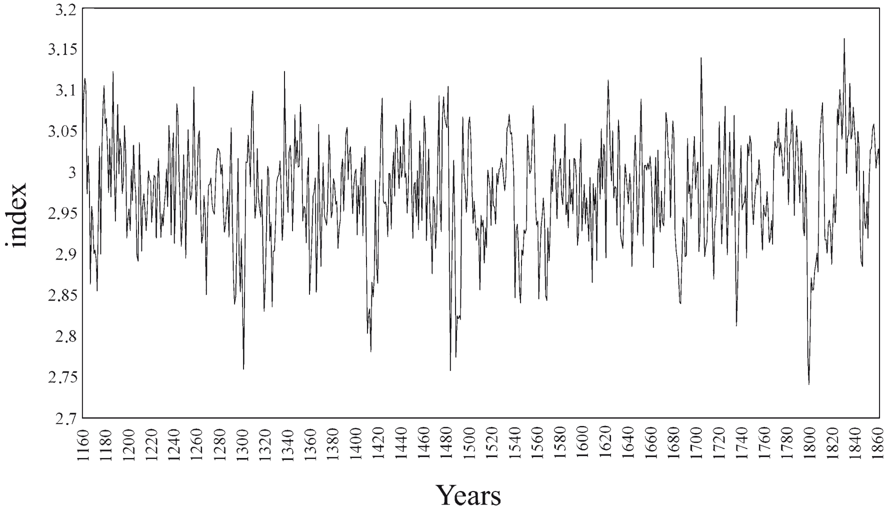

Fig. 7.7 Reconstructed and smoothed indexes of selected seasons categories in Kujawy and Pomorze region in years 1168–1870 (Zielski and Krąpiec 2004)

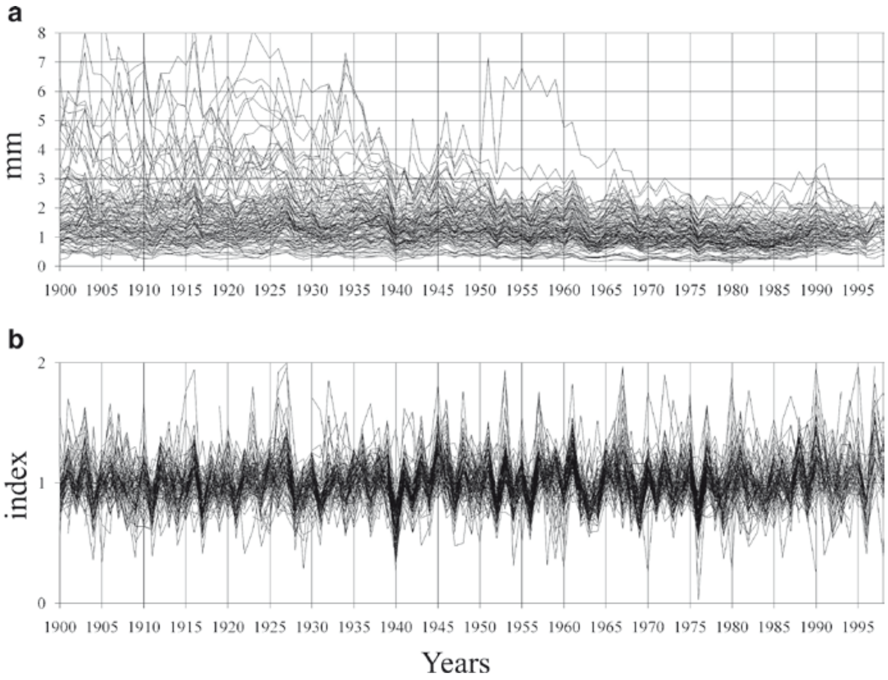

Fig. 7.8 (a) Raw data and (b) residual chronologies of Scots pine for sites from Poland (Zielski et al. 2001)

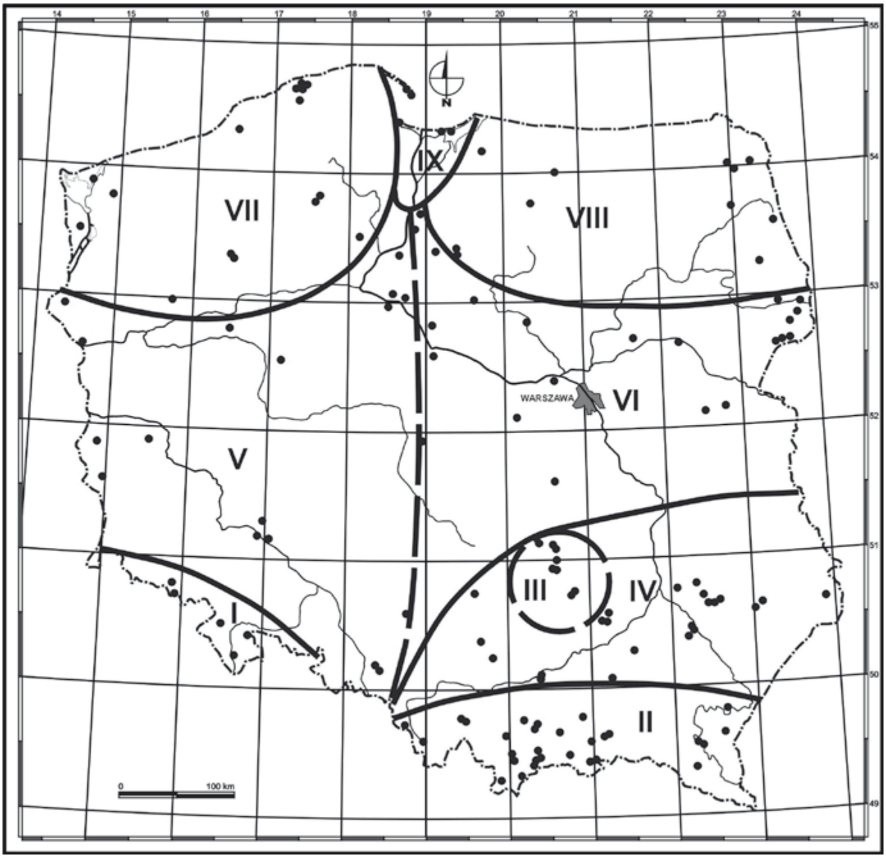

Fig. 7.9 Sites location and established homogenous regions of Scots pine increment pattern in Poland (Wilczyński et al. 2001)

Indexation increased the short-term (annual) variance of chronology, the main cause of which was, undoubtedly, climate conditions. As a result, Poland was divided into eight homogenous dendrochronological regions (Fig. 7.9) (Wilczyński et al. 2001; Zielski et al. 2001). The selected regions cover most climatic regions of Poland.

Temperatures in the winter months and in the beginning of spring were factors which differentiate the pine chronologies in a west-east direction, whereas the summer temperature/rainfall conditions vary on a north-south axis.

Similar research was carried out on the second most important tree species in Poland, the Norway spruce (Figs. 7.10 and 7.11). Region 1a grouped trees growing outside the natural range, and region 1b, trees from the natural boreal-Baltic area. Region 2a groups spruce sites in the so called "spruceless area", whereas 2b is a region of the Hercynian-Carpathian distribution of *Picea abies*. Comparison of

Fig. 7.10 Sites localisation (o marked), established homogenous regions, and distribution of meteorological stations (x marked) (Koprowski and Zielski 2006)

Figures 7.9 and 7.10 shows that homogenous groups of pine overlap with homogenous spruce groups. It is therefore possible to conclude that a combination of climatic and physical-geographical features control the formation of similar growth areas for both species within the Polish lowlands.

Bednarz (1976) revealed variations in seasonal climate from *Pinus cembra* tree rings in the Tatra mountains (Fig 7.12). The first half of the eighteenth century stands out as a period of strong continentality, and the beginning of decline of Arolla pine (*Pinus cembra*) tree-ring widths, indicating an increasing drop in temperature. This fact is supported by historical data showing the spread of glaciers in the Tatra mountains at this time (Maruszczak 1991).

One of the most important developments in the dendroclimatological research has been the introduction of X-ray densitometry, which revealed the strong correlation between the latewood density of coniferous trees and summer temperatures. These results are particularly striking in the cases where trees are growing in extreme

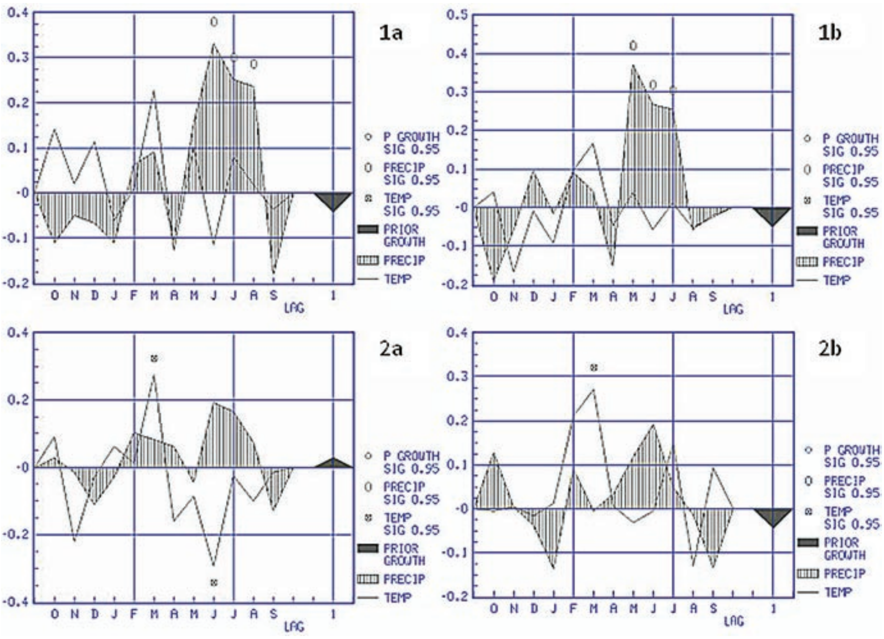

Fig. 7.11 Typical climate-growth relationships for each region. Significant values (confidence level 95%) for particular months are marked above (counted by PRECON programme) (Koprowski and Zielski 2006)

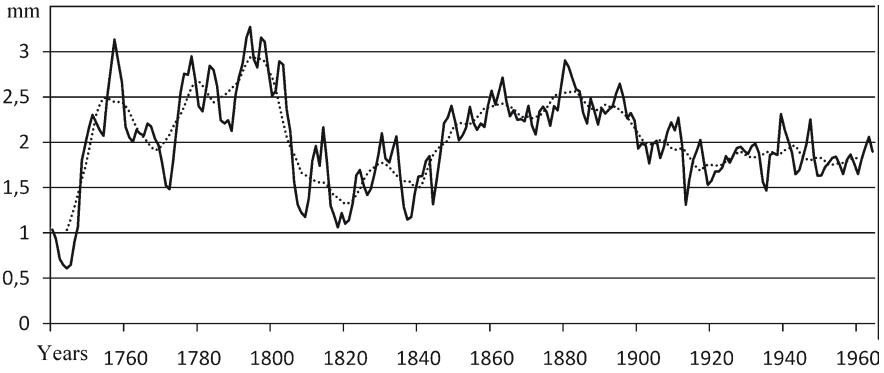

Fig. 7.12 Rhytm of thermal changes in years 1740–1956 in *Pinus cembra* tree rings from Tatra mountains, dotted line – consecutive 10-years means, solid line – tree ring widths. According to Bednarz data (1976) (Maruszczak 1991)

conditions, for example on the higher elevations in mountains, and in the subarctic zone, close to the polar border of forests (northern treeline), where the most important factor limiting tree growth is climate. On these sites it has been shown that summer temperature is the most important factor controlling the tree-ring widths of coniferous species. European studies have shown that summer (April to September) temperature during the period 1750–1850 were particularly significant in limiting tree-ring widths, especially in the northern half of the continent. It was shown that "summer" temperature in Europe from 1812 to 1816 and in the 1830s were lower than the long-term mean (Briffa et al. 1988). In the Tatra mountains, in Poland and Slovakia, this research was done by Büntgen et al. (2007) (Figs. 7.13 and 7.14).

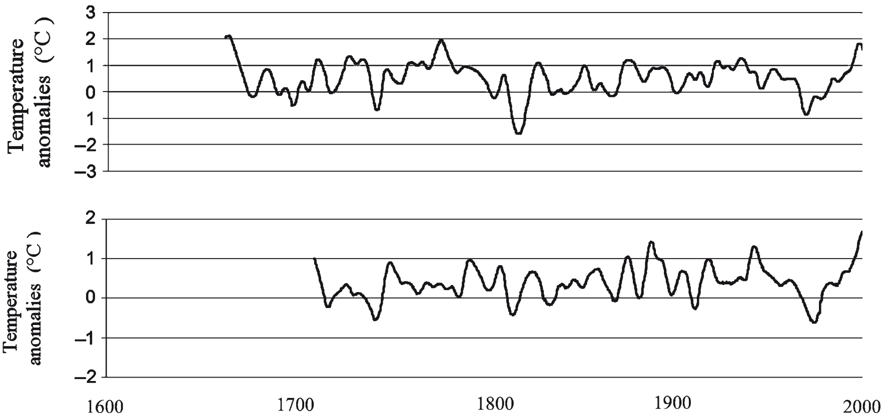

Fig. 7.13 Tatra June–July and April–September temperature reconstructions. The tree-ring widths (**a**) and the maximum latewood density (**b**) (Modified Büntgen et al. 2007)

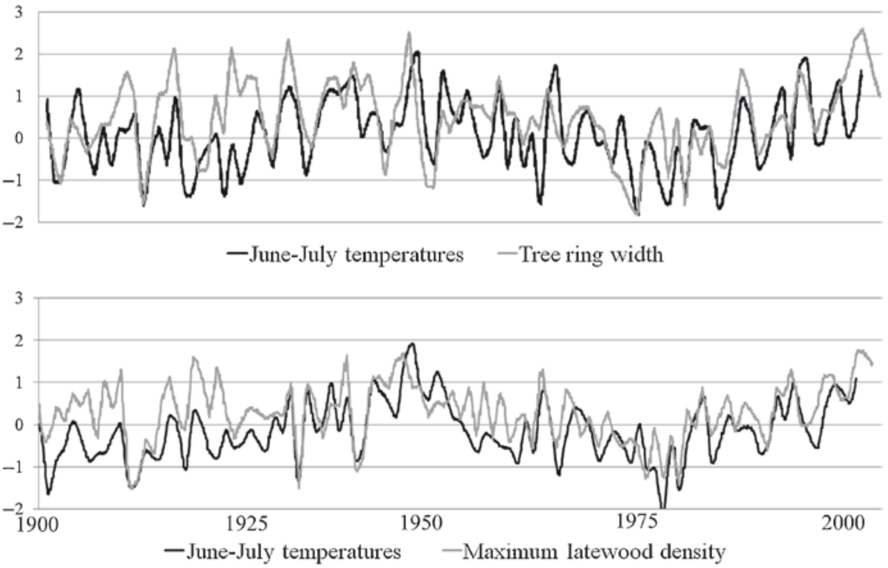

Fig. 7.14 Comparison of the observed (black) and predicted (grey) temperatures, after scaling (**a**) the tree-ring width (TRW)-based mean chronology against June–July temperatures, and (**b**) the maximum latewood density (MXD)-based mean chronology against April–September temperatures (1901–2002). Temperatures are expressed as anomalies from the 1961–1990 mean. Correlations were significant at the 99.9% confidence level (Modified Büntgen et al. 2007)

For example Figure 7.15 shows a temperature reconstruction for the months January to April for 1170–1994 created from Scots pine chronologies (Przybylak et al. 2005). Figures 7.16 (spruce) and 7.17 (pine) present indexed chronologies and extreme years, produced using a moving window method (Wójcik et al. 2001).

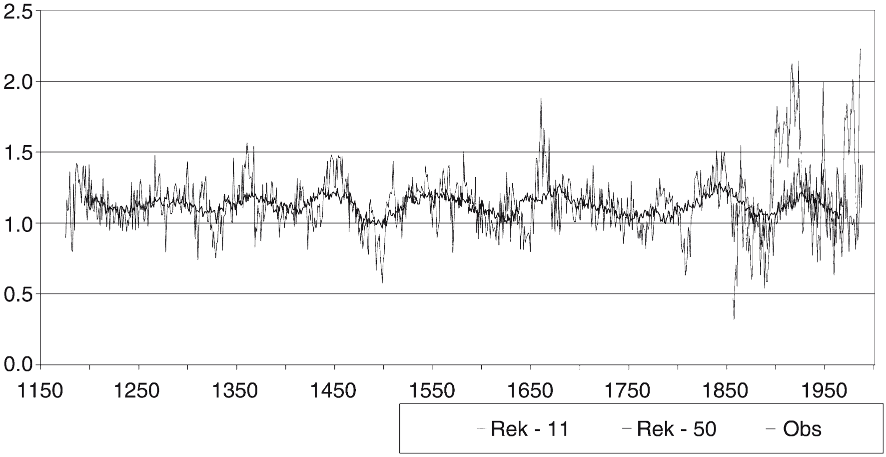

Fig. 7.15 Reconstruction of mean January–April air temperature (ºC) in Poland for the period 1170–1994 using a standardised chronology of Scots pine tree-ring widths (*Pinus sylvestris* L.) (Modified after Przybylak et al. 2005) Rek-ll, Rek-50 - 11- and 50-year running means; reconstruction using areally-averaged air temperatures from Warsaw, Bydgoszcz and Gdańsk for calibration, Obs – mean January–April areally-averaged air temperature from Warsaw, Bydgoszcz and Gdańsk (Przybylak et al. 2005; Przybylak 2007)

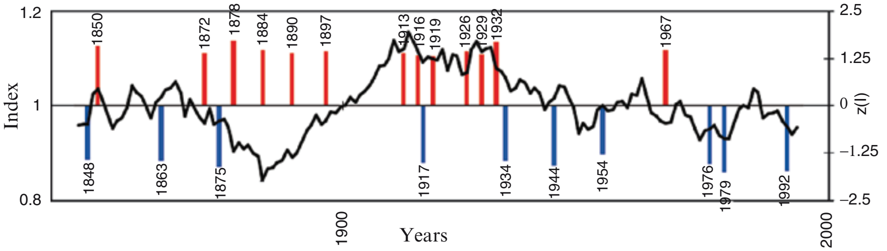

Fig. 7.16 Master plot of extreme years of Norway spruce in north-eastern Poland (Wójcik et al. 2001)

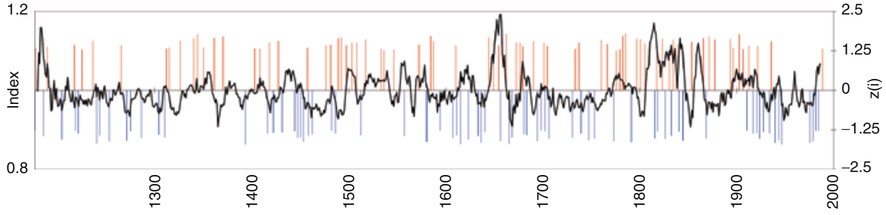

Fig. 7.17 Master plot of extreme years of Scots pine in north Poland (Wójcik et al. 2001)

The frequency of wide and narrow tree-rings in the chronologies show long periods of growth above the long-term mean, for example pine in the fourteenth century, the end of the nineteenth century, and below long-term mean growth, for example, in the decades after 1940. Similar results were obtained for Norway spruce.

7.4 Conclusions

The reconstruction of temperature conditions for Poland, based on tree-rings of coniferous trees (pine, spruce and fir) have been presented, and the high dendroclimatological potential of other trees growing in Poland was also shown. As yet relatively few reconstructions have been carried out. One reason for this is that during the 1980s when such research was being carried out elsewhere, long historical and archaeological chronologies were not available in Poland. Such data have commercial application in wood dating, and this sometimes leads to problems in the sharing of information.

Given that there are observed relationships between temperature variation and tree-ring chronologies, the most useful potential for climatic reconstructions may be the multi-millennial oak chronologies from natural sites such as the alluvial deposits of the River Vistula, and from archaeological sites, such as the Hallstat era settlements in Biskupin.

Analysis of climate/growth relations was also conducted with other, non-native species. It is worthwhile remember that this kind of research was carried out on Douglass fir, growing on many sites in Poland (Feliksik and Wilczyński 2004). Reaction of this tree to climate is similar to related with Douglass fir, together in *Pinaceae* family, Scots pine and can also proved about well adaptation of *Pseudotsuga* to environmental conditions of Poland. These observations can have an important bearing in discussions about the possible prediction of forest composition in the presence of prejected climate changes.

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Chapter 8
Geophysical Data

Jan Šafanda and Jacek Majorowicz

8.1 Introduction

The thermal "memory" of the Earth under its surface permits the reconstruction of a long-term ground surface temperature history (GST). Data comes from temperature profiles measured in fluid-filled deep wells. In recent decades the Functional Space Inversion (FSI) technique has mostly been used (Shen and Beck 1991; Shen et al. 1995) for this purpose in variety of regional, continental and global studies (e.g. Čermak 1971; Lachenbruch and Marshall 1986; Harris and Chapman 1998, 2001; Pollack and Huang 2000; Majorowicz et al. 2004a; Bodri and Čermak 2007).

Reconstructions of GST histories using the FSI method usually have a low time resolution, which gradually deteriorates as the elapsed time increases. Such behaviour is a result of the diffusive propagation of the surface temperature changes causing the decrease of the temperature signal with increasing depth. As a result, the reconstructed GST using inversion techniques is averaged for longer and longer periods the further back we go. Harris and Chapman (1998) have proposed a different approach to the method. According to them, the most realistic application of the geothermal method is its use in determining average GST prior to the period of instrumental observation. They called their method "Pre-observational Mean Temperature" (POM). In the accepted model it is assumed that annual GST variations in the period of instrumental observation are the same as air temperature variations measured in a standard meteorological station. The pre-instrumental air

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temperature mean and its offset from the GST is determined by the best fit between the measured and synthetic anomalies of rock temperature with depth, when the POM is used together with measured air temperature series in calculating the synthetic profile.

Recently, reconstructions of the GST history for Poland using well temperature profiles in equilibrium wells have been constructed and compared with proxy and instrumental records of recent centuries climatic change (Majorowicz et al. 2001, 2004b, 2008; Šafanda et al. 2004). First results were based on precise temperature logs in south western Poland in the Sudets region The results came from well temperature logs taken in an observational well, sufficiently old to be in thermal equilibrium, of the Polish Geological Institute by the Geothermal group of the Geophysical Institute of the Czech Academy of Sciences. These logs followed earlier work on GST history from temperature logs taken south of the border in Czech Republic where GST warming signatures were derived using inversion techniques (Šafanda et al. 1997).

In this paper, we present a summary of the results of the borehole temperature logs across Poland (Fig. 8.1) derived GST history for the last 500 years. We compare it with the longest homogenised Surface Air Temperature (SAT) series of Warsaw (Lorenc 2000) station, where the observations started in 1779.

8.2 Review of GST Reconstruction in Poland Using Geothermal Data

Majorowicz et al. (2001, 2004b, 2008) and Šafanda et al. (2004) analysed available temperature logs for Poland, deriving the amplitude of the temperature change in recent centuries (Majorowicz et al. 2001, 2004b), as well as the long term climatic change of the Pleistocene-Holocene transition and the recent climatic changes of the last 100 years (Šafanda et al. 2004; Majorowicz et al. 2008). The FSI technique was used. It permitted reconstruction of the GST for the last 500 years (Majorowicz et al. 2001, 2004b). Comparison of the GST with the recently homogenised annual air temperature records from Warsaw (Lorenc 2000) and a summary of other proxy and instrumental records through Poland (Przybylak et al. 2005; Wójcik et al. 1999, 2000) showed that the all temperature profiles during the last 200 years were very similar. The amplitude of GST warming deduced from the individual inversions of well temperature data using the FSI method was (0.9°C ± 0.3°C). The inversions of the deep continuous logs and of the deep accurate temperature depth profiles showed excellent agreement with the homogenised Warsaw temperature time series (Majorowicz et al. 2004b). However, when shallow accurate temperature logs from the upper 150 m were inverted, the minimum GST shifted towards the beginning of the twentieth century in comparison with GST histories from the deep logs and the Warsaw temperature time series. The spurious minimum of the GST history was interpreted as being created artificially by the use of the inversion procedure on a temperature profile of restricted depth.

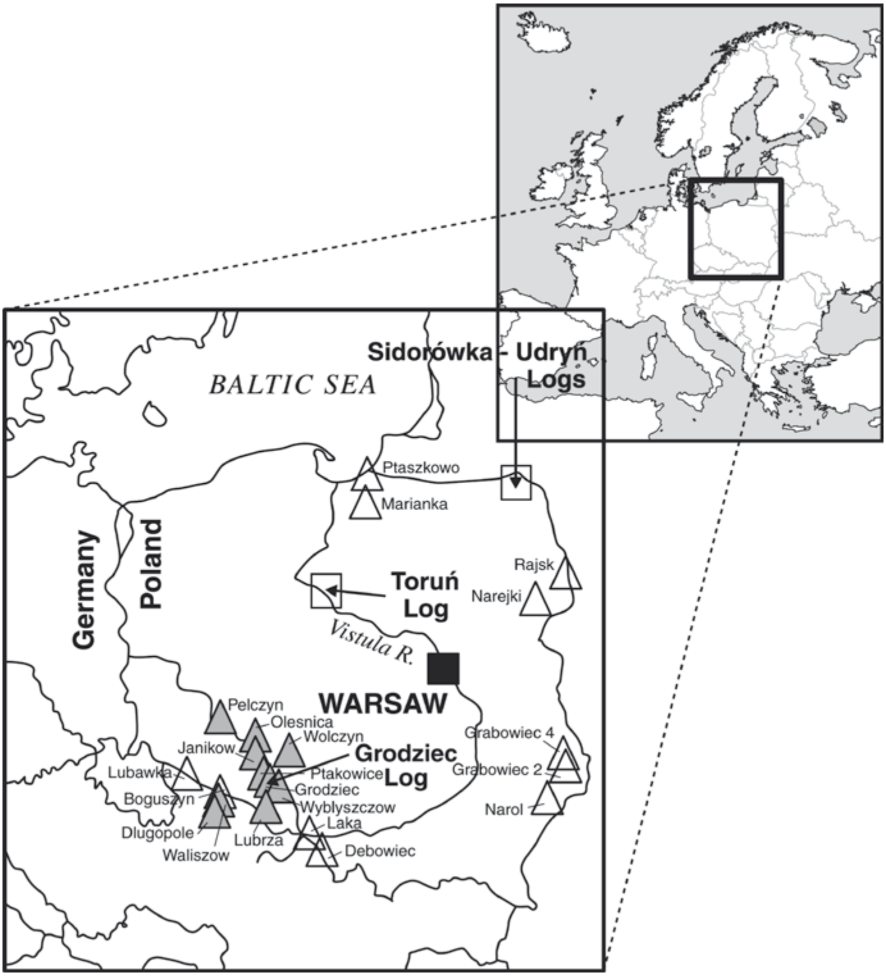

Fig. 8.1 Location of source data used in the present paper: *unfilled triangles* – boreholes with continuous temperature logs (11 deep wells with continuous industrial temperature logs done in 1970th); *filled triangles* – high precision point temperature logs taken in equilibrium observational wells in 1996; *open squares* – deep temperature logs taken after 2000 (Toruń 1 in 2005 -continuous log and 2006 precise point logs and Sidorówka in 2003); *black square* – long-term series of air temperature from Warsaw. All wells were used for the reconstructions presented in Fig. 8.3

Vertical distribution of transient mean anomaly of rock temperatures for Poland from continuous temperature profiles from deep >0.5 km wells allowed GST- POM reconstructions, using the method of Harris and Chapman (Harris and Chapman 1998). These were used for comparison with other proxy and instrumental records of change (Przybylak et al. 2005). The history of annual air temperature in Warsaw (Lorenc 2000) and the most probable long-term mean of the pre-observational GST history (i.e. that which best fits the observable temperature anomalies with the depth) compared well (Przybylak et al. 2005, see their Fig. 7B). The difference calculated between the mean temperature for the period 1951–1981 and the mean temperature for the pre-observational period (prior to 1779) was found to be 1.53°C. The modelling studies indicated that the contemporary long-term mean of the annual air/ground temperature in Poland is significantly higher (>1.5°C) than the long-term mean from the period 1500–1778. This difference is about two times greater than its analogous value calculated from borehole temperatures located in the Northern Hemisphere (0.7°C; Harris and Chapman 2001). It is also greater than the GST increase for SW Poland calculated using the FSI technique (some 1°C; Majorowicz et al. 2001, 2004b).

It seems that one reason for this divergence of the results in Poland might be the differences in the assumptions that are inherent in both methods. Harris and Chapman's method is based on the assumption that the range of GST change in the instrumental period of observation is the same as the range of air temperature change measured at meteorological stations. In the FSI technique, reconstruction of the GST history is obtained using measurement of rock temperature in industrial wells from the surface to 300–500 m depth.

The assumption in Harris and Chapman's method used by Przybylak et al. (2005) – that changes in air temperature are similar to changes in the GST – may not apply to all of the well sites, since changes in land use may have occurred. In such locations and where systematic snow cover has changed, the assumption of Harris and Chapman, that GST changes match SAT changes, may not be valid. It was found (Skinner and Majorowicz 1999) that anthropogenic changes to land surface, like clearing for farming can influence surface temperature change and temperature-depth anomaly. However, in Poland land changes are not as recent as in Western Canada and it was observed (Majorowicz et al. 2004b) that for the range of observed time series FSI reconstructed temperature variations from deep precise well logs agree very well.

8.3 GST History from Joint Inversion

Considering together the two sets of profiles, namely 11 deep profiles measured in the 1970s and 12 shallower profiles measured in the 1996–2006 period, enables us to detect confidently both the long-term and the recent signals of the GST history inherent in the data. The logs are shown graphically in the Appendix part (Fig. 8.2a–d). Their location is shown in Fig. 8.1.

The former set of about 500 m deep temperature logs documents the subsurface temperature field by the end of the 1970s, and they can provide information on the surface temperature variations in the second half of the last millennium, but the signal of the last 30–50 years before present is missing, as some of the temperature profiles start 30–50 m below the surface only. On the contrary, the latter set of mostly 100–300 m deep recent profiles contains signatures of the most recent variations, the reconstructed amplitude and timing of which can be biased due to uncertain estimates of the deeper, steady-state part of the profile (see Fig. 6b in Majorowicz et al. 2004b). In the case of the joint inversion, the steady-state part is provided by the deep profiles.

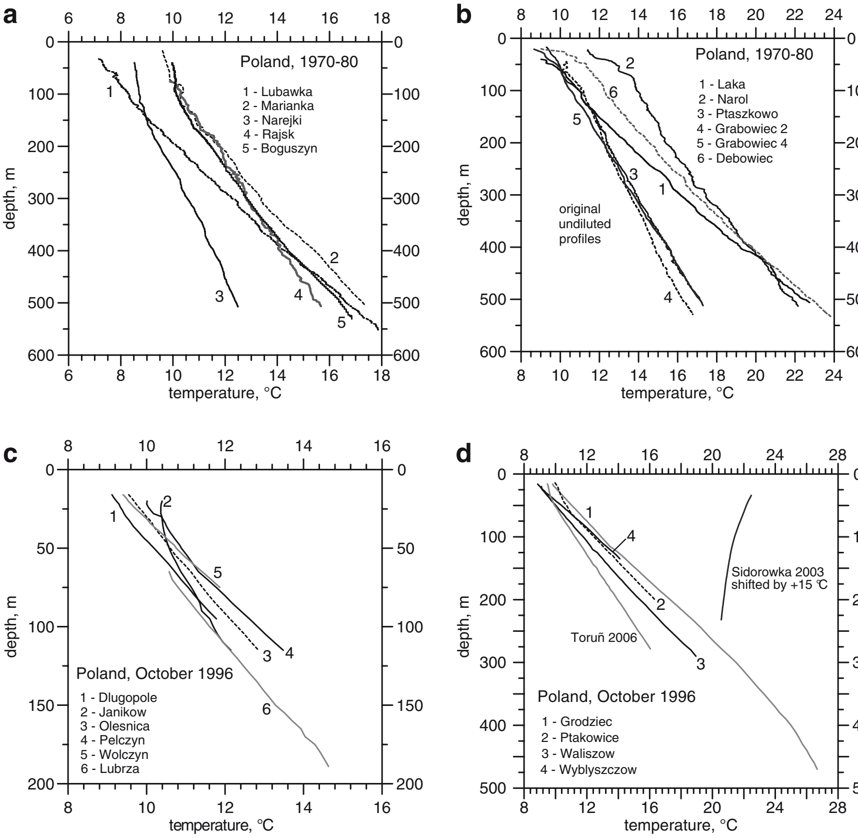

Fig. 8.2 (**a–d**) Thermal logs from Poland

The two joint inversions of the all 23 profiles shown in Fig. 8.3 differ in a choice of a priori standard deviations of the logged temperature data. The first choice of 0.5°C reflects a conservative estimate of a measurement precision of the ten profiles from the 1970–1980 period. The second choice distinguishes between these ten low precision logs (SD of 0.4°C) and the remaining high precision, more recent logs (SD of 0.1°C). As can be seen from Fig. 8.3, the corresponding GST histories differ appreciably only in the most recent history of the last 50 years, where considering the small SD of 0.1°C enabled extraction of the warming signal contained in the high precision logs. The inversion results suggest a gradual warming by 0.4°C since the beginning of the nineteenth through the middle of the twentieth centuries, followed by a more rapid warming by another 0.4°C by the end of the twentieth century.

The joint inversion of the whole set of the available profiles guarantees a robustness of the results, but on the other hand it may lead to suppressing amplitudes of the reconstructed GST variations. Therefore, we carried out also a joint inversion of

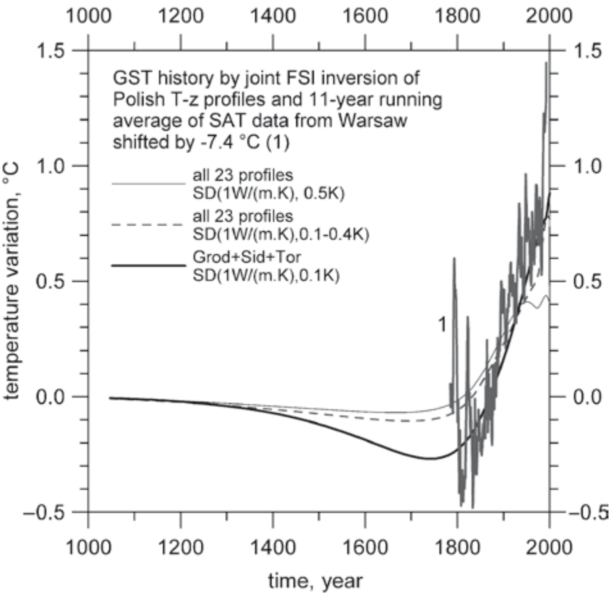

Fig. 8.3 Reconstruction of ground surface temperature (°C) (GST) history for Poland compared with homogenised instrumental temperature series from Warsaw (11-year running average) (Lorenc 2000). Note that Warsaw series is shifted by −7.4°C

three selected high precise temperature logs from wells at least 20 years in rest after drilling, namely that from boreholes Grodziec (16 m–470 m deep), Toruń (16 m–278 m) and Sidorówka (34 m–232 m), which span Poland from SW to NE. The results confirm the warming trend evidenced by the inversion of the all 23 logs. In addition to it, they indicate a GST minimum in the middle of the eighteenth century, followed by a gradual warming, which accelerated in the last decade of the twentieth century. An overall amplitude of the warming is 1.0°C–1.2°C.

Having in mind the decreasing resolution power of the geothermal method when going back in time, we see very good correspondence between the reconstructed history and the homogenised SAT series from Warszawa meteorological station (Lorenc 2000). The 11-year running average of the Warszawa series shifted by −7.4°C is superposed with the reconstructed history in Fig. 8.3.

8.4 Concluding Remarks

A very good correspondence of the results has been found between reconstructed series of annual mean GSTs and mean seasonal air temperatures reconstructed using documentary evidence from the longest series in Poland. Geothermal logs indicate that the ground surface temperature (GST) minimum in the middle of the eighteenth century is followed by a gradual warming, which accelerated in the last decade of the twentieth century. An overall amplitude of the warming is 1.0°C–1.2°C.

Other proxy records (Przybylak et al. 2005) also showed that the twentieth century was exceptionally warm. All mean winter 10-year air temperatures in the period 1501–1840 were colder than in the twentieth century. Anomalies of the majority of mean decadal temperatures oscillated between −2°C and −3°C in comparison with the 1901–1960 mean. On the other hand, summers were generally slightly warmer than in the twentieth century. This would suggest that high warming GST derived from inversion of well temperature logs was mainly non-summer driven.

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Chapter 9
Concluding Remarks to Part II

Rajmund Przybylak

Historical climatology has gained the status of a separate scientific discipline in recent years. The extraordinarily dynamic development of research in this field is closely connected to research into future climate scenarios, the past being the key to the future. Credible scenarios of future climates cannot be created without information about past climatic changes and the factors which affected them. First and foremost a knowledge of the range of natural climate variability is necessary, and this can be obtained only through the analysis of information concerning the weather and climate from the pre-industrial period (i.e. before 1850). Knowledge in this field is also necessary for the purposes of evaluating the potential contribution of natural factors in current and future climate changes. Furthermore, it allows us to answer unequivocally the question of how big the contribution of the anthropogenic factors is in these changes. A broader knowledge of climates of the past is also necessary to validate mathematical climatic models. If they simulate past climates well, it is possible to assume with great probability that simulations of future climates will also be credible. Moreover, the climate, particularly in its extreme manifestations, affects considerably the changes of both the natural and manmade environments (it is enough to recall the flood of 1997 in Poland or the extent of damages done by tropical cyclones in New Orleans and in Florida in 2005). Therefore, without a knowledge of climate changes it is not possible to explain credibly the extent of, and reasons for, the changes in man's environment (both natural and manmade) in the past millennium. A knowledge of the climates of past centuries has an inestimable practical value and thus paleoclimatic research, particularly that including the past millennium, should be conducted as broadly as possible. Polish science ought not to shirk its responsibilities in this respect, particularly considering that our knowledge in this field for the territory of Poland – despite the finding of various research projects in recent years – is still insufficient and lags far behind comparable research initiatives in other European countries. This is testified to in an article by Brázdil et al. (2005) titled "Historical Climatology

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in Europe: The State of the Art" which summarises the state of knowledge on historical climatology in the continent as a whole. From Polish perspective, further studies, partly published in Polish language and in national journals, could be added to extensive list of quoted references (e.g. Maruszczak 1991; Sadowski 1991; Wójcik et al. 1999, 2000; Majorowicz et al. 2001, 2004; Przybylak et al. 2001, 2004; Kotarba 2004).

As mentioned earlier, discovering the natural variability of the climate is of significance for the detection of climate changes and the factors affecting them, the scale of which can only be precisely and credibly determined through the use of indirect data for the past millennium. At present we have many climatic reconstructions at our disposal for selected regions of the world (e.g. Pfister 1999; Rácz 1999; Proctor et al. 2000; Glaser 2001; Brázdil 2002; Briffa et al. 2002a, b; Luterbacher et al. 2004; Pauling et al. 2006; see also Part 1), as well as for the Northern Hemisphere and the earth as a whole (e.g. Mann et al. 1998, 1999, 2008; Jones et al. 2001; McIntyre and McKitrick 2003; Moberg et al. 2005; Juckes et al. 2007).

Our present knowledge of the climate changes in Poland over the past millennium is varied. For obvious reasons it is much better for the period of instrumental observations. In the 1990s considerable effort was expended on obtaining homogeneous air temperature series. As a result there now exist at least ten such series (Górski and Marciniak 1992; Miętus 1996, 1998; Głowicki 1997; Trepińska 1997; Lorenc 2000; Vizi et al. 2000/2001; see also Chapter 5). The most valuable of them are the series from Warsaw (from 1779) and from Cracow (from 1792). The high correlation of air temperature in the area of Poland allows us to use the last two temperature series to characterise thermal conditions throughout Poland.

In recent decades knowledge of the climate history of Poland has increased considerably. This can also be said for our climatic knowledge of the so-called pre-instrumental period, though very seldom does this knowledge go back further than the past 500 years (cf. e.g. Michalczewski 1981, 1988; Maruszczak 1988, 1991; Sadowski 1991; Bednarz 1996; Wójcik et al. 1999, 2000; Bokwa et al. 2001; Limanówka 2001; Majorowicz et al. 2001, 2004; Przybylak et al. 2001, 2003, 2004, 2005; Oliński 2002a, b; Kaczka 2004; Kotarba 2004; Niedźwiedź 2004; Przybylak 2007; see also Chapters 5–8).

As may be seen from this brief review, our knowledge of the climate of Poland of the last millennium has increased considerably, though it is far from sufficient and is certainly too low in relation to the capabilities that Polish scientist possess. In comparison with leading European countries in this area (e.g. the Czech Republic, Switzerland) our knowledge of past climate changes in Poland is lagging behind. This stems from the fact that awareness among Polish researchers of the importance of this subject for scientific, social and economic development is still too low, although progress has been evident in recent years related to the increasing publicity given to the issue of global warming. On this point the need to intensify climate research (including paleoclimatic research) is frequently mentioned, as is the significant role of such work for the progress of the civilized world.

The dearth of research about climate changes in Poland in recent centuries prompted scholars at the Nicolaus Copernicus University Department of

Climatology, to organize an international conference in Toruń (Poland) in October 2007. The main its aim was to mobilise Polish and international researchers to investigate the history of weather and climate in Poland. The results of some of the resulting research efforts, published in Parts 1 and 3, testify to the success of the initiative – our knowledge in this area is now markedly greater, though a lot of work remains to be done.

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Part III
The Climate of Poland and Europe in Recent Centuries: New Findings Results

Chapter 10
Long-Term Changes of Bioclimatic Conditions in Cracow (Poland)

Krzysztof Błażejczyk and Robert Twardosz

10.1 Introduction

Fluctuations of climate during the last 200 years in many regions of our globe are well known. They influence all living organisms and human beings. Research of the changes of air temperature and other, individual elements of climate is undertaken frequently; however, studies dealing with fluctuations of bioclimatic conditions are rather rare. In Poland changes of bioclimatic parameters were studied in Cracow (Błażejczyk and Twardosz 2002; Błażejczyk et al. 2003), Łódź (Papiernik 2004), Kołobrzeg (Bąkowska and Błażejczyk 2007), and Szczawno (Błażejczyk 2007). In Europe multiannual series of bioclimatic indices are known from Slovenia (Cegnar and Matzarakis 2003), Croatia (Zaninovic and Matzarakis 2003) and Austria (Rudel et al. 2005, 2007). The rarity of retrospective bioclimatic research is due to the necessity of use of a wide complex meteorological elements, i.e. air temperature, cloudiness, wind speed, air humidity.

The aim of this paper is to present the fluctuations of selected bioclimatic indices in particular seasons in Cracow during the period of 1826–2006.

10.2 Materials and Methods

The research is based on data from Jagiellonian University climatic station that have been working continuously from 1792 in the Botanical Garden in Cracow (Trepińska 1997). Monthly values of the aforementioned climate elements for

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12:00 UTC were used for the period of 1901–2006. For the period of 1826–1900, the bioclimatic conditions were reconstructed based on midday air temperature.

10.3 Bioclimatic Indices Used

Meteorological data were used to calculate a set of bio-thermal indices. In the present paper the time series for January, April, July and October are taken into consideration as months representing particular seasons: winter, spring, summer and autumn.

Two groups of indices were applied:

- Simple (but with physiologically relevant information): Wind Chill Temperature (*WCT*), *HUMIDEX* and accepted level of physical activity (*MHR*)
- Biothermal (based on human heat balance considerations): Physiological Subjective Temperature (*PST*), Physiological Strain (*PhS*)

Wind Chill Temperature (*WCT*, in ºC) indicates thermal conditions caused by low air temperature and wind speed in cold season:

$$WCT = 13.12 + 0.6215t - 11.37(1.5v)^{0.16} + 0.3965t(1.5v)^{0.16}$$

where: t is air temperature (ºC) and v is wind speed (m s^{-1}).

According to Environment Canada (www.msc.ec.gc.ca), *WCT*-related hazards are as follows:

WCT (°C)	Description	Health concern
Greater than −10	Low	Slight increase in discomfort
−10 to −25	Moderate	Uncomfortable, exposed skin feels cold, risk of hypothermia without adequate protection
−25 to −45	Cold	Risk of frostbite, check face and extremities (e.g. toes, ears) for numbness or whiteness, risk of hypothermia
−45 to −60	Very cold	Warning level, exposed skin freezes in minutes, serious risk of hypothermia
Less than −60	Extreme	Danger level, outdoor conditions are hazardous, exposed skin freezes in 2 min

HUMIDEX (°C) represents outdoor temperature in warm season felt by man in hot and humid environment. It is calculated as follows (www.ccohs.ca):

$$HUMIDEX = t + 0.5555(vp - 10)$$

where vp is air vapour pressure (hPa).

According to Environment Canada, *HUMIDEX*-related hazards are as follows:

HUMIDEX (°C)	Danger category	Heat syndrome
<30	Caution	No discomfort. Fatigue possible with prolonged exposure and activity
30–40	Extreme caution	Some discomfort, possible heat stroke, heat exhaustion and heat cramps due to prolonged exposure and activity
40–55	Danger	Great discomfort, avoid exercise. Heat cramps or heat exhaustion likely. Heat stroke possible due to prolonged exposure and activity
>55	Extreme danger	Heat stroke imminent with continued exposure

Accepted level of physical activity (*MHR*, W m^{-2}) indicates the limit value of activity which does not provoke the rise of heart rate above 90 beats per minute in given meteorological conditions. *MHR* is calculated as follows:

$$MHR = [90 - 22.4 - 0.25(5t + 2.66vp)]/0.18$$

According to ISO standard (ISO 8996; Fanger 1970; Błażejczyk 2004) different kinds of activities lead to particular metabolic energy productions (*M*). For example, a sitting person $M = 60$ W m^{-2}, a standing posture $M = 70$ W m^{-2}, at walking 4 km/h $M = 135$ W m^{-2}, at walking uphill 4 km/h $M = 210$ W m^{-2}, when playing tennis $M = 270$ W m^{-2}, when playing football $M = 440$ W m^{-2}.

The other indices applied were derived from the human heat balance model **MENEX_2005** (Błażejczyk 2007; Błażejczyk and Matzarakis 2007). The general equation of the heat balance assumes the form:

$$M + Q + C + E + Res = S$$

where: *M* is metabolic heat production (both basic metabolic rate, and metabolic energy production due to activity and workload), *Q* is a person's radiation balance, *C* is heat exchange by convection, *E* is heat loss by evaporation, *Res* is heat loss by respiration and *S* is net heat storage, i.e. changes in body heat content. For long periods (24 h or longer) *S* can be considered equal to zero, in that heat gains are equilibrated by heat losses. All fluxes are expressed in W m^{-2}. Equations used for the calculations of the human heat balance and bio-thermal indices are provided in the Annex 10.1.

As output the MENEX_2005 model provides several characteristics, such as the components of the human heat balance and various indices that were used in the present paper. They illustrate various aspects of the man-environment relationship.

Physiological Subjective Temperature (*PST*, °C) represents the subjective perception of the thermal environment by persons after 20 min of adaptation to ambient conditions. The perception is the effect of signals from cold and warm receptors in the skin and in the nervous system. The particular ranges of *PST* indicate various thermal sensations in man as follows:

Less than −36.0°C	Frosty
−36.0 to −16.1	Very cold
−16.0 to −4.0	Cold
4.1–14.0	Cool
14.1–24.0	Comfortable
24.1–34.0	Warm
34.1–44.0	Hot
44.1–54.0	Very hot
>54.0	Sweltering

Physiological Strain (*PhS*, dimensionless) expresses the predominant adaptation processes in a cold or warm environment that equilibrate heat gains and heat losses. *PhS* also indicates which physiological processes adapt human organism to given outdoor conditions (Błażejczyk 2003, 2005). The following scale of physiological strain intensity is applied:

<0	Extreme hot strain
0.0–0.25	Great hot strain
0.26–0.75	Moderate hot strain
0.76–1.50	Thermoneutral (slight strain)
1.51–4.00	Moderate cold strain
4.01–8.00	Great cold strain
>8.00	Extreme cold strain

The values of bioclimatic indices were obtained for monthly data. Because of that, they can not be considered as fully physiological characteristics, but as indicators which illustrate the multiannual variability of bioclimatic conditions formed by climatic parameters.

All the bio-thermal indices were calculated with the use of BioKlima v.2.5. software package (www.igipz.pan.pl/geoekoklimat/blaz/bioklima.htm). Statistical relationships were analysed using STATGRAPHICS Plus 2.1 software package.

10.4 Results

10.4.1 Reconstruction of Bioclimatic Conditions for the Years 1826–1900

As mentioned above, we have at our disposal a detailed, complete set of meteorological data (air temperature – *t*, cloudiness – *N*, vapour pressure – *e*, relative humidity of air – *f*, wind speed – *v*) that are necessary for the calculations of bioclimatic indices for the period of 1901–2006. The reconstruction of bioclimatic indices for the years 1826–1900 was performed in three steps.

In the first step the bioclimatic indices (*WCT*, *HUMIDEX*, *MHR*, *PST* and *PhS*) were calculated for the last 106 years based on the full set of meteorological data. In the next step, the values of bioclimatic indices were correlated with midday monthly air temperature. A good correlation between the compared values was found. For simple indices (*WCT*, *HUMIDEX*, *MHR*), the determination coefficients were equal to 100%. For the biothermal indices derived from the human heat balance (*PST*, *PhS*) the relationships were slightly weaker because of their complexity (the values of *PST* and *PhS* depend not only on air temperature but also on cloudiness, air vapour pressure and wind speed). However, the determination coefficients were still very high (96–97%, Fig. 10.1). Finally, these regression equations were used to calculate the bioclimatic indices for the period of 1826–1900.

10.4.2 Fluctuations of Bioclimatic Conditions

The results obtained for particular seasons show different tendencies in changes of bioclimatic conditions during the studied period. Statistically significant trends (at 99% confidence level) were observed for winter months. Statistical significance for the biothermal indices (*PST*, *PhS* (at 95% confidence level)) was also found for spring (Table 10.1).

In January, the Wind Chill Temperature increased by 2.17°C per 100 years. A significant rise of 0.95°C per 100 years was also noticed for the Physiological Subjective Temperature. Both indices show a gradual increase during the analysed period. However, two periods with low temperatures were observed: from 1848 to 1851, and from 1940 to 1942 (Figs 10.2 and 10.3). On the other hand, for the *MHR* and *PhS* indices, a significant winter decrease was found (Figs 10.4 and 10.5) during last 180 years. All the indices show a gradual softening of bioclimate in winter months. Sensible temperatures (*WCT*, *PST*) significantly increased. The accepted level of physical activity (*MHR*) decreased from about 380 W m^{-2} in the first years of the studied period to 350 W m^{-2} in the last. Also, the values of *PhS* indicate milder physiological reactions to cold: they changed from very intensive in the first half of the nineteenth century to moderately intensive in the beginning of the twenty-first century.

For the spring months the trends in bioclimatic indices are still statistically significant. However, the relationships are weaker than in January. The *PST* increased from about 1°C at the beginning to 4°C at the end of the studied period (Fig. 10.3). The *PhS* indicates a gradual reduction of the intensity of physiological processes adapting the human organism to cold (Fig. 10.5).

For summer and autumn we have not found any statistically significant trends in bioclimatic indices. Both simple and biothermal indices did not change during the studied period. However, in July two sub-periods of relatively warm conditions were noted. The first one occurred in the first decade of the studied series, and the second one in the years 1990–1995.

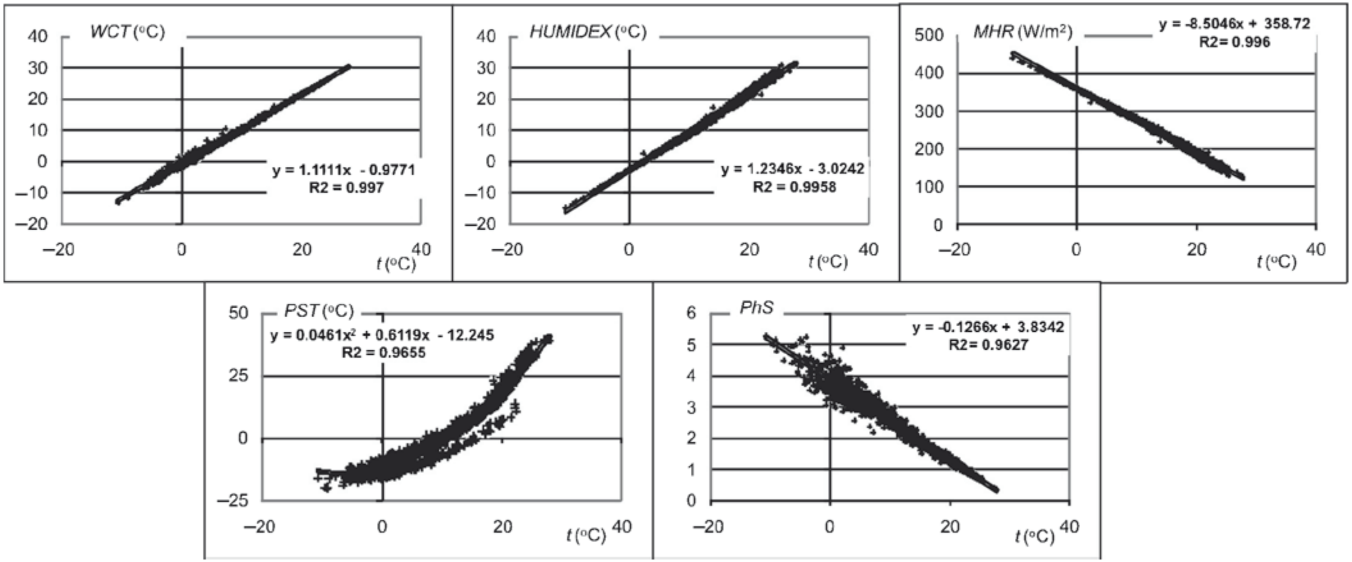

Fig. 10.1 Statistical relationships between the mean monthly midday air temperature (*t*), and the bioclimatic indices (*WCT*, *HUMIDEX*, *MHR*, *PST*, *PhS*) for Cracow, 1901–2006

Table 10.1 Statistical characteristics of long-term trends in bioclimatic indices in Cracow (Poland), 1826–2006

Bioclimatic	January		April		July		October	
indices	d	r	d	r	d	r	d	r
PST (ºC)	**0.95**	**0.218**	***1.37***	***0.162***	–0.10	–0.009	0.62	0.075
WCT (ºC)	**2.17**	**0.305**	–	–	–	–	–	–
HUMIDEX (ºC)	–	–	–	–	–0.17	0.039	–	–
MHR (W m^{-2})	**–15.10**	**–0.291**	2.80	0.076	–1.10	–0.037	–0.60	–0.018
PhS	**–0.36**	**–0.392**	***–0.10***	***–0.145***	0.03	0.061	–0.07	–0.112

d, trend rate of index per 100 years; r, correlation coefficients

Trends statistically significant at 99% confidence level are in **bold**, at 95% confidence level – ***in bold, italic***

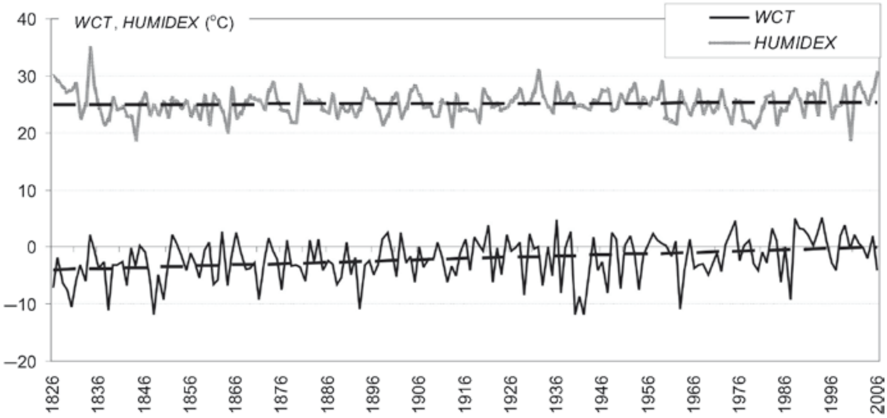

Fig. 10.2 Long-term changes of wind chill temperature (*WCT*) and *HUMIDEX* indices in Cracow, 1826–2006

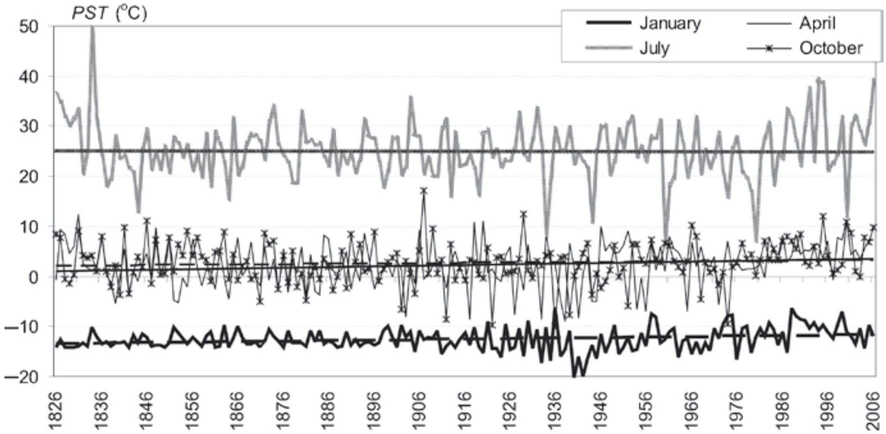

Fig. 10.3 Long-term changes of physiological subjective temperature (*PST*) index in particular months in Cracow, 1826–2006

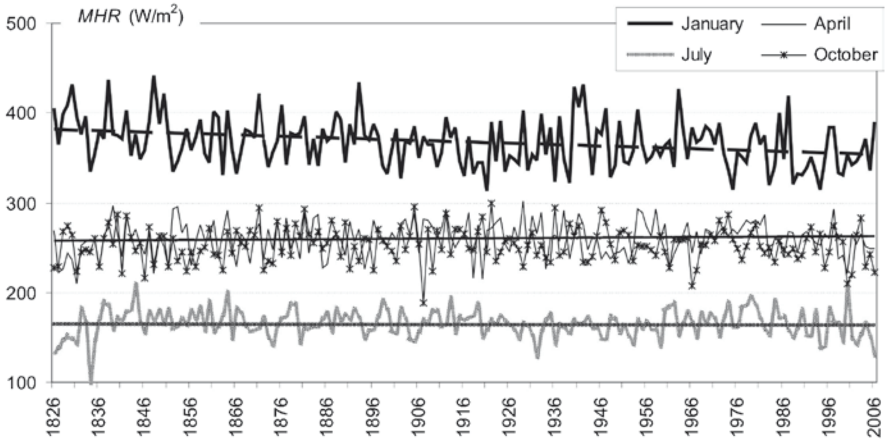

Fig. 10.4 Long-term changes of the index of accepted level of physical activity (*MHR*) in particular months in Cracow, 1826–2006

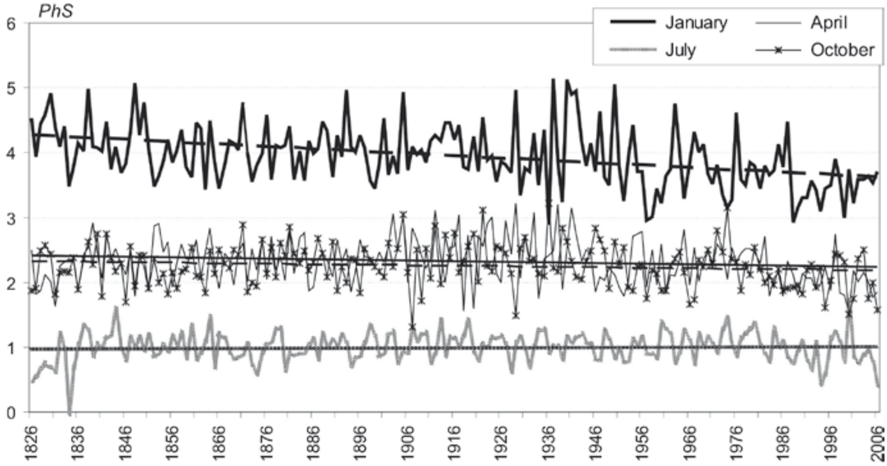

Fig. 10.5 Long-term changes of physiological strain index (*PhS*) in particular months in Cracow, 1826–2006

10.5 Discussion

Several studies have dealt with recent fluctuations and changes in climate. The changes in air temperature (t) are well established. Trends for t observed in Poland are similar to those noted in Central Europe as a whole (Kożuchowski et al. 1994; Niedźwiedź et al. 1994; Trepińska 1997; Kożuchowski and Żmudzka 2002). Kozłowska-Szczęsna and Podogrocki (1995) described a trend for the actual sunshine duration (ASD) in Warsaw over the period of 1903–1990 showing a general decrease in ASD of 78 min per year.

The changes in particular meteorological elements are correlated with fluctuations in air circulation which can be illustrated by three indices: western circulation, southerly circulation and cyclonicity (Błażejczyk et al. 2003). In southern Poland the long-term variation is the greatest in the case of the western circulation index which is influenced by the Atlantic air masses. A relatively low variability was noted for the southerly circulation index. The cyclonicity index shows that the anticyclonic circulation dominated in southern Poland over the last century.

The variability in sensible climate was studied rarely. Błażejczyk and Twardosz (2002) as well as Błażejczyk et al. (2003) have studied the changes in two bioclimatic indices in Cracow for the period of 1901–2000. Mean annual *STI* values of subjective temperature showed a slightly positive secular trend of 2.24°C. However, for predicted clothing insulation a slight negative trend (–0.11 clo per 100 years) was established. Both trends point to a gradual intensification of the heat stress in southern Poland.

Similar trends were observed in biothermal features of weather for the period 1965–2000 for west-southern and northern Poland (Bąkowska and Błażejczyk 2007; Błażejczyk 2007) as well as for central Poland (Papiernik 2004). The author found also close relationships between weather conditions in particular years and the intensity of tourist flows in the studied regions.

For the period of 1951–2000, Cegnar and Matzarakis (2003) have found that Slovenia's climate is changing as well. The results of their study show significant spatial and seasonal differences. Significant changes were noted both for single meteorological elements, and for the Physiological Equivalent Temperature (*PET*), a complex bioclimatic index.

Till now the longest period of bioclimatic variability (1867–2000) was analysed by Zaninovic and Matzarakis (2003) for the Croatian city of Hvar. The researchers used two indices: *PET* and Predicted Mean Vote. Both indices showed increasing trends in all seasons. These positive trends were the result of increasing temperatures, and decreasing wind speeds. The greatest significant change was found for the *PET* in winter, and for mean annual *PET* values (around 0.4°C per 100 years).

The changes of bioclimatic indices established in the present study are similar to those reported for Poland and for Southern Europe by other authors.

10.6 Conclusions

The bioclimatic indices considered in the present research show a variation during the studied period (1826–2006). They indicate significant changes in bioclimatic conditions, mainly in winter season. However, in summer and autumn months the changes in bioclimatic conditions are insignificant.

Annex 10.1 Equations used for the calculations of the human heat balance and bio-thermal indices

$$Q = L + R$$
$$L = (Lg + La - Ls)\cdot Irc$$
$$Lg = 0.5\cdot[0.97\cdot\times 5.667\cdot\times 10^{-8}\cdot(273 + Tg)^{4}]$$
$$La = 0.5\cdot\{0.97\cdot\times 5.667\cdot\times 10^{-8}\cdot(273 + t)^{4}\cdot[0.82–0.25\cdot 10^{(-0.094\cdot vp)}]\}$$
$$Ls = 0.95\cdot\times 5.667\cdot\times 10^{-8}\cdot(273 + Tsk)^{4}$$
$$Tsk = (26.4 + 0.0214\cdot Mrt + 0.2095\cdot t - 0.0185\cdot RH - 0.009\cdot v)+0.6\cdot(Icl - 1) + 0.00128\cdot M$$
$$Irc = hc'/(hc' + hc + 21.55\cdot\times 10^{-8}\cdot T^{3})$$
$$hc = (0.013\cdot ap - 0.04\cdot t - 0.503)\cdot(v + v')^{0.4}$$
$$hc' = (0.013\cdot ap - 0.04\cdot t - 0.503)\cdot 0.53/\{Icl\cdot[1 - 0.27\cdot(v + v')^{0.4}]\}$$
$$Icl = 1.691 - 0.0436\cdot t \quad (\text{at } t < -30^\circ\text{C } Icl = 3.0 \text{ clo, and at } t > 25^\circ\text{C } Icl = 0.6 \text{ clo})$$
$$Mrt = [(R/Irc + Lg + La)/(0.95\cdot 5.667\cdot\times 10^{-8})]^{0.25} - 273$$
$$R = (1.64 + 0.254\cdot h)^{2}\cdot(1 - 0.01\cdot ac)\cdot Irc \ (\text{at } h < 4^\circ)$$
$$R = (103.6\cdot \text{Ln}h - 140.6)\cdot(1 - 0.01\cdot ac)\cdot Irc \quad (\text{at } h > 4^\circ \text{ and } N <= 20\%)$$
$$R = 1.4\cdot e^{(5.38 - 16.07/h)}\cdot(1–0.01\cdot ac)\cdot Irc \quad (\text{at } h > 4^\circ, N = 21–50\%)$$
$$R = 1.4\cdot e^{(5.01 - 11.8/h)}\cdot(1 - 0.01\cdot ac)\cdot Irc \quad (\text{at } h > 4^\circ, N = 51–80\%)$$
$$R = 0.951\cdot h^{1.039}\cdot(1 - 0.01\cdot ac)\cdot Irc \quad (\text{at } h > 4^\circ, N > 80\%)$$
$$E = he\cdot(vp - vpsk)\cdot w\cdot Ie–[0.42\cdot(M - 58) - 5.04]$$
$$vpsk = e^{(0.058\cdot Tsk+2.003)}$$
$$w = 1.031/(37.5 - Tsk) - 0.065 \quad (\text{at } Tsk > 36.5^\circ\text{C } w = 1.0, \text{ at } Tsk < 22^\circ\text{C } w = 0.001)$$
$$he = [t\cdot(0.00006\cdot t - 0.00002\cdot ap + 0.011) + 0.02\cdot ap - 0.773)]\cdot 0.53/\{Icl\cdot[1–0.27\cdot(v + v')^{0.4}]\}$$
$$Ie = hc'/(hc' + hc)$$
$$C = hc\cdot(t - Tsk)\cdot Irc$$
$$Res = 0.0014\cdot M\cdot(t–35) + 0.0173\cdot M\cdot(0.1\cdot vp–5.624)$$
$$PhS = C/E$$
$$PST = iMrt–\{[|SR|^{0.75}/(5.39\cdot\times 10^{-8}) + 273^{4}]^{0.25}–273\} \ (\text{at } SR < 0)$$
$$PST = iMrt + \{[|SR|^{0.75}/(5.39\cdot\times 10^{-8}) + 273^{4}]^{0.25}–273\} \ (\text{at } SR >= 0)$$
$$iMrt = \{[R + (La + Lg)\cdot Irc + 0.5\cdot Ls]/(0.95\cdot 5.667\cdot\times 10^{-8})\}^{0.25} - 273$$

ac –albedo of clothing (%)
C – heat exchange by convection (W·m^{-2})
h – Sun altitude (°)
hc′ – coefficient of turbulent heat transfer through clothing (K W^{-1} m^{-2})
Icl – clothing insulation (clo)
iMrt – mean radiant temperature under clothing (°C)
L – net long-wave radiation in man (W·m^{-2})
La – thermal radiation of atmosphere (W·m^{-2})
Ls – thermal radiation of human body (W·m^{-2})
Mrt – mean radiant temperature (°C)
PhS – physiological strain (dimensionless)
Q – radiation balance in man (W·m^{-2})
Res – respiratory heat loss (W·m^{-2}),
S – net heat storage (before acclimation, W·m–^{2})
t – air temperature (°C)
T – air temperature (K)
Tg – ground temperature (°C)
Tsk – skin temperature (°C)
*Tsk** – skin temperature (after acclimation, °C)
v – wind speed (m·s^{-1})
vp – vapour pressure (hPa)
w – skin wetedness (dimensionless)

ap – air pressure (hPa)
E – evaporative heat loss (W·m^{-2})
hc – coeff. of turbulent heat transfer (K·W^{-1}·m^{-2})
he – coefficient of evaporative heat transfer (hPa·W^{-1}·m^{-2})
Ie – coefficient reducing wet heat transfer through clothing (dimensionless)
Irc – coefficient reducing dry heat transfer through clothing (dimensionless)
Lg – thermal radiation of ground (W·m^{-2})
M – metabolism (135 W·m^{-2})
N – cloudiness (%)
PST – Physiological Subjective Temperature (°C)
R – absorbed solar radiation in man (W·m^{-2})
RH – relative humidity of air (%)
SR – resultant value of net heat storage (after acclimation, W·m^{-2}); *SR* is calculated in the same way as *S* taking into account skin temperature adapted to increased evaporation (*Tsk**) and air temperature replaced by *iMrt*
v′ – body motion (1.1 m·s^{-1})
vpsk – vapour pressure at the skin surface (hPa)

The results show a gradual softening of the bioclimatic conditions in winter. It is manifested by a decrease of the risk of frostbite and overcooling of the body (indicated by *WCT*), a 20% decrease of the accepted level of physical activity (*MHR*), an increase of the Physiological Subjective Temperature (*PST*) of about 2°C, and a reduction of the cold Physiological Strain (*PhS*) of about 25%.

The indices used in the present studies show not only general trends due to observed climate change but they also indicate changes in specific reaction of an organism. Because they provide physiologically relevant information they can be wildly applied in research of tourism, health care, urban planning etc.

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Chapter 11
Climate Warming in the Czech Republic: Evidence Stored in Shallow Subsurface

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11.1 Introduction

There is clear evidence that the world climate has been undergoing a general warming. This warming was typical for the most of the last century, following the previous relatively colder nineteenth century. An important question to answer is whether this warming is just a manifestation of natural climate variability and a certain "return" to previous conditions or an indication of a new (and permanent) trend. What is alarming, is the matter of fact, that the warming rate has been accelerating in the last 3 or 4 decades. The 1990s was the warmest decade of the last century (IPCC 2001) and global mean surface temperature deviations (related to the 1961–1990 average) were in 1998 and in 2002–2007 the absolutely warmest since the world data have been collected in 1861 (NASA 2008, WMO 2005). Also the Czech meteorological records confirmed the growth of the mean annual air temperatures (Kalvová 2001, see also http://www.chmi.cz). The increase of the global mean temperature is accompanied by changes of many climatic and environmental variables (Hansen and Lebedeff 1987; Jones et al. 1999). The observed climate change does not only mean a change of average values, but may present additional changes in climate variability leading to the increasing occurrences of extreme phenomena such as floods or droughts. If the warming is to continue in the future, serious environmental changes present a risk for the population of many countries, see plentiful recent reports presented during the Paris (February 2007) and Brussels (April 2007) IPCC assemblies. The Czech Hydrometeorological Institute published Climate Atlas of Czechia with a detailed description of climate evolution in the Czech Republic for 1961–2000 (Tolasz et al. 2007).

The nonlinear climate system is under effects of many forcing agents – natural (solar and volcanic activity, natural aerosols) as well as anthropogenic (massive deforestation, industrial pollution and emissions of greenhouse gases, land-use).

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In order to describe the climate evolution and to attribute it to the individual forcing factors, a robust record of the past climatic changes is required. Equally important is to improve the knowledge of the spatial distribution of the present-day warming rate and its environmental confidence. Direct evidence of climate change and its variability based on instrumental measurements covers only a relatively short period. The longest European temperature records started at the beginning of the eighteenth century (Camuffo and Jones 2002). The Czech longest continuous temperature series covers more than two centuries (Prague-Klementinum), see e.g. Hlaváč (1937) or Brázdil and Budíková (1999). More detailed database of measurements based on a dense station network is available for the last 4 or 5 decades. From all these records, it is possible to detect a significant evidence of gradually changing conditions.

There is an alternative, relatively new, but powerful method (so called borehole climatology), which relies on the inversion of the present-day subsurface temperature-depth profiles into the ground surface temperature history (GSTH) (Čermák, 1971; Lachenbruch and Mareschall, 1986; Pollack and Chapman 1993). For a comprehensive summary of this method see e.g. Pollack and Huang (2000), Majorowicz et al. (2004) or Bodri and Čermak (2007). Inverting almost one hundred borehole temperature logs from the Czech territory into the GST-history revealed a past climate scenario of the last millennium (Bodri and Čermak, 1995, 1997, 1999). Numerous shorter meteorological surface air temperature (SAT) series completed by shallow subsurface temperature monitoring offered a quantitative estimate of the present day warming rate of 0.02–0.04 K/year (Čermak et al. 2000). There is no doubt that combining several approaches, namely the instrumental and proxy data analysis, can enable better understanding of the Earth's climate history and that the knowledge of the past will facilitate a more reliable assessment of the future of the climate system (Harris and Chapman 1998; Huang et al. 2000).

11.2 Rationale

The observed increase of air temperature is linked to the increase of the surface (soil) temperature. The response to changes in the surface conditions slowly penetrates downwards into the shallow subsurface (Fig. 11.1). Subsurface temperature field at depth of several tens to several hundreds of meters contains a record of what has happened on the surface in the past, i.e. the long-term ground surface (soil) temperature history (GSTH). This information can be recovered from present-day borehole temperature-depth profiles and used to reconstruct the GSTH of several past centuries (see e.g. Lewis 1992). Amplitude of the surface temperature changes is attenuated and time delay increases with depth (Čermak et al. 1993). The high-frequency component of the transient temperature signal from the surface is progressively filtered out as it propagates to depth (Pollack and Chapman 1993). Seasonal temperature variations, in dependence on the thermal conductivity and diffusivity of the near surface rock, practically fade out below the depth of 20–30 m. As the (meteorological) air temperature series exhibit certain variability and the relatively

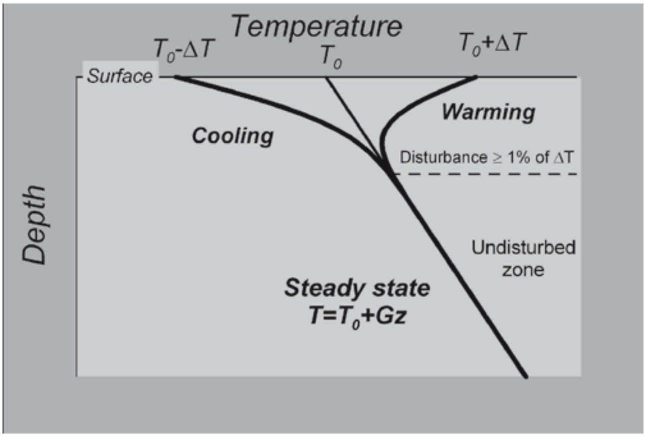

Fig. 11.1 Response of the subsurface temperature field to the change on the surface. Temperature-depth profile measured in a borehole indicates the surface warming/cooling signal as a departure from the (undisturbed) steady-state geotherm

"warmer" and "colder" years may occur irregularly, a relatively long time span is generally needed to provide reliable statistical results. Since the ground smoothes the temperature extremes, the magnitude of the present day climate warming, as the reflection of the long-term climate evolution, can be more easily obtained by the temperature monitoring at shallow depths just below the penetration reach of the seasonal temperature variations and in a considerably shorter time interval.

The geothermal method to reconstruct past climate history addresses the analysis of the downward diffusion of variation of the subsurface temperature field with time. While this method has a low time resolution (being diffusion controlled), it is directly related to the past temperature on the surface (unlike all other proxies). It is an advantage that the time span of most GST-histories extracted from borehole data exceeds that of meteorological SAT data, so they can be used to "extend" the SAT time series back into the pre-instrumental period. This can be done only in case that ground and air temperatures track each other on a long-term scale. Although there are papers suggesting that the climatic temperature record in the Earth is compatible with measured SAT series (e.g. Harris and Chapman 1995), the air and ground temperature coupling is governed by the energy and mass fluxes at the Earth's surface which represent a complex system of competing physical and biological processes (Beltrami and Mareschal 1995). Therefore the effect of other climate variables, such as precipitation and evaporation, transpiration, moisture, soil freezing, snow and vegetation cover changes need to be taken into account (Harris and Chapman 1995; Možný and Kott, 2003). While this fact somehow limits the practical use of the routine inversion procedure, at the same time it offers interesting applications such as detecting long-term changes in the vegetation cover (Čermak and Bodri 2001) and also the possibility to distinguish between the natural and potential anthropogenic components of the present-day warming (Čermak et al. 2000).

11.3 Subsurface Temperature Monitoring

As a part of the “Borehole and Climate” program of the International Geological Correlation Program (IGCP 428), two experimental shallow holes were drilled in two different environments to monitor the depth response to the downwards penetrating signal of the changing surface temperatures. The first 40 m deep hole was drilled in October 1992 on the campus of the Geophysical Institute in Praha Sporilov (50º02’27” N, 14º28’39” E, 275 m a.s.l.). The hole is located on a low E-W trending ridge. The upper four meters of the lithological column represent soil and a man-made loose material backfill of low conductivity (1.7–2.0 W/mK), underlain by silt to clayey shale of gradually increasing conductivity, below 10 m the conductivity is practically constant (3.2 ± 0.2 W/mK) (Šafanda 1994; Štulc, 1995). The corresponding diffusivity of the upper strata is only 0.4×10^{-6} m^2s^{-1}, lower strata is characterized by values of $0.73–0.9 \times 10^{-6}$ m^2s^{-1}.

While the Sporilov hole is located on the rim of a large urban area, the site for the second hole was selected at Kocelovice in south-central Bohemia at a distance of about 70 km SSW of Praha in a typical farming area . The 40 m deep Kocelovice hole (49º28’02.2” N, 13º50’18.7” E, 519 m a.s.l.) was drilled in 1997. The borehole site is near one of the main Czech meteorological stations on a gently grassy slope in slightly undulating terrain. The hole penetrates a compact granite body with a mean conductivity of 3.1 ± 0.1 W/mK, covered by about 1–2 m thick soil layer. The diffusivity was not measured, but can be estimated as $1.2–1.3 \times 10^{-6}$ m^2s^{-1}.

Both holes were equipped with a measuring chain of temperature sensors (thermistors) spaced at selected depth levels covering the whole 0–40 m depth section. Both holes are filled with water, the depth of which slightly varies between 4 and 5 m in Kocelovice hole and is stable at 9 m depth in the Sporilov hole. In addition to the subsurface temperatures, air (SAT) temperatures are monitored at 0.05 m, 1 and 2 m above surface. At Sporilov also precipitation is recorded and at the Kocelovice meteorological station a complete set of various information is completed (wind speed and direction, direct and reflected solar radiation, snow layer thickness, air humidity, soil moisture and vapor tension).

11.4 Monitoring Temperatures

Regular temperature variations at the surface occur at temporal scales, such as diurnal or seasonal/annual. The typical magnitude of the daily variations amounts 10–15ºC, the amplitude of the seasonal variations may amount to 20–30ºC and more. Inter-annual and long-term temperature change patterns are irregular. As the surface, temperature signal propagates downward, its amplitude decreases exponentially with depth due to the diffusive process of heat conduction, each variation vanishes over a vertical distance related to the period of change and to the thermal diffusivity of the ground. The shorter period fluctuations attenuate more rapidly.

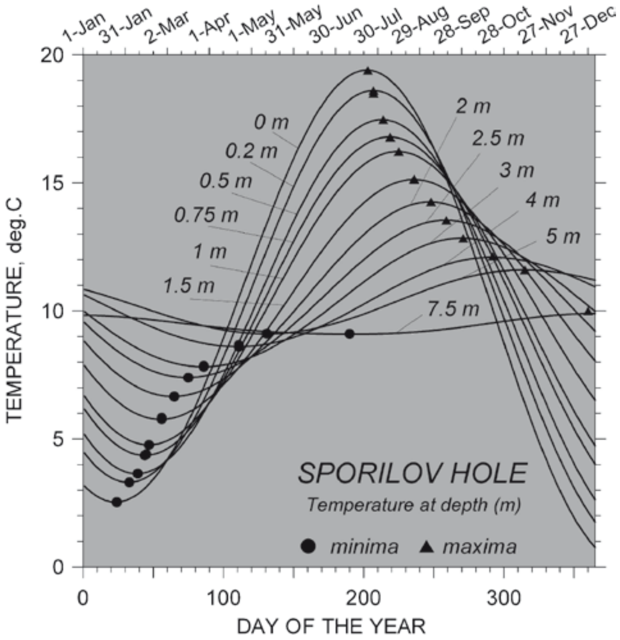

Fig. 11.2 Characteristic temperature distribution in shallow subsurface corresponding to the annual temperature variations on the surface (daily variations ignored). The individual curves illustrate the amplitude decrement and phase delay of the temperature response penetrating downwards. Based on 6-year-long temperature monitoring in the Sporilov hole

Figure 11.2 demonstrates the amplitude attenuation of the temperature signal when propagating downwards and the delay of its phase by presenting the results of the 12-year temperature monitoring in the Sporilov hole. The daily temperature wave is practically not observable below 1 m depth. On the other hand, the temperature at 1 m depth represents integrated average of the daily signal of the previous day(s). Similarly, annual GST oscillations practically vanish at about 15–20 m depth, the temperature field below 20–30 m depth is free of any response to the annual or shorter temperature variations and contains exclusively the fingerprints of longer scale evens with characteristic time of several last years.

The 12-year (1994–2005) record of temperature recorded at 38.3 m depth in the Sporilov hole (Fig. 11.3) clearly demonstrates the yearly increases of temperature (records 2000–2005). Bottom panel summarizes the general temperature increase from 10.63°C in 1994 to 10.99°C in 2005 together with early warming rates ranging from 0.02 K/year in 1994 to 0.04 K/year in 2006 (with the mean of 0.0296 K/year). Even when the observed warming rate at depth is not identical with the SAT warming, it can well serve as a certain measure to describe the recent climate evolution.

Figure 11.4 presents monitoring series of temperature at 40 m depth in borehole Kocelovice, where due to technical problems only two shorter monitoring series

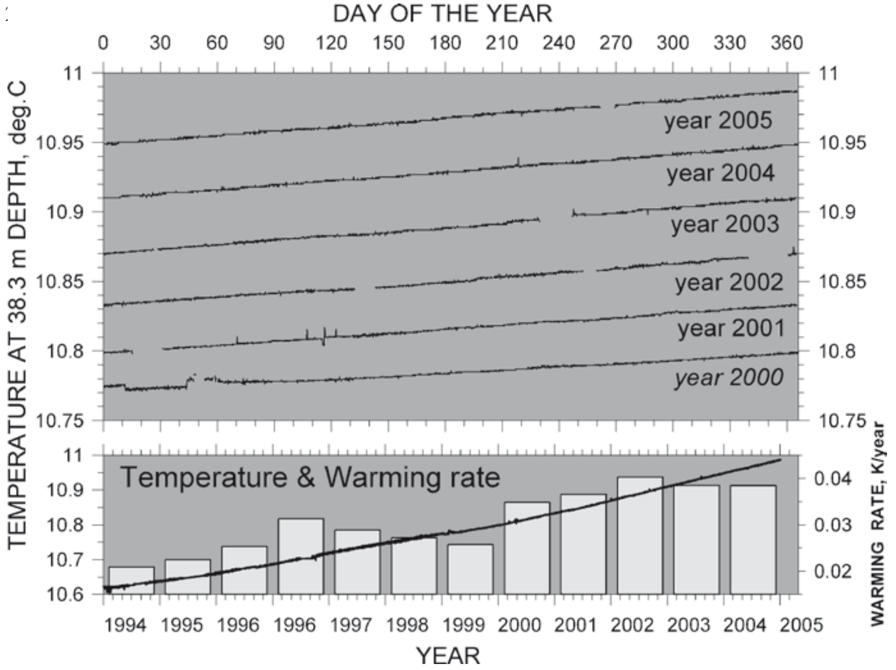

Fig. 11.3 Results of temperature monitoring at 38.3 m depth (Sporilov hole), years 2000–2005. Bottom: the 12-year record together with the warming rates calculated for the individual years

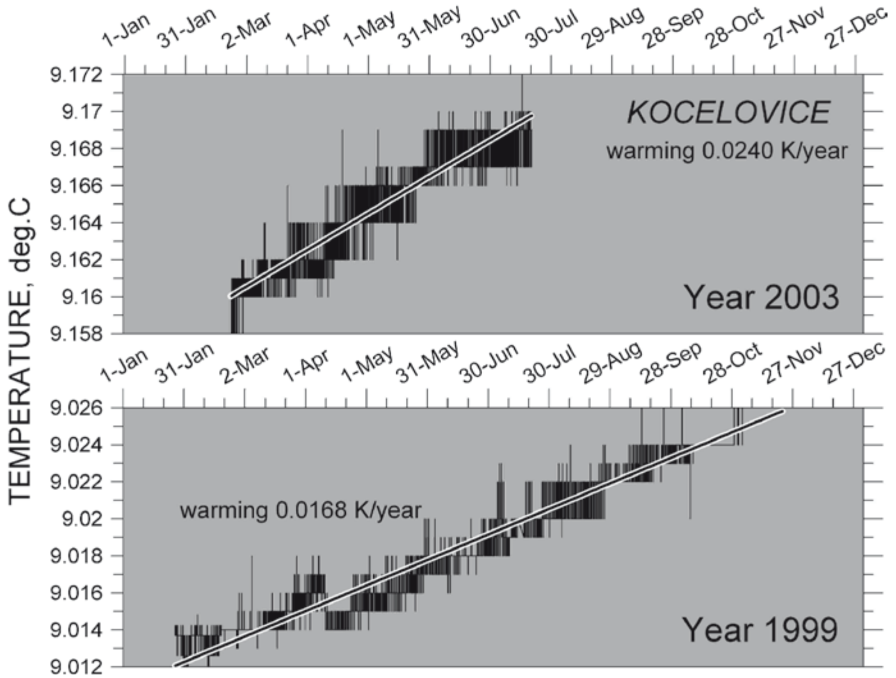

Fig. 11.4 Results of temperature monitoring at 40 m depth (Kocelovice hole). Two records correspond to 1999 and 2003 monitoring series

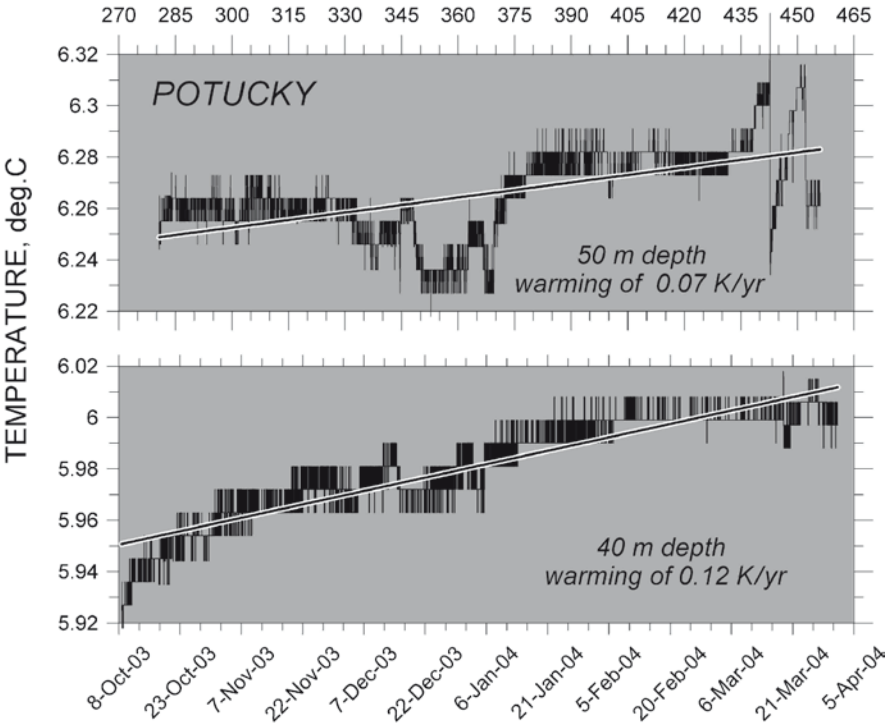

Fig. 11.5 Results of temperature monitoring at 40 and 50 m depths (Potucky hole). Contrary to Sporilov and Kocelovice data, temperature field at Potucky is less stable and obviously disturbed by local hydrogeology

could be obtained, both confirmed warming rate, namely 0.0168 K/year (in 1999) and slightly higher rate of 0.0240 K/year in 2003. In years 2003–2004 a similar experiment was performed in an abandoned hole at Potucky site located in the Ore (Krušné Hory) Mountains, north-western Bohemia (50.43ºN, 12.78ºE, 864 m a.s.l.). The site is in close vicinity of a forested area of coniferous woods (mostly Norwegian spruce, *Picea abies*), and served for several experiments (see further). The temperature data in this hole, however, may be disturbed by complex hydrological conditions in the subsurface and are thus less reliable. The monitoring confirmed surprisingly high warming rates (Fig. 11.5), namely 0.12 K/year at 40 m depth and 0.07 K/year at 50 m depth, which so far are difficult to interpret. It is, however, interesting to mention, that the north-western part of the country belongs to the areas most industrially polluted and that the meteorological SAT record from the near-by station Fichtelberg also revealed a steep increase of air temperature in the last 25 years of 0.0537 K/year (Fig. 11.6).

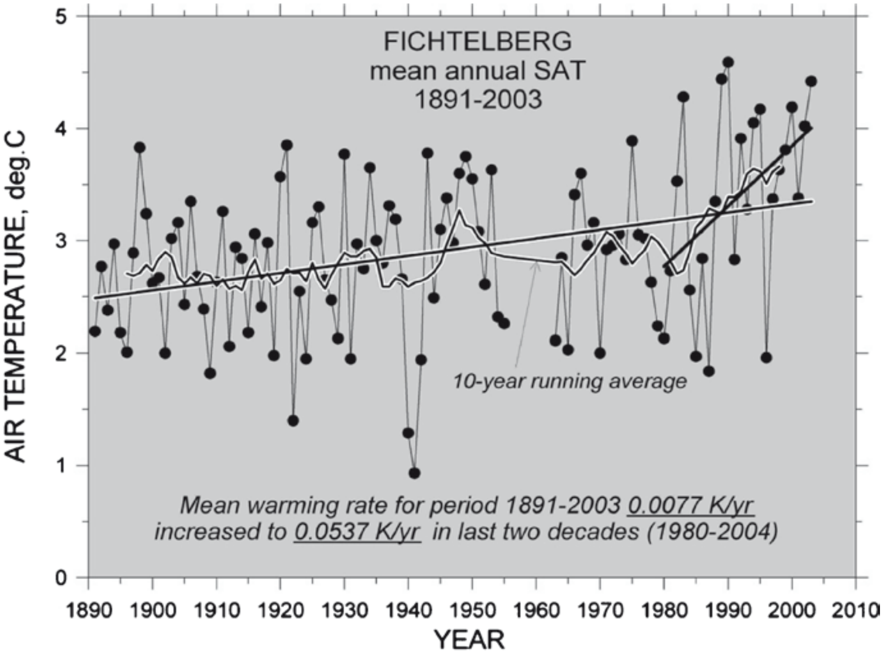

Fig. 11.6 Surface air temperature measured at Fichtelberg meteorological station (1891–2003)

11.5 Surface and Near Surface Effects

11.5.1 Snow Cover and Ground Freezing

Modeling the GST-SAT coupling have confirmed that on longer timescales the GST represents a good SAT indicator and their variations repeat each other (see e.g. González-Rouco et al. 2003, 2006). The problem can be, to what extend the observed GST variations can track SAT changes on a shorter timescale, such as the monthly or yearly series. No doubt, that large spatial-scale GST differences are determined by ground heating by incoming solar radiation, its transformation, distribution and the amount of heat penetrating into the subsurface. Thermal balance on the ground surface is thus determined not only by the actual air temperature, but also by the surface absorption and reflection. Of special concern is the GST-SAT coupling in locations, where e.g. the ground loses a substantial part of information about air cooling in winter because snow insulates the ground and reflects the incoming solar radiations. Even when snow is sporadic, the complicated latent heat effects and winter freezing/thawing processes can complicate the heat transfer. Of similar importance can be the GST-SAT coupling due to rain precipitation producing changes in moisture content, infiltration, evaporation and runoff, as well as the seasonal (micro)vegetation changes and chemical weathering.

To understand the GST-SAT coupling, the experimental site (microclimate station) was built on the campus of the Geophysical Institute in 2002 to monitor the shallow subsurface temperature field below several characteristic surfaces, namely bare soil, sand, grass and asphalt. Air temperatures at 5 and 200 cm above surface as well as soil temperatures at depth levels of 2, 5, 10, 20 and 50 cm are recorded at 5 min interval. All yearly (2003–2005) air temperature averages at 5 cm above the ground are surface dependent, but appeared lower than the soil averages for all types of surface. The differences between air temperature at 5 cm above the ground and the soil temperature at 2 cm depth amounted to 1.4–1.6 K, 1.8–2.0 K, 0.2 -0.4 K, and 4.1–4.8 K for bare soil, sand, grass and asphalt, respectively. These results hint that on the annual scale the soil is warmer than the air and corroborates the similar observations reported by e.g. Backer and Ruschy (1993)) and Putnam and Chapman (1996). The interannual variability is also surface type dependent and ranges within the first tenths of degree Kelvin.

In general, the magnitude of the GST-SAT difference may exhibit significant variations. Subsurface heat conduction as well as the factors related to the movements and/or diffusion of air and/or moisture masses (wind, evaporation/transpiration, vertical soaking of soil moisture and precipitation) tends to equalize air and soil temperatures. Soil temperature generally follows the air temperature course when average SAT is above 0°C, but the GST-SAT coupling is violated at the presence of snow in winter when the air temperature drops below zero. Snow insulates the ground surface and reduces heat loss. As an example Figure 11.7 shows the temperature variations of the air (SAT) temperature together with the 2 cm depth soil data under different surfaces and illustrates the effect of the snow cover on the GST-SAT coupling. During the week February 20–27 the SAT-GST data decoupled, then the coupling started to restore after snow cover thawed away (on January 28) and continued till February 8 when new snow appeared again. For the most of February till the early March the GST-SAT data decoupled again. Similar results were obtained at Potucky (Fig. 11.8), where temperature was recorded at 2 cm depth and 5 cm height above ground. The coupling of the temperatures is almost perfect in fall and spring and breaks down during most of the winter.

Smerdon et al. (2004, 2006) have generalized the results of the above experiments in the relation to several temperature time series measured at other localities, namely at Fargo (North Dakota), Cape Henlopen State Park (Delaware) and Cape Hatteras (North Carolina). These sites represent different kinds of subsurface strata and/or climatic settings located within the mid-latitude zone, and can be used for the spatial consideration. On the annual scale the GST signal (even attenuated and phase shifted) generally follows the SAT variations. The slight differences between annual GST and SAT signals may occur in both winter and summer seasons. The GST-SAT difference depends on the site location and its climate and terrain characteristics. The GST-SAT decoupling at Fargo occurs mainly during the winter, whereas at Capes Henlopen and Hatteras the observed attenuation of the GST signal has taken place during the summer season. The seasonal partitioning of the GST-SAT decoupling is caused mainly by the corresponding partition of the summer precipitation and snow. While the Fargo location is characterised by the modest

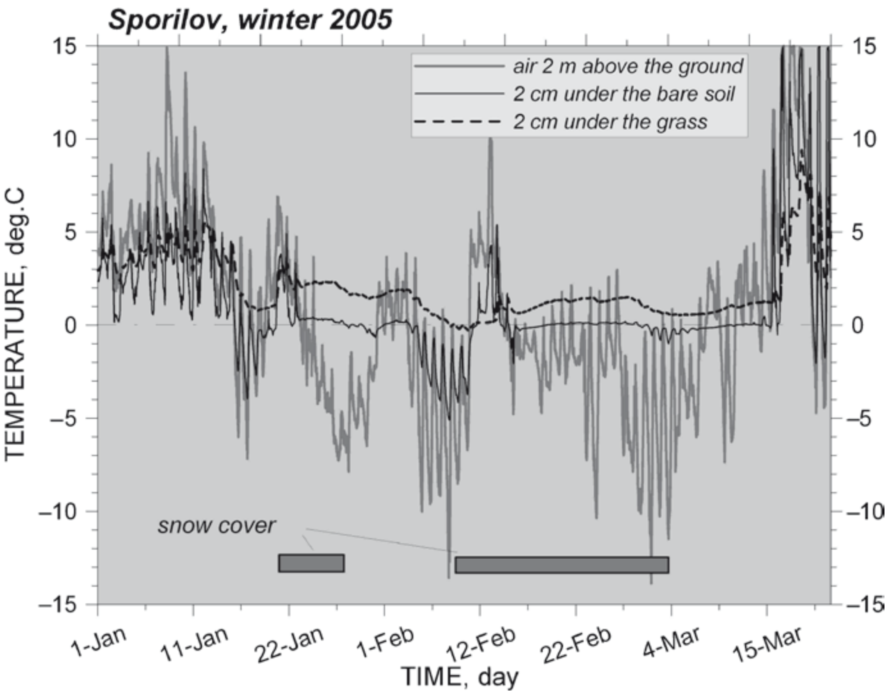

Fig. 11.7 Time series of air (at the height 2 m) and soil temperatures (at 2 cm depth) recorded under different surface at Prague-Sporilov. Soil temperatures follow SAT at temperatures above 0ºC, but are decoupled when the surface is covered by snow

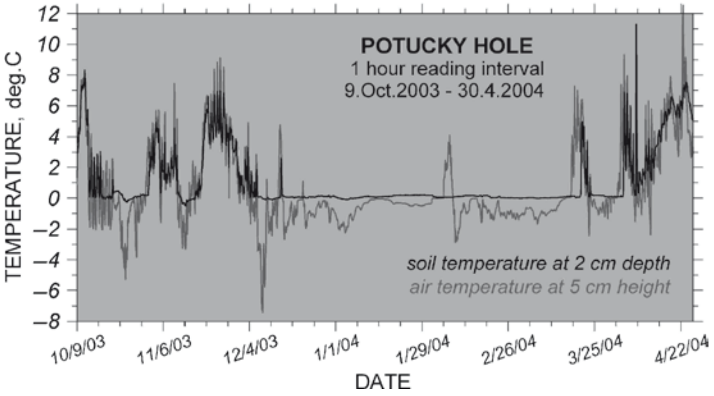

Fig. 11.8 Time series of air (at 5 cm above surface) and soil (at 2 cm depth) temperatures recorded at Potucky hole in 2003–2004 winter. Between mid December 2003 and March 20, 2004, when the ground was covered by snow, soil temperature was practically constant and showed practically no response to the SAT variations

rainfall and significant amount of snow, the Cape Henlopen and Hatteras stations have negligible or no snowfall. Similarly to the Czech monitoring results, the North American stations confirmed influence of the snow cover on the GST-SAT coupling. In all investigated locations snow cover has affected heat transfer in the surface in such a manner that mean daily soil temperature under snow cover was warmer relative to the SAT.

The above experiments have detected also finer features of the GST-SAT decoupling during cold season, such as the dependence of the soil temperature on the thickness of snow layer and snow quality, the date when the first snowfall started, and the effect of the vegetation cover. Numerical modeling by Gosnold et al. (1997) of the GST-SAT tracking in the presence of the snow cover have detected that the winter soil temperatures are more sensitive to the presence or absence of snow rather than to variations in its thickness. Thus, the exact amount of the winter snowfall is unlikely a decisive factor of the GST-SAT coupling in winter. Our monitoring experiments have also revealed certain effect of the surface type on the ground-air temperature tracking. The grassland preserves the snow cover longer than the bare surface, where snow is not isolated from the ground. Combination of snow and grass provides better insulation and the temperature under such surface remains above zero, the rate of snow melting is thus surface dependent. The thicker snow cover is characteristic for the grass. Similar studies were also done by the research group of the Utah University, see for more discussion in Bartlett et al. (2004, 2005, 2006)

It is to be stressed that our results are representative of the typically mid-latitude seasonal GST-SAT relationships, i.e. for mild winters, with relatively less snow and generally late snowfall. Winter temperatures are rarely cold enough to cause a massive soil freezing. At high-latitude regions where SAT temperature remains below 0°C for a considerably longer time, the effect of freezing may even surpass the influence of the snow cover, depending on the date what comes first, snow or frost. Here we can only partly contribute by demonstrating the effect of the soil freeze/thaw events on the GST as reflected by the relatively rare situation on the time series at Potucky site (Fig. 11.9). The period October–December 2003 was characterized by the absence of snow and by two episodes of the sharp air temperature fall below 0°C. The ground temperature at shallow depths of 2 and 10 cm remained almost constant, close to 0°C and to 1–1.5°C, respectively, demonstrating a so-called "zero-curtain effect" that occurs due to latent heat released from the freezing of soil. Recorded temperatures indicated that the soil freezing at Potucky station during this period did not penetrated deeper than 10 cm. The uppermost "active" layer experienced a complex combination of heat transfer from the frozen upper and undisturbed lower layer as well as the heat release from the advancing freezing front, the corresponding temperature-time series reflected pure influence of the freeze/thaw processes on the GST. The anomalous SAT variations were significantly attenuated at the depth of 50 cm with a time delay of days. Temperatures at that depth are lower than the highest positive air temperatures by approx. 3–4 K and may be higher than the lowest negative air temperatures by 8–10 K.

Figure 11.10 shows the ground temperatures under sand and grass surfaces during February 2006 at the Prague-Sporilov station. Due to several frosty days and

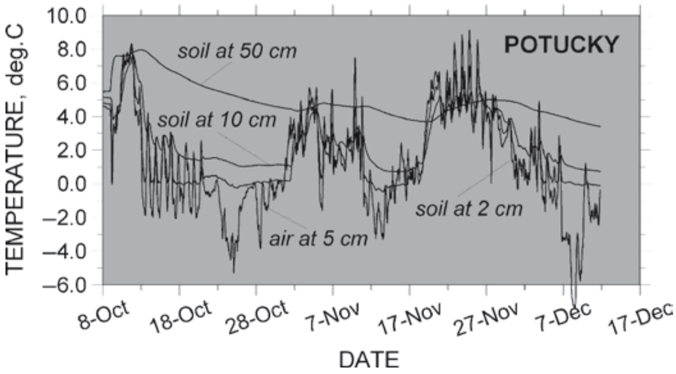

Fig. 11.9 Time series of air (at 5 cm height) and soil temperatures at 2, 10 and 50 cm depth at Potucky hole (October–December 2003)

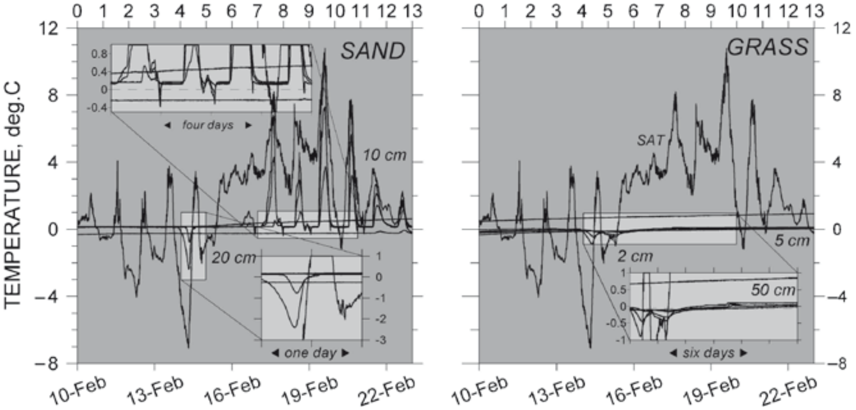

Fig. 11.10 Shallow soil temperatures at different depths below sand and grass surface during short freezing cycles in February 2006. Data from Sporilov hole

absence of snow in January, the subsurface temperature below both surfaces dropped below the freezing point. Temperature at 20 cm depth was stable at approx. 0°C and/or −0.3°C under the grass and the sand, respectively. The higher temperature under the grass occurred due to insulation effect of the vegetation cover. In the first half of February, when SAT was oscillating around zero, the GST under both surfaces remained practically constant. Its sharp decrease between 2 and 5 cm depths was observed only on February 14–15 and was the result of a similar SAT drop. During the second half of February, when the air temperature increased above zero, the subsurface temperature under the sand surface followed the SAT course. However, the phase changes of soil moisture substantially reduced the GST variations. The surface temperature variations vanished at the interface of the frozen and thawed soil layers and remained at zero temperature. Temperature at 20 cm depth was practically constant, that hints that all heat coming from the surface was spent to melt the soil moisture (Fig. 11.10, left). Under the grass, where insulation of the surface and low thermal diffusivity of the soil slowed down the penetration of the surface warming, at all measured depth soil temperature remained close to 0°C (Fig. 11.10, right).

11.5.2 Rain Precipitation

Summer soil temperature is controlled by combined effect of air temperature variations and soil moisture content. An increase in rainfall during summer season can increase both surface wetness and soil moisture. This requires more energy consumption for evaporation and produces cooling of the ground surface (Yasunari et al. 1991; Matsuyama and Masuda 1998). In principle, such soil moisture feedback mechanism may explain soil cooling during summer, when air temperatures increase. Rain precipitation is thus another factor determining the subsurface thermal regime because it affects the amount of soil moisture and therefore the amount of energy removed from soil by latent heat flux. Because the thermophysical properties of the subsurface rock, like thermal conductivity and heat capacity, depend on the water content, the rainfall can influence not only energy balance of the ground surface-air system, but also thermophysical and/or hydrological characteristics of the ground. Regions with low porosity and permeability will likely be less affected, while less consolidated medium will experience more pronounced changes.

Primarily influence of the precipitation on the GST-SAT coupling occurs on the very short time scales (during and just after rain events) through advective transport of heat by falling water that may significantly contribute to the development of shallow subsurface temperatures. Figure 11.11 displays temperature difference between the ground surface ($T_{z=0}$) and temperature at 2 cm depth measured in a dry and in a rainy period at Prague-Sporilov. During a 10-day interval with no rain the differences have shown quasi-periodic oscillations with maximum positive values in the daytime and negative values at night. The range of variations achieved ~9 K. The temperature differences were negative after rain events over both day and night (air temperature at wet surface is lower than at 2 cm depth, like e.g., June 30-July 2 and/or July 5–6 intervals). Its variations were significantly reduced and ranged within only ~3–4 K. On the other hand, evaporation goes relatively quickly, thus, depending on the rain strength the "dry" regime was restored after 1–2 days after rainfall.

The role of rain precipitation appears to be far more important on seasonal and/or annual scales because of its possible seasonal persistence. In the mid-latitudes snowfall and soil freezing represent generally sporadic events and their effect on the GST-SAT coupling is not perceptible already under decadal averaging. On the contrary, rainfall occurs more regularly during much of the summer and its annual distribution remains preserved for the long periods. The Prague site represents typical example of the seasonal timing of precipitation. Daily precipitation at Prague has no significant linear long-term trend, but is characterized by

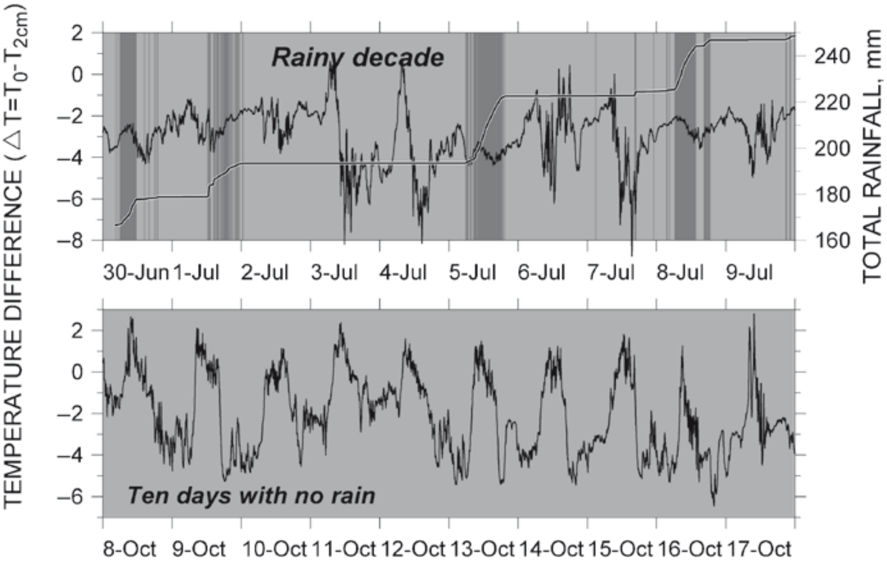

Fig. 11.11 Temperature differences between ground surface and soil temperature at 2 cm depth at Prague-Sporilov station; comparison of the rainy decade with dry period. *Top panel* also shows total rainfall amount

a certain seasonal character (Bodri et al. 2005); the wetter season falls on May–August period and the precipitation minimum occurs in winter. Figure 11.12 shows time series of daily averages of SAT temperature (at 5 cm height) and soil temperatures at the depths of 0.05, 1, 2 and 5 m measured at station Prague-Sporilov during the "rainy" year 2000. The amount of precipitation is shown by the histogram below. Detectable high-frequency oscillations of the soil temperature record in summer are caused mainly by the rains that change the moisture content of the soil and correspondingly affect both latent and sensible heat flow at the ground surface. As seen, rainfall events are accompanied by the corresponding changes of both air and ground temperatures. The main observation fact about summer GST-SAT interrelation is that the rainfall does not cause total decoupling of both temperatures similar to that what occurs in winter due to snow cover and freezing/thawing cycles. The air temperature record at 5 cm height and the GST records at the air-soil interface practically repeat each other. Correlation of both temperatures amounts to 0.96.

Surface temperature oscillations are practically imperceptible at 2 m and at deeper levels. Ground temperatures below 1 m depth are steadily lower than air temperatures from May to September and are higher than the air temperatures from November to February. At shallow depths variations of the GST around SAT are more erratic. At the shallow subsurface soil temperatures remain steadily higher than air temperatures only during November–February). During most of the year shallow GST irregularly oscillates above and below air temperature depending on

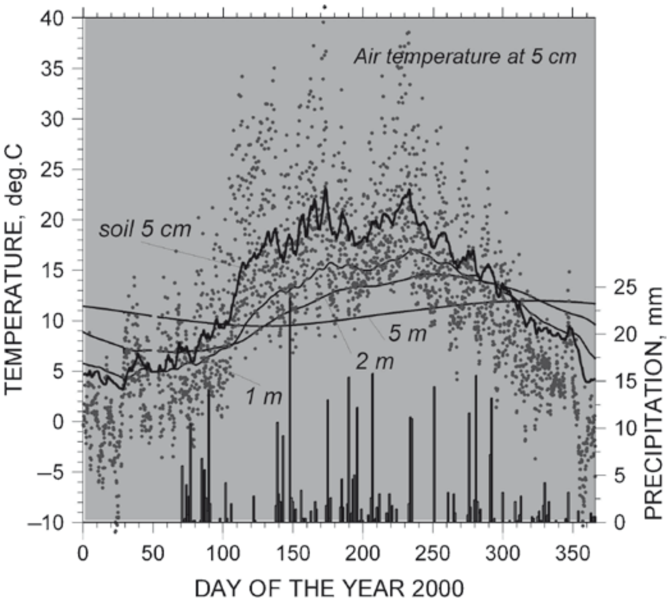

Fig. 11.12 Time series of daily averages of air temperature (5 cm height) and soil temperatures at 5, 100, 200 and 500 cm depth (Prague-Sporilov station). The histogram below shows precipitation amount

the temporal pattern of the rainfall. These oscillations likely will disappear under long scale averaging.

11.6 Meteorological Data and Regional Warming Pattern

Long-term meteorological SAT series from a number of Czech stations were compared with the ground surface temperature evidence obtained by inverting almost one hundred borehole temperature-depth profiles (Bodri and Čermak 1999). Both sets of data showed a certain similarity, which suggested that, the urban and industrial areas with higher population might have recently experienced greater warming than areas predominantly farming. It was presupposed that shallow temperature monitoring may usefully help to assess the potential anthropogenic component of the present (global) warming (Čermak et al. 2000). Now, we have repeated this procedure with the updated SAT data from 32 local meteorological stations for period 1960–2006. Regardless of the nature of the year-to-year fluctuation, all records documented local warming, with a characteristic regional mean of 0.0284 K/year (Fig. 11.13).To void the differences in the recorded local temperatures due to the altitude of the individual station reduced temperatures (relative to the mean of the particular station) are shown. The calculated cross-correlation coefficients between the SAT records from the

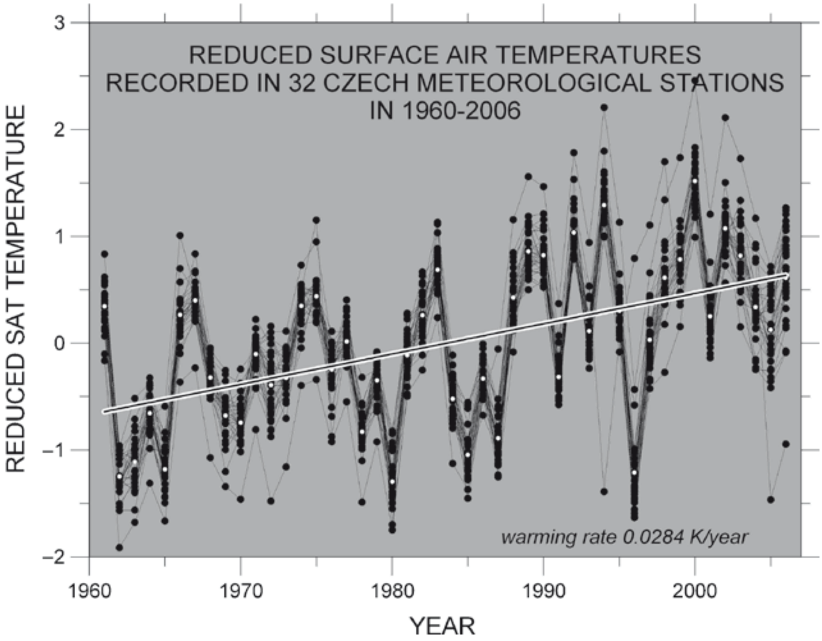

Fig. 11.13 Reduced surface air temperatures recorded in 32 local meteorological stations in the Czech Republic (1960–2006)

individual stations ranges from 0.92 to 0.99, which means that the whole territory of the Czech Republic can be considered as a single homogenous unit and the few existing gaps in data series could have been repaired by using data from the near-by stations with an appropriate datum-offset. All individual warming rates well fitted to the general interval of 0.01–0.04 K/year (Fig. 11.14) (with minimum of 0.0146 K/year at Olomouc station and maximum of 0.0384 K/year at Doksany) with an average value of 0.0284 K/year, which supports the reality of the continuing warming. The previous works (Čermak et al. 2000) focused the attention to decide whether the present warming is just a natural phenomena or there is a certain anthropogenic contribution reflecting the negative consequences of human activities. Figure 11.15 presents a histogram of the warming rates, when the respective sites were subdivided into three categories: (a) sites located in typically farming regions and (c) sites located in the typically industrial regions or near large urban centers. All remaining sites were rated as (b) mixed, when it was difficult to unambiguously affiliate the respective site to one of the above category. Whatever, such subdivision may be a speculative, the predominantly agriculture (rural) regions seem to be characterize by lower warming than industrial regions. Modification of land surface, production of waste heat, pollution and lack of vegetation, that all contribute to the irreversible change in the energy balance. The "urban heat island effect" known in meteorology describing the fact that average temperatures are higher in metropolitan than in rural areas may be thus applicable on the larger regional scale.

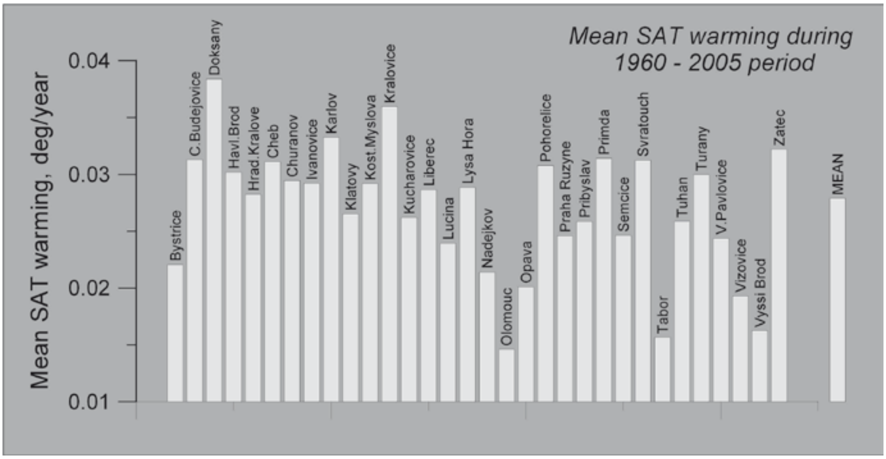

Fig. 11.14 Mean SAT warming recorded in the individual meteorological stations

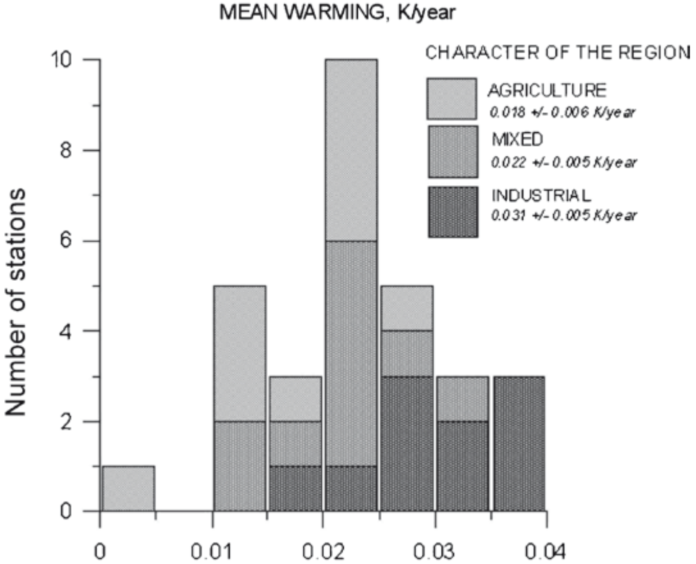

Fig. 11.15 Histogram of observed warming rates (1960–2006) vs dominant character of the region (farming, mixed, industrial)

11.7 Conclusions

Monitoring results have shown that the SAT forcing represents the main cause for the GST changes and this fact supports the use of the GST as an indicator for the climate reconstruction. Differences between the GST and SAT signals are closely linked to the processes occurring at the ground surface and in the shallow subsurface of upper first few meters.

GST-SAT coupling over short-term timescales (such as single year) is complex. The winter snow cover and freeze/thaw effects may present serious influences causing GST-SAT decoupling. Because snow cover insulates the ground in the cold season, its systematic and persistent variations may distort their relation and hinder the direct comparison of both variables. In regions with short-duration snow cover its random fluctuation tends to vanish in longer averages. The summer rain precipitation and the corresponding moisture transpiration and evaporation have likely weaker effect on the GST-SAT decoupling.

On the daily scale, the GST may be either warmer or cooler than SAT and their difference progressively increases as the seasons become more extreme. However, the mean annual GST is generally always higher than the SAT. For the mid-latitude regions their difference amounts to 1–2 K. This value is higher in the regions of deep, long-duration snow cover or of extreme soil freeze/thaw cycles. The GST-SAT difference may be also much higher under artificial cover-types, such as concrete and asphalt exposed to direct solar radiation. The GST-SAT comparison may also be problematic in regions subjected to significant land use changes. Although snow does decouple SAT and GST on a daily and perhaps monthly basis, ground temperatures still track climate change as long as the characteristics of the snow season (onset and duration) has not changed systematically through time (Bartlett et al. 2004, 2005).

All detected processes that could break the GST-SAT coupling have only short-term effects on the heat transfer in the shallow subsurface, particularly of daily to seasonal timescales. In general, the short-term GST-SAT differences cannot considerably violate the assumption on the tracking of both temperatures on the long timescales.

The shallow-depth temperature monitoring proved to be a useful tool to assess a certain measure proportional to the present-day warming rate. The 12-year (1994–2005) experiment at Sporilov clearly demonstrated a gradual increase of warming rate within the range 0.025–0.040 K/year with a mean value of 0.0296 K/year. Shorter record from Kocelovice revealed lower warming rate of 0.0168–0.0240 K/year. Both values are in good agreement with the observational results of local meteorological SAT series and with the GST histories extracted from the deeper holes. The observed higher warming rate at Sporilov relative to Kocelovice together with the results of the SAT data from a number of local meteorological stations may confirm the assumption of regional character of the present-day (climate) warming and reflects an anthropogenic contribution to warming.

The monitoring technique itself, if applied in an extensive area network of enough measuring sites, may suitably contribute to knowledge of regional aspects of the recent climate evolution.

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Chapter 12
History of the Gdańsk Pre-Instrumental and Instrumental Record of Meteorological Observations and Analysis of Selected Air Pressure Observations

Janusz Filipiak and Mirosław Miętus

12.1 Introduction

As proven by the course of historical events, meteorological and climatic conditions determined the social and economic development of particular nations and regions. Despite a significant, scientific and technological progress they have still been deciding about the development of numerous areas.

Recently observed the climate change has significant consequences for the future of environment and mankind (IPCC 2007). Changes which we experience now have the global extent, anthropogenic origin, probably are non-inversed and very difficult to delay. Contemporary, instrumental meteorological observations cover only the period of last couple of centuries. For many reasons it is not satisfactory and therefore all attempts to prolong instrumental records in the past are very important. Many affords have been spent to search the missing early instrumental records as well as pre-instrumental information on past weather and climate (Manley 1974; Bärring et al. 1999; Jones et al. 1999; Camuffo and Jones 2002) For these reasons data archaeology and data rescue play an important role in modern climatology.

The history of meteorological observations in Poland has not been completely identified yet, what is mainly due to the fact that this country has a complex history.

In 1795, when Poland vanished from the political map of Europe, the development of particular areas and their inhabitants was determined by foreign superpower for 123 years. In the twentieth century, two World Wars were waged on the territory of Poland. The second of the mentioned above was aimed at a total destruction of Polish cultural and historical achievement.

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The extend of destruction, in terms of cultural heritage, technological infrastructure and the health condition of Polish population, led to focusing mainly on the reconstruction of the country from all the damages after the II World War. Similarly, Polish climatologists and historians, although perfectly educated and prepared to work with material evidence and old documents, were not interested into the history of meteorological observations at all. It must be emphasized that the search for the archive of a pre-war National Institute of Meteorology was held shortly after the war; however, it constitutes the only significant attempt of searching in such wide scale. Hence, it enabled some historical materials to be found and brought back to Poland.

It was not until the early 1990s when the search of historical meteorological materials was started in Polish libraries and archives. The research involved a significant number of abroad institutions, as well. This led to the discovery in the archive of the German Weather Service (DWD) archival materials concerning the territory of the contemporary northern and western Poland from the mid nineteenth century until 1945 (Miętus 1997). Some of the materials were brought to Poland in 2005 (Miętus and Czechowicz 2005).

Fleming (2002), in the history of meteorology explains the activities of many European scholars clearly and extensively, in terms of meteorological observations, the explanation of weather processes and the construction of the instruments. However, a little attention is given to the activity of the scholars and enthusiasts in these fields on the contemporary territory of Poland. Only the almanacs are rated, as being a popular way of presenting the seasonal and annual weather prediction, used mainly for agricultural purposes. Poland is marked as a place of the first editions of the mentioned above almanacs. Unfortunately, these issues are not considered important or significant. What is more, Fleming mentions Johann Kanold and his *Wrocław collection* (in German *Breslauer Sammlung*, 1717–1726). He emphasizes Kanold's influence on the development of the network of European meteorological observations and on the documenting (collecting and publishing) of the results of the observations. He does not, however, mention any Polish town which was to cooperate with Kanold. It is probably due to the fact that those aspects of activity in Poland have not been well known yet.

Limited amount of analysis carried out by the Polish climatologists, such as Trepińska (1988, 1997), Miętus et al. (1994), Miętus (1996, 1998a, 2007), Lorenc (2000), Bokwa et al. (2001), Limanówka (2001), Przybylak et al. (2005), Filipiak (2007a, b, 2009) include lots of interesting pieces of information concerning the subject mentioned above, although they are incomplete, and do not answer many questions.

The earliest known observations that come from the territory of Poland are dated to the sixteenth century. Bokwa et al. (2001) and Limanówka (2001) give lots of examples of notes concerning weather conditions in Cracow in early sixteenth century conducted by Marcin Biem, a professor in Cracow Academy (Jagiellonian Academy). Bokwa et al. (2001), Przybylak et al. (2005) and Nowosad et al. (2007) described also the climatological conditions in the north-eastern Poland in the second half of seventeenth century on the base of Jan Chrapowicki, the Polish nobleman and diplomat who was very enthusiastic about the weather and made notes about it almost every day.

However, Miętus et al. (1994), in accordance with the views presented by Klemm (1976), consider Abraham Rockenbachs, who conducted irregular meteorological observations from 1561 to 1564, as the most probable first meteorological observer in Polish Pomerania.

The paper focuses on the history of meteorological observations and measurements in Gdańsk since the moment when the first observers began to describe the weather conditions in the end of the seventeenth century till the last decades of the nineteenth century when the first national meteorological networks were established. Air pressure data were used as an example to evaluate the quality of the archival data and to perform some short climate analysis assessing the ability of the reconstruction of the climatic conditions in Gdańsk during the instrumental period.

12.2 We Have Known About This for Years

Taking Klemm's (1976) paper and two Hellman's works (1883 and 1901) into consideration, Miętus et al. (1994) quantified the beginning of meteorological observations in Gdańsk to be in 1655, and named Fryderyk Buethner (1622–1701), the first meteorological observer in this town. According to historians, Buethner was the fist mathematics professor in Academic Gymnasium and was at the same time given the position of a Chancellor of a parish school at Saint John's Church located in the centre of the town. Apart from being a mathematics professor, Buethner was a passionate astronomer and astrologist, what was common at those times. He was probably keeping touch with Jan Heweliusz (1611–1687), a famous astronomer from Gdańsk. He kept vivid correspondence with Wawrzyniec Eichstadt (1596–1660), who worked in Szczecin and collected notes concerning weather for at least 7 years.

Hellman (1883) mentions that Buethner's notes which concerned the weather in Gdańsk were included in manuscripts entitled "*Observationes meteorol. singulis diebus Callendarii annotae*". However, it is difficult to state whether that was true and where the *Callendars* were kept in Hellman's times. Hellman himself changed his mind and firstly pointed at the collection of Gdańsk Library and then the Bookshop of founded in 1742 the Natural Science Research Society of Gdańsk. Hellman probably did not study these *Callendars* or maybe did not even see them at all, as his opinion is based mainly on the earlier expressed opinions of other scholars who lived at Buethner's times. Fryderyk Buethner is considered to have been famous and appreciated by the society even outside Gdańsk, what is proven by the fact that he was given the privilege to publish the *Callendars* on his expense, what was very rare in those times. On the basis of other documents, Hellman noticed that, Buethner's work was not individual but he took advantage of gymnasium students. Despite having a positive recommendation of these notes, Hellman (1901) gives only one example of the observations, namely: *18.01.1657 – harsh blizzard, calm at noon, clear sunny*.

12.3 That Was the Beginning According to New Findings

Through the years, Buethner's *Callendars* were considered lost forever. The search carried out in the 1990s in two main libraries in Gdańsk, namely the Gdańsk Library of Polish Academy of Science (PAS) and the Main Library of Technical University of Gdańsk, the heir of the library of the Natural Science Research Society of Gdańsk, founded in eighteenth century was futile. The researches, carried out abroad or in other towns of Poland, have not been successful, as well. Buethner's *Callendars* were not even mentioned in the Great History of Gdańsk (Cieślak 1993) which was published in many volumes.

According to Miętus (2007), another query of the resources of the libraries mentioned above in 2005 enabled to find interesting meteorological materials, however, in the case of *Callendars* the results were fruitless, as well. The discovery of unknown materials was caused by the fact that the library of PAS had to move to another, new building. Therefore, the magazines were looked through and the catalogues updated due to the fact that "new" resources were found.

Among the materials that were discovered one can find a collection of regular publications marked by Wilhelm Misocacus. This collection is entitled "*Prognosticum oder practica auffs Jahr…*". They were released from 1577 to 1593, many years before the Buethner's *Callendars*. Each periodic "*Prognosticum...*" includes the description of the weather in terms of the seasons (Fig. 12.1).

It is not known, however, what those descriptions were based on, as the information about Misocacus observations is missing. A brief analysis of Misocacus works led to setting him an example of a typical scholar of those times, probably an astrologist, who shared the opinion about the astronomical influences upon the weather.

The next representative of a mentioned above stream in Gdańsk is Peter Krueger, a mathematics professor, who published "*Neuer und alter Schreibcallendar auffs Jahr...*" in the years 1609–1639. He described the predicted system of stars and then forecasted weather.

It was not until 2006, when Janusz Filipiak from the University of Gdańsk (Miętus 2007) came across a collection of Buethner's *Callendar* dated to years 1662–1701. The *Callendars*, that were discovered, were entitled "*Neuer und Alter SchreibCallendar/auffs Jahr nach unsers Herren Jesu Christi geburt MDCLXXIII auff den Danziger und umbliegender Behrter*". Hence, a question may be raised, namely whether or not we have come across another publication proving Buethner's activity as an astronomer and a meteorologist.

A straight answer is difficult to be given and impossible until Buethner's "*Observationes* ..." (mentioned by Hellman) are found and compared with the *Callendars*.

The analysis of the contents of the works recently found enables to estimate its actual state and scientific utility. The technical state seems to be intact. The writing is clear. All the information is written in tabular form (Fig. 12.2). One chart describes one month. Each month takes up two pages. On one side, always the left

PROGNOSTICVM
Oder Practica / auffs Jar nach der geburt vnſers
HERRN vnd Seligmachers Jeſu Chriſti/ 1577.
zu Ehren der Löblichen Königlichen Stadt
Dantzigk Gepractiſieret durch
D. Wilhelmum Miſocacum/Medicum vnd Aſtro-
nomum daſelbſt reſidirende.

Saturnus vnd Mars, tanquam cauſæ ſecundariæ
ſein Herren dieſes Jars, Mars vnd Venus Mithülffer.

lichen Obrigkeit mitt / Vnnd ein Königreich wird viel diſtruction vnd verfolgung leiden / vnd verſtört werden/ Auch ſollen die Regenten etlicher ſtedten/als Obrigkeit/ Juriſten/ Richter vnd Aduocaten betrübet ſein/ vnd geengſtigt werden / vnd etliche reiche Leute von jren Gütern beraubet werden (Gott beſſers.) Diß ſind die vornemſten zufellungen welche in dem gantzen Winter drewen/biß zum anfang des zukommen Lentzen.

Vorenderunge der Lufft in dem Vorwinter.

Vollmon den 6. Decembris/am Donnerſtage des morgens vmb 4. vhr 43. minuten/kalt wetter geneigt zu ſchnee vnd froſt/ bißweilen mit klarer lufft/ windig/ ſonderlich den 11. vnd 12 dennoch geneigt zu ſchnee.

Letzt viertel den 12. Decembris/vormittag vmb 9. vhr 28. minuten/ſehr kalt/froſt/mit klaren tagen/ Sonabend geneigt zu vielem ſchnee / mit groſſer turbation in der lufft Dinſtag widerumb kalte lufft mit froſt/vnd etliche dunckel kalte tagẽ/ biß zum ende dieſes Letztẽ viertels.

New Chriſtmon den 20. Decembris/am Donnerſtag des morgens vmb 7. vhr 38. minuten/ſehr kalt vnd froſtig/mit ſchönen klaren tagen/ bißweilẽ auch mit fliegenden dunckele wolcken/ auff den Chriſtabend ſehr kalt/ auff den Chriſtag ein wenig linder wetter/darnach widerumb froſtig.

Erſt viertel den 28 Decembris/am Freitage vormittag vmb 11. vhr 53. minut. ſehr kalt / froſtig mit klaren tagen vnd windig. Montag geneigt zu ſchnee. Von dem 2. vnd 3. January böß wetter mit groſſer turbation

B ij in der

Fig. 12.1 "*Prognosticum…*" by Misocacus, 1577 (from the collection of the Gdańsk Library of the Polish Academy of Science)

one, detailed astronomical information was put, including as follows: a date (day, month) and an extended non-astronomical information. There are different types of information on the other side (always the right one). They concern such data as: historical information, for example the history of Prussia in episodes, which, if we take the chronological *Callendars* into consideration, may be compared to a contemporary series. They were published in yearbook, month by month. The last column on the left which occupies at least a half of page's width, is left blank (without any printing).

The *Callendars*, published by Buethner, included mainly astronomical information, so they may be treated as astronomical ones. Moreover, in his *Callendars*, Buethner enclosed the information about the weather, as well. They are extremely brief and use only the following terms: *cold/hot air, windy, ground-frost, sunny, cloudy etc*. What is interesting about it, is that those pieces of information are printed. They are not the notes of the actual weather conditions on a particular day, as they were printed before the year they concerned. What are they then? How should they be treated? It seems that the discussed issues are explained in the volumes of *Callendars* which include hand-written registrations at the edge left column of the chart (the one that was left blank). There, the information, concerning the weather conditions is written either by one person or few people (different type

Hornung

Hat XXVIII. Tage.

In dem der kalte Nord/ durch Lufft und Felder reiſſet/
Mit Schnee und Ungeſtüm und Kälte umb ſich ſchmeiſſet/
So ſchone deines Bluts: Ins Eyß hau lieber ein/
Und fange jetzt/ was ſonſt dir wil dein Fiſchfang ſeyn

Fig. 12.2 *The Calendar* by Buethner, April 1674 (from the collection of the Gdańsk Library of the Polish Academy of Science)

of handwriting). Those registrations have some corrections made by another person or are marked with a symbol of acceptance. We may assume that Buethner's *Callendars* are forms of a tale about the weather, expected on particular days of the year (a kind of a forecast), and the hand-written elements were to verify prepared "forecasts" and to improve their accuracy in the coming years.

Everything leads to the conclusion that this opinion is justified, as Buethner lived and worked in Gdańsk at the same time as Heweliusz, the pride and household name of the town. It is very likely that they knew each other and worked nearby. Heweliusz, during public presentations of his research and the discussion carried out in the company of noble citizens of Gdańsk, had probably mentioned about the difficulties that he encountered during his observations, to name one – weather conditions. Bad weather, cloudy sky, rain or snow and low temperature must have disabled or limited his astronomical observations. Buethner's *Callendars* were away of assistance given to Heweliusz, a hint how to conduct the research and observations. It is difficult to support or reject this theory. What is not known, is how Buethner prepared his first versions of weather tales, published in the first annual *Callendar*. Perhaps, he had previously done some observations and included them in the mentioned by Hellman "*Observationes meteorol. Singulis...*" It is possible, if we take into consideration the fact that Hellman's notes, concerning the weather had come from 1657, while the *Callendars* really started in 1662. Moreover, it seems that Buethner shared a common view that weather is determined and influenced by the celestial bodies and repeats itself every 7 or 8 years. Thus, the information printed by Buethner in "*Neuer und Alter Schreibcallendar...*" may be considered a first preserved weather forecast for Poland and other regions, as well.

In Gdańsk, Daniel Gabriel Fahrenheit (1683–1736) took his fist steps literally and metaphorically. He was born in a merchant family. He was a keen physicist, who constructed different types of instruments, such as thermometers, weather glasses and altimeters. He was said to have been the inventor in 1713 of mercury thermometer and a thermometric Fahrenheit scale. Unfortunately, the date of inventing the scale and the process itself are ambiguous. Januszajtis (2005) claims Fahrenheit introduced his own scale in 1714, however, the experiments carried out in 1724 contributed to the correction of this scale. There is every possibility that the invention of this scale was inspired and supported by previous thermometric measurements, which had been conducted by Fahrenheit in Gdańsk in an extremely cold winter of 1708/1709.

Hellman (1883) and Momber (1906) mention an unknown publication that included the notes on the weather of en extremely harsh winter of 1709/1710. Unfortunately, neither of them gave the source of their information. Momber (1906) considered Johann Kanold (1717–1726, "*Sammlung von Natur – und Medicin – wie auch hierzu gehörigen Kunst – und Literatur – Geschichten*") as the source including the results of regular meteorological observations in Gdańsk in 1717. This publication has still been out of reach by us.

In Johan Adam Kulmus's (1721) and Janus Meteoroscopus's (1727) works we can find a wide range of information concerning weather. The authors not only name the dates of the occurrence of particular weather phenomena, but also try to give a careful and detailed consideration of their sources.

It was Momber (1906), who mentioned the thermometric measurements conducted in 1739 by Michael Christoph (Christian) Hanow in the Florentine scale. Hanow was the professor of Mathematics and Philosophy. He was the member of the Natural Science Research Society in Gdańsk, which was founded in 1743. Hanow is the author of more than 100 works in the field of physics, meteorology and natural science. He had been co-editing "*Danziger Erfahrungen*" (*Gdańsk Experiences*) since 1739, and was the editor of "*Acta Societatis Physicae Experimentalis*" since 1743. From the meteorological point of view, of his most significant achievement, we can consider the conduction of daily measurements and meteorological observations. The effects of those measurements carried out from 1739 to 1752 can be found in "*Danziger Erfahrungen*". Similarly, the Main Library of Gdańsk Technical University, owns the manuscripts of Hanow's observations, in three volumes coming from the whole period of observations, namely 1739–1772 (Fig. 12.3). The measurements have been carried out four times a day and include the following data: temperature, atmospheric pressure, total precipitation, humidity and the direction of wind. Apart of this Hanow attached information about daily weather conditions and the phenomena, as well as astronomical ones (Filipiak 2007a).

Furthermore, in his works Hanow described his views on nature and the beginnings of all the processes that influence the weather in a detailed way (the second volume of "*Philosophiae naturalis – Aerologia at hydrologia, scientiam, aeris, et aquae*"). In the second volume of the work entitled "*Selteheiten der Natur und Ekonomie*" we can find a notice about the probable beginning of the measurements conducted with instruments in Gdańsk (after Januszajtis 2005).

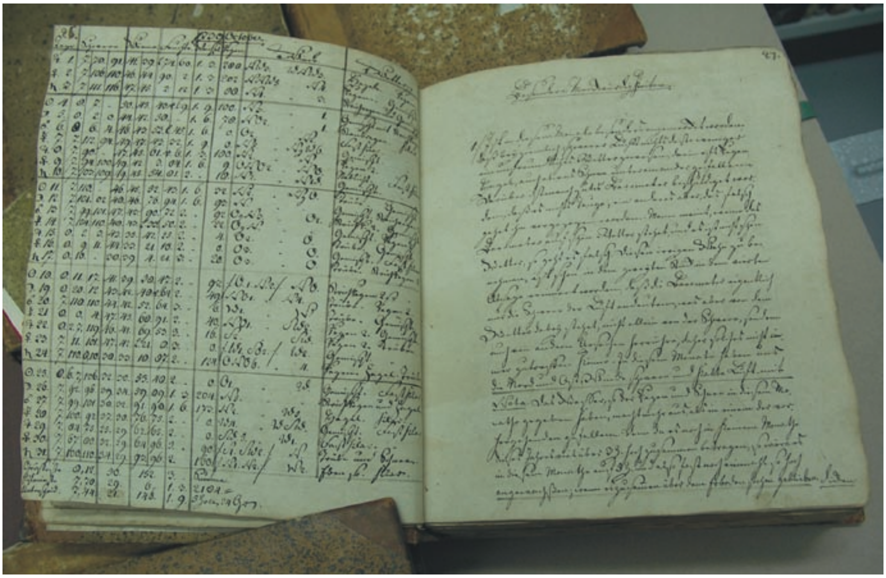


Fig. 12.3 The manuscript of meteorological records by Hanow (from the collection of the Main Library of the Technical University in Gdańsk)

> *a thermometer famous for its accuracy which was in use in 1709… numerous people sent their servants to the house of Wilke to see how cold it was. The Wilke's thermometer belonged to and was described by Krikart… He was believed to had owned this instrument 20 years earlier, but it was Fahrenheit, who filled it with alcohol in 1708.*

Gottfried Reyger, a well known botanist from Gdańsk was interested also in medicine, mechanics, electricity and meteorology. He claimed, in his works, that his meteorological measurements were carried out in 1730–1749 (in one of his works he even mentioned the period up to 1755). However, specific information about the results of the observations is missing. The following Reyger's works should be listed: *Beobachtungen der Witterung in Danzig, die Beschaffenheit der Witterung in Danzig volume 1, vom 1722 bis 1769* and *volume 2, vom Jahr 1770 bis 1786*. Those works include a broad analysis of weather conditions in terms of several dozen years in Gdańsk. Those analyses do not, however, focus on quantity, therefore results of measurements and observations are not quoted. It seems that due to the fact that the Scientific Society in Gdańsk led a very active life and met for public debate, Reyger in fact carried out meteorological observations but his notes have either been lost forever or have not been found yet.

Two manuscripts including the results of the measurements of the temperature and the direction of the wind together with the description of the weather from 1744–1784 and the recordings of atmospheric pressure from 1755–1760 and 1764–1784 were left by Carl Gottfried Minor. He was another keen meteorologist from Gdańsk and an associate member of the Society. His name, together with the year 1752, was engraved on the famous so-called *Fahrenheit thermometer*, which was the eighteenth century instrument inscripted with a few measurement scales, such as Fahrenheit, Réaumur and Florentine. This may suggest the name of the owner, as well as the manufacturer of this instrument.

The results of the measurements of atmospheric pressure, temperature and wind direction conducted twice a day can be found in Johann Eilhard Reinick's manuscript written in Latin; information on weather phenomena was also added. Reinick was a medicine doctor as well a trained physician. He was especially interested in research concerning the influence of height on pressure.

Johann Conrad Eichhorn's notes found among the archival collection include the results of his meteorological measurements conducted from 1764 to 1790. They concerned mainly the measurements of the atmospheric pressure, read with varied frequency (from two to even four times a day) and of sporadically taken recordings of the temperature and the direction of wind. In one of the Eichhorn's manuscripts a very interesting and useful figure which presents the comparison of three different temperature's scale used in Gdańsk has been found (Fig. 12.4). This figure allows recalculating the readings of temperature by Reiger, Fahrenheit and Eichhorn.

A manuscript that was probably written by Fuellbach comes from the turn of eighteenth and nineteenth century. Fuellbach was a watchmaker and an astronomer's assistant. The content of the material, concerns the results of the measurements from 1783 to 1806 conducted in the astronomical observatory which was destroyed by the French during the battle in the beginning of nineteenth century. The manuscript, however, is incomplete from 1783 to 1784 and in 1795. The measurements of the atmospheric pressure, temperature and power of the wind were taken every morning and evening (and since 1787 at noon, as well).

The next meteorologist in Gdańsk was Sturke, about who little is still known. His manuscript includes the measurements and meteorological observations conducted from 1788 to 1812. The observations were done twice a day, between sunrise and sunset and they included pressure, temperature and direction of the wind. There are some pieces of information missing in the materials that were discovered. Moreover, there are numerous interruptions in terms of measurements from 1788 to 1789 and a complete lack of information from 1811. Unfortunately, we don't know what caused the disturbances in the notes. Significant advantage of

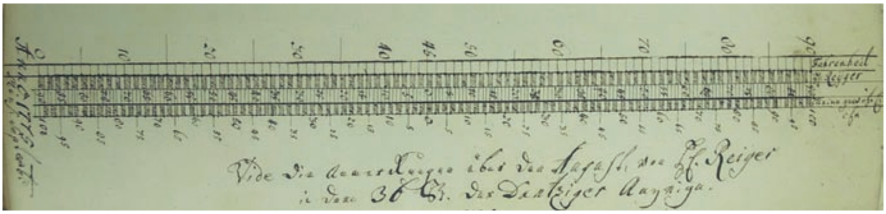


Fig. 12.4 The comparison of three different temperature's scale used in Gdańsk prepared by Reiger (from the collection of the Main Library of the Technical University of Gdańsk)

Sturke's work is numerous descriptions of the atmospheric phenomena, which took place in Gdańsk.

It was at the end of eighteenth century, in 1793, when Johann Kleefeld, a legal advisor and director of the town library, started his thermometric measurements. Unfortunately, there were significant objections to their accuracy. According to Momber (1906), Kleefeld started regular thermometric measurements in the area of the contemporary Długa Street (house number 51, in the city centre), after mastering the methodology and the instruments. The location of his observatory was the following (after Momber 1906):

> *The house was situated in the centre of the town. A lot of sunlight entered the room on the south, but in winter, the house was in the shade of nearby buildings. The north side of the building looked out onto the yard and was illuminated by direct sunlight only in summer and only in early morning hours as the nearby tall buildings (including the Church) limited the horizon. Similar problems were encountered on the east side of the building sheltered by the town hall. A direct north-east wind could only enter the yard. The instruments, such as thermometer or hygrometer were installed at the height of 28 Paris feet on both the south and the north side.*

Kleefeld read the instruments (mercury thermometers in Réaumur scale) only when they were in the shade. The observations from 1813 to 1845 were in accordance with the regulations of Societas Meteorologica Palatina in Mannheim at 6 a.m., 2 p.m. and 10 p.m. The hours of morning observations had oscillated between seven and eight in the morning until 1812 and had been taken at 9 a.m. for several months.

Simultaneously, Kleefeld's work was followed by the measurements of temperature, atmospheric pressure, direction and power of wind and the occurrence of rain, storm or other meteorological phenomena, conducted by Fryderyk Strehlke from 1826 to 1831 and from 1839 to 1850 in 2-h intervals of time. Strehlke's observatory from 1839 to 1850 was situated in the churchyard of the house of the headmaster of old Saint Peter's Gymnasium, (43.2 Paris feet high). From May to August, the thermometers were not sheltered against the sunlight in the early morning hours. Strehlke, according to the regulations of the Prussia Meteorological Institute, conducted his observations three times a day, namely at 6 a.m., 2 p.m. and 10 p.m., until August 1880. He changed the place of his observations seven times, moving them sometimes to distant districts of the town. There is some information missing in Strehlke's observations. The most significant ones are the lack of observations at 6 a.m. from October 1843 to November 1847. The lack of sheltering of the thermometers from the morning sunshine from April to September is a negative feature of Strehlke's observations from 1841 to 1850.

After Strehlke's death meteorological observations in Gdańsk were conducted only in the Navigation Academy. They were limited to three times a day registration (8 a.m., 12 p.m. and 4 p.m.) of temperature and pressure. However, according to contemporary scholars (Momber 1906) those observations were far from quality ones.

A meteorological observatory in Nowy Port (Neufahrwasser) was set up in 1876. This observatory did measurements at 8 a.m., 2 p.m. and 8 p.m., according to the regulations of the Nord Deutsche Seewarte in Hamburg. Moreover, the maximum and minimum temperatures were registered twice a day. The station was situated 2 m above the see level, the thermometers were installed 2 m above the ground.

12.4 The Gdańsk Air Pressure Series – Evaluation of Metadata

The identification, collection of information and data sources have significantly increased the volume of historical meteorological data from Gdańsk available for the analysis of the regional and local climate change. However, the scale of problems to deal with is considerable. The reconstruction of the climatic series comprises scanning of the documents, digitization of the contained data and its interpretation which is both time and money-consuming. This task is still in progress which is caused by the scope of the material.

Collection of dispersed archived materials and creation of their digital image is not a sufficient action to receive the reliable long-term climatic series. Another very important issue is that it is difficult to obtain reliable material from measurements lasting many years. In the paper below the atmospheric pressure data can be used as an example demonstrating the potential ability to reconstruct the long-term climatic series of Gdańsk and problems connected to the interpretation of climatic trends.

As was described in the above introduction the history of meteorological observations and measurements in Gdańsk is long and complicated. The entire instrumental series can be divided into a sub-periods which can be listed in following manner. The Early Observers period, 1739–1806, covers the initial years of the measurements when they were conducted with the instruments mostly invented by the observers themselves, often in their flats. No general regulations of observations existed till 1780, when the international network of weather observations in which meteorological data were simultaneously recorded according to the observational code was set up (Societas Meteorologica Palatina organized by Johann Hemmer, court chaplain to Karl Theodor, Prince Elector of the Palatinate). This leads us to the recognition of the next sub-period – The First Meteorological Networks, covering the years from 1807 to 1875. The measurements were conducted with the instruments produced by the renown manufacturers and professionally calibrated. However, the instruments were still located in the homes of the observers. Only during the second half of the nineteenth century the first national meteorological networks were established. The third sub-period – Modern Measurements – began in 1876 when the station in Neufahrwasser started to work. Since then the measurements in Gdańsk were done only in the meteorological stations operated by the professional observers according to the generally obligatory standards and regulations.

Three ten-year periods were selected to present the variability of the atmospheric pressure in Gdańsk (Fig. 12.5). Each one of the selected series corresponds with the periods of history of meteorological observations. On the basis of the results of the analysis the problems connected with the methodology of the measurements, incomplete metadata and interpretations of the data can also be highlighted and explained.

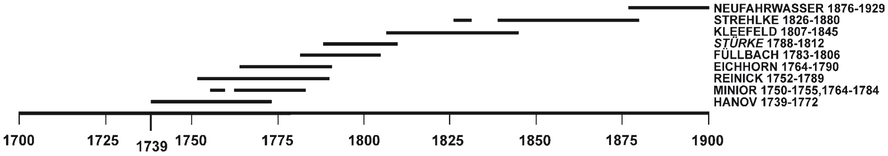


Fig. 12.5 Temporal distribution of the identified periods of air pressure measurements till the end of the nineteenth century

12.4.1 Reinick Series

As it was pointed out above Johann Eilhard Reinick conducted measurements from the beginning of 1752 till the last days of 1789. The notes concerning the atmospheric pressure contain the records of the element readings twice a day – in the morning, at 7 a.m. (titled in manuscript as *mane*) and in the evening, at nine, sometimes 10 p.m. (*vespere*) (Westphal 1820). Though Reinick started to measure temperature also in the afternoon (*p. meridie*, which most probably means *post meridie*), he did not change the observation hours of atmospheric pressure measurements apart from rare events when Reinick registered additional record at 12 or 3 p.m.

Reinick's barometer was scaled in Paris inches and lines (1 Paris in. = 27.07 mm). The way of registering the pressure records changed twice during the observations period. Initially Reinick wrote his readings in inches divided into 12 lines (recorded as e.g. 27 in. and 9½ lines). In February 1756 it has changed into the division of inches into 120 parts (e.g. 28 in. 51 lines) and finally 2 months later Reinick started to register pressure in inches divided into 12 lines, which by turns were divided into 12 parts (e.g. 27 in. ten lines seven parts (Gran?)).

We have still not found the detailed description of the measurement place. Kleefeld (1826) describing the temperature measurements in Gdańsk stated only that Reinick's observational place is located about 40 Paris feet above sea level. Establishment of the place of Reinick's observations is somewhat difficult. Actually we can do it hypothetically, basing on the information presented in the short history of meteorology in Gdańsk described in the *Schriften der Naturforschende Gesellchaft in Danzig*, volume 8, edited in the 150th anniversary of institution of that society. The most probable place of observations, building of Gruene Tor, was marked in the Fig. 12.6. It is about four-floor high building located on the Motława River bank, closing the Royal Route – the most representative road in Gdańsk. The windows of the building are oriented W-E. Maybe the lately found another manuscript by Reinick – *Von der Schwere und ausdehunden Kraft der Luft* will give more precise answer. Unfortunately, similarly to other found manuscripts, the information was recorded in the Gothic handwritten character in the eighteenth century German language (with borrowings from Polish and Dutch) so consulting both a historian and translator is necessary.

The Reinick series is characterized by the accuracy and care. Only in the initial year 1752 as well as in the final period of observations, in 1789, weeks before Reinick's death, the gaps and missing values can be observed. The total sum of the

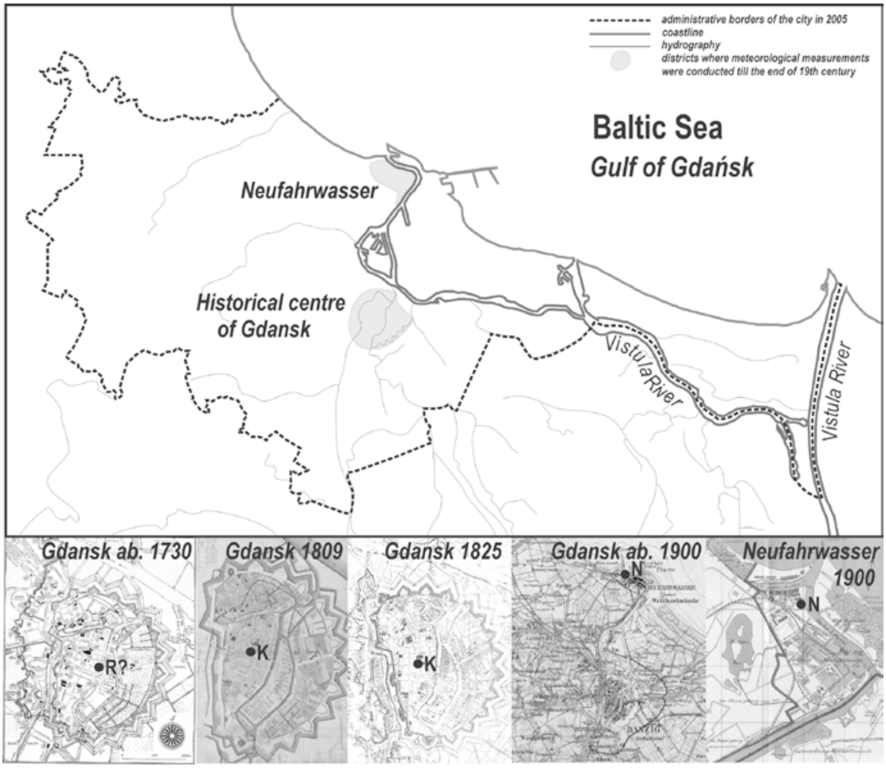


Fig. 12.6 The maps of Gdańsk presenting the development of the city and the places of measurements and meteorological observations described in the paper: R? – Reinick (1752–1789, probable place), K – Kleefeld (1807–1845), N – Neufahrwasser (1876–1919)

missing values in the 10-year-long period 1752–1761 selected for analysis does not exceed 2% of observations.

12.4.2 *Kleefeld Series*

Describing the location of his observatory (Fig. 12.6), as was cited above, Kleefeld (1826) added the detailed information about the position of the barometer. According to the Royal Government levelling it was elevated 41 Paris ft and 11.863 in. above sea level (43 Reinische ft and 5.5), which means 13.64 m a.s.l. In his manuscript (both rough and fair copies) Kleefeld registered atmospheric pressure in Paris inches and lines, by turns in the printed version of the results of his observations we can notice unusual values without explanation about units, for example 338. After the checking it became clear that Kleefeld expressed the values of element in Paris lines only.

During the whole observation period a Pistor barometers were used, as Kleefeld stated "*All what I describe were observed with the best instruments from Pistor, Mendelssohn, renard and Chevallier in Paris*". The important fact is that temperature inside the room where the barometer was exposed was measured too. The most probably it was thermometer annexed to the barometer and it was scaled in Réaumur scale.

The Kleefeld series have a few serious gaps. They occurred often during the initial period of observations (till 1809) and the observations at 2 p.m. were the most incomplete. Much less numerous gaps can be observed in the morning and evening observations registers. After the 1809 the gaps were very rare. They occurred in November and December 1813 and were caused by the bombardment during the siege of the city by Russian troops. Unfortunately, the part of instruments was destroyed then (hygrometer and rain gauge).

12.4.3 Neufahrwasser Series

The complete records of the observations conducted in the seaside district of Gdańsk – Neufahrwasser (Fig. 12.6) were published in *Deutschen Meteorologischen Jahrbuch*. Data were enriched with the important information about the instruments' exposition. Additionally, in 1927 Johann Staben published in *Schriften der Naturforschenden Gesellchaft in Danzig, vol. 17* article *Zum Klima von Danzig-Neufahrwasser*. Thus, the barometer was mounted 4.5 m above the ground (11.1 m above sea level). The observations were conducted by the head of the Hauptagentur der Deutschen Seewarte (Staben 1927).

Though the data in *Jahrbuch* were complete, the period 1881–1890 selected for analysis is, unfortunately, characterized by two gaps. The periods Jan–Feb 1885 and May–Jun 1886 are missing because of the errors during the scanning of the data. All the data presented in *Jahrbuch* were reduced to 0°C, gravity and to sea level.

12.5 Reduction of the Pressure

All pressure data obtained from the measurements should be recalculated. The reduction to sea level pressure, gravity and 0°C should be taken into account. The procedures of the reductions are explained in details in WMO publication (WMO 1983). Additionally introduced corrections may concern thermal stratification, adhesion and hysteresis (Róždżyński 1995), however its influence on the barometer registers in such analysis is negligible. As our analysis applies to the historical data conversion of units to hPa has to be done.

Thus the reduction was performed to all data of Reinick and Kleefeld series. Reduction to 0°C was based the assumption that Reinick's and Kleefeld's barometers were accurate at that temperature, however it is more certain with the respect to the Pistor barometer used by Kleefeld. Reduction was made using the equation (Moberg et al. 2002):

$$p_0 = g_n \bullet \rho_0 \bullet H_T \bullet (1 - \gamma \bullet \Delta T) \bullet 10^{-5}$$

where

$$\Delta T = T - T_{0^\circ C}$$

where ρ_0 is air pressure reduced to 0°C (273.16 K), g_n is normal gravity acceleration (9.80665 m s^{-1}), ρ_0 is density of mercury in normal conditions (13.57904 × 10^3 kgm^{-3}), H_T is height of the mercury column in barometer at temperature T (in °C), γ is the bulk expansion of mercury (1.818 × 10^{-4} K^{-1}) and T is the temperature at measurement moment (in °C).

There was no problem to use as T the barometer temperature in case of Kleefeld series (with conversion of R° to C°). The earlier measurements were lacked in such measurements. The simple calculation with taking into account only the temperature from the Reinick's thermometer exposed outside was also not advisable since the homogenization of that series has not been applied yet. Provided that the measurements were carried out by Reinick in the heated room the thermal coefficients characteristic for the each month were adopted basing on the Kleefeld's temperature readings conducted in similar conditions. The error of such calculation is generally lower than ±0.1 hPa and its accuracy can be regarded as sufficient.

The reduction to normal gravity was performed using the formula (Moberg et al. 2002):

$$p_g = \frac{g_\pi}{g_n} \cdot p_o$$

where p_g is air pressure at station altitude reduced to 0°C and normal gravity, and g_n is gravity at station latitude (9.81078 ms^{-1} at 54°20'N).

And the reduction to sea level was made using the equation (Moberg et al. 2002):

$$p_s = p_g \bullet e^{\left(\frac{g_\pi \cdot z}{R \cdot T_m}\right)}$$

where p_s is air pressure reduced to 0°C, normal gravity and sea level, z is barometer altitude in meters, R is gas constant for dry air (287.04 J × K^{-1} × kg^{-1}) and T_m is mean air temperature in K in the air column between station level and sea level.

12.6 Selected Statistical Analyses of the Pressure Series

The three selected pressure series were briefly analysed in terms of some properties of daily, monthly and annual values. Additionally, the short comparison with the homogenous pressure data from Uppsala (observations from 1722) and Stockholm (from 1756) was performed. The reconstruction and homogenization of the chosen series was performed within the EU project IMPROVE. Uppsala is located about 600 km and Stockholm about 550 km north from Gdańsk, which are rather long distances. Unfortunately, no other stations with long enough homogenous daily air pressure series exist. However, the important issue was the similarity of the geographic environment of all three stations' location in the basin of the Baltic Sea, in the lowlands. The next feature is the proximity of both stations to the sea (Gdańsk – in the coast, Stockholm – 25 km from the sea and Uppsala 70 km).

Figure 12.7 represents the course of daily means of atmospheric pressure within three selected 10-year-long Gdańsk series. The daily means were calculated as the arithmetic average of the available values, that is in case of Reinick series it was defined as an average of morning and evening observations and in case of other series it is an average of three daily observations.

The range of the mean daily air pressure in all selected periods varies from 970 hPa to 1,050 hPa. The mean air pressure in the following periods equals as follows: 1,011.6 hPa (Reinick series), 1,016.0 hPa (Kleefeld series) and 1,013.5 hPa (Neufahrwasser series). The differences between particular periods are considerable thus the question about the reasons arises. So far, the initial analysis of the course of the daily means in the selected periods highlights the very high values in 1811 and during the first half of 1812. The measured air pressure daily means were greater than 10–15 hPa on average in comparison with the following years.

The comparison of Kleefeld series with the data from Swedish stations in Uppsala (Fig. 12.7) and Stockholm confirms the anomalously high values of air pressure in the indicated period in Gdańsk. The difference of annual value of air pressure between Gdańsk and Swedish stations in 1811 exceeded 10 hPa and was 4 hPa in 1812 while in the following years of the described period it was 2–3 hPa. Most probably it is the evidence of inhomogeneity in the Gdańsk series.

In two other selected periods 1752–1761 and 1881–1890 it is possible to observe the great variability of air pressure daily means in Gdańsk, but the constant anomalously high difference between the registers in Gdańsk and Uppsala (Fig. 12.7) as well as between Gdańsk and Stockholm no longer exist. However sporadically existing great differences between air pressure daily means in Gdańsk and Uppsala are surprising, for example 27–28 Feb 1753 (Fig. 12.8). The daily mean air pressure in Gdańsk was almost 40 hPa higher than in Uppsala what is unlikely taking into account the development of synoptic situation. The greatest noted gradients between Gdańsk and Uppsala reached no more than 30 hPa for example when very active pressure low crossed along the Baltic Sea in 26–27 Feb 1990 (Miętus 1998b). In case of the extremely strong pressure high the noted gradient did not exceed 20 hPa (30 Jan 1972, Miętus 1998b). While there is a lack of other long daily air pressure registers from the area of the Southern Baltic Sea basin (the Stockholm series begins with 1756) it is difficult to point out which series is erroneous. When we analyze the registers of Reinick and Uppsala series from the proceeding and following few days and, additionally, the values of air pressure noted in Gdańsk simultaneously with Reinick by the other observer – Hanow (Hanow 1739–1772) it is clearly showed that the pressure values from analyzed days in Uppsala series are incorrect.

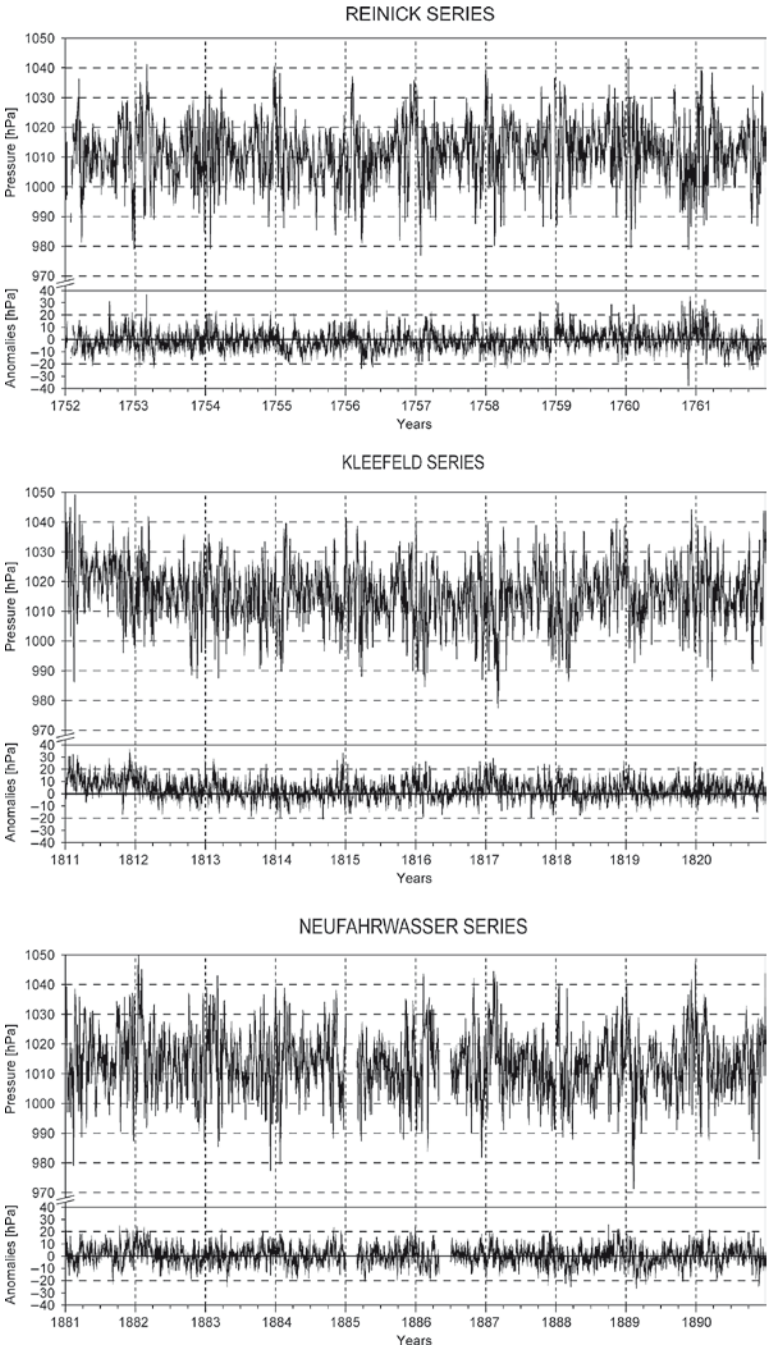


Fig. 12.7 Daily mean pressure values of the Gdańsk series in three selected periods and differences between Gdańsk and Uppsala series.

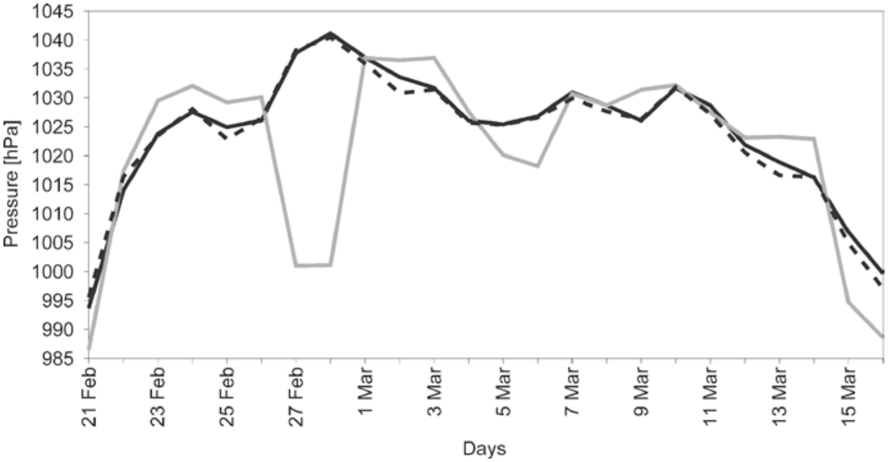


Fig. 12.8 Daily mean pressure in Gdańsk (Reinick series – *black solid line* and Hanow series – *dashed line*) and Uppsala (*grey line*) in the period 21.02-16.03.1753

Another considerable discrepancies between Reinick and Uppsala series values occurred in the wintertime 1760/61. However, additional reference air pressure series from Stockholm is available for this period. The air pressure values registered in Gdańsk were also greater than in Stockholm, but the differences between Gdańsk and Stockholm were in half less than those between Gdańsk and Uppsala.

The additional, homogenous data from Stockholm helps to assess the inter-station comparative analysis of Gdańsk series. What is important, the correlation coefficient between Gdańsk and Stockholm series is somewhat greater than for the pair of station Gdańsk-Uppsala. For the period 1756–1762 the value of correlation coefficient between Gdańsk and Stockholm daily means is 0.82, while in the case of the Gdańsk versus Uppsala it is 0.77. In the subsequent periods the correlations between Gdańsk and Swedish series generally increased. In case of period 1811–1820 it was 0.80 for the pair Gdańsk-Stockholm and 0.78 in case of Gdańsk-Uppsala, and for the latter period the values were 0.83 and 0.81 respectively. The Swedish series are better intercorrelated, the correlation coefficient is almost one, however in the case of the period 1756–1761 its value is 0.94.

The smallest discrepancies between Gdańsk series and Swedish data are characteristic for the latter of the selected periods. The annual air pressure mean in Gdańsk-Neufahrwasser was greater than 0.8 hPa than in Stockholm and 0.6 hPa than in Uppsala. The comparison in the initial period (1752–1761) showed that Uppsala was characterized by the pressure greater by 0.9 hPa than Gdańsk. During the period 1811–1820, as was mentioned above, the mean difference of annual air pressure in Gdańsk and Uppsala was considerable and exceeded 3 hPa.

The differences between air pressure daily means in Gdańsk-Neufahrwasser and Uppsala very rarely are greater than 20 hPa. Only during winters of 1882/83 and 1888/89 the episodes of the great pressure gradient between Polish and Swedish coasts occurred, resulting in severe wind erosion in the area of Southern Baltic.

Table 12.1 Standard deviation values of daily mean air pressure (hPa) in Gdańsk, Uppsala and Stockholm in the analysed periods

	Period		
Station	1752–1761	1811–1820	1881–1890
Gdańsk	9.50	9.47	10.19
Stockholm	–	11.69	12.03
Uppsala	11.99	11.26	12.01

However, the difference between Gdańsk and Stockholm was always smaller than between Gdańsk and Uppsala.

The greatest variability of the air pressure In Gdańsk was observed during the period 1881–1890, when the standard deviation of daily means equalled 10.19 hPa (Table 12.1). During both earlier periods the value of this estimator was smaller by about 0.70 hPa. Both Swedish stations were characterized by the greater dispersion of air pressure values than it was recorded in the case of Gdańsk.

The great scatter of air pressure values is characteristic for the cold season what is reflected in the standard deviation. Greatest absolute values of this estimator in the period 1752–1761 were met in Gdańsk and Uppsala in January (respectively about 11.88 hPa and 13.59 hPa). The latter seasons, compared with eighteenth century, had lower absolute values of standard deviation. In the period 1811–1820 the absolute values of standard deviation were characteristic for March in Gdańsk (10.65 hPa) and in Swedish stations in January again (12.18 hPa in Stockholm and 12.52 hPa in Uppsala) meanwhile in the period 1881–1890 October was the month of the greatest dispersion of analyzed element values (10.77 in Gdańsk, 14.18 hPa in Stockholm and 14.24 in Uppsala). The smallest standard deviation values of air pressure in the period 1752–1761 were characteristic for August in Gdańsk (4.54 hPa) and June in Uppsala (6.62 hPa). In the period 1811–1820 it was July, when the absolute minimum values of standard deviation occurred in each station: 5.19 hPa in Gdańsk, 6.06 hPa in Stockholm and 6.18 hPa in Uppsala. In the latest period the smallest absolute values in April were characteristic for each of the stations. The value of this estimator was 6.92 hPa in Gdańsk, 8.32 hPa in Uppsala and 8.36 hPa in Stockholm.

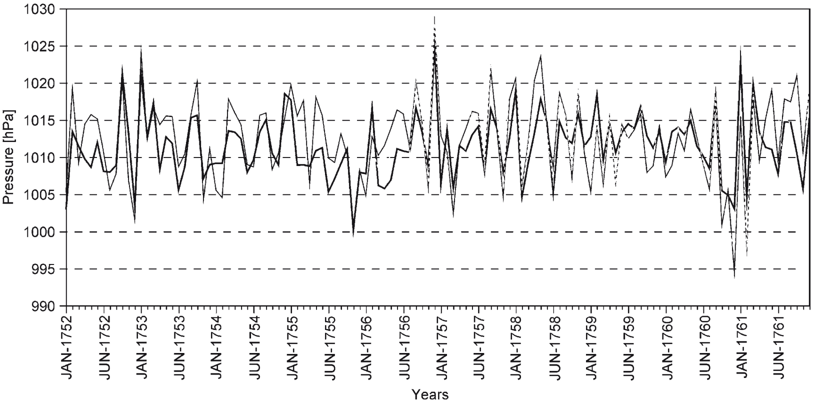
The air pressure ≥ 1,030 hPa was relatively twice more frequently in Gdańsk in the latter periods when it constituted over 6% of all registers of air pressure, in comparison with the initial one, when it was over nearly 3.3% of observations (the frequency of occurrence was not expressed in absolute values because of the different number of air pressure registers per day in the analysed periods). Such high pressure was registered first of all in January in the period 1752–1762 and 1811–1820 meanwhile in the period 1881–1890 the pressure ≥ 1,030 hPa occurred most frequently in February. The very few cases of such high pressure were noted in the warm seasons. The air pressure ≤ 990 hPa occurred much more rarely than cases with high pressure in Gdańsk (Reinick series – 2% of observations, Kleefeld series – 1% and Neufahrwasser series – almost 1.5%) and they were noted the most frequently in January (Reinick series) and March (Kleefeld and Neufahrwasser series). During the months of the warm season (from April to September) such low pressure had not been observed almost at all.

The results of analysis of Figs. 12.9 and 12.10 clearly highlight the synchronicity of air pressure variability in the area of the Southern Baltic Sea basin. Analyzing the courses of monthly mean pressure values in three analysed stations in the period 1752–1761 we can find the greatest differences between Gdańsk and Uppsala in the first half of 1752, in 1755 and in 1761. For the later period, 1811–1820, the differences between Gdańsk and Swedish stations were characteristic from the beginning of the period to the half of 1820, as it was stated above; then all series were synchronous. However, the air pressure registers in Gdańsk till the end of the period were somewhat greater than in Swedish stations. Bärring et al. (1999) analyzing monthly pressure variations in Lund from 1780 to 1997 defined period 1780–1820 as experiencing high pressure in early spring (March and April). One can observe in the period 1811–1820 (Fig. 12.9) a number of high air pressure values in March and April exceeding 1,017 hPa (1813, 1814, 1817), but no significant tendency is noticeable. In the last analysed period the occurrence of discrepancies between mean monthly values in Gdańsk and Swedish stations in autumn and winter 1881 and in autumn 1883.

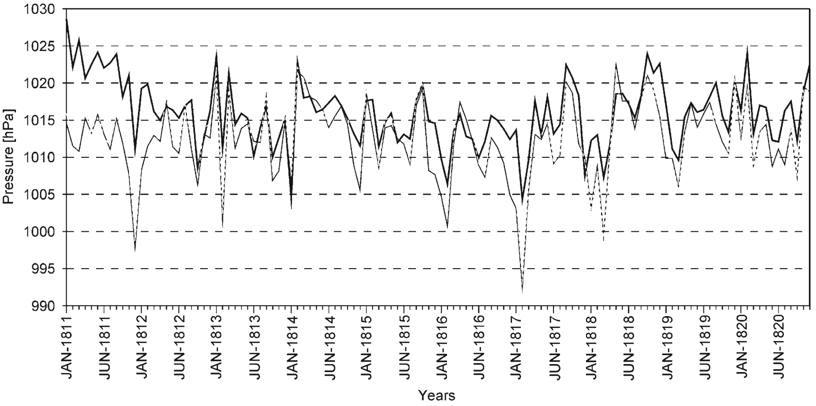
The mean annual pressure cycles of daily means in Gdańsk in the analysed period were compared with the analogical ones in Swedish stations (Fig. 12.10). One can observe the substantial coincidence of variability of air pressure in the area of the Baltic Sea basin. Among the most typical features are: considerable air pressure changes in January and February, relatively high pressure in spring, summer minimum and successive increase in autumn till the following minimum in November and December. In the period 1752–1761 very low minima in February and November as well high pressure in September and January occurred. The values of element in Uppsala and Stockholm were greater than in Gdańsk from April till September. In the period 1811–1820 minimum in the beginning of March was stronger than in November. The greatest absolute values of air pressure were noted in the second half of March. The air pressure in Gdańsk dominated the values in Swedish stations within the whole year. The period 1881–1890 was characterized by the very strong maximum in January and February and then in September. Minima of air pressure occurred in March and in late autumn.

The series from Gdańsk and Swedish stations were additionally compared to the average annual cycle form Hel, 1971–2000 (Miętus et al. 2002–2004), located 25 km far from Gdańsk in a peninsula (unfortunately there were too many relocations of station in Gdańsk in this period which eliminated the possibility of use of this series). Statistically insignificant changes of air pressure in Europe in the scale of instrumental measurements period were reported by Bärring et al. (1999) in the analysis of the long-term variability of air pressure in Lund since 1780, Maugeri et al. (2002) in the paper on the series from Milan (since 1763), and Bergström and Moberg (2002) who reconstructed air pressure in Uppsala since 1722. Thus one might observe the most important features of variability of air pressure in the different periods in the area of the Southern Baltic Sea basin within instrumental observations period. In the first of periods selected for analysis daily means of air pressure in Gdańsk and Uppsala were lower than those in the last normal period of the twentieth century in Hel during the whole year. The second of the analyzed periods was

REINICK SERIES



KLEEFELD SERIES



NEUFAHRWASSER SERIES

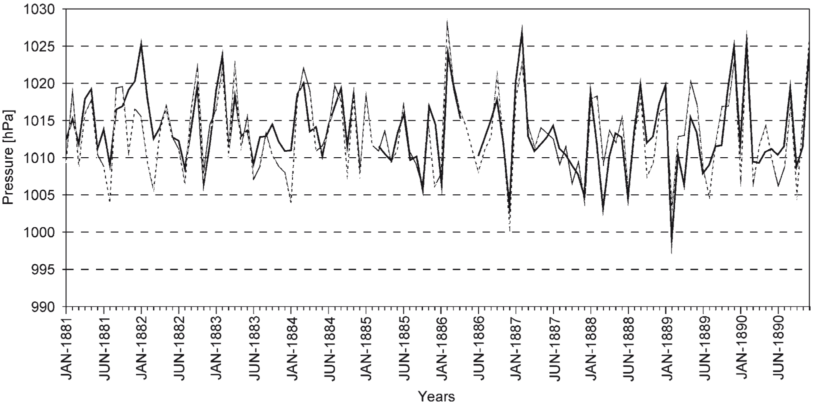


Fig. 12.9 Monthly mean pressure values of the Gdańsk (*bold solid line*), Uppsala (*thin solid line*) and Stockholm (*dashed line*) series

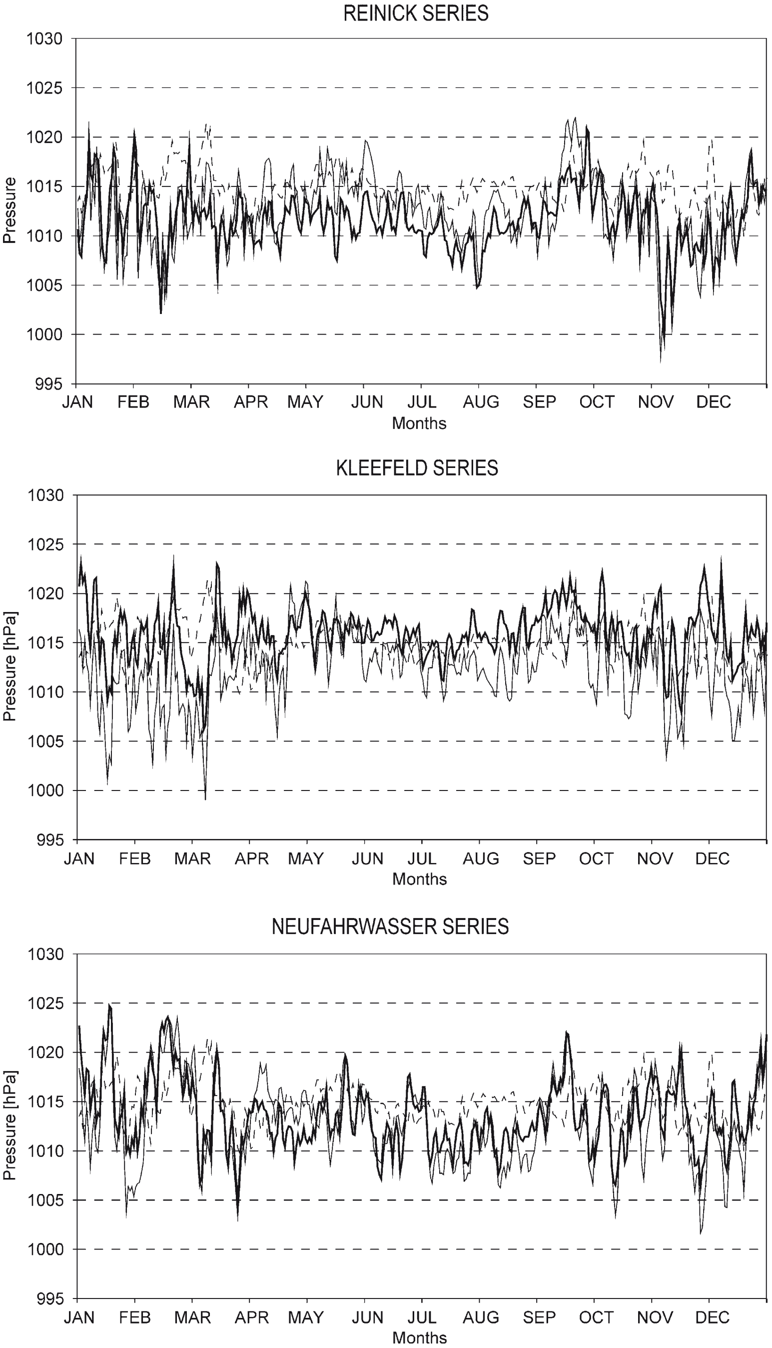


Fig. 12.10 The annual course of daily mean air pressure in Gdańsk (*bold solid line*), Uppsala (*thin solid line*) and Hel (period 1971–2000, *dashed line*)

characterized by the similar air pressure values in Gdańsk as in Hel, apart from the greater pressure in Gdańsk in spring and early autumn. In Swedish stations the lowest air pressure values in January and February occurred. In the latter period the air pressure in Gdańsk and in Swedish stations was comparable with the values in Hel except for the lower summer minimum in the nineteenth century.

Results of the analysis obtained so far proved the air pressure measured in Gdańsk to be consistent with the registers in Swedish stations. The observed differences can result from the effects of natural variability of the element in the stations distant more than 500 km from each other but can also occur due to different number and times of pressure observations. The calculation of daily mean values from the different number of observations conducted in various hours can not be sufficient to obtain the reliable research material. Thus the knowledge of real daily pressure cycle is necessary to construct model appropriate to eliminate the bias caused by the changing times of observations. It was possible to present here the seasonal mean diurnal pressure cycle in Gdańsk, 1987–2000 (Miętus et al. 2002–2004) (Fig. 12.11), which is consistent with the results presented in literature (Chapman and Lindzen 1969; Maugeri et al. 2002). Two maxima (at 9 and 21 UTC) and two minima (six and 12 UTC in winter and three and 15 UTC in the other seasons) can be observed. Taking into account the Reinick's observations conducted twice a day, respectively at 7 and 21–22 LT (local time) it is clearly showed

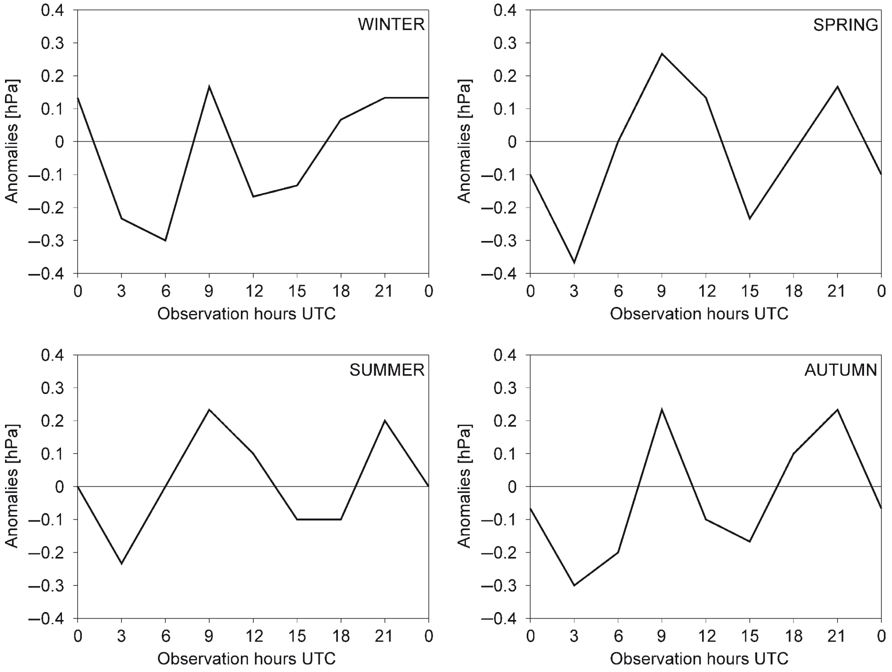


Fig. 12.11 Seasonal mean diurnal pressure cycle in Gdańsk, 1987–2000, calculated from eight observations per day, the observation times are presented according to UTC

that the simplified way of calculating the daily mean based only on two observations can cause the errors. The method of correction has to be applied to adopt all data to the real values of daily mean. For instance the greatest absolute errors found in early period observations in Milan (before 1834) were equalled 0.5 hPa in May. However, they did not exceed 0.2 hPa generally (Maugeri et al. 2002).

12.7 Summary

The analysis concerning the collection of information and other notes about meteorological observations and measurements conducted in Gdańsk seem to influence and enrich the hitherto existing knowledge on meteorological observations, as well as the beginning of regular measurements. A described history of meteorological observations taken by particular keen scholars ascertains the opinion that regular measurements and observations embarked in Gdańsk had started even before 1739 and they have been continued up to now.

It seems to be possible to reconstruct climatic series of Gdańsk since 1739. The data from earlier sources are still not available or refer to isolated periods. Additionally, sometimes they are characterised by considerable subjectivity. The most complete data characterizes elements such as air temperature, atmospheric pressure and wind speed and direction. The series of the other elements (humidity, precipitation, cloudiness) have got periods with missing data. The short breaks in observations took place not only in the eighteenth century but also in following centuries. It has been caused by the breaks during the wars, short discontinuations of the observations, or the limitation in the frequency of the readings of the instruments.

The preliminary results of atmospheric pressure data analysis collected by Reinick, Kleefeld and station in Neufahrwasser in Gdańsk did not reveal the errors in data which could eliminate them from the further analysis. However, the number of problems appeared concerning for example anomalously high values of atmospheric pressure of the Kleefeld series in comparison with both two other Gdańsk series as well as series from Uppsala and Stockholm.

The next important issue is related to the data homogenization and metadata. In practice it is difficult to obtain homogeneous data from long-term measurements. Climatic series, apart from natural variability of the climate, show additional impact of artificial factors. The homogeneity of the Gdańsk series, like many other long series, is disturbed by numerous random phenomena like relocations of the measurement places, changes in instruments as well as slow and persistent change of the surroundings of the station connected to the development of the city. In the scale of the examined period from 1739 till the beginning of the 20th Gdańsk enlarged its area and population several times. Only the application of homogenization methods will allow to uncover the heterogeneity in series and removal of the effects of artificial changes by introducing appropriate numerical amendments.

The comparative analysis of series from Gdańsk and Uppsala revealed also considerable discrepancies between data from some particular days from the eighteenth century, which was the most probably caused by the errors in the Swedish data. However, the paper was not intended as the attempt to question the homogenous series from Uppsala. The chance to verify the existing climatic datasets from the area of the Southern Baltic Sea basin appeared as well as more intensified assessment on climate change in this area will be possible soon.

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Chapter 13
A Composite Reconstruction of the Russian Arctic Climate Back to A.D. 1435

Vladimir V. Klimenko

During the last 100 years our planet apparently is passing through the fastest and the most significant warming in the history of civilization. Orthodox climatology and, in particular, that part of it, which prefers to base its conclusions on the data of numerical modeling, states that global warming is to increase significantly in the polar regions. In particular, one of the principal modern instruments for climate studying – general circulation models (GCMs) – states that the maximal temperature increase is to happen in autumn above water area of the Arctic Ocean (Kondratiev 2004; Pfeifer and Jacob 2005). However, basing on more than 100 year record of meteorological observations in high latitudes, one can state now that nowhere in the world the theory is so much far from the reality as it is in the Arctic (hereafter under this term we mean the Eurasian coast of Arctic Ocean between Norway and Chukotka). The Arctic is a real climatic paradox, as the most detailed data of observations taken within the last 50 years shows no significant warming until the beginning of the present century; and now, where it nevertheless happens, major temperature increase occurs in winter and spring, but not in autumn seasons (Przybylak 2000; Klimenko et al. 2001).

In this connection, data about Arctic climate fluctuations in the historical past, which may facilitate formation of more correct understanding of possible reasons and scales of changes in the past and in future, attracts high interest.

Due to considerations expressed the Global Energy Problems Laboratory (GEPL) of the Moscow Energy Institute (MEI) in collaboration with the Seminar of East European History of the Rhine University (Bonn, Germany) in 2002–2006 conducted a study of documentary evidence about climate condition in the basin of the Barents and Kara Seas as well as on the adjacent territory of the north-east of the European part of Russia and the western Siberia in the sixteenth to twentieth centuries. The map of the study region and neighbouring Arctic areas with the most

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important meteorological stations, each of which has at least 120 years of observational record, is given in Fig. 13.1. On the same figure the locations are indicated, for which detailed palaeoclimatic reconstructions are available, which are performed by dendroclimatic methods (Briffa et al. 1992; Earle et al. 1994; Mac Donald et al. 1998; Gervais and Mac Donald 2000; Kirchhefer 2001; Hantemirov and Shiyatov 2002; Naurzbaev et al. 2002). The box indicates region boundaries in the basin of the Barents and Kara Seas (BKS), for which in the present work a reconstruction of mean annual air temperatures (and hereafter the term "temperature" refers to the annual one if not stated otherwise) is developed.

In this work we tried to introduce in a scientific circulation either little-known, or unpublished before in Russian, or unpublished at all evidence of the European and Russian navigators, travellers and researchers, who have visited the basin of the Barents and Kara Seas. In total we gathered about 3,000 pieces of documentary evidence, containing this or that climatic and natural history information – a full collection of this evidence and origin sources are presented elsewhere (Klimenko and Astrina 2006; Astrina 2007). Unfortunately, we have to admit that the volume and density of the information received in the separate time intervals (especially it concerns the fifteenth and the first half of the seventeenth centuries) is not sufficient in order to perform a correct quantitative palaeoclimatic reconstruction on its basis. That's why for such a reconstruction a decision had been taken to combine historical-climatic research results with the data of numerical modelling of BKS region climate (region I in Fig. 13.1), recently undertaken in our work (Klimenko and Mikushina 2005).

Simulations were carried out with a regressive-analytical climate model, developed in the GEPL of the MEI (Klimenko et al. 1997; Klimenko and Mikushina 2005). This model gives an opportunity to calculate variations of annual average and seasonal average temperatures depending on changes of main climatic factors, information of which one can find in Table 13.1.

To investigate the relationship between regional temperatures and natural climate factors the multiple linear regression model was used. Its coefficients were calculated by the least square method from the smoothed instrumental data for the period 1863–2006. The estimation of the anthropogenic sensitivity of BKS region temperature to the forcing of greenhouse gases and aerosols was implemented in studies of climate variations through 1889–2004 (Klimenko and Mikushina 2005). The resulting temperature trend of the regressive-analytical climate model was determined by the joint influence of anthropogenic and natural factors with the significant role of the latter. The resulting trend is statistically significant on the 95% level, multiple determination coefficient is 0.51. It is completely consistent with the picture of the historical climate data, reconstructed on the basis of the documentary evidence of 1499–1911. Simulation results are shown in the Fig. 13.2 together with the data of instrumental observations. A final version of annual average temperatures reconstruction together with the data of instrumental observations and forecast until the end of this century are shown in Fig. 13.2. The produced reconstruction demonstrates that during the past six centuries climate of the studied Arctic sector experienced significant fluctuations which by both their scales and rate match those which were detected by the instrumental observations during the twentieth century. In particular, significant and

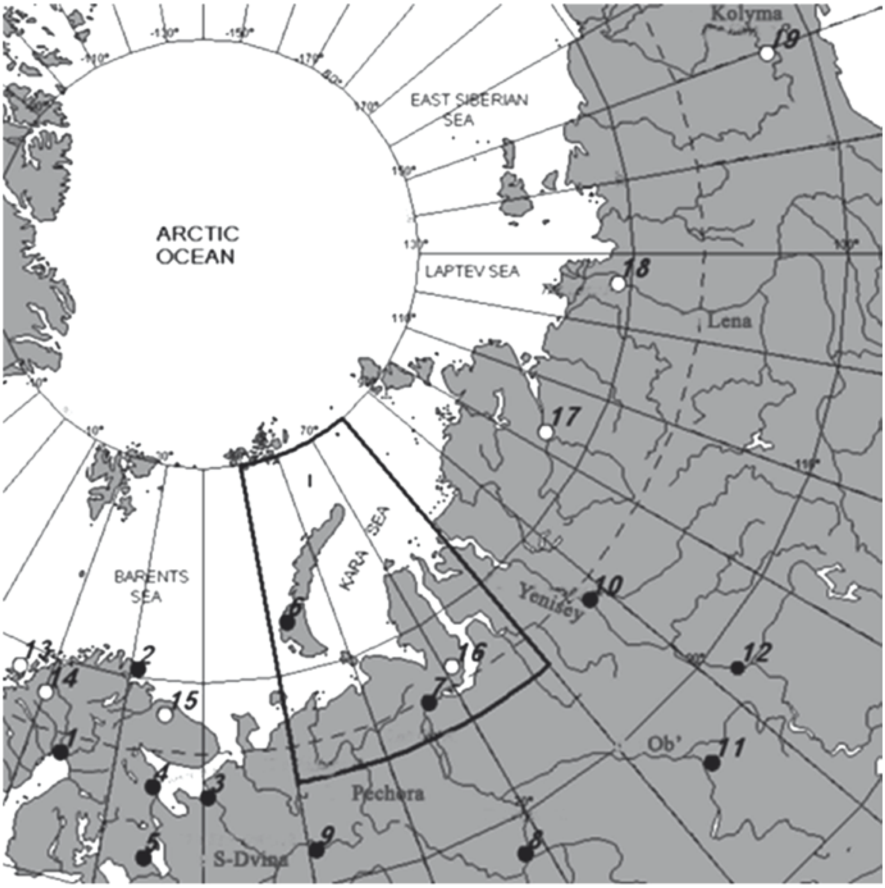

Fig. 13.1 The Russian Arctic and boundaries of a study area (I). Location of long-term meteorological stations: (1) Haparanda; (2) Vardø; (3) Arkhangelsk; (4) Kem; (5) Petrozavodsk; (6) Malye Karmakuly; (7) Salehard; (8) Tobolsk; (9) Syktyvkar; (10) Turuhansk; (11) Tomsk; (12) Yeniseysk. Location of tree-ring chronologies: (13) northern Norway; (14) Torneträsk Lake; (15) Kola Peninsula; (16) Southern Yamal; (17) eastern Taymyr; (18) the Lower Lena River; (19) the Upper Kolyma River

well-known Arctic warming, which took place in the 1920–1940s, apparently, was not unique – similar in scale warmings took place in the nineteenth century as well as in the late eighteenth century, and some weaker ones – at the beginning of the eighteenth and in seventeenth centuries, as well as in the first part of sixteenth century. The most significant cooling took place in the mid-fifteenth century, end of the sixteenth century, second half of the seventeenth century, early and late nineteenth century. All these prominent climatic events have quite a definite confirmation in our collection of a comprehensive documentary evidence. A greater part of this evidence has never been considered in a climatic context, that's why we think it's appropriate to demonstrate at least a part of it here.

Table 13.1 Major climatic factors, relevant variables and information

Climate forming factors	Variables, expressing climate forming factors influence	Source
Concentration of greenhouse gases of the atmosphere (carbon dioxide, methane, nitrous oxide, ozone, freons, etc.) and concentrations of troposphere aerosols (sulphate aerosols of anthropogenic origin mainly)	Total forcing of greenhouse gases and troposphere sulphate aerosol	Klimenko et al. (2000)
Volcanic activity (concentration of stratosphere, mainly sulphate, aerosol)	Acidity index $$ AI_c^N $$ for Northern hemisphere	Klimenko et al. (1997); Hammer et al. (1980)
Solar activity	Maximal Wolf numbers, i.e. maximal average annual values in each Schwabe cycle	Mikushina et al. (1997)
The Earth rotation velocity (Rot)	Average annual fluctuations of the Earth's day length from atomic day length ΔT	1790–present – Sidorenkov (2002); 1429–1790 – extrapolation by trigonometric trend with the principal period of 79 years
North Atlantic Oscillation winter index (NAOI)	Difference of normalized sea level pressures ΔP according to data from Lisbon station (Portugal) and Stykkisholmur station (Iceland)	1864–present Hurrell (1995); 1823–1863 Jones et al.(1997); 1429–1822 Glueck and Stockton (2001)

One hundred years before the first West European navigators arrival, the Russian North was a large deserted area, being under the formal control of Velikyi Novgorod. The main impulse, which caused people from Novgorod to come to the Far North, till the very shore of the "Cold Sea" (name of the Barents Sea up to the nineteenth century), was a search of goods for Novgorod market, furs in the first turn. People from Novgorod descended to the sea by rivers and portages and travelled by boats ("ushkuyas") along the sea shore, arranging temporary settlements, and were involved in plundering at convenient moments. At this, local population robbery was covered by the slogan of christening of "savage Lapps", "Karelia children" and "bloody Samoeds". To Belomorye and Murman, in Pechora and Yugra not only hunters came, but also soldiers for tributing or just plundering. Local population often resisted to this brigandage of Novgorod "boyar children and varmint people", and bloodshed resistance battles not always finished in favor of Russian violators. However, not just a persistent resistance of the local population, but also extremely hard natural conditions of the North facilitated those facts that until the collapse of Velikiy Novgorod

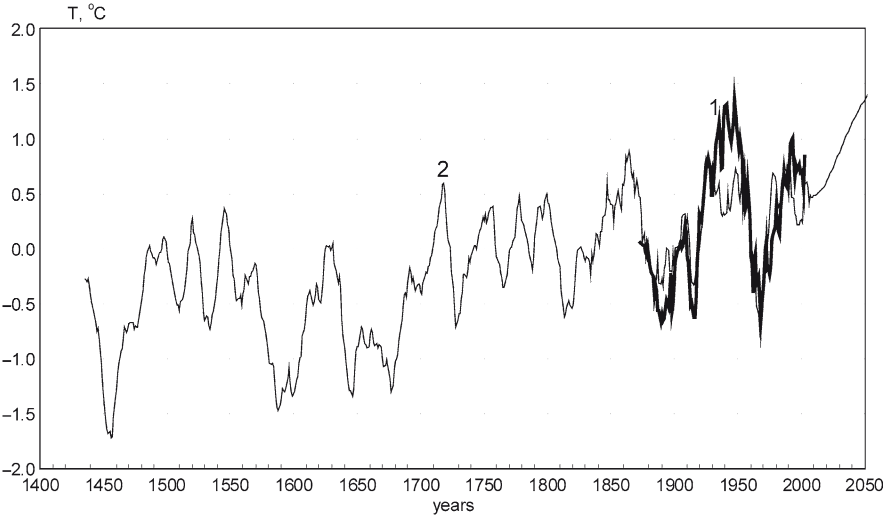

Fig. 13.2 Mean-annual temperature record (smoothed 10-year values) in the Barents and the Kara Seas basin since A.D. 1435. (1) Instrumental observations; (2) Reconstructed temperature (with reference to the period 1951–1980)

(1478) actual colonization of the seashores by Russians didn't start. In the mid-fifteenth century, except several small settlements in the lower reaches of the Severnaya Dvina, Onega and Varzuga rivers, the only permanent settlement, situated directly at the seashore, was Solovetskiy Monastery, founded in 1435.

Together with Novgorod collapse the way to Yugra (the lower Ob' River) fell completely into Moscow's hands, but only in 1499 in the mouth of Pechora River near Pustoe Lake, a famous Pustozersky fortification was built ("stockaded town was built in the tundra place, cold and forestless"). It was the first step made by Russians to the Arctic Ocean shores. We think it wasn't accidentally that Pustozersk was founded at the time of a short Arctic warming, when its climate suddenly became warmer and approached the modern one (hereafter the "modern climate" refers to the average temperatures observed in 1951–1980) by its characteristics (see Fig. 13.2). Having reached the Arctic Ocean shore, Russians, naturally, couldn't resist navigation – for trading aims as well as for fishing and whaling. Possibly at this very time some unknown Russian navigators discovered Novaya Zemlya – an exact date of this event is still unknown, however there is a very important evidence, pointing exactly the boundary between the fifteenth and sixteenth centuries. Italian writer Mauro Urbino in his book, published in 1610, writes the following: "Russians, sailing in the northern sea, discovered about 107 years ago an unknown island, inhabited by Slavs and subjected to eternal cold. It is bigger than Cyprus island and on the maps it is indicated as Novaya Zemlya" (Vise 1934).

Colonization of Kola Peninsula by Russians began undoubtedly later, and its first visible sign also coincided with a new phase of warming in the Arctic, which lasted this time for more than 30 years, since the middle of the 1530s to the early 1570s.

(Fig. 13.2). At this time on Murman at the Kola River bank a permanent settlement, although small, arises – according to the evidence of Dutchmen, who were permanent visitors to Murman, except church there were only three houses. In the 1530s at the western Murman, in Pechenga, the northernmost monastery in the world was founded. About people, who carried out a civilizing mission in this remote region, we can find evidence in extracts of a diary of the Dutch Simon van Salingen, who met personally with the monastery founder, Tryphon by name. Before becoming a monk, Tryphon, as he said, had been a drunkard, "robbed and beggared a lot of people and shed a lot of blood" (Kharusin 1890). In the sixteenth century the Pechenga monastery had an extensive economy, based mainly on fish and salt, and also sea ships were constructed there. The monastery became richer not only for the account of trade, but also for the account of vivid exploitation of local population–Lapps (Saami). A famous researcher of Russian Lapps N. Kharusin wrote that Pechenga monastery "till the certain extent, was a disaster for Lapps" (Kharusin 1890). About everyday life of the monastery monks the following extracts from an inquiry which took place when the monks became too much out-Herod: "Monk Illya is always drunk and steals monastery property, and the reason of his becoming a monk was a penalty which he would have had for robbery". And about other monks: "He is always drunk, spends all his time in a kabak (pub)", "he is a groggy person", "he has a lot of lush", etc., later a rigid order had been given to the monks from this monastery "not to let women into cells under any reason" (Vise 1934).

A flood of Russians to the Far North increased especially in the middle of the sixteenth century – it is usually considered to take place because of political oppression of Moscow which became harsher during Ivan the Terrible rule. According to the same van Salingen, people "because of the tyranny predominated at that time in Russia, escaped and went to live in Lapland". However, we think that significantly improved climatic conditions had also played a positive role in this movement of people to the North. In this connection, it's necessary to give some additional comments that average decadal annual temperatures in the middle of the sixteenth century exceeded the temperatures in the coldest decades of the fifteenth and sixteenth centuries by more than 2°C (Fig. 13.2). In the North of the European territory of Russia such increase of temperatures is equivalent to moving southwards at the distance up to 550–600 km. Thus, at the warmest times inhabitants of Belomorye could enjoy the climate, which was representative rather for Vologda or Yaroslav regions and didn't experience some stress after leaving the historical center of the country. Implicitly, in favor of this judgment that fact attests that in the late sixteenth century under conditions of a new cold wave, nobody wanted to escape not only to Murman, but even to more benign Belomorye, and Moscow had to undertake serious forced actions to inhabit the lower reaches of the Severnaya Dvina River, where in 1584 Arkhangelsk town was founded, which had been initially called as Novokholmogorsk town. Upon Arkhangelsk foundation, Moscow, because of political considerations closed the Murman "shelters" (ports) in Kola, Varzuga and Kevrola, and confined a foreign trade to the mouth of the Severnaya Dvina River. However, some time later Englishmen and Dutchmen continued using Murman "shelters".

In the middle of the sixteenth century in England a serious public concern arose, resulted from the sea monopoly for the eastern trade of Spain and Portugal established by that time. These countries completely controlled the southern sea routes around Africa and America, but why not to try reaching China and India from the North, moreover, if the most prominent geographers of that time (Schöner, Mercator, Ortelius) accepted such a possibility? The first large English expedition which sailed to find a new alternative northern sea passage to the East was headed by a noble Hugo Willoughby, who wasn't however too experienced navigator (it was a usual practice in Europe at those times). This expedition was organized by the Company Merchant Adventurers for the Discovery of Regions, Dominions, Islands and Places Unknown, later called Muscovy Company. A squadron consisting of three ships left England on 20 (30) May 1553. During a hard storm near North Cape the ship *Edward Bonaventure* under the command of Richard Chancellor was separated from the other ships. Willoughby pressed to sail eastwards and on 14(24) August saw a land, the greater part of researchers thinks it was Kolguyev Island. After this the expedition moved northward, but met with ice and turned to the south-west, where, on 28 September (8 October) anchored in the mouth of the Varsina River on the eastern Murman. Here Willoughby decided to spend winter; the first in the history wintering in the Far North ended with tragedy – all 63 participants died apparently from cold and scurvy. Next spring Russian hunters found the expedition's wintering place, where they also found both ships with crew members' bodies. Also Willoughby's log was found which had the last notice made in January 1554.

The third ship of the expedition under the Chancellor command was luckier: Chancellor reached the mouth of the Severnaya Dvina River, where he established trading relations with Russians. Pretending to be an English ambassador, Chancellor was invited by Ivan the Terrible to Moscow, which, by the way, he describes as follows: "I think Moscow is more spacious then London and its suburbs, but this city is ugly and built without any order". In 1554 Chancellor came back to England, as a result of his traveling diplomatic and trading relations between Moscow and England had been established.

Having established trading relations with Moscow, Muscovy Company didn't leave its main objective – to search for the north-eastern passage to China and India. In 1556 a new expedition left England on the small ship *Searchthrift* under the command of Steven Barrow, who served as a pilot on Chancellor's ship before. On 14 (24) July Barrow was near Kanin Nos, on 24 July (3 August) – at the Pechora River mouth, and on 4 (14) August he reached the south-eastern coast of Novaya Zemlya. Thus, Barrow became the first foreigner who saw this arctic isle. At the Novaya Zemlya coast he met some Russian hunting ships; a helmsman of one of them called Loshak gave him an information he was interested in about sailing to the Ob' River mouth. From this we can make a conclusion that Russians were quite familiar with a sea route to the Ob' River in the mid-sixteenth century – according to our climate reconstruction (Fig. 13.2), we think that this route might be passed for the first time in the 1480s–1490s. On the last days of August Barrow sailed near Vaygach Isle trying to reach the Kara Sea through Yugorsky Shar. However, on 3 September he had to give up his attempts and turn back as persistent northern winds were blowing and caused “terrible bulk of ice which he saw by his own eyes”. On 21 September (1 October) Barrow came to Kholmogory where he arranged wintering. The ice situation during the pioneering voyages of Englishmen was not so much hard and corresponded to the present one, what confirms our simulation data (Fig. 13.2).

After Barrow’s expedition Holland joined the race of searching for the north-eastern sea passage. In the 1560s Dutchmen had active trade with Russians not only on Murman coast and in Belomorie, but also in Pechora region. In 1565 Dutchmen founded a trading post in Kola. Oliver Brunell from Brussels played a great part in developing trading relations with Moscow. This person’s biography is very unusual – in about 1570 he worked as a steward for the Stroganovs family who were famous merchants and established steady trade with Ostyaks (Hanty) and Nentsys in the lower reaches of the Ob’ River, they exchanged cheap “German” goods for valuable furs. Before this Brunell lived in Kholmogory where he studied Russian language. Naturally soon he was taken as a spy and was put into Yaroslav prison from where the Stroganovs begged him off. Between 1577 and 1580 Brunell by order of the Stroganovs travelled twice to the lower reaches of the Ob’ River, the second one was done by sea from the Pechora River mouth. Thus, it was Brunell who was the first foreigner to have passed the northern sea route to the Ob’ River mouth. In about 1584 Brunell fit out a ship for his own expedition in order to sail to China, but this time ice didn’t let him pass further than Vaygach. At that time annual average temperatures in the Barents Sea region were close to their historical minimum (Fig. 13.2) and there is no wonder that Brunell’s expedition even led by an experienced Russian pilot, couldn’t reach its goal.

In summer of 1580 Englishmen Arthur Pete (he also served on Chancellor’s ship) and Charles Jackman became, it seems, the first west Europeans who by their own brought their ships to the Kara Sea. This is what they saw on their way from Vardhus (modern port of Vardǿ in Norway) to Yugorsky Shar: “Winds between NO and SO kept them there (near Vardhus – author’s note) till 1 (11) July. As they continued their way to the East they met a lot of ice and on 7 (17) July saw at the 70°5′N latitude a land, surrounded by ice which they took for Novaya Zemlya. They stayed near that place till 14 (24) [July], and sailed then to SO and came on 18 (28) [July] at Vaygach, where they filled their stocks of fresh water and wood. Then they entered the Kara Sea and found there so impassable ice that they stuck there for 16–18 days surrounded by thick fog. With great difficulties they went back to Yugorsky Shar on 12 August and decided to return home, so, on 22 [August] (1 September) their ships were separated from each other” (quoted in Litke 1835).

From the point of view what is known to us about the Arctic (Arctic Atlas 1985); a described situation with ice in this period can be characterized as moderately hard – such conditions could be met in colder periods of the twentieth century – this is confirmed by results of our simulation (Fig. 13.2). But by the end of the sixteenth century, when Willem Barents in 1594–1597 made three voyages to the eastern part of the Cold Sea which is called now after him, he had no chance to reach his goal. During the last of these voyages on 21 (31) August 1596 his ship was captured in Icy Harbor (Ijshafen), and the crew had to spend winter on the north-eastern coast of

Novaya Zemlya; several seamen, including Barents himself, couldn’t stand that winter burden and died. We know exactly that Barents was aware of Pete’s and Jackman’s voyage – a handwritten description of this voyage together with other valuable artefacts were found in their wintering place in Novaya Zemlya by a Norwegian whaler Elling Karlsen in 1871. You will never know if that knowledge had a fatal role in the fate of the last Barents’ expedition. As before that time when the ship had been captured forever, Dutchmen during the last days of August did their best to pass by the Kara Sea to the south-west, the same as English did shortly before. But could they imagine that unstable arctic climate would suddenly become so cold (Fig. 13.2) and cut their way for rescue? In fact, notes of Dutch expedition participants (Gerrit de Veer and Jan Huyghen van Linschoten) depicted that hard situation with ice even in summer, which was almost the same as it could be during certain hardest years in the early or second part of the twentieth century. Following are the extracts of those notes:

1594	
Guba Krestovaya Gorbovy Isles	“On 13 (23) July they met so much of ice, that round-top horizon (mainmast basket) was completely covered by it, then they were casting about between this ice and Novaya Zemlya coast and on 26 (5 August) came to Cape of Uteshenya”
Muchnoy Nos Cape (Cherniy Cape now)	“ … ice traverse was almost impossible”
Sakhanin Isles	On 12 (22) August “They met there a large quantity of ice and they had to sail southwards” “Large bulks of ice which was — like today — drifted from Karskie Vorota Straight restricted his (Barents) advance into this area. That’s why he couldn’t reach the southernmost point of Novaya Zemlya and had to stick to Matveev and Dolgiy Isles”
Cheshskaya Guba	“On 5 (15) July they met a lot of ice and several times took fog for a land. The latitude was according to astronomic observations 71°20′N. On 7 (17) July they saw Kaninsky coast. During the next two days they met a lot of ice again, which was drifted out of a bay situated between Kanin and Svyatoy Nos (Cheshskaya Guba), and which stopped and stayed near Kolguev Isle, on the shallow […], they found there that ice in a form of high hills”
Pechorskaya Guba	“On 18 (28) (July) they came to the Pechora. […] Stormy weather from the East”. “Eastern current which brought a lot of ice”
1595	“On 7 (17) August they sailed round North Cape and on 17 (27) met piles of immovable ice. They calculated its latitude which was 70°5′N. And their distance from Novaya Zemlya which was 12–13 miles. Having overcome great difficulties they passed through new ice bulks and sailed next day to Dolgy Isle, and on 19 (29) in Yugorskiy Shar, fully surrounded by drifting ice […]. On 25 (4 September) Dutchmen tried to move further eastwards, but met such great quantity of ice, that they had to hurry back to their previous place of anchorage. On 2 (12) of September ice moved away a bit and they again started their voyage and at last entered the Novoe Severnoe (the Kara Sea — author’s note). But there they met new huge ice bulks from which they hardly could escape near Myasnoy Isle (12 miles eastwards from Yugorskiy Shar entrance — author’s note), where they were surrounded by ice completely”. (quoted from Litke 1835)

Thus, quoted extracts from observations definitely show that in the late sixteenth century hard ice conditions ruled in the study region – suffice it to say that at present starting from the late July and until the early September all western coast of Novaya Zemlya and south-eastern part of the Barents Sea are normally free from drifting ice. Consequently, at the time of Barents' voyages mean annual temperatures were significantly lower than modern, what fully corresponds to the modeling results (Fig. 13.2). One more extremely interesting circumstance, connected with the destiny of the famous Dutch expedition. The original map of Novaya Zemlya, drawn by Barents himself survived and it is shown in Fig. 13.3. This figure shows that at Barents' times the northernmost extremity of Novaya Zemlya was not Karlsen Cape, situated at 77°01′N and 67°30′E, but Bol'shoy Ledyanoy Mys (Yshoeck), situated several miles eastwards from it. At the end of the sixteenth century a technique of geographic latitudes determination was high leveled enough and it was impossible even to expect that such an experienced navigator as Barents was unable to determine a correct location of the isle extreme northern point. Conseguently, one may assume that 400 years ago Bol'shoy Ledyanoy Mys really stretched much further northwards and probably was a tidewater part of an inland ice sheet. Now, at the epoch of a warmer climate there is no sign of Bol'shoy Ledyanoy Mys any more and this name now bears a usual foreland, vicinage of which keeps one of the greatest mystery of the Arctic – Barents's tomb mystery. Thanks to widely known Gerrit de Veer's notes (de Veer 1936) eyewitness of those events, the circumstances of the last days of Barents' life are well-known. On 14 (24) June 1597 15 men who survived wintering in Ice Harbor started the way back by two oar boats, made from the debris of the destroyed vessel. On 20 June near Bol'shoy Ledyanoy Mys at the same time on these two boats, sailing in a thick fog, two persons died – Commander Willem Barents and his servant Klaas Andris Gautejk. As Gerrit de Veer stated both were buried in an "ice tomb". So, it could

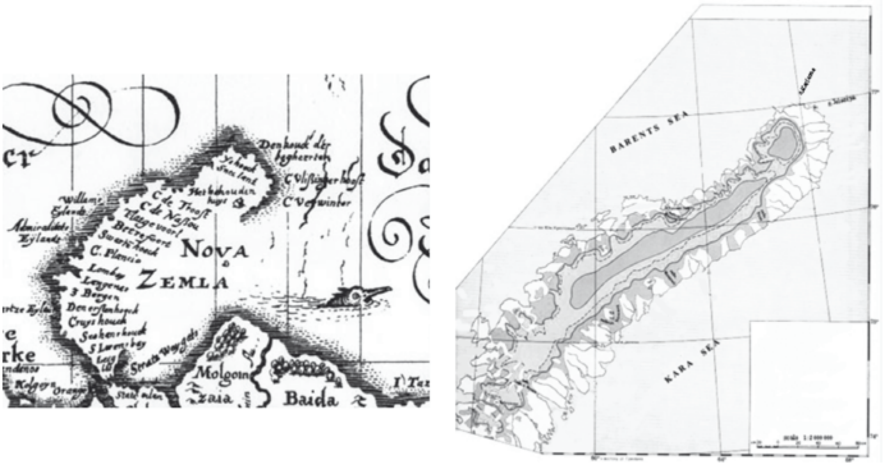

Fig. 13.3 Map of the Novaya Zemlya northern coast: *left* – Willem Barents' manuscript; *right* – modern (both from Arctic Atlas 1985)

be implied that this place was the ice anchored to the coast or a tidewater glacier. This glacier later melted and disappeared without a trace as well as the bodies kept by it. No wonder that regardless of all possible efforts of Dutch and Russian expeditions – the latest of them were dedicated to the year of Barents' memory (1997) – to find any signs of this tomb failed. We think that the glacier of Bol'shoy Ledyanoy Mys could disintegrate as far back as in the first half of the seventeenth century,[1] when the climate of this part of the Arctic became much warmer and navigation in the Artic seas developed greatly.

At this time a number of English (Hudson) and Dutch (Van Hoorn, Boosman, Cornellison) expeditions reached a coast of Novaya Zemlya and even penetrated the Kara Sea. In 1607 a famous English explorer Henry Hudson (in Russia he is better known under the name of Gudson, after whom bay and strait in Canada and river on which New York City stands were named) reaching 80º23′N near Spitsbergen, set the astonishing world record. This record was broken only 200 years later by an English whaler Skoresby, who managed to reach 81º30′N in 1806. Our temperature reconstruction shows that both record voyages were made during epochs when the climate of this part of the Arctic had been significantly warmer than usual (see Fig. 13.2). Not less amazing events took place near the southern coast of the Barents and Kara seas: in 1601 at the distance of 180 km from the Taz River mouth and more than 2000 km from Arkhangelsk a prosperous trading town of Mangazeya came into being, with the population of two thousand inhabitants at its best years. The name "Mangazeya" derives from "mongomzi" – the name of Nenets tribe which used to live there. In legend "about people unknown on the eastern side and about languages different" (the late fifteenth century) it says: "On the eastern side behind the Yugor' land, above the sea, Samoyed' people live, called malgonzei". In Mangazeya not only merchants and state officials lived, "different people" came there, escaped from "state taxes, and some of them from robbery and from their clans, from different debts" (Vise 1934). During the first decades of the seventeenth century up to 16–17 ships per year came to Mangazeya, famous for fur fairs and "fish tooth" trade (walrus ivory) – in comparison with the next eighteenth century each voyage like that would have been a great exploit. But even in the seventeenth century a sea route to Mangazeya was considered to be hard, because it passes through "impassable evil places of great ice", where it was necessary to suffer from "different needs". And, nevertheless, "Mangazeya town, being deep into 'cold tundra', almost under the Polar circle, among bellicose tribes of 'bloody Samoyad' and other 'hostile' indigenous people, cut off from Russia and even from other parts of Siberia by Mangazeya Sea storms, notwithstanding all disadvantages of its location, had been during 50 years of the seventeenth century one of the most important centers of Russian trade in Siberia" (Bakhrushin 1929). Continuing the series of successful voyages of the early seventeenth century, in 1610 a ship under the command of Kondratiy Kurochkin sailed down the Yenisey River from Turukhansk and, without any obstacles, passed the Kara Sea

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[1] Modern observation of glaciers of Novaya Zemlya northern isle (Zeeberg and Forman 2001) show that glaciers which were in the tidal zone were able to retreat with a great speed, exceeding 300 m per year.

for two days and came to the Pyasina River mouth. No later than in 1618 unknown Russian seafarers sailed round the northernmost Eurasia point – Chelyuskin Cape – and therefore overcame the most difficult part of the northern sea route. The rests of wintering of this unique expedition were found only in autumn 1940 on the coast of Faddey Bay 130 km south-east from Chelyuskin Cape. Wreck of the ship and rigging were also found – it leaves no doubts that travellers came there by sea (Okladnikov 1957).

Russian government's reaction to the suddenly appeared possibility of northern navigation was firm and peculiar – in 1619 Tsar Mikhail Romanov under the threat of death penalty prohibited to use "Mangazeya sea route" due to the reason that this route may be used by foreigners and "Germans will be able to come to Mangazeya from their lands bypassing Arkhangelsk". Moreover, the government wanted to counteract the trade of Russian merchants with foreigners on the North, as there they could escape taxation ("they will begin to trade with Germans, hiding behind Yugorskiy Shar, on Kolguev, on Kanin Nos and the state treasury will loose this taxation"). Of course, people there at first protested against such a destructive innovation, but they had to surrender when under the petition of local voivode Prince Kurakin "hard order" came from Moscow, disobeyed were threatened by "being executed cruelly and their houses are being destroyed completely". In result, "that route, under the tsar's order, under the threat of death penalty, from great ocean sea (the Barents sea) into Mangazeya Sea (the Kara Sea) as well as from Mangazeya Sea into the Great Ocean is prohibited for anybody". To observe the order fulfillment a permanent outpost had been established in Yugorskiy Shar. Thus, the destiny of Mangazeya had been predetermined, but the town had been dying for several decades more and was finally abandoned only in 1672, when new sharp cooling (Fig. 13.2) made human's living there impossible. Mangazeya hadn't reborn. The place where prosperous polar town stood was forgotten and found by accident only in 1900. Until 1927 no scientific expedition visited this site.

It goes without saying that at the time of warming in the seventeenth century (possible, that partially also during the previous one, in the middle of the sixteenth century) unknown Russian seafarers made great geographical discoveries in the Russian Arctic. These discoveries were almost unknown during a long period of time. The point is that in 1609 a Dutch trade agent in Moscow, Isaac Massa, copied the map of "North Russia", and he published it in 1612 in Holland, together with the following notes: "I had a friend in Muscovy, his brother had been on the North of Russia and he made a big map of those countries. He visited personally Vaigachskiy Strait and knew all locations till the Ob' River, but about countries which situated further he only heard … All, what I know, I collected with great difficulties and I owe this to my friendship with several Moscow courtiers, who gave me this data after numerous refuses to do so. They could pay with their lives for this, as Russian people are really distrustful and can't stand to disclose secrets of their country" (Pasetsky 2000). Amazing on Massa's map (see Fig. 13.4) is that not only Matochkin Shar strait, dividing Novaya Zemlya into two parts, had been indicated, but also the whole north of Russia from

Fig. 13.4 Map of the North Russia by Isaac Massa (A.D. 1609) (Atlas of geographical discoveries … 1964)

Norway boundaries to western reaches of Taymyr, including Beliy Isle, Oleniy, and Sibiriakov isles, the Ob', Yenisey and Pyasina Rivers, i.e. many lands, officially discovered only 150 years later.

Cooling came to the Arctic, apparently, about the mid-seventeenth century – beginning from that time we have a significant number of evidence about aggravation of ice conditions, bad weather conditions in summer, crop failures, famine years, severe winters, etc. Thus, starting in summer 1652 from Arkhangelsk, the governmental expedition under the command of Ivan (according to the other data – Roman) Nepluev, run into ice near Kanin Nos already, where nowadays the sea is sometimes ice free even in winter. Because of the ice the expedition couldn't approach the south coast of Novaya Zemlya; however during the previous decades it caused no troubles at all (Borisenkov and Pasetsky 2003). This time the expedition managed to reach "Burlov coast", situated near Dolgiy and Matveev Isles. Here they had to stay for really difficult wintering during which the greater part of the crew died. The least part of survivors came back to Pustozersk, the center of Yugor region at that time, situated in the lower reaches of the Pechora River. The same tragedy stroke the next expedition of Ivan Nekludov, sent in 1672 in order to search for silver on Novaya Zemlya (legends about rich silver mines on Novaya Zemlya existed for a long time among people from Novgorod, but no precious metals had been found on the isle). Nekludov, just like his predecessor, died without having reached the goal he had to attain (Pasetsky 1980).

English expedition of Captain Wood (1676) started out for search of north-eastern passage between Spitsbergen and Novaya Zemlya. His ships met ice at the end of June 1676 (according to the Julian Calendar): "On 22 June, when they were at 75°53′N of latitude and 39°48′E of longitude to the east from Greenwich, low and connected with each other ices appeared, stretching from west-north-west to east-south-east" (Litke 1835). Attempts to overcome this "rather solid and impassable wall" failed: near Novaya Zemlya, where ice "connected with the coast", Wood suffered shipwreck and had to land where he and his crew were found in several days by the escorting ship *Prosperous*. Being shocked by his failure, Wood stated that to find north-eastern passage was impossible as Spitsbergen and Novaya Zemlya are connected with each other by impassable ice masses.[2] This point of view didn't change even after 1688, when the last attempt of the western Europe to find the north-eastern passage to Asia had been taken. Dutchman Flaming, having been sailed to Novaya Zemlya in 1664 already and having been encouraged by the results of the previous sailing, when he reached the middle of the Kara Sea under 74°N, decided to start the second expedition. And this time he managed to reach Zhelaniya Cape (77°00′N, 68°31′E) – extreme north-eastern point of Novaya Zemlya, but it was impossible to move eastwards any more. Flaming's expedition was the last from 150-year epic of persistent but unsuccessful attempts to find north-eastern passage to Asia. During extremely cold decades of the second half of the seventeenth century (see Fig. 13.2) these attempts were sentenced to fail – as a result the idea to find the sea route to China passing the northern Asia had been postponed for almost 200 years. In general, by the late seventeenth century under the influence of described above events there was an opinion that Novaya Zemlya was a part of a landmass which stretched through the Cold Sea eastwards and possibly connected there with Eurasia or America. Nobody in the Western Europe or on the Russian North knew that Novaya Zemlya was an island! Until the middle of the eighteenth century the Kara Sea had often been displayed on maps as a great bay landlocked from its three sides. This point of view had been clearly expressed in the text and in the title of the most important document of that epoch – "Description why it is impossible to reach Chinese state from Arkhangelsk town and then to Eastern India", which was compiled under the order of Tsar Aleksey Mikhailovich.

The destiny of arctic sailings could be different as in the late seventeenth century the climate of high latitudes again became significantly warmer (see Fig. 13.2). It can be proved by various sources, evidence of which this time belong to inland regions only: Solikamsk Chronographer, notes of journeys of different authors – Bell, Unkovsky, Chirikov, Messerschmidt and others. The main source of climate information is evidence on break-up and freezing of rivers, as it was rivers which had the main transport function then, not only in summer but in winter also. This is a summary of some observations:

1719	Solikamsk Chronographer registers the date of the Kama River freezing: "on 13 (24) day of October the Kama and other rivers froze over, in 3 days after this it became warm and rain started and ice melted. Rivers froze over again at Phillip's Lent" (Berkh 1841) (i.e. after 28 November (9 December) — Authors' note)
1719–1720	Bell passed Western Siberia on his way to "Asian lands" and in winter 1719–20 suffered from "severe cold", noticing that frosts in Solikamsk were harder then in other journey points being closer to the North. It's known from his diary that for example in 1720 it was possible to sail to the Ob' River by boat even at the end of September, snow at Irtysh fell out on 4 October, and the Irtysh itself froze over on 13 October, the day before it began to be covered with sludge (Bell 1776)

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[2] At present this famous ice wall exists also, but usually it is destroyed in August-September and in the warmest years it doesn't even exist from April through November.

1724	Unkovsky — an envoy to Djungar Taichjy-Khan — noted in his diary on 6 April 1724, that sleigh way at the Irtysh River began to be destroyed, on 16 April of the same year the ice broke up at the Tura River. (Unkovsky moved through usual at that time route down on Irtysh to Tobol'sk and then up on the Tobol and Tura rivers to Tumen' and then to Solikamsk.) (Embassy to Tsevan Rabtan ..., 1887)
1725	A famous German scientist and explorer of Siberia Daniel Gottlieb Messerschmidt noted that in October of 1725 on the Ob' River near the Vakh River mouth a really high snow had been, and on 12 October floating ice appeared. About Surgut he wrote "that there are no cereals. The land thaws out not earlier than in June and in August there are frosts again. Cabbage grows but doesn't form heads; carrot, and onion as well as horse-radish grow and ripe well here". On 20 October of the same year the Ob' River in the region of the Irtysh mouth in the middle was still free of ice; however there was a lot of it near the banks already. On the next day, 21 October, Messerschmidt's boat had been frozen into the ice in Kuriya Bay, on 27 October the river froze over completely (Nachricht von Daniel Gottlieb … 1782). According to Lieutenant Alexei Chirikov's data, on 10 October 1725 the Ilim River froze over (right tributary of the Angara), however "there was almost no snow on the land" (Vakhtin 1890). In the diary of Petr Chaplin (as well as A. Chirikov, he was a participant of the First Kamchatka expedition) we can find a note about the Irtysh break-up on 4 May 1725. "On the Irtysh River ice broke up and in three days after this [river] was ice-free" (ibidem).

Comparison of this and other data with modern ones shows that in the early eighteenth century the duration of ice occurrence on the upper Kama and western rivers of Siberia was shorter than nowadays or nearly the same, thus, it indicates the fact of short-term warming in the Arctic. Of course we don't have and can't have any direct evidence about changed navigation conditions in the arctic seas,[3] as at that time Europeans accepted the fact that it was impossible to sail that way, and Russia was in a war with Sweden. It's interesting that, during the Great Northern War, in 1713 Fyodor Saltykov made a report to Peter I with a proposal "About a search of a sea route" round the northern coasts of Asia to China, but then this proposal, of course, couldn't be accepted. It was decided to come back to the idea of exploration of the Arctic Ocean coasts in 20 years only. The Great Northern Expedition (1733–1743) faced incredible difficulties, as it took place during the next new period of cold in the Arctic (Fig. 13.2).

So, a famous scientist Johann Georg Gmelin, a participant of the academic group of the expedition, made the following interesting observations about the severe winter of 1735 in Eniseysk: "5 January. Crows and sparrows fell down to the ground as dead and they could become alive again only if taken into a warm

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[3] It's just known that till the end of this warm period, i.e. until the late 1720s Dutch whalers regularly came to Novaya Zemlya – pits dug by them on the western coast for whales' fat melting out were encountered till the late 18th century. However in the second quarter of the 18th century when the ice situation aggravated landing to Novaya Zemlya became more dangerous and foreign whalers abandoned the waters of Novaya Zemlya for a very long time – until the middle of the next nineteenth century.

room. Residents tell, such occasions happen not often. I learned that in the forests there were a lot of animals died from the frost and a lot of people caught on their way by frost had their blood frozen in their veins".

During the Great Northern Expedition rather detailed instrumental meteorological observations were made for the first time, often daily, however, the quality of such observations, unfortunately, was rather low. At that time in Russia a temperature scale and thermometers of Delisle were used for scientific research, which weren't precise and reproducible (it should be mentioned that in this 150° scale the boiling point was at 0°, and freezing point was at 150°). So, in the sailing logs of boat "Ob'-postman" under the command of Pilot F. Minin it's written: "9/20 June 1738: 19°C (121° Delisle). 10/21.6 at 13.00 17°C (124°D), at 21.00 18°C (123°D), at 12.00 19° (121°D); 11/22.6 at 12.00 8°C (138°D); 12/23.6 air is cold, at 17.00 7°C (139°D), at 12.00 19°C (122°D); 14/25.6 at 12.00 18°C (123°D); 15/26.6 at 12.00 17°C (125°D); 16/27.6 at 21.00 23°C (115°D); 17/28.6 at 21.00 17°C (125°D); 19/30.6 at 13.00 23°C (115°D); 21.6/2.7 at 14.00 20°C (120°D), at 20.00 20°C (120°D); 22.6/3.7 at 12.00 13°C (130°D); 23.6/4.7 at 19.00 13°C (131°D), at 12.00 11°C (133°D); 24.6/5.7 13°C (130°D); 25.6/6.7 at 12.00 3°C (145°D), at 21.00 3°C (146°D)" (Log-book of the boat Ob'-postman ..., D. 30).

Obviously, it's hard to imagine, that in June of 1738 in Yenisey Bay, where boat was situated at that time, such high temperatures (up to 20–23°C) could really take place – because in such case it's impossible to understand why during this voyage Minin couldn't advance further than the North-Eastern Cape (73°32′N 80°33′E), where nowadays the sea is absolutely free from ice at maximum temperatures usually not exceeding 14–15°C. In confirmation of above stated, Table 13.2 presents data of instrumental meteorological observations at Dickson's station (73°32′N 80°15′E) from which it follows that within the last 70 years maximum June temperatures were only three times higher than 19°C, but according to the sailing log of Minin it happened five times only in June 1738!

In winter of 1738/39 Minin's expedition anchored at Isakovo wintering place, situated in the southern part of Yenisey Bay under 70°37′N. Here in spring of 1739

Table 13.2 June days with the highest daily average (T_{ave}) and maximum (T_{max}) temperatures recorded at Dickson meteorological station (observation years 1936–2005)

Year	Month	Day	T_{min}	T_{ave}	T_{max}
1943	6	21	10.6	16.1	22.2
1943	6	20	10	16	21.3
1984	6	30	11.8	16.1	20.7
1984	6	29	3.1	10	18.9
1957	6	26	5.6	13.4	18.7
1941	6	24	6	10.4	18.3
1943	6	19	5.6	12.1	17.7
1943	6	22	7.9	10.6	17.5
1982	6	30	1.9	6.2	16.8
1943	6	18	6.9	10.2	16.8

the following observations were made: “20/31.5 at 12.00 0°C (150°D); 23.5/3.6 light snowing; 24.5/4.6 light snowing and then snowstorm, at 9.00 –2°C (153°D); 25.5/5.6 at 9.00 –3°C (154°D); 26.5/6.6 at 12.00 average wind, cloudy weather, light snowing, warm air; 27.5/7.6 light snowing, at 9.00 great snowstorm; 28.5/8.6 south-south-east (wind), cloudy, great snowstorm, heavy wet snowing; 29.5/9.6 wet snowing, at 9.00 south-east (wind) –6°C (159°D); 30.5/10.6 snow, storm, at 9.00 1°C (149°D); 31.5/11.6 wet snow, at 9.00 1°C (148°D); 1/12.6 at 1.00 1°C (149°D), fog; 2/13.6 wet snow; 3/14.6 at 9.00 –1°C (152°D); 4/15.6 heavy snow; 5/16.6 snow, cold air; 7/18.6 snowstorm at 9.00 –5°C (158°D); 8/19.6 ice broke up; 9/20.6 snow and fog, snowstorm; 10/21.6 fog and snow, snowstorm; 12/23.6 at 9.00 2°C (147°D); 14/25.6 at 9.00 2°C (147°D); 15/26.6 at 9.00 2°C (147°D); 16/27.6 at 9.00 2°C (147°D), drifting ice on Yenisey; 17/28.6 at 9.00 1°C (149°D)” (Log-book of the boat Ob’-postman ..., D. 42). These temperature changes are closer to the real situation and, in particular, show rather cold summer and late break-up on Yenisey that year. May be due to this reason sailing in 1739 was rather unsuccessful, but next year of 1740 Minin at last managed to reach 75°15′N (Sterlegov Cape nowadays), where on 21 August he entered “impassable and motionless ice, […] behind that ice it was impossible to advance northwards due to the severe frosts” (Lieutenant Ovtsyn’s voyage, D. 4081).

In September 1740 the boat sailed up the Yenisey River and anchored for wintering in the mouth of the Dudina River (at the place of the modern city of Dudinka), where it, ice-bound, had to stay until July 1741. In spring and summer of 1741 the following observations were made on board: “21 April –48°C (222°D), sun shining; 22.4/3.5 –48°C; 23.4/4.5 snowstorm,–48°C; 24.4/5.5 wet snow, –48°C; 25.4/6.5 cloudy, –48°C, snow; 26.4/7.5 snowstorm,–52°C; 27.4/8.5 –52°C, snow, snowstorm; 28.4/9.5 –51°C, cloudy, snowstorm; 29.4/10.5 snowstorm, –48°C; 30.4/11.5 cloudy, snow, storm, –60°C; 1.5 snow, –51°C; 2.5 –51°C, fog; 3.5 cloudy, snowing; 5.5 –54°C, cloudy, heavy snowstorm; 6.5 clear, –52°C; 7.5 –51°C, clear; 8.5 clear, –49°C; 16.5 clear, –23°C; 17.5 clear, –21°C; 18.5 cloudy, –12°C, snowing; 19.5 cloudy, snowstorm, –25°C; 20.5 at 13.00 –16°C, at 9.00 –23°C; 21.5 heavy snowstorm, –23°C; 22.5 clear, –17°C; 23.5 snowing, –19°C; 24.5 snowing, –15°C; 15.6/26.6 snowing, ice motion on the Yenisey; 16.6 clear, –23°C; 17.6 clear, –17°C; 18.6 clear, –19°C; 19.6 clear, –7°C; 20.6 clear, –8°C; 21.6/2.7 there is still ice on the Dudina River, –3°C; 24.6/5.7 clear, there is a lot of ice still on the Yenisey, 11°C; 25.6/6.7 cloudy, there is no ice already on the Yenisey, –8°C” (Log-book of the boat Ob’-postman ..., D. 53). Of course, it’s hardly possible that in May–June 1741 air temperatures could be so low (for comparison, absolute minimum according to the data of meteorological station in Turukhansk for the last 100 years was recorded in May at –26,6°C, and in June –8,2°C – see Table 13.3), but nevertheless we again have obvious evidence of a very late drifting of ice in the lowest reaches of the Yenisey River and its tributaries as well as extremely cold spring and summer of 1741.

Apart from rather contradictory data of instrumental observations we have a significant number of other evidence from the Great Northern Expedition participants at our disposal, showing the picture of extremely hard ice conditions. Thus, ships started from Arkhangelsk in 1734 under the command of S. Muravyov and

Table 13.3 Days in May–June with the lowest daily average (T_{ave}) and minimal (T_{min}) temperatures recorded at Turukhansk meteorological station (observation years 1936–2005)

Year	Month	Day	T_{min}	T_{ave}	T_{max}
1986	5	2	–26.6	–16.1	–7.8
1999	5	1	–26.1	–13.1	–1
1986	5	1	–25.7	–18.2	–12.1
1970	5	11	–23.1	–14.8	–8.2
1964	5	3	–21.7	–16.8	–4
1986	5	5	–21	–12.4	–6.6
1986	5	6	–20.5	–9.2	–0.8
1991	5	2	–20.4	–13.2	–4.9
1964	5	4	–20.3	–11.4	–2.7
1970	5	2	–20.2	–11.1	–2.9
1962	6	1	–8.2	1	6.7
1992	6	1	–7.7	–4.8	–1.8
1968	6	5	–7.2	–3	0.8
1967	6	1	–7	–2.4	3.2
1987	6	4	–5.8	–3.5	–1.3
1987	6	3	–5.7	–3.8	–0.1
1968	6	4	–4.8	–2.7	–0.2
1968	6	6	–4.8	0	5.7
1987	6	5	–4.7	–2.5	1.1
1964	6	5	–4.5	–2.8	1.5

M. Pavlov, for two consecutive years had been trying to round Yamal Peninsula from the north, but failed. In 1736 Stepan Malygin, an experienced seaman, was appointed as a head of the western detachment, but even he at the beginning couldn't achieve a success – ships of his expedition had to winter on the Kara River, and only in summer of 1737 Malygin and Skuratov during their fourth attempt managed to round Yamal and reach the Ob' mouth. Malygin, the commander of expedition, after whom the strait in the Kara Sea is named and, as well as a street in Moscow, was rude and cruel person. According to the words of his crew, he abused his men badly, "broke heads till blood" and severely beat them up. With local population Malygin had a lively trade, changed polar foxes' fur for spirits, and also "oppressed differently". Generally, it should be said, that later all commanders of the western and the Ob'-Yenisey detachments were prosecuted due to the reason of constant quarrels with each other or abuses and outrages. Success and virtue rarely accompany each other.

Events in the Ob'-Yenisey detachment of the expedition developed synchronically. Beginning with the summer of 1734 Lieutenant Dmitry Ovtsyn on the boat *Tobol* made three unsuccessful attempts to leave Obskaya Guba into the Kara Sea, but every time ice stopped him: in June 1735 under 68°40' N, in August 1736 – under 72°40' N, almost at the entrance to the ocean. Only in summer of 1737 Ovtsyn managed at last to enter the Arctic Ocean and in late August he reached the Yenisey mouth. The early seventeenth century comes into one's mind at once, when this route of the Great Northern Expedition had been yearly passed by about 15 ships making the whole route from Arkhangelsk and back during the same navigation. My own observations may be added to this, as I repeatedly sailed in the Kara Sea between 68 and 74°N during 1980s, but I have never seen floating ice there.

Full of staggering tragedy the Great North Expedition took lives of a lot of people, commanders and sailors, and as a result it brought the greatest geographical discoveries, but at the same time its initial geopolitical plans failed as it was shown that it was impossible to sail in Arctic seas safely. Russian government had to accept this fact, but the idea of discovering the northern route to Asia had been so much attracting that it was returned to it again and again. One of the most active and influential adherent of this idea was M.V. Lomonosov, who expressed this idea in his widely-known poem:

> Severe nature hides
> from us the entrance vainly.
> From the evening coast
> I see eastwards with my clever eyes:
> Russian Columbus amidst the ice
> is in hurry despising doom.

A plan developed by Lomonosov had been accepted by Catherine II who had just been enthroned, and in summer of 1765 a small squadron left Arkhangelsk under the command of Vassiliy Chichagov, which had a secret mission to pass through the Arctic Ocean to American coasts and further westwards, through Bering Strait to Kamchatka. This enterprise was kept "in secret, even from Senate till time to disclose it comes". In early summer of 1765 Chichagov faced ice in such a place where there is normally no ice nowadays even in winter – near Bear Island: "26.5 cloudy and foggy, L 74°10'L 40°24', icing at midnight; 27.5 Berren-Island (Bear Island): snowing, thick fog, ice on NNW" (Description of expedition of Chichagov, Popov and Babaev …, D. 92). Nevertheless, the sailors continued their voyage but on the north-west of Spitsbergen at latitude 80°26' N they met heavy ice and had to return to Arkhangelsk. Chichagov's failure (a plan of that expedition from the point of view of the modern knowledge about the Arctic was absurdly and that's why it was impossible to expect any success) caused an extreme discontent in the Board of Admiralty, and the commander of the expedition had been accused in "seamen thought about the returning too early and their great fear made them come back". Nevertheless, Lomonosov's authority and his cabinet plan were so much strong that the Admiralty ordered "to repeat the voyage", and next 1,766 year Chichagov was sent to Spitsbergen again. But unfavorable ice conditions accompanied his voyage this year too: "7.6 Berren Island: ice between north and west. Cold, cloudy, isle is foggy; 10.6 L 77°09'L 25°29' scattered snow, other ships are invisible under the thick snow, thick ice on south-south-west, later from north through east to south; 13.6 at night a bit of snow fell out, L 77°17'L 26°32'; 18.6 air is warmer then before, ice, large seal herds, snow, L 77°50'L 22°36'; 23.6 rigging is covered with hoar, fog, ice, snow, L 77°48'L 19°54'; 27.6 cloudy, cold, fog, rigging and sails are covered with hoar, L 78°03'L 19°46'; 3.7 1\4 of sea is covered by thick ice, L 77°06'; 15.7 snow, L 76°55'; 19.7 cloudy and cold, a lot of ice, L 77°48'L

18°53’; 24.7 foggy and snowy, rigging is covered completely with hoar, seals and sea hares, L 78°58’L 24°50’; 18.8 Spitsbergen: there is a lot of ice in the bay” (ibidem). This time the expedition failed to proceed further than 80°30′N – nowadays in this region the boundary of pack ice is situated 70–100 km northwards.

In 1768 a ship under the command of Fyodor Rozmyslov came to Novaya Zemlya, the aim of it was again the search for silver and also “description and observation of what is found… through the Novaya Zemlya strait”. There are the following notes in the ship’s log: “20.7 scattered clouds, sun shining. Since midnight the wind is weak and changeable, cloudy, in the morning scattered clouds, sun shining. On 22 July calm, Ninth Camp, cloudy. On 27 July, same place, since midnight the wind is calm, scattered rain”. Since 15 August there are more notes about cold air: “On 22 August in Britvinsky Strait it’s cloudy since midnight, scattered snow. At 5 o’clock it’s cloudy and cold, at 9 scattered clouds, sun shining. On 26 August Matochkin Shar, cloudy weather, rain, storm at night, at 9 am sometimes sun shining, storm. 14.9 storm since the evening, cloudy weather. 15.9 Matochkin Shar, snowing at night, light frost in the morning. 16.9 cloudy and snowing. 19.9 frost in the morning. 20.9 frost with snow at night” (Log-book of the merchant A. Barmin’s vessel ..., D. 137). Rozmyslov and his team had to winter on Novaya Zemlya; during wintering they continued their weather observations: On 1 October a notice is left about “Matochkin Shar is covered with ice. On the 25th a team wintering on Derevyannyi Mys came to Rozmyslov and report that the Kara Sea was covered with ice to the horizon also. This month there were prevailing weak eastern winds at cloudy weather, and it was snowing almost every day” (Litke 1835). Since the end of April 1769 more detailed notices appeared, as the team, apparently, started to prepare for the departure and followed the changes in the air and in the sea more carefully. “7.5.1769 frost and sun shining. 14.05 frost and sun shining. 15.5 cloudy and snow broth. Heavy mountain air like a smoke …” (Log-book of the merchant A. Barmin’s vessel ..., D. 137). On 27 June 1769 “ice in the strait reached thickness of two arsheens (about 1.5 m – author’s note). On the 30th it was seen that rain and water coming down from mountains significantly reduced the thickness of snow coverage” (Litke 1835). From the same text we learn that that year “Matochkin Shar became free of ice only on 2 August”.

The data given leaves no doubts that low temperatures prevailed in the European part of the Arctic until the late 1760s, and it corresponds to the results of our calculations (Fig. 13.2). Under these circumstances Russian Government abandoned further efforts to reach high latitudes – ironically it happened just before a new and the most significant for 350 years warming of the Arctic took place (Fig. 13.2). But again, just like in the early eighteenth century, nobody used the advantages of such circumstances, and the next cohort of explorers came to the Arctic only in half a century. For 50 long years after Rozmyslov’s voyage a single expedition had been sent to Novaya Zemlya shores. This expedition, headed by a mining engineer Vassiliy Ludlov, had been equipped at the own expense of State Chancellor Count N. P. Rumiantsev and had an aim to explore minerals and map coastlines of the island. The small ship *Pchela* (35 tons) under the command of pilot Grigoriy Pospelov left Kola on 11 (23) July 1807 and, having met no (!) ice, on 29 July (10 August) entered Kostin Shar strait off the south-western coast of Novaya Zemlya. The expedition made several landings on the island and by the end of summer successfully came back to it's base. Participants of the expedition made meteorological observations, from which it follows that the summer of 1807 in the region was unusually warm. Apparently it was the last signal of the passing away warming as in just a few years the situation in the Arctic has drastically changed.

It became clear when after the end of Napoleonic wars the Russian Government again turned it is attention northwards and took a decision to make a detailed charting of the Barents and Kara seas coasts. With this aim in June 1819 the old, confiscated from the English ship *Novaya Zemlya* left Arkhangelsk under the command of Aleksey Lazarev, a brother of the outstanding seafarer Michael Lazarev, who at that very time was sailing to the coasts of undiscovered yet Antarctica. The northern team failed completely, having reached none of the aims – they could neither enter the Kara Sea, nor even reach the southern coast of Novaya Zemlya! The commander of the expedition stated that according to the evidence, received from hunters and Pomors, nobody from Pomor people, who sailed for hunting into those waters, had ever "found coasts" of that island due to the reason that they had always been surrounded by pack and floating ice. The same idea Lazarev expressed in his report for the Minister of the Navy I. I. Traverse and in his letter to I. F. Krusenstern. Any attempt to send an expedition on a ship he considered as being a victim, useless for science, sea navigation and trade (Pasetsky, 1980). The commander of the expedition noted "extreme ice conditions of the sea and really bad weather conditions", and also that "the whole south coast up to Britvin Cape had been surrounded by impassable ice barrier". It is obvious, that Lazarev's voyage happened in a really cold year, possibly one of the last in the phase of the next cold period in the Arctic. Along with this, an astonishing expedition failure and a total scepsis of its commander had to be accompanied with really unique circumstances. And such circumstances did exist – the point is that on 5 April 1815 the largest over a few last 1,000 years eruption of Tambora volcano occured, causing a significant (by 0.5–0.7 C) temperature drop in the northern hemisphere, which had been the most pronounced in the high latitudes during 3–4 years after the eruption. It is absolutely clear that Lazarev's expedition was preceded by not a single, but rather several severe winters and cold summers, such as in 1816 which entered the history as "a year without summer" (Stothers 1984) – there could have been no more unfortunate time for an arctic voyage at all. Of course at that time nobody even thought to take into account such exotic circumstances as an eruption of a tropical volcano, and Lieutenant Lazarev had to stand disgrace and humiliations in full – almost everybody accused him in cowardice and mismanagement! Neither Litke, nor Nordenskiöld who later sailed the same region but under the much more advantageous circumstances had a word of mercy to him – the latter wrote that "expedition under the command of such a man had to fail". However, several years passed and the situation changed completely.

Lieutenant Friedrich Litke's voyages to Novaya Zemlya in 1821–1824 were more successful – for the first time in the whole history of this archipelago exploration it was possible to sail along its whole western coast for four straight years and to describe it in details. In logbooks of the *Novaya Zemlya* brig, constructed purposely for this expedition, weather conditions had been fixed in details as well as ice conditions, wind direction and clouds – it helps to make a conclusion that in the early 1820s a significant warming had been observed in this sector of the Arctic and this perfectly corresponds to the data of our calculations (Fig. 13.2). Here is a summary of the most interesting observations: the Severnaya Dvina River near Arkhangelsk in 1821 broke up in the middle of May: "at last, on 30 April (12.5) the ice on the Dvina broke up, but the river got free of it completely only in five days", and in the next 1822 it broke up on 23 April, Litke himself noticed that for "more than 50 years there hadn't been such an early drifting of ice" (ibidem). Winter of 1822 was extremely mild. In March 1822 Litke noticed "unusually early beginning of spring […] Approximately till the middle of the way to Arkhangelsk the snow melted almost completely". Litke also gave this evidence of a local population: "Lapps told that the last winter there was unusually warm; there was little ice, and that's why in many regions in spring sea seal hunting almost failed". Finally, according to Litke's own observations, it was "unusually warm and stormy winter. Kol'skiy Bay, which is usually for 20 or 25 miles from Kola covered with ice, this year wasn't almost frozen even near the town. On the coast of the White Sea fishery had been very unsuccessful, as there was lack of ice, on which Pomors use to hunt sea animals, so called serky and others" (ibidem). Winter of 1823 was, apparently quite usual, and in spring of 1823 drifting of ice on the Dvina occured in time, usual for the present time too: "On 27 April (9.5) ice broke up, on 6 (18) May it disappeared".

The author of this article dedicated several papers to the influence of climate on the world historical process (see e.g. Klimenko 2003). This influence for sure is applicable for personal destinies as well and may be nowhere so distinct as in the history of the Arctic. Lieutenant Lazarev started his voyage in a wrong time – and he died in disgrace and obscurity. Another Lieutenant – Litke – weighed his anchor only a few years later, and ice suddenly let him pass. He made a brilliant career, was one of the founders of the Russian Geographical Society, became an Admiral and the Head of the Academy of Sciences, a world-renowned scientist and of course he never thought that he wouldn't have had all that if there hadn't been a small peak in the temperature in the early 1820s. Despite a relative success of his mission, Litke for the rest of his life had kept a feeling of continuous danger which accompanied his voyage in the Arctic – being Admiral already and Deputy Head of the Russian Geographical Society he continued to argue that "the sea link with Siberia is a kind of impossible things". This statement was fully supported by another famous explorer – Academician Karl Ernst von Baer, who headed a complex scientific expedition to Novaya Zemlya in autumn 1837. Due to his authority during the next decades there was an opinion that Novaya Zemlya was a gloomy and dead desert, and the Kara Sea was "an ice cellar" and it contributed to the opinion about inaccessibility of this sea. Both scientists at the end of their lives were hardly assaulted, especially when in the late 1860s a new era in an arctic navigation history began, and all previous opinions about impossibility to sail in high latitudes at once collapsed. Baer was accused in "geographical deception", and a prominent German geographer Oscar Peschel wrote: "All what had been told us about Novaya Zemlya and the Kara Sea is a rude and shameful mystification.

Unavailability of the Kara Sea is a pure fiction; it can serve for fishing and not just as ice cellar". But all this will happen later, when a unique warming period comes to the Arctic (see Fig. 13.2), but at the beginning of the century warming wasn't so much significant but pretty short and soon changed to a colder period soon, which prevailed with some interruptions in the North until the late 1850s. A piece of the most significant evidence characteristic of that cold period and which hadn't been published before in the special literature is the following.

In the journal "Otechestvenniye zapiski" in 1849 "Notes on the way from Petersburg to Barnaul" were published, written by an unknown author. In these notes, in particular, some exact dates of freezing-over and breaking-up of Western Siberia rivers are given, indicating longer periods of freeze-up in comparison with modern ones: "Breaking up of the Irtysh (in Tobolsk) may be: the earliest on 30 April (12 May) (1832) and the latest on 15 (27) May (1833)… In Tomsk the river breaks up between 13/25 (1839 and 1840) and 29 (11 May) April (1833 and 1841), and freezes over on 8/20 October (1840) and 5/17 November (1834)" (Notes on the way from Petersburg to Barnaul 1849). From the same source we learn about returning of frosts in Tomsk Province in 1847: "twofold spring last time was in 1847", and about a severe winter in 1848/49 in Yekaterinburg: "winter is the most severe, in December there are constant frosts, often up to –35° Reaumur (–44°C), what never happened here before".

In 1858 traveller Russel-Killough made quite precise observations of temperature regime and weather conditions, as he was traveling through the western Siberia to India. He had a thermometer with him and made a number of observations, belonging to late November-early January, most of which were recorded in Tomsk, where Russel-Killough stayed for almost a month. In Nizhniy Novgorod on 15 (27) November the lowest temperature observed was –30°R (–37,5°C), and in Kazan' on 30 November (12 December) –28°R (–35°C). When crossing the Irtysh on 3 (16) December 1858 he wrote down the following: "then below –35°R (–44°C) (beyond thermometer limit), and the same for another two days, sometimes thermometer showed for several minutes–40°C. Sheepskin coat, pillow, clothes were dead frozen, toes were frostbitten for the rest of the life, horse is covered with a layer of ice etc., I heard that frost reached up to –42,5°C". In Tomsk on 18–20 December (30 December–1 January) temperature dropped at strong wind down to –47…–48°C (Russell-Killough, 1871).

Some extracts of already known texts are consistent with these notes, for example, 1834: "very frosty winter on the north-east of European part of Russia. Frosts reach more than up to 40°R (50°C). And in Vologda, Prezovets, Velikiy Ustug and near Vitebsk mercury in thermometers was frozen".

1834	Vologda province	"On 5 July and on 12 August frosts damaged crops"
1835	Northern Russia	"In 1835 since early November and up to 20 December frosts reached up to 40 Reaumur degrees (lower than –50°C). Severe winter of 1835–36 in Olonets Province. Frosts reached up to 32°R (40°C)"
1841	Vologda Province	"On 10 July in Yarensk there was an early frost, damaging winter and spring crops"

1841–1842		"In Vyatka on 31 May (12 June) snow fell out, ½ arsheen deep; the same happened along Siberian highway for 300 verst; local news said (but it's quite hard to believe), that there on 2 (14) June people were sleighing. In Belozersk region on 25 August (6 September) spring crops were damaged by frost".
	Arkhangelsk, Petersburg Provinces	"Long winter with heavy snow, especially in March, lasted till the middle of May"
1852	Northern Russia	"Frosts were in June in Arkhangelsk Province. On the 14th hoar was seen on the grass. 'Such coldness … at that time nobody from old people would remember. In order not to catch cold, it was necessary to heat stoves in houses and to wear warm underwear'. Cold and rainy weather in Vologda Province, in a number of regions there a fever appeared"
		"In Arkhangelsk guberniya, Kholmogory and Shenkursk Province in the first half of August there were frosts at night which damaged crops"
1857		"In July in Vologda Province frosts were observed (–5°C)"
1860		"March of 1860 is likely to become the coldest of the century in the whole Siberia and the European part of Russia till the Moscow meridian"
		(Extracts from the texts according to Borisenkov and Pasetsky 2003)

During the same years polar seas became again inaccessible. Here is one example – for almost 20 years (from 1844 through 1862) one more mariner from a famous family, Pavel Krusenstern (a grandson of the first Russian circumnavigator) unsuccessfully tried to sail from the White Sea to Siberia; during his fourth voyage in 1862 his vessel the *Ermak* was crushed by ice off the western coast of Yamal. This fatal voyage was sponsored by a famous "North devotee" Mikhail Sidorov, who earlier established a high reward of 14,000 rubles to the one who will pass from Europe to the Yenisey mouth. This prize had never been awarded.

At last, in the 1860–1870s new warming came to the Arctic again, maybe, one of the most significant for the last 500 years (Fig. 13.2). After centuries of endless failures the intensity of navigation in the Barents and Kara Seas grows, and this was connected with such names of enthusiasts like Mikhail Sidorov, Alexander Sibiryakov, Oscar Dickson, Ludwig Knoop etc. They managed to realize a number of successful commercial voyages from European ports to the Ob' and Yenisey mouths, between 1875 and 1884 23 out of 43 ships which started their voyages having successfully completed their mission (Dahlmann 2001). In the 1870s numerous Norwegian ships of sea animals hunters appeared near Novaya Zemlya, who came there to look for seals, walrus and other sea animals. Only in 1870 about 80 –90 Norwegian ships, as well as eight Russian ships hunted in this region which was so dangerous and almost inaccessible not so long ago. In September 1871 a captain of one of such ships named Elling Karlsen, found on the north-western coast of Novaya Zemlya a wintering camp of Barents and his companions, which nobody saw before for almost 300 years. During these exceptionally warm years

(1878–79) a Swedish explorer Adolf Erik Nordenskiöld on the ship *Vega* managed to round Eurasia from the north and reached the Pacific for the first time in the history. I think that an unprecedented success of the Arctic navigation in these years was significantly conditioned by drastically improved ice condition, which in its turn, was a result of a sudden warming in the high latitudes of Eurasia. In fact, beginning from 1869 till 1881 ships' log-books had been fixing unprecedented number of extremely favorable seasons concerning the ice condition, when the Kara Sea almost freely had been passed by a great number of ships in all directions. Absolutely unique was a navigation in 1878, when Nordenskiöld on the *Vega* passed through the whole Kara Sea up to Chelyuskin Cape, without having met any drifting ice on his way. Only on 29 September the ship came to anchor near Pitekay settlement on the coast of Chukotka Peninsula which is only 220 km away from the entrance to Bering Strait. Thus, within a single navigation on an ordinary trading ship a route had been passed which all previous seafarers couldn't manage for 400 years! The same year Norwegian sea hunter Edvard Johannesen on the schooner *Nordland* reached far to the north-east of the Kara Sea, to the waters where nobody has ever been before, and under 78° N discovered an island, named by him the Island of Uyedineniya (Seclusion), the last big island on the Earth found without a help of an icebreaker. Amazingly but according to Johannesen's description "*the island was completely free* (italics are mine – author's note) from snow …", and this points to unusually warm summer of 1878. After him nobody had seen the Island of Uyedineniya for the next 40 years, till the expedition on the *Eclipse* in 1915. It's obvious, that the new cold period began in the Arctic in the early 1880s, which brought about nearly a total termination of navigation in the high latitudes: breakages and accidents of the ships followed one after another, and the both largest ship-owners, Ludwig Knoop and Alexander Sibiryakov, had to interrupt a regular connection with European ports. At the end of his life Sibiryakov couldn't hide his disappointment: "Navigation in the Kara Sea hides a lot of difficulties, with which it's necessary to fight and that's why it is not suitable for commercial aims" (ibidem). If just during 4 years (1876–1879) 13 successful voyages from Europe to the Western Siberian rivers mouths were completed, then during the next 10 years (1880–1889) there were only 7. The epoch of a commercial navigation in the Kara Sea renewed only after 1911 and this time it was connected not only with warming which was just in it's initial stage (Fig. 13.2), but also with a development of a network of hydrometerological radio stations which significantly increased the safety of navigation.

A reconstruction of annual average temperatures (Fig. 13.2) is the first, produced for this Arctic region on the basis of documentary evidence and model simulations. Along with this, during the last 20 years both in Europe and the Russian Arctic a great number of dendroclimatic studies had been taken which resulted in reconstruction of summer temperatures back several centuries or even (millennia). On Fig. 13.5 a comparison of this work's data with the results of dendroclimatic reconstructions, covering nearly the whole area of the northern Eurasia from the coastal line of the northern Norway to the western Beringia, are given. Taking into account a significant geographical remoteness of the study

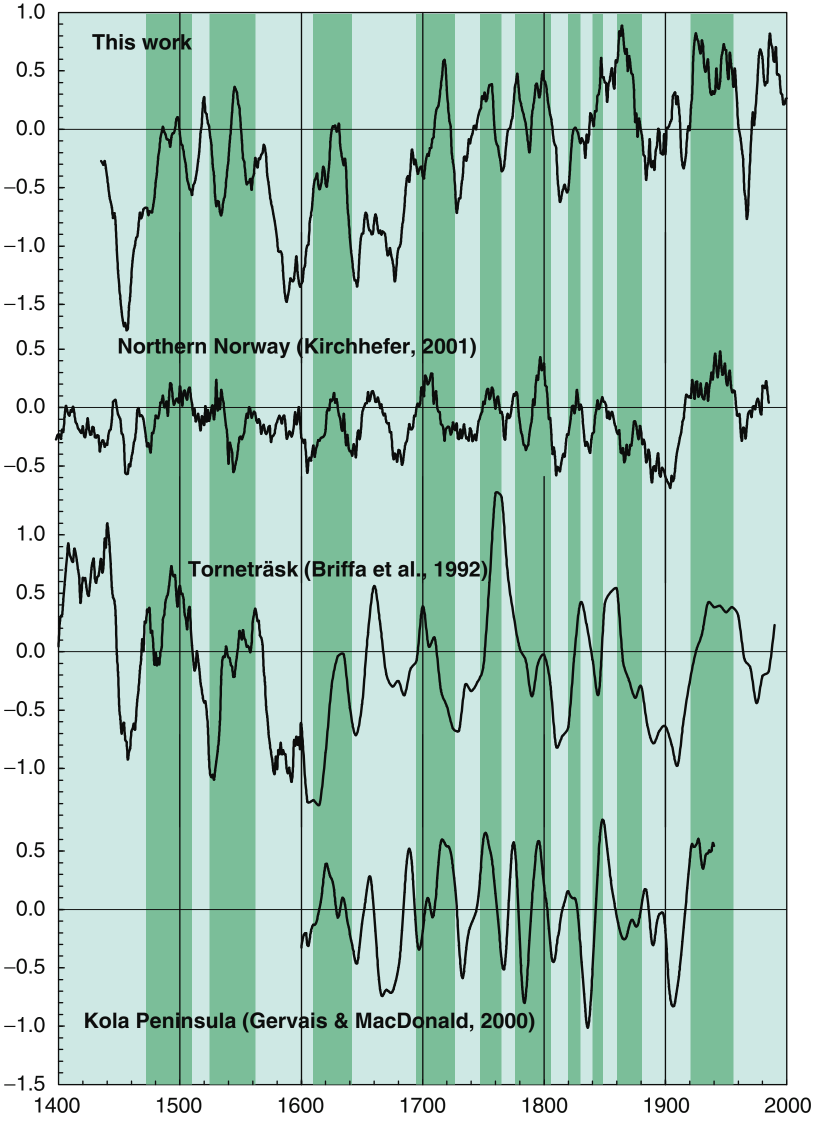

Fig. 13.5 This work's data as compared with the data of tree-ring reconstructions of summer temperatures for North Eurasia (smoothed with the 10-years moving average filter)

regions and principal differences in reconstruction methods, a correspondence of various data sets should be regarded as remarkable. In fact, almost all significant warm episodes (1470–1510, 1520–1555, 1610–1640, 1695–1725, 1775–1805, 1820–1830, 1840–1850, 1920–1950) happened with a remarkable synchronism in all study regions. Moreover, not only the sign, but also a scale of temperature anomalies appeared to be similar in the most of cases – thus, in all study regions the temperature in 1470–1510, 1695–1725 and 1775–1805 sometimes exceeded the modern level. A significant and absolutely clear warming of the 1820s (it had been recorded by early instrumental observations on subarctic stations of Arkhangelsk, Syktyvkar and Haparanda) wasn't observed on the eastern Taymyr and in the low reaches of the Lena River, but was clearly pronounced on the Kolyma. Warming of 1840s, which is also confirmed by early instrumental observations of not only European but Western Siberian (Tobolsk) stations also, left clear signs in the western part of Eurasia, but was hardly seen in the region to the east of the Ob' River. On the contrary, warming of the 1860s and 1870s, having a prominent place in our reconstruction, was accompanied by a period of cold in the western region (northern Norway, northern Fennoscandia and on Kola Peninsula), at least, in the warm season of the year. At the same time this warming was quite strong on Yamal, Taymyr, and in the low reaches of the Lena River and, in particular, on the Kolyma, where it had been the most significant during the nineteenth century.

The general picture of cold periods is also very much the same for all reconstructions under consideration and indicates the most significant cold periods between 1450–1465, 1590–1610, 1645–1690, 1725–1750, 1805–1820 and 1880–1920. It's interesting that in western regions the peak of coldness came to the mid-fifteenth and the turn of the sixteenth–seventeenth centuries while in the eastern regions (Taymyr, the Lena and Kolyma Rivers) the coldest period was indicated in the early nineteenth century.

A striking synchronism of climate fluctuations on the whole territory of the northern Eurasia confirms the existence of a common mechanism, regulating those processes. Our climate model gives an opportunity to indicate the main reasons of climate changes in the Arctic, among which there are natural factors, namely – the Earth's rotation velocity, atmosphere circulation pattern, sun and volcanic activity – which played the dominant role up to the middle of the twentieth century. As to the anthropogenic influence, it became noticeable only in the last 50–60 years, and it is likely to increase in the nearest future.

Simulations with a climate model clearly show that attempts of monocausal explanation of arctic climate fluctuations are predetermined to be a failure – in fact, it is impossible to explain a very complicated and as though unsystematic character of these fluctuations by a single factor influence. Thus, periods of abnormally low and high temperatures corresponded to the epochs of the lowest for the last 600 years solar activity, so called Spörer (A.D. 1420–1530) and Maunder minimums (A.D. 1645–1715) (Fig. 13.2). More often warm episodes were accompanied by periods of a high rotation velocity of the Earth, but strong cold periods happened too, for example, in the early nineteenth century. Thus, each significant climatic event during the last six centuries has been determined by a unique combination of the main climatic factors. Thus, a famous warming of the Arctic in the 1920–40s has been conditioned by a favourable combination of a rather high rotation velocity, zonal character of the atmospheric circulation (high NAO index), elevated solar activity and a complete absence of significant volcanic eruptions. Moreover, an outstanding role of natural factors explains the well-known climatic paradox of the last 20 years period, when with increasing to the absolute high average global temperatures, larger parts of the Arctic still remain significantly colder than in the second quarter of the twentieth century. Moreover, in the Arctic study area the temperature trend during the last 20 years is altogether negative (Fig. 13.2).

We have a limited possibility to make an additional check-up of our palaeoclimatic reconstruction with the help of the data of earlier instrumental observations, made in the adjacent parts of arctic and subarctic regions. Immediately in the BKS region (sector I in Fig. 13.1) only two meteostations are situated, each having an observational record longer than 120 years – Malye Karmakuly (since 1876) and Salehard (since 1886). In the immediate proximity from the study area there are several more stations, some of which are having an observational record since the early or mid-nineteenth century. The main information about these stations is given in Table 13.4.

Thanks to the recent work (Klingbjer and Moberg 2003) a record of Haparanda station in the northern Sweden is the longest continuous instrumental record in the Arctic, with more than 200-year period of observation. Haparanda station data confirms the existence of a series of warm summers during the initial period of observations up to 1808, in particular during the record Skoresby's voyage (1806) and successful Pospelov's expedition (1807), when temperatures of each summer month were higher than modern. A subsequent cold period of the 1810s was rather pronounced and was the strongest for the whole 200-year record of observations. Also a sequence of very cold years has been recorded at that time on stations of Arkhangelsk, Petrozavodsk and Syktyvkar what confirms completely our hypothesis about a strong cooling, preceded the tragic voyage of A. P. Lazarev.

On the contrary, the 1820s appeared to be extremely warm – thus, in separate years (1821, 1822, 1825, 1826) mean annual temperature on the stations mentioned above exceeded modern values by 2–2.5°C, and in Arkhangelsk the absolute temperature maximum for the whole period of observations was recorded (1826). At the end of

Table 13.4 Arctic and subarctic stations at which lengthy monthly data records are available

No.	Station	Latitude °N	Longitude °E	Time span of observations	Percent of missing monthly data
1	Haparanda	65.8	24.1	1802–2006	0.5
2	Vardø	70.4	31.1	1829–2006	5.1
3	Petrozavodsk	61.8	34.3	1816–2006	14.4
4	Kem	65.0	34.8	1862–2006	0.9
5	Arkhangelsk	64.6	40.5	1813–2008	1.0
6	Syktyvkar	61.7	50.8	1817–2008	11.8
7	Malye Karmakuly	72.4	52.7	1876–2006	20.9
8	Salehard	66.5	66.5	1886–2008	3.4
9	Tobolsk	58.2	68.2	1832–2008	12.9
10	Tomsk	56.4	86.0	1837–2008	14.2
11	Yeniseysk	58.5	92.2	1853–2008	11.1

the 1820s a sharp coldness came which lasted for more than 10 years – during this period in Petrozavodsk (1829) and on the both stations in western Siberia, Tobolsk (1839) and Tomsk (1840) absolute temperature minimums for the last 180 years were recorded. Similarly all stations represented in Table 13.4 reconstruct a picture of the rather warm 1840s and cold 1850s. Extremely cold year A.D. 1862 indicates, apparently, the upper boundary of the latter cold period. As it follows from this discussion, data of earlier instrumental observations during the first 60 years of the nineteenth century shape rather consistent picture with our reconstruction data. However our reconstructed warming of the 1860–70s doesn't have an adequate counterpart in the instrumental data and this aspect deserves a separate discussion. The point is, that unfortunately, all Russian stations, listed in Table 13.4, except only Arkhangelsk and Petrozavodsk, have a significant percentage of missing data during these particular years, nevertheless, some of them (Syktyvkar, Petrozavodsk, Yeniseysk) do give high temperatures anomalies in separate years: (1863, 1864, 1869, 1872, 1874), close to absolute maximums over the entire record of observations.

Along with this, as it has been mentioned above, implicit observations, including the ones on South Yamal, situated immediately in the BKS region (Fig. 13.5), confirm the fact of a pronounced warming of the Arctic in those years. However, as to the scale of this warming on the average through the region, it has formed, apparently, as a result of an occasional coincidence of several favourable circumstances. To confirm this is the fact that arctic climate fluctuations are amazingly synchronous, but almost never coincide in magnitude (Fig. 13.5). It means that temperature anomaly in the BKS region could well reach values corresponding to our reconstruction. I feel, it's worth to cite here an evidence of an authoritative contemporary of the events described, Prince Peter Kropotkin, who served then as Scientific Secretary of the Russian Geographical Society. I suppose, this evidence shows that in the scientific society of that time there were no doubts that some really unusual events were taking place in the Arctic. "In A.D. 1869–1871 brave Norwegian whalers absolutely unexpectedly proved that the navigation in the Kara Sea was possible. To our great astonishment, we learned that into 'a cellar always full of ice', as we routinely called the Kara Sea, small Norwegian schooners entered and ploughed it in all possible directions. Inventive Norwegians visited even the place of wintering of the famous Dutch Barents, which, as we thought, had been hidden from humans by ice fields, more than 100 years old. Our marine scientists decided that such an unexpected success of Norwegians could be explained exclusively by the warm summer and by exclusive state of ice" (Kropotkin 1988).

Thus, we have all grounds to assume that in the Arctic study area the indicated significant warming really took place. There is no other good reason, except a significant warming, which could explain the unprecedented success in navigation and outstanding geographical discoveries, accomplished in these years.

Thus, the analysis of the climate fluctuations, following from historical evidence, is fully consistent with model simulations and early instrumental observations data. The developed reconstruction is based on the results of instrumental meteorological observations of the last century and is well correlated with other temperature reconstructions, elaborated by dendroclimatic methods. It allows to argue that forecast of climate changes in the Russian Arctic sector may be quite reliable. Extrapolation of values of the major climatic factors has been made on the basis of considerations, presented elsewhere (Klimenko et al. 2000; Klimenko and Mikushina 2005). Results of the corresponding model calculations, shown in Fig. 13.2, allow to conclude that as a result of a restraining influence of natural factors maximal temperature marks, recorded between A.D. 1930–1950, will not be exceeded in the first part of the current century. Only after 2050 a very strong and long-term warming will come to the Russian Arctic, the scale and duration of it will become unprecedented in the context of the last 600 years as well as in the context of a few last millennia (Klimenko 2001). Unlike all previous, this warming will be generally conditioned by anthropogenic factors, and namely by continuing accumulation of greenhouse gases in the atmosphere and gradual atmosphere's release from troposphere sulphate aerosol.

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Chapter 14
Growth/Climate Relationships in Tree-Ring Widths of *Picea Abies* in Lithuania and Poland

Marcin Koprowski and Adomas Vitas

14.1 Introduction

14.1.1 Aim of Study

Tree-ring-widths together with parameters including wood density, stable isotope content and the presence of reaction wood (anomalous, high-density cells produced as a result of mechanical stress, termed 'compression wood' in conifers) are frequently used as bio-indicators to study environmental conditions (Schweingruber 1996). Some factors such as frost or summer drought, may have an immediate effect on ring width, other factors such as wintertime drought may have a delayed effect on tree-ring-widths, since the growing tissue is dormant. The effect of different factors is seen as variation in ring size and structure, which changes systematically, or vary slowly throughout the life of the tree (Fritts 1976).

Spruce is a popular tree species in European forestry, and in dendrochronological and dendroclimatological research. Previous dendrochronological studies on spruce in Poland have generally focussed on trees from the mountainous region (Bednarz et al. 1998–1999; Feliksik and Wilczyński 2000a, 2000b, 2001; Savva et al. 2006). Lowland spruces in Poland and Lithuania have been studied mainly by authors of this paper: Zielski and Koprowski (2001, 2002); Koprowski and Zielski (2002, 2006, 2007); Vitas (2002, 2004). Because of the

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transition zone between Atlantic and continental climates, we decided to generalise the climate-growth response of spruce on the selected sites in natural stands in Poland and Lithuania as a basis for climate reconstruction. Dendrochronological regionalisation allows usage of a limited area for each reconstruction.

14.1.2 Climate of Study Area

Climatic conditions and biogeographical differences are expressed as influence of oceanic and continental climates. The Polish lowland (60%) belongs to the Middle-European Lowland, and has generally sub-Atlantic vegetation, and a predominantly oceanic climate. The mean yearly precipitation – 450–700 mm, and the mean yearly temperature – 7–9°C. Southern Poland is characterised by uplands and mountains. Northeastern Poland and Lithuania were connected to the Lowland East-Baltic-Belorus. The dominance of the Atlantic climate decreases from the south to the northeast of the research area (Kondracki 2002). Average yearly temperature in Lithuania is +6.1°C (−4.9°C in January and +17.0°C in July). The western region of Lithuania is characterized by highest amounts of precipitation per year (up to 930 mm), warmest winters (January temperature of −2.8°C) and the longest period of vegetation (200–206 days). The smallest amount of precipitation (520–620 mm per year) is characteristic of North Lithuania. Warmer winters and summers than those in the North and East are indicative of South Lithuania. The most continental climate conditions with the shortest period of vegetation (185–192 days) and coldest winters (−5.0°C to −6.8°C) are characteristic of East Lithuania (Bukantis 1994).

14.2 Material and Methods

14.2.1 Tree Sites and Sampling Method

Almost 2,000 samples were taken from 45 sites from different habitats in eastern Poland and from 47 sites in Lithuania[1] (Fig. 14.1). Between ten and 30 dominant trees, without visible disease symptoms, were selected from each site. Two core samples were taken from each tree, one from the west and one from the east, using a Pressler borer, at a height of approximately 1.30 m above ground level. Samples from Polish Uplands were taken with mean elevation of approximately 200–300 m a.s.l.

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[1] Site descriptions available upon request

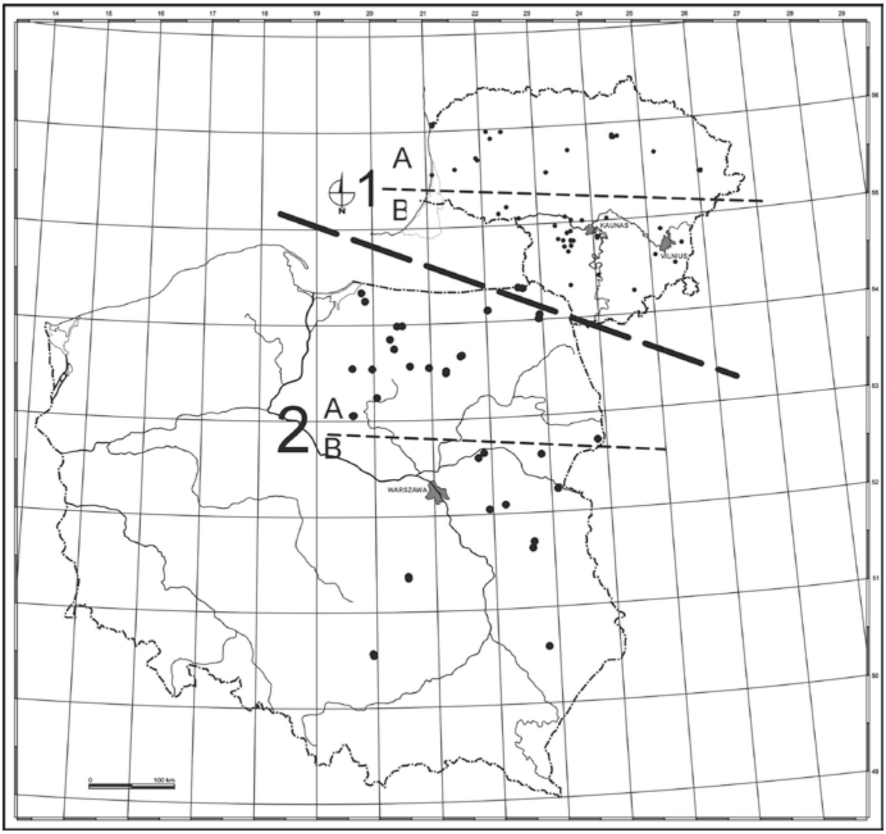

Fig. 14.1 Sites location, established homogenous regions

14.2.2 Local Chronologies

The core samples were treated in the standard way and measured to the nearest 0.01 mm by means of a mechanical instrument with a computer registering the ring widths. The samples from each site were then used to construct local chronologies. A number of methods were used to assess the cross-matching between the samples:

- The Students-*t* test. Only the samples whose *t*-value was greater than 4.0 were used to build a chronology.
- Gleichläufigkeit. The CATRAS program (Aniol 1983) was used to compute the % Gleichläufigkeit (% GL). This is a non-parametric measure of the congruity of two growth curves, which consists of comparing subsequent intervals (Eckstein 1969; Schweingruber 1983).
- The accuracy of the fit was tested by the COFECHA program (Holmes 1986; Grissino-Mayer 2001).

- Each sample was analysed by means of skeleton plot method (Douglass 1939; Schweingruber et al. 1990). To check the measuring mistakes, pointer years were detected and applied.

The following two types of chronologies were used for further investigations:

- Raw data chronology – composed of averaged annual growth values and presented in the form of actual numerical values.
- Residual chronology, which was built by CRONOL, a tool from the DPL package (Holmes 1984).

14.2.3 Regionalisation

Hierarchical cluster analysis (HCA) was used to distinguish regions with similar increment patterns. This method has been successfully employed by Leuschner and Riemer (1989) and Wilson and Hopfmüller (2001) to distinguish groups of trees at varying altitudes. The STATISTICA program was used to perform the HCA. To maximise the between-group variance, while minimising the within-group variance, Ward's method was used, with Pearson's correlation coefficient being used as a measure of the similarity.

14.2.4 Dendroclimatological Analysis

Climate-growth relationships were calculated by means of the PRECON program (Fritts 1996). This program applies a bootstrap response function to estimate the error using random sampling from the data. The response function method has been described in detail by Fritts (1976), and Briffa and Cook (1990). The bootstrapped procedure provides an alternative to testing the significance and stability of the regression coefficient (r) in time. It is based on the evaluation of a large quantity of data (subsamples). It has been found that with more than 50 sub-samples, the results do not vary considerably. The regression coefficient is calculated for each randomly selected sub-sample. If this is repeated 50 times, we get 50 regression coefficients, and 50 independent verifications of the correlation. At the final stage, the results of these parameters are calculated on the basis of the preceding 50 measurements (Guiot 1993). Climate data from October of the previous year to September of the current year served as independent variables, and the residual chronologies for each site were used as dependent variables. In all bootstrap calculations, 50 bootstrap replications were calculated.

Mean monthly temperatures and monthly precipitation sums were collected from 16 meteorological stations of the Institute of Meteorology and Water Management in Warsaw and four meteorological stations from Lithuania.

14.3 Results and Discussion

14.3.1 *Dendroclimatological Regionalisation*

Regionalisation was made by comparison of 79 local chronologies, distinct regions with a similar increment pattern were identified by HCA. Some chronologies were rejected because of young age of trees. We were able to recognize four main groups, where linkage distance is higher than two (Fig. 14.2). Group 1 is composed of Lithuanian sites and two sites from north-eastern Poland. Group 2 consists of sites only from Poland. The first group is divided into two smaller groups "1a" and "1b". Trees from the region "1a" grow in northern Lithuania and from the group "1b" in the southern part of the country and in Poland (Figs. 14.1 and 14.2). These chronologies split from the same branch in the hierarchical tree, and indicate that the yearly variance of tree-ring widths share some of the variation with the trees from other sites. The border between region "1a" and "1b" is approximately the same as between northern and southern climate regions of Lithuania, but this line divides the eastern area into north and south. Two sub-groups from region 2 represent trees from north-eastern Poland on the one hand and from middle and southern Poland on the other. The border between these groups (2a and 2b) confirms the idea that spruce from the Hercynian-Carpathian centre reached the middle Wisła and Bug River, and the southern border of boreal-Baltic range is the border between two ranges. The problem of spruce range and dendrochronological regions was discussed in detail by Koprowski and Zielski (2006). Savva et al. (2006) grouped *Picea abies* chronologies at different elevations, and they observed that shifting elevational pattern may be associated with the length of the growing season. The shortest vegetation period is characteristic of East Lithuania (185–192 days) and Suwalskie Lakeland (185–190 days). This gives an approximate difference of 3 weeks in comparison with west and south-east Poland. In western Lithuania, the vegetation period lasts 200–206 days. The border between regions 1a and 1b is rather more connected with rainfall. The northern part of Lithuania has the smallest amount of precipitation, especially in comparison to the western part – up to 930 mm. In Poland, the dominance of the Atlantic climate decreases from the south to the northeast, while the effects of the continental climate increase. This is expressed as a higher mean yearly precipitation, a decrease in the vegetation growth period, and a greater yearly temperature amplitude. Regionalisation accomplished for other species e.g. pine in Poland (Wilczyński et al. 2001) gave similar results as for spruce. This suggests that supra-regional factors like climate play an important role in determining tree-ring growth, in some way independently from local environmental conditions and tree species.

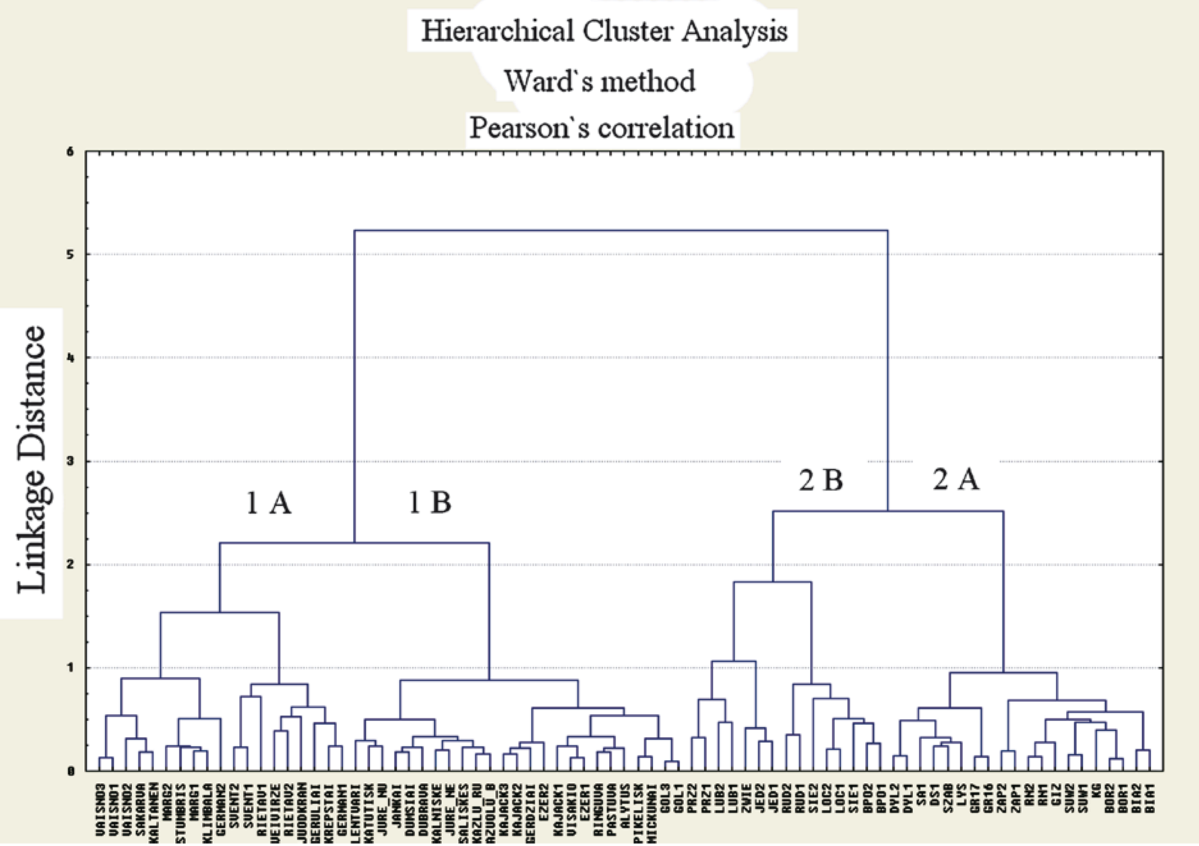

Fig. 14.2 Results dendrogram of cluster analysis

14.3.2 Growth/Climate Relationships

In the second part of our paper, we would like to focus on climatic conditions, which determined tree growth and may be a key factor understanding the spatial distribution of increment patterns. Results of the dendroclimatological research are presented in Tables 14.1, 14.2, 14.3 and 14.4. Trees from the region "1a" respond mostly to precipitation during the vegetation period, especially from June to July (Table 14.1) and the variance explained by climate varies from 46% to 2%. Trees from most sites respond to precipitation, whilst only three sites are sensitive to temperature. Regions 1b and 2a seem to be temporal instable. The reaction to climate is mixed; some trees react more to precipitation, some to temperature (Tables 14.2 and 14.3). Wilson and Elling (2004) took into account the problem of temporal instability in growth-climate response and demonstrated some implications for dendroclimatic reconstructions. They concluded that, due to SO_2 forcing in southern Germany, the calibration period for spruce ring-width will be restricted to the 1871–1978 period. Spruces from lowlands (regions 1b and 2a) are most flexible on weather conditions in the vegetation period. In the region 1b (most Lithuanian sites) the role of precipitation also lasts for 2 months from May to June, while in north-eastern Poland this extends to July. Trees from a few sites respond negatively to high summer temperatures. A quite different correlation was stated by Bednarz et al. (1998–1999) for Babia Góra National Park (Carpathian Mts.). Here, high June–July precipitation had a negative effect on tree growth, on the contrary to summer temperature, which is strongly positively correlated with tree-ring-widths. This is due to high annual precipitation meaning and therefore moisture is not a limiting factor, and summer droughts are extremely rare. Negative correlation to summer precipitation in cooler regions was found too by Mäkinen et al. (2000, 2003) or Miina (2000). Trees from warmer regions of eastern Finland (Mäkinen et al. 2003), or in the lower altitude mountains in Germany (Dittmar and Elling 1999; Wilson and Hopfmüller 2001) and the northern part of this country (Eckstein et al. 1989) react in the same way. The role of precipitation and temperature during the vegetation period was also described by Kahle and Spiecker (1996), Mäkinen et al. (2001), Meyer and Bräker (2001), Dittmar and Elling (2004).

On some sites, the influence of different climate conditions from other months was noted. The warm November temperatures had a negative influence at two sites in the Forest Inspectorate areas of Lidzbark (Grodki 17), Goldap and site Mickunai. The reason for that could have been the disruption to the tree passing into its winter phase if trees are not tough enough that is a gradual temperature decline in winter months prepares plants to withstand frost (Obmiński 1977). In certain Polish spruce sites, high temperatures in January and February produce a positive influence meaning the subsequent formation of wide rings is observed. During earlier investigations carried out in the Olsztyn Lake District (though on a shorter sequence of climatic data), one of the sites showed a negative impact of high February temperatures (Zielski and Koprowski 2002). This may be a result of snow loading on the branches. This phenomenon is strengthened when wet snow falls at the temperature

Table 14.1 Region 1a. Relationships between residual chronology and monthly values of temperature and precipitation in previous year (O-October, N-November, D-December) and current year (J-January, F-February, M-March, A-April, M-May, J-June, J-July, A-August, S-September), p-positive dependence, n-negative dependence. RSQ-R^2, CL- variance explained by climate, P GRO- variance explained by prior growth, TOT- total explained variance

Site	Temperature												Precipitation											RSQ:		
	Previous year			Current year									Previous year			Current year								CL:	P GRO:	TOT:
	Months												Months													
	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	F	M	A	M	J	J	A	S			
German 1																				**p**	**p**			0.39	0.01	0.4
German 2									**n**															0.45	–0.04	0.41
Geruliai						**p**														**p**				0.41	–0.04	0.37
Juodkran																				**p**	**p**			0.46	0.08	0.54
Kaltanen																				**p**				0.35	–0.18	0.17
Klimabala																								0.12	–0.01	0.11
Krepsiai	**p**					**p**															**p**			0.24	–0.03	0.21
Merg 1																								0.19	0.00	0.19
Merg 2																				**p**				0.23	0.12	0.35
Rietav 1																								0.08	0.07	0.15
Rietav 2																				**p**				0.28	0.06	0.34
Sakarva																				**p**				0.11	–0.23	–0.12
Stumbris																								0.07	0.1	0.17
Svent 1																								0.02	–0.25	–0.23
Svent 2																								0.02	–0.09	–0.07
Vaisno 1																				**p**				0.26	–0.07	0.19
Vaisno 2																				**p**				0.36	–0.15	0.21
Vaisno 3																				**p**	**p**			0.28	–0.02	0.26
Veivirze																								0.02	–0.05	–0.03

Table 14.2 Region 1b. Symbol and shortcuts as above

Site	Temperature												Precipitation											RSQ:		
	Previous year			Current year									Previous year			Current year								CL:	P GRO:	TOT:
	Months												Months													
	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	F	M	A	M	J	J	A	S			
Alytus																				**p**				0.07	0.06	0.13
Ąžuolų Būda																								0.08	0.19	0.27
Dubrava 2															**p**									0.17	0.13	0.3
Dumsiai			**p**																					0.14	0.07	0.21
Ežerélis 1																				**p**				0.39	0.11	0.5
Ežerélis 2																								0.33	0.2	0.53
Gerdžiai		**n**				**p**			**n**		**n**													0.33	0.21	0.54
Goll						**p**														**p**				0.47	0.13	0.6
Gol3																				**p**	**p**			0.52	0.081	0.6
Jankai									**n**				**p**						**p**					0.26	0.12	0.38
Jūré Ne													**p**											0.11	0.04	0.15
Jūré Nu																								0.07	0.14	0.21
Kajackai K						**p**														**p**	**p**			0.37	0.08	0.45
Kajackai P						**p**																		0.25	0.08	0.33
Kajackai S						**p**													**p**					0.37	0.02	0.39
Kalniské																								0.14	0.01	0.15
Katutiskés																**p**								0.21	0.07	0.28
Kazlų Rūda																								0.09	0.11	0.2
Lentvaris		**n**													**p**									0.39	0.1	0.49
Mickūnai																								0.37	0.17	0.54
Paštuva																				**p**				0.23	0.12	0.35
Pikeliškés															**p**									0.23	0.11	0.34
Ringuva											**n**									**p**				0.43	0.17	0.6
Šališkés																			**p**					0.13	0.00	0.13
Višakio Rūda											**n**								**p**					0.26	0.17	0.43

Table 14.3 Region 2a. Symbol and shortcuts as above

Site	Temperature												Precipitation											RSQ:		
	Previous year			Current year									Previous year			Current year								CL:	P GRO:	TOT:
	Months												Months													
	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	F	M	A	M	J	J	A	S			
Suwalki 1																			**p**	**p**	**p**			0.54	0.15	0.69
Suwalki 2																			**p**	**p**	**p**			0.532	0.092	0.624
BPN																			**p**	**p**	**p**			0.457	0.147	0.604
Borki 1									**n**															0.462	0.154	0.617
Borki 2																			**p**	**p**				0.427	0.182	0.609
Sarny 1																			**p**	**p**				0.491	0.106	0.597
Gizewo					**p**														**p**		**p**			0.436	0.133	0.57
Ruciane Nida 1																			**p**	**p**		**p**		0.48	0.126	0.606
Ruciane Nida 2																				**p**				0.437	0.129	0.566
Dwa Stawy 1									**n**										**p**	**p**				0.476	0.144	0.621
Kamienna G																								0.401	0.17	0.571
Szabruk																			**p**		**p**			0.575	0.081	0.655
Grodki 16									**n**										**p**	**p**				0.448	0.093	0.541
Grodki 17		**n**							**n**										**p**		**p**			0.505	0.115	0.666
Zaporowo 1						**p**									**n**						**p**			0.456	0.155	0.611
Zaporowo 2						**p**									**n**									0.44	0.101	0.541
Dylewo 1																			**p**	**p**	**p**			0.491	0.093	0.584
Dylewo 2	**p**								**p**									**p**	**p**	**p**	**p**			0.595	0.115	0.71
Lysowo						**p**												**p**		**p**				0.545	0.123	0.667

Table 14.4 Region 2b. Symbol and shortcuts as above

Site	Temperature												Precipitation												RSQ:		
	Previous year			Current year									Previous year			Current year									CL:	P GRO:	TOT:
	Months												Months														
	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	F	M	A	M	J	J	A	S				
Rudka 1							**n**												**p**	**p**	**p**			0.543	0.199	0.742
Rudka 2						**p**	**n**												**p**					0.434	0.18	0.613
Biala Pdl. 1						**p**			**n**															0.406	0.091	0.498
Biala Pdl. 2				**p**		**p**																		0.417	0.122	0.539
Lochow 1				**p**					**n**											**p**				0.537	0.118	0.655
Lochow 2						**p**			**n**															0.411	0.078	0.489
Siedlce 1						**p**		**n**																0.395	0.122	0.516
Siedlce 2																				**p**	**p**			0.531	0.00	0.531
Przysucha 1						**p**																	**n**	0.401	0.09	0.491
Przysucha 2						**p**																		0.412	0.073	0.485
Jedrzejow 1						**p**																		0.436	0.197	0.634
Jedrzejow 2						**p**																		0.315	0.309	0.624
Lubartow 1																								0.33	0.157	0.487
Lubartow 2																							**n**	0.401	0.151	0.552
Zwierzyniec																								0.38	0.137	0.517

of 0°C (Modrzyński 1998). Skre and Nes (1996) found that high winter temperatures may cause an increased needle loss and lead to growth reduction in the following season. A negative correlation between February temperature and subsequent ring width was observed in Finland (Miina 2000; Mäkinen et al. 2000).

Spruce from southern sites grows under the influence of the highland climate, with a stronger role of March temperature. In the Ustron Forest District of the Polish mountains, the low temperatures of the end of winter and during spring were a limiting factor. The higher the altitude of the site, the longer the period of time during which higher temperatures positively influenced cambial activity (Feliksik and Wilczyński 2000b).

14.4 Conclusions

Dendroclimatological research on Norway spruce in Poland and Lithuania gives an opportunity to extend the knowledge of spruce ecology and to follow the climate growth relationships in regard to climate reconstruction. Regionalisation based on growth increment patterns divided the research area into four regions, the most northern sites (Lithuania and north-eastern Poland) are more sensitive to rainfall during the vegetation period. In northern Lithuania precipitation from June to July is the most important for tree growth, while in southern Lithuania this period is from May to June. In north eastern Poland the influence of precipitation from May to July prevails. We concluded that tree-ring-widths from these three regions (1a, 1b, 2a) are mostly determined by precipitation during the vegetation period, especially from May to July. Differences in growth patterns are not so clearly related to the length of vegetation period, which varies from 185–192 days in East Lithuania and 185–190 days in Suwalskie Lakeland to 200–206 days in western Lithuania. The border between the length of a vegetation period in Lithuania extends from north to south while the border of selected dendrochronological homogenous regions runs from the West to the East. This difference is rather connected with rainfall; the smallest amount of precipitation is noted in northern Lithuania whilst in Poland the effects of continental climate increase from the south to the northeast. This is expressed, among other parameters, as higher yearly mean precipitation. The decrease in dominance of the Atlantic climate from the south to the northeast is also responsible for distinguishing regions 2a and 2b. This is visible in their reaction to climate. Trees from the southern part of Poland (region 2b) are more sensitive to March temperature. We concluded that, with regard to climate reconstruction, it is possible to reconstruct precipitation from May to July for north-eastern Poland and Lithuania.

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Chapter 15
Multi-Annual Variability of Cloudiness and Sunshine Duration in Cracow Between 1826 and 2005

Piotr Lewik, Dorota Matuszko, and Maria Morawska-Horawska

15.1 Introduction

The Cracow series of nephologic and heliographic observations is unique on a global scale, due to its uniformity as to the place of measurements, their uninterrupted continuity, as well as its length and the reliability of data. Only on the basis of long and uninterrupted climatologic series is it possible to obtain reliable information about trends and tendencies with a certain level of significance and Cracow's observations belong to such a series.

The present study aims at characterizing the multi-annual variability of cloudiness and sunshine duration in Cracow on the basis of archive data from the 1826–2005 period.

15.2 Cloudiness

The commencement of the uninterrupted observation series dates back to 1826. However, "The records of daily meteorological observations" ("Dzienniki codziennych spostrzeżeń meteorologicznych") only includes the results of fixed time observations of cloudiness on a 0–10 scale starting on 1 December 1862.

The present study uses archive materials from the following sources: the cloudiness in the 1826–1852 period has been reconstructed on the basis of a publication

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by Wierzbicki (1873) concerning the monthly number of clear and overcast days; the data for 1853–1862 come from a manuscript by Karliński (Morawska 1963) which lists the mean monthly values of cloudiness; and data for the years 1863–2005 have been obtained from "The records of daily meteorological observations" with fixed time observations of cloudiness. The amount of cloudiness in the initial period of the observations has been reconstructed by means of two methods: by using the following formula:

$$z = a + b \cdot \left(\left(s - k\right) / n\right)$$

s – number of overcast days, *k* – number of clear days, *n* – number of days in a given period,

a, *b* – calculated numerical parameters (Gorczyński and Wierzbicka 1916), as well as by applying regression analysis.

The regression equation has the following form:

$$z = a + b \cdot k + c \cdot s$$

The cloudiness calculated by means of both methods was almost identical. The correctness of the applied method has been verified on the basis of the values of actual cloudiness for the 1854–2005 period (Fig. 15.1). A similar course of oscillations has been registered in all months. Clear and overcast days for the entire 1826–2005 period have been identified according to the guidelines provided by Wierzbicki (1873) and valid in the nineteenth century. According to the guidelines, the mean daily cloudiness on clear days equalled from 0.0 to 3.3, whereas on overcast days it amounted to 6.7–10.0. The application of the data concerning the number of clear and overcast days permitted to lengthen the examination period by 37 years, that is move back to 1826.

The amount of cloudiness recorded from 1826 to 1852 has been assessed on a 4-degree scale (Morawska 1963), from 1853 to 31 December 1990 on a 1–10 scale

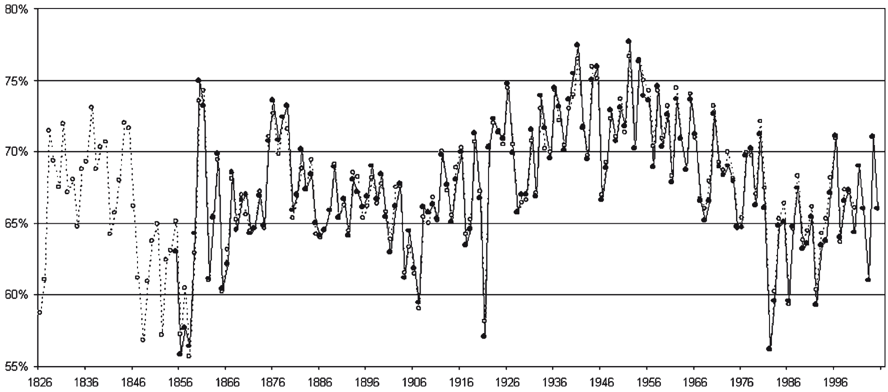

Fig. 15.1 Mean annual cloudiness in Cracow between 1853 and 2005 – actual and calculated by extrapolation for the years 1826–2005

and from 1 January 1991 onwards on a 1–8 scale. In order to obtain comparable data, the values of cloudiness have been standardized according to a 10-degree scale and converted to percentage values.

The mean annual cloudiness in Cracow during the entire series (1826–2005) totals 67.5% and thus, it is 0.4% lower than the mean calculated on the basis of the results of fixed-time observations carried out between 1863 and 2005. In the analysed multi-annual period, the value of the mean annual cloudiness repeatedly underwent considerable changes (Fig. 15.2). The course of cloudiness, smoothed by means of a Gaussian filter, is a sinusoid with a changing amplitude (Fig. 15.3). The segmentation of the course of the cloudiness data series according to Alexandersson (1986), refers to the division into NAO circulation epochs and splits the series into the following intervals: 1826–1846 (mean cloudiness, ca. 68%), 1847–1858 (mean cloudiness, ca. 60%), 1859–1921 (mean cloudiness, ca. 67%), 1922–1966 (mean

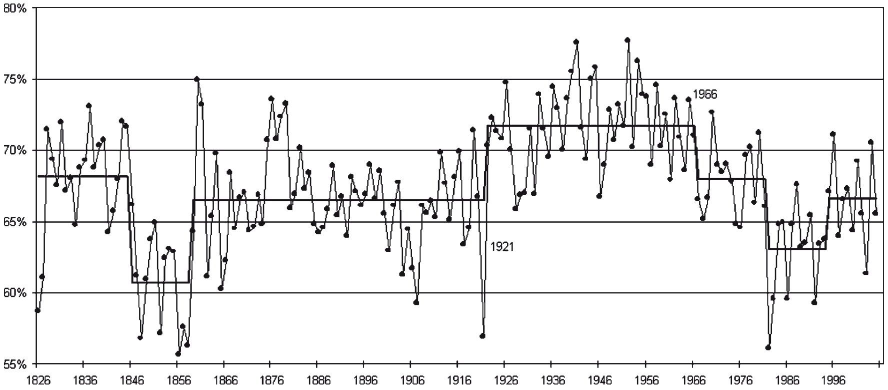

Fig. 15.2 Mean annual cloudiness in Cracow between 1826 and 2005 and its segmentation according to the Alexandersson test

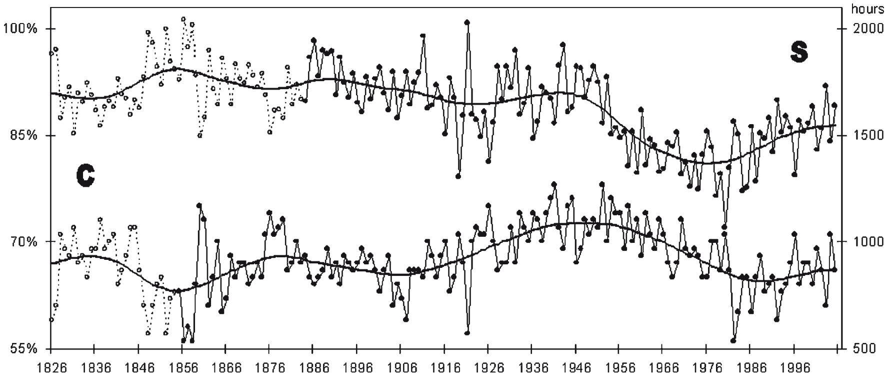

Fig. 15.3 Cloudiness (C) and sunshine duration (S) in Cracow between 1826 and 2005, smoothed by Gaussian filter. *Solid line* – actual values, *broken line* – extrapolated values

cloudiness > 70%), 1967–1981 (mean cloudiness, ca. 68%), 1982–1994 (mean cloudiness <65%), 1995–2005 (increase in cloudiness >65%). All the tests used for the segmentation of the series indicated a breakthrough in the amount of cloud cover: first, between 1921/1922 and to a lesser degree in 1966/1967. In the analysed multi-annual period, the mean annual cloudiness minimum equalled ca. 56% (1856, 1858, 1982), and the maximum, 78% (1941, 1952). The highest values of mean monthly cloudiness reached 98% and were registered in February 1913 and 1952, as well as in December 1959. The absolute minimum (32%) was recorded in March 1921.

The entire analysed period is characterized by a small increase in cloudiness in Cracow, which is statistically significant at a confidence level of 0.05. The course of cloudiness in the twentieth century, and especially in its second half, exhibits a significantly greater variability than it does in the nineteenth century. This can be a result of the significantly greater dynamics and the range of changes in circulation conditions (Ustrnul 2007). The course of cloudiness, both in terms of the mean values and the extreme phenomena, seems to be correlated with the cyclonicity index. The index has been calculated by means of a method presented by Niedźwiedź (1981) and on the basis of data received from the same author. This can be illustrated using the year 1921 as an example, in which the minimum (−228) of the index within the entire investigated period occurred. The mean annual cloudiness (57%) in that year was close to the absolute minimum. In the years characterized by the greatest cloudiness (1941 and 1952), high values of the index could be observed. The values of the index increase from 1922 onwards, with a maximum in the 1960s, when western circulation is also weakened (Ustrnul 2007).

In the first half of the twentieth century, a growing trend in cloudiness was observable. It was especially clearly visible in autumn. The second half of the century was characterized by a downward trend, very pronounced in wintertime. The decrease in cloudiness observed since the beginning of the 1950s was also recorded at other stations in Poland (Wibig 2004) and in the countries of the former Soviet Union (Sun and Groisman 2000), as well as in Potsdam and other regions of the globe. The presented results from Cracow are also concurrent with the results of work by Henderson-Sellers (1986) regarding the changes in cloud cover in Europe.

The occurrence of similar tendencies everywhere in Europe indicates that circulation is the predominant reason for cloudiness variability in Cracow, which is also modified by local factors. In addition, it confirms earlier conclusions concerning this issue (Morawska 1963). The role of local factors intensified after World War II, during a period of territorial and industrial growth of the city, which occurred during the years with the greatest cloudiness. The increase in the emission of air pollutants caused a greater concentration of condensation nuclei in the atmosphere and contributed not only to the increase in cloudiness but to a change in its structure as well. The emission of anthropogenic heat, amelioration of land and replacing vegetation areas with artificial ones caused a decrease in the frequency of occurrence of morning fogs and stratus clouds as well as an increase in the amount of convective ones (Morawska-Horawska 1985; Matuszko 2003).

Cracow's cloudiness is most strongly correlated with the cyclonicity index (r = +0.38) and to a lesser degree with the optical thickness of volcanic aerosol (http://data.giss.nasa.gov/modelforce/strataer) (r = −0.32). These two factors account for 34% of cloudiness variability. The cyclonicity index reflects the frequency of occurrence of cyclonic meteorological situations, irrespective of the direction of advection (Niedźwiedź 1981). However, if the directions of the influx of air are taken into account, it is easy to state that advections in cyclonic systems from all directions except SE (r = −0.01) contribute to high cloudiness. The advections which are especially strongly correlated with cloudiness are the ones originating from the following directions: E (r = +0.37), N (r = +0.33), W (r = +0.33). An anti-cyclonic wedge is an especially unfavourable situation (r = −0.38). The fluctuations of cloudiness in Cracow are cyclical, exhibiting the following periods, expressed in years: 3.0–3.6, 5.7–8.9, 16.4, 20 and 60, on the basis of a harmonic analysis. These results are similar to those obtained for the 1880–1979 period (Morawska-Horawska 1985).

15.3 Clear and Overcast Days

The number of clear and overcast days, calculated according to Wierzbicki's criterion and used in his work (Wierzbicki 1873), is greater in comparison to the number of such days determined according to the currently valid guidelines (Matuszko 2007).

On average, 69 clear days occur in Cracow. This value varies in individual years, because in certain years with little cloudiness the number of clear days was twice as high or twice as low (Fig. 15.4). The curve of the multi-annual course of the annual number of clear days exhibits a downward trend, although in the second half of the twentieth century an increase in the number of such days could be observed.

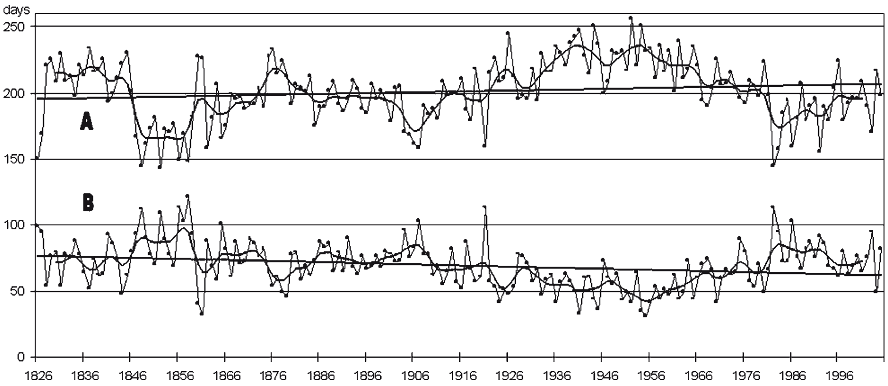

Fig. 15.4 The number of clear (B) and overcast (A) days in Cracow between 1826 and 2005, leveled by a 31-element Gaussian filter, and their trends

It is worth mentioning that a large number of clear days (over 70, and even 100 a year) occurred in the 1850s. The fewest clear days, fewer than 60 a year, were registered in the period comprised between 1924 and 1972. In the multi-annual course, only March presents a growing trend of the number of clear days, and spring can be characterised by the smallest decrease in their number. The most significant downward trend can be observed in summer, especially in June. This fact can be explained by the increase in convective cloudiness which dominates in the warm part of the year and whose increase can often be noticed in the second half of the twentieth century in Cracow (Matuszko 2003), Łódź (Wibig 2004) and the countries of the former Soviet Union (Sun et al. 2001).

In Cracow, there are three times as many overcast as clear days, 201 per year on average. In the multi-annual course, the annual number of overcast days increased, although expressed by a weak trend (Fig. 15.4). In the majority of the months a growing trend is observable, and the number of overcast days only decreased in October. The largest number of overcast days in the multi-annual period (30 days each) was registered in December 1945 and January 1953.

15.4 Sunshine Duration

The measurements of sunshine duration in Cracow were started in 1883, using a Campbell-Stokes heliograph. They have been carried out in the same exact location ever since. In 1941 the measurement instrument was replaced, which many studies fail to mention. Due to the necessity to homogenize the measurement series, a comparison of the readings of the new and the old heliograph was carried out (Morawska 1963). For the purpose of the present study, the values of corrections for individual months have been calculated, on the basis of the regression equation and using the values of corrections based on the comparison from the years 1957/58. The calculations also took into account the annual course of the optical mass of the atmosphere, the length of time when the Sun was located higher than 5° above the horizon and the coefficient of transparency and vapour pressure. The new values of the corrections acquired a regular annual course. The mean annual difference in the readings of both instruments is significant and equals 8.5%. After they have been applied to the readings of the old heliograph, tests showed the homogeneity of the entire series which was not observable before.

The publication of Wierzbicki (1873) was used, as it contains the monthly values of the number of clear and overcast days from the 1826–1852 period. These numbers, as well as the cloudiness values calculated on their basis, were used to calculate the value of sunshine duration. Equations of multiple stepwise backward regression and standard regression equations were used. Then, various methods of extrapolation of annual sunshine duration were compared. The methods were based on various juxtapositions of the following causative variables: annual cloudiness, cloudiness in particular months, the number of clear and overcast days and the number of said days together with the NAO index and air temperature. The degree of adjustment of various regression functions to the data was considered. In addition, the variability of the multi-annual course of sunshine duration was compared, both for the extrapolated part and the part obtained from observations. It was found that the best results were obtained by means of standard (not stepwise) regression on the basis of cloudiness values for all 12 months (Fig. 15.5). The dependence of sunshine duration on cloudiness was determined on the basis of the corrected data from the old heliograph, that is from the period in which there was no strong anthropogenic interference. The mean annual difference between the values from the measurements and the extrapolated values, calculated from the years 1884–1941, equals 76 h.

The reconstruction of the series up to 1826, that is its extension to 180 years, allowed for a new, broader perspective on the variability observed in the course of the annual sums of sunshine duration in Cracow (Fig. 15.3). The shape of the curve smoothed by the Gaussian filter resembles a descending sinusoid. The mean annual sum of sunshine duration, calculated on the basis of data for 1884–2005, corrected due to the replacement of the heliograph, equals 1,595.5 h. The mean calculated for the 1826–2005 period (in which the values for 1826–1883 were calculated on the basis of monthly values of cloudiness) equalled 1,639.6. The maximum annual sum of sunshine duration for the 1884–2005 period equals 2,022.1 and occurred in 1921. In the reconstructed part of the series, a slightly higher value can be noticed: 2,040.3 in 1856. The lowest annual sum of sunshine duration (1,067.2) was registered in 1980.

In the multi-annual course of sunshine duration it is possible to observe periods of relative stabilization, which can last for several decades, during which values in individual years oscillate around the average level for the given period. In order to determine the change points separating the periods of relative stabilization in the course of sunshine duration in Cracow, five different statistical methods were used: the sequential *t*-test analysis of regime shift – STARS (Rodionov 2004), the Standard Normal Homogeneity Test – SNHT (Alexandersson 1986), Two-Phase

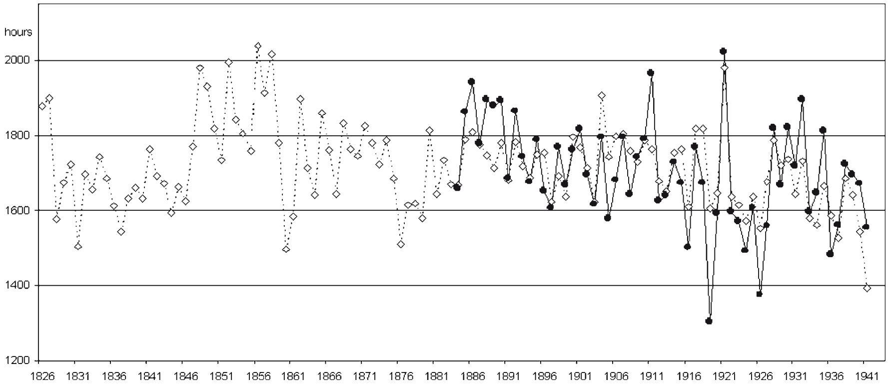

Fig. 15.5 Mean annual sunshine duration in Cracow between 1884 and 1941 and its values calculated by extrapolation for 1826–1941

Regression – TPR (Easterling et al. 1996), as well as procedures presented by Hubert et al. (1989) and by Taylor (2000).

All of the methods used for the segmentation of the series, pointed firstly to 1954 as the year of the change. Four out of five methods indicated 1988 and 1847, as well as 1859, in which however, the change was weaker. Three methods pointed to 1912. Eventually, the Rodionov test was used to carry out the segmentation of the sunshine duration series (S, Fig. 15.6).

The course of sunshine duration throughout the entire 180-year-long period exhibits a very clear, steep decrease in sunshine duration between 1953 and 1954, and then its subsequent, further diminishing until 1987 (T, Fig. 15.6). The downward trend of the 1954–1987 period is statistically significant at the level of 0.03. The decrease in sunshine duration was especially visible between 1953 and 1980. After 1987 there was an increase in the average level around which the values of sunshine duration for 1988–2005 oscillated. However, they do not reach the level which was observable before 1954. They do not even reach the values which could be expected due to the extension of the line of the downward trend from the years 1826–1953! (T, Fig. 15.6)

Taking the entire 1826–1953 period into consideration, it is possible to see numerous fluctuations in the course of the annual sums of sunshine duration. However, throughout the entire period they oscillate around an almost identical level. A small downward trend can be observed; however, it is not statistically significant. Analysing the 1826–1953 period in detail, it is possible to divide it into certain sub-periods. The years 1847–1858 are especially noteworthy, with their increased sunshine duration, which is especially clear when compared with previous years. It is also possible to see that in the 1859–1911 sub-period the oscillations in sunshine duration were weaker and occurred around an average level that was slightly higher than in the 1912–1953 period.

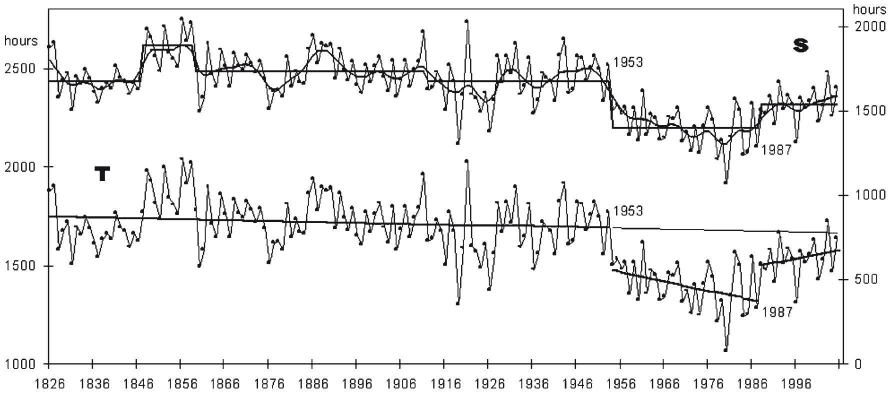

Fig. 15.6 Mean annual sunshine duration in Cracow between 1826 and 2005, smoothed by a nine-element Gaussian filter, and its segmentation (S) according to the Rodionov test, together with trends (T)

The above described method of describing the course of sunshine duration within the last decades is based on objectively determined dates of the change points and on the assumption that these points separate periods of relative stabilization. The multi-annual course of sunshine duration can also be presented in a different way; by describing the trends (Fig. 15.6) which are characteristic of individual sub-periods: a slight decrease between 1826 and 1953, a rapid drop between 1953 and 1954, a very clear negative trend in the 1954–1987 period (especially strong between 1955 and 1980) and a leap to a higher level between 1987 and 1988. The period after 1988 is too short for us to determine whether it is possible to observe oscillations around a certain stable level or rather a permanent increasing trend. The most visible change in the course of sunshine duration, which occurred in 1954, is to a large degree related to the increase in the amount of air pollution caused by the opening of a steelworks in Cracow and the increase in dust and gas emissions from other industrial and municipal facilities/plants (Morawska 1963; Lewińska 2000). The emission of pollutants only dropped in the 1980s as a result of a decrease in industrial production. It needs to be emphasized that the decrease in sunshine duration between 1955 and 1980 occurred in spite of the decrease in cloudiness and the number of overcast days and in spite of the increase in the number of clear days. The decrease in the intensity of direct radiation, caused by the decrease in atmospheric transparency was identified by means of actinometrical measurements (Morawska-Horawska and Olecki 1996). Between 1968 and 1985, direct radiation in Cracow, in comparison to the area outside the city, was on average 17% lower in individual years. In winter, that is during the heating season, it was lower by 30–40%. The sunshine duration in Cracow is clearly correlated ($r = -0.57$) with the total solar irradiance (ftp://atmos.sparc.sunysb.edu/pub/sparc/clim_force/solar/arrcc_mod_s.txt), stronger than with the number of sunspots, the cyclonicity index ($r = -0.54$) and cloud cover ($r = -0.47$). Because the degree of cloud cover is also correlated with the cyclonicity index ($r = +0.38$), the primary natural causes of the variability of sunshine duration are in the first place changes in solar activity and in the macro-scale circulation (Fig. 15.7). Anti-cyclonic meteorological situations are favourable conditions for sunshine, especially the ones with advection from the following directions: W ($r = +0.49$), SE ($r = +0.29$), SW ($r = +0.28$), NW ($r = +0.26$), as well as an anti-cyclonic wedge ($r = +0.23$). A north cyclonic (Nc) situation is especially unfavourable ($r = -0.39$).

Together, the changes in irradiance and the cyclonicity index explain 44% of the variability of sunshine duration within the entire analysed period. In turn, in the years after 1969, in which anthropogenic factors are very strong and for which data about dust content in Cracow's air are available (Voivodship Sanitary and Epidemiological Station in Cracow) of cloudiness and dust content. The cyclonicity index is positively correlated with irradiance ($r = +0.37$), and cloudiness is also positively correlated with the index ($r = +0.38$). In the periods of increased solar activity, the frequency of cyclonic situations and the amount of cloudiness increase, while sunshine duration decreases. This is probably due to the intensification of Atlantic cyclonic pressure patterns and their increased activity or the change in the course of their itinerary from the Ocean to Europe. The correlation of sunshine

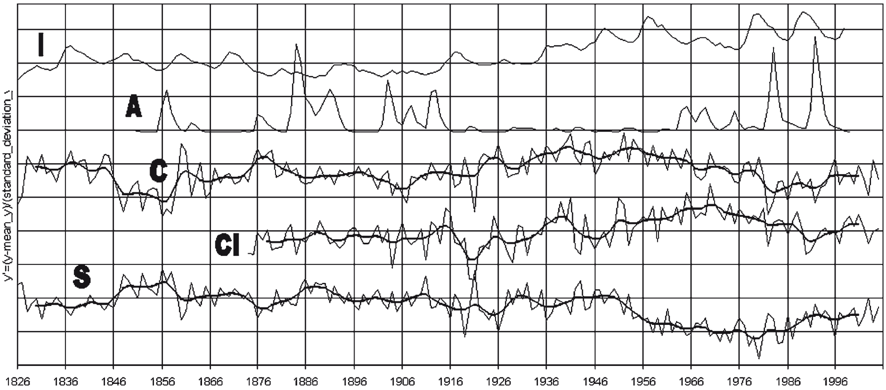

Fig. 15.7 Standardized courses of sunshine duration (S) and cloudiness (C) in Cracow between 1826–2005, as well as of the cyclonicity index (CI), stratospheric aerosol optical thickness (A) and total solar irradiance (I). The course of S, CI, C – smoothed by a nine-element Gaussian filter. In order to make it possible to compare data expressed in various units, they have undergone a standardization procedure. The values of the variables have been converted to standardized *y*' values; *y*' = (*y*-mean_*y*)/(standard_deviation_*y*)

duration with irradiance ($r = -0.57$) and with the number of sunspots ($r = -0.22$) is negative. In the periods of increased solar activity, sunshine duration decreases (Fig. 15.7). This is a result of various complex and interrelated radiation, photochemical and dynamic processes occurring in the troposphere, stratosphere as well as on the surface of the Earth.

Even slight changes in the solar constant can cause various indirect effects, especially because one third of the variability of the inflow of total solar irradiance is caused by UV radiation fluctuations. The increase in the intensity of solar radiation in the periods of high solar activity causes the creation of larger amounts of ozone. The enriched ozone layer absorbs UV radiation with greater intensity, at the same time reducing its inflow to the surface of the Earth and the sunshine duration measured at the surface. The instability of UV radiation inflow, which is caused both directly by the changes in solar activity and indirectly by the changes in the amount of ozone in the atmosphere, exerts considerable influence on the cloudiness and sunshine duration in Cracow. Changes in cloudiness ($r = +0.40$) and sunshine duration ($r = -0.55$) are obviously strong and significantly correlated with the content of ozone in the atmosphere over Poland, measured in the observatory in Belsk (Central Geophysical Observatory at Belsk).

Moreover, sunshine duration is also influenced by the most explosive volcanic eruptions which discharge dust and gases to the stratosphere. For instance, in 1912, following the eruption of Mount Katmai in June, only low values of sunshine duration were registered in Cracow in September (Morawska 1963). The correlation of Cracow's sunshine duration with the optical thickness of the stratospheric volcanic aerosols (on the 50th parallel, at the altitude of 15–20 km, http://data.giss.nasa.gov/modelforce/strataer/) is almost zero. However, this does not have to indicate a lack of influence of volcanoes on sunshine duration in Cracow, but can rather result from the fact that various opposing direct and indirect effects of volcanic activity neutralize each other. It is well known that volcanic dusts and aerosols absorb and scatter direct solar radiation and decrease sunshine duration. Increased scattering favours the photodissociation of ozone. Chlorine released during the eruption decomposes ozone particles. Due to the loss of ozone, more UV radiation reaches the surface of the Earth and sunshine duration increases. The amount of ozone over Poland is significantly correlated with the optical thickness of volcanic aerosol ($r = -0.43$).

Coefficients of correlation with the AO Thompson index (http://jisao.washington.edu/ao/aojfm18992002.ascii) are a proof of the influence of macro-scale circulation on sunshine duration and especially on the cloudiness in Cracow. They equal $r = +0.29$ and $r = -0.42$ for sunshine duration and cloudiness, respectively, calculated for winter months (JFM) and $r = +0.17$ and $r = -0.36$ for the whole year. The coefficient of correlation of these elements with Hurrel's NAO index (http://www.cgd.ucar.edu/cas/jhurrell/indices.data.html#naostatann) equal $r = +0.14$ and $r = -0.33$ for sunshine duration and cloudiness, respectively, calculated for winter months (JFM) and $r = +0.18$ and $r = -0.28$ for the whole year.

Cloudiness and sunshine duration in Cracow do not appear to be correlated with the activity of the solar corona, which emits solar wind, and they are weakly and insignificantly correlated with cosmic radiation (ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/COSMIC_RAYS/kiel.tab), which supplies condensation nuclei by ionizing air. Sunshine duration is significantly and weakly ($r = -0.27$) correlated with geomagnetic activity (aa indices: http://www.wdcb.ru/stp/data/geomagni.ind/aa/aa/AA_YEAR).

15.5 Results and Conclusions

1. The analysis of the data concerning the number of clear and overcast days form the 1826–1852 period made it possible to calculate the cloudiness in that precise time frame, and on that basis, to extrapolate the values of sunshine duration, which was not recorded at that time. Thanks to that, both of these vital meteorological elements obtained a 180 year-long data series.
2. The segmentation of the course of cloudiness divides the series into seven main periods (…–1846, 1847–1858, 1859–1921, 1922–1966, 1967–1981, 1982–1994, 1995–…), with different degrees of cloudiness and tendencies. The overall trend for the entire period is a growing one, clear days exhibit a downward trend and overcast days an increasing one.
3. Cloudiness is most strongly correlated with the cyclonicity index ($r = +0.38$), and somewhat more weakly with the optical thickness of volcanic aerosol ($r = -0.34$). The changeability of atmospheric circulation and volcanic aerosol account for 34% of the variability of cloudiness.
4. The segmentation of sunshine duration showed six periods (…–1846, 1847–1858, 1859–1911, 1912–1953, 1954–1987, 1988–…). The overall sunshine

duration trend obtained from the entire period is a downward one, mainly due to the low values in the second half of the twentieth century.

5. The segmentation of the course of cloudiness and sunshine duration is not fully asynchronous. The asynchronicity occurring until the mid-nineteenth century is caused by the method used to obtain values of sunshine duration on the basis of cloudiness. Starting with the 1920s a synchronization of the course of cloudiness and sunshine duration begins, caused by anthropogenic factors. This is another proof of the lack of an exclusive influence of cloudiness on sunshine duration. A classical example of such a situation is the last 50 years, in which a significant influence of air pollution in Cracow on the values of sunshine duration has become observable.
6. Sunshine duration is most strongly correlated with irradiance ($r = -0.57$), and to a lesser degree with the cyclonicity index ($r = -0.55$) and cloudiness ($r = -0.47$). The first two factors account for 44% of the variability of sunshine duration in the entire analysed period.
7. The positive correlation of irradiance with the cyclonicity index ($r = +0.37$) suggests that it can contribute to a growth of cyclonic activity which causes an increase in the cloudiness observed in Cracow.

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Chapter 16
Changes in Sea Surface Temperature of the South Baltic Sea (1854–2005)

Andrzej A. Marsz and Anna Styszyńska

16.1 Stating the Problem

There have been hundreds of works written on the changes in the air temperature over Poland and neighboring countries. These changes, at least, during instrumental observations are well known. The literature dealing with the changes in sea surface temperature of the Baltic Sea is relatively poor. Soskin (1963) analyses the changes in sea surface temperature (SST) in the period 1900–1950 and notes in the 20s–30s of the twentieth century the increase in temperature in relation to the preceding period. Betin and Preobraženskij (1962) while dealing with the severe character of winters in Europe refer to a series of information about the presence of ice cover in the Baltic Sea and its duration (tenth–eighteenth centuries). This, in an indirect way, gives some information regarding many centuries' changes in winter water temperature. These data however, are not continuous as they base on historic documents (chronicles, diaries, and harbour, merchant and customs documents) and enable to derive only very general conclusions, regarding changes in the temperature of waters of the Baltic Sea, limited solely to winter periods.

Numerous remarks about changes in SST over short periods and in small sea areas can be found in works dealing with biological oceanography and ecology of the Baltic Sea; they concern different periods after the 1960s. Even, the impressive in size, hydro meteorological monograph of the Baltic Sea (Terziev et al. 1992), except for a map illustrating distribution of SST, does not deal with many-year changes in SST. Some Polish monographs on coastal climate or on Polish coastal zone mention changes in SST (e.g. Miętus et al. 2004) in the off shore area. Systematic measures of water temperature at measuring points of IMGW,[1] which in

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most cases are located in port waters and the very reading is done close to the shore or in a distance of a few meters from the shore, provide the data.

In 2003 the authors (Marsz and Styszyńska 2003) making use of the data from COADS[2] presented changes in SST in the sea area covering the Gdańsk Bay and the Gdańsk Deep in the years 1871–1992. They stated that there is statistically significant positive trend in SST in this sea area (+0.009°C year^{-1}, $p < 0.005$) and strong correlation between changes in SST and the character of winter atmospheric circulation observed in the examined period. Zblewski (2006) carried out a detailed analysis of changes in SST in the whole Baltic Sea in the period 1982–2002, in which very strong increase in air temperature was observed over the Baltic Sea and in regions adjacent to the Baltic Sea. The aim of this work was to find out how the strong warming of the atmosphere influences SST. The author noted that strong positive trends, in most cases are statistically significant and what is more, indicate clear seasonal variability in space almost in the entire surface of the Baltic Sea. The annual trends in SST defined by Zblewski turned out to be much stronger than those noted by the authors in the many- year period 1971–1992. Siegel et al. (2006) analyzed changes in SST of the Baltic Sea from Arkona Deep to the end of the Bothnia Bay over the period 1990–2004. The conclusions they have arrived at, are, to a great extent, similar to the results obtained by Zblewski (2006).

The most recent works on changes in SST in the Baltic Sea were published in 2008. Assessment of Climate Change for the Baltic Sea Basin (2008; later referred as ACCBSB) presents the results of modeling of changes in heat amount in the Baltic Sea and its regions which were observed in 1958–2005 and 1970–2005. As it can be seen in the results presented by ACCBSB (2008; Fig. 2.49) a visible increase in the heat amount in the Baltic took place in 1958–2005. Hansson and Omstedt (2008) basing on the data from the twentieth century reconstructed the SST course and Maximum Ice Extent (MIE) for the last 500 years. The above mentioned results indicate that in the twentieth century SST was higher than in the last 500-year period and that the highest decadal values of SST were observed in the 1930s and in the 1730s. The changes in SST and MIE in the Baltic are within the limits of natural climate variability.

Changes in SST in open waters of the Baltic Sea,[3] because of the presence of a specific for this sea density stratification, occur only under the influence of local elements responsible for climate formation. The heat resources transported into the Baltic Sea with waters flowing from the North Sea have no contact with the sea surface and that is why the processes of heat advection with the transported waters are completely neglected for changes in SST. In the same way, changes in the sea surface caused by human activity are neglected. Such activities performed on land by changing the way the land is used, changes in its moisture, forming city islands of warmth may have influence on the temperature of ground and on the air temperature.

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[2] COADS – Comprehensive Ocean-Atmosphere Data Set.

[3] Open, that is, situated in a certain distance from the shore, outside the area being under the influence of processes active in the coastal zone, where the local, especially in the sea areas close to the port and in the regions in the vicinity of river estuaries anthropogenic and natural deformations in the course of SST can be observed. This work completely neglects problems of changes in SST in coastal and sheltered regions, dealing only with changes present in open waters.

Changes in SST are influenced by annual heat balance. On the side of heat gain in the sea surface the only element that matters is the gain of solar radiation and atmospheric re-radiation. On the side of loss there is radiation from the sea surface and heat flux from the sea surface to the atmosphere. The latter is made up of sensible heat flux (turbulent exchange) and of latent heat flux (latent heat of evaporation). The values both of the streams of heat gain, as well as, heat losses are influenced by changes in weather phenomena both periodically and aperiodically. Because of great heat volume of water and large masses of water and at the same time great thermal inertion of the layer of the Baltic waters above halocline, SST 'records' in its course rhythm of changes in weather conditions observed over longer periods and at the same time with different scale of delays, influences the course of these conditions. Taking into consideration the above, it can be stated that changes in SST of the Baltic represent resultant of the changes in regional climatic conditions over the examined period and are free of anthropogenic influence.[4]

The aim of this work is to present the course of changes in annual SST in the southern part of the Baltic Sea, observed over the period of the past 152 years, that is in the period from 1854 to 2005. The analysis of the course of changes in SST of the Baltic Sea carried out for a longer period can solve a lot of problems and the ones which seem to be most important, that is defining the scale of changes in SST, defining the cooling and warming periods observed in the sea surface of the Baltic Sea, defining the concordance of changes in the course of SST and the air temperature on land in the vicinity of the examined sea area and explaining what climatic signal is indicated by changes in SST.

16.2 Data

The basic data were made up of chronological series of monthly values of SST from the data set ER SST v.2.[5] This set contains global values of monthly SST which are average values for areas $2°\phi \times 2°\lambda$, with evenly nominated central points of these areas (grid organization). The set ERSST v.2 for the period 1854–1992 is transformed from COADS SST data, for the later period – high resolution satellite data, calibrated by measurements in situ. How this set is constructed and what techniques are used to get rid of interference, how the mean values and how the climatologic homogeneity are obtained, can be found in works by Smith and Reynolds (2004). The data from this set are less accurate in the preliminary period and from both world wars because of not equal number of data used for estimating mean values.

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[4] The only anthropogenic factor which has influence on changes in SST of the Baltic Sea is the change in the concentration of CO_2 in the atmosphere. This results in changes in elements of the radiation balance. The changes in CO_2 concentration are global so changes of the elements of the radiation balance over the Baltic should be the same as over the area adjacent to this sea.

[5] The full name of the data set NOAA NCDC ERSST version2 is improved extended reconstructed global sea surface temperature data based on COADS data.

The analysis of changes in SST in the Baltic Sea made use of a grid with coordinates 56°N, 18°E whose time series describes the mean SST defined within the limits 55–57°N, 17–19°E. The surface area of the sea area calculated as a flat area is 27,618 km^2. Figure 16.1 presents the location of this surface. The described sea area almost in 100% covers water surface and characterizes open waters of the southern part of the Baltic Sea.

The standard estimation error for the mean monthly SST in the examined sea area in most cases is within the range from ±0.01 to ±0.04°C, maximum errors reach ±0.61°C (data set NOAA NCDC ERSST version2 err). Figure 16.2 presents the distribution of estimation error for annual SST calculated as mean value of monthly errors in a given year. The highest values of standard estimation errors for monthly temperature, except for single cases, are noted in April.

The values of annual temperatures used for this analysis were calculated from the values of mean monthly temperatures as mean arithmetic values. Changes in annual SST in this grid point are very strongly correlated (r = 0.97–0.99)[6] with

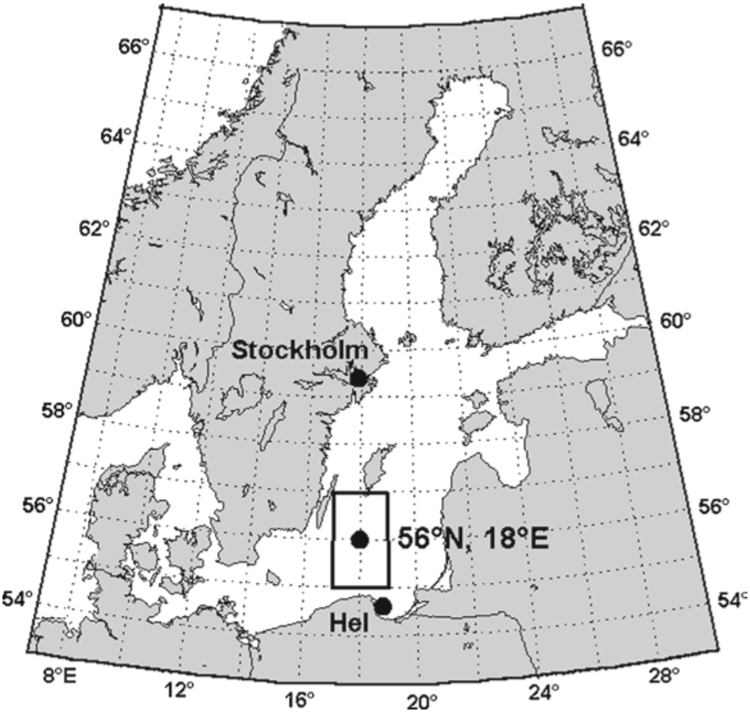

Fig. 16.1 The location of areas whose mean annual temperatures were analysed in this work. Grid 56°N, 18°E is marked with *black point*

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[6] r – Pearson's linear correlation coefficient.

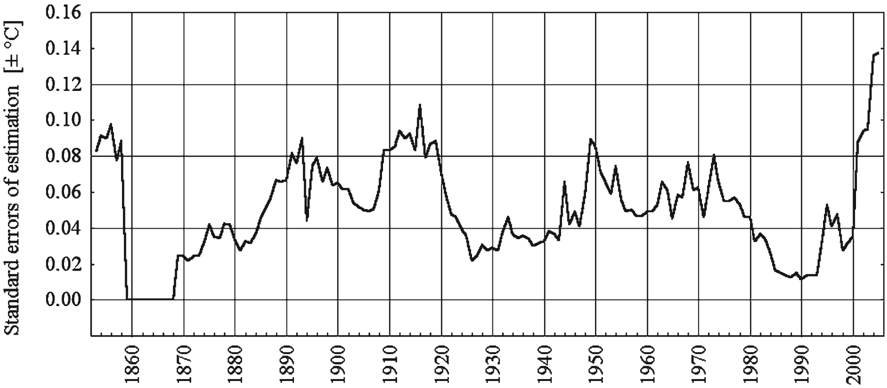

Fig. 16.2 Distribution in time of standard errors of estimation of mean annual SST in grid 56°N, 18°E

the changes in SST in the adjacent to the examined grid points and this makes it possible to state that they are representative for a far greater sea area than the examined surface.

The data showing the air temperature from Stockholm station up to 1889 are derived from the data set GHCN v.2 (Peterson and Vose 1997) and for the year 1890 from the data set Nordklim (Tuomenvirta et al. 2001) The data characterizing the temperature at Hel till the year 1995 are taken from the work by Miętus (1998) and in the following years they were supplemented with official data from IMGW. The quality of these data has been checked by the authors of these series and they are homogeneous. The values of NAO indexes used in this work are taken from the data set accessible in official web sites WWW CRU and J. Hurrell.

This work made use of standard methods in statistical analysis; when analyzing signals a standard analytical methodology of electrical courses was employed (Osiowski and Szabatin 1995). The principle of this method is that the following elements are analyzed one by one, that is the course of deviation from the mean value, low and up band signal envelopes whose aim is to define the components of modulation, spectral analysis of a signal whose aim is to define spectrum of modulating harmonic and harmonic being beating-up of modulating signals[7] and identification of impulse interference.

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[7] In case when two (or more) signals are received in the summing up system, processes of beating up (mixing) of signals forming new harmonics are observed. The basic harmonics of beating up are the sum and difference between primary frequencies. In case when certain phase shifts between primary signals are present, the amplitude of beating up harmonics can be higher than the amplitude of modulating signals. The summing up system in this case is the surface layer of the sea.

16.3 The Course of Mean Annual Value of SST of the Baltic Sea

In the examined 152-year period the mean annual SST is 8.83°C (σn = 0.61; σn – standard deviation). The range of changes in SST is found within the limits from 10.17 (year 1990) to 6.76°C (year 1941) which result in an amplitude equal 3.41°. The course of SST indicates to a great interannual changeability with clearly marked many-year changeability. In order to define the periods of changes in SST it is more convenient to use the standardised[8] course of SST (Fig. 16.3). It can be easily noticed that the characteristic feature of the course of SST in the examined period is asymmetry noted in the frequency of the decreases in SST below −1 and −2 σn in relation to how frequently the limits +1 and +2 σn are exceeded.

Over the period from 1854 to 1933 the frequency in SST drops below −1 σn and is significant (20 times, twice, in this number, the limit was exceeded below −2 σn), whereas the frequency of exceeding the limit +1 σn by SST is scarce (twice and in this number 0 cases when the limit +2 σn was exceeded). From the year 1934 the situation changes, that is more frequent are the cases when SST exceeds the limit +1 σn (18 such cases including the one above +2 σn) when compared to situations when the temperature drops below −1 σn (nine cases including the one below −3 σn). At the turn of 1933/1934 a clear change in the character of the changeability (rhythm) of SST can be observed. In the first period a year-to-year changeability in SST characterised by not too large amplitude can be noted with the 2–3 year periodicity and majority of negative deviations. In the second period (1934–2005) the 5–10 year periodicity is noted and is characterised by large or very large amplitude with majority of positive deviations, thus the year-to-year changeability in SST

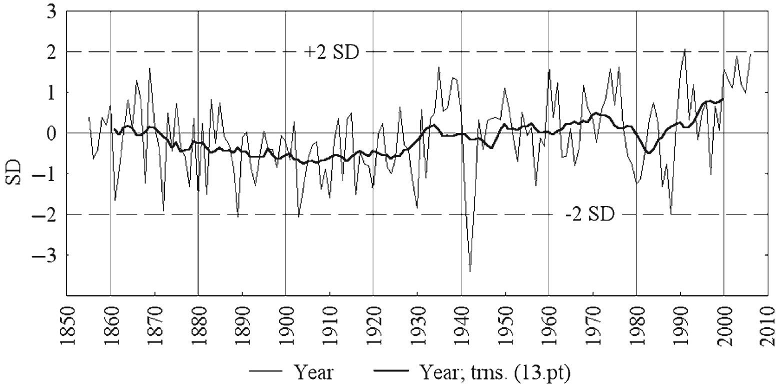

Fig. 16.3 The course of standardized annual SST (in relation to 100-year period 1901–2000) in grid 56°N, 18°E. Marked levels +2 and −2 σn (SD). *Bold line* – course adjusted by 13-point moving average

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[8] Standardization was carried out with reference to mean 100-year value from 1901–2000.

recedes into the background. The negative deviations of SST become more significant than in the former period and take evidently more time.

The course of cumulated deviations from the mean annual many-year value makes it possible to distinguish the following periods in the course of annual SST:

1. The years 1854–1875 – the mean annual value of SST is slightly higher that the mean value of the entire period (~8.88°C), stable in time course of SST (trend around 0; $-9.974 \cdot 10^{-5}$°C/year)
2. The years 1876–1932 – the mean annual value of SST is slightly lower than the mean value of the entire period (~8.56°C), the cooling period (trend −0.002°C/year)
3. The years 1933–1939 – sharp increase in SST, the mean value significantly higher than the mean value of the whole period[9] (9.45°C), trend +0.029°C/year
4. The years 1940–1947 – dramatic cooling, the mean SST value lower than the mean of the entire period (8.41°C), trend −0.013°C/year
5. Years 1948–2005 – gradual increase in SST interrupted by periods of strong cooling, the mean SST, the mean value higher than the mean value of the whole period (~9.10°C), trend +0.009°C/year

If we take the strong cooling period in the 1940s as the minimal value of the course, then the observed in 1941 the absolute minimum, will divide the examined period into two parts, that is the one during which the decrease in SST (−0.002°C/year) was noted and the mean SST is about 8.7°C and the other period in which the increase in SST (+0.012°C/year) is observed and the mean SST is about 9.0°C.

Very strong fluctuations of SST which were observed between the beginning of the 1930s and the end 1940s raise a question about the true limit between both great periods of changes in temperature of the Baltic surface. The analysis of the course of SST in which the short term fluctuations are neglected or/and their amplitude is decreased (adjusted by 13 point moving average), will make it possible to set the limit between these two periods at the turn of 20s and 30s of the twentieth century (see Fig. 16.4a). The warming period in the 1930s, despite being followed by a period of strong cooling of the sea surface, 'fits' the pattern of following warming which is characterised by the fact that the following increases in SST are higher than decreases in SST, even if they are significant. Tentatively it can be assumed that the limits between these periods can fall in the year 1929 which divides the whole period into two equal parts. In such a case in the period 1854–1929 a decrease in annual SST (−0.0065°C/year, $p < 0.013$), can be noted, whereas in the period 1929–2005 an increase, a little higher than the previously observed decrease, (+0.0072°C/year, $p < 0.030$) is noted.

The annual temperature resulting from averaging monthly values of SST depends on changes in these values. In the course of SST observed in the sub-polar latitudes, the annual temperatures are influenced by the heat resources left in the waters after winter cooling of the sea surface as well as by the increase in heat

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[9] Rapid increase in SST in this period causes that the entire decade 1931–1940 is clearly warmer than the average temperature; see Hansson and Omstedt (2008).

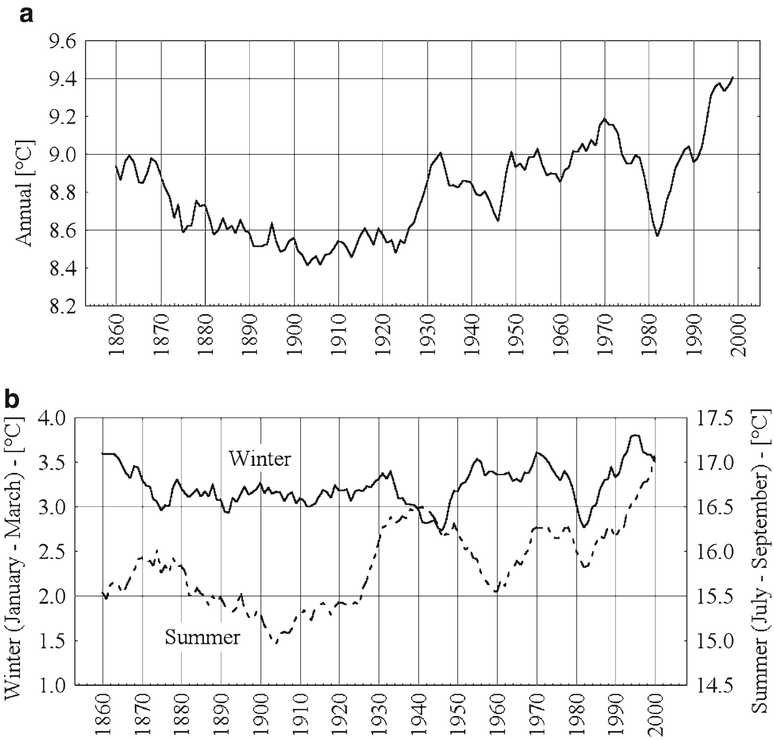

Fig. 16.4 The course of SST in grid 56°N, 18°E adjusted by 13-point moving average. (**a**) the course of annual mean SST, (**b**) the courses of mean SST from the winter cooling (January–March) and summer warming (July–September) of the sea surface. Note – please pay attention to different scaling of SST in each part of the drawing

resources in the sea surface at the end of the summer warming period. In the analysed sea area the maximum SST can be observed in August and July or even in September. The minimum value is noted in March, February or April and exceptionally, in some years in January.

The correlation between the annual SST with the mean values noted in winter cooling periods (mean January–March) and the maximum summer warming (July–September) is very strong in the examined area. It is described with the following formula:

$$\mathrm{SST_A} = 1.103(\pm 0.339) + 0.395(\pm 0.029) \bullet \mathrm{SST_W} + 0.406(\pm 0.023) \bullet \mathrm{SST_S}, \quad (1)$$

where:

$\mathrm{SST_A}$ – mean annual SST in the sea area within the limits of 55–57°N, 17–19°E; °C,

$\mathrm{SST_W}$ – mean SST in the sea area as above from the period January–March (winter),

$\mathrm{SST_S}$ – mean SST in the sea area as above from the period July–September (summer).

This correlation explains 84% of annual variances of SST ($R = 0.91$, $F(2,149) = 385$, $p < 0.0000$).[10] In this formula the summer SST variability explains 63% and winter SST variability 21% of mean annual SST variances.

In order to illustrate to what extent the process of winter cooling and summer warming periods affect the annual changeability in SST in the examined sea area, the courses of changes in SST_W and SST_S adjusted by 13-point moving average are presented (Fig. 16.4b). This problem is not to be discussed here. At this stage what is pointed out are the different courses of both components and the increasing amplitude of winter and summer SST as a function of time. It should also be underlined that summer SST is correlated with winter SST. After the period of winter cooling some smaller or bigger residual heat resources in water are left and they have significant influence on temperature, the water reaches at the end of the summer warming of the sea surface. In the entire, 152-year, series changes in winter mean value of SST (January–March) explain about 10% variances of mean summer SST (July–September) ($R \sim 0.3$, $F(1,151) = 16.4$, $p < 0.0001$). This means that after winter season, when there was lower heat absorption from the sea surface (which is represented by higher SST in March–April), summer SST is higher; the course of winter SST affects the course of summer SST. The changeability in mean winter SST explains about 49% of mean annual SST variances ($R = 0.7$, $F(1,150) = 141$, $p < 0.000001$). If we take into consideration additional influence of winter SST on summer SST then, it turns out that changes in temperature during the winter cooling of the sea surface have important influence on the annual SST. This winter SST depends on weather phenomena present in a given winter.

16.4 Correlation Between Sea Surface Temperatures with NAO

Annual SST of the Baltic indicates strong correlation with the processes of heat absorption in winter season. Because winter atmospheric circulation affects the temperature of air transported over the sea, its humidity and the speed of the wind it has influence on the amount of heat absorbed from the sea surface. That is why the annual SST of the Baltic is relatively strongly correlated with different circulation indexes which characterize the course of winter atmospheric circulation (Koslowski and Glaser 1999; Chen 2000; Marsz and Styszyńska 2000, 2003; Omstedt and Chen 2001; ACCBSB 2008; Hansson and Omstedt 2008).

Because of the length of the analysed series, the only possible index of winter atmospheric circulation to be used and to cover the whole period is NAO CRU index (Gibraltar – SW Iceland; Jones et al. 1997), whose series starts in 1823. Winter Hurrell index (Lisbon – SW Iceland; Hurrell 1995) commences 10 years later than the beginning of the analysed series of SST – namely in 1864.

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[10] R – multiple regression coefficient of correlation, F – value of Fisher-Snedecor test (in brackets degree of freedom), p – statistical significance level (probability of random result).

In the whole series (1854–2005) averaged for the period January–March NAO CRU index is correlated with annual SST of the Baltic Sea and this correlation is highly significant ($p < 0.00001$), however the strength of this correlation is moderate ($r = 0.4156$). Calculated for the same period as the Hurrell index was, that is (December–March), the NAO CRU is correlated with the annual SST with a similar strength within the whole examined period ($r = 0.4049$, $p < 0.00001$). Similar value ($r = 0.4277$, $p < 0.00001$) is obtained for a series 1864–2005 (142 years) for a correlation of annual SST with Hurrell NAO index which is calculated as a mean value from the period December–March.

The analysis carried out for the following 30-year periods of correlations between annual SST and winter NAO CRU index calculated for the period July–March and NAO Hurrell index indicated that they are not stationary. The results of the analysis are presented in Table 16.1.

It has been noted that correlations with NAO CRU index were gradually strengthened in the following 30-year periods, changing from relatively weak and insignificant ones to very strong and statistically very significant. Similar correlations between annual SST and NAO Hurrell index indicate similar course in the following 30-year periods but also here the strongest and most significant correlations are observed in the 30-year period 1971–2000. These differences in the strength of the correlation between SST and both NAO indexes result from different places of the data (Gibraltar, Lisbon) used to create each of these indexes; generally speaking, for the Baltic Sea it is the Hurrell index which provides more precise information about the advection from the sector W-SW (Marsz and Styszyńska 2000).

Weak and statistically not significant correlations of annual SST with NAO CRU index register the situation when the Iceland Low activity was relatively little and the Azores High was located westward causing that the frequency of advection of warm air masses from the Atlantic towards the Baltic Sea in winter was restricted. The research carried out earlier (Marsz and Styszyńska 2000) indicate that in the period from the latter part of the 1860s till the last years of the nineteenth century the Iceland Low was relatively weak. In that period a far greater role had depressions over the Scandinavian Peninsula, which were closely connected with strong advections of cold air from NW-NNW, than that of NAO in the process of

Table 16.1 Values of coefficients of correlation between annual SST and winter NAO CRU index and NAO Hurrell index (r) and the level of their statistical significance (p) for the following 30-year periods. Statistically significant values of correlation are in bold

	NAO CRU Index		NAO Hurrell Index		
Period	r	p	r	p	N
1854–1880	0.3027	0.125	–	–	27
1881–1910	0.3173	0.088	**0.4152**	0.022	30
1911–1940	0.3315	0.074	0.3589	0.051	30
1941–1970	**0.5618**	0.001	**0.3658**	0.047	30
1971–2000	**0.7233**	0.00001	**0.6844**	0.00001	30

winter cooling of the Baltic. Only in the years 1902–1903 a rapid drop in atmospheric pressure was observed in the region of Iceland during winter season.[11] The Icelandic Low activated rapidly. However, the Azores High started moving east and north east already from 1895. In winter more often than previously warm air was transported from the W sector to SW sector and not as it used to happen before from NW-NNW; this was connected with positive phases of NAO. This case was noted by statistically significant correlation of SST with Hurrell index in the period 1881–1910 but it was not noted by correlation with NAO CRU.[12] At the turn of the 20s and 30s of the twentieth century the activity of the Icelandic Low decreased again; the course of winter cooling of the Baltic was influenced by different than NAO circulation processes. At the same time the structure of synoptic processes changed into favourable for warming the ocean surface in summer (strong continentalization). As a result correlations between annual SST and both NAO indexes, although not changing the sign, they stop being statistically significant.

In the following two 30-year periods (1941–1970 and 1971–2000) the activity of NAO increased gradually and this led to the increase in the strength and level of correlation significance between annual SST and NAO. Especially during the last 30-year period (1971–2000) the processes of winter cooling of the surface of the Baltic Sea were influenced by advection of sea air from SW and W controlled the NAO. During this time NAO indexes indicated very high ‘concentration in time’ of high positive values (years 1973, 1981, 1983, 1989–1990, 1992–1995, 1999–2000) and also positive indexes, with values not observed during the whole preceding process of instrumental observations, were noted (years 1989 (5.08); 1990 and 1995 (3.96-twice). In these years ‘winters without winters’ occurred over the south and central Baltic during which the heat absorption from the sea surface was much lower, leaving far greater resources of residual heat in waters. As a result a very high increase in annual SST took place.

The last years (2000–2005) and especially last year (2006) for which there are still some data lacking seem to be different from a pattern of changes in SST typical of the last several dozen of years. The winter cooling intensity increased, when compared to preceding years characterized by very high NAO indexes during winter. However, they still remain weaker than during the last several dozen of years. On the other hand, the intensity of summer warming processes increased considerably when compared to last several dozen of years and this can result from the increased frequency of occurrence of heights accompanied by advection of air masses from SW. High temperature and relatively high humidity of air flowing over

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[11] In the years 1902 to 1903 there was a decrease in winter (July–March) pressure over SW Iceland from ~1004 hPa to ~991 hPa. After the year 1903 the pressure over the SE Iceland started gradually increasing but the level from the years 1870–1900 then was observed as late as at the turn of 20-ties and 30-ties of the twentieth century.

[12] In situation when the Azorean High moves NE, the pressure in Gibraltar can be relatively low (Gibraltar S of the edge of the high) and the value of the NAO CRU index is lower, whereas barometric gradient between Icelandic Low and Azorean High becomes strong (the decreased distance between both atmospheric activity centres) and the sea air is transported farther E-NE than in situation with the centre of the Azorean High locates over the Azores.

the Baltic are accompanied by clear decrease in wind speed and lower cloudiness (effect of stable balance). All this leads to significant reduction in heat loss for evaporation and turbulent exchange resulting in clear increase in SST at the end of the summer warming period and this, in turn, results in high SST in autumn and at the beginning of winter.

16.5 Correlations of SST with the Frequency of Occurrence of Synoptic Situations of a Certain Type

It can be assumed that the annual temperature of the Baltic Sea surface should indicate correlations with synoptic situations present over this sea area. From the point of view of the mechanisms responsible for the changes in SST, it seems interesting to define what synoptic situation was and when it had the greatest influence on the value of SST. In order to provide answers to these questions an analysis of correlations between the frequency of atmospheric circulation of Osuchowska-Klein types (1978, 1991) and annual SST in the examined grid was carried out (Osuchowska-Klein 1978, 1991). This analysis, because of the fact that the catalogue with low circulation types by Osuchowska-Klein comprises data from the period from 1901 to 1990, does not cover the whole examined period of changes in SST (1854–2005) but provides an extensive (90 years) although covering only 90 years, reliable sample of the occurring correlations.

This analysis was carried out in this way that it was assumed that the annual SST (SST_A) in a given examined period is the function of frequency of Osuchowska-Klein, individual types of low circulation from January to December. The character of this function is described by linear function (multiple regression). The consecutive monthly frequencies (from January to December) of all circulation types (A, CB, D, B, F, C2D, D2C, G, E2C, E0, E, E1 and BE) without type X (unmarked) are taken as independent variables and that gives a potential equation with 156 independent variables. Using the method of gradual regression, taking F to use ≥ 10.0 and tolerance ≥ 0.1, the values of constant term and regression coefficients were estimated, limiting the number of independent variables of this equation to the first four starting in the sequence of entering (more than 20 cases for one independent variable). As a result of the above described procedure the following equation is formed:

$$\begin{aligned} SST_A = 8.4389(\pm 0.0094) - 0.0916(\pm 0.0179)E0_{01} + 0.0633(\pm 0.0099) \\ E_{08} + 0.0876(\pm 0.0189)C2D_{02} + 0.0795(\pm 0.0232)D2C_{02}, \end{aligned} \quad (2)$$

and its statistical characteristic is as follows: R = 0.72, adj. $R^2 = 0.50$, F(4.85) = 23.1, BSE = 0.44.

This relation indicates that 50% of variances of annual SST explain the frequency of four types of lower circulation types- number of days with E0 circulation type in January ($E0_{01}$), E type in August (E_{08}), C2D type in February ($C2D_{02}$) and

D2C type in February ($D2C_{02}$). The changeability in frequency: of E0 type in January explains 16.3% of changeability in annual SST, E type in August – 17.1%, C2D type in February – 12.1%, and of D2C type in February – 6.6%.

Equation [2] explains that the processes of winter cooling of the sea surface (three out of four variables originate from the winter season) have the greatest influence on the changeability in annual SST. Such findings are compliant with the earlier results of research into relations between the annual SST and winter and summer SST and into the influence the winter atmospheric circulation has on the value of annual SST. The determining influence of the frequency of circulation E type in August (high pressure over the Scandinavian Peninsula and over the Baltic during the maximum warming of the sea surface) and the frequency E0 type in January (north-east and east anticyclone circulation during the most intensive winter cooling) on the changeability of annual SST is both clear and comprehensible. However, the great role of warm circulation types in February – C2D and D2C which affect the changeability of annual SST is quite astonishing. The occurrence of these circulation types in February restricts the heat absorption from water surface thus, it makes further stronger decrease in SST impossible and in this way it contributes to the increase in the residual heat resources in water after ‘winter’. The increased number of these types of circulation in February eliminates also the possibility of occurrence of other, ‘cooler’ types of circulations.

16.6 Relations of Air Temperature Over Coastal Areas with SST

Changes in SST which cause that over vast areas exchange of heat between the ground and atmosphere takes place, have direct influence on air temperature. What is more, SST by having influence on the type of atmospheric balance and in this way also on cloudiness may be said to have influence on the air temperature in an indirect way. In turn, the air temperature by controlling the heat import from the sea surface affects SST. In this way the courses of both physical values over a given sea area are correlated with one another.

The air temperature over coastal stations quite accurately, though not perfectly, reflects changes in SST. This work is limited to presenting the changes between annual SST and annual temperature at two stations located close to the Baltic coastline, that is at Stockholm and at Hel. The courses of annual air temperature at the stations located on the South and Central Baltic Sea are strongly correlated with each other. Dealing with greater number of stations will not contribute to the analysis.

In the whole, 152-year observational, period the coefficients of correlation between annual SST and annual air temperature at Hel and Stockholm are almost exactly the same (r equals 0.7611 and 0.7562 respectively) and what is obvious they are highly significant. In the same period the annual temperature at Stockholm and Hel indicates visibly stronger correlation ($r = 0.8675$, $p < 0.000001$). It should be pointed out that the forced decrease in the amplitude of changes in SST in the range of minus temperatures causes that the value of coefficient of correlation between both annual values of temperature becomes lower and the correlation between annual air temperature and SST cannot be perfect. It happens because SST cannot drop below the freezing point/temperature of water of given salinity, whereas the winter air temperature can fall considerably below 0°C.

The course of annual air temperature at Stockholm and Hel stations and annual SST adjusted by 13-point moving average is presented by Fig. 16.5. It can be clearly seen that there is considerable decrease in amplitude of SST in relation to the amplitude of air temperature.

Greater discrepancies between the course of air temperature and SST are marked at the initial segment of the examined course – more or less[13] to the 1920s. The air temperature in this period increases and SST drops. Also in the period 1854–1894 more significant differences in the course of annual air temperatures between Stockholm and Hel are noted. It is difficult to find the reasons for such discrepancies at this stage. However, it is worth mentioning that the series of annual air temperature at Stockholm before making the series homogeneous[14] shows clearly fewer discrepancies with the course of annual SST in the period from 1900 to 1950, and in the whole period 1854–2000 in which the data were not verified and made homogeneous, the series is a little more correlated with annual SST ($r = 0.7812$, $p < 0.000001$) than the verified series.

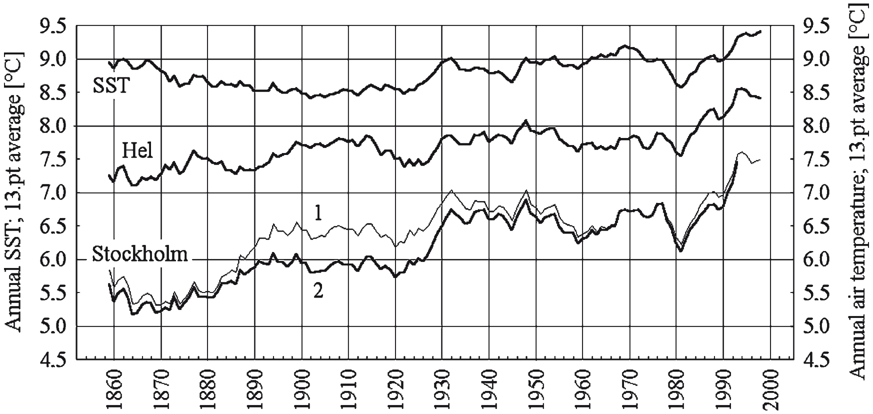

Fig. 16.5 The course of annual SST in grid 56°N, 18°E and annual air temperature at Hel station and Stockholm (1 – homogeneous series, 2 – series not made homogeneous). The courses adjusted by 13-point moving average

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[13] As both courses have been adjusted by 13-point moving average, more precise defining the limit of discrepancies is unnecessary.

[14] It a series from the period 1854–1995, from the year 1996 to 2000 amended with official data from the station in Stockholm.

Table 16.2 Values of coefficients of correlation (r) between annual SST and annual air temperature at Stockholm and Hel stations (Stockholm 1 – a series of data verified and made homogeneous, Stockholm 2 – a series without statistical filtering) and Hel (a series of data verified and made homogeneous) in consecutive 30-year periods. All values of coefficients of correlation in the table are statistically significant with $p<0.005$, larger than 0.6 with $p < 0.000$

Period	n	Stockholm 1	Stockholm 2	Hel
1854–1880	27	0.6665	0.6612	0.5529
1881–1910	30	0.6085	0.7022	0.7287
1911–1940	30	0.8950	0.9044	0.8272
1941–1970	30	0.8098	0.8240	0.7381
1971–2000	30	0.9276	0.9262	0.9137

The analysis of correlations between annual air temperatures at Stockholm and Hel and SST in the examined grid carried out for consecutive 30-year periods (the same for which the analysis of correlations with NAO was made) indicates that these correlations are non stationary in the function of time. The values of correlation coefficients are presented in Table 16.2.

It can be noted that the strength of the correlations of annual air temperature at the Baltic stations is greatest in the 30-year period 1971–2000. As opposed to correlation between SST and NAO in the years 1911–1940 when the strength considerably decreased (see Table 16.1), the relations between the air temperature and SST in the same 30-year period were clearly stronger and the statistically significant decrease in the strength of the correlations was observed in 30-year period 1941–1970. Due to the fact that the period 1971–2000 is characterised by mild winters and the period 1941–1970 by severe winters, it can be assumed that in the periods in which there is an increase in the frequency of mild winters there is also stronger convergence of the course of annual air temperature with the annual SST of the Baltic Sea.

16.7 The Problem of Climatic Signal in Series of Values of Mean Annual SST of the Baltic Sea

In order to explain what signal or climatic signals are carried in annual SST of the Baltic Sea, the series was analyzed in a way that is typical of signals analysis used in tracing courses of electric values (Osiowski and Szabatin 1995). Because it is not clear what the interference and what the signal in the course of annual SST of the Baltic Sea is, it is not acceptable to make any *a priori* assumptions in this respect. That is why it is also unacceptable to employ preliminary filtering of the series of data and the analysis is carried out on standard data without their further transformation.

The spectral analysis detects in the examined series presence of periodicity. Apart from long term periodicity, equal to the whole length of the series (152 years), a half of the length (76 years) and a quarter of the length of the series (35.5

years), which are normal statistical artifacts connected with Fourier analysis, indicates also short term periodicity. They ar e ~12.4-year periodicity, ~7.7-year periodicity, ~5.0- year periodicity and about 2-year periodicity.

The 12.4 periodicity is dominating as far as amplitude is concerned; on a spectral density scale it reaches the value of about 5.4 and is higher than all long term harmonics (see Fig. 16.6). Smaller amplitude can be noted in 7.7 – year and 5.0-year periodicity (4.7 and 4.9 on the scale of spectral density respectively). The smallest amplitude has the approximately 2-year periodicity (2.9 on the scale of spectral density).

12.4-year periodicity whose peak is made up of 13.1-year, 12.4-year and 11.3-year periodicities can be associated with the changing activity of the Sun. It falls into the range 10–13 years characteristic for the variability of Wolf number whose average periodicity in the years 1700–1995 was defined as 11.1 years. A great number of works (e.g. Boryczka 1998; Black et al. 1999; White et al. 1997; Boryczka et al. 2001; Coughlin and Tung 2004) indicate that there are statistically significant correlations between the changeability of the Sun activity and changeability of individual climatic elements and the intensity of some oceanic and troposphere processes. In spite of the fact that the changeability of solar constant connected with the changeability of the Wolf number is very small (less or about 0.1% of the constant; Kristjansson et al. 2002) and the changes in radiation can only be observed in UV band, which causes that the mechanisms of this changeability influence on the course of atmospheric processes are not clear, Foukal (2002) shows that these little changes in radiation explain about 20% variances of changes in global temperature in the period 1915–1998.

The ~7.7-year periodicity, with the peak values of spectral density made up of 7.3-year, 7.7-year and 8.0-year periodicity can be associated with, so called,

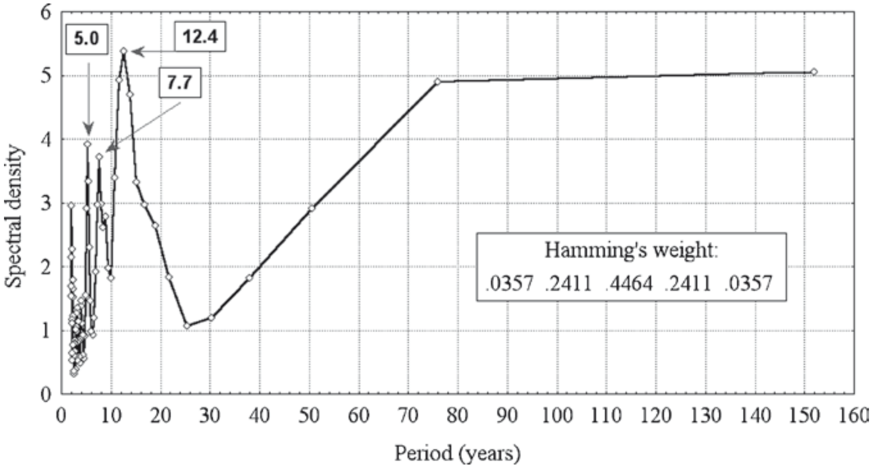

Fig. 16.6 The results of spectral analysis of standardized annual SST (adjusted by 5-element Hamming filter). The marked periodicity of peak values of spectral density (years)

'quasi -8-year periodicity',[15] commonly recognised from the course of air temperature over Poland and the neighbouring regions (Kożuchowski and Marciniak 1994; Żmudzka 1995; Boryczka 1998; Kożuchowski 2000; Fortuniak et al. 2001) and the course of some natural processes indicating stronger correlation with the course of air temperature (e.g. sea ice formation; see Kożuchowski and Girjatowicz 1997) or with the increase in wind speed (e.g. the number of winter storms over the Baltic Sea).

The quasi -8-year periodicity marked in the course of temperature is connected with the course of circulation processes present over the region of the Atlantic and NW Europe- primarily with NAO. Boryczka et al. (2000, 2001) define the periodicity of NAO CRU index (Jones et al. 1997) for the period from December to March as 7.7-year periodicity and for one year as 7.8-year. Marsz (1999) finds 7.78-year periodicity for one year in the course of Hurrell NAO index. Fortuniak (2000) appoints the limit of statistically significant quasi-7-year (7.37) periodicity in the course of air temperature over Europe; the area of the South Baltic Sea is covered by this scope.

The ~12-year and ~7–8-year periodicity are so strong that their presence can be found in the course of annual SST of the Baltic Sea adjusted by 13-point moving average. This kind of filtering, to a great extent, suppresses periodicity shorter than 13 years.

The ~5-year oscillation noted in the course of annual SST of the Baltic most probably originates from beating up (sum) of basic harmonics; ~7.8 years and ~12.4 years. The occurrence of about 2-year oscillation in connected with the changeability of SST of the Baltic Sea from year to year.

If the 12-year periodicity is really connected with the changing activity of the Sun (Wolf numbers) then it would mean that this signal is most clearly marked in periodical components of changes in annual SST. However, the changeability in the number of sunspots in the examined period is very weakly correlated with the course of the annual SST ($r = 0.18$, $p < 0.02$). The changeability of the number of sunspots[16] explains only 3.3% variances of annual SST in the entire 152-year period. The winter atmospheric circulation is on the second place with regard to amplitude of modulating signal, despite being strongly correlated with the course of annual SST, it explains a dozen or so % variances of SST in the same period. It is a kind of paradox.

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[15] In a yearly course in a series made up of 152 consecutive values a strong signal of 7.7-year period is detected. In the course of seasonal values of SST (January–March, July–September, and October–December) and in monthly courses of the same duration statistically significant or less frequently not significant periodicity falling into the periods from 8.09 years to 7.19 years can be found. The authors think that too much attention should not be paid to slight differences in the duration of the periods noted here. It is enough to change the length of the analyzed series (shorten) by 1-5 and the spectral analysis detects in the same series periodicity about 0.1–0.3 years different from the one defined earlier

[16] Data from National Geophysical Data Center, Solar-Terrestrial Physics Division (E/GC2), Boulder, Colorado.

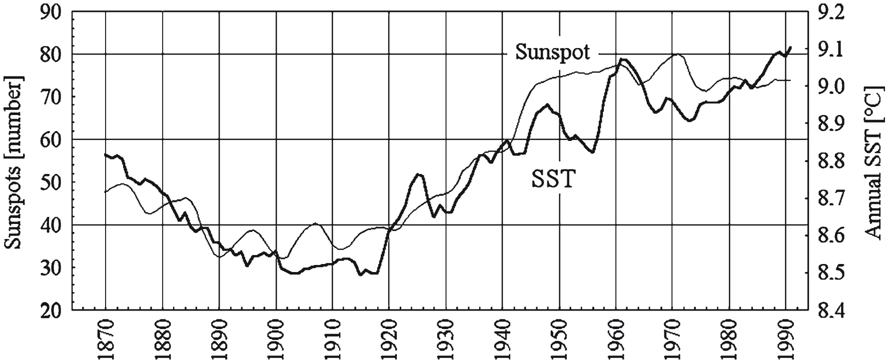

Fig. 16.7 Adjusted by 31-point moving average courses of annual values of SST in grid 56°N, 18°E and annual number of sunspots (1854–2005)

However, if the problem of long term activity of both modulating components is considered, this paradox becomes even more puzzling. Because the periodicity connected with the changing activity of the Sun falls within the limits of 11–13 years, in order to filter this changeability and to find out sub-trends a longer filter of doubled periodicity should be used. Here 31-point moving average of chronological series of sunspots number and annual SST was used. The picture that is obtained (see Fig. 16.7) seems to suggest that the long term changeability in the number of sunspots can really attribute, together with changeability in the character of winter atmospheric circulation, to long term changes in SST of the Baltic Sea and influence the occurrence of long term sub-trends in series of SST. If this conclusion is true, it can mean that the increase in annual SST from the 20s to the 30s of the twentieth century can also be influenced by the increase in the Sun activity. The same analysis carried out to explain if there are similar correlations between winter (January–March) NAO CRU index and the changing activity of the Sun does not find any correlations between these elements.

Acknowledgments We would like to thank NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, for making from their website data set NOAA_ERSST_v2 available by ftp from WWW (http://www.cdc.noaa.gov/). We would also like to express our gratitude to National Geophysical Data Center, Solar-Terrestrial Physics Division (E/GC2), Boulder, Colorado, USA, for making series of data with annual values of sunspots number in the period 1700–2005 available.

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Chapter 17
Ground Surface Temperature Histories Reconstructed from Boreholes in Poland: Implications for Spatial Variability

Darius Mottaghy, Jacek Majorowicz, and Volker Rath

17.1 Introduction

In recent years, geothermal logs have been used to reconstruct ground surface temperature histories (GSTH) (Nielsen and Beck 1989; Dahl-Jensen et al. 1998; Pollack et al. 1998; Huang et al. 2000; Šafanda and Rajver 2001; Kukkonen and Joeleht 2003). In spite of the fact that the temporal resolution of the reconstruction is low and the coupling of surface air temperature to ground temperature is still not well understood, such reconstructions represent the most direct record of past temperatures and are potentially valuable in analyzing past climate conditions. Many authors performed reconstructions on various timescales, from a few 100 to 100,000 years. The short-time reconstructions serve to investigate natural and anthropogenic climate change, whereas the longer reconstructions aim to understand temperature variations back to the last Glacial and its transition to our current climate.

In this study we present results from ground surface temperature histories reconstructed from two deep boreholes in Poland. Our main interest lies in the magnitude of the Pleistocene-Holocene Warming (PHW). It is well known that there are large differences in the PHW depending on the location, this is studied for example by Demezhko et al. (2007) for Northern Eurasia. However, there is still a lack of data for a densely sampled spatial distribution of reliable reconstructions of the PHW magnitude.

One data set origins from the Udryn borehole, located in northeastern Poland. It is a low heat flow region due to the presence of a norite-anorthosite massif, with values around 40 mW m^{-2}. The second data set originates from Czeszewo which is situated further west (Fig. 17.1). Here, heat flow is considerably higher (>80 mW m^{-2}).

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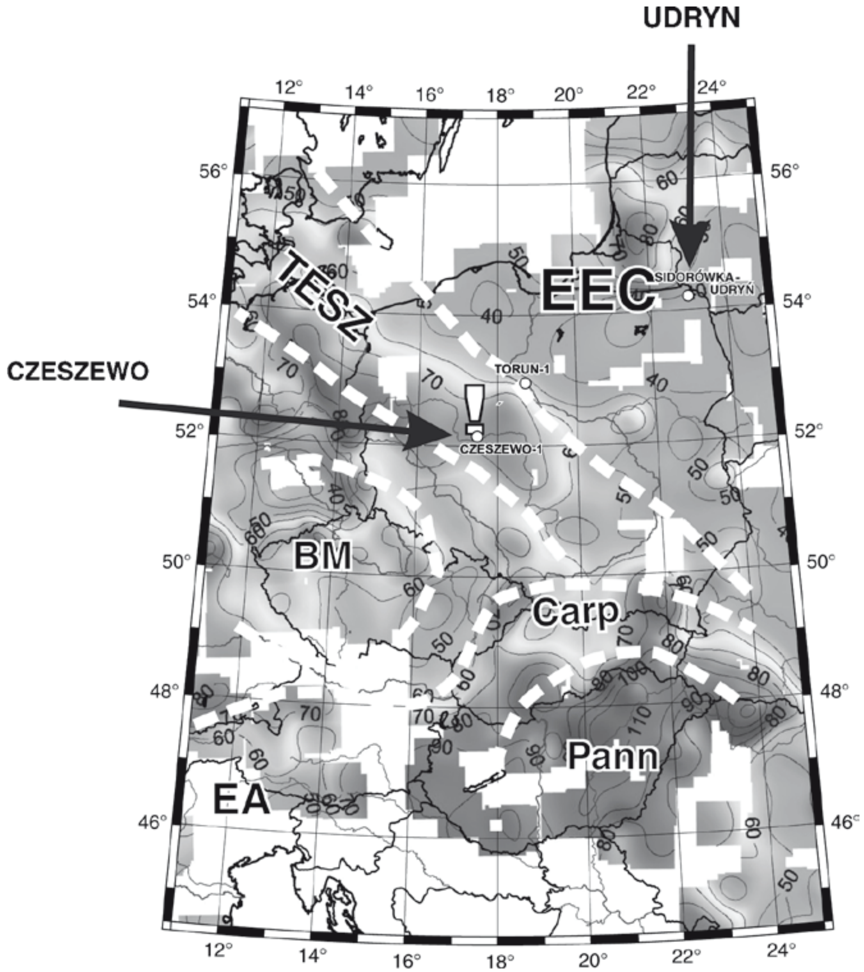

Fig. 17.1 Location of the boreholes Czeszewo and Udryn on a heat flow map (Majorowicz et al. 2007) of eastern Europe (mW m^{-2}), uncorrected for paleoclimatic effects

In both cases there is a continuous temperature, porosity, and thermal conductivity log available. These are favorable conditions for a reliable reconstruction of GSTH by inversion.

17.2 Inverse Method

We invert borehole temperatures for GSTH using the Tikhonov method. In the following we shortly describe the equations and relations involved in the forward model, the inverse technique, as well as the regularization parameters, which are necessary for the type of inversion applied here.

17.2.1 Forward Model

The solution of any inverse problem requires that the corresponding forward model is known and adapted to the physical processes involved. As the use of analytical solutions does not allow for appropriately complex situations, we use a straightforward numerical solution of the heat equation by finite difference methods. This gives us considerable freedom of introducing more realistic physics of the systems, as the non-linear dependencies of the system parameters on temperature and pressure, and, in particular, the effects of latent heat.

The one-dimensional, purely conductive heat equation in a porous medium can be written as:

$$\frac{\partial}{\partial z}\left(\lambda_e \frac{\partial T}{\partial z}\right) + h = (\rho c)_e \frac{\partial T}{\partial t}, \tag{1}$$

where λ is thermal conductivity (W m^{-1} K^{-1}), ρ is density (kg m^3), c is specific heat capacity (J kg^{-1} K^{-1}), and h is volumetric heat production (W m^{-3}). The subscript e marks effective parameters of the porous medium, and can be interpreted as properties of a two-phase mixture between solid rock and fluid-filled pore space. This mixture is characterized by porosity Φ. Usually, the geometric mean is chosen for thermal conductivity, that is, $\lambda_e = \lambda_w{}^{\Phi}\,\lambda_m{}^{(1-\Phi)}$, with the indices w and m denoting the fluid and matrix contribution. Volumetric quantities like (ρc) are averaged arithmetically, taking $(\rho c)_e = \Phi\,\rho_w c_w + (1-\Phi)\,\rho_m c_m$.

For the paleoclimate application we have in mind, Equation (1) usually is solved with the appropriate boundary conditions, namely a fixed but time-dependent temperature at the top ($z=z_0$),

$$T = T(t) \text{ at } z = z_0, \tag{2}$$

and fixed heat flow at the bottom,

$$\frac{\partial T}{\partial z} = -\frac{q_b}{\lambda} \text{ at } z = z_b. \tag{3}$$

Equation (1) is understood to allow all coefficients, boundaries, and sources, to be nonlinearly dependent on temperature. Most rocks matrix properties exhibit moderate dependencies on temperature, while pressure can safely be neglected for the depths under consideration here (Chapman 1986). As we are aiming at deep boreholes constraining the history of ground surface temperature for some 10,000 years, we have to extend the numerical model to depths of several 1,000 m, and temperatures of up to 200°C accordingly. This requires taking the temperature dependencies of the thermophysical properties into account. In many practical situations, the upper layers of the subsurface are of sedimentary origin and show considerable porosities up top 40%. In this case the physical properties of the fluid have a distinct influence, as they change with temperature, but unlike the matrix, they are also pressure-sensitive. We implemented the relations given in Table 17.1, defining the temperature (and pressure in the case of fluid density) dependence of the physical

Table 17.1 Dependencies fluid and ice properties on temperature and pressure

Property	Reference
$\lambda_f T$	Phillips et al. (1981)
$c_f T$	derived from enthalpy given by Zylkovskij et al. (1994), salinity neglected
$\rho_f(T,P)$	from Zylkovskij et al. (1994), salinity neglected
$\lambda_i(T)$, $c_i(T)$, $\rho_i(T)$	Lide (2000)

parameters within the forward module. For the domain characteristic of the boreholes investigated in this study (<5,000 m depth), a comparison of the fluid properties with the ones from Wagner and Pruß (2002) assures that deviations are in an admissible range (<2%). Certainly, these errors are much smaller than the ones induced by neglecting of salinity which can play a major role in some permafrost environments (Ippisch 2001).

Equation (1) is solved by a standard one-dimensional finite difference scheme, allowing for irregular grids, variable coefficients, time-dependent boundary conditions, and source terms. The resulting non-linearity is handled by a simple fixed-point iteration, which proved to be adequate to the problem. Time-stepping is done by a general two-level scheme, including the well-known Forward/Backward Euler and Crank-Nicholson schemes (see, e.g.,Wood 1990) as special cases.

The simplified form of the heat equation used in the forward problem of palaeoclimate inversion is easily modified to incorporate the effects of the presence of the ice phase, which turned out to be of first-order importance for the Udryn study (see Section 17.3). Details of theory, implementation, and the validation of the approach can be found in Mottaghy and Rath (2006). The approach chosen is of course a simplification of a process which is far more complicated than described here (Ippisch 2001). For the application to palaeoclimate inversion we have restricted ourselves to the simplified approach, as mainly processes with large time constants are important, and thus the processes in the upper few meters of the subsurface do not play a significant role for the reconstruction of palaeotemperatures at scales larger then a few years.

17.2.2 Inverse Technique

Given observed data, that is, recent borehole temperature measurements as a function of depth, $d_i = T(z_i, t_0)$, the GSTH, $T(0, t)$, can be estimated by a regularized least-squares procedure. To achieve this, an objective function is set up to be minimized:

$$\Theta = \left\| \mathrm{W}_d(\mathrm{d} - \mathrm{g}(\mathrm{p})) \right\|_2^2 + \tau_0 \left\| \mathrm{W}_p^0(\mathrm{p} - \mathrm{p}_a) \right\|_2^2 + \tau_1 \left\| \mathrm{W}_p^1(\mathrm{p} - \mathrm{p}_a) \right\|_2^2 \tag{4}$$

Here, d − g(p) ≡ r is the residual vector between the data d and the solution of the forward problem g(p) at these points for a given parameter vector p. The weighted norm of this residual represents the data fit. Data weighting is introduced by W_d, which is usually used to standardize the residuals, that is, its diagonal is set to the inverse square root of the data covariance. The second term in Equation (4) is defined by the application of a linear operator W_d on the deviations of the model parameters p from their preferred values p_a.

To solve the inverse problem we try to find the minimum of functional (4) by formally differentiating equating the result to zero. This leads to the well-known normal equation,

$$\left[(\mathbf{W}_d\mathbf{J})^T\mathbf{W}_d\mathbf{J}+\tau_0(\mathbf{W}_p^0)^T\mathbf{W}_p^0+\tau_1(\mathbf{W}_p^1)^T\mathbf{W}_p^1\right]\delta\mathbf{p}= \tag{5}$$
$$(\mathbf{W}_d\mathbf{J})^T\mathbf{r}-\tau_0(\mathbf{W}_p^0)^T\mathbf{W}_p^0(\mathbf{p}-\mathbf{p}_a)-\tau_1(\mathbf{W}_p^1)^T\mathbf{W}_p^1(\mathbf{p}-\mathbf{p}_a),$$

which can be iterated as a modified Gauss-Newton iteration with $p^{k+1}=p^k+\delta p^k$, where δp is determined for each iteration by Equation (5). The derivative matrix *J* (*J*acobian) results from the differentiation of the residuals d – g(p). It is defined as:

$$J_{ij}=\frac{\partial g_i}{\partial p_j},$$

where p_j are the model parameters. Differentiation is done by an adaptive method using divided differences.

To solve the linear system (5), an equivalent formulation can be found, which is very flexible and allows using a variant of the well-known conjugate gradient method for its solution:

$$\begin{bmatrix}\mathbf{W}_d\mathbf{J}\\ \tau_0^{\frac{1}{2}}\mathbf{W}_p^0\\ \tau_1^{\frac{1}{2}}\mathbf{W}_p^1\end{bmatrix}\delta\mathbf{p}=\begin{bmatrix}\mathbf{W}_d^T(\mathbf{d}-\mathbf{g}(\mathbf{p}))\\ -\tau_0^{\frac{1}{2}}\mathbf{W}_p^0(\mathbf{p}-\mathbf{p}_a)\\ -\tau_1^{\frac{1}{2}}\mathbf{W}_p^1(\mathbf{p}-\mathbf{p}_a)\end{bmatrix} \tag{6}$$

This rectangular system of linear equations is efficiently solved in each iteration by conjugate-gradient type methods like CGLS or LSQR (Björck 1996; Hansen 1997). Methods using only the gradient of an objective function like the one defined in Equation (4), that is, the Jacobian only enters through the matrix-vector product $-J^T$ r, may be a good alternative choice for the minimization technique. The most prominent of these are the variants of Nonlinear Conjugate Gradients (NLCG), or Quasi-Newton (QN) algorithm (see, e.g., Nocedal and Wright 1999). However, the above-mentioned methods make it difficult to optimize regularization parameters.

In the case of GSTH inversion, we parameterized the surface temperatures as a series of step functions for *p*. Number and temporal spacing of steps are set a priori, leaving the temperature values for each period as inversion parameters. These parameters are associated to the time steps indirectly. The time discretization of the forward problem thus can be chosen following numerical requirements, independently from the inverse grid employed. Due to the diffusive character of the underlying physics, the use of a mesh spaced logarithmically in time and space is useful to reduce computing times.

17.2.3 Regularizing Operators

In this study a smoothing operator will be used for regularization. We propose a combination of differential operators of different order, namely $L_0=I$, and L_1. This operator represents the discrete first derivative with respect to time, and is defined as

$$\mathbf{L}_1 = \Delta t^{-1} \begin{bmatrix} -1 & 1 & & 0 \\ & -1 & 1 & \\ & & \ddots & \\ 0 & & -1 & 1 \end{bmatrix}. \tag{7}$$

The product of the matrix defined in Equation (7) with the parameter vector p may be interpreted as the discrete approximation of its first derivative by forward divided differences, where Δt is the time spacing of the inverse mesh, which is assumed to be constant for the moment.

If L_0 is used, the minimum distance between the solution and the prior model is sought. This, however, often leads to solutions displaying unwanted short-period oscillations. Regularizing with the L_1 operator penalizes solution roughness, and guarantee smooth solutions if the weighting parameter τ_1 is chosen large enough. The L_1 operator as defined above favors "flat" solutions (Hansen 1997).

In the GSTH inversions presented here, we used a temporal inversion grid which decreases logarithmically during the time of simulation. Also, we used only the difference matrix, neglecting the denominator in Equation (7). This approximately amounts to weighting the derivative with a time dependent factor corresponding to the local average step length. By this simple approach variations at late times are less damped than at early ones.

For the inversions shown below, we look for the best value of τ, with τ_0 = const and $\tau_1\} = \tau\tilde{\tau}_1$ with the tilde denoting the fixed base value. In particular when comparing different data sets, methods, or results, it is important to give a repeatable and objective way of choosing $\tilde{\tau}_1$. Common methods for the choice of this parameter are the L-curve (Hansen 1992) or the GCV criterion (Wahba 1990). Here, we use the latter one, its application on GSTH inversions is described in detail in Rath and Mottaghy (2007).

17.2.4 Data Preparation

Since the present ground surface temperature and the basal heat flow enter the inversion as predetermined boundary conditions, we ran forward models with a

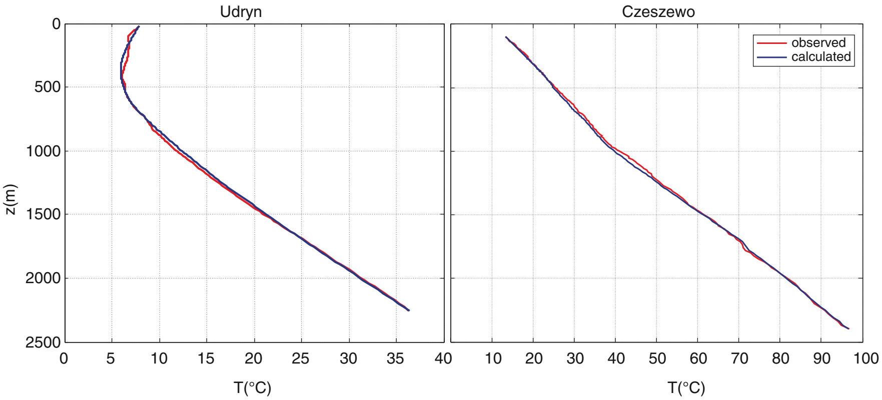

Fig. 17.2 Determination of boundary conditions (Table 17.2) for the inversion by forward modeling. The *gray line* depicts the measured temperatures in the borholes, the *black line* represents the forward model

Table 17.2 Present mean annual GST and surface air temperature (SAT, 2 m height), and basal heat flow at 5 km, as used in the inversion

Location	Present GST	Present mean annual SAT	Basal heat flow
	°C	°C	(mW m^{-2})
Udryn	8	6	37.2
Czeszewo	10	8	81.5

simple step function representing the GSTH. As a result, we obtain a first, rough fit of the modeled temperatures (Fig. 17.2) to the data with boundary conditions as in Table 17.2. The best fit shows that present mean ground surface temperatures are 2 K higher than present mean surface air temperature (SAT). This is a reasonable value, although as mentioned above, the coupling between GST and SAT is not trivial and subject of current research (e.g. González-Rouco et al. 2009).

Since we are interested in the long term climate, we do not loose information when omitting data in the upper 20 and 200 m in the Udryn and Czeszewo case, respectively (Fig. 17.2). In doing so we could stabilize the inversion results considerably.

For the actual inversion, the specification of a prior model is necessary. If there is information on the GSTH from other sources, this can be taken into account within the prior. Otherwise, a zero prior is used.

17.3 Results and Discussion

The inversion method is applied to data from Udryn, shown in the upper left panel of Fig. 17.3. We used the total temperature log from 20 to about 2,300 m. As using a constant prior implies an unrealistic assumption of mean temperatures before the

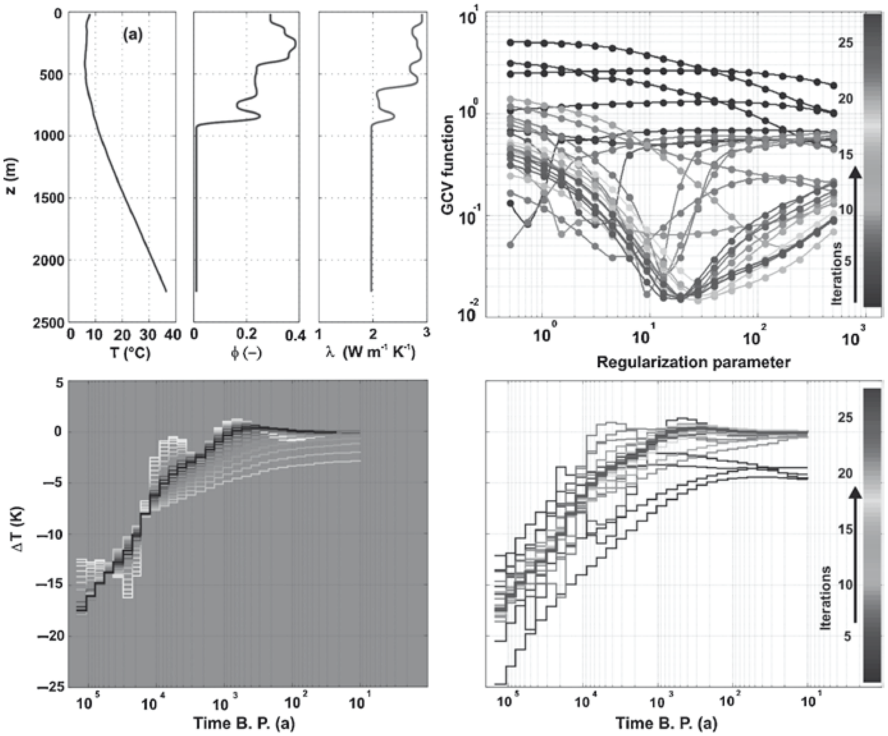

Fig. 17.3 Results from GSTH reconstruction for the Udryn borehole with an optimized regularization parameter. The upper left panel shows the temperature log, porosity, and the thermal conductivity along the borehole. *Upper right*: GCV functions for each inversion iteration. *Lower left*: reconstructed GSTH for the last iteration, combined with the results for the regularization parameters used for associated GCV function. *Lower right*: reconstructed GSTH for each inversion iteration

initiation of the simulation, a smooth transition is chosen from the recent GST of 8°C to an initial value of −8°C. This particular prior model entering the regularization was inspired by the results of Šafanda et al. (2004). Test runs with a zero prior yield similar results, however, the numerical stability was not sufficient.

The lower right panel shows the a posteriori GSTH, where the iteration process is made visible by different grey levels. The best model for *each iteration* are obtained with an optimized regularization parameter τ found by the minimum of the GCV function, which is plotted in Fig. 17.3 (upper right) versus τ. Here, the iteration number is given by the grey level. Twenty five inverse iterations were necessary to reach the final model. The data fit is defined by

$$RMS = \left[\sigma\sqrt{N}\right]^{-1} \left\|(\mathbf{d}-\mathbf{g}(\mathbf{p}))\right\|_2^2$$

Here, $\sigma = 0.25$ K is the uncertainty in measured temperatures at N depths. The RMS of the final model at the GCV minimum is 0.84.

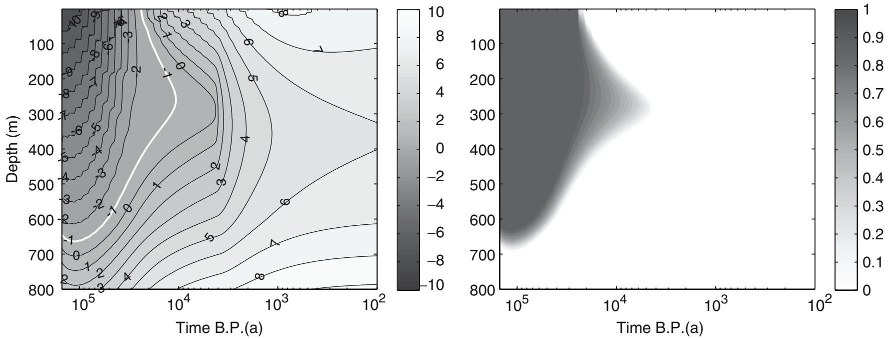

Fig. 17.4 Permafrost formation at the Udryn site from the inversion model shown in Fig. 17.3. *Left*: Temperatures (°C) in the top 800 m of the model. *Right*: Ice content of the porous medium. A value of 1 implies that all porosity is filled up with ice. Defining permafrost thickness by the −1°C isotherm (*white line*), it reaches a maximum depth of 650 m shortly after the beginning of the simulation. No ice is present after ≈4 ka BP

The lower left panel demonstrates the influence of the regularization parameters on the reconstructed GSTH in the *last iteration*: the black line is the model determined by using the regularization parameter found at the minimum of the GCV function. However, the other models are plotted in different gray scales, the darker the closer to the minimum. The GST history shows that there was a large PHW with about 18 K. Thus, the mean ground surface temperature during the last glacial maximum (LGM) was about −10°C. The Udryn area is a low heat flow region (40 mW m^{-2}, see Fig. 17.1), in addition to the low temperatures this implies the formation of a thick permafrost layer. This is shown in Fig. 17.4, where the temperature distribution and ice content are plotted with respect to time, applying the inversion model from above.

The same procedure is performed using the data from Czeszewo. Here, we used the depth interval 200–2,400 m and a zero prior, however, using a similar prior as for the Udryn data yields the same results. As seen from Fig. 17.5, the result stabilizes after a few iterations, with RMS = 1.22 at the GCV minimum. From the inversion, the PHW is about 10 K, which means that the mean GST during the LGM was around 0°C. Although both locations are only about 400 km apart, temperatures in Czeszewo were much higher during the LGM. This and the high heat flow in the Czeszewo region prohibited very likely the formation of permafrost. The higher temperatures during the LGM are confirmed by recently published results from Torun (Majorowicz et al. 2008). Its location (130 km NE of Czeszewo) is shown in Fig. 17.6, together with the movement directions of ice lobes during the main state of the Vistulian Glaciation.

This figure suggests explanations for the different temperatures during the LGM. The advance of the ice sheet in the western part of Poland extents further to the south. One the one hand this may imply a longer period of ice coverage in Czeszewo, and on the other hand a "protection" of the Udryn location by the warmer, marine influence. Besides this, a longer exposure to cold air masses

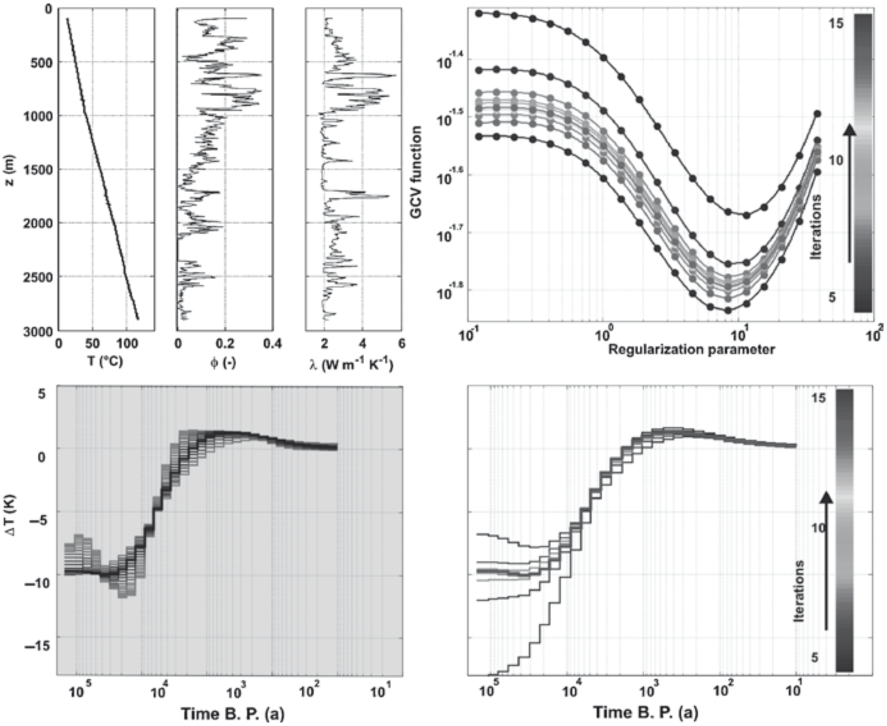

Fig. 17.5 Results from GSTH reconstruction for the Czeszewo borehole with an optimized regularization parameter. Description of panels see Fig. 17.4

(katabatic winds) at the rim of the glacier is likely to be the reason for the very low mean GST at the Udryn location during the LGM. The warmer temperatures further in the west are supported by GSTH reconstructions from boreholes in central Europe (Clauser et al. 1997).

17.4 Conclusions

We conclude that there have been large differences in temperatures during the LGM within a few 100 km on the East European Platform. Besides the general increase of the continental component of the climate from west to east, the advance and retreat of the glacier during the Vistulian (Weichselian) glaciation caused a large spatial variability. For a reliable characterization of the PHW magnitude within such a regional scale more modeling is necessary. Although the quantitative comparison of borehole temperature observations with the output of large scale climate models is far from trivial (González-Rouco et al. 2009), we believe that these borehole data provide valuable information.

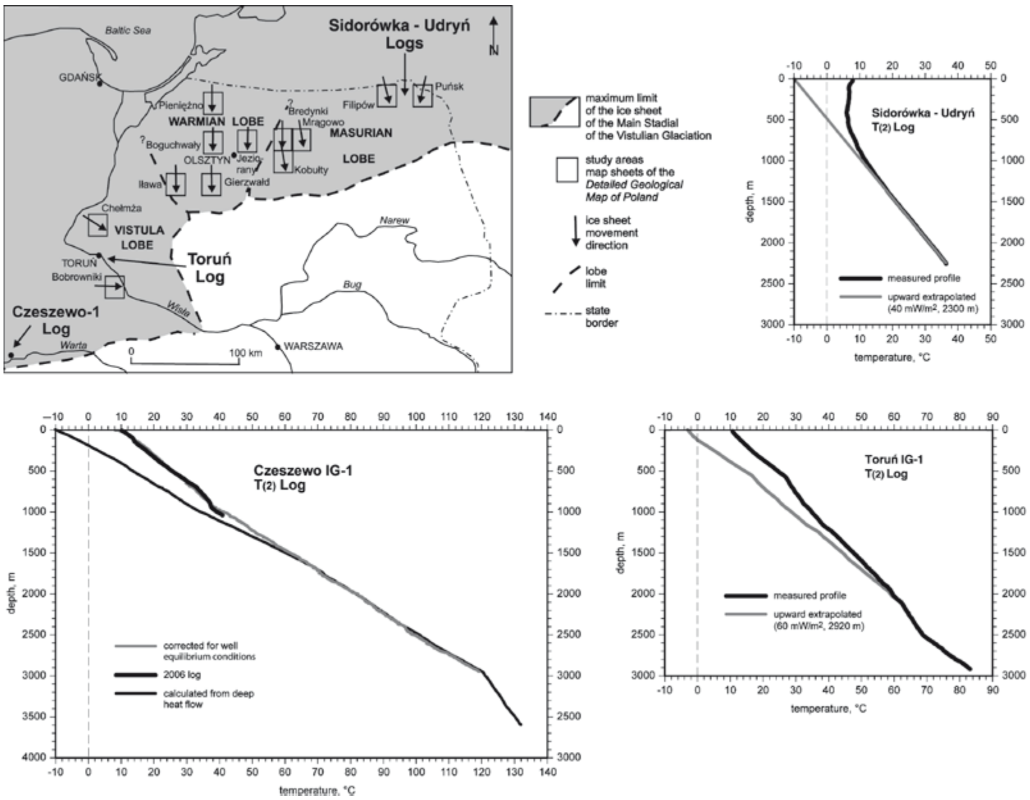

Fig. 17.6 Locations of the boreholes on a map showing the movement directions of the ice sheet of the Main Stadial of the Vistulian (Weichselian) Glaciation in Poland, as reconstructed from the orientation of glacial morpholineaments according to Morawski (2005). Additionally, temperature logs and extrapolations of the studied boreholes are plotted, together with another one in Torun (taken from Majorowicz et al. 2008)

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Chapter 18
Precipitation Extremes and Disastrous Floods in Central Europe in July 1897

Jan Munzar and Stanislav Ondráček

18.1 Introduction

The high water of July 1897 which took place in nearly two thirds of the territory of Bohemia, Moravia and Silesia, Lower and Upper Austria, and a great part of Germany brought sights of apocalyptic destruction. Consequences of bitter floods in 1858 and 1882 having not yet faded away from the memory of inhabitants in the mountain areas which form a natural boundary between Bohemia and Silesia, the region was affected from 28 to 30 July 1897 by the precipitation of extreme intensity following after several days of rains (Hellmann 1897, Trabert 1897). All water courses in the Krkonoše Mts. rapidly overflew the banks on both sides of the border and the process of destruction began.

18.2 Precipitation Extremes

The rain intensity reached its peak on 29 July 1897 after 8 p.m. Historical records describing the event of this night paint in bright emotionally the ghastly raging dark night falling down on the highest Czech mountains, evoking the image of the biblical Flood. Unlike the biblical event the high water of July 1897 entered the lives of many thousand people quite unexpectedly and without any warning. Especially the two main rivers – Labe (Elbe) and Úpa became dimensionless streams of water - sweeping, pulling down and taking away everything that was standing in their way.

While in the summer of 1997 the hitherto records of multiple-day total precipitation were exceeded in numerous localities in the Czech Republic, the 1-day total precipitation of 345.1 mm from 29 July 1897 gauged at the Nová Louka

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station (780 m a.s.l.) in the Jizerské hory Mts. (Polish: Góry Izerskie, German: Isergebirge) was not surmounted (Kakos 1997). The 24 h precipitation amount is likely to be at least a Central-European record until today. Although the 1-day total precipitation amounts of 300 mm and more are exceptional in Europe's climate, they were recorded two times in the summer of 1897: apart from the above mentioned 345.1 mm, a nearby gauging station Jizerka (formerly Wilhelmshöhe) in the Jizerské hory Mts. measured an amount of 300 mm on the same day (Table 18.1). Czerwiński (1998) mentioned as regional daily precipitation extreme during this synoptical situation 376 mm, but it is undoubtedly a mistake. On the Polish side was the greatest daily amount of precipitation 239 mm on the station Śnieżka (1603 m a.s.l.).

During the catastrophic floods in Central Europe in August 2002 a new absolute German national record was measured (312 mm/day) at the Zinnwald-Georgenfeld station (877 m a.s. l.) in the Ore Mts. (Czech:Krušné hory, German: Erzgebirge) from the morning of 12 to the morning of 13 August, i.e. with 34 mm still missing to surmount the Central-European extreme from 1897. In the Czech Lands was in August 2002 an extreme value "only" 278 mm on the station Knajpa (967 m a.s.l.) in special net of Czech Hydrometeorological Institute on 13 August 2002. In Poland is continually valid absolute one day precipitation record 300 mm from the station Hala Gąsienicowa (1520 m a.s.l.) in High Tatra Mts. on 30 June 1973 (Table 18.2).

As to the synoptic causes of the extreme precipitation, it was in fact the cyclone progressing along the Vb trajectory in the sense of van Bebber's classification. On 28 July 1897, an extensive low pressure zone developed over

Table 18.1 One-day total precipitation amounts from 29–30 July 1897 in the Czech-Polish borderland region

Amount [mm]	Date	Station	Altitude [m a.s.l.]	Country
345	29.7.1897	Nová Louka/Neuwiese	780	CZ
300	29.7.1897	Jizerka/Wilhelmshöhe	870	CZ
266	29.7.1897	Pecpod Sněžkou/Riesenhain	812	CZ
239	29.7.1897	Śnieżka/Schneekoppe	1603	PL
225	29.7.1897	Schronisko Księcia Henryka/ Prinz Heinrich Baude	1400	PL
220	29.7.1897	Kościół Wang/Kirche Wang	873	PL

Table 18.2 One-day precipitation records in Central Europe

Amount [mm]	Date	Station	Altitude [m a.s.l.]	Country
345	29.7.1897	Nová Louka	780	CZ
323	5.6.1947	Semmering	1012	A
312	12.8.2002	Zinnwald-Georgenfeld	877	D
300	30.6.1973	Hala Gasienicowa	1520	PL
232	12.7.1957	Salka	111	SK

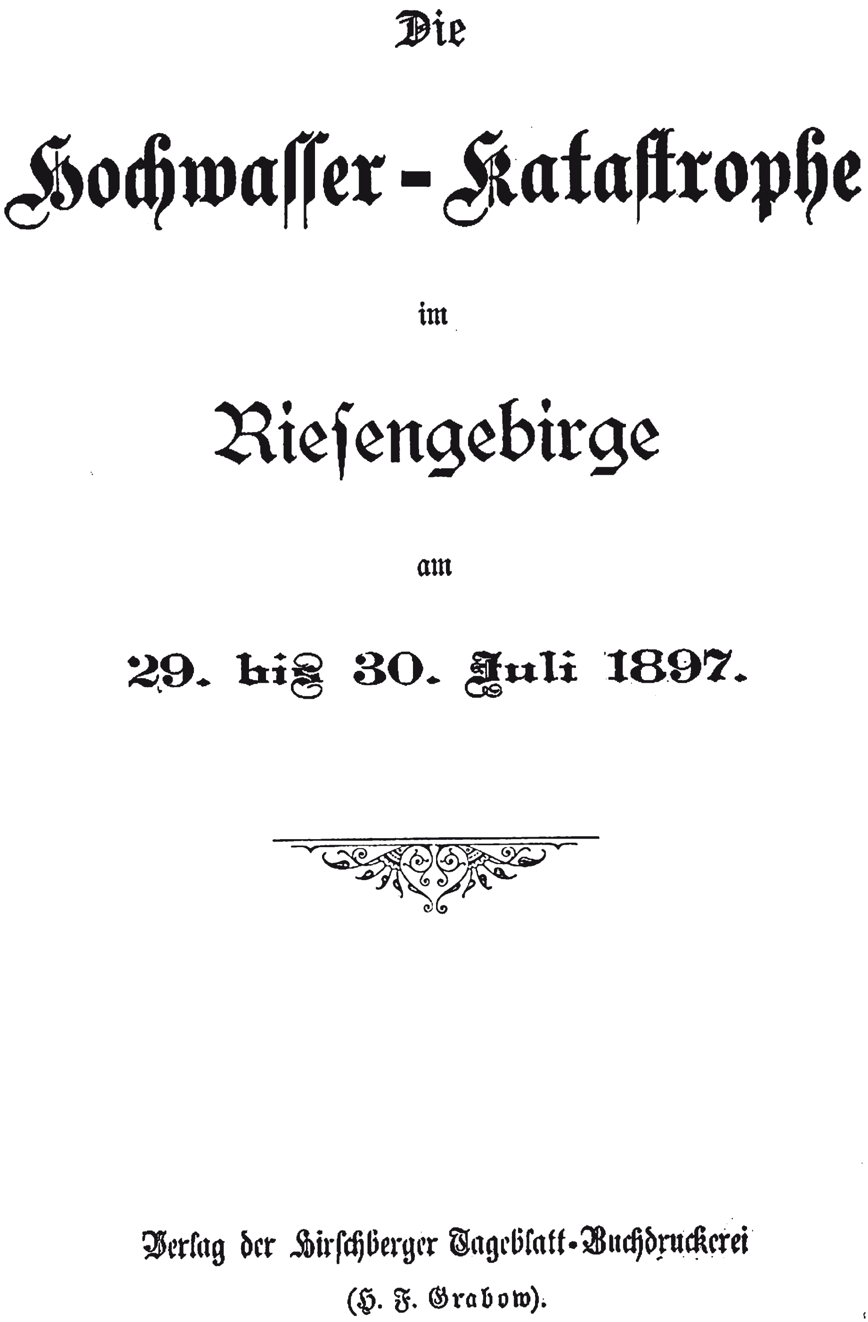
Central Europe, which had three cores (1,005 hPa): one above the northern part of the Adriatic sea, one above Hungary and one above southern Poland – that "merged" on 29 July 1897 into one centre (1,006 hPa) in the north of the High Tatra Mts. At the same time, the pressure gradient above the Czech territory increased with the north-western to northern flowing and an extreme retrograde displacement occurred of the cyclone centre towards the west to south-west.

18.3 Floods and Their Impacts

One of characteristic features of the flood at the end of July 1897 was its large area impact. Flood waves on watercourses were recorded nearly in the whole today's territory of the Czech Republic but they reached the highest extreme in the Upper Labe (Elbe) Basin where the floods were unprecedental. Disasters on streams flowing from the Krkonoše Mts., namely on the Upper Labe (Elbe) River itself and on its left-bank tributary Úpa River, were compared to the Apocalypse. The extreme character of floods in this region corroborates also the extremity set up for culmination discharges delivered on the Labe R. at the Labská Station (beneath Špindlerův Mlýn) and on the Úpa R. at the Horní Maršov Station. According to Brázdil et al. (2005), the floods in these two localities belonged to events occurring on average once in a thousand years. Some hydrologists argue that the recurrence interval was not so extensive. In any case, however, there is a general agreement that the concerned floods were more than the hundred-year ones.

The disastrous flood showed in Bohemia also on the Lužická Nisa/Lusatian Neisse R., left bank tributary of the Odra R. and on the streams flowing down from the south-eastern slopes of the Krušné hory (Erzgebirge) Mts. The extreme floods were recorded also on their German side in Saxony, unprecedented on many water streams until the year 2002, which can be documented by historic floodmarks recorded since 1815 on the wall of a mill on the Freiberger Mulde R. in the town of Döbeln (Pohl 2004). It was as late as in August 2002 when the hitherto highest water course culmination from the beginning of August 1897 was pushed to the second place, being surmounted by 126 cm. The extraordinary character of floods on the left-bank tributaries of the Elbe R. in Saxony in summer 1897 is documented by numerous other floodmarks in the region. Although the Elbe River itself was in Germany affected by the high water, its water level increase was insignificant in the context of other flood cases.

Great floods occurred in 1897 also in the Odra River Basin. The flood on the Odra R. in Bohumín, i.e. on the then Prussian-Austrian border, was "only" a flood that occurs on average once in two to five years. However, the flood was gradually gaining strength further down the Odra R. course in the today's Poland (the then Prussia). The reason were left-bank tributaries of the Odra River draining the mountain ranges of the Sudeten. Extreme floods were recorded for example in the watershed of the Nysa Kłodzka/Glatzer Neisse R. The largest inundations in the



Die

Hochwaſſer-Kataſtrophe

im

Rieſengebirge

am

29. bis 30. Juli 1897.

Verlag der Hirſchberger Tageblatt-Buchdruckerei

(H. F. Grabow).

Fig. 18.1 Front page of the occasional print “Flood disaster in the Krkonoše Mts. from 29–30 July 1897” (Jelenia Góra/Hirschberg 1897)

Odra River Basin in July 1897 occurred however on water streams flowing down from the Krkonoše Mts. and from the Jizerské hory Mts., particularly on the Bóbr/ Bober River and on its left-bank affluent Kwisa/Queis R., and/or Nysa Lużycka/ Lusatian Neisse R.

Historic publications issued shortly after the extreme flood disaster describe its course and tremendous losses in northern Bohemia, Saxony and Silesia. The main indicator of destruction is typically the number of casualties. The analysis of historic and later assessments of this flood event speak of 120 life victims on the Czech side of the Krkonoše Mts. (of these 17 in a small village of Dolní Maršov on the Úpa River). Life victims documented so far on the Czech side of the Krušné hory (Erzgebirge) Mts. are 4 and 23 were recorded on the German side. As to Silesia, historic print published towards the end of 1897 in Jelenia Góra/Hirschberg Die Hochwasser Katastropheim Riesergebirge… (Fig. 18.1) speak together of a minimum number of 20 human lives lost, but according to Fischer (1898) were 28 casualties.

The disastrous flood with great damages (illustrated here with examples Figs. 18.2, 18.3, 18.4, 18.5) became an important impetus for a range of flood-control measures in all affected countries and regions. Numerous acts of law and flood-control regulations were issued and a decision was made on hydraulic engineering works that would contribute to the regulation of extreme discharge and to the mitigation of flood damages in the future.

Fig. 18.2 Hotel Deutscher Kaiser in Špindlerův Mlýn (CZ) on 30 July 1897 (Photo F. Joffe – archives of P. Scheufler)

Fig. 18.3 Jedlica R. from the Bóbr/Bober R. basin and destroyed houses in Kowary (PL) after the flood in summer 1897 – according to Sawicki (2004)

Fig. 18.4 Jelenia Góra-Sobieszów (PL): Woody depositions on the bridge after the flood 1897 blocked stream channel in the Bóbr/Bober R. basin (http://wroclaw.hydral.com. pl)

Fig. 18.5 The German Emperor Wilhelm II and his entourage on the new bridge in the village of Brzeziniec (PL) in the Kwisa/Queis R. basin after the flood in 1897 (Source: Bunte Bilder aus dem Schlesierlande, Breslau 1903)

18.4 Conclusion

The floods of summer 1897 were a typical example of the hydrometeorological extreme reaching beyond the country borders and affecting a number of European countries (e.g. Munzar, Ondráček et al. 2007). Since the culmination of rivers and streams occurred at night, a minimum number of life victims in Central Europe was about 175 as found by us. Material losses on dwelling houses, industrial plants, bridges, roads, farmland and crops were immense, thousands of people lost their lodgings. However, a positive consequence of the disaster was in the changed perception of flood-control measures (e.g. Czerwiński 1998). This extreme flood event closed the nineteenth century which is today often referred to as a “century of great floods”.

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Chapter 19
Summer Temperatures in the Tatra Mountains During the Maunder Minimum (1645–1715)

Tadeusz Niedźwiedź

19.1 Introduction

This chapter presents a variability of summer temperatures (JJA) in the Tatra Mountains during the period of a relatively low solar activity, known as the Maunder Minimum (MM, 1645–1715). During this period a sunspot absence was observed frequently (Eddy 1976). There is no doubts that a reduced solar radiation was the direct cause of cooler than normal conditions associated with the so-called "Little Ice Age (LIA)" (Grove 1988). However, the 500 years lasting LIA (1350–1850) cannot be fully explained by solar variations. Long-term changes of the summer temperatures on the timber-line in the Tatra Mountains is connected with sunspot numbers, other astronomical factors and NAO only indirectly, and can be explained mainly by the variation of air-mass circulation (Boryczka 1998; Migała 2005).

Results covering the summer temperatures in the Tatra Mountains during the MM, are based on a reconstruction of temperatures at the upper timberline on the northern slopes (about 1,500 m) for the period 1550–2004 (Niedźwiedź 2004). Reconstruction of temperatures was based on the proxy tree-ring width data of *Pinus cembra* for 1732–1969 (Bednarz 1984) and *Picea Abies* for 1766–1965 (Feliksik 1972) and 1699–1978 (Schweingruber et al. 1979) from the Tatra Mountains. As an additional source a data from the Eastern Alps (Bednarz and Niedźwiedź 2006) for the period 1552–1995 were taken under account, because they are well correlated (correlation coefficient r = 0.657 is significant on the level 0.1%) with the Tatra temperatures (Bednarz 1984; Niedźwiedź 2004). They were compared with the newest data of Kaczka (2004) covering the tree ring indices for 1540–2003. However, it must be remembered that the accuracy of reconstructed values of summer temperatures is rather low. Standard error of estimation from the regression equation base on the tree ring width data for the years before 1700 is equal ±1.0 K, and ±0.8 K for the first half of eighteenth century.

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The results were compared with other selected reconstructions of summer temperatures for the other parts of the Carpathian Mountains (Szychowska-Krąpiec 1998; Bednarz et al. 1999; Büntgen et al. 2006, 2007), the Alps (Frank and Esper 2005), Poland (Sadowski 1991; Przybylak et al. 2005; Przybylak 2008), Czech Republic (Brázdil 1990, 1992, 1994, 1996; Brázdil and Kotyza 1990), Central Europe (Wanner et al. 1995; Pfister 1999; Luterbacher 2001; Luterbacher et al. 2001, 2004; Brázdil et al. 2005; Glaser 2008) and larger area (Briffa et al. 1998; Bradley 1994; Bradley and Jones 1995), as well as with the oldest instrumental temperatures series from Central England (Manley 1974).

19.2 Summer Temperatures During the Maunder Minimum and During the Adjacent Periods

The reconstructed summer (JJA) mean temperature fluctuations are revealed at Fig. 19.1 and Table 19.1. The period of the MM is not homogeneous. According to summer temperatures the investigated period can be divided into two distinctly observed phases. The first one is a relatively cool period connected with the second phase of the LIA. It started in 1576, 70 years before the beginning of MM, and lasted till 1675 (Niedźwiedź 2004). It means that during the LIA temperatures variability was caused not only by solar variations. There is a possibility that it was also connected with the circulation factors and volcanic activity.

Shindell et al. (2001) explained the lowest values of winter temperatures of the past millennium in the Northern Hemisphere and Europe during the MM by a weak solar forcing and negative North Atlantic Index (NAO).

The second phase of the MM, often known as the Late Maunder Minimum (LMM) covers the period between 1675–1676 and 1715 (Luterbacher et al. 2000). It is characterised by relatively great and irregular changes in air temperatures. Directly after the MM a relatively warm period started, connected with an increased solar activity during the eighteenth century, which ended in 1789. It was followed by the Dalton Minimum (DM) in solar activity, starting the last phase of the LIA.

19.2.1 Relatively Cool Period Preceding the Maunder Minimum (1576–1675)

The period which followed the warm period (1550–1575) is known as the second phase of the LIA. In the Tatra Mountains the summer temperatures were at the similar level as in the second half of the twentieth century (Table 19.2) but with the smaller annual variability (standard deviation is only ±0.65). Summer of 1625 was the coolest one. It was 1.1 K cooler than summers in a period 1961–1990. Also summers of 1592 and of 1639 showed a similar tendency (Δt K −1.0 K). The second half of the sixteenth century in Poland was also wet in Poland (Niedźwiedź 2004)

Table 19.1 Reconstructed average summer (JJA) temperature (°C) on the northern slopes of the Tatra Mountains – 1520 m in the period 1570–1829

Year	0	1	2	3	4	5	6	7	8	9
1570	11.1	11.2	11.2	9.7	10.3	10.5	9.4	10.0	9.8	9.0
1580	9.0	9.1	9.2	9.6	9.1	9.1	9.0	8.8	9.1	9.2
1590	9.7	8.9	8.6	9.2	9.4	9.9	9.3	10.6	10.9	10.4
1600	9.2	9.3	9.2	9.5	10.1	10.0	9.4	9.5	9.4	10.0
1610	10.2	10.7	9.1	10.3	10.3	10.1	10.0	9.4	9.9	10.1
1620	10.5	9.6	11.2	10.4	10.3	8.5	9.3	11.1	9.0	10.5
1630	9.2	9.8	8.9	9.4	9.2	9.3	9.8	10.6	9.5	8.6
1640	10.4	9.8	9.4	10.4	10.8	10.2	10.0	9.2	9.4	9.4
1650	9.2	9.1	9.5	9.6	9.4	9.9	9.2	9.2	9.4	10.1
1660	9.7	11.4	8.7	8.7	10.6	10.9	11.1	9.8	9.7	9.8
1670	9.0	9.8	9.5	10.2	9.5	8.8	11.0	9.4	11.0	10.7
1680	11.3	11.3	11.9	12.1	11.4	10.2	11.9	12.2	11.2	9.3
1690	9.6	9.5	9.5	10.4	10.1	9.1	9.3	9.9	9.8	10.4
1700	11.1	11.4	11.7	11.5	10.3	10.2	10.7	10.9	10.9	9.4
1710	9.5	10.0	11.0	9.7	10.8	10.8	9.4	9.6	9.8	10.2
1720	11.2	10.4	10.3	9.1	10.0	9.3	10.7	10.0	10.8	10.9
1730	10.1	10.1	9.9	10.1	10.4	10.0	10.0	10.6	11.6	12.3
1740	10.1	9.1	9.8	9.0	9.1	10.1	10.2	10.1	10.6	10.1
1750	10.1	10.1	10.7	10.7	10.7	9.8	10.3	10.7	10.2	10.9
1760	10.6	10.7	9.4	10.3	9.9	9.7	9.9	10.1	9.9	9.8
1770	9.9	9.9	9.9	10.2	10.9	10.7	10.7	10.5	11.6	9.8
1780	10.6	10.7	9.8	10.5	11.4	10.5	10.1	10.4	10.9	11.1
1790	11.4	11.3	10.3	9.8	9.8	8.8	9.5	10.4	9.7	8.3
1800	8.8	8.5	10.2	9.1	11.4	8.3	8.8	11.1	10.4	9.5
1810	8.4	12.0	10.4	9.1	10.2	9.4	9.6	10.9	9.3	10.1
1820	10.0	8.6	10.6	10.9	9.8	9.4	10.6	9.8	9.4	8.9

Note: Standard error of estimation ±1.0 K for the years before 1700 and ±0.8 K in 1700–1719 with frequent summer floods. According historical sources cited in Kotarba (2004) and Niedźwiedź (2004), extremely wet conditions were related in the Tatra region also in summers of 1605, 1617, 1618 and 1621.

During the cool period preceding the MM in the Alps the glaciers achieved their maximal extend (Grove 1988). As for the Western European data, the summer of 1601 is considered to be the coolest one (Briffa et al. 1998; Pfister 1999).

19.2.2 The First Phase of the Maunder Minimum (1645–1675)

The cool period mentioned above lasted till the first phase of the MM, when the mean summer temperatures were 0.2 K warmer than in the years 1576–1675 (Table 19.2). Exceptional variations of temperatures were observed between 1661 (very warm summer) and 1662–1663 (two the coolest summers), as a strong fall down amounted 2.7 K (Table 19.1, Fig. 19.1). During the cool and extremely wet summer of 1662 on 5 August the largest natural rock-fall catastrophe in the Tatra Mountains took place (Kotarba 2004). The summer of 1662 was also indicated with the lowest tree-ring width indices (Kaczka 2004) within the whole seventeenth century. In the whole area of Central Europe summers of 1662 and 1663 were reported as extremely rainy and cold (Glaser 2008). Cold and wet weather was noticed again in the last year of the analysed period (1675) in the Tatra Mountains as well as in the area of Central Europe (Glaser 2008).

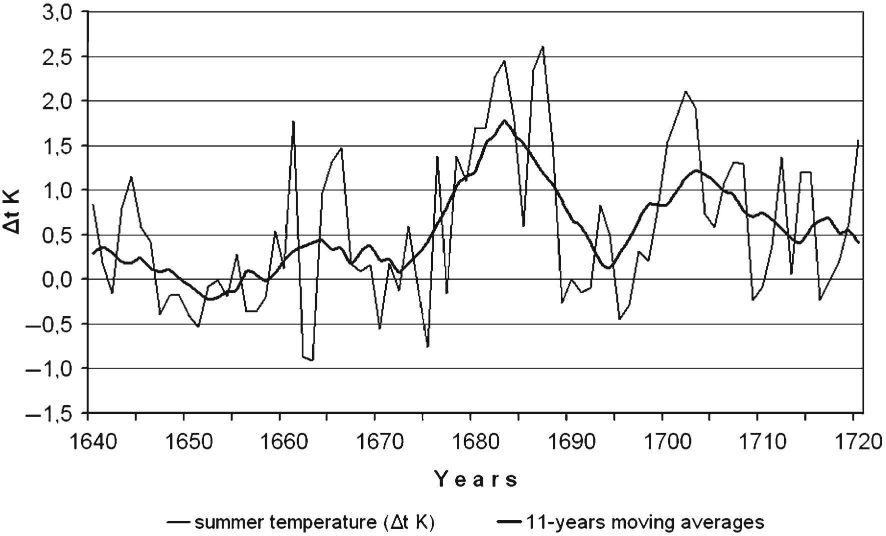

Fig. 19.1 Summer temperature in the Tatra Mountains near the upper tree-line during the Maunder Minimum (1645–1715) and surrounding years. Deviations of JJA temperature from the normal 30-years average 1961–1990 (Δt K). The graph covers the period 1640–1720. The first 11-year moving average on 1635–1645 is centred on 1640, the last one on 1715–1725 is centred on 1720

19.3 The Late Maunder Minimum (1676–1715)

During the LMM the mean summer temperature in the Tatra Mountains was 0.9 K warmer than in the first phase of the MM (Table 19.2). This period was characterised by large temperature variability (standard deviation is ±0.87). Difference between the coolest (1695) and warmest summer (1687) amounted 3.0 K (Fig. 19.1). At the beginning of the period (1676–1688) summers were very warm, followed by eleven cool years (1689–1699), and continued with mixed thermal conditions at the end (1700–1715).

19.3.1 The Warm Phase of the Late Maunder Minimum (1676–1688)

The warm phase of the LMM was observed not only in the Tatra Mountains but also in other regions of Poland (Przybylak et al. 2005; Przybylak 2008), as well as in Czech Republic (Brázdil 1996). Basing on historical sources Sadowski (1991)

Table 19.2 Selected statistic characteristics of the reconstructed average summer (JJA) temperature on the northern slopes of the Tatra Mountains. Deviations (Δt K) are calculated according to the average for normal 1961–1990 period (9.6°C)

Period	Number of years	Δt K	Standard deviation	Max Δt K	Year of max	Min Δt K	Year of min
1961–1990[a]	30	0.0	0.73	1.7	1963	–1.5	1978
1951–2000[b]	50	0.4	0.82	2.9	1992	–1.5	1978
1576–1675[c]	100	0.4	0.65	1.8	1661	–1.1	1625
1645–1715[d]	71	0.6	0.89	2.6	1687	–0.9	1663
1645–1675[e]	31	0.1	0.65	1.8	1661	–0.9	1663
1676–1715[f]	40	1.0	0.87	2.6	1687	–0.4	1695
1676–1688[g]	13	1.6	0.78	2.6	1687	–0.1	1677
1689–1699[h]	11	0.2	0.44	0.9	1693	–0.4	1695
1700–1715[i]	16	1.1	0.71	2.1	1702	–0.2	1709
1716–1789[j]	74	0.7	0.60	2.7	1739	–0.5	1741
1790–1820[k]	31	0.3	0.99	2.4	1811	–1.3	1805

[a] standard WMO normal period.
[b] the second half of the twentieth century.
[c] relatively cool period – the second phase of the Little Ice Age.
[d] Maunder Minimum.
[e] the first phase of Maunder Minimum.
[f] Late Maunder Minimum.
[g] the warm phase of the Late Maunder Minimum.
[h] the cool phase of the Late Maunder Minimum.
[i] the last phase of the Late Maunder Minimum.
[j] the period with relatively high solar activity.
[k] Dalton Minimum – beginning of the last phase of the Little Ice Age.

recounted five hot summers in the period 1680–1689. During the thirteen-year period summer temperatures were 1.6 K warmer than normally (Table 19.2, Fig. 19.1). Exceptionally warm was the summer of 1687, with the mean temperature only 0.3 K lower than the warmest summer of 1992 in the whole 1550–2007 series. Very warm was also the summer of 1683. In the dendrochronological series of Kaczka (2004) as the warmest was recognized the summer 1686. This exceptionally warm period was not emphasized in West Central Europe (Glaser 2008) and Central England (Fig. 19.2; Manley 1974).

19.3.2 The Cool Phase of the Late Maunder Minimum (1689–1699)

This 11 summers were the coolest ones in the whole seventeenth century in the Tatra Mountains (Table 19.2, Fig. 19.1). The small variability of temperatures from year to year was also typical for this period. This cooling was noticed in the whole Central Europe (Luterbacher et al. 2004; Glaser 2008), the Alps (Frank and Esper 2005; Büntgen et al. 2006) and in Manley (1974) temperature series for Central England (Fig. 19.2). In the Tatra Mountains and other parts of Europe the summer of 1695 was noticed as the coolest one. Such large cooling was explained mainly by the intense volcanic activity in previous years: Hekla on Iceland and Serua

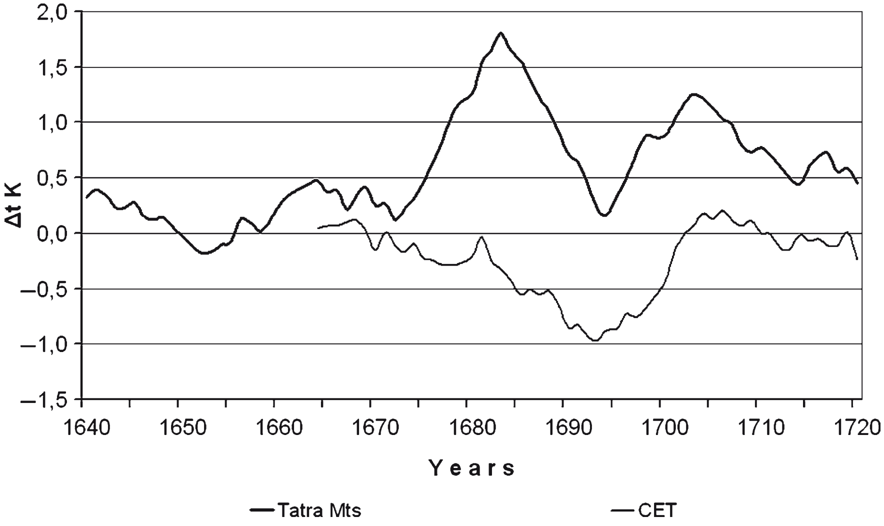

Fig. 19.2 Comparison of the summer temperature in Tatra Mountains and instrumental series of temperature for Central England (CET) after G. Manley (1974). Δt K – deviations from normal period (1961–1990) are smoothed by a 11-year moving averages. The graph covers the period 1640–1720. The first 11-year moving average on 1635–1645 is centred on 1640, the last one on 1715–1725 is centred on 1720

(Indonesia) in 1693, and Aboino (Indonesia) in 1694 (Grove 1988). It caused the large expansion of glaciers in the Alps during 1690–1720.

19.3.3 The Last Phase of the Late Maunder Minimum (1700–1715)

The last phase of the LMM in the Tatra Mountains was relatively warm (Table 19.2, Fig. 19.1), but with fluctuations of temperature from year to year and a decreasing trend. The warmest summer was at the beginning of the period: in 1702. The coolest one in 1709. The first decade of the eighteenth century was also very warm in the Czech Republic (Brázdil 1992). The large variability of temperature during this period was also typical for the Alps (Luterbacher et al. 2001).

19.4 The Periods After the Maunder Minimum (1716–1820)

After the MM started the 74-year long period (1716–1789) with a relatively high solar activity. In the Tatra Mountains this period was 0.7 K warmer than a normal one (Table 19.2). Significant temperature variability, with lots of extremes was observed between 1716 and 1736. Exceptional were summer frosts in 1716, and snowfalls in July and August of 1724, which appeared in lower parts of the Tatras (Niedźwiedź 2004). Three very warm summers appeared in years 1737–1739. Summer of 1739 was the warmest during the eighteenth century (Δt +2.7 K), as well as the second warmest in the whole reconstructed temperature series. Two cold phases were noticed in 1741–1745 and 1762–1772. The summer of 1741 was the coolest in the eighteenth century (Δt −0.5 K).

After this relatively warm periods, at the end of the eighteenth century a very intense cooling, connected with the Dalton Minimum (1790–1820) of solar activity, started. It was a beginning of the last phase of the LIA. Summer temperatures in the Tatra Mountains were even lower than during the MM (Table 19.2). The lowest temperatures were observed in 1805 (Δt −1.3 K). In Western Europe the most evident was an extremely cool and wet summer of 1816, which was named “the year without a summer” (Grove 1988), but as the recalled data show, in the Tatra Mountains and other parts of Poland this summer was not so extreme.

19.5 Conclusions

This paper presents main features in variability of summer temperatures in the Tatra Mountains during the Maunder Minimum (1645–1715) and during the adjacent periods.

- The period of MM is not homogeneous and can be divided into two phases.
- The first phase (1645–1675) is a relatively cool and is a part of the second phase of LIA (1576–1675).
- The second phase of MM – Late Maunder Minimum (1676–1715) is characterised by relatively great and irregular changes in air temperature.
- A cool part of LMM (1689–1699) is in Tatra Mountains not so extreme as a strong cooling during the Dalton Minimum (1790–1820).
- The warmest summer temperature during MM is indicated in 1687, and coolest in 1663.
- Large similarities exist in the long-term course of summer temperatures in the Tatra Mountains and in other parts of Central Europe, except the warm episode 1676–1688 at the beginning of LMM.

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Chapter 20
Seasonal Differentiation of Maximum and Minimum Air Temperature in Cracow and Prague in the Period 1836–2007

Katarzyna Piotrowicz

20.1 Introduction

The latest, fourth IPCC (2007) report states that mean temperature on Earth increased by approximately 0.74°C between 1906 and 2005. In the northern hemisphere, the second half of the twentieth century was the warmest period since almost 1,000 years ago (IPCC 2007). Increases in temperature were also observed in a large part of Europe during the twentieth century (Yan et al. 2002; Moberg and Jones 2005; Alexander et al. 2006; Moberg et al. 2006). The pace of these changes was fastest within the last quarter of the century (Frich et al. 2002; Klein Tank and Können 2003).

The observable increase in mean annual air temperature is not synchronic in all parts of the globe, neither spatially nor seasonally (Frich et al. 2002; Klein Tank and Können 2003; Beniston and Stephenson 2004; Moberg and Jones 2005; Alexander et al. 2006; Brohan et al. 2006). It is common knowledge that air temperature changes are subject to zonal and regional variability. Some regions of the world are heated more than others, while temperatures in other parts of the globe may even drop (Frich et al. 2002; Klein Tank et al. 2002; Alexander et al. 2006; Moberg et al. 2006; IPCC 2007). Studies of seasonal variability of air temperature indicate that in wintertime, temperatures increased most in Central and Eastern Europe – up to 3.5°C/10 years (Brázdil et al. 1996; Jones et al. 2002; Wibig and Głowicki 2002). In northern Europe, winter temperatures slightly decreased. Summer temperature trends did not exhibit a single direction of change either; however, temperatures predominantly tended to decrease rather than increase. As far as autumn is concerned, an almost unchanging growing trend of air temperature has been recorded in Europe over the last 100 years (Schönwiese et al. 1994).

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According to Alexander et al. (2006) warming can be observed in all the seasons; generally speaking, March to May exhibit the largest and September to November the smallest change. Thus, it seems that the issue of the direction of change of the multi-annual course of air temperature on a regional, or even on a local scale, remains unsolved.

Kożuchowski and Marciniak (1986) state that climate changes are more visible at higher latitudes than in the equatorial belt, and in winter rather than in summer months. This statement is also partly confirmed by the latest research (Frich et al. 2002; Jones et al. 2002; IPCC 2007). Moreover, deviations from mean multi-annual air temperature values are greater in the interior of the continents located in the temperate and polar zones. In consequence, research on climate change conducted in temperate regions, at high latitudes and in the interior of continents, is especially important. According to Bryson (1974), climatic conditions of such frontier areas are a particularly sensitive indicator of climatic oscillations. Central Europe, which covers Poland and the Czech Republic, among other countries, is located precisely at a temperate latitude, in an area where oceanic and continental air masses collide.

One of the elements used to describe the thermal conditions of a certain town or region is an analysis of extreme (minimum and maximum) values of air temperature. According to Kłysik and Fortuniak (1995), the changeability of extreme temperatures is the simplest indicator of climate change. In recent years, interest in the extreme values of various meteorological elements has grown considerably. Said elements are perceived as a more sensitive indicator of climate change than mean temperature values (IPCC 2007). Average trends, for 75 stations mostly representing west Europe, show a warming for maximum and minimum temperature (Moberg et al. 2006). According to Alexander et al. (2006) in Europe the changes in minimum temperature extremes are higher than of maximum temperature extremes. Winter has, on average, warmed more (1.0°C/100 years) than summer (0.8°C/100 years), both for daily maximum (Tmax) and minimum (Tmin) temperatures (Moberg et al. 2006). The magnitude of the trends is also generally greater for minimum temperature (Alexander et al. 2006). This has also been confirmed by results of research conducted by other authors (Yan et al. 2002).

According to scientists drafting IPCC (2007) reports, as a consequence of the increase in temperature, the number of cold and frosty days is set to decrease, while the frequency of occurrence of hot and very hot days is likely to grow. Over 70% of the global land area sampled showed a significant decrease in the annual occurrence of cold nights and a significant increase in the annual occurrence of warm nights (Alexander et al. 2006). Frich et al. (2002) obtained similar results.

Analysing particularly long and homogenous measurement series is a basis for a reliable evaluation of the variability and climate change trends (Moberg et al. 2006; Lorenc 2007). Such series are not very frequent in Europe (Jones et al. 2002), which is why the results of research involving an analysis of the multi-annual course of individual meteorological elements are so important, especially when compared with other stations. It is thanks to them that it is possible to estimate a regional variability of the changes or the overall variability of climate.

Numerous studies on climate change in Europe have been published in recent years, focusing on the regional scale. The investigations are mostly based on mean annual or seasonal air temperature values (Brunetti et al. 2000; Yan et al. 2002; Degirmendžić et al. 2004; Moberg and Jones 2004, 2005; Lorenc 2007). According to the author, studies on the seasonal differentiation of climate are especially valuable, as a great variability of air temperature of individual seasons has been observed since the 1990s (Kożuchowski et al. 2000; Kożuchowski and Żmudzka 2001; Wibig and Głowicki 2002).

The study presents an analysis of the annual differentiation and change tendencies of minimum and maximum air temperature at meteorological stations which are representative of the climatic conditions prevalent in urban areas of Central Europe, located below 300 m a.s.l. Besides natural factors such as relief, hydrologic relations or vegetation, also the economic activity of man (build-up, industry, transport, etc.) exerts considerable influence on the climate of such cities. However, it is not possible to state clearly whether the contemporary warming is caused by climate fluctuations or rather by anthropogenic factors. Nevertheless, if we compare the change tendencies of minimum and maximum air temperatures in Cracow and Prague, it is possible to assess the regional differentiation of the climate of this part of Europe, especially since the Cracow series of daily Tmax and Tmin has not been included in any of more large-scale analyses that have been undertaken (Brázdil et al. 1996; Wibig and Głowicki 2002; Moberg et al. 2006). Prague series has been used, but only rarely.

20.2 Data and Methods

The paper draws on the daily values of maximum (Tmax) and minimum (Tmin) air temperature measured at the Historic Station in Cracow (50°04′N, 19°58′E, 220 m a.s.l.) and in Prague-Klementinum (50°05′N, 14°25′E, 197 m a.s.l.) between 1836 and 2007. Available are only the data for the last 172 years, although both stations were established much earlier. Today they both possess series of air temperature measurements – the Prague series starts in 1775 whereas Cracow’s series dates back to 1792.

The data, especially concerning mean monthly temperatures, have repeatedly been compared with other stations and with one another, and deemed homogeneous (Trepińska 1984; Brázdil and Budíková 1999; Kyselý 2002). Thus far, the daily values of extreme temperatures from the two stations have not been compared.

In Cracow, extreme thermometers (maximum and minimum ones) have only been in use since the 1st of July 1837. Earlier values, obtained between the 1 January 1836 and the 30 June 1837 have been reconstructed, applying measurements taken at 7, 12, 15 and 21 Cracow local time of observation. Maximum temperature values for this period may be slightly lower than they really were, and the values of minimum temperature may by higher, which will be taken into consideration in the conclusions.

Both stations posses quite detailed documentation of the instrumental position and observation routines (Trepińska 1982; Brázdil 1993; Kożuchowski et al. 1994; Brázdil and Budíková 1999). In Cracow, they were not altered throughout the entire analysed period (Trepińska 1982), while in Prague before 30 May 1889, the location of the thermometers was changed several times (Brázdil and Budíková 1999; Kyselý 2002). According to Hlaváč (1937, see Brázdil 1993; Brázdil and Budíková 1999), the aforementioned changes have not affected the homogeneity of the measurements.

The present study describes the variability of extreme air temperatures in individual months and seasons. The trends of their changes in the multi-annual period have been investigated, alongside the change tendency of the so-called characteristic days, i.e. days with severe frost (Tmax < −10°C), frosty (Tmax < 0°C), hot (Tmax > 25°C) and very hot (Tmax > 30°C) ones. Apart from analyzing the values for individual months or quarters representing the seasons, the dates of the beginning and end of thermal seasons have also been determined individually for each year.

20.3 The Tendencies of Change of Maximum and Minimum Air Temperature

Between 1836 and 2007, the mean annual maximum temperature of the air in Cracow equalled 12.8°C and 13.1°C in Prague. It was by 0.3°C higher in Prague. In the case of minimum air temperature, the difference was greater. It amounted to 1.4°C (Table 20.1). The mean multi-annual value of Tmin in Cracow equalled 4.6°C, and 6.0°C in Prague. Other mean values for individual months have been listed in Table 20.1.

Analysing the mean monthly values of air temperature between 1826 and 1975, Trepińska (1984) stated that all seasons are warmer in Prague than in Cracow. A comparison of the Tmax values for the last 172 years showed that in summer and autumn, as well as from April to October, Tmax was higher (up to 0.4°C in May) in Cracow than in Prague, or they were equal (Table 20.1). Mean values of Tmin were always higher in Prague.

The values of standard deviation presented in Table 20.1 indicate a slightly greater variability of air temperature in Cracow. The mean maximum temperatures of July, August, summer and year were characterized by a slightly higher variability in Prague. Trepińska (1984) also pointed put that the situation is similar in the case of mean temperature.

In the multi-annual course of maximum and minimum air temperature in individual seasons (Fig. 20.1), it is possible to observe a gradual increase from the beginning of the analysed period onwards. The following were the warmest seasons in terms of Tmax and Tmin in Cracow and Prague: spring of 2007, summer of 1992, 2003, 2007, autumn of 2000 and 2006 and winter of 1989/90 and 2006/07. These values are enough to be able to state that particularly warm seasons

Table 20.1 Mean monthly and seasonally maximum (Tmax) and minimum (Tmin) air temperatures (°C) and their standard deviations (σ) in Cracow and Prague in the period 1836–2007

Months	Cracow				Prague			
seasons	Tmax	σ	Tmin	σ	Tmax	σ	Tmin	σ
Jan	0.1	3.2	–5.4	3.7	1.5	2.9	–3.0	3.2
Feb	2.0	3.4	–4.3	3.8	3.2	3.1	–2.1	3.4
Mar	7.0	3.0	–0.7	2.5	7.7	2.7	0.9	2.1
Apr	13.6	2.3	4.1	1.6	13.5	2.2	5.1	1.5
May	19.4	2.2	9.0	1.6	19.0	2.2	9.8	1.5
Jun	22.8	1.8	12.4	1.2	22.5	1.8	13.3	1.2
Jul	24.5	1.7	14.1	1.2	24.2	1.9	15.0	1.1
Aug	23.7	1.6	13.5	1.2	23.5	1.8	14.5	1.1
Sep	19.3	1.9	9.8	1.3	19.3	1.9	11.0	1.2
Oct	13.4	2.2	5.4	1.7	13.2	1.8	6.5	1.5
Nov	6.2	2.3	0.6	2.1	6.5	2.0	2.1	1.8
Dec	1.6	2.8	–3.4	3.1	2.7	2.6	–1.3	2.7
Year	12.8	1.0	4.6	1.1	13.1	1.1	6.0	0.9
Spring	13.3	1.7	4.1	1.4	13.4	1.6	5.2	1.2
Summer	23.6	1.2	13.3	0.9	23.4	1.3	14.3	0.8
Autumn	13.0	1.4	5.3	1.2	13.0	1.3	6.6	1.0
Winter	1.2	2.3	–4.4	2.5	2.5	2.1	–2.1	2.2

were registered at the end of the twentieth century and at the beginning of the twenty-first century; their temperature can be counted among the highest values recorded since the beginning of instrumental measurements. Such a concentration of warm years and seasons occurred simultaneously at both of the analysed stations (Fig. 20.1).

The change tendencies of Tmax and Tmin were calculated on the basis of linear regression for the entire period in question (Table 20.2). The greatest increase was observed for Tmin in Cracow. In December, said temperature increased by 2.32°C/100 years and in January and winter by 2.25°C/100 years. In Prague, Tmax increased more than Tmin. The growing trend of Tmax resulted to be especially significant in March (2.17°C/100 years).

In Cracow, in summer as well as in the three individual months of said season, the maximum temperature of air did not exhibit and tendency of change. The gradients assume the values from –0.24 in June to 0.47 in August, but they are not statistically significant. In Prague, however, Tmax significantly rose in individual months and seasons within the last 172 years (Table 20.2).

In spring Tmin and Tmax rose at a comparable rate in Cracow (1.38 and 1.48°C/100 years, respectively). In turn, in Prague, the increase in Tmax was faster (1.89°C/100 years) than the one in Tmin (1.17°C/100 years).

The rate of changes in temperature is lowest in autumn, although it is still characterised by higher and higher values. In Cracow Tmin increased somewhat faster (1.26°C/100 years) than in Prague (0.84°C/100 years), whereas Tmax increased faster in Prague (1.17°C/100 years) than in Cracow (0.70°C/100 years).

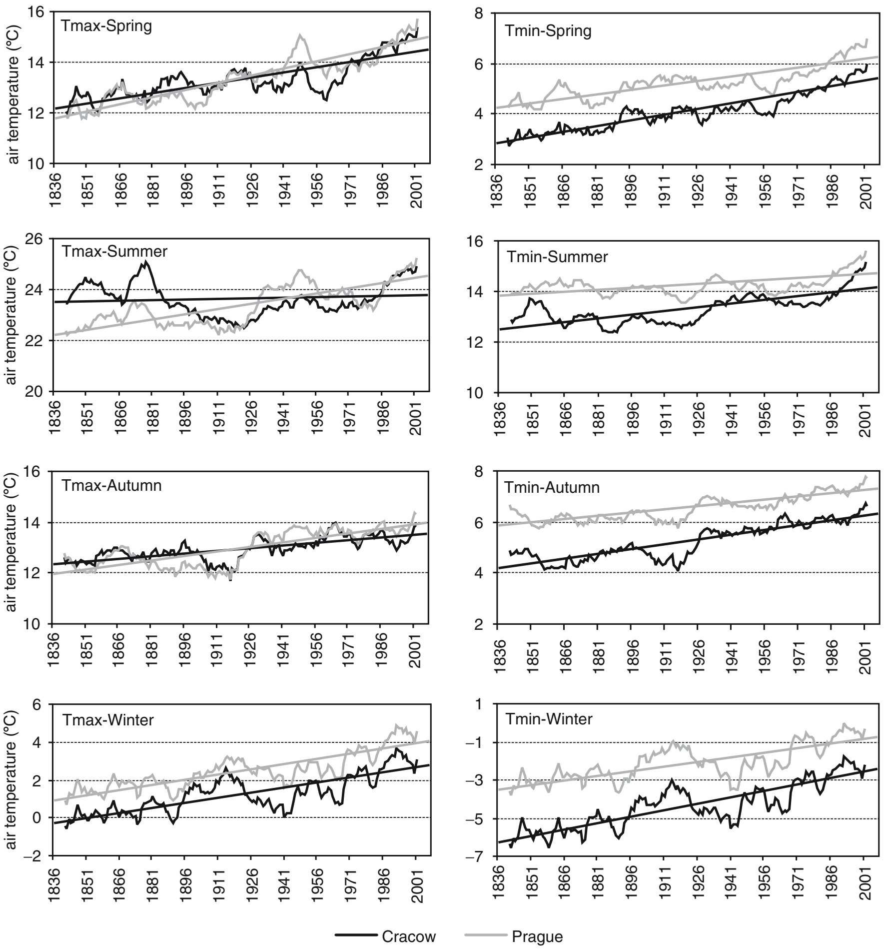

Fig. 20.1 Courses of maximum (Tmax) and minimum (Tmin) air temperatures smoothed by 11-year moving average and their linear trends in Cracow and Prague in the period 1836–2007

Summing up, it can be stated that the rate of changes in Tmax and Tmin is not the same in all the seasons in both cities, although they are located at a similar latitude (50°N) and altitude (ca. 200 a.s.l.) and in the centre of large cities. The direction of change in air temperature, however, is almost the same. Summer temperature is an exception. That is why, in order to conduct a detailed analysis of the variability of the maximum air temperature, its tendencies and the dynamics of change at both stations, it was also necessary to investigate the seasonal distribution of hot, very hot and frosty days as well as days with severe frost.

Table 20.2 Coefficients of the linear trend equation (°C per 100 years) of the mean monthly and seasonally maximum (Tmax) and minimum (Tmin) air temperatures in Cracow and Prague in the period 1836–2007

	Cracow		Prague	
Months seasons	Tmax	Tmin	Tmax	Tmin
Jan	1.88	2.25	1.87	1.79
Feb	1.45	2.09	1.70	1.42
Mar	1.78	1.88	2.17	1.59
Apr	1.28	1.37	1.66	1.01
May	1.07	1.20	1.85	0.91
Jun	–0.24[a]	0.72	1.27	0.38[a]
Jul	0.27[a]	1.03	1.49	0.61
Aug	0.47[a]	1.13	1.36	0.54
Sep	0.10	1.05	0.81	0.62
Oct	0.53	0.87	1.00	0.55
Nov	1.46	1.88	1.69	1.36
Dec	1.97	2.32	1.79	1.60
Year	1.00	1.48	1.56	1.03
Spring	1.38	1.48	1.89	1.17
Summer	0.17[a]	0.96	1.37	0.51
Autumn	0.70	1.26	1.17	0.84
Winter	1.79	2.25	1.80	1.61

[a] Not significant coefficients at the 0.05 level.

20.4 The Tendencies of Change of the Number of Hot Days (Tmax > 25°C) and Very Hot Days (Tmax > 30°C)

The mean number of hot and very hot days between 1836 and 2007 in Cracow equalled 43.2 and 7.2, respectively. In Prague these values amounted to 39.2 and 5.8 days. These values show that said days occur with a slightly greater frequency in Cracow. However, in the multi-annual course, there were periods when there were more days with Tmax > 25°C and Tmax > 30°C in Prague (Fig. 20.2). Nevertheless, there is a strong correlation between the occurrence of these days in Cracow and Prague. The correlation coefficients equalled 0.610 (Tmax > 25°C) and 0.427 (Tmax > 30°C). Lower values of the coefficient for very hot days indicate greater influence of local conditions on the frequency of their occurrence. A more detailed analysis of the occurrence of hot and very hot days in Cracow can be found in the author's earlier works (Piotrowicz 2003b; Piotrowicz and Wypych 2006). Said works describe the occurrence of series of such days.

Since the 1950s, it has been possible to observe a gradual increase in the frequency of occurrence of hot and very hot days in Cracow and Prague (Figs. 20.2 and 20.3). The calculated values of the trend for the number of days with Tmax > 25°C equalled 4.5 in Cracow and 3.6 days/10 years in Prague, and for days with Tmax > 30°C they equalled 1.8 and 1.5 days/10 years. The rate of change of said

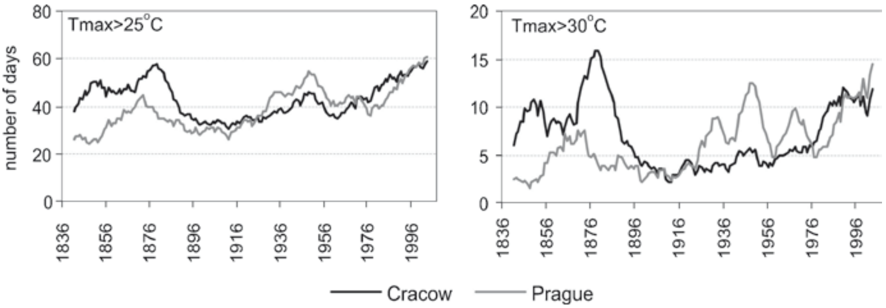

Fig. 20.2 Courses of number of hot (Tmax > 25°C) and very hot days (Tmax > 30°C) smoothed by 11-year moving average in Cracow and Prague in the period 1836–2007

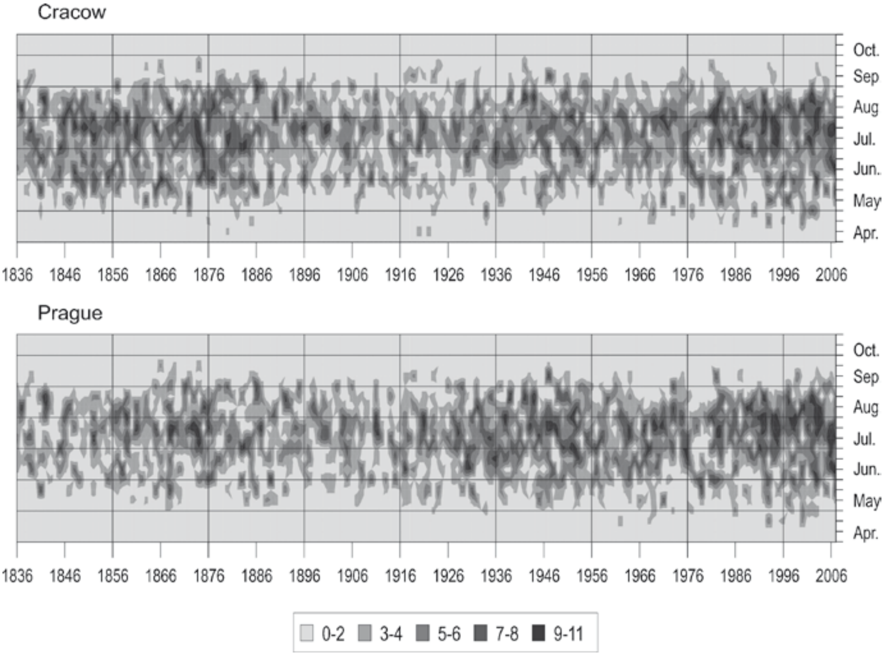

Fig. 20.3 Number of hot days (Tmax > 25°C) in particular 10-days period in Cracow and Prague in the period 1836–2007

days is somewhat greater in Cracow. Comparing the results obtained in the previous chapter, it is possible to draw a conclusion that despite the lack of the tendencies of change of maximum temperature in the summer season in Cracow, the frequency of occurrence of hot and very hot days increases. Unfortunately such a conclusion might result to be wrong if the seasonal differentiation of the occurrence of the analysed days is not checked previously.

In Cracow and Prague, days with Tmax > 25°C occur from April to October. The potential period of the occurrence of very hot days is slightly shorter. In Prague, it lasts from May to September and in Cracow from April to September.

Since the 1960s, it has been possible to notice an increase in the frequency of the occurrence of hot days in the third decade of April and in May (Fig. 20.3). It is statistically significant at the level of 0.05. The increase in maximum temperature in spring and in May is related to, among other things, the increased number of days with Tmax > 25°C. An analysis of the multi-annual course of days with Tmax > 30°C did not show any significant changes in the seasonal differentiation of these days.

20.5 Tendencies of Change of Frosty Days (Tmax < 0°C) and Days with Severe Frost (Tmax < −10°C)

The climate of Central Europe is characterised by the occurrence of frosty days and days with severe frost in wintertime. Due to the increase of air temperature in winter, a decrease in the number of days with Tmax < 0°C and Tmax < −10°C can be expected.

In the entire analysed multi-annual period, the decrease in the number of frosty days equalled 27.7 in Prague and 23.7 days in Cracow, and in the number of days with severe frost, it equalled 1.8 and 3.9 days. The slower rate of these changes is related to the fact that they do not occur every year. Even during very mild winters they can be registered both in Cracow and in Prague. The reason for their occurrence is the advection of cold air masses, which most of the time encompass a large part of the continent. It is possible to assume that in the case of air temperature in wintertime, its course is synchronic in large areas of Central Europe. This can be confirmed e.g. by the multi-annual course of frosty days and days with severe frost in Cracow and Prague (Fig. 20.4) and the calculated correlation coefficient. It equalled 0.915 in the case of Tmax < 0°C and 0.589 for Tmax < −10°C.

Most often, days with severe frost occur in January and other winter months. However, they can also be registered in October and November and in March and April (Piotrowicz 2003a). Since 1836, the potential period of occurrence of frosty days has been growing significantly shorter (Fig. 20.5). The first day with Tmax < 0°C occurred about 20 days later than at the beginning of the analysed period. The last day, in turn, was recorded 20 days earlier, both in Cracow and Prague. Thus, the potential occurrence period is a month shorter than it used to be in the nineteenth century.

At the analysed stations, days with severe frost first occurred in November, but they were more frequent in Prague (1.1% of all days) than in Cracow (0.8%). In Cracow, days with Tmax < −10°C also occurred in March, and in Prague they were last recorded in February. In the multi-annual period, the time span of their occurrence did not change as significantly as in the case of days with Tmax < 0°C. These days occur most frequently in the three winter months, from December to February.

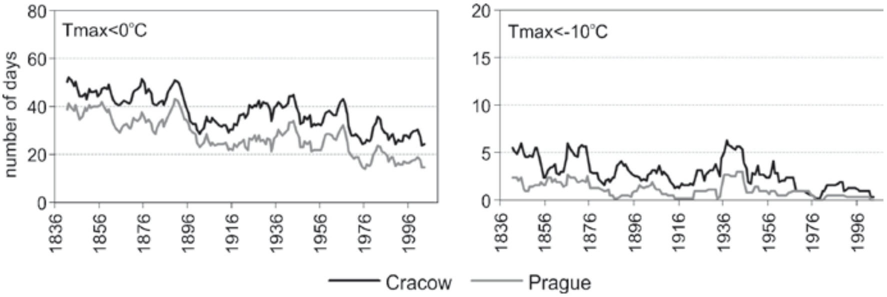

Fig. 20.4 Courses of number of frosty days (Tmax < 0°C) and days with severe frost (Tmax < −10°C) smoothed by 11-year moving average in Cracow and Prague in the period 1836–2007

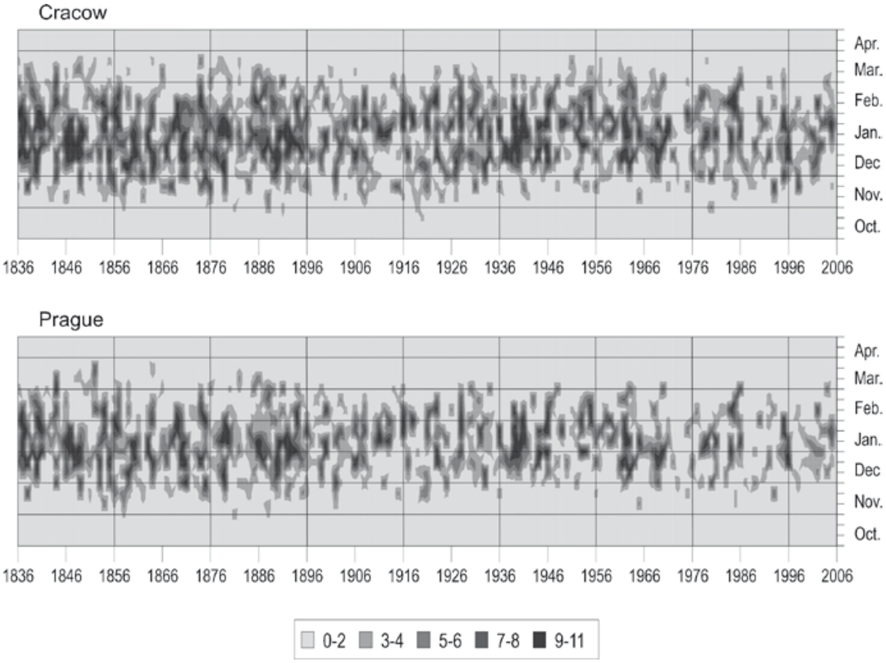

Fig. 20.5 Number of frosty days (Tmax < 0°C) in particular 10-days period in Cracow and Prague in the period 1836–2007

20.6 Discussion and Conclusions

The analysis of maximum and minimum air temperature variability in Cracow and Prague presented in the paper refers to the tendencies of change in the thermal conditions in Central Europe (Klein Tank et al. 2002; Yan et al. 2002; Klein Tank and Können 2003; Alexander et al. 2006; Moberg et al. 2006). The increase in temperature in Cracow and Prague was in most cases synchronic. The correlation coefficients between the course of Tmax and Tmin and the number of characteristic days (hot, very hot, frosty and days with severe frost) indicate the uniformity of thermal anomalies in a large part of Central Europe. In winter, these correlations are very high (the coefficient equals 0.8, 0.9), whereas in summer and in the course of days with Tmax > 25°C and Tmax > 30°C they are smaller (0.4–0.6), although statistically significant at the level of 0.05. This may result from clear differences in the course of summer temperature at both stations before 1890 (Fig. 20.1). Probably, the homogeneity of the series was disrupted, especially in the case of Tmax. For the January 1836 – June 1837 period, in Cracow, Tmax and Tmin were obtained from main-observation-time values. As mentioned in the “Data and methods” section, the reconstructed Tmax values for Cracow are certainly lower than it would seem from the reading of a maximum thermometer, while in Prague, the thermometers were relocated several times before 1890. According to Kyselý (2002), although the observations have been continuous since 1775, the years 1901–97 are mainly examined, as the period with the most credible data.

An analysis of monthly, seasonal and annual mean values of Tmax and Tmin in Cracow and Prague within the last 172 years showed that maximum temperature from April to October, as well as that in summer and autumn, was usually higher in Cracow than in Prague. In the case of Tmin, the station in Prague recorded higher temperatures. Generally, also the variability of the analysed temperatures is greater in Cracow, both from year to year and in individual seasons. Only the mean values of Tmax for July, August, summer and the entire year were characterized be a slightly greater variability in Prague.

In the multi-annual course, it is possible to notice a gradual increase in air temperature in Cracow and Prague. Years and seasons at the turn of the twenty-first century were very warm. In many cases they could be counted among extreme values. These were the highest air temperatures since the beginning of instrumental observations. These results are consistent with analyses conducted for other stations in Europe and in the world (Frich et al. 2002; Wibig and Głowicki 2002; Degirmendžić et al. 2004; Alexander et al. 2006; Moberg et al. 2006).

In Cracow, since 1836, the greatest increase in temperature has occurred in the case of Tmin, especially in December, January and winter. In Prague, maximum temperature, especially in March, was characterized by the greatest growing trend.

In Cracow in summer, maximum air temperature did not show a clear tendency of change (neither was it statistically significant), whereas in Prague it increased significantly. However, this regional differentiation, identified on the basis of a

172-year-long measurement series, is in line with the results of research carried out by other authors (Yan et al. 2002; Moberg and Jones 2004; Alexander et al. 2006; Moberg et al. 2006).

The rate of changes of Tmax and Tmin in intermediate seasons in Cracow and Prague was comparable. It was slightly greater in spring than in autumn.

In order to conduct an in-depth analysis of the variability of maximum air temperature, its trends and the dynamics of change at both of the analysed stations, it was necessary to investigate the seasonal distribution of the number of characteristic days: hot, very hot, frosty and days with severe frost. An important decrease in the number of frosty days and days with severe frost was observed at both stations. The potential period of their occurrence became a month shorter. However, in spite of the occurrence of very mild winters in recent years, days with Tmax < 0°C or even Tmax < −10°C can occur, although with low frequency, from November to March (Tmax > 0°C) or from December to February (Tmax < −10°C) and in Cracow even to March.

The number of hot and very hot days, especially since the 1950s, has increased at both stations. More and more often, they are recorded earlier, at the end of April and in May. It results that, in spite of a very clear tendency of change in summer temperature, days with Tmax > 25°C and Tmax > 30°C have started occurring more and more often.

Many studies analysing both mean and extreme temperature change tendencies have been published recently. They draw on multi-annual measurement series from stations representing various climatic regions of Europe, as well as on data obtained by means of re-analyses (Klein Tank et al. 2002; Moberg and Jones 2004; Moberg et al. 2006).

According to some researchers, the temperature rise in recent decades is basically associated with an increase in warm extremes, rather than with a reduction in cold extremes (Klein Tank and Können 2003; Yan et al. 2002). However, other authors have reached the opposite conclusion. Alexander et al. (2006) point out that generally a much larger percentage of land area in Europe shows significant change in minimum temperature extremes than in maximum temperature extremes implying that in many places, our world has become less cold rather than hotter. It is especially obvious in the case of a clear decrease in the annual occurrence of cold nights. The results included in this study are in line with this suggestion.

Thus, an analysis of temperature change tendencies for various periods may lead contradictory results. Klein Tank and Können (2003) investigated the trends in indices of climate extremes on the basis of daily series of temperature observations from more than 100 meteorological stations in Europe between 1946 and 1999. They noticed that if the period is split into two sub-periods (1946–75 and 1976–99), the tendencies of change are not “symmetrical” – warming of the cold and warm tails of the distributions of daily minimum and maximum temperature in Europe. This is further confirmed by the results of research carried out by Moberg et al. (2006).

The causes of the analysed variability of thermal conditions in Central Europe are still unclear. It seems that natural factors, such as atmospheric circulation, play an important role. They are intensified by anthropopressure, e.g. the urban heat island.

The observed increase in temperature considerably exceeds the natural changeability of the climate (IPCC 2007). Philipp et al. (2007), for the period 1850–2003, explored long-term changes of the atmospheric circulation and its impact on long-term temperature variability in the central European region. The preliminary results of their research indicate that tentative estimations of central European temperature changes based solely on seasonal cluster frequencies can explain between about 34% (summer) and 59% (winter) of temperature variance on the seasonal time scale. Also Yan et al. (2002) believe that changes in atmospheric circulation lead to changes in temperature.

According to Scaife and Folland (2008) North Atlantic Oscillation may influence air temperature changes in the winter season in Europe. However, it is unknown whether the observed rate of changes in atmospheric circulation and the NAO will persist in the coming decades.

As the IPCC (2007) report states, climate changes can be attributed to human activity with a 90% probability. Alongside other researchers, also Stott et al. (2004) attribute temperature increases to anthropogenic factors.

Anthropogenic factors, including the urban heat island (UHI), influenced the increase in maximum and minimum temperature in the entire analysed period in Cracow and Prague alike. Brázdil and Budíková (1999) analysed the impact of the UHI on seasonal and annual temperature values in Prague Klementinum, using measurement data from stations located outside the city for the years 1922–1995. Urban warming was most conspicuous in winter and in spring (0.063°C/10 years), and the smallest and least significant in summer (0.01°C/10 years). These values are somewhat higher than previously estimated (Brázdil 1993). Since the 1960s, a stagnation in the development of the UHI has appeared (Brázdil, Budíková 1999). The degree of urban warming prior to 1922 is difficult to assess because of a lack of a suitable set of homogeneous reference stations. When analyzing the values of air temperature in Cracow and two selected nearby cities, Kożuchowski et al. (1994) noticed an increasing trend of air temperature in neighbouring stations, but it was two twice as small (0.11ºC in 10 years) as the one in Cracow (0.24ºC in 10 years). According to Trepińska and Kowanetz (1997), however, it seems impossible to consider the contemporary warming process a result only of the development of the city. The influence of growing urbanization cannot dominate natural processes, which take place in the atmosphere above Cracow (Trepińska and Kowanetz 1997).

It is also worth considering, like Kożuchowski and Żmudzka (2001) did, whether the increase in maximum and minimum temperature is permanent, or if it is only a short-term oscillation.

The measurement series from Cracow and Prague have been considered as referential ones and are used to complete the missing data from other stations. In consequence, learning more about the change tendencies of extreme temperatures at those stations and comparing them can be helpful in further climatologic analyses. In this kind of analyses, Central Europe is represented by a scant number of stations (Jones et al. 2002; Klein Tank and Können 2003; Moberg and Jones 2004; Moberg et al. 2006). The oldest measurement series ought to be investigated with special caution, as they can turn out not to be homogeneous. Moberg and Jones

(2005) were right in claiming that a larger number of stations possessing long-term homogeneous measurement series is indispensable to be able to explore the regional differentiation of temperature change tendencies, including temperature extremes. The station is Cracow can become one of them.

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Chapter 21
Climate Changes in the Central and North-Eastern Parts of the Polish-Lithuanian Commonwealth from 1656 to 1685

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21.1 Introduction

Developments in the study of historical climatology in recent decades are evident in many countries. Aside from the traditional methods which have been used up to now to reconstruct climate in historical times (documentary evidence, dendrochronological data etc.; for a review see e.g. (Bradley 1999)), a new, very promising, technique has recently become available for a more precise analysis of the marine and lake sediments, with significantly greater time resolution, acceptable for the analysis of climate change in a period of 1–2 millennia. This new technique, together with the traditional ones, allows us to improve our knowledge about historical climate variation. Improved knowledge, in turn, is very important for determining the range of climatic changes which were driven mainly by natural factors. It also allows us to more accurately determine the role of anthropogenic factors in current climate change. More complete information about the historical climate is also helpful for the validation of climate models.

In Poland in the last 10–20 years, significant research progress has been observed in the field of historical climatology. To reconstruct the history of the pre-instrumental climate in Poland, three types of proxy data have been used: documentary evidence, dendrochronological data and geophysical data (Majorowicz et al. 2004; Przybylak et al. 2005). As a result, our knowledge concerning the climate of Poland in the last millennium is markedly greater. For a review of present state of knowledge see e.g. (Majorowicz et al. 2004; Przybylak 2006, 2007; Przybylak et al. 2005) or Part 2.

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The aim of the present paper is to reconstruct climatic conditions and climate changes in the central and north-eastern parts of the Polish-Lithuanian Commonwealth (hereafter Poland) for the period 1656–1685 based on a diary written by Jan Antoni Chrapowicki. Chrapowicki was a nobleman who was a Vitebsk Voivode and a member of the Polish parliament. He began keeping his diary in 1656 and continued it up to his death on 3 November 1685. For more details see (Bokwa et al. 2001; Nowosad et al. 2007).

Researchers who have attempted to reconstruct Poland's climate history based on this diary have had a problem with the reliability of the source for the entire period. Unfortunately we only have the original edition of Chrapowicki's diary extant for the years 1656–1664 (Chrapowicki 1978). Fortunately, two independent handwritten copies of this diary have also survived, which were transcribed in the eighteenth (1786) and nineteenth (1852) centuries (Chrapowicki 1988). These copies, however, are not complete and contain many omissions, abbreviations and simplifications. Of these two copies, the eighteenth century one, covering all the years of the original diary, is particularly unreliable as regards weather details. On the other hand, the nineteenth century copy is significantly more faithful to the original diary, but only covers the years 1660–1667. Comparison of the weather notes in both copies for the same days for the common period (1665–1667) reveals that the eighteenth century copy contains significantly less information than the nineteenth century one, with the weather notes usually being shortened. On the other hand, similar comparison of the original diary and its nineteenth century copy for the years 1660–1664 shows insignificant differences. For more details as well as some examples see (Nowosad et al. 2007). As a result, studies which have been carried out up to now have analysed the climatic conditions in Poland only for the period 1656–1667 (e.g. (Bokwa et al. 2001; Nowosad et al. 2007)).

In the present paper, the climatic conditions of Poland for the whole period covered by the diary (1656–1685) are described for the first time. For this purpose, the eighteenth century copy of the diary was used for the years 1668–1685, but the temperature and precipitation data obtained were corrected (homogenised) based on the assumption that the climate during the whole study period was stationary. Analysis of the existing climate reconstructions for this period for Poland (Briffa et al. 2002; Przybylak et al. 2005) as well as for other areas in Europe (e.g. for the Netherlands: (Lamb 1977), p. 476) confirm the correctness of this assumption.

21.2 Area of Investigations

Chrapowicki was a politician, a member of Polish parliament and owner of many estates located in different areas of the Grand Duchy of Lithuania. He traveled extensively, frequently staying away from home for months at a time, both in order to maintain his estates and to participate in parliamentary sessions, which took place in 15 years of the study period (1658, 1659, 1661, 1664–1665,

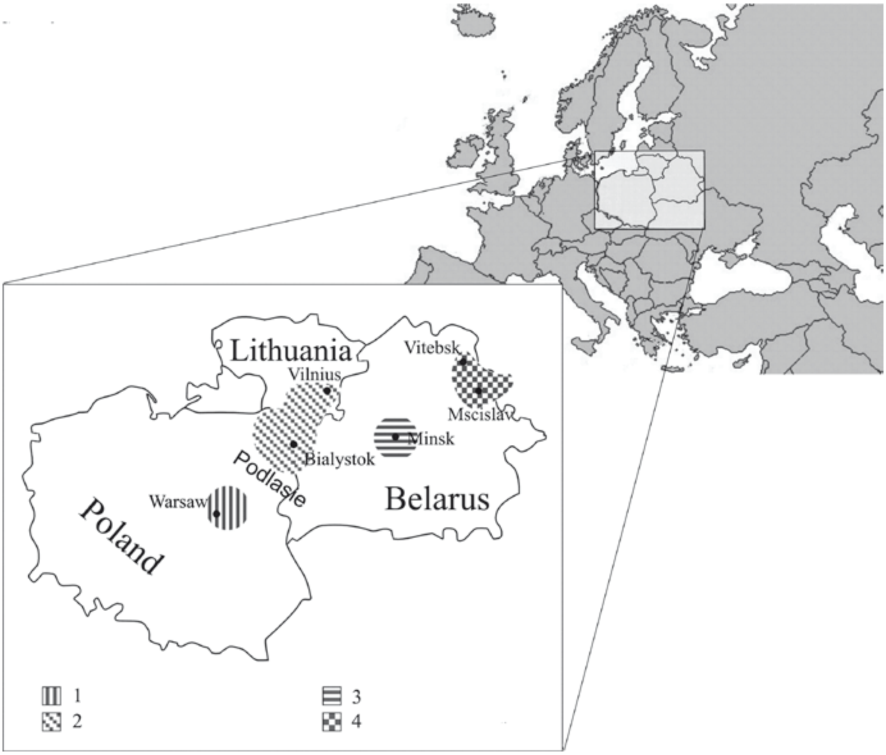

Fig. 21.1 Location of areas for which Chrapowicki's weather notes are available and the location of meteorological stations from which contemporary climate data were taken. 1 – the region of Masovia, 2 – Podlasie and the region of southern Lithuania, 3 – the region of Minsk, 4 – the region of Vitebsk and Mscislav

1667, 1668, 1669, 1670, 1673, 1674, 1677, 1681, 1683, and 1685). These sessions lasted, on average, over two months. Generally his stays were limited to the four areas shown in Fig. 21.1: the region of Masovia (Warsaw), Podlasie (Grodno) and the region of southern Lithuania, the region of Minsk, and the region of Vitebsk and Mscislav. For the first region, the majority of his weather notes come from Warsaw. On the other hand, entries for the other Masovian areas were most often made during his short trips from Lithuania to Warsaw and to home, which tended to last a few days. His stays in Podlasie and southern Lithuania tended to be long, lasting for over half a year in the years 1656–1659, 1662, 1665, 1671, and 1679. The fewest entries are available for his stays in the region of Minsk. His first visit here is dated 1660. From 1666 onwards his stays were more frequent but their duration was rather short, lasting from around 2 weeks to a couple of months. Finally Chrapowicki stayed very often in the region of Vitebsk and Mscislav between 1666 and 1685. The duration of the visits here varied from more than 10 days to about 5 months. For more details see (Nowosad et al. 2007).

21.3 Data and Methods

21.3.1 Historical Period

Chrapowicki's original diary (1656–1664) and its nineteenth century copy (1665–1667) (Chrapowicki 1978; Chrapowicki 1988) as well as the eighteenth century copy (1668–1685) (*Diaryusz Życia…*, 1786, vols. 2–7) have been used to reconstruct daily, monthly, seasonal and annual temperature and precipitation conditions. Chrapowicki was a very reliable observer of weather and was also very assiduous in chronicling it. As a result, there are only 408 days out of the whole period covered by the diaries for which there are no comments on the weather (about 4% of the whole period). Weather notes are also not available for another 200 days (see Table 21.1) due to the loss of some pages of both the original diary and its copies. For more details see (Nowosad et al. 2007).

The temperature characteristics for each day were classified as above normal (index +1), below normal (−1) or normal (0) using Chrapowicki's weather notes, though these are not always unequivocal. Therefore Table 21.2 provides an extensive list of the contents of these notes (written in the original old Polish) which were the basis for the above mentioned thermal classification. Please note that the same content of the entries in different months of the year may be interpreted in different ways (the day may be classified as normal in one month, while in another month it may be above or below normal etc.). That is why examples of notes are given for different months and seasons. Due to a significantly greater stabilisation of temperature in winter and summer, it was possible to use the same notes for thermal classification for all months belonging to these seasons. On the other hand, such an approach for transitional seasons is erroneous and therefore examples of the contents of weather for these seasons' notes are stratified into months. The average conditions in the historical period (which

Table. 21.1 Annual number of days for which weather notes are available in Chrapowicki's diary, 1656–1685 (After (Nowosad et al. 2007))

Year	Number of days	Year	Number of days	Year	Number of days
1656	326	1666	361	1676	359
1657	354	1667	354	1677	347
1658	357	1668	361	1678	356
1659	356	1669	267	1679	364
1660	360	1670	304	1680	358
1661	353	1671	341	1681	351
1662	358	1672	324	1682	289
1663	363	1673	320	1683	355
1664	359	1674	340	1684	346
1665	364	1675	351	1685	291

Table 21.2 List of the contents of Chrapowicki's notes, which were the basis for the thermal classification of days according to a three-degree scale. Indices: above normal (+1), normal (0) and below normal (−1)

Season		
Month	Index	Content of notes
December–February	+1	ulżyło, odelgło, ciepło, bez mrozu, ulżyło od mrozu, dobrze w dzień ugrzało, odwilgło bardzo, nie zimno, ciepło bardzo, kropił deżdż, pluskota, niemroźno, z rana mróz w dzień ugrzało, z rana przymrozek potem wolne zimno, nic nie marzło, dzień zimny ale bez mrozu, dziś odwilgło dobrze po tak ciężkich mrozach, wilgotny, plugawy, dzień z rana zimny
	0	mróz, śnieg padał, mróz mierny, zimno, pogoda zimna, mroźno, mróz w nocy w dzień odwilgło, marzło, dzień miernie zimny, mróz drobny, chłodny, miernie zimno, mróz wolny, poczęło trochę krzepnąc, dzień chłodny jednak, zimno, dzień pogodny
	−1	mróz potężny, mróz trzaskający, mróz szalony, mróz bardzo potężny, srogi mróz, potężny mróz trzaskający, mróz okrutny że trudno się ukazać było, dzień srodze mroźny, dzień srodze zimny, [dzień] niesłychanie mroźny, dzień niewypowiedzianie mroźny, mroźno srodze, dzień straszliwie mroźny, mróz ogromny, dzień niepamiętnie mroźny, mróz srogi i trzaskany, mróz nad moc srogi, mróz trzeszczący, mróz najsroższy, mróz okrutny, wielki mróz, mróz dobry, mróz porządny, mróz spory, mróz duży, dzień mroźny bardzo, dzień zimny bardzo, marznąć dobrze poczęło, przykro mroźny (dzień), mróz bardzo ostry, mróz rzyśki, ciężko mroźny, dzień cudownie mroźny, mróz tęgi, walny mróz, mróz ostry, mróz z srogim wiatrem, w nocy mróz spory a w dzień trochę ulżyło, w nocy mróz spory i pomarzło
March	+1	ulżyło, odelgło, ciepło, bez mrozu, ulżyło od mrozu, dobrze w dzień ugrzało, odwilgło bardzo, nie zimno, ciepło bardzo, dzień wszystek dżdżysty i plugawy, dzień cieplejszy po mroźnym dniu, ciepło, ciepło piękne, ciepło żyzne, dzień ciepły miernie, pluskota ze śniegiem, pogoda nie marzło, chłodno z rana, potem ugrzało, ciepło utemperowane
	0	mróz, pogoda z mrozem, mróz z wiatrem zimnym, śnieg padał, mróz mierny, przymrozek, nie tak zimny jednak, zimno, chłodno, w dzień nic nie ugrzało, nie bardzo zimny, śnieżny
	−1	mróz potężny, mróz trzaskający, mróz szalony, mróz bardzo potężny, srogi mróz, potężny mróz trzaskający, mróz okrutny że trudno się ukazać było, dzień srodze mroźny, dzień srodze zimny, [dzień] niesłychanie mroźny, dzień niewypowiedzianie mroźny, mroźno srodze, dzień straszliwie mroźny, mróz ogromny, dzień niepamiętnie mroźny, mróz srogi i trzaskany, mróz nad moc srogi, mróz trzeszczący, mróz najsroższy, mróz okrutny, wielki mróz, mróz dobry, mróz porządny, mróz spory, mróz duży, dzień mroźny bardzo, dzień zimny bardzo, marznąć dobrze poczęło, przykro mroźny (dzień), mróz bardzo ostry, mróz rzyśki, ciężko mroźny, dzień cudownie mroźny, mróz tęgi, walny mróz, mróz ostry, mróz z srogim wiatrem, w nocy mróz spory a w dzień trochę ulżyło, w nocy mróz spory i pomarzło dzień zimny bardzo, zimno bardzo, dzień srodze zimny
	+1	niesłychanie gorąco, dzień srodze gorący, dzień gorący, miernie gorący, nadto gorąco, ciepło, niezbyt gorąco, parno, parno srodze, ciepło żyzne, dzien majowy, dzień pogodny ciepły bardzo, pogoda z wiatrem ciepłym, ciepło (tylko do 10 IV)

(continued)

Table 21.2 (continued)

Season Month	Index	Content of notes
April	0	chłodno, w dzień nic nie ugrzało, nie bardzo zimny, dzień wszystek dżdżysty i plugawy, dzień cieplejszy (po mroźnym dniu), dzień ciepły miernie, dzień nie zimny, ciepło piękne, wiatr ciepły, ciepło utemperowane, w nocy mróz mierny a w dzień pogoda piękna, odwilgło, przymrozek, wiatr chłodny i zimno (do 15 IV), ciepło mierne
	−1	mróz, mróz dobry, mróz wielki, mróz spory, mróz mocny, mróz porządny, mróz potężny, mróz trzaskący, mróz niesłychany, zimno (do 15 IV), dzień zimny bardzo, dzień srodze zimny, śnieżny, wiatr spory i zimny bardzo, śnieg z deszczem
	+1	niesłychanie gorąco, dzień srodze gorący, dzień gorący, miernie gorący, nadto gorąco, niezbyt gorąco, parno, parno srodze, ciepło żyzne
May	0	ciepło, dzień ciepły miernie, dzień nie zimny, ciepło piekne, wiatr ciepły, ciepło utemperowane, dzień majowy
	−1	mróz, mróz trzaskący, mróz niesłychany, zimno, dzień zimny bardzo, dzień srodze zimny, śnieżny, chłodno, zimno bardzo, w dzień nic nie ugrzało, nie bardzo zimny, dzień wszystek dżdżysty i plugawy
	+1	gorąco, bardzo ciepło, gorąco bardzo, gorąco wielkie, dzień do podziwienia gorący, gorąco strasznie, srogi upał
June–August	0	ciepło, pięknie ciepło, dzień niegorący, miernie gorąco, parno, nie bardzo jednak chłodno, pogoda, pogoda piękna, deszcz przepadał czasem, deszcz często padał, dzień chmurny czasem
	−1	zimno bardzo, zimno srogie, srodze zimny, zimno, zimny, chłodno, dzień bardzo plugawy ze dżdżem, mróz, mróz wielki, mróz duży, mróz spory, dzień plugawy jak jesienny, dzień prawie jesienny, dzień różny i deszcz kropił, dzień miernej pogody
	+1	dzień bardzo piękny, gorący, ciepły bardzo, dzień ciepły wszystek jak na wiosnę, ciepły jako w lecie, dzień gorący bardzo, nadzwyczaj ciepły, miernie gorąco
September	0	ciepło, niezimno, ciepły dosyć, dzień pogodny, ciepły, wesoły, jak wiosenny, nie zimny jednak, dzień pogodny piękny jakby był późnej wiosny, dzień pięknej pogody że pszczółki jak wiosną latały
	−1	mroźno, mróz spory, pogoda z mrozem dobrym, mgła i mróz w dzień mierny, śnieg poprószył i marznąć poczęło, mróz dobry, zimno, mróz spory, mróz dobry, mróz lepszy, mrozek mierny, dzień pogodny z przymrozkiem, mróz porządny, dzień mroźnej pogody, srogie zimno, w dzień pogoda i marzło, dzień mroźny, dzień pogodny z srogim mrozem, mróz spory, marzło dobrze, dzień srodze zimny, w nocy i w dzień mróz dobry, marzło dobrze, marzło dobrze, mroźny, marzło, zimno srodze, mróz niezgorszy, mróz był wielki tej nocy, pogoda, wiatr zimny bardzo, chłodno dobrze, bardzo zimno, jesienna niepogoda, cały dzień plugawy, dżdżysty, chłodny, dzień brzydki cale
	+1	wesoły jak wiosenny, nie zimny jednak, piękny jakby był późnej wiosny, dzień pięknej pogody, że pszczółki jak wiosną latały, miernie gorąco, ciepły bardzo, gorący, dzień gorący bardzo, nadzwyczaj ciepły
October	0	ciepło, niezimno, ciepły dosyć, dzień pogodny

(continued)

Table 21.2 (continued)

Season		
Month	Index	Content of notes
	−1	srogi mróz, mróz wielki, mróz trzaskający, pogoda z mrozem potężnym, mróz bardzo wielki, mróz potężny, srodze mroźny, w nocy i w dzień mróz trzaskący, mróz potężny, że aż stawy zamarzły, mróz wielki, mróz potężny, mróz niewypowiedziany, mróz okrutny, potężne zimno, mróz srodze potężny, mroźno, mróz spory, takaż pogoda z mrozem dobrym, mgła i mróz w dzień mierny, śnieg poprószył i marznąć poczęło, mróz dobry, zimno mróz spory, mróz dobry, mróz lepszy, mrozek mierny, dzień pogodny z przymrozkiem, mróz porządny, dzień mroźnej pogody, srogie zimno, w dzień pogoda i marzło, dzień mroźny, dzień pogodny z srogim mrozem, mróz spory, marzło dobrze, dzień srodze zimny, w nocy i w dzień mróz dobry, marzło dobrze, marzło dobrze, mroźny, marzło, zimno srodze, mróz niezgorszy, mróz był wielki tej nocy, pogoda wiatr zimny bardzo, wiatr zimny bardzo, chłodno dobrze, bardzo zimno, jesienna niepogoda, cały dzień plugawy, dżdżysty, chłodny, dzień brzydki cale
	+1	ciepło, niezimno, ciepły dosyć, dzień pogodny, ciepły, wesoły, jak wiosenny, nie zimny jednak, dzień pogodny piękny jakby był późnej wiosny, dzień pięknej pogody że pszczółki jak wiosną latały, miernie gorąco, dzień bardzo piękny, dzień pogody pięknej, dzień pogodny jakby w septembrze, ciepły bardzo, dzień ciepły wszystek jak na wiosnę
November	0	pogoda wiatr zimny bardzo, wiatr zimny bardzo, chłodno dobrze, bardzo zimno, jesienna niepogoda, cały dzień plugawy, dżdżysty, chłodny, dzień brzydki cale, dzień pogodny z przymrozkiem, dzień mroźnej pogody, mrozek mierny, śnieg poprószył i marznąć poczęło, mroźny, marzło, mróz
	−1	srogi mróz, mróz wielki, mróz trzaskający, pogoda z mrozem potężnym, mróz bardzo wielki, mróz potężny, srodze mroźny, w nocy i w dzień mróz trzaskący, mróz potężny, że aż stawy zamarzły, mróz wielki, mróz potężny, mróz niewypowiedziany, mróz okrutny, potężne zimno, mróz srodze potężny, mroźno, mróz spory, takaż pogoda z mrozem dobrym, mgła i mróz w dzień mierny, mróz dobry, zimno mróz spory, mróz dobry, mróz lepszy, mróz porządny, srogie zimno, w dzień pogoda i marzło, dzień mroźny, dzień pogodny z srogim mrozem, mróz spory, marzło dobrze, dzień srodze zimny, w nocy i w dzień mróz dobry, marzło dobrze, zimno srodze, mróz niezgorszy, mróz był wielki tej nocy

will hereafter be referred to as ‘normal’ or ‘the historical norm’) are taken as the weather conditions which prevailed most generally during Chrapowicki’s lifetime (1612–1685).

For each month the average thermal index was calculated using the simple arithmetic mean of the daily indices and then, working from all the monthly indices, the annual average index was calculated. In addition, each month was also classified as above normal (index +1), below normal (−1) or normal (0) using the aforementioned average monthly values of daily indices. Index ‘+1’ was attributed to the values >0.333, index '−1' to the values <−0.333, and index '0' for values varying between −0.333 and 0.333. Seasonal indices were calculated using the proposal made by (Pfister et al. 1994) of adding the monthly indices for each season (DJF, MAM etc.). In this way seven different thermal characteristics of seasons have been obtained: extremely warm (index +3), very warm (+2), warm (+1), normal (0), cold (−1), very cold (−2) and extremely cold (−3).

In the general category of 'days with precipitation' we included those days for which information about different kinds of precipitation (rain, snow, drizzle etc.) was recorded in Chrapowicki's notes, regardless of the intensity of this precipitation. For the modern period, a day with precipitation is taken to be a day in which precipitation amounted to ≥ 0.1 mm.

Up to now, as was mentioned earlier, climatic reconstructions based on Chrapowicki's diary were made only for the period 1656–1667, for which the original diary and its nineteenth-century transcription exist (e.g. (Bokwa et al. 2001; Nowosad et al. 2007)). The eighteenth-century transcription differs significantly from the original diary, e.g. weather descriptions are usually shortened (for details see (Nowosad et al. 2007)). Thus, without corrections, this rich source of information cannot be used.

21.3.2 Correction Procedure

As has already been noted, the temperature and precipitation corrections have been introduced based on the hypothesis that during the whole period covered by Chrapowicki's diary (1656–1685) the climate was stationary. The period can be divided into two subperiods: 1656–1667 (and 1658–1667 for precipitation) and 1668–1685. For the first period, reliable data describing climate conditions are available, while for the second period the information available about the weather regime is limited and simplified. A clear break in the homogeneity of the data (annual frequency of thermal indices and annual number of days with precipitation) is seen in 1668 (see Figs. 21.2 and 21.3). From this year onwards there are significantly more normal days, fewer below normal (i.e. cold) days and significantly fewer days with precipitation. Moreover, in the case of precipitation, the first 2 years were acknowledged as listing an unreliably low number of days with precipitation.

21.3.2.1 Procedure for Temperature Corrections for the Period 1668–1685

Annual Data

The original annual number of days with particular thermal indices (−1, 0, +1) in the period 1668–1685 were calculated according to formula (21.1).

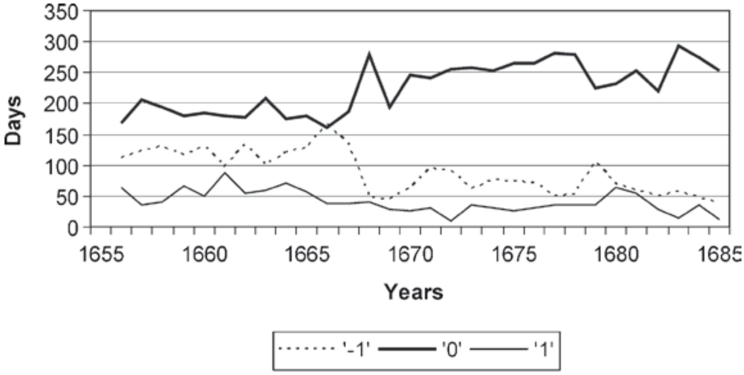

Fig. 21.2 Number of days with temperature below normal (−1), normal (0), and above normal (+1) in the central and north-eastern parts of Poland from 1656 to 1685. Original data not corrected

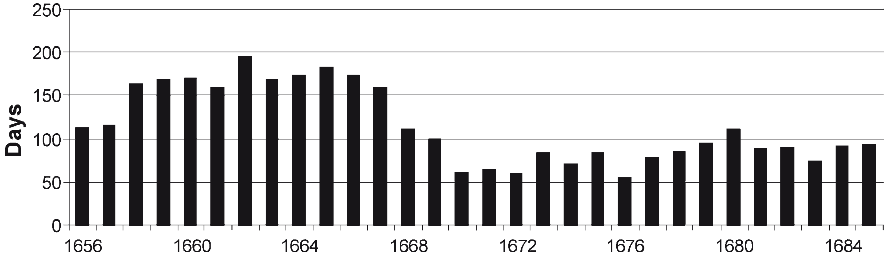

Fig. 21.3 Annual number of days with precipitation in the central and north-eastern parts of Poland from 1656 to 1685. Original data not corrected

$$P_{\mathrm{Ncorr}} = P_{\mathrm{Norig}} \times \mathrm{Pn} / \mathrm{PN} \qquad (21.1)$$

where:

P_{Ncorr} – corrected frequency of occurrence of days with thermal index ('−1', '0' or '1') in a given year (N) from the period 1668–1685

P_{Norig} – original frequency of occurrence of days with thermal index ('−1', '0' or '1') in a given year (N) from the period 1668–1685

Pn – average frequency of occurrence of days with thermal index ('−1', '0' or '1') in the period 1656–1667

PN – average frequency of occurrence of days with thermal index ('−1', '0' or '1') in the period 1668–1685

If the annual total number of all these kinds of days was different to the number of days for which weather notes in Chrapowicki's diary exist (see Table 21.1) then corrections were introduced using relations between the frequencies of occurrence of particular thermal indices in a given year. The corrected values of days with particular thermal indices for the whole period are shown in Fig. 21.4.

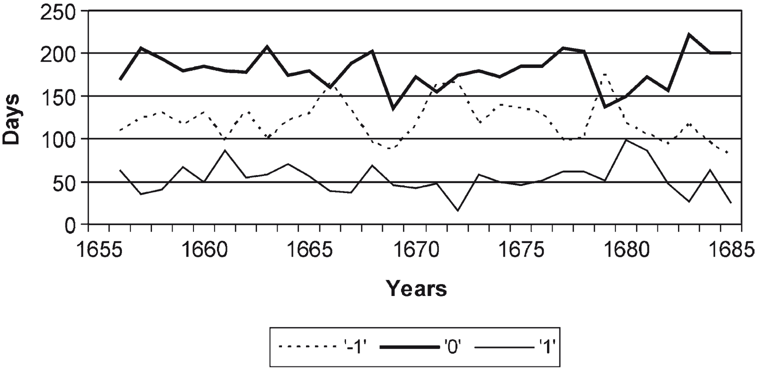

Fig. 21.4 Number of days with temperature below normal (–1), normal (0), and above normal (+1) in the central and north-eastern parts of Poland from 1656 to 1685. Corrected data

Monthly Data

Monthly average values of indices have been calculated separately for the periods 1656–1667 and 1668–1685 based on the original data. In the next step, monthly average differences of values of indices have been calculated between the periods 1656–1667 and 1668–1685. The average differences calculated in this way have been added to the original values of monthly indices from the period 1668–1685.

21.3.2.2 Procedure for the correction of number of days with precipitation for the periods 1656–1657 and 1668–1685

Monthly and Annual Data

A small number of gaps existing in the monthly series have been filled using their average values calculated for the period 1671–1684, excluding 1680. The year 1680 was excluded both because it was an extreme year and because the weather notes copied were probably transcribed more reliably in comparison with other years. Figure 21.3 shows a column graph presenting annual numbers of days with precipitation derived from Chrapowicki's weather notes for the period 1656–1685. It is evident that in the years 1656–1657 and 1668–1685 these precipitation characteristics are clearly underestimated. It seems to us that the reason for the excessively low values in the first 2 years is connected with Chrapowicki's lack of experience in noting the occurrence of precipitation. The occurrence of light precipitation was probably not noted. The second period, with a low annual number of days with precipitation, is directly influenced by the source of the data used, i.e. the handwritten eighteenth century copy which, as was mentioned earlier, is a shortened and simplified version of the original diary.

The average monthly numbers of days with precipitation have been calculated for the periods 1658–1667, 1671–1684 (except 1680) and separately for 5 selected years: 1656, 1657, 1668, 1669, and 1680, all of which had significantly more precipitation days (>95 days) than other years which were corrected. Ratios between average monthly figures for precipitation in the period 1658–1667 (homogeneous series) and the aforementioned two groups of years have been calculated and used as a multiplier to correct underestimated values in the periods 1656–1657 and 1668–1685.

The corrections have not been done separately for the number of days with rainfall, snowfall, and rainfall with snowfall. It seems to us that the weather information available in the handwritten eighteenth-century copy for the years 1668–1685 does not allow us to introduce corrections reliably. Thus, we present these precipitation characteristics only for the period 1658–1667.

21.3.3 The Contemporary Period

For the comparison purposes, long-term average precipitation characteristics (annual number of days with precipitation, snowfall etc.) have been collected for the four meteorological stations located in the present area of Poland (Warsaw and Bialystok) and Belarus (Minsk and Vitebsk). For stations in Warsaw, Bialystok and Minsk, the data come from the period 1931–1960, while for the station in Vitebsk data cover the period 1971–2000. Each station represents one of the four regions described earlier (see Fig. 21.1). However, the reader should be aware that a fully reliable comparison is not possible, because for the historical period the data are not complete for each region. They can be treated roughly as areally averaged values. On the other hand, temperature comparisons of the mean winter and summer conditions, as well as the spring and autumn conditions, between historical and present periods have been done respectively by (Bokwa et al. 2001; Przybylak et al. 2005), and therefore are not presented here.

21.4 Results and Discussion

21.4.1 Air Temperature

Figure 21.4 presents the annual number of days with normal, below normal and above normal thermal conditions in Poland from 1656 to 1685. Fully reliable comparison between years could not be made due to the different numbers of days covered by the Chrapowicki's weather notes - from only 268 days in 1669 to 365–366 days in many years. Therefore, the relative frequency of their occurrence was calculated using as a 100% value the number of all indexed days in a given year (Fig. 21.5). It is clear that in the study period normal days prevailed, with an average frequency of 51%. In particular years the frequency of these days fluctuated between 37.8% in 1679 to 66.1% in 1685. Only in 3 years (1666, 1671 and 1679) were days with below normal thermal conditions more frequent than normal days. In all the years analysed, cold days (below normal) were twice as frequent as warm days (above normal). Their average annual frequencies in the study period were 34% and 15%, respectively. Also year-to-year variability is significantly greater for cold days (SD = 6.1%) than for warm days (4.9%) (Fig. 21.5). Working from these results, it is difficult to estimate quantitatively the thermal conditions occurring in the 30 years of analyses. To do this, average values of indices for months and years have been calculated (Figs. 21.6 and 21.7).

Figure 21.6 shows that all the years in the study period were colder than the historical norm (negative values of indices). In the case of the first correction method (based on monthly data), the coldest year was 1666 with the value of the thermal index reaching −0.351, while the warmest was 1661 (−0.031). Besides

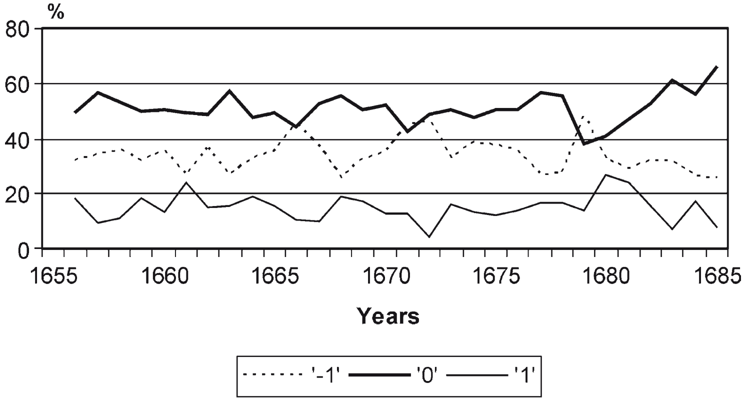

Fig. 21.5 Annual relative frequency of occurrence of days with temperature below normal (−1), normal (0), and above normal (+1) in the central and north-eastern parts of Poland from 1656 to 1685. Corrected data

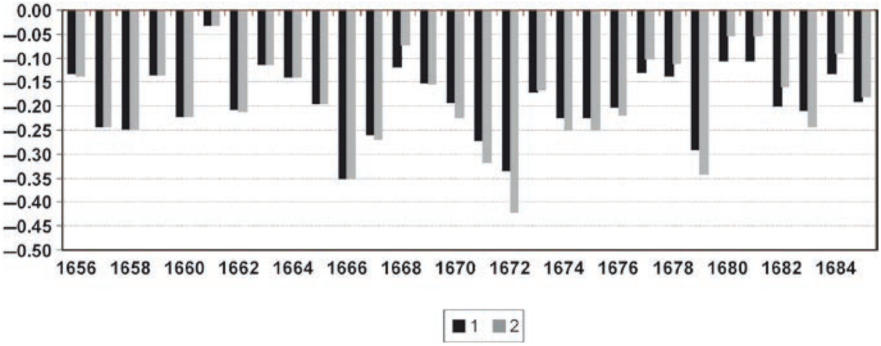

Fig. 21.6 Annual average values of thermal indices in the central and north-eastern parts of Poland from 1656 to 1685. 1 – correction based on monthly data, 2 – correction based on annual data

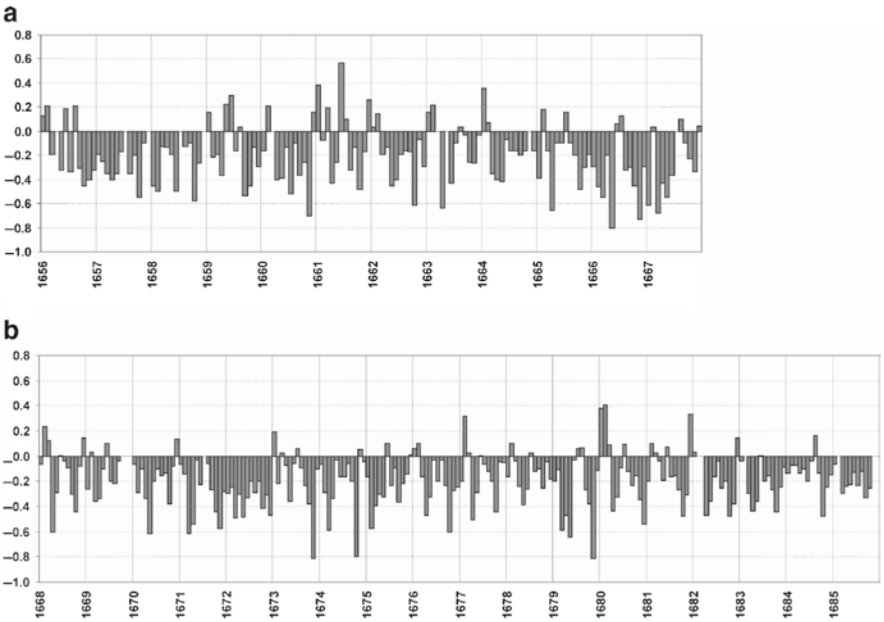

Fig. 21.7 Monthly average values of thermal indices in the central and north-eastern parts of Poland from 1656 to 1685. (a) 1656–1667, (b) 1668–1685 – corrected using data from 1656–1667

these 2 years, the years 1667, 1671, 1672 and 1679 can also be regarded as very cold (index < –0.25). On the other hand, the years 1663, 1668, 1680 and 1681 were relatively warm (with an index of around –0.10). Generally similar results have been obtained using the second method of correction of thermal indices based on the annual data. However, in this case the year 1672 is the coldest, while the year 1666 is the second coldest. To the above mentioned set of warm years we can also add the years 1677 and 1678.

Figure 21.7 provides a more detailed insight into the thermal conditions, presenting values of average monthly thermal indices. Again, it is evident that the majority of the months were colder than normal (negative indices). Positive indices occurred only in 63 months (17.9% of all months). From January 1659 to February 1662 almost twice the frequency of warmer-than-normal months was noted in comparison to their average frequency in the entire study period (34.2%). In this period, the month with the highest thermal index (0.567) occurred (June 1661). On the other hand, the coldest month (in relation to the norm for a given month) was November in the years 1673 and 1679. In both cases the thermal index was –0.810. The two longest periods with only negative monthly indices were noted from September 1656 to November 1658 and from January 1671 to December 1672.

Looking at the annual course of average values of thermal indices in Poland from 1656 to 1685 (Fig. 21.8) it is clear that all months were colder than their historical norm. However, significantly the greatest coldness (thermal indices below –0.2) was noted in spring and autumn months, in particular in April and October. On the other

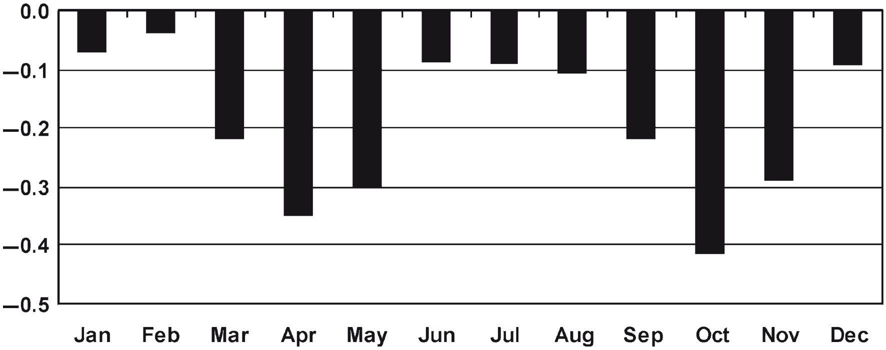

Fig. 21.8 Annual course of average values of thermal indices in the central and north-eastern parts of Poland from 1656 to 1685

hand, the least coldness occurred in the winter and summer months. Analysis of seasonal thermal indices (Fig. 21.9) fully confirms the above findings. Generally, normal conditions (index '0') prevailed in winter and summer. Cold ('−1') and especially warm ('+1') winters and summers were very rare in the study period. On the other hand, very cold (index '−2') and extremely cold ('−3') springs were noted very often, in 10 and 5 years respectively (Fig. 21.9). In autumn, such cold conditions were only a little less frequent, in 9 and 2 years respectively.

In comparison with present conditions (see (Przybylak et al. 2005)), winters were significantly colder by about 1°C, while summers were warmer (by about 0.5°C). (Bokwa et al. 2001) also using Chrapowicki's diary, counted the frequency of frosty days in Poland for the period 1656–1667 and stated that these days were significantly more frequent than at present. Based on this finding they came to the conclusion that winters in the study period were more severe than today. (Bokwa et al. 2001) also studied the occurrence of days with slight frost and found that in the study period they occurred earlier in autumn and later in spring than today. This means that both spring and autumn were colder in comparison with the present climate. (Briffa et al. 2002) analysed dendrochronological data and found that the warm half-year (April–September) in Poland in the period 1656–1685 was warmer by about 0.5°C than the 1961–1990 mean. Roughly similar results for the Czech lands, based on documentary evidence, have also been presented by (Brázdil 1996).

21.4.2 Atmospheric Precipitation

Weather notes in Chrapowicki's diary referring to atmospheric precipitation allow us first of all to analyse its occurrence, and to divide it into types (rain, snow, and rain with snow). Annual numbers of days with precipitation in the study period (1656–1685) varied from 112 in 1676 to 206 in 1679 (Fig. 21.10). The average (annual) number of days over 30 years was 169.6 (46.5% of days in a year).

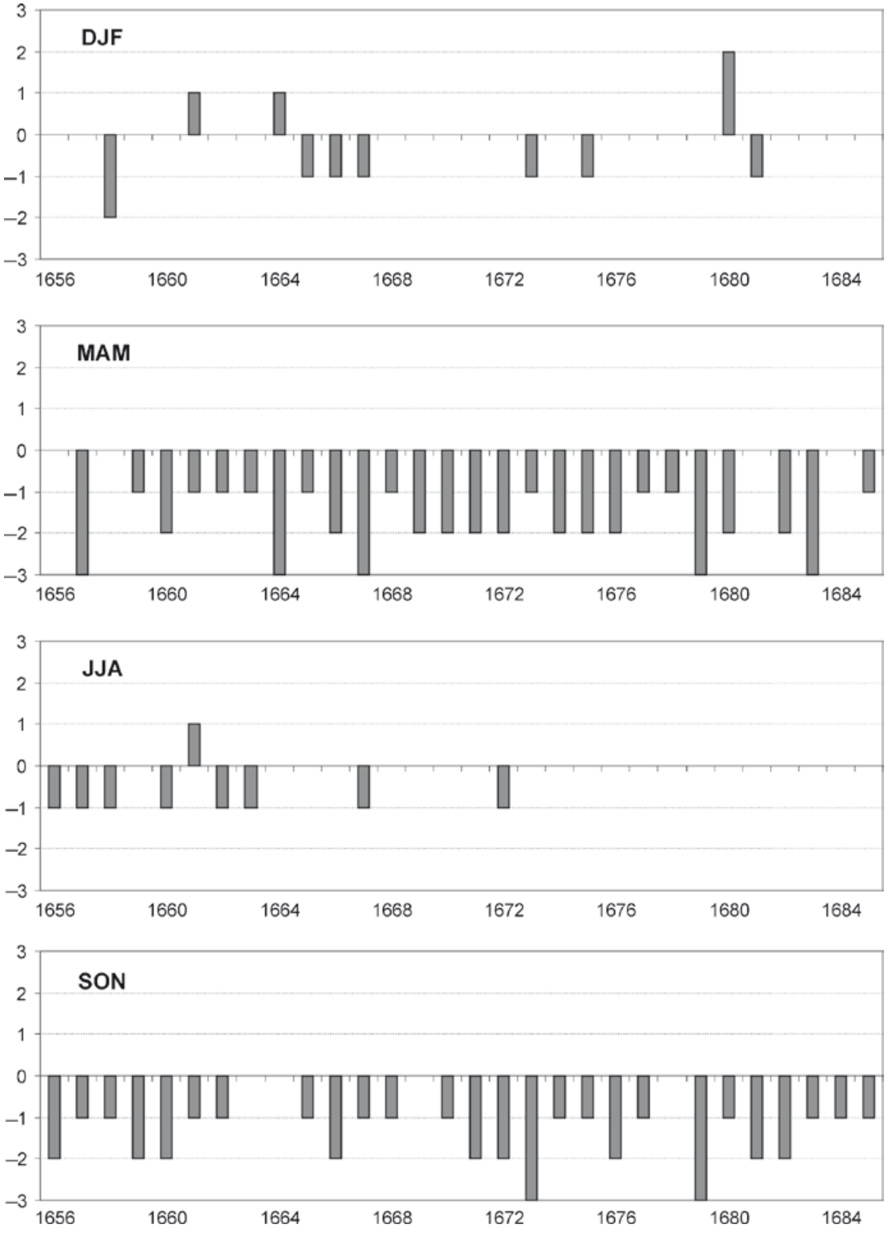

Fig. 21.9 Values of thermal seasonal indices in the central and north-eastern parts of Poland from 1656 to 1685

Chrapowicki notes that 1676 was a very dry year: *Tego roku straszne Panowały Susze, że Zboża wypalało w Polach* [‘This year has seen terrible droughts which have burned the corn in the fields’]. No such information is provided in the diary

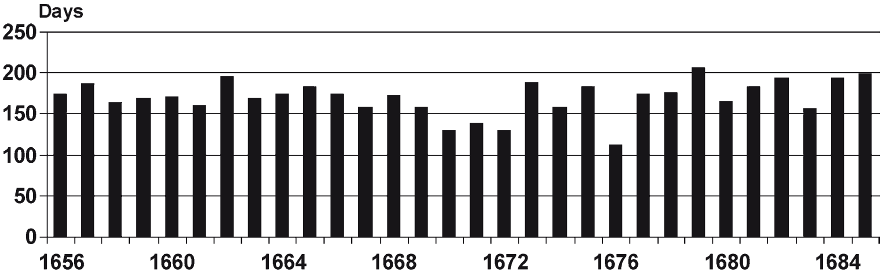

Fig. 21.10 Annual number of days with precipitation in the central and north-eastern parts of Poland, 1656–1685. Corrected data

for any other year. Thus, the agreement existing between the new corrected data presented in this paper and this diary entry confirms to some degree that the procedure used to correct the data is reliable. It is also worth noting that the summer season of 1676 was warm and dry over a prolonged period in the Low Countries (G. Demarée, personal communication).

In the annual course of the average number of days with precipitation (1656–1685), two maxima are observed, in summer and winter (from 15 to 17 days a month, except February) (Fig. 21.11b). Clearly the lowest number of days with precipitation occurred in spring, particularly in March and April (only about 10 days). Rainfall was observed in all months of the year, and was the dominant type of precipitation from April to November (Fig. 21.11b). The greatest 10-year (1658–1667) average number of days with rainfall occurred in July (17.5), while the lowest was in April (10.2). From December to March snowfall dominated and it was observed in about 10 days in the winter months and slightly more than 6 days in March. It is worth noting that snowfall also occurred once in July (on July 7, 1661) (Fig. 21.11a). Days with both rainfall and snowfall were observed very rarely in Poland in the period 1658–1667 (on average ≤ 2 days). In the annual course they were noted from October to May, with maximum figures noted in January (2 days).

Contemporary precipitation conditions in the areas of Poland analysed are presented in Figs. 21.12 and 21.13 based on data gathered for four meteorological stations: Warsaw, Bialystok, Minsk and Vitebsk (though snowfall data was only gathered from the first two stations). From Fig. 21.12, it can be seen that the number of days with precipitation slightly increases when we move from the west (Warsaw) to the east (Vitebsk). The annual courses of days with precipitation and snowfall at present are roughly similar to those shown for the historical period. The main difference is seen during the winter months, for which a significantly greater number of days with precipitation (Fig. 21.12) are observed in present areas of Belarus (Minsk and Vitebsk stations) than in summer. In the case of snowfall, it is worth noting that in the mid-twentieth century (1931–1960) snowfall occurred in September, something which was not observed in the period covered by Chrapowicki's diaries.

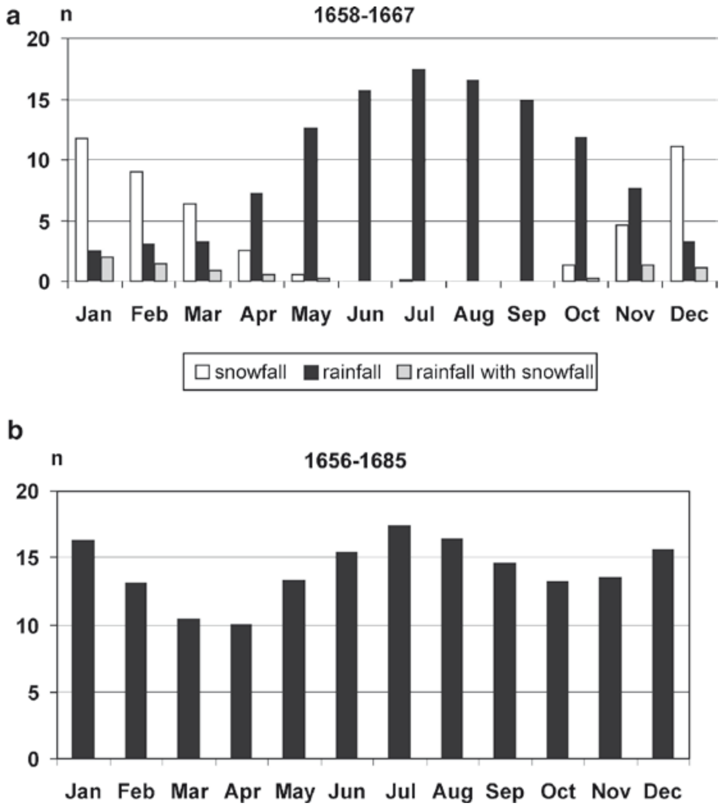

Fig. 21.11 Annual course of average number of days (n) with snowfall, rainfall and rainfall with snowfall (a) as well as with precipitation (b) in the central and north-eastern parts of Poland from 1656 to 1685

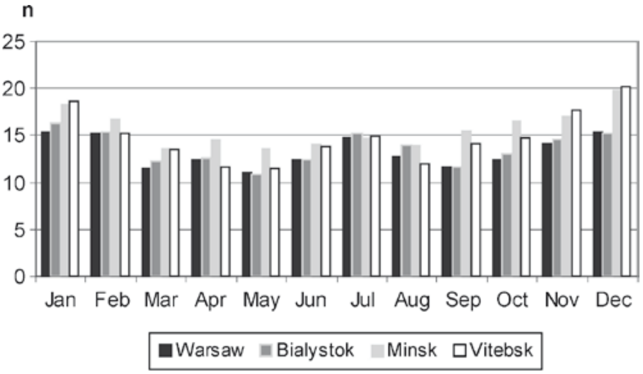

Fig. 21.12 Annual courses of number of days (n) with precipitation in the north-eastern part of Poland and in Belarus from 1931 to 1960 (for Vitebsk: 1971–2000)

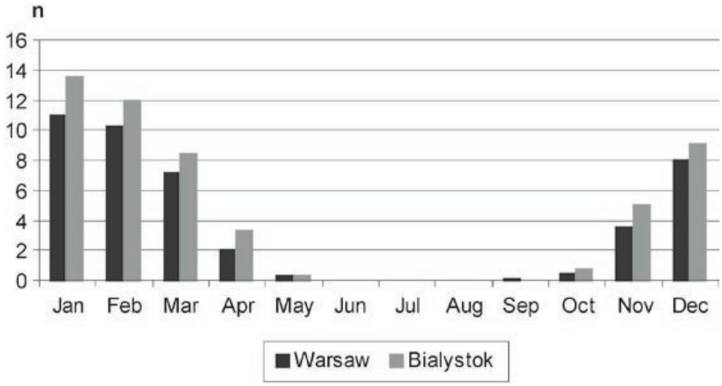

Fig. 21.13 Annual courses of number of days (n) with snowfall in the north-eastern part of Poland from 1931 to 1960

A comparison of the historical and contemporary number of days with precipitation and snowfall is shown in Fig. 21.14. As was mentioned earlier, the entire period covered by Chrapowicki's diary was used to calculate the total number of days with precipitation, while only the 10-year sub-period 1658–1667 was used to calculate the number of days with snowfall. Annual totals of days with precipitation were greater in the historical period than contemporary totals by 6–11 days in the area of north-eastern Poland, and lower by 8–19 days in the area of Belarus. However, as can be seen in Fig. 21.14a, monthly differences do not exceed 5 days. In the warm half-year they were positive (more days with precipitation than today), while in the cold half-year they were negative. These differences are roughly 50% smaller when the areally averaged number of days with precipitation are taken into account (using average values from the four contemporary stations analysed). This reduction in differences is a consequence of the pattern of spatial distribution of the annual number of days with precipitation, which reveals that they are less frequent in Poland than in Belarus. Therefore the reconstruction based on Chrapowicki's notes, which roughly represent an average value for the whole study area, must overestimate / underestimate the annual number of days with precipitation for Poland/Belarus respectively, when only data from stations are used. On the other hand, when areally averaged values for the present-day conditions are used, this effect is reduced.

As regards number of days with snowfall, the pattern is different, although differences between historical and present periods generally do not exceed 3 days (Fig. 21.14b). However, in the first half of the year we note more days with snowfall in the modern period than in Chrapowicki's time, while in the second half of the year, this situation is reversed. It is open question whether this pattern represents climate change between historical and modern periods or whether it results from the different lengths of the periods that Chrapowicki stayed in these areas.

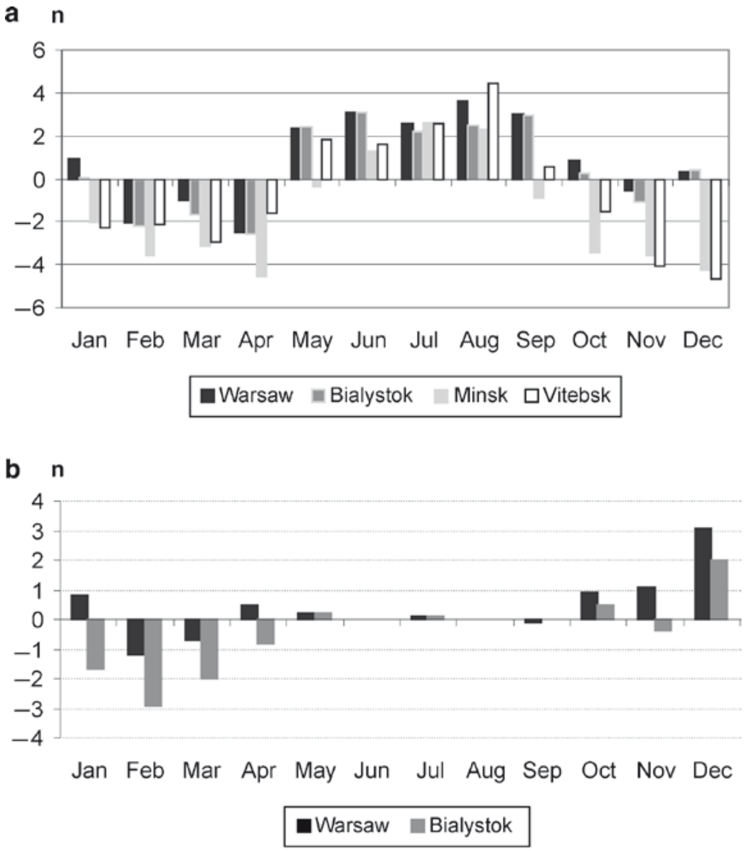

Fig. 21.14 Differences in number of days (n) with precipitation (a) and snowfall (b) between the historical period (1656–1685 and 1658–1667, respectively) and the modern period (1931–1960)

21.5 Summary and Conclusions

For the first time, Chrapowicki's diary has been used to reconstruct the history of Poland's climate for the entire period (1656–1685) covered by it. Up to now, researchers have tried to reconstruct climate only for the first 12 years of the period for which the original diary and its reliable handwritten nineteenth century copy survived (e.g., (Bokwa et al. 2001; Nowosad et al. 2007)). From 1668 onwards, Chrapowicki's diary is available only in its eighteenth century handwritten copy, which is a shortened and simplified version of the original diary and as such is an unreliable source of information. For the purposes of the present paper, weather information concerning temperature and precipitation conditions obtained from this eighteenth century copy has been corrected (homogenised) based on the assumption that the climate was stationary during the entire study period. Analysis of the existing climate reconstructions for this period for Poland (Briffa et al. 2002;

Przybylak et al. 2005) as well as for other areas in Europe (e.g. for the Netherlands: (Lamb 1977), p. 476) confirm the correctness of this assumption.

Daily temperature characteristics were classified as above normal (index +1), below normal (−1) or normal (0) using Chrapowicki's weather notes, which, however, are not always unequivocal. Therefore Table 21.2 provides an extensive list of the contents of these notes (written in the original old Polish) which were the basis for the above mentioned thermal classification. For each month the average thermal index was calculated using the simple arithmetic mean of the daily indices and then, working from all the monthly indices, the annual average index was calculated. For the general category of 'days with precipitation' we classified those days for which, in Chrapowicki's notes, information about different kinds of precipitation (rain, snow, drizzle etc.) was recorded, regardless of the intensity of this precipitation.

For purposes of comparison, long-term average precipitation characteristics (annual number of days with precipitation, snowfall etc.) have been collected for the four meteorological stations located in the present areas of Poland (Warsaw and Bialystok) and Belarus (Minsk and Vitebsk), the first three for the period 1931–1960 and the Vitebsk station for the period 1971–2000. On the other hand, temperature comparisons between the historical and present periods of both the mean winter and summer conditions and the spring and autumn conditions have been carried out respectively by (Przybylak et al. 2005) and by (Bokwa et al. 2001), and therefore are not presented here.

The present analysis, together with the previous climate reconstructions for Poland, reveal that the thermal conditions in the study period were colder than present, and also colder than the average weather conditions during Chrapowicki's lifetime (1612–1685). The greatest negative temperature anomalies occurred in spring and autumn, while summer and winter were near the historical norm. However, in comparison with the present conditions, historical winters were significantly colder, while summers were slightly warmer. Precipitation conditions, estimated according to their frequency of occurrence, seem to be roughly similar to present conditions.

At the end of our paper we should also emphasize that the differences noted between the historical and present-day climate conditions could also partly be a result of the methodology used, and/or shortcomings present in the diary.

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Chapter 22
The Climate of Polish Lands as Viewed by Chroniclers, Writers and Scientists

Janina Bożena Trepińska

22.1 Introduction

Atmospheric phenomena and events have always attracted people's interest. Following the evolution of human civilization, people achieved some degree of disregard for atmospheric activity drawing away from watching the environment, while paying special attention to some extreme events only. Systematic recording of weather signs, like blooming trees or flooding rivers was carried out even in ancient civilizations, allowing us to reconstruct climate changes. Historical climatology (Niedźwiedź 2003) is a relatively young field of science, concerned with research and reconstruction of climate conditions of the period preceding instrumental measurements. The key substance for this research consists above all of historical sources: annals, documents and astronomical almanacs. Such records belong to the so-called proxy data, covering also several "natural recorders" of weather, like tree rings, varved clays on lake bottoms as well as oxygen ^{18}O isotope level within pack ice, icebergs and ice caps. However, dendroclimatological reconstruction in Europe, by means of tree rings, concern summer temperatures only. A methodology using different aspects of proxy data is presented by Pfister and Brázdil (1999). The term "proxy" is used to denote any material that provides in direct measure of climatic elements.

The types of information in historical climatology are presented by Pfister et al. (1999). Then it collects the records on the basis of natural and man-made sources by the direct observations and indirect references – proxy data. The archives information can be some results arising from a research of natural materials like fossil flora and fauna, from the noted observations of natural hazards, anomalies of weather, different time of grain and vine harvest and a pictorial and an epigraphical documentary. The chronicles, historical novels, even romances can be included to the sources of historical climatology Schönwiese (1997).

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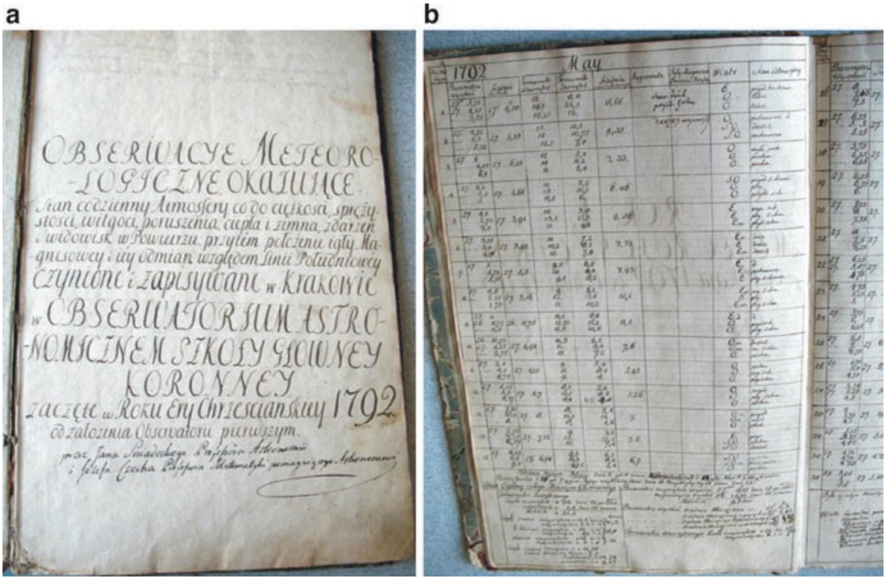

OBSERWACYE METEORO-
-LOGICZNE OKAZUIĄCE
Stan codzienny Atmosfery co do ciężkości, spręży-
stości, wilgoci, poruszenia, ciepła i zimna, zdarzeń
i widowisk w Powietrzu, przytem położenia igły Ma-
-gnesowey i iey odmian względem Linii Południowey
CZYNIONE i ZAPISYWANE w KRAKOWIE
w OBSERWATORIUM ASTRO-
-NOMICZNEM SZKOŁY GŁÓWNEY
KORONNEY
ZACZĘTE w Roku Ery Chrześciańskiey 1792
od założenia Obserwatorii pierwszym.
przez Jana Śniadeckiego Professora Astronomii
i Józefa Czecha Professora Matematyki pomagaiącego Astronomowi

Fig. 22.1 Pages of the weather diary by Professor Jan Śniadecki in Cracow, a. The first page of diary, b. The page for May 1792

Climatologists commonly distinguish two periods: descriptive and instrumental, of presenting the courses of meteorological elements and climate changes (Bärring et al. 2002). In the former, weather and climatic conditions are reconstructed on the basis of proxy data (Pfister et al. 1999) whereas in the latter, the reconstruction is carried out drawing on data and taking into account an exact description of measurement time and location, so as to provide information on the homogeneity of the series. The second period began with the introduction of systematic instrumental measurements and visual observations.

Instrumental measurements in the Polish lands were executed as early as in 1779. A change of the observation site required a homogenization of the Warsaw series, undertaken by Michalczewski (1980) and Lorenc (2000). At the end of the eighteenth century, some weather observations were also carried out in Wroclaw. However, the most homogeneous series of meteorological observations came from Cracow, where Professor Jan Śniadecki of the Jagiellonian University Astronomical Observatory started air pressure and air temperature measurements, as well as visual weather observations in 1792 (Trepińska 1982, 1997b; Kowanetz and Trepińska 2000) – Fig. 22.1.

22.2 Weather Accounts in Chronicles

The climate of Central Europe, including the Polish lands, displays considerable weather instability, typical of the temperate zone. Remarks concerning the weather were recorded by medieval and Renaissance chroniclers when a king, prince or other ruler declared a war. Thanks to that, more or less accurate accounts are known, describing the weather circumstances of great battles that were often decisive for the destiny of nations. Furthermore, we often come across descriptions of extreme weather conditions that destroyed crops, causing famine, poverty and epidemics (Burroughs 1999). Many chroniclers included more or less systematic and accurate descriptions of weather sequences in their accounts (Pfister et al. 1999).

In scientific and popular scientific literature there are many accounts of atmospheric events causing plagues of bad harvest, hunger and even extermination of social groups. Unfavorable climate changes triggered rises in grain prices and economic deterioration in many countries, as well as probably increased incidence of diseases associated with cold, damp weather, such as rheumatism, pneumonia and tuberculosis (Lamb 1972; Burroughs 1999). A great database untitled EURO-CLIMHIST was set up at the University of Bern in the 1990s. It comprises ca. 600,000 data from European continent (several European countries) from AD 750 to the mid-nineteenth century (Pfister et al. 1999).

Highly appreciated Polish mediaeval chroniclers, including Gallus Anonymous (twelfth century), Wincenty Kadłubek (1161–1223) and above all, Jan Długosz (1415–1480), mentioned multiple weather phenomena in their works: extremely severe and mild winters, droughts causing wildfires and bad harvest, long-lasting floods, etc. (Polaczkówna 1925; Kornaus 1925).

The most highly valued Polish chronicles including considerable proxy data on unusual atmospheric events were written in the fifteenth century by Jan Długosz (Kornaus 1925). Listed there are the years of bad harvest, severe winters or hot summers, which are an obvious proof of the climate of Polish lands in the Middle Ages. Długosz drew on numerous records left by his predecessors, including several annals (*Rocznik Małopolski, Rocznik Wrocławski*), countless records by monastic chroniclers and other sources only roughly identified (Polaczkówna 1925). The geographical aspects of Długosz's works attracted the interest of Wincenty Pol, a nineteenth century Polish poet and geographer. Thanks to later research by the Polish geographer Eugeniusz Romer (1871–1954) and his students at the Jan Kazimierz University in Lvov, the years with seasons displaying anomalous features were put together. There are numerous accounts of extremely severe and mild winters or dry and wet summers. Selected examples from the fifteenth century are listed below (Polaczkówna 1925):

- 1408/1409 – frosty and snowy winter,
- 1410 – hot summer with a drought,
- 1411/1412 – winter ended very early, without slight frosts, allowing for early vegetation growth,
- 1439/1440 – extremely long winter with severe frosts, lots of birds perished,
- 1451 – summer began on 25 July (St. James Day) with continuous rainfall and floods,
- 1464/1465 – frosty and snowy winter,
- 1473 – hot summer, fires and deterioration of sources.

The authoress (Polaczkówna 1925) attempted discover the cyclical occurrence of severe winters and cold wet summers according to E. Brückner's 35-year cycle hypothesis, in which warm and dry years alternate with cold and wet ones. In the light of later research this hypothesis remains unconfirmed.

Jan Długosz portrayed one of the greatest medieval battles, fought near Grunwald on 15 July 1410, where Polish and Lithuanian troops led by the Polish King, Władysław Jagiełło smashed the forces of the Teutonic Order. On the basis of Długosz's account, the astronomical and weather circumstances of the battle were reconstructed by the Cracow astronomer Mietelski (1971). His description exemplifies the possibility of exploiting accurate annalistic notes for scientific research – both in the field of history and climatology. The victorious tactical action of the Polish King can be interpreted using the description of the battlefield after the passage of an atmospheric cold front with a thunderstorm and rainfall during the preceding night.

22.3 Examples of Weather Descriptions in Historical Novels and Romances

Many Polish writers drew their knowledge from annals and records by the aforementioned medieval chroniclers. Weather information referring to a specific date is the most valuable. Obviously, only few selected examples drawn from novels shall be quoted here. Weather events and phenomena were described so commonly that each choice can be limited only. However, most precious are accounts of weather events and phenomena related to a specific place and time.

The Polish novelist, Henryk Sienkiewicz (1846–1916), winner of the 1905 Nobel Prize in literature, mastered the art of portraying historical events, but his descriptions of the setting were also quite colorful. The first part of his historical trilogy *Ogniem i mieczem (With fire and Sword)* begins with a presentation of the weather circumstances prevailing in the year the plot starts. This fragment is worth quoting:

> …1647 was a strange year in which manifold signs in the sky and on the earth seemed to announce disasters of some kind and unusual events… Finally, so mild a winter set in, that the eldest folks could not recall the like of it. In the southern provinces ice did not confine the rivers, which, swollen by the daily melting of snows, emerged from their beds and flooded the banks. Rainfalls were frequent. The steppe was drenched and became an immense slough. The Sun was so warm at noon that… in Bratslav Province and on the Wild Fields a green fleece covered the steppes and plains in the middle of December (H. Sienkiewicz, *Ogniem i mieczem (With Fire and Sword)*, p.5, vol. I., PIW, Warszawa 1967).

The descriptions of the weather in one chosen day only, are often in a Polish literature. The Polish writer Józef Ignacy Kraszewski (1812–1887) famous for penning numerous romances and historical novels, used to begin his books with a weather account. The extract quoted below represents one of them:

> …it was on 24 July 1788…Evening was pretty late, whilst the air appeared smothery and stuffy, like before the storm, though no harbinger appeared in the sky. Only in the North, where not many clouds were in sight, something glittered feebly now and again…Hot air, thick and unstirred by any blow, was hard to breathe with (J.I. Kraszewski, Syn *marnotrawny (The Prodigal Son)*, p. 7, Ludowa Spółdzielnia Wydawnicza, Warszawa 1961).

Another Polish author Władysław Reymont (1867–1925), was the master in his literary production at description of weather in the seasons of the year. He won the Nobel Prize in 1924 having written the great national epic entitled *Chłopi (The Peasants)*. Consisting of four parts, each given the name of one season (*Autumn, Winter, Spring, Summer*), the novel refers to the annual cycle of weather that forms the backdrop of all the events affecting the life of a little rural community. The local dialect used by the author is unusually suggestive, though tricky to translate into another language. Two selected fragments from *Autumn* and *Summer* are quoted below:

> ….Autumn was going deeper and deeper. Black days crawled into empty, deaf fields and faded a way in the woods, still fainter, still quieted in forests…And with every dawn the day was getting up lazier, stiff with the and frosted all over, in the painful silence of evanishing soil. The sun, pallid and heavy, bloomed from an abyss, wreathed with crows and jackdaws… Rough, frigid wind run behind them, ruffling stiffened waters, nipping the remains of verdure, tearing last leaves off poplars sloping over the cart ways. (W. Reymont, *Chłopi, tom I, Jesień (The Peasants*, vol. I, *Autumn)*, p. 84, Świat Książki, Warszawa 1999).

> …Scorching heat so increased, that no one could hold out longer at all, as dust closed the throats. Sun whitened and some long whitish trails began overcastting clear sky, whilst scorching air quaked and shimmered like boiling water – it was going to storm. (W. Reymont, *Chłopi, tom IV (The Peasants*, vol. IV, *Summer)*, p. 279, Świat Książki, Warszawa 1999).

A lot of weather motifs can be found in poetry. Numerous Polish poets, especially of the Romantic period, never overlooked weather accounts in their works which often astonish us with the precision of their vocabulary. It is safe to say that poetry cannot exist without references to weather phenomena. It seems necessary to mention the Polish national bard Adam Mickiewicz (1798–1855), whose great poem *Pan Tadeusz (Master Thaddeus)*, includes plenty of beautiful stanzas concerning nature, presenting atmospheric phenomena and their effects on people and the rural environment.

In 1849, the Polish poet and geographer Wincenty Pol (1807–1892), was appointed the first professor of geography in Poland, thus founding the Geographical Chair of the Jagiellonian University (Niemcówna 1923; Jackowski and Sołjan 2006). In his poems, such as *Pieśń o ziemi naszej (Song of Our Land)*, references to weather accounts are very frequent. Poetic terms like: "*naked Tatras stand in snow*", *"with clouds standing above them", "sudden storm will thunder in the summer"* are deeply rooted in the Polish language.

Another poem, *Song of the Cloudy Valley* by Seweryn Goszczyński (1801–1876), expresses the dreadful mood of a gloomy day in the Tatra Mountains.

22.4 The Weather Observation Series in the Period of Non-Instrumental Observations

Limanówka (2001) presents another issue within the scope of historical climatology, attempting to transform verbal accounts into numerical records. In her monograph, she uses historical data covering the systematic daily accounts of weather in Cracow conducted between 1502 and 1540 by Marcin Biem, Professor of Cracow Academy. This unique series of observations written in Latin has been transformed into numerical charts, allowing for the reconstruction of weather circumstances in sixteenth century summers and winters. Between 1502 and 1540, considerable annual fluctuation of air temperatures appeared. Winters were severe; with mean temperature by 1°C–1.5°C lower than today. The authoress stated that the climate of Polish lands displayed much more continental features back then. An extremely frosty winter appeared in 1513/1514, while the winter of 1529/1530 was unusually mild.

The research covers the first half of the sixteenth century, regarded as the transition period to the Little Ice Age, while at the same time including the Spörer Minimum Period (1450–1534). According to climatologists, lower solar activity led to the occurrence of lower than average air temperatures in Europe, due to changes in atmospheric circulation. Most important is the reliability of the reconstructed series of air temperature (and other meteorological elements) records. In this case (Limanówka 2001), the calculated coefficients of correlation with Western-European series of weather reports are extremely high, thus this reconstruction of the sixteenth century weather circumstances is of great scientific value.

22.5 The Weather Observation Series in the Instrumental Period

Natural sciences developed greatly in the second half of the nineteenth century. Discovering many laws of physics, progress in medicine and various biological observations aroused considerable interest in man's natural environment, including the atmosphere.

Meteorological instruments were probably first introduced in England (Staszewski 1966; Lamb 1972; Linacre 1992; Burroughs 1999). However, the thermoscope, a simple instrument used for air temperature measurements was discovered in 1593. It was constructed by Galileo Galilei and his pupil Santorio (Linacre 1992; Trepińska 1997a).

Similarly, the world-first network of instrumental measurements was started in the seventeenth century. Reference works on historical climatology (Bärring et al. 2002) discern the Early Instrumental Period (1780–1860) and the Modern Instrumental Period (after 1861). Among European networks of regular measurements one should mention the Palatinian (Mannheim) network, run in the second part of the eighteenth century. The Clementinum Observatory in Prague was a very important institution during the eighteenth and the nineteenth centuries, as well, having started its first meteorological observations in 1752. Regular records of observations were kept from 1779 onwards (Pejml 1975), which exerted important influence on the development of regular meteorological measurements in Poland, particularly in Cracow. The talented scientist Jan Śniadecki – astronomer, mathematician, geographer, and the first head of the Jagiellonian University Astronomical Observatory – not only started regular (visual and instrumental) weather records, but also created the first instruction for executing observations, describing the place and time of measurements in detail (Śniadecki 1837; Trepińska 1982, 1997b).

Wincenty Pol, already mentioned for his poetry, approached climatology not only from a poetical viewpoint. His "*Studies on the Geography of Poland*" (Niemcówna 1923) describes the climate of the Polish lands introducing the author's own denomination for prominent climatic features, as well as for various flora and fauna species. Moreover, he was the author of a climatic regionalization of the Polish lands. His descriptions also cover climatic features, concerning three specified regions: the Carpathian Mts., the wet southern highlands with south-eastern steppe highlands and the northern plains, including the lake lands and the Baltic coast. He characterised weather conditions and climatic features of specified regions, as well as their influence on landscape relief. He did not, however, resort to the numerical data concerning meteorological elements, obtainable from the meteorological stations already operating although he tried to define the length of the seasons in some regions. In the upper Vistula River basin (characterised somewhat more accurately) the area between the Raba and the Biała Rivers has been singled out for being most strongly influenced by western, oceanic winds with winter storms. To the east of this area, summer thunderstorms prevail and – generally – eastern winds.

The key conclusion emerging from his climatological investigations is that the territory of Poland (at that time) was climatically diversified and different from the surrounding areas, representing *a transition link to them, concerning several notions and natural phenomena* (Niemcówna 1923). Wincenty Pol has been widely recognized for his attempt at introducing substantial number of names for various weather phenomena into Polish climatology.

Meteorological and climatological considerations of Professor Pol are of a rather descriptive nature, although he appreciated the value of weather observations. He believed that the atmosphere is a result of interaction between water and land areas. According to him the course of air temperature and rainfall were the most important features of climate. He attached both general and local significance to winds, considering the latter as resulting from different values of air temperature.

The merits of Wincenty Pol include the introduction of many meteorological terms into the Polish language. Some of them are still used today, whereas others have become archaic, and as such no longer used in scientific terminology. His considerations, often intuitive and sometimes inconsistent, had a limited impact on the evolution of climatology. It is almost certain that Professor Eugeniusz Romer got acquainted with Pol's hypothesis during his scientific researches.

22.6 The Importance of Systematic Weather Reporting for Science, as Exemplified by the Galician Network of Meteorological Stations

The Kingdom of Galicia and Lodomeria, or simply Galicia, was the name given by the Austrians to the southern part of Poland, which became the northern most province of the Austrian Empire with the partition of Poland in 1772. Originally covering about 83,000 km² (32,000 square miles) Galicia was enlarged in 1795 to 132,000 km² (51,000 square miles), encompassing western and eastern Galicia with Cracow and Lvov (Lemberg, now Lviv) serving as capitals respectively. In 1803 the two parts were united and Lvov – then having the larger population of the two cities – remained the capital of the whole Kingdom. In 1809 Cracow became part of the Duchy of Warsaw and in 1815–1846 the City and its surroundings formed a free city-state called the Republic of Cracow, annexed by Austria in 1846 as the Grand Duchy of Cracow, whilst all the authorities, offices and institutions for the Duchy remained uniform with the rest of Galicia until the end of World War I in November 1918. With a new constitution proclaimed in Vienna in 1867, all the provinces became quite autonomous. Thus, Galicia was given a land parliament and a local government as well as some judicial independence and freedom of speech and press. Land parliament had its executive official body, called the land board (Hanik 1972; Adamczewski 1996). These political events had some importance for the development of natural sciences, including the idea of performing regular meteorological observations and publishing their reports in some special publications. The autonomy gained from Austria allowed these reports to be written in Polish.

The development of natural and medical sciences, as well as countless discoveries in physics, favoured the experimental approach among scientists researching natural disciplines.

Weather observations in the Polish lands aroused the interest of physicians associated within the Balneological Committee of the Cracow Scientific Society. Conviction spread among them that the observations should be conducted in places that stood out for their therapeutic values, mineral water sources, as well as favourable landscape and climatic qualities.

In 1865, the Physiographic Committee in Cracow was set up, with a Meteorological Section established the following year. There were several meteorological stations in Galician towns and smaller localities, with the key role played by the station of the Jagiellonian University Astronomical Observatory in Cracow. It was founded in 1792 by the first director of the Observatory Jan Śniadecki, Professor of astronomy. Another astronomer, Professor Franciszek Karliński, headed the Observatory for 40 years (1862–1902), perforce making it the central post within the Galician network. Here, instructions were drafted, all observation results were gathered and master instruments for comparison of readings were kept (Kowanetz and Trepińska 2000; Mietelski 1997). Dr Daniel Wierzbicki, astronomer and observer, was the author of many works, predominantly including reports, short works and graphic papers on the progress of particular meteorological elements (Wierzbicki 1875). The Meteorological Section exerted great influence on the methods of observation and investigations of similar meteorological stations. F. Karliński lectured on meteorology, even after the establishment of the Geography Department at the University.

Thus, the Galician meteorological network came into existence thanks to the posts already run, which to a large extent was due to the lack of funds for setting up new ones. It functioned in line with the instruction valid in most European countries (Hanik 1972).

Three periods of the development of the network's development can be distinguished. In the 1866–1885 period several new posts were set up, increasing the number of stations within the Galician network (Fig. 22.2). Between 1886 and 1903, the weather reports published became widely known, whilst most stations were taken under the protection of the Physiographic Committee Meteorological Section, which flourished during that period. Unfortunately, between 1904 and 1918, the number of stations decreased, thus diminishing the importance of the Galician network. All the meteorological stations run within the Galician network were included into the Polish Meteorological Institute network, which came into being in independent Poland in 1918.

Undoubtedly the biggest obstacle in running the stations was financial deficit. Owing to insufficient allocations from the Physiographic Committee, the stations' equipment fell short of the necessary tools. Many observers from small localities – teachers, physicians, priests, railway employees – recorded data for free. Their generous, systematic work was often unpaid, as their actions were governed by an ideological approach to reporting weather and gathering phenological remarks. The results of their observations were originally published in the *Reports of the Physiographic Committee*, followed by *Materials to the Climatography of Galicia*. The scope of the published data varied in particular cases, but records of air temperature, air pressure and precipitation were always the most important of all

Fig. 22.2 Map of the Galician Meteorological Network (1865–1919) according to Hanik (1972)

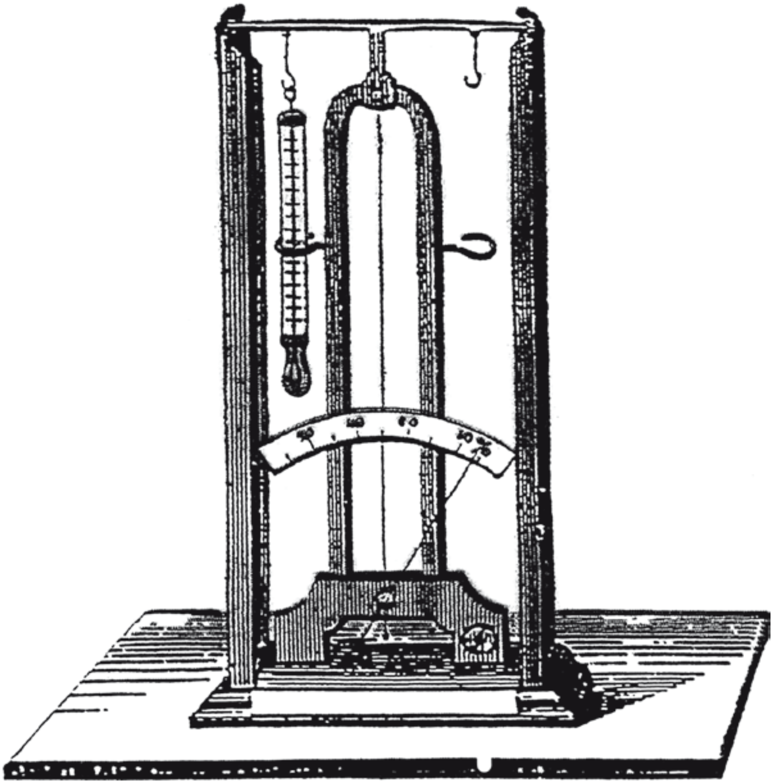

Fig. 22.3 Portable meteorological instrument used at meteorological stations in Galician Meteorological Network in nineteenth century

instrumental observations. Later, since 1883 in Cracow, the effective sunshine duration was recorded (Fig. 22.4).

Records of measurement results, either published or preserved in archives, make up a very valuable source of information for the research of climate changes.

Weather observations formed the basis for a dynamic growth of atmospheric sciences. The number of European meteorological stations at the end of the nineteenth century is estimated at more than 15,500. Many European scientists took care of publishing scientific works, often very exhaustive and comprehensive. Also in Cracow Apolinary Pietkiewicz (1829–1891) published his meteorology textbook in 1872. Modelled on the works by Ludwig Kämtz from Dorpat (now Tartu), the book acquired very limited fame. Much better reviews were given to the textbook by Maurycy Pius Rudzki (1862–1916), who headed the Jagiellonian University Astronomical Observatory from 1902 to 1916. Even contemporary readers of his *Principles of meteorology* (Rudzki 1917) are impressed with the wealth of knowledge it has preserved and the logic of his scientific discourse.

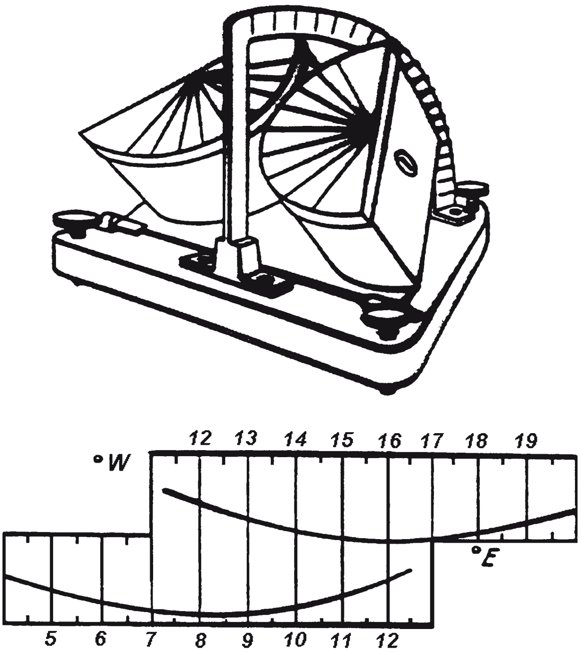

Fig. 22.4 Untypical sunshine recorder, the Jordan photographic heliograph, used at the Astronomical Observatory of the Jagiellonian University from 1887 to 1908 (described by Trepińska 1982)

22.7 Conclusions

Weather and climate have always substantially influenced the conditions of human life. Even the ability to forecast weather and disregard for formidable atmospheric phenomena, achieved in the process of civilization evolution, did not avert the threats posed by the atmospheric environment. The purpose of this paper was to adduce several accounts of unusual weather and climatic cases in Poland, described in historical chronicles and novels, as well as to recall the attempts of numerical handling of weather data with visual and instrumental measurements. The organization of meteorological observations is exemplified by the mentioned Galician network of meteorological stations, run in southern Poland between 1866 and 1918. The development of meteorology (later on climatology) in Poland has sound bases. Scientists' interest in weather research as early as in the sixteenth century has been well documented, whereas the meteorological stations established at the end of the eighteenth century and during the nineteenth century offer reliable data, that can be useful for plenty of very essential inquiries concerning the present climate changes. Drawing on different sources, historical climatology significantly broadens our knowledge about the climate fluctuations in Poland and Europe, confirming the existence of the recent warming process.

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Chapter 23
Observations and Measurements of Precipitation in the Polish Province of Galicia in the Nineteenth Century

Robert Twardosz and Marta Cebulska

23.1 Introduction

Among the oldest meteorological observations in Poland are the sixteenth century observations of the weather in Cracow by Professor Marcin Biem, unique at a worldwide scale, which have been described in detail in the literature (Pfister et al. 1999; Limanówka 2001). The first instrumental measurements started in Warsaw, in the mid-seventeenth century. During the eighteenth century meteorological measurements were conducted in several Polish cities, but the records from most of them contain gaps. The oldest extant precipitation measurement series was recorded in Gdańsk during 1739–1770. It has been studied in detail by Filipiak (2007). The promising beginning of meteorological studies was visibly impeded by Poland's loss of independence in 1795. Southern Poland was incorporated in the Hapsburg Empire and given the name of Galicia. The province enjoyed a relatively high level of autonomy and, in the mid-nineteenth century, was granted a partly locally elected government, thus helping a revival in the natural sciences, including meteorology. Meteorological research conducted in Galicia has been studied and documented by Hanik (1960, 1972), Trepińska (2007) and Twardosz (2007). At the beginning of the nineteenth century, Galicia had an area of 132,000 km^2 and approximately four million inhabitants (Trepińska 2007). The city of Lvov was the capital and the largest city (Fig. 23.1).

In this chapter the authors concentrate on the visual and instrumental observations of precipitation made during the nineteenth century in Galicia. A particular focus was devoted to observations made at the meteorological station of the Astronomical Observatory at Jagiellonian University in Cracow, which are still a source of climatological data. The study limits itself to a period between the begin-

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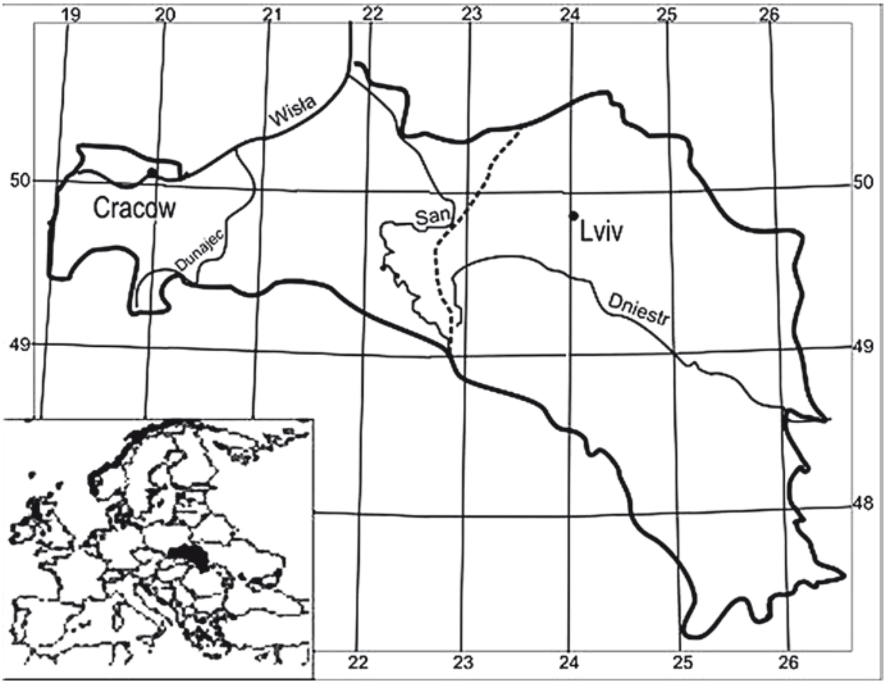


Fig. 23.1 Map of Galicia (the *dashed line* marks today's national border between Poland and the Ukraine)

ning of the continuous observation of precipitation in Cracow and the establishment of the Hydrographic Office in Lvov (now Lviv), a branch of the Central Hydrographic Office in Vienna. In the late nineteenth century, the Hydrographic Office had nearly 400 weather stations and precipitation posts across Galicia.

23.2 Observations and Measurements of Precipitation Until the Mid Nineteenth Century

The first instrumental measurements of precipitation in Galicia were made by a medical doctor named Van Roy in Lvov, in October 1811 (Hanik 1960). He published his findings in the local newspapers *Gazeta Lwowska* and *Rozmaitości*. A monthly summary of precipitation totals measured at the same stations were also published by Hellmann in 1906 (Hellmann 1906). Niedźwiedź and Twardosz (2004) devoted much work to the Lvov records and they have now been largely completed. Monthly data are available from 1824 with a repairable gap of 1842–1851. Alongside the Prague and Warsaw series, the Lvov precipitation records are among the longest in Central Europe.

Cracow's Jagiellonian University (UJ) had the greatest impact on the development of Galician meteorological research. On 1 May, at the initiative of the eminent scientist Jan Śniadecki, the UJ's Astronomical Observatory opened its meteorological station. This was the only such station that operated at an academic institution in Galicia during the first half of the nineteenth century. Observations were made by astronomers and meteorologists according to an instruction manual written by the founder himself. It is thanks to that instruction manual that the observations were carried out and recorded in a uniform manner from such an early stage, which increases their credibility to the point that they are used in historical climatology research today.

The new station started with visual observations of precipitation, including the occurrence, type and intensity of precipitation, for example drizzle, rain, downpour, rainstorm, etc. (Fig. 23.2).

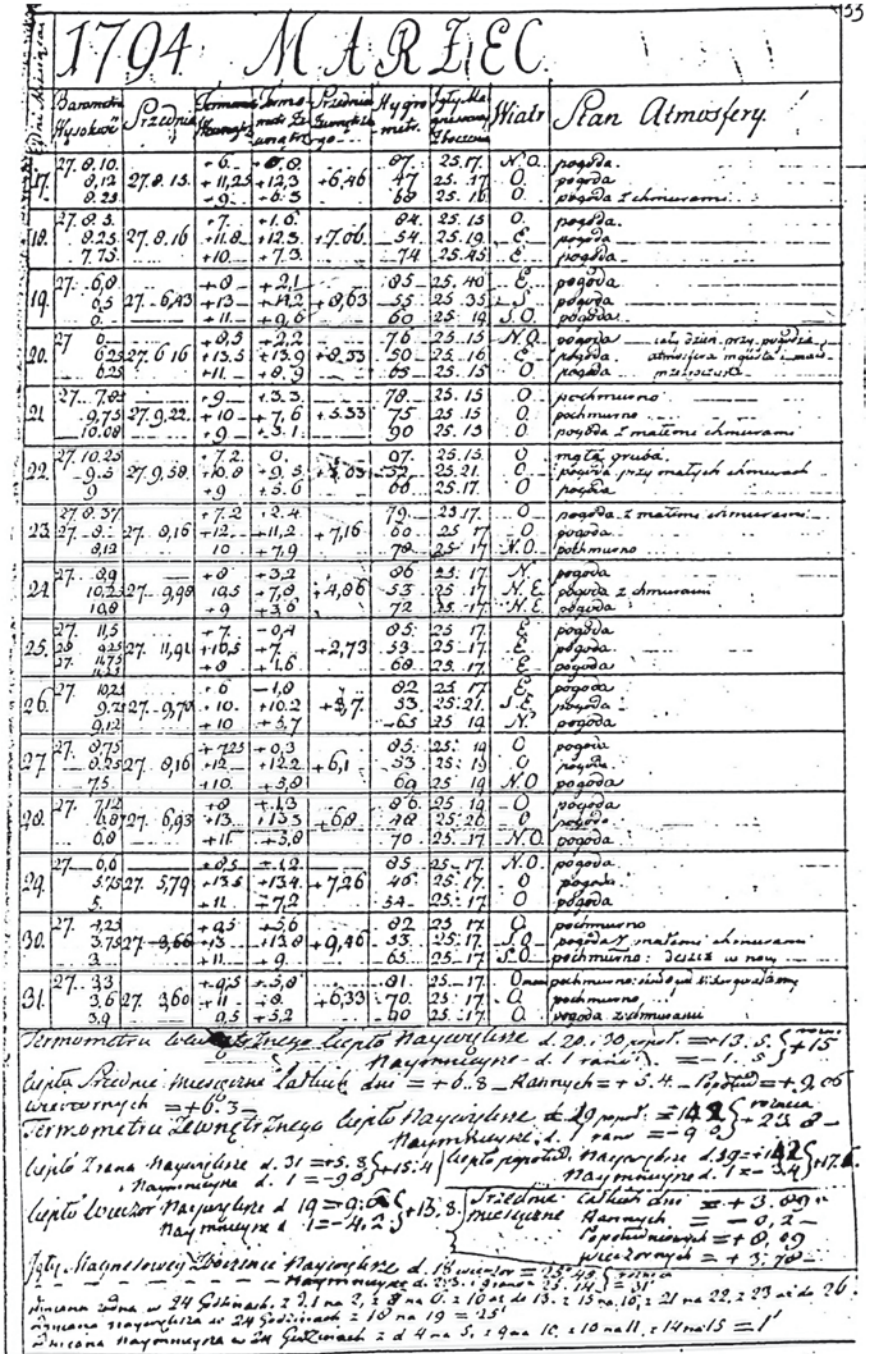
There were also other stations in Galicia operating in the first half of the nineteenth century, but most of them did not operate on a continuous basis. Hanik (1972) says that up until 1858 there were 12 stations from which meteorological observation records are extant (Fig. 23.3). The data include precipitation in certain cases. The stations in Rzeszów and in Biała (today Bielsko-Biała) were owned by the Central Meteorological Authority in Vienna. Others were private with the exception of Cracow. They were mostly organised and run by the intelligentsia, in particular secondary school teachers, but also by medical doctors and clergy (Kuczyński 1868; Wierzbicki 1889).

23.3 Observations of Precipitation in the Second Half of the Nineteenth Century

23.3.1 Instrumental Observations in Cracow

During the nineteenth century, Cracow's observatory provided a scientific and organisational basis for the establishment of a network of precipitation stations and posts of the Physiographic Committee, the first of its kind in Polish lands. The second half of the century was the peak of the station's development. It was headed by Professor F. Karliński, an eminent astronomer, mathematician and meteorologist. Working with his associates, Dr. S. Kuczyński and Dr. D. Wierzbicki, he elevated the meteorological research conducted at the station to a very high level and the station was made the central point in a new network of meteorological stations and precipitation posts organised at the time. Every 2 years, its instruments were used to calibrate the instruments of other stations across Galicia (Kuczyński 1868; Hanik 1960).

In August 1849, decades after its establishment, the Cracow's station started its own precipitation measurements and the monitoring has continued on the very same spot (13.6 m above ground on a terrace at the Astronomical Observatory) to this day without a single gap.



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1794 MARZEC.

Dni Miesiąca	Barometr Wysokość	Srzednia	Termometr Wewnętrzny	Termometr Zewnętrzny	Srzednia Zewnętrznego	Hygrometr	Igły Magnesowey Zboczenie	Wiatr	Stan Atmosfery
17.	27.8.10. 8,12 8.23	27.8.13.	+6 +11,25 +9	+0.8 +12,3 +6.5	+6,46	87 47 68	25.17. 25.17 25.16	N.O. O. O.	pogoda. pogoda pogoda z chmurami
18.	27.8.3. 8.25 7.75	27.8.16	+7. +11.8 +10.	+1.0. +12.5. +7.3.	+7.06	84. 54. 74	25.15 25.19. 25.45	O. E E	pogoda. pogoda pogoda
19.	27.6,0 6,5 0.	27.6,43	+8 +13 +11.	+2,1 +12,2 +9,6	+8,63	85 55 60	25.40 25.35 25.19	E S S.O.	pogoda pogoda pogoda.
20.	27 0 6.25 6.25	27.6.16	+8,5 +13.5 +11.	+2.2 +13.9 +8.9	+8.33	76 50 65	25.15 25.16 25.15	N.O. E O.	pogoda — cały dzień przy pogodzie pogoda. atmosfera mglista i mało pogoda przezroczysta.
21	27.7.83 9,75 10.08	27.9.22.	+9 +10 +9	+3.3. +7,6 +5.1.	+5.33	78. 75 90	25.15 25.15 25.13	O. O. O.	pochmurno pochmurno pogoda z małemi chmurami
22.	27.10.25 9.5 9	27.9.58.	+7.2. +10.8 +9	0. +9.5. +5.6	+5.03	87. 52 66	25.15. 25.21. 25.17.	O O O	mgła gruba. pogoda przy małych chmurach pogoda
23	27.8.37 27.8. 8,12	27.8,16	+7.2 +12. 10	+2.4 +11,2 +7,9	+7,16	79. 60 78	25.17. 25.17 25.17	O O N.O.	pogoda z małemi chmurami pogoda pochmurno
24	27.8,9 10,23 10,8	27.9,98	+8 10,5 +9	+3,2 +7,8 +3,6	+4,86	86 53 72	25.17 25.17 25.17	N. N.E. N.E.	pogoda pogoda z chmurami pogoda
25.	27. 11,5 28 9.25 27. 11,75 11,25	27.11,91	+7. +10,5 +8	−0,4 +7 +1,6	+2,73	85 53 68	25.17. 25.17. 25.17.	E E E	pogoda pogoda. pogoda
26.	27 10,25 9.75 9,12	27.9,70	+6 +10. +10	−1,0 +10.2 +3,7	+3,7	82 53. 65	25.17 25.21. 25.19	E S.E. N.	pogoda pogoda pogoda
27	27.8,75 8.25 7.5	27.8,16	+7,25 +12 +10.	+0,3 +12.2 +3,8	+6,1	85. 53 69	25.19 25.19 25.19	O O N.O	pogoda pogoda. pogoda
28.	27.7,12 6.8 6,8	27.6,93	+8 +13. +11	+1.3 +13.5 +3,8	+6,8	86. 48 70.	25.19 25.20. 25.17	O O N.O.	pogoda pogoda. pogoda.
29.	27.6,0 5.75 5.	27.5,79	+8,5 +13,5 +11.	+1.2. +13.4. +7,2	+7,26	85 46 54	25.17. 25.17. 25.17	N.O. O O	pogoda. pogoda. pogoda
30.	27.4,25 3.75 3	27.3,66	+9,5 +13 +11.	+5,6 +13.8 +9.	+9,40	82 33. 65	25.17. 25.17. 25.17	O S.O. S.O.	pochmurno pogoda z małemi chmurami pochmurno: deszcz w nocy
31.	27.3,3 3.6 3.9	27.3,60	+9,5 +11 9,5	+5,8 +8. +5,2	+6,33	81. 70. 80	25.17. 25.17. 25.17.	O O O	pochmurno: [illegible] pochmurno pogoda z chmurami

Termometru Wewnętrznego ciepło Nayweksze d. 20. i 30 popoł. = +13.5 } różnica +15
Naymnieysze d. 1 rano = −1.5 }
Ciepło Średnie Miesięczne Całych dni = +6.8 _ Rannych = +5.4 _ Popołudniowych = +9.06
Wieczornych = +6.3
Termometru Zewnętrznego ciepło Nayweksze d. 29 popoł. = +14.2 } różnica +23.2
Naymnieysze d. 1 rano = −9.0 }
Ciepło Zrana Nayweksze d. 31 = +5.8 } +15.4
Naymnieysze d. 1 = −9.6 }
Ciepło popołud. Nayweksze d. 29 = +14.2 } +17.6
Naymnieysze d. 1 = −3.4 }
Ciepło Wieczór Nayweksze d. 19 = 9.6 } +13.8
Naymnieysze d. 1 = −4.2 }
Średnie Miesięczne Całych dni = +3.09
Rannych = −0.2
Popołudniowych = +8.09
Wieczornych = +3.70
Igły Magnesowey Zboczenie Nayweksze d. 18 wieczór = 25.45 } różnica = 31'
Naymnieysze d. 23. i 9 rano = 25.14 }
Zmiana żadna w 24 Godzinach. z 7 i 1 na 2, z 8 na 9. z 10 aż do 13. z 15 na 16, z 21 na 22, z 23 aż do 26.
Zmiana Nayweksza w 24 Godzinach z 18 na 19 = 25'
Zmiana Naymnieysza w 24 Godzinach z d 4 na 5, z 9 na 10, z 10 na 11, z 14 na 15 = 1'

Fig. 23.2 Example taken from the diaries of the Jagiellonian University Meteorological Station, March 1794. Precipitation is recorded in the last column as qualitative data (deszcz = rain)

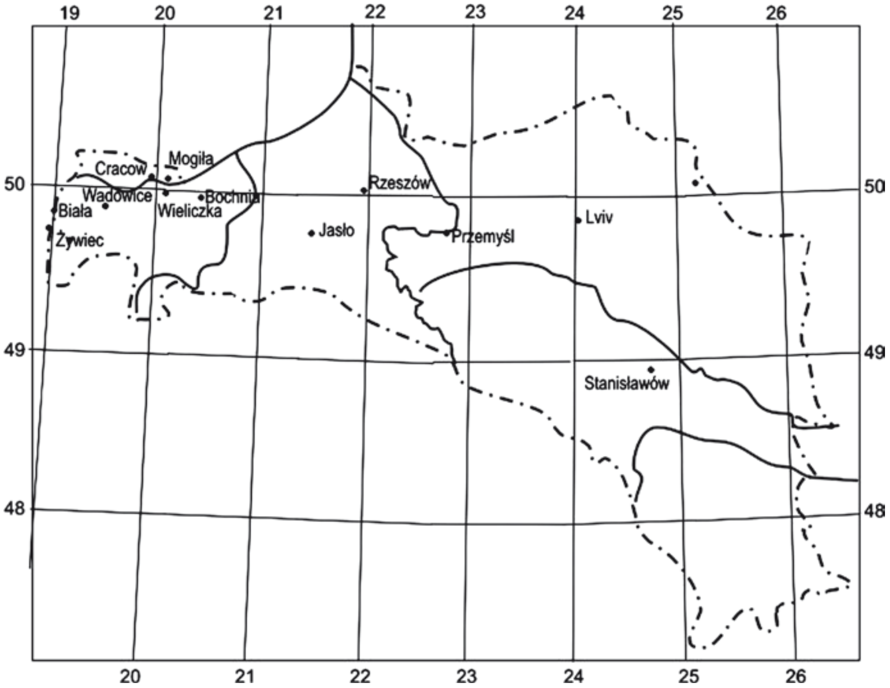

Fig. 23.3 Meteorological stations in Galicia before 1858

During the nineteenth century, the observers used a number of different precipitation meters (Demarée 2003; Maciążek 2005) known at the time as ombrometers. What is known about those instruments is only that their receptor surface was larger than the Hellman's instruments used subsequently (twentieth century). Before 1856, precipitation was measured with Horner's instrument and the totals were quoted in Viennese lots. Between December 1856 and November 1893, a rain gauge was used that had the receptor area equal to one Parisian square foot (Wierzbicki 1887). As was demonstrated by Kuczyński (1868), the dimensions of the instrument (oblong, 1,055 cm^2) produced an area slightly larger than the measure used for the size of one Parisian square foot. For this reason the actual measurements were subject to adjustments. During the period 1863–1875, precipitation was measured in Paris lines after which this was replaced by direct millimetres. One Paris line equals 2.255829 mm of water (Diary of F. Karliński 1851–1852). The instrument was replaced again on 14 November 1893. From measurements of Kania (*Manuscript...*) it transpires that the receptor surface of the new instrument equalled ca. 1,088 cm^2.

From 1863, the measurements were conducted three times per day and were logged in daily logs. This made it possible to bring those records of precipitation totals in line with today's precipitation day (Twardosz 1997a,b). This cannot be done with the records earlier than 1863, because the measurement was taken once per day in the evening and the required timing uniformity is not met.

Pluviometric measurements are particularly significant and in Cracow they were initiated by Professor Karliński as early as in 1886. We know that two pluviographs, known at the time as ombrographs, were used at the stations. Between 1 June 1886 and 31 August 1887, a Swiss made Hottinger instrument was used with a reception surface area of 1,055 cm^2, which was then replaced by a self-recording Rung instrument with a reception area of 1,025 cm^2 which served until 1920 (Karliński 1893). Archival materials suggest that the Hottinger ombrograph was still in use in Cracow at the beginning of the twentieth century. The same pluviograph types were also used elsewhere in Europe (Demarée 2003). The readouts were directly in millimetres. In 1893, Karliński published the tabled results of the self-recorded observations for the period of April-October during 1886–1893 in his *Sprawozdania Komisji Fizjograficznej*. This volume by Karliński should be regarded as a pioneering work.

23.3.2 Organisation of a Network of Weather Stations and Precipitation Posts

When the *Central Anstalt für Meteorologie und Erdmagnetismus* (Central Meteorological Authority) of Vienna, established in 1851, failed to foster uniformity of observations or the expansion of the network of stations in Galicia, the initiative in meteorological research was taken over by the Cracow Scientific Society (Towarzystwo Naukowe Krakowskie), established in 1815.

The network-building effort was started by the Cracow Society's Balneological Committee in 1857. The Committee was active mainly in the Carpathian spas where it opened a small number of stations for balneological purposes, most of which only operated on a temporary basis. Hanik (1960) specified that the Balneological Committee had its stations in the three spa resorts of Szczawnica, Krynica and Iwonicz.

In 1865, the Cracow Society established a Physiographic Committee (Komisja Fizjograficzna) and a year later the new Committee set up a Meteorological Section, which played a significant role in meteorological research in Galicia by covering this province with a network of stations. Working closely with the Physiographic Committee of the Tatra Society (Towarzystwo Tatrzańskie) they set up another network of meteorological stations in 1876. The research activities of the Tatra Society helped increase the density of mountain measurements, especially in western Galicia. The organisation and management of the new network was entrusted to Dr. D. Wierzbicki, a member of the research staff at the UJ's Astronomical Observatory.

The main task of the new meteorological station network, centred on Cracow, was to collect data to improve information on the climatography of Galicia. The networks indeed provided valuable data for such publications as E. Romer's *Geograficzne rozmieszczenie opadów atmosferycznych w krajach karpackich*, the pioneering study of precipitation distribution published in 1895 (Romer 1895).

The study was based on annual precipitation data from 238 stations, including 124 Galician stations that provide records for the period 1876–1890.

Two networks, subsequently added by the Provincial Executive Board (Wydział Krajowy) (since 1881) and by the Hydrographic Office (since 1895), were linked to Lvov University and the Polytechnic. The networks were intended to collect data for practical purposes, mainly to be used in river training. In 1895, the Executive Board's network quickly took over the newly established network of the Hydrographic Office. The Office in Lvov was a branch of the Central Hydrographic Office established in the Ministry of Interior in Vienna by a Pole, Romuald Iszkowski (Ingarden 1910).

The number of stations systematically increased between 1866, when the Meteorological Section was established by the Physiographic Committee, and the end of the century (Fig. 23.4). This increase accelerated in 1895, the year when the establishment of the Hydrographic Office caused the most rapid expansion of the network. The numbers were much greater in western than in eastern Galicia, a difference probably mostly attributable to the deficiencies in the latter's transport infrastructure. The gap in the network density in eastern Galicia was filled by the network of the Executive Board and of the Hydrographic Office centred on Lvov.

Each station had a detailed manual on the taking of observations. Great attention was devoted to the quality of the measurements and the observation staff had the rank of public officials (Przepisy 1895). The first instruction manual for meteorological stations was written by Kuczyński (1866), who modelled it on similar documents from other countries. Copies of the manual reveal that certain meteorological instruments were purchased in Vienna. Rain gauges, regarded as less precise instruments, were commissioned by the Meteorological Section from Cracow-based craftsmen. Measures for ombrometers were ordered from Kappeller. The instruments did vary slightly from station

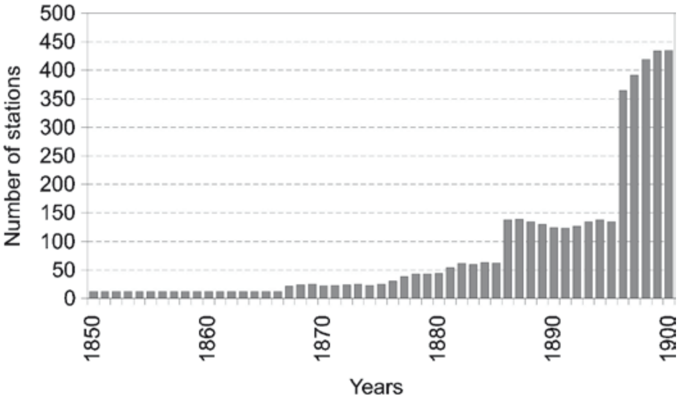

Fig. 23.4 Numbers of meteorological stations and precipitation posts operating in Galicia during the years 1850–1900

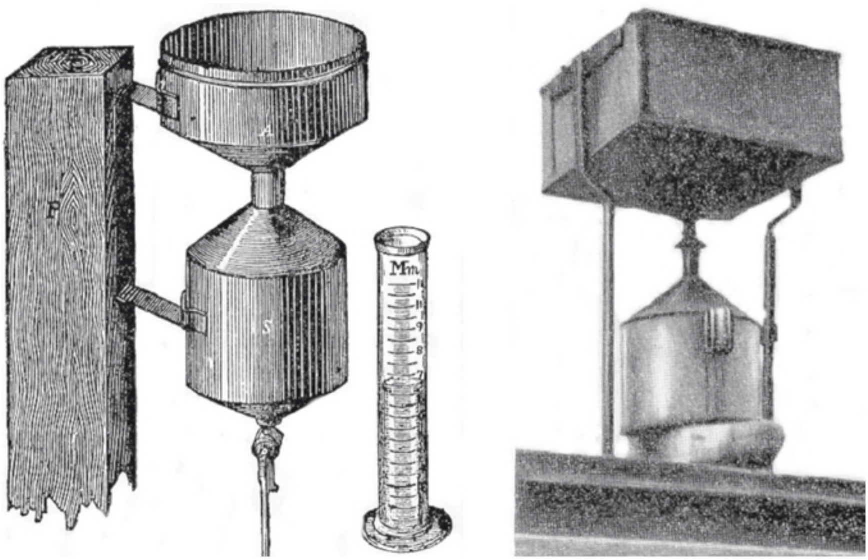

Fig. 23.5 Rain gauges used in the nineteenth century (Kuczyński 1868; Wierzbicki 1889)

to station in terms of reception area (Kuczyński 1868), or form factor, that is circular (e.g. Przemyśl), square (e.g. Rzeszów and Cracow), and even rectangular (e.g. Lvov) (Fig. 23.5). An old type of rain gauge is in use at the same spot in Cracow to this day.

The network of the Executive Board and Hydrographic Office used a single design of rain gauge with an area of 500 cm^2 (diameter of 252.3 mm and circumference of 792.7 mm) (Instrukcja 1886; Przepisy 1895). The same rain gauges were used by the network of the Central Meteorological Authority of Vienna. Initially readouts were taken three times per day (Kuczyński 1868), and then only once a day, at 7:00 am (Instrukcja 1886).

The Physiographic Committee was very successful in its publishing activity. Data collected in Galicia were published in the *Sprawozdania Komisji Fizjograficznej* journal (Reports of the Physiographic Committee) and normally included annual records from 20–30 stations. Also the Executive Board pursued a publishing activity with its *Stan Wody na Rzekach Galicyjskich oraz Opad Atmosferyczny według Spostrzezeń roku...* (Water Level on Galician Rivers and Precipitation According to Observations from…). Every annual published for the period 1887–1894 had a map of isohyets drawn at 100 mm intervals. In their publications both networks used calculations and summaries performed by F. Karliński at the UJ's Astronomical Observatory in Cracow. Precipitation data collected in Galicia from 1895 to 1912 was also published by the Central Hydrographic Office in Vienna in their *Jahrbuch Hydrographischen Zentralbureaus k. k. Ministerium fűr őffentliche Arbeiten*.

23.4 Nineteenth Century Pluvial Conditions in the Light of Observations and Measurements from Cracow

The Cracow records of meteorological observations and measurements provide a very great amount of information about the evolution of precipitation in southern Poland. The longest unbroken series of data involves precipitation frequency (days with precipitation). Based on a dependency of precipitation totals on the number of precipitation days (≥0.1 mm) Twardosz (1999) hindcasted monthly, seasonal and annual precipitation totals for the period 1812–1849 and in this way extended the length of the series by 38 years.

Figure 23.6 presents the long-term number of days with precipitation (≥0.1 mm) and annual precipitation totals. Both characteristics reveal considerable fluctuations. During the first half of the nineteenth century, there is great variability in the number of days with precipitation, which manifests itself in a high fluctuation from year to year and by the occurrence of periods with either large or small precipitation frequencies. Particularly high precipitation frequencies were observed in the 1830s and 1840s, mainly as a result of an increased frequency of summertime precipitation

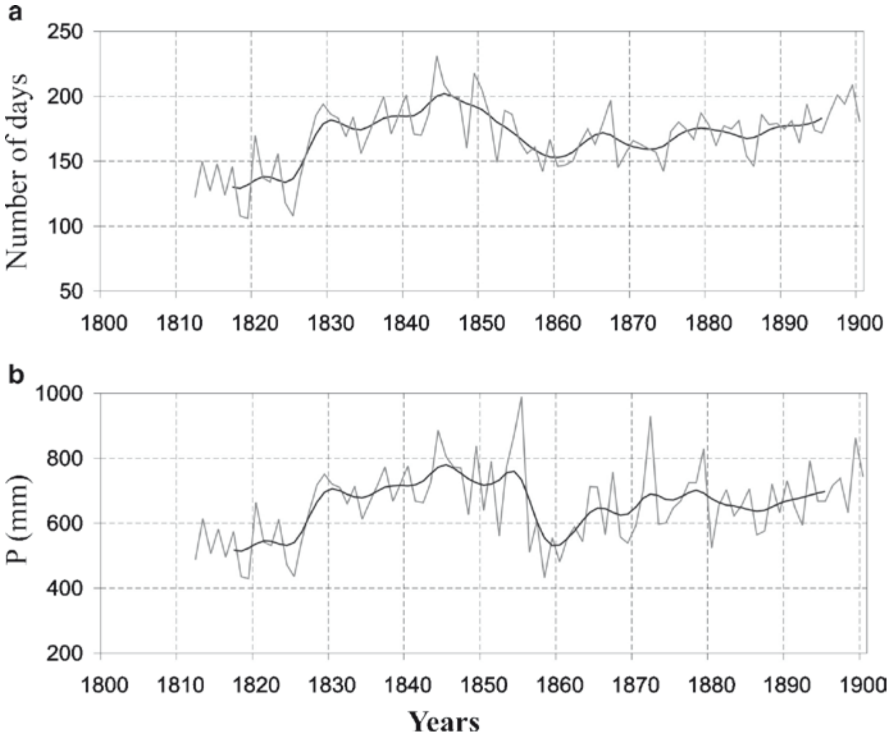

Fig. 23.6 Annual days with precipitation (**a**) and annual precipitation totals (**b**) in Cracow during 1812–1900. Curves smoothed by 11-year Gauss low pass filter

(Fig. 23.7). The greatest number of days with precipitation, 231 (63% of days in the year), was recorded in 1844. A review of archival materials showed that the numbers of days with precipitation were clearly higher than the long-term average in each month of that year. This included 30 precipitation days in July and 27 days in August, which are also the record numbers for July and August in the entire history of instrumental measurements in Cracow. The July rains were also rather intensive, because most of the days feature precipitation at all three observation times. Rainstorm incidence was also high. Other years with very high numbers of days with precipitation, that is above 200 (or 55% of the days in a year) included: 1840 (201), 1845 (209), 1849 (219), 1850 (205). The increased precipitation frequency of the 1840s was also seen in other seasons (Fig. 23.7).

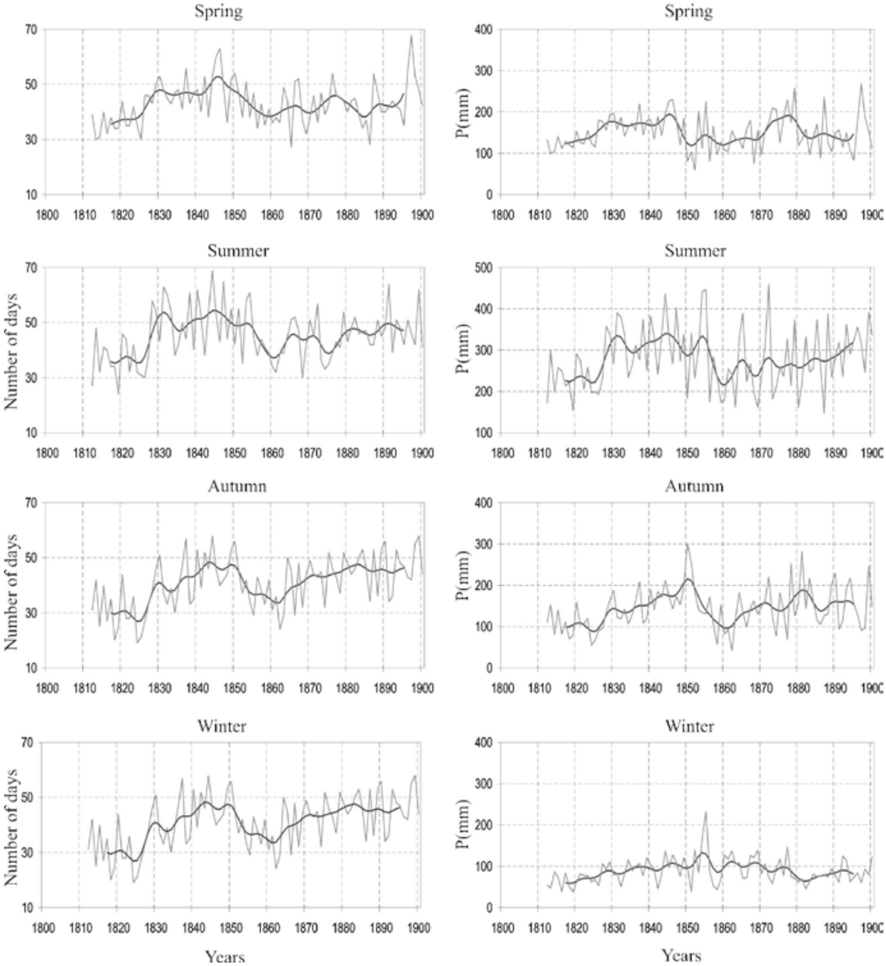

Fig. 23.7 Seasonal days with precipitation (*left column*) and seasonal precipitation totals (*right column*) in Cracow during the period 1812–1900. Curves smoothed by 11-year Gauss low pass filter

Low precipitation frequencies were recorded in the 1810s and 1820s and this resulted in low totals from hindcasting (Fig. 23.6). These low frequencies are seen in all seasons. The lowest number of days with precipitation was recorded in 1819 at 106 days, or 29% of days. This overall number was reflected in low counts in all months, from 4 days in September to 13 in March. Other years with low numbers of days with precipitation included: 1814 (127), 1816 (124), 1818 (108), 1824 (118), 1825 (108).

There was a markedly lower degree of fluctuation in annual rainfall amounts and annual number of precipitation days, especially in the former, from year to year in the second half of the nineteenth century (Figs. 23.6 and 23.7) which, it appears, was linked with the ending of the little Ice Age around 1850 (Twardosz 2000).

Using cumulative deviations of precipitation totals from the average during 1812–1900 (Fig. 23.8) four periods of deviations above and below the average were identified. The first period of deviation above the average ran from 1827 to 1854 and the second started in 1891. Deviations below the average were recorded from 1812 to 1826 and again during the period 1855–1870. Previous research has confirmed that precipitation totals in Cracow show significant correlation with precipitation totals in Warsaw (Niedźwiedź and Twardosz 2004).

Figure 23.9 shows a 24-h pattern of precipitation totals from ombrographic records collected between April and October during the period 1886–1893 by Karliński and published in the *Sprawozdania Komisji Fizjograficznej* (1893). An analysis reveals a maximum between hrs 16:00–17:00 Central European Time CET (UTC + 1).

Based on archival materials available (published and manuscript) the authors have started building a precipitation database with monthly resolution using the longest records available. So far, the data from Bielsko-Biała and Rzeszów have been completed, supplemented and verified for uniformity. These are the stations with the longest records after Cracow and Lvov.

All the other data series were tested against the Cracow series as a reference point using the Alexandersson (1986) Standard Normalised Homogeneity Test (SNHT). The *Anklim* package downloaded from the Internet (http://www.sci.muni.

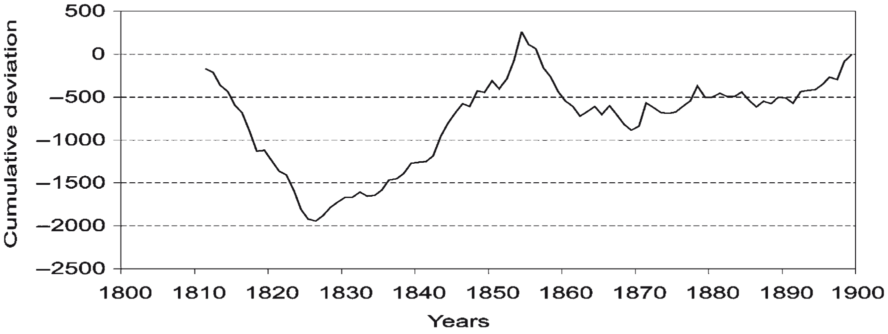

Fig. 23.8 Cumulative deviations of annual precipitation totals from the 1812–1900 average in Cracow

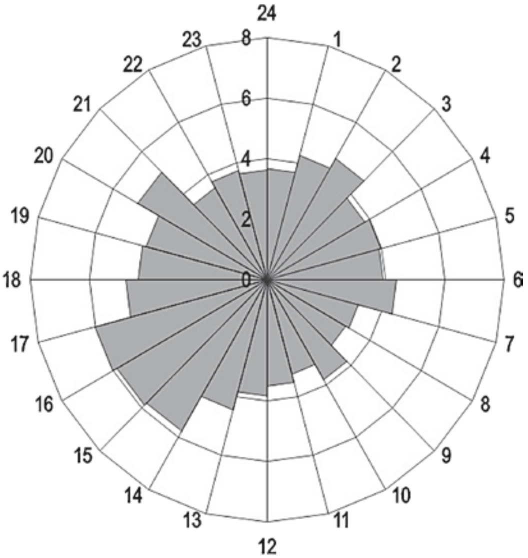

Fig. 23.9 Diurnal precipitation pattern (% of daily totals) in Cracow

cz/~pest) (Štěpánek 2009), was used for this purpose. After eliminating several incorrect values, the tests revealed that there were no grounds, at a significance level of 95%, for considering any of the precipitation series as non-homogeneous.

Figure 23.10 provides an example of annual precipitation totals as recorded in Bielsko-Biała representing western Galicia, in Rzeszów for central Galicia and in Lvov for eastern Galicia. Compared to the Cracow records, these stations reveal a greater variability of precipitation.

23.5 Conclusions

The rich history of meteorological studies conducted in nineteenth century Galicia suggests that Polish society was very effective in taking the opportunity offered for the development of science when the partitioning regime granted a high degree of autonomy to the province. The greatest contribution to the development of networks of meteorological stations and precipitation posts was made by the Jagiellonian University in Cracow which has maintained continuous observations at the same place since 1792.

The Cracow series, with its broad scope of precipitation observations and fully documented records is particularly valuable. The series includes a uniquely long pluviographic record collected since 1886.

A review of the Cracow series reveals that the 1830s and 1840s were characterised by an increased frequency of precipitation, while the opposite is true during

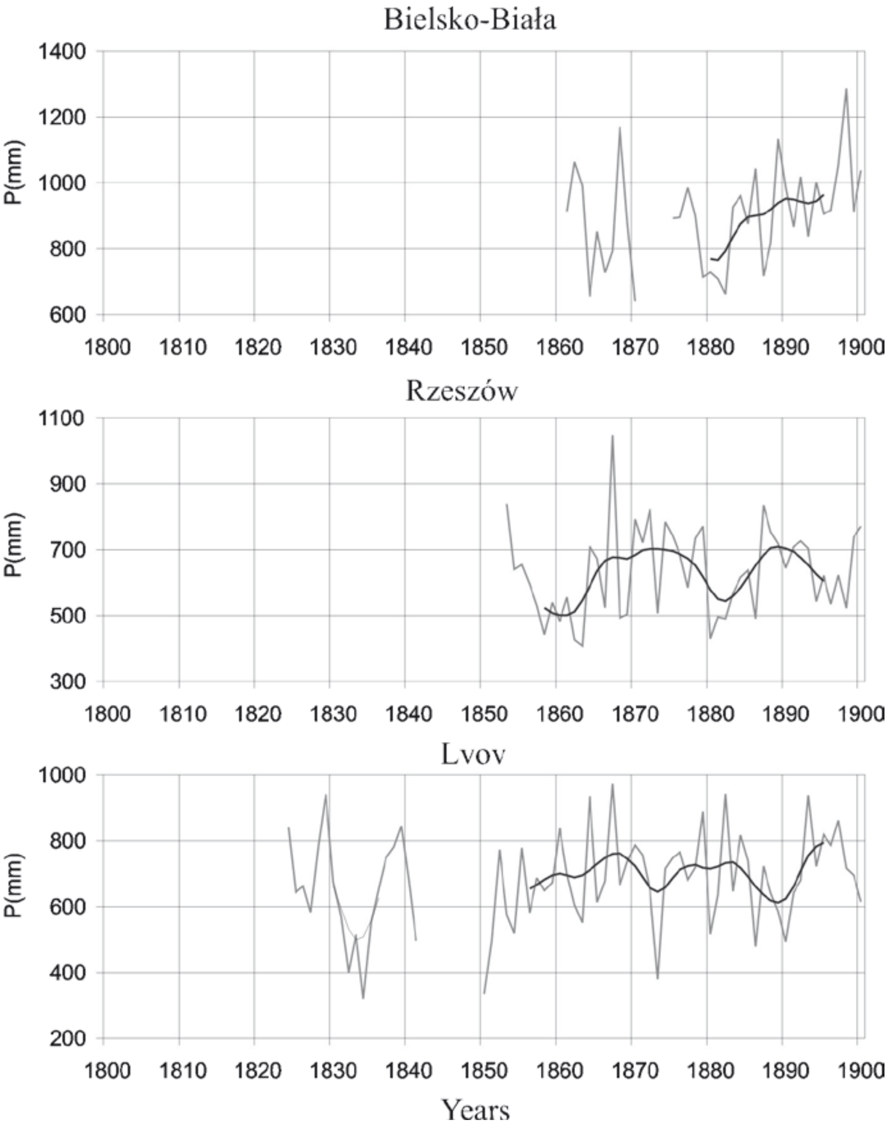

Fig. 23.10 Annual precipitation totals at selected stations in Galicia. Curves smoothed by 11-year Gauss low pass filter

the 1810s and 1820s. The second half of the nineteenth century was marked by a clearly lower degree of fluctuation in number of precipitation days from year to year. The Galicia precipitation data pool is large and has only been marginally exploited. The uniform precipitation record from Cracow offers an opportunity to hindcast, perhaps back to the mid-nineteenth century, many other precipitation series and in this way to better understand the climate at that time.

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Chapter 24
Variability of the European Climate on the Basis of Differentiation of Indicators of Continentalism

Agnieszka Wypych

24.1 Introduction

The climate in Europe is shaped by geographical location, relief and the parallel orientation of orographic barriers, as well as the presence of a huge continental mass in the East and the Atlantic Ocean on the West. The primary factors are the supply of solar energy and atmospheric circulation, the influence of which varies seasonally. The presence of permanent and seasonal pressure centers determines the advection of definite air masses (Martyn 1992). The climatic interactions within the ocean–atmosphere–continent system are comprehensively characterized by the annual air temperature amplitude. Apart from the influence of land size it also reflects the influence of other elements – hipsometry and relief. The interaction of these mutual dependences, “climate continentality,” has long been a subject undertaken by many European and Russian scientists. The intensity of climatic influence of the ocean on the land mass is expressed by several indices of which serve to describe existing relations in definitive formulas.

Visible global climate change, particularly apparent in the rise of air temperature, affects temperature amplitude, and therefore the course of climate continentality indices.

According to Bryson (Kożuchowski and Marciniak 1992), climate conditions of the borderlands, within zones of both sea and continental air masses, are sensitive indicators of change. The transitionality of the Polish climate, which manifests itself in the presence of both oceanic and continental influences, enables the spatial and temporal analyses of their changeability. In 1947, Romer suggested the oceanisation of the European climate, citing the rise of average annual climatic values, particularly the slight decline in summer temperatures (Romer 1947).

The observed tendencies of temperature changes, as well as a decline in the range of precipitation totals (showing effects of pluvial oceanisation) are confirmed

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in many Polish and foreign climatological research works (e.g. Ewert 1966; Kożuchowski and Wibig 1988; Kożuchowski and Marciniak 1992, 2002). The authors confirm a relationship between periods of increased continental and oceanic influence and the course of circulation indices, however they unanimously emphasize the lack of visible coexistence of thermal and pluvial continentality (Kożuchowski and Wibig 1988).

The aim of this research is to define the regularity in the spatial and temporal diversity of thermal and pluvial continentality indices in Europe. This will define the characteristics of European climate changeability with respect to the range and the intensity of oceanic air mass influence. The role of atmospheric circulation will also be considered as a factor in the shaping of climate conditions.

24.2 Material and Methods

Monthly air temperature and precipitation totals gathered in the project entitled "European Climate Assessment" (Klein Tank et al. 2002) were used in the research. Ten stations situated in the temperate latitudes between 48° and 53°N were chosen (Table 24.1, Fig. 24.1). For each year values of the chosen thermal and pluvial continentality indices were calculated (Table 24.2), along with their basic measures of dispersion: standard deviation and changeability coefficient. The analysis was carried out with particular consideration of the long-term

Table 24.1 Source material characteristic

	Location			Data periods	
Station	φ latitude	λ longitude	h m a.s.l	Temperature	Precipitation
Paris	48°49'N	02°20'E	75	1901–2000	1886–2000
Frankfurt	50°07'N	08°40'E	103	1870–1944	1870–1944
				1946–1983	1946–1983
				1986–1999	1983–1990
					1993–1999
Munich	48°10'N	11°30'E	515	1879–1944	1879–1944
				1948–1998	1948–1988
Berlin	52°27'N	13°18'E	55	1876–2000	1876–2000
Prague	50°05'N	14°25'E	191	1775–2000	1805–2000
Vienna	48°14'N	16°21'E	198	1901–2000	1901–2000
Cracow	50°04'N	19°58'E	220	1792–2000	1901–2000
Kiev	50°24'N	30°32'E	166	1900–1996	1900–1942
					1944–1996
Poltava	49°36'N	34°33'E	160	1900–1940	1900–1940
				1944–1981	1944–1981
				1983–1990	1983–1990
Lugansk	48°34'N	39°15'E	59	1905–1919	1900–1906
				1921–1941	1909–1919
				1944–1996	1921–1941
					1943–1996

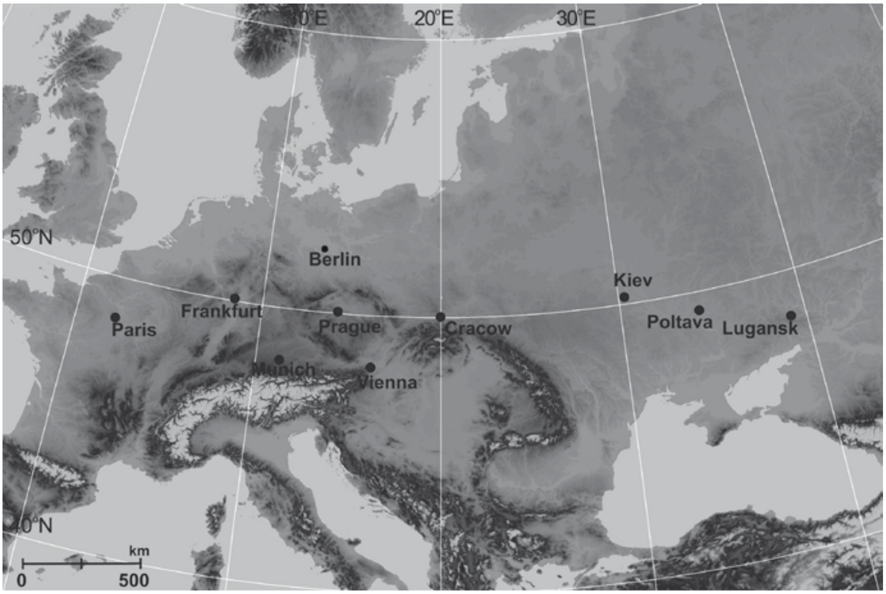

Fig. 24.1 Location of the selected European stations

Table 24.2 Selected continentality indices

Indice/Author		Formula
Thermal continentality	Ewert (1996)	$K = \frac{A - (3.81 \sin \varphi + 0.1)}{38.39 \sin \varphi + 7.47} 100$ A – annual amplitude of temperature φ – geography latitude
	Johansson-Ringleb	$K = 0.6(1.6 \frac{A}{\sin \varphi} - 14) - D + 36$ A – annual amplitude of temperature φ – geography latitude D – difference of mean autumn and spring temperature
Pluviothermal continentality	Rychliński	$K = 4 \frac{A - 12 \sin \varphi}{\sin \varphi} \frac{l}{L}$ A – annual amplitude of temperature φ – geography latitude l – annual precipitation total L – long-term annual mean precipitation total
Pluvial continentality	Vemičs index of precipitation	$K = \frac{R_{III-IX}}{R} 100$ R_{III-IX} – precipitation totals of selected months R – annual precipitation total
	Quotient of the winter and summer precipitation totals	$K = \frac{R_{XII-II}}{R_{VI-VIII}}$ R – precipitation totals of selected months

variability of the Ewert index (thermal) and Vemič index (pluvial). A detailed study of these values enabled identification of climate continentalism and oceanism periods and phases in Europe.

In most cases, the data gathered between 1901 and 2000 was used. Cracow was chosen as the base station because it is highly representative of Central Europe (the Historical Station of the Climatology Department of the Institute of Geography and Spatial Management of the Jagiellonian University). Long-term courses of the continentality indices in Cracow were correlated with the monthly index of the NAO based on the difference of normalized sea level pressures (SLP) between Ponta Delgada, Azores and Stykkisholmur/Reykjavik, Iceland (Hurrell et al. 2003) and with regional circulation indices by Niedźwiedź (1993). The indices are as follows: P – progression index (westerly zonal index), S – meridional circulation index (with the southern component) and C – cyclonicity index. These simplify characterization of the most important features of atmospheric circulation in a given year. The construction of the regional circulation indices was based on indices worked out by Murray and Lewis with further modification to the Polish classification of circulation types (Niedźwiedź 1993).

24.3 Thermal Continentality

The influence of air temperature is the simplest index that enables identification of continental and oceanic interaction on the thermal conditions of Europe. It is expressed in annual temperature amplitudes. Combined with increased intensity of continental influences, the annual and daily amplitudes values rise as well. The characteristic features of continental climates are a warm summer and severe winter, as well as warmer temperatures in spring than autumn (Martyn 1992).

The long-term mean values of the thermal continentality indices calculated for the aforementioned stations situated in Europe (Table 24.3) confirm the weakening of oceanic influences from the West to the East. The air temperature amplitude value varies from 17.4°C in Paris to 30.5°C in Lugansk.

For the stations situated in Germany the influence of the continent's shape and the altitude on the course of isoamplitudes is apparent. Northernmost Berlin, because of its proximity to the coast, distinguishes itself with a lower air temperature amplitude, about 1.0°C less than in Munich. The increasing climate continentality farther inland is confirmed by calculated values of the thermal continentality indices. Apart from the amplitude, these values also take into account the geographical location (latitude) and the difference between autumn and spring temperatures (Johansson-Ringleb index). The indices (Table 24.3) range in value from about 40% (Ewert index) on the West of the continent (Paris – 39.6%) up to 70% for the stations situated by the Black Sea (corresponding to 48.9% and 66.6% for the Johansson-Ringleb index). The calculated values suggest a border condition located between oceanic and continental climate types at 19°E – isoamplitude 23°C or with a shift (of about 06°λ) to the West – isoline 50% (Ewert index).

Table 24.3 Long-term mean and standard deviation values of thermal and pluvial continentality indices

		Continentality indices						
		Thermal			Pluviothermal	Pluvial		
Station		Ampl. (°C)	Ewert (%)	J-R* (%)	Rychliński	Precipitation totals (mm)	Vemič (%)	Quotient of the winter and summer precipitation totals
Paris	Mean	17.4	39.6	48.9	44.1	621.4	58.6	0.99
	σ	2.3	6.4	3.1	12.2	111.0	12.8	0.46
Frankfurt	Mean	20.0	46.1	52.8	55.9	638.5	60.4	0.81
	σ	2.7	7.5	3.4	16.6	122.6	14.4	0.46
Munich	Mean	20.9	50.0	54.4	64.2	930.0	71.8	0.42
	σ	2.8	8.0	3.5	15.7	123.2	11.2	0.17
Berlin	Mean	20.6	46.4	52.3	56.2	589.0	62.9	0.72
	σ	2.9	7.6	3.4	16.2	92.0	13.6	0.30
Prgue	Mean	21.9	51.1	54.7	65.8	476.6	73.8	0.37
	σ	2.8	7.8	3.4	18.0	88.6	16.4	0.23
Vienna	Mean	22.1	53.2	56.0	70.1	653.2	65.3	0.66
	σ	2.6	7.3	3.2	14.4	108.8	14.6	0.32
Cracow	Mean	23.2	54.6	56.3	70.9	678.9	71.8	0.41
	σ	3.1	8.6	3.9	18.6	111.5	15.6	0.20
Kiev	Mean	27.3	65.8	61.8	92.7	525.4	63.9	0.78
	σ	3.5	9.8	4.4	32.5	153.2	21.9	0.50
Poltava	Mean	29.2	71.1	64.2	102.0	309.0	59.7	1.09
	σ	2.3	10.1	4.7	36.4	111.0	25.8	1.07
Lugansk	Mean	30.5	75.5	66.6	115.1	360.8	64.6	0.76
	σ	3.9	10.9	4.9	42.6	136.9	27.8	0.60

*Johansson-Ringleb index

The stations situated farther inland (e.g. Kiev, Poltawa) distinguish themselves with larger fluctuations of index values for the given period. The standard deviation calculated for the Ewert index ranges from 6.4 in Paris up to 10.9 in Lugansk. The variation of other thermal indices' standard deviations is slightly smaller (Table 24.3).

The long-term indices changeability in all stations shows a statistically insignificant decline ($\alpha = 0.05$) (Fig. 24.2). Over the course of many years, the periods found to be dominated by oceanic and continental influences are very clearly defined; moreover they exist synchronically for all stations.

The thermal conditions at the end of the nineteenth century show continental influence as prevailing. In the first two decades of the twentieth century the influence of the Atlantic Ocean increased, which is also observed in the second half of the twentieth century. Between 1901 and 2000 the clear predominance of the oceanic climate was interrupted by periods with continental thermal conditions. These short-term episodes took place from the 1930s to 1950s at different times for the stations considered (Fig. 24.2). The alternate periods of oceanism and thermal continentality distinguished themselves with varying degrees of interaction. They are more remarkable in stations of continental climate type. In Lugansk, Poltawa, Kiev and even in Cracow the deviations from the long-term means amounted to ±15–20% ($\pm 1{,}5\sigma$). The biggest force was that of continental influences. The last phase of climate oceanism appeared inside the continent in only about 1970 and lasted up to the end of the twentieth century (Fig. 24.2).

24.4 Pluvial Continentality

The influence of the ground on precipitation has its effects on the annual totals as well as variances in precipitation throughout the year. Pluvial oceanism is characterized by high levels of precipitation appearing relatively evenly throughout the year, with a slight increase during the autumn–winter period. Maximum precipitation levels typically coincide with an increase in continental influences (Martyn 1992).

The annual mean precipitation totals for the considered European stations vary from 930 mm in Munich to 309 mm in Poltava. This spatial diversity is caused by the distance from the ocean and topographic relief (Fig. 24.1). The low precipitation totals in Prague result from that station's localization in the rain shadow from the nearby mountain ranges, whereas the high totals in Munich are correlated with that city's altitude (Table 24.1). The pluvial continentality increase from the West to the East can be noticed in the trend of annual totals, which is confirmed by the pluvial indices values (Table 24.3). In Paris the ratio of the winter and summer precipitation totals equals 0.99. This value indicates equal levels of precipitation throughout the year. The index reaches lower and lower values in the Eastern parts of the continent, dropping to 0.41 in Cracow. The values calculated for Munich (0.42) and Prague (0.36) are exceptions; their geographical locations affect the

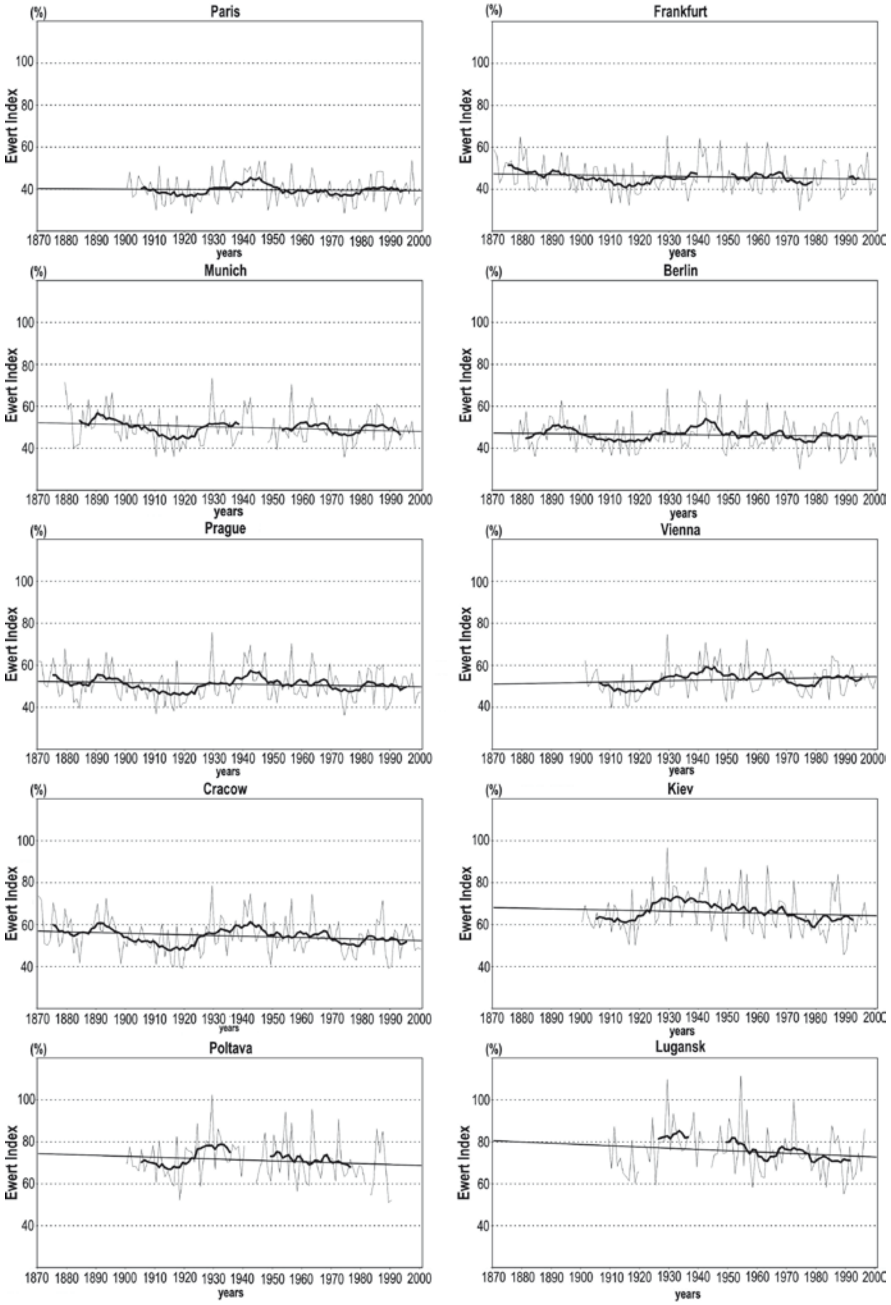

Fig. 24.2 Multi-annual courses of Ewert thermal index values (%) in selected European stations smoothed by 11-year running average (*solid line*). *Straight line* – linear trend

annual precipitation distribution (Table 24.3). In the stations situated deep within the continent such as Kiev, Poltawa and Lugansk, the ratio of winter to summer totals increases. This can be related to the influence of the Black Sea on the pluvial conditions. Similar spatial diversity is shown by the Vemič index (Table 24.3).

The stations situated in the eastern Europe distinguish themselves with more intensive long-term changeability of precipitation totals. The standard deviation reaches 27.8% in Lugansk (Vemič index), a value twice as high than in the case of Paris (12.8%; Table 24.3).

The long-term changeability of the pluvial continentality indices is statistically significant only for the stations exhibiting the continental climate type (Kiev, Lugansk). During the years considered, Poltawa experienced a large drop in the Vemič precipitation index (Fig. 24.3), however, this has not been the case over the long term for other stations. In Kiev and Lugansk, for instance, there was a significant increase in the Vemič index (Fig. 24.3). There is also a clear decline in the ratio of winter to summer precipitation totals that confirms the pluvial continentality of precipitation in this part of Europe. Due to the lack of support for this observed tendency, the precipitation data from Poltawa station is considered suspect with regard to homogeneity and was excluded from further analysis. Cracow and Vienna aside, the stations situated in Western and Central Europe experienced an increase in continental influence, however statistically insignificant, in Vemič's annual precipitation distribution index (Fig. 24.3). The winter to summer precipitation ratio doesn't consider overall decline, so it should be assumed that increased springtime precipitation (from March to May) is an important factor.

For the long-term courses of indices, it is difficult to distinguish periods of oceanism or continentalism in pluvial conditions. The changeability coefficient reaches values consistently greater that those of the thermal indices. The stations in Kiev and Lugansk are exceptions as the tendency of pluvial continentality is statistically significant. Up to the 1950, oceanic influences determined precipitation conditions. In the second half of the twentieth century (apart from some individual cases) Vemič's index values exceeded their long-term mean by about two times the standard deviation, confirming the precipitation continentality prevalent in that time period.

24.5 Climate Continentalism in Relation to Atmospheric Circulation Patterns

Atmospheric circulation is a primary factor influencing climate conditions. Understanding its variability with time is useful in calculating the changeability index of certain climate components. The intensity and type of circulation can be described in a quantitative way by several types of indices. The foundation of developed circulation indices is the estimation of changes in circulation conditions and the description of their influence on their behavior of meteorological components (Ustrnul 2002).

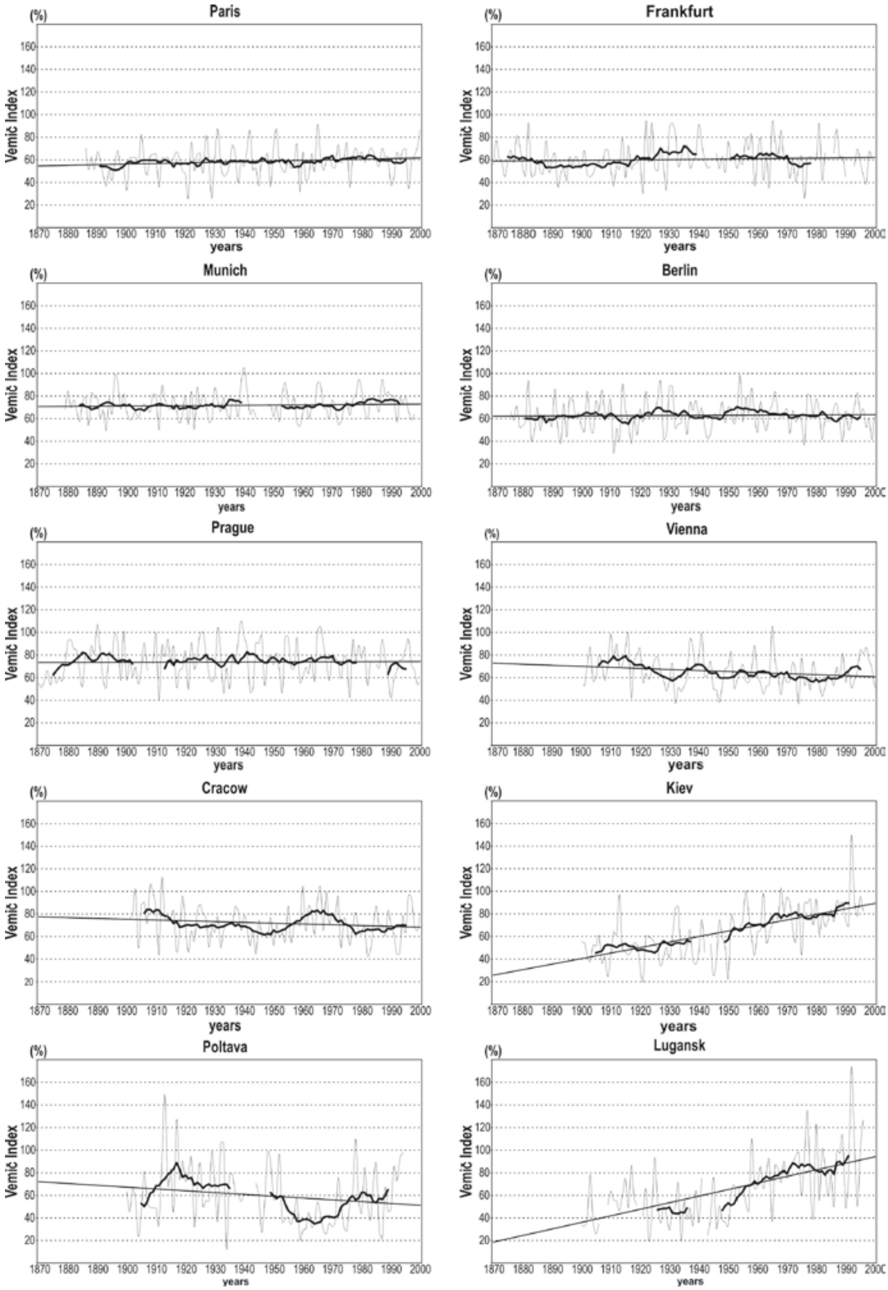

Fig. 24.3 Multi-annual courses of Vemič precipitation index values (%) in selected European stations smoothed by 11-year running average (*solid line*). *Straight line* – linear trend

The varying intensity of oceanic and continental influences on the analyzed area confirms the importance of atmospheric circulation in the shaping of pluvial and thermal continentality in Europe. The correlation coefficient values between the continentality indices and NAO index, as presented in Table 24.4, also outline the significant influence of local conditions.

The correlation is statistically significant for the pluvial continentality indices exclusively for the stations situated deep within the continent. The correlation coefficient values range from −0.25 (Kiev) up to −0.336 (Lugansk) for precipitation totals and −0.225 (Cracow) and −0.291 (Lugansk) for Vemič's index (Table 24.4). The insignificance of the statistical correlation between the NAO and the ratio of winter to summer precipitation totals confirms that zonal circulation plays a very important role especially in the shaping of annual precipitation totals. Their annual distribution also remains under the influence of meridional circulation. This refers primarily to the autumn months (October and November) as well as in late spring and summer (from May to August) when the highest frequency of southern air mass advection is recorded (Gerstengarbe et al. 1999).

Though slight, statistically significant circulation influence on thermal conditions is confirmed by the air temperature amplitude correlation coefficients calculated for Frankfurt, Munich and Prague (−0.192, −0.219 and −0.224, respectively) and for the Ewert index (−0.176, −0.216 and −0.223, respectively).

Specific analysis of the influence of atmospheric circulation on the changeability of continentality indices in Cracow, conducted thanks to the use of regional circulation indices constructed for southern Poland (Table 24.5), shows that the parallel air masses flow influences thermal conditions. The correlation coefficient reaches statistically significant vales for the Progression index (P), however there is a lack of significant links between zonal circulation and precipitation totals changeability. Zonal circulation and annual precipitation distribution also lack any significant correlation (Table 24.5). The long-term behavior of the annual precipitation totals is influenced by the Cyclonicity index changeability; an increase of the precipitation totals often accompanies more frequent occurrences of cyclones.

24.6 Conclusions

The characteristics of the long-term changeability of the thermal and pluvial continentality in Europe show that the geographical location influences the extent of the climate oceanisation and its tendency to change. For the stations situated in Central and Eastern Europe (Cracow, Kiev, Poltawa, Lugansk) the changeability of the thermal and pluvial conditions shown by the indices described herein is remarkable (statistically significant for precipitation). In the Western part of the continent the fluctuation of the indices' values are considerably smaller and do not exhibit a significant directional change.

The observed climatic warming, most clearly demonstrated by the increase of temperature during the winter months, is not confirmed by the course of the thermal

Table 24.4 Correlation coefficients between selected continentality indices and NAO index (values significant at the level of significance α =0.05 are bolded)

	Continentality indices						
	Thermal			Pluvio-thermal	Pluvial		
Station	Ampl.	Ewert	J-R*	Rychliński	Precipitation totals	Vemič	Quotient of the winter and summer precipitation totals
Paris	–0.095	–0.095	–0.052	**–0.221**	–0.107	–0.120	0.113
Frankfurt	**–0.192**	**–0.176**	–0.118	**–0.197**	–0.063	–0.058	–0.104
Munich	**–0.219**	**–0.216**	–0.154	**–0.283**	–0.144	–0.044	–0.123
Berlin	–0.152	–0.131	–0.030	–0.114	0.016	0.014	–0.007
Prague	**–0.224**	**–0.223**	–0.135	**–0.216**	–0.093	–0.045	–0.124
Vienna	–0.077	–0.079	0.012	–0.129	–0.076	–0.050	–0.066
Cracow	–0.169	–0.169	–0.063	**–0.297**	**–0.314**	**–0.225**	–0.093
Kiev	–0.027	–0.021	0.102	**–0.294**	**–0.250**	–0.159	–0.021
Poltava	0.031	0.031	0.118	–	–	–	–
Lugansk	0.106	0.136	0.183	**–0.306**	**–0.336**	**–0.291**	0.042

*Johansson-Ringleb

Table 24.5 Correlation of coefficients between selected continentality indices and regional circulation patterns by Niedźwiedź (1993) in Cracow (significant values at the level of significance α =0.05 are bolded)

	Continentality indices						
	Thermal			Pluvio-thermal	Pluvial		
Index	Ampl.	Ewert	J-R*	Rychliński	Precipitation totals	Vemič	Quotient of the winter and summer precipitation totals
Progression (P)	**–0.270**	**–0.270**	**–0.207**	**–0.293**	–0.090	–0.103	0.030
Meridional circulation (S)	0.053	0.053	–0.006	0.056	0.035	0.060	–0.013
Cyclonicity (C)	–0.112	–0.112	–0.167	0.169	**0.395**	**0.289**	–0.009

continentality indices. The trends in recent climatic oceanisation are not statistically significant, however – as previously mentioned – are more prevalent in the stations of the continental climate type.

The long-term changeability of the pluvial continental indices is remarkable only deep within the continent. In Cracow, Kiev and Lugansk an increase in continental climatic features in the annual precipitation distribution is observed.

Atmospheric circulation and local conditions influence the tendencies of climate continentality's changeability in Europe. Over long-term courses of the thermal continentality indices, the oceanisation periods – particularly in the beginning and in the second half of the twentieth century – occur simultaneously with increases in influence of zonal circulation. No such link exists in the case of pluvial indices. The inconsistency between the changeability's direction of pluvial conditions and climate oceanisation tendency at the end of the last century suggests that apart from circulation factors, local factors – such as anthropopression – are important in developing the climate changeability, especially in continental areas.

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Chapter 25
The First One Hundred Years (1791–1890) of the Wrocław Air Temperature Series

Krystyna Bryś and Tadeusz Bryś

25.1 Introduction

Wrocław (Breslau) is one of only a few cities in Central Europe[1] that can claim to have contributed to the early history of continuous temperature measurements. The reconstructions of meteorological elements necessary for research in this field have to be firmly founded on representative instrumental measurements in order to provide a reliable insight into the past with the use of these same stations and their homogeneous series. Only reconstructions which are informed by the latest geophysical research can be used in the development of reliable climatic models for more accurate long-term forecasts.

The extant climatic data were often derived from station where there were changes in both the locations and observation times of measurements. Therefore they require careful homogenization which, in restoring the uniformity of the series, will reconcile the possible, physically explicable changes of measurement values by which it is constituted. What is important in this verification process is the cross-referencing of the checked series with the values occurring in the immediate vicinity of the station being examined. Mean monthly temperature values from other Silesian stations are relevant in relation to the early temperature measurements in Wrocław.

The published data (Galle 1857, 1879) for these stations cover only the period between 1806 and 1851; they do not include the very beginning of the so-called "Wrocław series". The present reconstruction will focus on monthly average air

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[1] In the second half of the eighteenth century there were at least 100 meteorological stations in Europe, along with several operational networks. However, most of these (especially in Central Europe) were short lived and worked no longer than a few years or decades.

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temperature (Tp) values in the first 100 years (1791–1890) of the series, taking into account the historical temperature measurements in the Silesian region.

25.2 The Beginnings of the Wrocław Air Temperature Series

The first permanent meteorological observations in Wrocław to include air temperature (Tp) measurements most probably date back to the late seventeenth century (Hellmann 1883, 1914; Landsberg 1983; Munzar 2003; Pyka 2003).[2] However, systematic air temperature measurements originally began in February 1791, were carried out at three observation times, and have continued until the present (taking into consideration changes in station location)[3]. They were made by scholars at the Astronomical Observatory, based in the Mathematics Tower of the Universitatis Leopoldinae Vratislaviensis (the Latin name for Wrocław University, founded in 1702 by the Jesuits). Temperature measurements were taken there as a continuous series at least until the end of 1930, at either the north-east or the north-west window (depending on the shadow cast by the building) at a height of 88.3 French ft, that is h = 28.7 m above ground level. In the first decades of the Observatory's activity the location was sometimes changed (Galle 1879), which may have had a substantial impact on the homogeneity of the series during the nineteenth century (this issue will be examined more closely later in this work).

The compilation of the observation data from the first 85 years, from 1791 to 1875, was achieved thanks to the astronomer Galle (1857, 1879), renowned for the observational discovery of Neptune made on the basis of Le Verrier's calculations. In his early monograph *Grundzüge der Schlesische Klimatologie*, Galle (1857) published Wrocław air temperature data recorded in the years 1791–1854 at the

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[2] The first systematic, instrumental temperature measurements were conducted by David von Grebner in Wrocław in 1710 and lasted until 1721 (Hellmann 1883, 1914; Landsberg 1983). The results of these measurements were published by Grebner after 1721 in the form of a manuscript, which was kept in the library of the University of Wrocław and which possibly survived the havoc and destruction of the war (Pyka 2003). These measurements preceded his earlier meteorological observations (also connected with air temperature) starting in 1692 in Wrocław. It was not until 1717 that the comparative temperature series from two Silesian stations (Wrocław and Oława) and one Slovakian station (Preszow) came into existence, as reported in the serial encyclopedic press *Breslauer Samlungen* (Hellmann 1883, 1914; Munzar 2003). This comparative temperature series, which began in 1717, was carried out by Kanold until 1726 and then continued by Büchner in 1727–1730. Pyka's publication (2003) contains the erroneous information, stating that Johann Kanold started his meteorological examinations in Wrocław in 1679, which is actually the year of his birth.

[3] The nineteenth-century changes in the location of measurements in the University building were assiduously recorded by Galle (1879). Later changes were connected with the transfer of measurements from the University building, situated in the old city centre, to the outskirts of Wrocław (Krzyki, Gądów, Biskupin, Strachowice), and have been presented by Pyka (2003) and Bryś and Bryś (2010).

Breslau-Sternwarte Observatory ($\phi = 51°06'56.5''$N, $\lambda = 17°02'10.6''$E, H station = 118.0 m ASL, $H_{Tp} = 146.7$ m ASL). They were presented in the form of mean daily, monthly and annual values, as well as extreme temperature values. These measurements were conducted with the use of mercury thermometers with Réaumur scales (1.0°C = 0.8°R), used for the Wrocław measurements until the end of the 1870's. The observations, except for the years 1837–1845 (Galle 1879),[4] were carried out at three regular times 6h, 14h and 22h local time, which were respectively, according to notation of hours 18h, 2h and 10h, as noon was at that time denoted in astronomy as 0h (or 24h) while midnight was denoted as 12h. This was the case until the end of 1886. As of 1 January 1887, morning observations throughout the former German meteorological network were conducted at 7h (6h GMT), and evening measurements were made at 21h (20h GMT), leaving 14h (as before). The mean daily temperature was calculated as the mean mathematical value of the temperatures taken at 6h, 14h and 22h (i.e., 5h, 13h, 21h UTC), and as of 1887 according to the equation: (7h + 14h + 2 × 21h)/4.[5]

25.3 The Correction of the Influence of Location Changes on Air Temperature Measurements in Wrocław in the Nineteenth Century

From 1801 to 1831 air temperature measurements conducted in the Breslau-Sternwarte Observatory were transferred from the Tower of Mathematics to another part of the University. They were located at a height of 13.3 m, on the second floor, in a northern window of the main building of the University attached to the University church. In the year 1832 measurements were relocated to the earlier location, at a height of 28.7 m. However, on numerous occasions and for only short periods usually as the result of renovation works, the temperature measurements were transferred to the previous height of 13.3 m, and were taken in northern windows of the second floor of the Tower, in the magnetic room. According to Galle's (1879) estimates, this was the case for about a quarter of all measurements taken in

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[4] In the years 1837–1845 and 1852–1875, observations were conducted five times a day. In the first 8-year period, they were taken at 6h, 9h, 12h, 15h, 21h, and from 1852 they were taken at three standard times (6h, 14h, 22h), and additionally at 10h and 18h. However while calculating the mean daily temperatures only the three mentioned standard times were taken into consideration (Galle 1879). The issues of correcting Galle's data and calculations of the means for 1837–1845 are discussed in the next sections of the paper.

[5] Local Central-European Time (CET) is also used in the remaining chapters of the paper.

the period 1791–1878. It is likely that most of these changes took place after 1852[6] and were taken into consideration by Galle (1879) by introducing the pertinent corrections into the calculation of the Tp daily mean value. Consequently it was necessary to take into account a correction for the remaining period of 1801–1831. On the basis of the measurements taken by Galle (1879) in 1871–1872 at a height of 13.3 m,[7] at the same time as the standard measurements taken at a height of 28.7 m, a statistically significant regression equation can be derived that provides a reliable correction of the mean monthly Tp values (margin of error from −0.2°C to +0.2°C) during the 31-year period of the nineteenth century (Fig. 25.1). This correction had the primary effect of decreasing the values supplied by Galle for the winter months (on average of about 0.4°C), as the summer values were similar (within the limits of 0 to −0.1°C). Along with a later correction pertaining mostly to the years 1825–1845 (which will be explained below), this also resulted in an evident change in the courses of the mean annual values.

The authors' examples used as an empirical basis for correction are exhibited in detail in Fig. 25.1. On the left (the first example) we present the correlation of monthly air temperature (Tp) values, measured between November 1871 and August 1872 at a window on the second floor (at a height of 13.3 m over ground level) of the Wrocław University building with Tp values from synchronous standard measures at a height of 28.7 m in the Breslau-Sternwarte Observatory (data from: Galle 1879). The equation of linear regression was used for the purpose of location correction in the years 1801–1834.

On the right of the Figure (the second example) we present the courses of the differences (dif) between mean Tp values calculated according to two different types of old-time standard terms which were used in Wrocław (W-w) in the first decades of the nineteenth century, that is, the main observation times (6h, 14h and 22h) and an episodic observation time used in the years 1837–1845 (6h, 9h, 12h, 15h and 21h). The values for Wrocław in the years 1837–1845 were calculated on the basis of equations of multiple regression deduced from relations of the Breslau-Sternwarte Tp

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[6] In the work cited earlier from 1857, Galle does not note location changes. However, he mentions them in the later compilation (1879), where he only refers to the changes already mentioned before 1852 (i.e., concerning the years 1801–1831). In these references he cites the results of the simultaneous measurements on the second floor of the University building. More extensive redecorations and renovations took place in the Mathematics Tower in the years 1854–1855 as well as 1873–1874. A detailed calendar of location changes shows a connection between these works and the transfer of only some of the thermometric measurements to the second floor. On the basis of this and other inconsistencies with the quarter of all measurements mentioned earlier, it may be stated that Galle was concerned with all of the measurements, not just the standard thermometric measurements conducted in the Breslau-Sternwarte Observatory.

[7] Galle (1879) cites only the results of these measurements in the form of the *Tp* mean values from the following unequal periods (lasting sometimes over ten days) in the years 1871–1872. At a height of 13.3 m the *Tp* mean annual values (in both the described location situations) are about 0.3°C higher than at a height of 28.7 m. These results do not show considerable thermal distinctions between the two locations analyzed on the second floor.

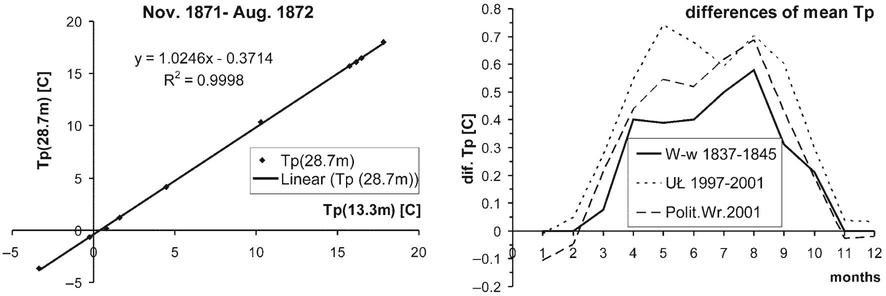

Fig. 25.1 Examples of some monthly air temperature (Tp) values calculated by Galle (1857), chosen by the authors as the empirical basis for correction. Explanations – in the text below

with Tp measurements from other Silesian stations. The comparative, verifying calculations were made by the authors for contemporary data (1997–2001) from Tp measurements at a height of 26 m in Łódź (UŁ – University of Łódź) and Wrocław (Politechnika Wrocławska – Technical University of Wrocław).

25.4 Other Corrections of the Wrocław Air Temperature Series

Meteorological measurements taken in 1791–1875 and carried out at the Breslau-Sternwarte Observatory[8] were probably lost in the archives of the University of Wrocław as a result of the war, as well as a fire in the University archives in May 1945. We only have access to the results published by Galle (1857, 1879), most often in the form of the mean daily or monthly values. The extant works enable us to verify only the correctness of the mean monthly Tp derived from the mean daily values, as well as to check the comparison of these mean monthly values with the mean Tp values acquired by Galle (1857) and with the measurements from other Silesian stations. Measurements either supervised or conducted by Galle in 1852–1875 were analyzed and verified by him with greater attention to accuracy. In contrast to his work from 1857, in which he limited himself to compiling the results of Silesian meteorological measurements, in his later work in 1879 he focused more on methodology and on data homogeneity. He recorded, among other things, important

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[8] Part of the archives of the University Library have not yet been properly catalogued or examined. Perhaps there still exist some unrevealed secrets, significant for the history of meteorological measurements in Wrocław. Such materials have not yet been discovered, despite multiple searches conducted over several years initially by Pyka (2003), and then by the authors of this study.

information regarding the range of location changes and observation times (which can be considered metadata) as well as the results of comparative, synchronically conducted measurements taken at different observation times and in different location conditions. As a result, it was possible not only to make the above-mentioned correction for the years 1801–1831, but also to acknowledge that the Tp data from 1852 to 1875 published by Galle (1879) are homogeneous and fully credible.

The state of the data from before 1852 is a different matter. Certain errors, though (with the exception of 1824) not very considerable (Fig. 25.2), were revealed after comparing the mean Tp values calculated by Galle with their values calculated according to his Tp mean daily values. More substantial discrepancies were noted in the years 1825–1832, during a comparison of the mean monthly air temperatures in Wrocław with notations from other Silesian stations. The cause may be found in a note made by Galle (1879), wherein he stated that a certain part of the measurements in these years were taken not by the main observer[9] but by his assistant, who conducted them in another place, and, one can surmise, neither very assiduously nor skillfully. On the basis of the regression equations derived for Wrocław and the other different Silesian stations then in operation, an appropriate

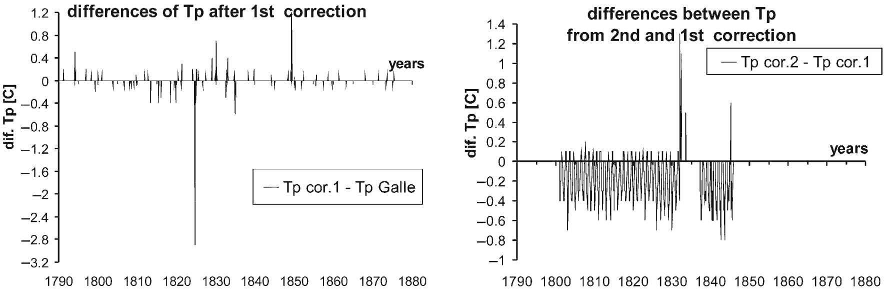

Fig. 25.2 The results of two correction steps (1st correction, 2nd correction) for monthly average air temperature (Tp)values in the years 1791–1875 in Breslau-Sternwarte. Explanation: Tp cor. 1 – Tp Galle – differences (dif.) between values calculated by the authors from daily data and those calculated by Galle (1857, 1879); Tp cor. 2 – Tp cor. 1 – differences between Tp values calculated by the authors in the 2nd and 1st correction steps

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[9] Meteorological observations in the Breslau-Sternwarte Observatory were conducted from 1791 to 1831 by Prof. Jungnitz, director of the observatory, clergyman, and future president of Wrocław University. From 1832 to 1851, Captain von Bogusławski, a professor, was in charge of the observations, and these were taken over by Prof. J. Galle until the year 1897. Many co-researchers and competent observers were connected with the observatory in that period, among others W. Günther, R. Büttner, and H. von Rotkirch, who later conducted meteorological observations (or calculated data from them) in other Silesian stations. In the years 1825–1831 Mr. Weiss fulfilled the responsibilities of assistant-observer, performing only part of the observations – yet it is unknown how many and in what range. Galle (1879) only wrote that some of the observations were carried out by Weiss on the third floor of the University building, although earlier (in the same monograph) he stressed that meteorological observations (including air temperature measurements) were conducted on the second floor from 1801 until the death of Jungnitz in 1831.

correction of the mean monthly Tp values was made over this same 8-year period for the Breslau-Sternwarte Observatory. This nearest comparative background was considered to be the most representative and verifiable reference for the temperature in Wrocław. Additionally, thermal relations were also checked against another, extra-regional climatic background comprised of outlying stations operative in that same period such as Berlin, Cracow, Prague and Vienna. This allowed us, among other things, to interpolate the missing monthly Tp value for January 1791 as temperature measurements were not carried out then in Wrocław. In relation to Galle's data, the above-mentioned attempts at verification introduced a substantial correction not only of the monthly values, but also in the range of the mean annual temperatures, especially concerning 1824–1830 (Fig. 25.3).

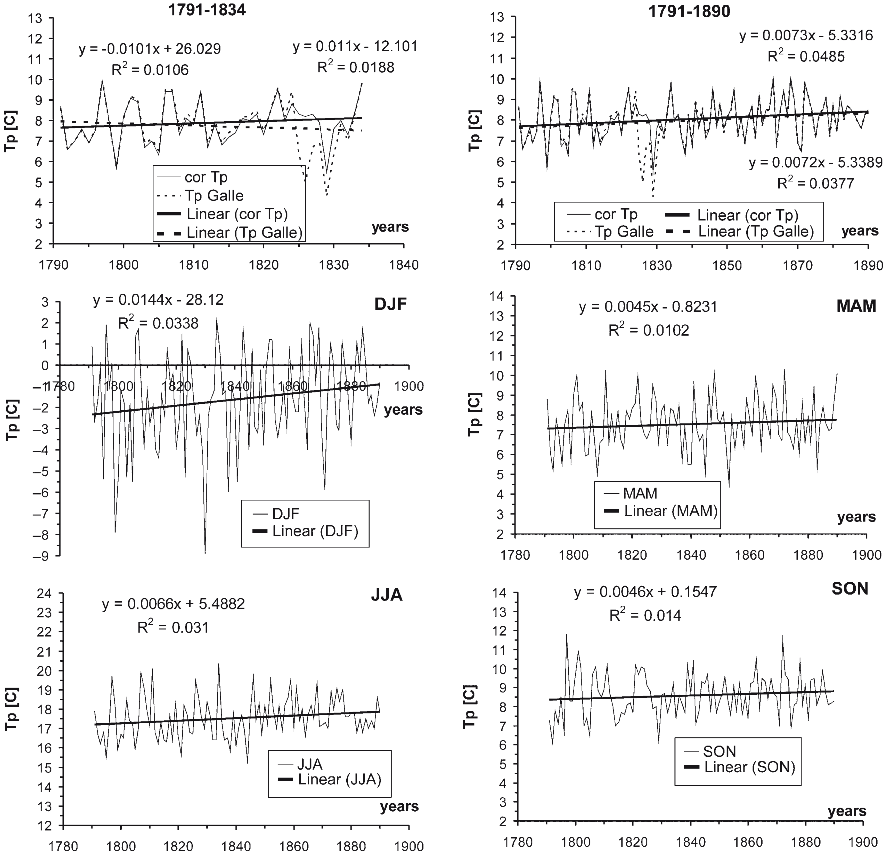

Fig. 25.3 The courses and linear trends of mean annual (upper graphs) and seasonal air temperature (Tp) in the years 1791–1890 in Breslau-Sternwarte: December–February (DJF), March–May (MAM), June–August (JJA), September–November (SON). Explanation: cor Tp – corrected Tp values; Tp Galle – uncorrected Tp values calculated by Galle (1857, 1879)

Another problem arose when we attempted to calculate the means for 1837–1845, that is, for a period when observations were made at 6h, 9h, 12h, 15h and 21h. The average Tp values calculated from these times for the period of March–October are different from the mean values of 6h, 14h and 22h. The biggest differences (0.5°C–0.8°C) at a height of 26 m (i.e., about 3 m lower than the measurements in Sternwarte) were noticed in Łódź and Wrocław (Fig. 25.1) between May and September. The correction of Galle's monthly means made by the authors of this paper is similar but smaller. The mean correction values, calculated on the basis of a multiple regression of values from other Silesian stations, were lower and amounted to about 0.6°C in August, 0.5°C in July, and about 0.4°C from April to June. The differences, which are presented in Fig. 25.1, are linked not only with the higher observation level in Sternwarte but also with the location of the Observatory near the Oder River. This specific location was a crucial factor that determined the lower values of the differences noted in Sternwarte compared with those noted in other places mentioned above (Łódź and Wrocław). Therefore, the corrected values have significant empirical support in the various analyses which have been made by the authors and can thus be considered credible.

The data contained in Galle's works (1857, 1879) relating to the years 1791–1875 were further supplemented with the air temperature values from the years 1876–1890. The values for this later 15-year period, probably also compiled by Galle, were collected from three different sources. The first source were the Wrocław statistical annuals for the years 1876–1890 (Breslauer statistic 1876–1890); the second, concerning the same years from 1879, are the meteorological annuals of the Prussian meteorological service (Ergebnisse 1879–1890); and the third source, containing data only in the form of mean monthly values for the years 1851–1930, were presented in Klimakunde (1939). Such an approach made it possible to carry out an independent verification of the applied temperature data.

25.5 Discussion of Results

Corrections of the Tp values made by the authors of this paper, contrary to those in Galle's data, show a rising tendency of mean annual temperature (Fig. 25.3) as early as the first decades of the nineteenth century. These changes did not yet significantly influence the century-long trend between the years 1791 and 1890, deduced by the authors on the basis of a compilation of unverified monthly values of Tp given by Galle, and exhibiting a warming tendency in Wrocław of 0.69°C/100 years. After all these corrections, this trend remained for all intents and purposes at an almost constant level of 0.73°C/100 years.

A decisive factor determining the direction of this centennial trend of mean annual Tp was a strong trend in the increase of winter (DJF) air temperature, which in the years 1791–1890 amounted to 1.47°C/100 years. The trends deduced for the remaining seasons were not of statistical importance but they also exhibited an increasing tendency (0.44°C/100 years for spring, 0.66°C/100 years for summer and 0.44°C/100 years for autumn). The year 1799 marked a crucial change in the winter temperature tendency. Earlier, probably over a period several times longer than 20 years (as indicated in the published data collected in De Bilt, Berlin, Vienna, Prague and Warsaw), Wrocław went through a period of decreased winter temperatures, as did the whole of Central Europe. After 1799, a new tendency of progressive increases in the Tp set in, rather weak at first until 1830 and then increasingly stronger (a trend of 2.21°C/100 years from 1799). The period 1799–1830 had an intermediate character for temperature changes in Wrocław, because years of very cold winters and autumns alternated with very warm years. Thus the first three decades of the nineteenth century were the final culmination of the Little Ice Age in Wrocław, marking a transition to a new era of progressive warming. Similar Tp courses were noted in Poland for Cracow (Trepińska and Kowanetz 1997) and Warsaw (Lorenc 2000). Earlier, Lamb (1995) had noted the transitional character of the 1820s and 1830s in Europe.

The temperature series from Wrocław and other stations from Central Europe show that the tendencies noted there and time of the most important temperature variations generally agree with the course of climatic changes in whole of Europe in the nineteenth century. The local differences in values of these trends are closely connected with the location of the analyzed station and various human-induced forcings. The influence of urban heat islands (Landsberg 1981) plays a significant role. These and other causes which also influence uncertainty estimates in regional and global observed temperature changes (Lamb 1995; Brohan et al. 2006) must be always taken into consideration.

Undoubtedly, the relatively infrequent instrumental air temperature measurements taken in Central Europe in the eighteenth century and the first decades of the nineteenth century constitute important reference points for a precise reconstruction of climate change (Flohn 1993; Lamb 1995). Difficulties in obtaining the Wrocław measurements from the archives resulted in a decision to publish part of the mean daily Tp values (1791–1800) cited by Galle (1857) in Table 25.1. In addition, we have included in Table 25.3 a version, of the earliest century-long series (1791–1890) of Wrocław mean monthly Tp values (Table 25.2) corrected using the procedure described above, as well as the longest Tp series from other Silesian stations (1805–1851).

25.6 Temperature Measurements in Other Silesian Stations

Temperature data sets from other Silesian stations permitted the authors to reconstruct the Wrocław Tp series. Most important here were the results of the longest measurements (i.e., those of over 10 years).

The first provincial series, taken from 1805 to 1851, was the Leobschütz series (now Głubczyce near Opole).[10] Observations there were carried out from a northern

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[10] The first meteorological measurements in the Silesian region outside of Wrocław took place in 1717–1730 in Oława (then Ohlau) and were connected with the work of Kanold and Büchner mentioned earlier (see: Note 2). The history of regular air temperature measurements, based on the model of three observation times and location stability, originated in the Lower Silesian province just 14 years after measurements were first begun in 1791 in the capital of Lower Silesia.

Table 25.1 Average diurnal air temperature (Tp) values [°C] in Wrocław (Breslau-Sternwarte Observatory) in the years 1791–1800

d. 1791	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1	*	*	1.5	2.1	15.6	16.4	20.9	24.4	15.9	7.5	–3.5	2.1
2	*	*	1.9	2.8	14.5	20.6	17.8	23.8	12.3	7.5	–2.9	3.6
3	*	*	4.4	5.0	7.9	17.1	18.1	18.0	14.4	8.6	–2.5	3.1
4	*	*	4.9	7.1	4.4	14.8	18.8	16.0	18.5	9.0	–0.9	3.1
5	*	*	6.3	9.6	4.4	16.0	16.9	17.3	16.5	8.9	–0.9	4.0
6	*	–5.4	7.0	9.4	3.6	17.5	17.3	19.1	14.4	9.9	–6.0	2.9
7	*	–4.1	4.3	9.9	2.8	17.5	16.5	20.6	14.9	10.5	–5.4	4.4
8	*	–2.1	1.5	9.0	5.5	17.8	18.1	22.5	16.6	12.3	–5.0	2.9
9	*	–2.9	1.4	10.3	6.8	17.3	17.1	18.0	17.1	9.3	–5.0	0.0
10	*	–1.3	3.6	12.6	10.0	14.6	14.9	17.3	16.1	10.6	–5.4	–1.6
11	*	–2.5	2.5	10.1	13.4	15.4	16.4	21.4	13.9	12.5	–1.8	–3.5
12	*	–0.4	1.8	11.4	13.0	10.0	18.1	23.1	13.6	13.8	–2.8	–3.8
13	*	2.5	4.6	6.4	14.0	11.4	14.0	22.9	14.6	14.1	–2.8	–3.3
14	*	2.8	4.5	6.3	14.5	13.0	13.1	23.0	15.5	14.1	–0.9	–0.4
15	*	4.0	6.4	8.0	13.0	15.3	15.0	21.4	12.9	14.0	2.1	–0.4
16	*	3.4	10.3	10.9	13.5	15.8	17.6	19.6	9.9	11.1	1.3	0.5
17	*	2.3	7.9	10.8	10.8	14.5	17.5	17.5	10.6	7.1	3.1	0.0
18	*	2.0	2.0	11.8	8.6	16.6	18.3	21.3	10.5	6.5	7.3	0.3
19	*	2.3	3.3	13.6	8.3	17.1	18.6	18.8	10.4	10.8	6.6	2.1
20	*	3.1	5.0	15.0	10.0	17.6	19.8	14.6	8.9	11.5	6.6	–1.3
21	*	4.8	4.9	15.6	13.1	13.8	18.8	18.5	10.3	13.4	5.0	–4.0
22	*	1.3	4.8	14.5	16.6	16.3	15.4	19.5	10.3	12.3	5.9	–6.3
23	*	0.3	5.0	14.5	17.9	16.3	18.1	18.4	9.6	10.9	5.6	–4.3
24	*	4.6	3.9	11.1	20.3	16.4	19.8	19.1	11.6	7.1	4.3	0.4
25	*	2.8	3.4	12.8	21.3	16.1	16.5	20.4	11.3	3.5	3.4	–2.3
26	*	1.6	1.9	9.4	14.6	16.8	20.9	17.1	10.1	3.4	5.3	–4.4
27	*	2.6	3.0	11.4	14.8	19.1	22.3	14.8	9.4	1.9	4.1	–1.0
28	*	4.0	4.0	10.8	17.4	20.3	20.9	16.8	9.1	–0.4	5.8	–3.0
29	*		4.8	13.5	15.9	21.0	19.3	15.4	9.4	–0.8	6.0	–0.6

30	*		6.0	14.4	12.9	22.5	22.1	14.0	8.8	−3.1	3.4	−0.4
31	*		1.9		13.1		22.6	13.5		−3.5		−1.5

d. 1792	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1	−5.0	3.6	−9.9	7.1	15.3	17.3	15.0	17.9	16.0	8.4	7.9	−0.4
2	−0.3	4.3	−9.1	8.4	8.0	20.0	12.1	18.1	17.1	7.3	7.5	−6.6
3	−0.4	4.4	−4.1	7.6	6.1	19.0	13.8	17.5	16.3	5.4	6.5	−7.8
4	−3.0	2.4	0.6	6.9	6.3	16.6	15.9	16.3	16.5	4.8	1.3	−6.0
5	−4.1	0.6	4.6	6.0	10.4	15.0	16.5	17.1	17.8	4.8	1.5	0.9
6	−3.0	−0.5	0.4	4.9	6.5	17.1	16.0	16.6	15.6	4.1	1.0	1.9
7	−0.9	−1.6	0.4	3.5	9.1	19.6	14.1	15.6	12.6	4.3	3.1	4.4
8	−8.1	3.6	2.5	4.1	12.3	21.6	17.8	15.9	14.8	4.4	4.6	−0.4
9	−9.3	1.5	1.0	6.9	9.6	12.8	20.0	18.4	15.0	3.4	5.4	0.0
10	−11.5	0.5	−5.9	8.3	5.9	16.4	21.6	18.8	15.6	2.8	2.1	3.4
11	−6.8	1.6	−7.1	8.3	4.0	19.1	19.8	18.4	11.4	2.9	4.4	2.8
12	−2.8	2.4	−5.4	10.1	4.8	13.8	22.3	18.5	9.6	4.0	1.5	2.3
13	−8.3	−6.5	−3.9	11.3	7.1	14.0	20.3	18.4	9.5	6.3	1.5	−0.3
14	−11.1	−5.9	−3.0	4.0	6.0	16.9	18.5	17.5	10.9	7.8	2.5	−3.4
15	−7.1	−7.3	1.9	1.6	5.3	11.5	17.9	15.6	12.0	10.6	7.1	−0.4
16	−4.4	−17.9	2.1	2.5	8.1	12.6	17.3	14.4	7.3	10.0	3.3	−3.4
17	−3.8	−15.0	2.0	6.3	10.3	12.8	21.0	16.6	8.1	9.6	2.3	−2.8
18	−3.4	−10.1	4.9	8.4	12.5	14.8	23.3	15.6	7.8	10.0	2.8	0.3
19	−2.8	−9.3	6.5	2.9	9.8	16.6	23.1	16.3	7.1	6.8	2.6	2.3
20	−4.1	−6.3	2.3	1.0	13.5	13.1	22.0	13.9	8.5	5.0	−1.9	3.1
21	−5.0	−6.3	1.1	−0.9	16.3	12.8	24.1	14.1	10.9	7.1	−3.3	2.9
22	−7.1	−5.6	2.3	1.5	15.3	12.9	17.3	16.3	10.9	8.5	−3.1	1.0
23	−6.1	−9.0	3.8	7.1	7.6	14.8	15.9	16.3	9.1	8.5	−2.5	0.3
24	−1.6	−5.4	4.9	10.0	7.1	17.8	16.3	14.4	9.1	8.1	−2.3	−1.6
25	−1.8	−4.0	7.1	10.9	8.8	17.3	14.0	14.0	8.1	6.0	−1.0	−1.3
26	3.4	−4.8	10.8	9.4	10.1	12.3	15.3	17.1	8.5	1.3	−2.1	−1.0

(continued)

Table 25.1 (continued)

d. 1792	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
27	3.8	−8.4	7.4	10.4	11.9	10.9	17.9	20.6	8.8	1.0	−0.3	0.9
28	3.1	−8.4	6.1	10.9	10.9	14.6	21.3	20.6	6.6	0.4	−2.3	−0.4
29	3.5	−9.3	5.9	13.8	16.6	14.6	13.3	19.1	6.9	−2.3	−1.5	−1.6
30	1.4		5.8	14.8	19.1	19.6	14.1	14.8	7.5	0.1	−1.0	−3.4
31	1.5		6.0		20.0		15.9	14.4		4.8		−3.1
d. 1793	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1	−3.1	−0.4	5.0	3.8	10.6	6.5	19.4	13.8	14.0	10.4	3.8	−0.4
2	−3.5	−0.6	5.0	0.4	10.0	5.9	20.6	15.9	18.8	12.1	3.8	4.1
3	−4.4	1.3	7.1	0.9	9.4	10.6	13.8	19.8	17.9	10.0	3.4	−3.8
4	−4.1	3.4	2.9	2.1	7.3	13.8	14.6	20.0	15.3	9.1	2.1	−6.3
5	−5.3	0.9	3.8	1.9	8.6	16.0	16.3	18.5	12.1	10.9	3.4	−5.9
6	−6.9	1.5	0.6	0.4	10.4	18.5	16.0	18.4	10.9	12.9	3.4	−5.4
7	−6.5	0.9	1.5	0.3	10.6	19.6	19.0	19.6	11.5	10.9	2.1	−0.4
8	−8.8	−0.4	−1.4	0.6	10.4	20.4	19.8	20.4	12.5	10.4	−0.9	−2.5
9	−15.3	−0.4	−1.5	2.4	12.1	18.8	16.3	18.5	13.8	11.3	0.0	−8.4
10	−16.0	−1.3	−3.5	3.4	16.3	14.6	15.9	17.1	14.6	11.3	1.3	−2.5
11	−11.9	−0.4	−4.6	5.4	18.5	17.9	16.0	17.8	12.9	10.9	5.4	−1.0
12	−5.6	0.1	−2.9	6.6	17.4	19.6	18.1	15.9	10.4	10.4	5.9	5.4
13	−5.9	−0.4	−1.0	7.9	17.3	17.9	18.1	16.6	11.6	12.5	3.8	−1.6
14	−6.0	−1.0	0.8	4.4	15.4	15.3	16.9	20.6	15.0	12.5	7.9	3.8
15	−5.6	−0.9	2.8	4.3	11.5	14.1	21.3	18.8	15.0	10.0	4.6	2.9
16	−7.3	−0.6	1.6	0.6	9.0	11.5	21.0	16.6	15.0	9.6	5.0	4.1
17	−7.3	0.0	2.1	2.9	9.1	14.6	25.4	14.6	12.1	6.6	4.6	5.6
18	−10.3	−1.0	3.8	2.3	10.9	9.0	29.0	16.6	11.3	6.3	5.0	2.1
19	−6.3	−1.6	4.6	5.9	8.8	8.4	26.3	14.1	10.9	7.9	3.8	3.9
20	−1.5	−0.8	1.6	3.4	10.0	11.3	19.8	15.1	5.4	7.9	1.6	2.1
21	−1.6	−1.4	0.3	3.0	10.9	9.6	16.5	13.4	3.8	7.9	0.4	1.4
22	0.3	−1.3	0.0	2.9	10.4	10.9	12.1	14.6	9.6	3.4	1.3	2.3

23	1.0	−1.1	1.3	4.0	6.6	10.9	11.6	18.4	11.6	1.6	1.3	2.1
24	0.6	2.5	1.3	4.0	6.3	10.3	14.1	12.9	10.5	1.3	1.3	1.0
25	−0.6	4.0	0.9	7.3	6.4	11.3	16.9	12.1	10.9	3.4	1.6	1.3
26	−5.3	2.5	1.0	8.5	6.5	12.1	18.4	10.9	10.0	10.0	0.9	0.1
27	−2.1	2.9	−5.9	6.3	7.1	15.6	19.6	12.9	7.9	11.6	1.6	−1.3
28	−0.9	4.1	−3.1	10.5	9.6	19.1	19.6	14.0	7.5	8.8	1.3	−1.0
29	1.0		1.6	10.6	9.5	19.6	19.3	14.6	11.3	9.1	−0.9	−1.0
30	1.0		2.6	11.5	7.1	20.1	16.6	13.8	12.9	9.6	−0.9	0.4
31	0.4		4.0		6.5		15.3	17.9		7.9		0.5

d. 1794	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1	−1.4	2.9	−6.5	1.4	13.8	10.9	17.5	21.6	14.8	8.5	4.0	1.3
2	−1.8	1.6	−2.9	−0.1	13.4	6.6	18.9	18.6	13.5	8.1	6.0	1.9
3	−1.4	0.3	−0.5	3.5	5.9	12.1	19.3	14.1	13.8	10.9	7.3	0.0
4	−1.8	−0.4	0.4	3.0	10.9	13.4	19.1	15.0	12.3	11.6	6.6	−0.4
5	−2.6	−1.6	5.4	3.1	14.6	12.1	16.4	14.8	10.5	9.9	6.9	−0.4
6	−6.3	−2.1	3.8	3.9	12.5	11.6	16.4	14.1	9.6	10.9	7.5	2.1
7	−7.1	−2.5	1.3	6.6	11.3	12.8	17.1	15.9	12.1	8.0	8.4	0.5
8	−2.8	−0.4	0.4	7.9	14.6	12.6	18.3	17.6	10.5	7.3	8.8	−0.4
9	−1.8	1.3	0.6	7.1	14.3	12.5	19.6	16.9	9.8	6.1	8.4	0.4
10	−1.0	2.3	1.3	7.5	13.8	11.6	18.0	14.6	8.4	6.0	6.1	0.5
11	−2.1	1.6	1.4	3.9	12.5	13.4	18.4	14.1	8.8	10.3	6.0	1.3
12	−1.3	1.3	3.4	5.0	***16.3***	17.1	17.9	13.9	9.6	11.0	4.4	1.5
13	0.5	0.3	3.8	4.9	11.6	16.6	18.0	12.5	10.0	9.1	3.1	−0.3
14	−0.9	1.3	3.1	7.5	9.6	18.0	18.8	13.1	9.6	9.6	3.0	−6.4
15	−0.4	2.5	5.0	9.6	13.0	16.6	17.9	13.4	7.9	8.9	2.1	−8.1
16	−1.0	2.5	7.8	8.5	13.4	16.3	16.8	14.6	8.4	7.1	1.3	−8.8
17	−0.6	0.0	8.0	7.9	11.8	17.1	19.6	15.4	10.3	6.0	−0.5	−9.4
18	1.3	0.3	8.9	7.9	12.1	20.0	18.4	16.4	12.5	7.5	−2.8	−11.8
19	0.3	−1.3	7.9	8.8	12.9	20.5	19.1	15.5	13.4	7.3	−2.3	−11.3

(continued)

Table 25.1 (continued)

d. 1794	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
20	1.0	−4.1	8.4	9.1	15.4	19.8	20.4	15.5	15.6	6.3	−1.3	−10.9
21	0.4	1.6	7.5	10.9	10.4	19.8	19.1	12.5	11.0	5.3	−3.5	−7.3
22	−4.6	5.0	5.5	10.0	9.1	18.4	19.1	13.9	11.0	5.0	−0.9	−6.8
23	−3.5	7.5	6.9	10.0	8.4	16.8	24.1	14.1	13.0	4.8	−1.3	−12.1
24	1.3	7.1	4.9	10.4	8.6	21.3	23.4	15.5	14.9	7.8	−1.9	−13.5
25	0.0	6.3	3.4	11.6	8.4	23.4	20.9	15.5	12.0	8.6	0.9	−4.3
26	0.5	3.8	3.0	12.3	11.6	22.5	20.0	17.3	8.9	9.6	3.4	−1.8
27	0.4	−1.8	5.1	13.5	11.3	23.4	18.9	18.6	7.5	6.6	2.4	−1.9
28	1.0	−5.4	6.0	13.4	12.3	12.3	16.6	16.3	6.6	6.4	2.5	−4.3
29	−3.4		6.4	9.6	11.6	15.0	17.5	15.1	7.5	5.6	1.6	−5.3
30	−0.5		6.6	10.9	12.1	15.1	18.8	13.8	8.8	3.0	2.8	−4.0
31	0.9		6.6		9.3		22.1	15.9		3.9		−6.6
d. 1795	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1	−8.4	−7.9	0.9	3.8	20.0	10.9	14.6	20.0	14.6	9.1	9.4	−8.1
2	−13.5	−7.3	−1.3	2.9	20.1	12.1	13.5	18.9	12.8	12.1	8.5	−3.5
3	−16.0	−3.8	−2.8	4.4	20.0	15.0	12.1	19.6	14.1	12.3	7.1	0.9
4	−14.6	−3.1	−1.0	5.0	17.1	16.6	15.0	17.9	16.0	12.3	2.5	3.8
5	−6.3	−1.4	−0.9	5.9	18.4	13.5	10.4	19.1	16.3	13.8	0.0	1.3
6	−1.8	−2.1	3.5	7.3	15.9	15.9	10.4	17.1	17.3	14.4	2.8	1.5
7	−1.0	−4.0	3.9	9.8	12.9	17.9	14.1	14.6	16.0	10.9	1.3	0.4
8	−1.3	−5.9	1.0	8.4	9.6	21.3	17.1	17.5	17.0	8.1	1.3	−0.9
9	−1.4	−0.9	−1.9	9.0	3.1	20.6	15.9	19.6	19.8	10.3	1.0	−1.0
10	−4.3	3.9	−1.8	10.0	3.9	22.3	18.4	14.6	18.5	12.8	−1.0	0.0
11	−7.3	4.9	1.3	9.1	7.1	22.3	15.9	14.6	18.8	9.6	0.6	−1.5
12	−6.5	2.5	0.5	9.0	5.1	19.6	17.9	14.9	14.8	8.4	−0.9	−1.5
13	−8.8	5.4	0.5	4.6	2.9	16.6	15.4	15.4	15.4	6.9	4.6	−1.0
14	−13.4	−1.6	−5.6	2.1	2.9	12.1	13.4	16.8	14.6	7.9	0.6	−1.6
15	−17.5	−5.1	−7.5	2.4	4.4	14.1	13.4	16.6	13.4	12.1	−1.3	3.8
16	−12.6	−4.1	−0.4	4.0	10.4	15.0	11.0	17.5	12.9	12.5	−0.6	3.4

17	−10.6	−6.0	2.9	10.6	10.9	16.6	10.9	16.6	12.9	11.3	−2.1	2.1
18	−11.1	−8.9	0.0	9.6	15.1	18.8	11.3	15.4	9.0	9.1	−2.9	1.9
19	−11.3	−9.8	−2.1	10.4	18.4	13.8	10.5	14.1	9.8	12.9	1.5	1.6
20	−15.1	−6.8	−1.3	12.1	20.0	12.3	12.5	13.9	9.1	11.5	4.4	1.5
21	−16.3	−4.4	−0.4	10.5	13.8	12.1	16.3	16.8	7.1	15.4	3.4	5.9
22	−17.8	−4.4	0.4	11.3	14.1	11.6	12.9	15.9	8.0	13.4	0.4	6.5
23	−17.9	−1.6	1.5	12.8	11.6	13.8	18.4	13.4	7.1	13.4	2.4	2.3
24	−16.0	0.8	1.1	11.3	13.4	11.9	17.5	14.1	8.4	12.3	2.5	2.3
25	−12.3	1.5	3.4	11.1	9.1	13.4	16.6	15.9	9.1	12.5	4.0	2.3
26	−10.5	2.6	4.8	14.6	5.5	14.6	15.9	15.4	12.5	13.8	3.4	1.9
27	−6.5	0.4	5.5	14.0	5.1	12.1	14.1	16.3	8.8	11.6	1.3	−0.9
28	−2.1	2.5	3.4	16.6	8.0	13.4	14.1	17.1	7.5	10.6	−1.9	0.3
29	−1.3		3.4	16.8	8.0	15.4	18.8	15.4	8.4	9.8	−1.0	5.3
30	−5.5		2.1	18.5	9.8	14.8	20.4	15.3	7.9	8.5	−0.3	5.0
31	−7.9		5.4		9.6		22.9	17.9		6.9		4.8
d. 1796	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1	4.1	9.4	−5.0	2.5	15.0	19.6	17.9	17.9	11.6	7.9	4.4	−2.9
2	3.4	7.5	−5.4	4.1	9.1	20.4	19.3	16.6	11.6	7.5	3.4	−4.8
3	3.8	6.6	−7.1	2.9	9.1	22.9	18.5	17.9	12.1	8.8	7.8	−9.1
4	1.9	4.1	−11.0	3.8	7.1	12.9	19.8	19.6	13.8	8.8	9.4	−4.6
5	3.5	5.0	−9.8	3.4	8.8	11.9	17.1	18.4	11.3	9.6	8.8	−5.3
6	4.8	4.0	−11.6	4.4	5.9	9.8	13.0	15.9	10.4	13.4	4.8	−3.8
7	4.6	3.1	−8.8	3.8	12.9	13.4	17.3	16.3	10.9	11.3	3.5	−2.8
8	2.1	2.1	−9.1	3.8	10.9	15.4	17.9	16.6	12.1	9.6	3.5	−2.9
9	0.9	4.0	−5.0	4.6	13.8	17.8	16.5	16.6	11.3	7.4	4.0	−3.8
10	1.3	2.3	−4.1	4.0	10.9	12.9	15.0	18.8	13.4	7.5	3.4	−4.0
11	4.1	0.6	−3.8	5.0	13.4	17.9	13.5	17.5	13.4	5.9	−0.6	−2.8
12	4.1	−2.1	−2.9	0.6	11.6	20.4	12.1	20.9	13.8	6.3	−1.0	−3.4
13	4.6	−1.6	−1.3	2.3	12.9	17.8	13.4	18.8	14.6	6.6	0.0	−3.1
14	5.0	0.3	−0.9	3.8	10.4	22.5	13.4	18.8	15.9	6.5	0.3	−2.5

(continued)

Table 25.1 (continued)

d. 1796	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
15	5.6	−1.0	−1.3	6.0	11.6	18.4	15.4	18.4	16.3	10.6	−1.9	−3.8
16	5.0	0.6	0.0	4.1	15.0	11.3	21.3	16.6	16.3	7.8	−1.0	−7.1
17	3.8	−1.3	0.9	6.0	13.8	15.0	20.4	17.9	16.6	5.3	−0.6	−5.3
18	5.3	0.0	−0.4	4.8	***14.0***	16.6	20.0	16.6	20.0	5.3	−1.6	−4.4
19	6.3	−1.5	0.0	6.3	13.0	17.5	20.0	15.4	14.1	10.3	−1.9	1.5
20	5.3	−2.8	0.9	5.9	16.6	20.9	17.9	16.3	12.9	9.8	−2.3	3.4
21	6.6	−3.5	2.1	5.4	17.3	15.4	20.0	17.1	13.4	7.1	−2.3	−0.6
22	6.3	−3.4	1.6	5.4	18.8	15.9	20.9	15.9	12.9	7.8	−2.3	1.0
23	6.0	−4.6	−1.9	5.3	15.4	17.8	19.8	17.5	11.3	10.9	−2.5	1.6
24	5.0	−3.8	−2.5	6.3	16.6	17.9	16.6	18.8	10.4	9.0	−2.9	0.9
25	4.6	−2.8	−2.1	4.1	15.3	15.4	17.5	18.4	10.4	5.3	−2.8	−2.3
26	3.5	−7.3	−1.0	10.4	17.9	20.9	18.8	18.4	9.6	3.1	−3.8	−7.5
27	6.3	−8.8	−1.5	11.5	15.4	22.5	20.4	16.3	8.4	2.8	−4.8	−7.3
28	6.5	−9.6	−0.6	15.4	21.6	22.9	19.6	16.6	9.6	2.8	−2.9	−6.0
29	5.9	−8.4	−0.4	12.9	15.9	16.3	18.8	14.1	7.9	3.5	−2.9	***−4.0***
30	7.9		0.0	13.4	19.1	17.1	17.9	12.1	9.1	5.6	−2.9	***−1.9***
31	7.9		1.6		19.1		19.1	12.1		3.8		***0.1***
d. 1797	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1	2.1	2.1	0.3	10.0	11.3	19.1	20.6	19.6	20.0	12.5	10.0	5.5
2	1.9	4.6	−1.5	9.0	12.3	18.4	21.8	20.0	18.8	12.1	9.0	6.1
3	1.6	4.8	0.4	9.1	13.4	18.8	19.6	20.6	18.8	11.6	8.8	4.0
4	−1.6	0.6	−0.4	7.1	12.8	19.6	20.1	20.4	16.6	11.8	8.4	3.1
5	−5.0	2.3	−0.9	9.9	12.3	18.0	20.4	20.3	16.6	11.6	7.9	2.5
6	−2.6	1.0	−0.3	9.1	11.9	20.5	15.9	20.6	16.3	12.0	7.5	2.3
7	−4.8	−0.9	−2.1	9.6	10.3	20.1	15.1	20.4	16.0	11.0	8.0	1.6
8	−4.4	−2.3	0.0	10.0	12.1	18.9	14.6	21.0	16.6	9.8	8.8	1.0
9	−4.8	−2.1	−1.5	11.6	13.8	20.9	15.5	21.5	16.5	10.3	8.0	1.9
10	−5.6	−1.5	−1.5	11.6	13.4	21.8	18.4	22.1	17.5	10.9	7.5	2.1

11	−8.3	1.5	−2.3	12.5	14.6	21.3	21.4	22.5	18.1	10.0	7.4	2.5
12	−7.1	1.9	−2.5	10.9	14.4	16.8	22.6	24.4	18.1	10.4	8.8	2.6
13	−3.9	4.1	−1.6	9.0	14.6	18.8	23.4	23.4	18.1	11.9	9.0	2.1
14	0.1	3.8	−1.6	9.0	15.3	21.9	23.9	21.6	17.9	12.3	8.8	0.3
15	0.9	2.9	0.0	7.4	15.6	21.4	22.9	20.6	17.1	10.9	8.1	0.4
16	−0.9	−0.4	−2.8	7.1	12.5	19.1	23.1	21.6	17.8	11.6	7.3	0.8
17	−1.4	0.6	−0.6	4.1	11.3	11.4	24.4	19.0	18.5	10.9	6.6	0.8
18	−1.4	1.0	−4.1	1.6	12.3	13.4	22.5	20.0	18.5	10.0	6.9	0.4
19	−0.5	0.9	−2.5	0.3	12.5	18.4	24.1	21.0	19.1	9.8	6.9	−1.3
20	0.1	0.6	−7.5	−0.4	11.6	15.0	23.1	17.5	18.8	8.4	7.1	−1.3
21	2.1	2.1	−5.0	−1.3	12.8	15.0	23.3	17.1	16.0	8.1	7.9	−1.3
22	3.9	3.3	−3.1	0.4	12.8	15.9	20.6	17.5	16.9	8.1	8.1	−0.6
23	2.9	2.1	−0.9	3.5	12.1	17.1	21.3	15.0	16.3	8.8	7.8	−0.9
24	0.0	2.1	4.4	7.5	13.8	16.3	21.6	15.4	16.6	9.4	7.1	−2.4
25	1.6	3.1	6.9	11.3	15.0	18.1	23.4	16.6	17.3	10.0	6.3	−2.8
26	−0.3	2.3	7.5	12.9	15.9	18.4	17.9	17.1	16.9	10.9	6.0	−3.8
27	0.4	−1.6	10.3	13.8	16.3	19.0	19.1	18.1	16.3	11.0	6.0	0.4
28	−0.1	0.3	10.4	14.0	16.5	20.0	21.5	20.4	16.3	10.6	5.9	0.9
29	0.5		10.9	15.0	16.9	19.1	19.1	21.6	15.6	10.0	6.5	−0.9
30	0.4		8.8	14.4	17.3	20.0	18.4	21.3	14.8	10.6	7.3	0.6
31	0.0		***9.0***		18.1		20.0	20.6		10.9		−2.1
d. 1798	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1	−0.9	0.9	0.4	0.6	10.3	15.9	20.9	19.8	14.1	10.9	4.6	4.0
2	−1.3	1.4	0.6	1.0	11.9	20.0	20.9	21.3	12.8	10.6	4.8	4.8
3	−0.6	3.9	2.8	2.3	12.8	20.6	18.4	20.4	12.3	11.5	7.8	4.6
4	−4.0	5.0	3.8	5.9	12.5	21.6	17.1	21.0	17.5	10.6	7.5	5.3
5	−4.8	0.1	6.5	6.3	11.9	19.8	19.6	22.8	21.5	9.6	6.3	3.8
6	−2.3	−3.0	2.6	10.6	12.9	20.3	20.4	19.6	20.4	10.0	6.0	0.4
7	−5.9	−3.0	0.3	10.9	13.4	20.3	20.3	15.9	19.8	9.4	6.6	0.4
8	−5.4	2.9	3.5	9.1	14.1	21.6	21.0	18.1	18.8	10.0	7.5	−5.3

(continued)

Table 25.1 (continued)

d. 1798	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
9	−9.1	0.9	4.8	7.9	16.6	19.6	20.0	18.5	19.6	9.6	6.6	−5.9
10	−7.8	2.9	5.0	4.1	16.6	17.5	20.0	19.0	21.3	8.5	6.3	−6.0
11	−5.9	5.9	3.6	1.9	16.3	16.6	21.3	18.8	20.9	7.8	6.0	−7.1
12	−3.4	5.0	0.4	4.6	15.3	15.9	20.3	18.4	17.8	7.3	5.0	−9.0
13	−2.9	4.6	−4.6	6.5	14.4	16.6	17.5	19.0	13.5	6.0	5.3	−11.9
14	−0.6	4.1	−0.6	8.4	14.8	14.0	17.9	18.5	14.1	4.6	4.1	−7.3
15	1.5	4.8	2.9	10.3	17.5	15.3	19.1	16.3	15.9	4.5	4.4	−8.1
16	1.3	6.3	5.9	11.3	20.4	18.4	17.9	18.8	13.8	4.1	4.0	−14.0
17	2.5	2.8	6.3	12.1	19.6	17.8	18.4	17.5	14.4	4.5	2.8	−15.9
18	0.3	0.4	5.4	13.8	14.1	19.1	18.1	16.5	15.4	7.3	2.1	−19.1
19	2.3	−0.4	3.8	13.8	12.8	18.1	17.5	17.1	15.6	7.1	−0.4	−19.1
20	1.4	−1.6	3.9	10.3	13.8	19.1	19.1	17.3	15.4	8.8	−1.3	−16.3
21	1.6	−2.9	1.0	8.8	12.1	17.5	18.4	17.5	14.6	7.3	−5.0	−14.1
22	2.3	−6.4	1.0	7.9	9.0	17.1	23.1	17.9	14.1	6.0	−5.3	−16.6
23	1.5	−5.3	0.3	6.6	9.0	17.8	18.5	14.6	14.6	4.9	−6.5	−19.6
24	0.6	−0.3	−2.5	8.5	9.6	17.9	17.5	16.6	14.0	4.8	−4.8	−20.9
25	−0.4	3.5	−2.5	8.8	11.6	14.4	17.5	15.0	13.8	6.0	−4.0	−20.0
26	−1.0	1.3	−0.9	8.5	16.3	17.1	17.9	13.8	13.8	6.3	−1.5	−13.4
27	−1.9	0.9	1.3	9.3	16.6	15.9	19.1	12.5	13.8	6.5	−3.8	−12.1
28	−1.0	−3.8	0.0	10.9	17.5	14.0	18.5	14.1	12.9	5.3	−4.1	−10.0
29	−2.9		1.5	11.5	18.1	19.1	17.8	14.4	12.1	3.8	−3.5	−7.9
30	−1.6		−0.3	10.4	19.0	21.3	16.9	14.6	11.5	5.0	0.4	−3.8
31	−1.0		1.6		19.6		17.9	14.6		5.6		−5.4
d. 1799	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1	−9.6	−8.8	1.6	−5.4	7.1	18.4	15.5	14.0	16.0	11.3	6.5	0.3
2	−11.6	−9.6	1.1	−4.6	4.1	17.3	17.6	15.1	15.8	11.5	8.1	1.5
3	−6.0	−3.3	1.8	−4.5	5.4	18.5	17.1	17.0	13.4	11.0	8.1	3.8
4	−5.4	−3.3	1.6	−3.5	7.1	17.0	16.5	17.4	12.8	11.6	8.4	2.3

5	−5.6	−3.9	−0.3	−2.1	7.9	18.8	16.9	19.4	12.9	11.5	9.0	0.9
6	−5.8	−11.0	0.1	−1.0	8.6	14.0	17.9	19.6	12.9	10.9	4.6	1.6
7	−7.3	−18.9	−0.4	6.0	10.3	15.1	18.0	22.6	11.4	10.9	7.1	0.3
8	−7.1	−19.9	0.6	6.9	14.6	17.1	18.8	21.6	9.8	10.4	6.3	−1.9
9	−9.4	−19.8	−1.4	9.0	16.9	19.6	20.8	21.8	11.0	9.8	5.6	−2.3
10	−9.6	−18.0	−1.6	9.1	17.4	16.9	19.4	20.5	11.3	10.0	5.9	−2.3
11	−12.9	−15.0	−0.5	7.4	13.5	18.6	18.9	18.6	10.6	8.5	5.0	−3.1
12	−19.4	−7.9	−0.4	7.8	9.4	11.8	19.4	18.4	11.6	9.1	4.1	−4.1
13	−18.8	−13.3	0.8	7.5	11.1	11.5	17.6	16.5	11.9	6.0	5.9	−3.1
14	−15.4	−15.8	1.3	6.9	9.9	10.0	14.3	15.8	10.4	6.6	6.0	−5.4
15	−14.8	−6.1	2.6	9.4	10.3	10.3	14.6	16.5	12.1	7.8	5.0	−7.0
16	−10.3	−1.5	2.8	14.0	14.1	11.0	16.1	16.5	11.3	6.5	2.9	−9.8
17	−11.3	0.6	0.4	12.1	11.3	11.5	14.0	16.8	11.3	7.1	5.6	−5.4
18	−11.6	−4.1	0.4	11.3	9.1	12.9	13.0	17.1	11.5	5.9	5.6	−5.5
19	−12.1	−2.5	0.4	11.3	10.3	11.0	15.1	16.4	11.9	5.6	3.8	−12.0
20	−13.3	2.0	0.3	8.8	15.0	11.3	15.9	17.6	13.1	6.3	5.1	−15.0
21	−12.3	2.6	−1.3	9.6	17.1	13.8	13.1	18.0	12.8	5.4	6.0	−14.6
22	−11.3	4.1	−2.9	9.1	13.1	16.1	13.6	16.6	12.3	6.3	6.1	−10.6
23	−11.0	3.6	−0.3	8.1	10.9	14.4	14.9	16.3	12.1	7.9	3.8	−10.4
24	−9.4	1.5	−0.9	8.4	11.5	13.8	16.1	17.0	12.3	6.5	2.1	−8.4
25	−1.0	1.6	−2.5	10.0	12.9	9.4	15.6	14.4	11.9	8.5	0.9	−7.1
26	−1.3	1.3	−0.9	7.1	9.0	10.1	14.9	13.0	12.1	9.0	0.9	−7.6
27	0.3	1.3	0.0	6.5	10.9	12.4	15.8	13.5	12.1	7.9	4.1	−12.8
28	−0.8	1.6	1.3	5.4	11.6	14.5	16.6	14.4	12.1	5.4	0.6	−22.8
29	−2.8		−3.1	6.5	10.4	14.3	17.1	17.1	10.9	6.3	−1.5	−23.4
30	−5.3		−5.1	6.0	11.5	14.4	15.5	15.1	11.3	5.4	0.4	−17.9
31	−5.9		−5.6		15.0		12.5	14.1		5.9		−10.3
d. 1800	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1	−9.8	4.0	−5.6	9.1	15.9	17.6	14.6	17.9	15.4	11.5	7.1	0.0
2	−8.9	3.4	−5.3	9.6	17.1	19.1	13.9	20.0	16.6	10.8	5.6	1.3

(continued)

Table 25.1 (continued)

d. 1800	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
3	−12.0	3.4	−3.8	9.0	16.6	19.1	16.0	20.9	16.0	9.8	7.3	0.8
4	−10.5	3.8	−4.0	9.9	15.3	19.0	16.5	23.8	14.0	11.8	8.8	−0.4
5	−11.8	2.8	−4.4	10.9	12.1	20.4	18.6	17.3	17.3	10.8	7.6	−1.3
6	−11.4	0.6	−6.9	12.1	13.5	20.0	20.5	15.3	18.1	10.1	5.9	2.5
7	−11.6	−1.8	−9.0	11.3	15.3	17.9	19.6	15.3	18.6	12.6	4.6	4.0
8	−8.8	−2.3	−11.6	13.4	16.9	13.8	22.0	14.4	17.9	14.6	7.3	1.5
9	−10.6	−6.9	−8.1	16.4	17.5	15.3	24.8	15.4	16.4	15.4	11.9	0.0
10	−13.3	−6.9	−8.4	16.6	17.4	14.6	20.8	18.0	17.0	14.4	7.8	0.4
11	−11.9	−10.4	−8.8	14.4	6.6	13.4	13.5	16.1	16.1	10.3	6.6	2.9
12	−8.4	−12.8	−8.3	8.3	6.0	14.8	17.1	17.9	13.3	11.1	10.0	2.1
13	−6.6	−12.3	−7.9	9.1	10.9	13.5	16.6	20.0	12.5	10.5	6.8	2.5
14	−3.5	−7.9	−2.9	11.8	13.8	15.3	14.8	21.5	13.8	9.9	5.8	2.5
15	−2.5	−3.6	−3.1	13.9	10.3	13.5	13.4	22.5	14.3	9.6	3.4	−0.3
16	−1.9	−2.8	−4.9	13.1	12.8	11.3	11.6	21.0	15.5	9.3	5.6	−2.9
17	−2.4	−4.3	−6.4	16.6	15.3	10.3	14.3	18.8	15.6	5.8	6.8	−4.5
18	2.6	−5.9	−5.9	17.3	14.4	10.4	13.8	20.8	16.3	5.4	6.5	−7.5
19	3.4	−7.0	−4.4	14.6	14.1	11.3	16.0	19.1	18.4	8.5	5.9	−11.3
20	0.3	−8.1	−5.0	15.4	14.8	13.1	13.8	21.6	18.4	8.8	2.0	−8.8
21	0.4	−6.9	−4.3	16.5	20.0	15.3	12.5	21.0	17.9	9.1	0.9	−4.4
22	−1.3	−4.8	−10.3	18.9	17.5	16.3	12.9	19.4	16.6	7.9	1.1	0.9
23	−0.9	−0.4	−10.5	19.8	21.3	13.4	14.1	19.0	14.8	5.3	4.3	1.9
24	−1.6	−1.3	−6.3	19.0	23.8	13.8	15.9	20.1	12.4	3.3	4.3	1.3
25	−0.6	−7.9	1.1	18.8	23.1	14.6	17.1	18.1	12.4	2.9	6.6	0.0
26	0.6	−9.6	0.9	19.6	20.0	16.5	16.5	19.1	11.1	7.1	5.1	0.6
27	1.5	−10.0	1.9	21.0	20.6	17.1	16.0	17.3	11.1	8.3	5.5	0.4
28	0.5	−7.8	2.9	20.8	19.8	15.6	16.6	17.5	11.5	7.6	1.9	−0.1
29	1.5		5.0	21.6	20.9	16.5	15.4	15.9	10.1	7.5	1.6	−0.9
30	1.8		6.3	20.6	21.3	17.3	14.6	16.1	11.6	6.1	−1.6	4.1
31	3.0		7.9		20.0		16.3	14.3		5.8		−1.0

Explanation: d. = days per month for the year in question; I, II … XII = months; * lack of measurements; bold italics indicate estimated values

Table 25.2 Average monthly air temperature (Tp) values in Wrocław (Breslau-Sternwarte Observatory) in the years 1791–1890

Year	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I–XII
1791	1.3	1.1	4.1	10.3	12.0	16.5	18.1	19.0	12.6	8.2	1.0	−0.4	8.7
1792	−3.4	−4.0	1.4	6.9	10.1	15.6	17.8	16.7	11.2	5.4	1.6	−0.6	6.6
1793	−4.8	0.4	1.0	4.3	10.3	14.1	18.2	16.3	11.9	9.0	2.6	0.1	7.0
1794	−1.3	1.1	4.0	7.7	11.8	16.0	18.9	15.4	10.7	7.6	3.0	−4.1	7.6
1795	−9.6	−2.3	0.6	9.3	11.2	15.3	14.9	16.4	12.6	11.2	1.7	1.2	6.9
1796	4.7	−0.4	−2.9	5.7	13.8	17.2	17.7	17.1	12.5	7.3	0.4	−3.1	7.5
1797	−1.1	1.4	0.6	8.3	13.7	18.4	20.6	20.0	17.3	10.6	7.6	0.8	9.9
1798	−1.6	1.1	1.9	8.1	14.5	18.0	19.0	17.4	15.7	7.2	1.9	−8.6	7.9
1799	−9.0	−5.8	−0.3	6.1	11.2	14.2	16.2	17.1	12.1	8.1	4.7	−6.8	5.7
1800	−4.3	−4.4	−4.2	15.0	16.3	15.3	16.1	18.6	15.0	9.1	5.4	−0.4	8.2
1801	−0.7	−2.5	5.2	8.1	16.6	15.4	17.8	16.3	16.6	10.9	5.1	−0.6	9.1
1802	−3.5	−1.4	3.3	9.6	11.7	16.7	18.4	20.2	13.6	11.3	5.4	0.7	8.9
1803	−12.5	−4.1	1.4	11.5	13.1	15.3	18.7	18.0	10.6	7.7	2.8	−2.8	6.7
1804	0.4	−3.1	−2.3	6.4	13.7	16.1	18.7	17.1	14.9	8.9	−1.8	−5.6	7.0
1805	−7.7	−3.1	0.8	5.7	11.6	14.6	17.0	16.0	15.3	4.4	0.0	0.9	6.3
1806	1.7	1.5	2.7	6.1	15.4	15.2	17.5	18.2	16.9	8.2	4.2	4.5	9.4
1807	−1.0	1.5	0.2	6.3	14.2	16.0	18.9	24.6	14.5	9.7	6.2	0.9	9.4
1808	−2.2	−2.5	−4.5	5.5	14.1	17.3	19.6	20.2	15.8	8.6	2.1	−6.5	7.3
1809	−6.4	1.9	0.2	5.1	14.5	16.8	18.1	19.0	14.9	7.1	3.6	2.6	8.1
1810	−3.7	−2.7	2.6	5.3	12.5	14.2	18.9	18.2	16.0	7.3	3.5	1.2	7.8
1811	−7.3	−2.2	4.3	8.3	17.3	20.5	20.8	19.1	14.4	12.1	4.0	0.9	9.4
1812	−5.4	−1.2	2.5	3.5	13.7	16.5	17.1	16.7	13.1	11.5	1.3	−8.6	6.7
1813	−5.6	2.6	1.2	9.6	13.2	14.6	17.5	16.3	13.6	7.2	3.2	0.4	7.8
1814	−5.1	−8.8	−0.5	10.1	10.5	14.4	19.7	17.7	10.9	6.7	3.4	1.1	6.8
1815	−6.0	0.8	3.7	7.7	13.1	16.9	15.7	16.5	11.3	8.6	1.6	−4.0	7.2
1816	−0.4	−2.7	1.7	7.2	11.6	15.7	16.9	16.4	12.9	7.7	2.4	−1.4	7.4
1817	1.1	2.6	2.7	2.8	13.3	17.9	17.5	17.7	14.2	4.6	4.2	−2.0	8.1
1818	−0.4	−0.2	3.7	8.3	12.5	15.9	17.9	15.5	14.1	7.2	3.1	−2.2	8.0

(continued)

Table 25.2 (continued)

Year	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I–XII
1819	−0.2	1.5	3.7	7.6	12.1	17.9	18.7	18.2	14.5	7.9	2.1	−4.8	8.3
1820	−6.7	0.1	1.8	9.0	14.2	13.8	16.1	19.8	13.1	8.5	1.4	−3.2	7.3
1821	−1.0	−3.3	1.4	11.0	13.5	13.4	15.8	17.4	15.0	9.1	6.4	2.5	8.5
1822	0.0	2.1	6.4	9.6	14.0	17.4	20.0	17.1	12.9	11.2	5.0	−2.5	9.5
1823	−11.3	−1.6	2.8	6.0	14.0	16.7	17.9	18.6	14.3	11.5	4.5	1.4	8.0
1824	−0.4	1.3	1.2	7.3	12.6	15.4	17.3	17.7	16.0	9.6	4.4	2.9	8.8
1825	−1.1	−1.8	−1.1	8.2	13.2	15.8	16.9	17.3	14.1	8.0	5.2	4.5	8.3
1826	−8.4	−0.8	3.0	6.8	11.8	17.0	21.1	20.3	14.2	9.9	2.4	0.8	8.2
1827	−3.1	−8.1	3.4	9.9	15.2	19.1	19.3	17.5	14.1	9.6	−0.2	1.3	8.3
1828	−5.3	−3.4	3.4	10.0	12.9	16.6	19.6	16.5	13.1	7.4	3.6	0.2	7.9
1829	−7.3	−5.7	0.2	7.9	11.6	15.3	18.7	16.8	14.6	6.2	−2.1	−11.2	5.5
1830	−9.8	−5.3	1.9	9.5	13.1	18.4	18.3	18.4	13.5	7.4	4.9	0.7	7.6
1831	−6.2	−1.7	1.8	11.0	12.8	15.8	19.5	17.5	13.1	11.3	1.6	−1.4	8.0
1832	−2.4	−1.0	1.9	6.8	11.1	15.5	15.2	18.4	12.2	8.6	2.4	−1.5	7.3
1833	−4.6	2.7	2.3	5.8	16.7	18.3	16.9	14.2	13.5	7.8	3.4	3.7	8.4
1834	2.1	0.3	2.1	6.8	15.7	18.3	22.6	20.1	15.5	9.0	3.2	0.8	9.8
1835	−0.5	1.7	2.6	6.7	13.2	16.8	18.6	16.4	15.0	7.9	−0.7	−2.5	8.0
1836	−2.4	0.8	8.0	8.0	9.5	16.6	16.6	15.9	13.4	10.5	1.9	0.8	8.3
1837	−1.9	−2.5	−0.5	6.3	11.3	15.6	15.5	18.4	12.0	8.6	3.9	−1.5	7.2
1838	−10.5	−5.9	2.6	6.1	13.5	15.7	16.6	15.1	14.9	7.2	0.9	−0.9	6.3
1839	−1.8	−0.1	−0.6	4.1	13.0	17.9	19.1	16.4	15.9	9.4	5.2	−2.0	8.1
1840	−1.7	−1.3	−1.7	6.8	11.3	15.3	17.2	15.9	14.1	6.1	6.1	−8.1	6.7
1841	−2.3	−6.0	3.6	9.1	15.9	16.3	17.1	17.6	14.4	11.9	4.4	2.7	8.8
1842	−5.8	−1.5	3.0	4.7	13.8	15.8	16.9	20.2	14.2	6.5	0.5	2.4	7.6
1843	−0.7	3.6	1.2	7.9	10.9	15.6	17.2	18.0	11.8	8.3	3.3	3.2	8.4
1844	−2.3	−2.3	0.5	7.4	13.1	16.0	14.9	14.9	13.8	9.6	4.6	−5.2	7.1
1845	−0.1	−6.8	−4.5	8.2	11.7	11.7	19.0	16.4	12.5	9.1	5.9	1.6	7.6

1846	−0.6	1.6	6.0	9.7	12.3	17.9	20.2	21.0	14.4	12.6	2.1	−3.2	9.5
1847	−3.9	−1.3	1.9	5.9	15.1	14.8	17.9	19.3	12.1	7.4	3.9	−0.9	7.7
1848	−10.6	2.3	5.4	11.5	13.4	19.1	18.6	17.2	13.1	11.0	3.5	0.7	8.8
1849	−3.2	2.0	1.3	7.5	14.6	16.7	17.3	16.2	12.2	7.9	2.9	−5.0	7.6
1850	−8.6	2.8	0.0	8.4	14.4	18.2	18.3	18.2	12.2	7.9	4.5	0.9	8.1
1851	−0.8	−0.3	3.4	10.3	10.6	16.1	17.8	17.7	12.6	11.7	1.7	0.2	8.5
1852	2.6	0.9	0.3	4.4	14.7	18.6	20.5	19.4	14.7	8.8	5.2	4.0	9.5
1853	1.2	−1.9	−3.3	4.4	12.4	17.2	19.1	17.6	13.6	9.8	1.6	−5.1	7.3
1854	−1.5	−1.2	2.3	7.0	14.5	15.4	18.9	16.6	12.9	9.3	0.6	1.6	8.1
1855	−3.4	−9.0	0.9	6.0	12.1	18.0	18.5	18.2	12.8	12.0	2.5	−7.1	6.9
1856	−0.3	0.5	0.0	9.9	12.8	17.3	16.5	17.0	13.2	10.2	−0.2	0.6	8.1
1857	−2.3	−1.2	2.1	8.3	12.6	16.9	18.6	19.0	14.9	11.8	0.7	2.0	8.7
1858	−4.0	−7.5	0.3	6.6	12.4	19.1	18.7	18.0	15.2	9.9	−2.4	−1.1	7.2
1859	0.6	2.9	5.7	7.5	13.2	17.1	21.0	20.2	13.0	9.4	3.0	−3.3	9.2
1860	0.8	−2.2	1.2	8.1	14.0	17.5	16.0	17.5	14.2	7.3	0.8	−2.4	7.8
1861	−6.7	2.7	5.0	5.5	10.6	18.8	19.7	18.7	13.7	9.1	4.7	−0.5	8.5
1862	−3.8	−2.4	5.1	9.3	15.4	16.4	18.3	17.5	14.7	11.1	1.9	−2.0	8.5
1863	2.6	2.4	5.1	7.9	13.9	17.1	16.9	19.9	14.9	11.9	4.8	1.9	10.0
1864	−6.3	0.0	4.8	5.1	9.1	17.7	16.4	15.7	13.9	7.7	2.0	−5.0	6.8
1865	−0.6	−6.7	−0.5	9.2	17.0	14.2	21.5	17.3	14.1	8.9	5.4	0.6	8.5
1866	2.7	2.8	1.9	10.1	11.1	20.2	17.6	17.0	17.5	6.3	4.1	1.7	9.4
1867	−0.7	3.4	0.7	8.2	11.9	16.5	17.6	18.5	14.2	9.0	2.1	−2.9	8.2
1868	−2.2	3.1	3.6	8.0	16.9	18.6	19.5	20.2	16.4	9.9	2.2	3.5	10.0
1869	−2.5	4.5	1.4	10.6	14.8	14.7	19.7	16.9	15.5	7.4	3.2	0.8	8.9
1870	−1.3	−8.8	−0.1	7.3	13.9	15.9	18.9	16.7	12.4	8.0	5.1	−6.7	6.9
1871	−7.3	−3.5	4.2	6.3	9.5	14.9	18.7	18.1	13.7	5.9	1.5	−4.4	6.5
1872	−0.5	−0.3	4.9	10.2	15.8	15.9	18.6	16.5	15.3	11.9	7.4	2.0	9.8
1873	2.2	−1.2	4.7	6.6	9.8	16.8	20.0	19.8	13.4	10.7	5.0	0.9	9.2
1874	0.2	−0.5	2.2	8.8	9.7	16.8	20.8	16.4	16.8	10.7	0.6	−1.5	8.5

(continued)

Table 25.2 (continued)

Year	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I–XII
1875	–0.6	–6.7	–1.1	6.6	13.3	19.6	18.5	19.2	13.2	6.4	1.2	–4.2	7.2
1876	–5.2	0.3	4.0	9.8	9.3	18.3	18.6	18.3	13.6	10.3	0.4	0.2	8.2
1877	1.8	1.3	1.3	5.9	10.7	19.2	18.4	19.3	11.2	7.2	6.3	–0.5	8.5
1878	–0.9	1.8	2.6	9.6	13.6	17.4	16.6	18.8	16.1	10.8	4.2	–1.3	9.1
1879	–3.3	1.0	0.8	7.1	12.0	18.0	16.6	18.1	15.8	8.0	0.6	–7.8	7.3
1880	–2.2	–0.4	2.3	10.0	11.4	17.0	19.3	17.2	14.6	8.4	4.3	2.9	8.8
1881	–5.8	–1.0	1.5	4.8	13.5	16.1	19.6	17.5	12.4	5.2	4.7	0.6	7.5
1882	1.0	1.8	7.3	8.4	12.5	14.6	19.5	16.2	15.7	8.8	3.7	0.1	9.2
1883	–1.3	0.7	–1.9	5.1	12.7	17.1	18.6	16.7	14.3	9.6	4.6	0.2	8.1
1884	2.3	2.6	3.9	5.2	13.4	14.5	19.2	16.5	15.2	7.9	1.1	2.4	8.7
1885	–3.4	2.0	3.3	10.2	11.7	18.6	18.4	15.4	14.0	9.1	2.7	–0.2	8.5
1886	–1.4	–4.1	–0.9	9.8	14.1	15.7	17.5	17.9	15.9	8.6	5.2	1.0	8.3
1887	–3.3	–2.0	1.5	8.2	12.0	15.2	20.1	16.9	14.6	6.7	4.8	–0.7	7.9
1888	–3.1	–3.4	1.0	7.1	13.7	17.0	17.0	17.0	13.8	8.0	2.5	0.8	7.6
1889	–4.2	–2.2	–0.4	8.8	18.4	20.5	18.3	17.2	11.4	9.8	3.4	–2.0	8.3
1890	1.8	–2.5	5.8	8.9	15.6	15.0	18.1	20.2	13.8	8.0	3.1	–6.7	8.5

Key: abbreviations I, II, III, etc. mean January, February, March, etc.

window on the first floor of a school at 6h, 14h and 21h. The mean monthly Tp values from the period March 1805–April 1849, calculated by Günther (see Note 9), were published by Galle (1857). The Tp values given in Celsius degrees and cited below in Table 25.3 (see electronic version), are the result of a simple calculation from the Réaumur scale, according to which temperature measurements were recorded in Silesia until the end of the 1870's. Apart from the correction of several monthly Tp values which turned out to be largely erroneous in contrast with the simultaneous values acquired from the Tp measurements taken elsewhere in Silesia, the rest of the values were established as correct and credible for the comparisons conducted.

Of significant comparative value (also taken into consideration in Table 25.3) are the temperature values taken over a 28-year period from October 1823 to June 1851 (except for January 1841) in the meteorological station run by Petzeld – the headmaster of the school in Nysa (then Neisse). The measurements, probably taken on the premises of the school, were conducted at the same times as those in Wrocław, that is at 6h, 14h and 22h. The results of these measurements were compiled in the form of mean monthly values by von Rotkirch (Galle 1857, 1879), an observer at the Breslau-Sternwarte Observatory. Verification of these data produced only a few errors which were corrected in a similar manner as the data from Głubczyce.

The next long series presented in Table 25.3 refers to the mean monthly Tp values from Kluczbork (then Kreuzburg) the period April 1823–December 1849 and was calculated from time values measured by the pharmacist Lehmann and then compiled by Günther (Galle 1857), an academic researcher at the Observatory. As had been the case in Wrocław and Nysa, the Kluczbork observations were conducted at three times 6h, 14h and 22h. Air temperature measurements were taken on the northern wall of the second floor of the pharmacy.

The Tp data for 1823–1838 taken at the Księginice Małe (Klein-Kniegnitz) station near Sobótka (Zobten) are also significant for the interpolation of the values from Wrocław. They were obtained by pastor Leopold in the northern window of an unheated room on the second floor of his house. Their comparative value is highest for the winter period as the observations were carried out during that season at 8h, 14h and 21h. Galle (1857) stated that these observations were compiled by Büttner.

Büttner also[11] compiled meteorological data resulting from observations and measurements conducted in the period 1825–1837 in Syców (Polnisch-Wartenberg) by a local physician, Dr. Hofrichter. The temperature measurements were carried out at a height of approximately 4 m above street level in a south-west window of the building in which the observer was working. From March to September inclusively, the observations were conducted at 6h, 14h and 22h, and in the remaining months at 7h, 14h and 22h. The data are complete apart from small gaps in the years 1835 and 1837.

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[11] The monthly Tp values from Lewin Brzeski (Löwen) compiled by Büttner (Galle 1857) from the years 1840–1849 were not used in the paper. However, all the observations were conducted there according to the three daily readings model which, except for the morning observation, differed from those at the other Silesian stations as they were performed at 6h, 12h and 18h.

Table 25.3 Average monthly air temperature (Tp) values in the most important Silesian meteorological stations outside Wrocław (i.e., those with the longest published measurement series) in the years 1805–1851

Month	I	I	I	I	I	I	I	II	II	II	II	II	II	II
Year	Głub	Klucz	Nysa	Szas	Syc	M.Ksg.	N.Rud.	Głub	Klucz	Nysa	Szas	Syc	M.Ksg.	N.Rud.
1805	*	*	*	*	*	*	*	*	*	*	*	*	*	*
1806	1.6	*	*	*	*	*	*	2.2	*	*	*	*	*	*
1807	–1.2	*	*	*	*	*	*	1.3	*	*	*	*	*	*
1808	–1.5	*	*	*	*	*	*	–2.3	*	*	*	*	*	*
1809	–4.1	*	*	*	*	*	*	1.4	*	*	*	*	*	*
1810	–3.0	*	*	*	*	*	*	–1.6	*	*	*	*	*	*
1811	–6.4	*	*	*	*	*	*	–1.3	*	*	*	*	*	*
1812	–4.4	*	*	*	*	*	*	0.0	*	*	*	*	*	*
1813	–4.3	*	*	*	*	*	*	2.2	*	*	*	*	*	*
1814	–3.9	*	*	*	*	*	*	–7.3	*	*	*	*	*	*
1815	–4.5	*	*	*	*	*	*	1.2	*	*	*	*	*	*
1816	0.0	*	*	*	*	*	*	–1.5	*	*	*	*	*	*
1817	1.3	*	*	*	*	*	*	2.7	*	*	*	*	*	*
1818	–0.1	*	*	*	*	*	*	0.8	*	*	*	*	*	*
1819	0.8	*	*	***1.5***	*	*	*	2.9	*	*	0.4	*	*	*
1820	***–5.4***	*	*	***–5.9***	*	*	*	1.1	*	*	–2.7	*	*	*
1821	0.5	*	*	0.4	*	*	*	–1.9	*	*	–1.0	*	*	*
1822	0.4	*	*	1.8	*	*	*	2.1	*	*	3.9	*	*	*
1823	–10.3	*	*	–10.3	*	–10.9	–13.8	–1.4	*	*	0.9	*	–0.3	–4.1
1824	–1.1	***–0.3***	***–0.2***	0.3	*	0.3	*	1.1	1.2	***1.2***	1.8	*	1.5	*
1825	–0.4	–0.9	–0.2	1.8	0.2	1.7	*	–1.6	–1.0	–1.9	0.0	–1.7	–0.3	*
1826	–7.7	–8.0	–7.3	–8.4	–8.8	–7.8	–7.8	–0.8	–0.9	–0.2	0.1	–1.3	0.5	–1.1
1827	–2.5	–2.7	–2.1	–2.8	–2.4	–2.7	–3.2	–6.4	–7.8	–7.3	–8.4	–6.7	–7.3	–8.4
1828	–4.0	–5.0	–4.0	–5.2	–4.6	–3.4	–4.4	–3.0	–3.4	–3.0	–2.7	–3.0	–2.6	–3.9
1829	–6.9	–6.7	–6.9	–8.0	–6.2	–7.2	–6.2	–5.6	–5.7	–4.5	–7.0	–5.1	–4.5	–6.4
1830	–9.5	–9.0	–9.9	–10.7	–8.7	–9.7	–9.1	***–5.6***	–5.0	–4.5	–6.5	–4.6	–4.5	–4.7

1831	–6.8	–6.2	–5.0	*	–5.6	–5.0	–6.6	–1.7	***–1.1***	***–1.1***	*	–0.2	0.9	–2.0
1832	–4.0	–2.0	–2.8	*	–2.2	–2.4	–3.9	–1.6	–0.6	–0.3	*	–0.4	0.0	–1.4
1833	–5.7	–4.3	–5.0	*	–4.3	–4.2	–7.0	***2.4***	2.2	3.4	*	2.4	3.6	1.0
1834	1.1	1.6	2.7	*	1.9	2.9	0.5	***0.8***	***0.4***	0.3	*	–0.1	0.7	–2.4
1835	–0.9	–1.0	–0.2	*	–0.3	–0.1	–2.8	0.3	1.3	1.8	*	1.8	1.9	–1.0
1836	***–3.4***	–3.3	–2.6	*	–2.7	–1.4	–5.3	–0.1	0.7	1.3	*	0.8	1.3	–1.4
1837	–3.3	–2.3	–1.3	*	–1.5	–1.1	–3.3	–3.5	–2.9	–2.6	*	–2.1	–2.4	–4.8
1838	–11.1	–9.8	–10.6	*	*	–11.0	–11.3	–6.2	***–5.7***	–4.6	*	*	–5.4	–8.3
1839	–2.5	–2.4	–1.5	*	*	*	–4.1	–0.7	–0.5	0.2	*	*	*	–2.6
1840	–2.8	–2.7	–1.4	*	*	*	–4.9	***–1.8***	***–1.3***	–1.4	*	*	*	–3.0
1841	–2.8	–2.3	***–2.4***	*	*	*	–4.8	–6.2	***–6.0***	–6.6	*	*	*	–7.5
1842	–6.5	–5.3	–5.9	*	*	*	–7.2	–1.7	–1.2	–1.4	*	*	*	–5.6
1843	–0.9	–0.4	–0.3	*	*	*	–2.7	5.0	5.0	5.3	*	*	*	3.1
1844	–3.7	–2.9	–1.8	*	*	*	*	–3.1	–2.6	–1.4	*	*	*	*
1845	0.6	0.4	0.8	*	*	*	*	–6.3	–6.9	–5.8	*	*	*	*
1846	–0.6	–0.8	***–0.5***	*	*	*	*	1.8	***1.7***	2.1	*	*	*	*
1847	–3.3	–3.8	–3.7	*	*	*	*	–1.8	–2.0	–1.0	*	*	*	*
1848	–10.3	–10.1	–10.8	*	*	*	*	1.6	2.0	3.3	*	*	*	*
1849	–3.3	–3.6	–2.9	*	*	*	*	2.1	1.4	1.8	*	*	*	*
1850	*	*	–8.8	*	*	*	*	*	*	3.3	*	*	*	*
1851	*	*	–0.4	*	*	*	*	*	*	0.0	*	*	*	*

(continued)

Table 25.3 (continued)

Month	V	III	III	III	III	III	III	IV	IV	IV	IV	IV	IV	IV
Year	Głub	Klucz	Nysa	Szas	Syc	M.Ksg.	N.Rud.	Głub	Klucz	Nysa	Szas	Syc	M.Ksg.	N.Rud.
1805	0.7	*	*	*	*	*	*	4.9	*	*	*	*	*	*
1806	3.2	*	*	*	*	*	*	6.1	*	*	*	*	*	*
1807	0.2	*	*	*	*	*	*	6.0	*	*	*	*	*	*
1808	–3.9	*	*	*	*	*	*	5.7	*	*	*	*	*	*
1809	0.5	*	*	*	*	*	*	4.9	*	*	*	*	*	*
1810	2.7	*	*	*	*	*	*	5.3	*	*	*	*	*	*
1811	4.3	*	*	*	*	*	*	8.2	*	*	*	*	*	*
1812	2.6	*	*	*	*	*	*	3.8	*	*	*	*	*	*
1813	1.6	*	*	*	*	*	*	9.3	*	*	*	*	*	*
1814	***0.2***	*	*	*	*	*	*	9.8	*	*	*	*	*	*
1815	4.0	*	*	*	*	*	*	7.4	*	*	*	*	*	*
1816	2.4	*	*	*	*	*	*	7.3	*	*	*	*	*	*
1817	2.6	*	*	*	*	*	*	3.1	*	*	*	*	*	*
1818	4.1	*	*	*	*	*	*	9.0	*	*	*	*	*	*
1819	5.2	*	*	3.1	*	*	*	8.7	*	*	8.1	*	*	*
1820	1.7	*	*	–0.7	*	*	*	9.0	*	*	8.2	*	*	*
1821	1.4	*	*	1.9	*	*	*	10.8	*	*	12.8	*	*	*
1822	6.4	*	*	8.0	*	*	*	9.6	*	*	11.7	*	*	*
1823	2.6	*	*	5.2	*	3.9	–1.0	6.6	***6.3***	*	7.9	*	7.1	2.4
1824	2.4	1.3	1.6	3.2	*	3.0	*	7.4	***7.7***	***7.3***	7.4	*	7.7	*
1825	–0.7	–0.8	–0.3	–0.1	–1.2	–0.7	*	8.1	7.9	9.0	8.6	7.3	9.4	*
1826	3.3	3.0	3.5	3.8	2.4	4.0	2.7	7.2	6.6	7.6	7.4	6.6	7.7	6.5
1827	4.3	3.5	***3.8***	4.7	3.7	5.0	3.7	10.2	9.6	10.4	10.1	10.5	10.3	9.2
1828	3.9	3.3	4.2	2.7	3.6	4.3	2.8	10.0	9.8	10.2	8.6	9.7	10.5	8.4
1829	0.3	0.4	1.3	***0.7***	0.9	1.0	–1.4	7.7	7.9	9.2	6.7	8.6	8.9	6.4
1830	1.6	1.8	2.8	1.9	2.6	3.9	1.1	9.0	9.3	10.2	*	10.1	10.7	8.5

1831	1.8	1.9	3.2	*	2.4	3.1	1.6	10.4	11.1	11.4	*	12.0	11.7	8.8
1832	1.4	2.0	2.9	*	2.3	2.9	1.1	7.3	6.6	7.5	*	7.6	7.9	5.4
1833	2.3	***2.5***	3.5	*	2.9	2.9	1.3	5.4	5.6	6.6	*	6.3	6.5	4.2
1834	1.0	1.1	2.6	*	2.2	2.6	–0.3	5.6	6.7	7.0	*	7.2	7.3	4.8
1835	1.9	2.5	3.8	*	2.9	2.9	0.5	5.7	6.1	7.2	*	7.2	7.9	4.8
1836	7.1	7.7	8.2	*	8.4	8.9	5.8	7.1	8.2	8.4	*	9.0	8.8	6.5
1837	–1.0	–0.5	***–0.8***	*	0.5	0.0	–2.6	6.2	6.5	6.9	*	7.5	6.7	3.5
1838	2.1	***2.5***	2.9	*	*	3.0	0.3	6.2	6.1	7.7	*	*	6.7	3.6
1839	–1.3	–0.8	–0.7	*	*	*	–2.4	3.2	4.1	4.1	*	*	*	1.8
1840	–2.3	–2.2	–1.7	*	*	*	–4.9	6.5	6.6	6.5	*	*	*	4.8
1841	3.7	3.3	3.9	*	*	*	1.5	9.3	9.4	9.3	*	*	*	7.5
1842	2.5	2.6	3.3	*	*	*	0.6	5.0	4.7	5.4	*	*	*	3.5
1843	0.8	1.1	1.4	*	*	*	–2.0	7.9	7.8	8.2	*	*	*	4.9
1844	1.3	0.1	***0.4***	*	*	*	*	8.1	7.0	8.0	*	*	*	*
1845	–3.9	–4.4	–3.6	*	*	*	*	8.2	7.9	10.0	*	*	*	*
1846	6.1	5.6	6.6	*	*	*	*	9.7	9.4	10.4	*	*	*	*
1847	1.7	1.8	2.5	*	*	*	*	6.2	5.7	6.3	*	*	*	*
1848	4.7	5.1	6	*	*	*	*	11.5	11.4	11.8	*	*	*	*
1849	1.6	1.0	1.9	*	*	*	*	7.7	***7.6***	7.8	*	*	*	*
1850	*	*	0.6	*	*	*	*	*	*	8.7	*	*	*	*
1851	*	*	3.8	*	*	*	*	*	*	10.5	*	*	*	*

(continued)

Table 25.3 (continued)

Month	V	V	V	V	V	V	V	VI	VI	VI	VI	VI	VI	VI
Year	Głub	Klucz	Nysa	Szas	Syc	M.Ksg.	N.Rud.	Głub	Klucz	Nysa	Szas	Syc	M.Ksg.	N.Rud.
1805	10.8	*	*	*	*	*	*	14.0	*	*	*	*	*	*
1806	14.8	*	*	*	*	*	*	14.5	*	*	*	*	*	*
1807	13.4	*	*	*	*	*	*	14.8	*	*	*	*	*	*
1808	13.4	*	*	*	*	*	*	16.1	*	*	*	*	*	*
1809	13.9	*	*	*	*	*	*	15.5	*	*	*	*	*	*
1810	12.5	*	*	*	*	*	*	14.1	*	*	*	*	*	*
1811	16.7	*	*	*	*	*	*	19.5	*	*	*	*	*	*
1812	13.1	*	*	*	*	*	*	16.1	*	*	*	*	*	*
1813	13.1	*	*	*	*	*	*	14.0	*	*	*	*	*	*
1814	10.4	*	*	*	*	*	*	13.9	*	*	*	*	*	*
1815	12.9	*	*	*	*	*	*	16.8	*	*	*	*	*	*
1816	12.6	*	*	*	*	*	*	15.7	*	*	*	*	*	*
1817	13.2	*	*	*	*	*	*	17.7	*	*	*	*	*	*
1818	12.6	*	*	*	*	*	*	15.6	*	*	*	*	*	*
1819	12.0	*	*	13.9	*	*	*	17.4	*	*	19.2	*	*	*
1820	14.5	*	*	13.5	*	*	*	14.3	*	*	13.4	*	*	*
1821	13.9	*	*	14.6	*	*	*	13.2	*	*	15.0	*	*	*
1822	14.3	*	*	16.2	*	*	*	17.7	*	*	18.3	*	*	*
1823	14.0	13.6	*	14.4	*	14.8	8.9	17.0	16.4	*	17.5	*	17.1	11.7
1824	11.7	12.4	11.6	12.0	*	12.0	*	15.5	15.2	15.7	15.3	*	15.5	*
1825	13.2	13.1	13.9	12.9	12.1	13.4	13.7	15.3	15.9	16.7	15.7	15.3	15.9	15.6
1826	12.2	11.9	12.2	12.0	11.8	11.9	10.7	17.2	17.1	17.9	17.0	17.4	17.1	16.1
1827	15.6	14.9	15.3	15.1	16.4	16.0	13.9	19.1	19.0	20.1	18.1	20.3	19.4	17.1
1828	12.9	12.7	13.1	11.7	13.0	13.2	10.8	17.2	16.6	16.7	16.0	18.2	17.1	15.0
1829	10.6	11.5	12.2	11.0	12.6	12.2	10.4	14.8	15.2	15.3	15.1	16.3	15.9	13.7
1830	13.6	13.1	13.8	*	14.1	13.8	12.0	18.6	18.2	18.9	*	19.2	18.7	16.1

1831	12.9	13.1	13.7	*	13.8	13.8	10.7	15.2	15.4	16.6	*	16.0	16.1	13.1
1832	10.9	11.0	12.2	*	11.8	12.1	9.5	15.4	15.4	16.4	*	16.5	16.1	13.0
1833	17.0	16.3	16.9	*	17.0	17.6	13.9	18.6	18.5	18.1	*	19.2	18.7	16.0
1834	15.9	16.0	16.5	*	16.7	16.8	13.7	18.2	18.5	19.0	*	19.0	19.0	15.7
1835	13.1	13.5	14.8	*	14.3	14.2	11.7	16.4	16.6	17.6	*	18.0	17.4	15.0
1836	9.1	9.7	10.4	*	11.0	10.2	8.3	16.6	16.7	17.8	*	18.2	17.7	14.6
1837	11.2	11.3	12.0	*	12.9	11.8	9.1	15.5	15.4	16.5	*	17.3	16.3	13.5
1838	13.0	13.7	13.8	*	*	14.0	11.6	15.6	15.9	15.9	*	*	16.3	13.1
1839	12.2	13.3	12.7	*	*	*	10.5	18.4	18.1	18.8	*	*	*	15.7
1840	11.4	10.9	11.4	*	*	*	9.6	15.6	15.2	16.7	*	*	*	12.7
1841	15.7	16.4	15.8	*	*	*	14.3	16.6	16.8	15.6	*	*	*	14.0
1842	13.2	13.9	13.8	*	*	*	12.2	16.3	16.1	15.9	*	*	*	13.9
1843	11.1	10.7	11.1	*	*	*	9.5	15.4	15.9	15.3	*	*	*	12.4
1844	12.7	13.5	12.9	*	*	*	*	16.7	16.1	16.2	*	*	*	*
1845	11.7	12.0	13.6	*	*	*	*	17.7	18.2	19.6	*	*	*	*
1846	12.8	12.4	12.7	*	*	*	*	18.6	17.4	17.3	*	*	*	*
1847	15.2	15.0	14.9	*	*	*	*	14.2	14.9	14.4	*	*	*	*
1848	12.5	13.3	12.5	*	*	*	*	19.1	19.7	18.8	*	*	*	*
1849	14.2	14.6	14.2	*	*	*	*	16.8	17.0	16.7	*	*	*	*
1850	*	*	14.5	*	*	*	*	*	*	17.9	*	*	*	*
1851	*	*	10.6	*	*	*	*	*	*	15.8	*	*	*	*

(continued)

Table 25.3 (continued)

Month	VII	VII	VII	VII	VII	VII	VII	VIII	VIII	VIII	VIII	VIII	VIII	VIII
Year	Głub	Klucz	Nysa	Szas	Syc	M.Ksg.	N.Rud.	Głub	Klucz	Nysa	Szas	Syc	M.Ksg.	N.Rud.
1805	15.9	*	*	*	*	*	*	***15.0***	*	*	*	*	*	*
1806	16.4	*	*	*	*	*	*	16.9	*	*	*	*	*	*
1807	17.8	*	*	*	*	*	*	22.1	*	*	*	*	*	*
1808	17.8	*	*	*	*	*	*	18.3	*	*	*	*	*	*
1809	17.7	*	*	*	*	*	*	17.9	*	*	*	*	*	*
1810	17.7	*	*	*	*	*	*	16.4	*	*	*	*	*	*
1811	20.0	*	*	*	*	*	*	18.2	*	*	*	*	*	*
1812	16.2	*	*	*	*	*	*	15.6	*	*	*	*	*	*
1813	16.9	*	*	*	*	*	*	15.4	*	*	*	*	*	*
1814	18.3	*	*	*	*	*	*	17.2	*	*	*	*	*	*
1815	15.2	*	*	*	*	*	*	16.5	*	*	*	*	*	*
1816	16.7	*	*	*	*	*	*	16.1	*	*	*	*	*	*
1817	17.8	*	*	*	*	*	*	17.1	*	*	*	*	*	*
1818	17.3	*	*	*	*	*	*	15.0	*	*	*	*	*	*
1819	18.1	*	*	19.7	*	*	*	17.0	*	*	18.7	*	*	*
1820	16.2	*	*	16.7	*	*	*	19.7	*	*	19.5	*	*	*
1821	16.1	*	*	17.8	*	*	*	16.2	*	*	18.2	*	*	*
1822	20.1	*	*	21.0	*	*	*	17.1	*	*	18.0	*	*	*
1823	17.9	***17.7***	*	17.2	*	17.6	12.9	19.4	18.2	*	18.7	*	18.8	14.8
1824	17.6	17.4	18.6	17.2	*	18.2	*	18.4	17.3	***17.7***	17.0	*	18.4	*
1825	17.1	16.9	17.7	17.2	16.6	17.7	15.7	17.8	17.2	17.3	16.7	17.0	17.6	15.8
1826	21.2	21.1	21.3	20.9	21.3	21.4	19.8	20.6	19.9	***20.5***	19.7	19.7	20.7	18.9
1827	19.9	18.9	19.5	18.7	20.0	20.1	17.7	17.9	***17.5***	***17.5***	17.3	18.7	18.0	16.5
1828	20.3	19.5	19.7	18.4	20.2	20.3	17.8	17.3	16.2	16.9	15.1	17.3	17.1	14.1
1829	19.6	18.5	19.4	17.8	19.9	19.1	16.9	17.3	16.4	17.3	15.7	17.5	17.2	14.2
1830	18.9	18.0	19.0	*	18.7	18.8	16.6	18.4	18.0	18.7	*	18.6	18.6	16.5

1831	18.9	19.5	18.9	*	20.0	19.5	16.1	17.4	17.0	17.3	*	18.1	17.9	14.6
1832	15.4	14.8	16.2	*	15.8	15.8	13.2	18.8	17.8	17.9	*	18.6	18.7	15.4
1833	16.5	16.8	16.5	*	17.5	17.7	15.0	14.1	13.8	13.8	*	14.5	15.0	11.0
1834	22.4	22.8	22.4	*	23.4	23.0	19.7	***20.2***	19.9	20.6	*	20.9	20.3	17.9
1835	18.3	18.5	19.4	*	19.9	19.5	16.2	***16.5***	15.9	17.6	*	17.3	17.4	15.2
1836	16.4	16.3	18.1	*	18.1	17.6	14.8	16.1	15.6	17.6	*	17.5	17.1	13.8
1837	15.6	15.3	16.2	*	16.5	16.6	13.6	18.8	18.5	19.3	*	19.8	19.6	16.3
1838	17.3	17.1	17.1	*	*	17.9	14.2	15.6	15.2	15.8	*	*	16.2	13.1
1839	19.2	19.6	19.4	*	*	*	16.6	16.4	16.3	17.1	*	*	*	13.9
1840	17.4	17.5	***17.2***	*	*	*	15.5	16.3	15.8	15.7	*	*	*	14.3
1841	17.5	17.6	17.3	*	*	*	15.5	17.8	18.1	17.6	*	*	*	16.4
1842	17.6	16.9	17.0	*	*	*	15.0	19.9	20.3	19.6	*	*	*	18.1
1843	17.3	17.5	17.1	*	*	*	14.5	17.5	17.9	17.8	*	*	*	15.2
1844	15.1	15.1	15.4	*	*	*	*	15.5	15.2	15.8	*	*	*	*
1845	18.3	19.3	20.6	*	*	*	*	16.5	16.4	18.2	*	*	*	*
1846	19.7	19.9	19.8	*	*	*	*	20.1	20.7	20.1	*	*	*	*
1847	17.7	17.5	18.2	*	*	*	*	19.1	19.2	18.5	*	*	*	*
1848	18.1	18.9	18.3	*	*	*	*	17.7	17.1	17.6	*	*	*	*
1849	*	17.0	16.8	*	*	*	*	*	16.2	16.1	*	*	*	*
1850	*	*	18.0	*	*	*	*	*	*	18.5	*	*	*	*
1851	*	*	*	*	*	*	*	*	*	*	*	*	*	*

(continued)

Table 25.3 (continued)

Month	IX	IX	IX	IX	IX	IX	IX	X	X	X	X	X	X	X
Year	Głub	Klucz	Nysa	Szas	Syc	M.Ksg.	N.Rud.	Głub	Klucz	Nysa	Szas	Syc	M.Ksg.	N.Rud.
1805	***14.7***	*	*	*	*	*	*	4.0	*	*	*	*	*	*
1806	16.4	*	*	*	*	*	*	7.8	*	*	*	*	*	*
1807	13.9	*	*	*	*	*	*	8.9	*	*	*	*	*	*
1808	15.2	*	*	*	*	*	*	7.6	*	*	*	*	*	*
1809	14.3	*	*	*	*	*	*	6.6	*	*	*	*	*	*
1810	15.4	*	*	*	*	*	*	7.0	*	*	*	*	*	*
1811	13.8	*	*	*	*	*	*	11.8	*	*	*	*	*	*
1812	12.5	*	*	*	*	*	*	10.6	*	*	*	*	*	*
1813	***13.0***	*	*	*	*	*	*	7.2	*	*	*	*	*	*
1814	10.4	*	*	*	*	*	*	7.3	*	*	*	*	*	*
1815	10.7	*	*	*	*	*	*	8.6	*	*	*	*	*	*
1816	12.5	*	*	*	*	*	*	7.7	*	*	*	*	*	*
1817	13.6	*	*	*	*	*	*	5.4	*	*	*	*	*	*
1818	13.6	*	*	*	*	*	*	8.1	*	*	*	*	*	*
1819	13.8	*	*	14.2	*	*	*	8.6	*	*	7.4	*	*	*
1820	13.1	*	*	12.0	*	*	*	9.4	*	*	6.1	*	*	*
1821	15.3	*	*	16.2	*	*	*	9.9	*	*	10.9	*	*	*
1822	13.6	*	*	13.5	*	*	*	11.8	*	*	12.5	*	*	*
1823	***14.0***	13.8	*	13.8	*	14.3	*	***11.9***	11.4	11.8	10.4	*	11.4	*
1824	16.8	16.1	16.2	15.8	*	16.8	*	10.6	10.1	10.2	10.1	*	11.0	*
1825	14.2	13.8	14.4	14.0	13.9	14.9	13.4	9.3	8.1	8.9	8.1	7.5	9.3	7.0
1826	14.3	13.8	***14.4***	13.3	13.6	15.0	13.6	10.6	10.0	10.7	9.7	9.6	10.7	9.8
1827	14.1	13.8	14.0	14.0	15.0	14.9	12.7	10.6	10.0	9.6	9.2	10.0	10.2	8.7
1828	13.0	12.5	13.5	12.0	13.9	14.2	12.1	8.6	7.3	8.1	7.2	8.1	8.0	6.8
1829	***14.7***	14.5	15.1	13.6	15.1	14.8	12.9	7.0	6.2	7.2	5.3	6.7	7.2	5.4

1830	13.1	13.3	13.7	*	14.2	14.0	12.1	7.1	7.3	8.5	*	7.8	8.6	6.7
1831	12.6	12.6	13.2	*	13.5	13.4	11.0	10.6	11.1	11.8	*	11.1	12.3	10.0
1832	11.7	11.4	13.5	*	12.7	13.3	10.2	8.1	8.4	9.9	*	8.7	9.5	6.8
1833	13.4	13.6	13.3	*	14.3	13.7	12.0	8.2	7.8	8.2	*	8.3	8.3	6.0
1834	15.0	15.1	***15.8***	*	16.0	16.9	13.5	8.2	***8.6***	10.2	*	8.5	9.9	6.8
1835	14.0	14.4	15.2	*	15.4	15.7	12.5	7.6	8.0	8.7	*	8.7	8.6	6.6
1836	13.5	13.0	14.1	*	13.9	14.1	11.1	10.7	10.7	11.3	*	11.5	11.2	9.1
1837	11.8	11.9	13.3	*	13.5	13.0	9.8	8.4	8.6	9.3	*	9.1	9.3	6.5
1838	14.5	14.9	15.1	*	*	*	12.6	7.0	7.4	7.4	*	*	*	5.8
1839	15.6	15.9	15.9	*	*	*	13.1	9.2	9.5	9.9	*	*	*	7.8
1840	14.5	14.3	14.3	*	*	*	11.8	5.9	6.0	6.9	*	*	*	4.7
1841	14.1	14.7	13.9	*	*	*	13.2	12.0	12.0	12.7	*	*	*	11.0
1842	13.9	14.1	14.3	*	*	*	12.7	6.6	6.4	7.2	*	*	*	4.6
1843	11.5	11.5	12.4	*	*	*	9.4	8.7	8.4	9.5	*	*	*	5.9
1844	***13.7***	13.8	14.3	*	*	*	*	9.6	9.8	***10.3***	*	*	*	*
1845	12.5	12.4	***12.9***	*	*	*	*	9.4	9.0	10.2	*	*	*	*
1846	14.8	14.0	14.6	*	*	*	*	12.4	12.5	13.0	*	*	*	*
1847	11.9	***11.7***	12.9	*	*	*	*	7.3	7.0	8.3	*	*	*	*
1848	12.9	12.8	13.2	*	*	*	*	11.2	11.1	11.2	*	*	*	*
1849	*	12.3	12.7	*	*	*	*	*	7.9	8.6	*	*	*	*
1850	*	*	12.3	*	*	*	*	*	*	8.8	*	*	*	*
1851	*	*	*	*	*	*	*	*	*	*	*	*	*	*

(continued)

Table 25.3 (continued)

Month	XI	XI	XI	XI	XI	XI	XI	XII	XII	XII	XII	XII	XII	XII
Year	Głub	Klucz	Nysa	Szas	Syc	M.Ksg.	N.Rud.	Głub	Klucz	Nysa	Szas	Syc	M.Ksg.	N.Rud.
1805	0.1	*	*	*	*	*	*	0.7	*	*	*	*	*	*
1806	4.2	*	*	*	*	*	*	3.4	*	*	*	*	*	*
1807	6.2	*	*	*	*	*	*	0.9	*	*	*	*	*	*
1808	2.2	*	*	*	*	*	*	–5.3	*	*	*	*	*	*
1809	2.6	*	*	*	*	*	*	2.5	*	*	*	*	*	*
1810	3.1	*	*	*	*	*	*	0.7	*	*	*	*	*	*
1811	3.7	*	*	*	*	*	*	0.4	*	*	*	*	*	*
1812	2.1	*	*	*	*	*	*	–6.5	*	*	*	*	*	*
1813	2.9	*	*	*	*	*	*	–0.1	*	*	*	*	*	*
1814	4.0	*	*	*	*	*	*	1.3	*	*	*	*	*	*
1815	1.9	*	*	*	*	*	*	–3.8	*	*	*	*	*	*
1816	3.1	*	*	*	*	*	*	–1.4	*	*	*	*	*	*
1817	4.4	*	*	*	*	*	*	–0.6	*	*	*	*	*	*
1818	3.7	*	*	*	*	*	*	–1.1	*	*	*	*	*	*
1819	3.6	*	*	0.6	*	*	*	–3.0	*	*	–6.7	*	*	*
1820	3.0	*	*	***1.7***	*	*	*	–2.4	*	*	–7.4	*	*	*
1821	6.5	*	*	7.5	*	*	*	2.9	*	*	3.9	*	*	*
1822	5.8	*	*	5.8	*	*	*	–1.1	*	*	–1.5	*	*	*
1823	4.6	4.7	***5.2***	4.5	*	4.5	*	1.2	1.4	***1.7***	1.5	*	1.9	*
1824	4.8	4.9	4.7	6.0	*	6.3	*	3.1	3.6	3.2	4.9	*	4.8	*
1825	5.7	5.0	***5.9***	5.4	4.6	6.0	5.3	4.9	4.7	5.2	4.3	3.5	5.0	4.5
1826	3.1	2.7	3.7	2.7	2.3	3.0	2.7	1.3	0.8	1.5	1.0	0.5	1.2	0.5
1827	–0.3	0.2	0.6	–0.5	0.4	0.3	–1.1	***1.8***	1.5	1.6	1.1	1.9	2.6	0.3
1828	4.5	3.7	3.7	2.2	4.0	4.1	3.2	0.6	0.3	1.5	–0.1	0.9	1.6	0.3
1829	–2.0	–1.8	–0.5	–2.4	–1.1	–0.8	–2.3	–11.1	–10.5	–10.9	–12.6	–10.6	–10.3	–9.5

1830	4.5	5.2	5.5	*	5.5	5.9	4.1	–0.5	1.2	1.0	*	0.9	0.6	–0.4
1831	0.8	1.8	***2.5***	*	2.2	2.5	0.7	–1.7	–0.7	0.1	*	0.1	0.4	–1.9
1832	1.2	2.3	2.9	*	2.1	2.5	0.9	***–2.6***	–2.1	–1.4	*	–1.6	–0.8	–3.7
1833	3.1	3.0	4.2	*	3.3	3.9	1.3	1.9	2.9	3.9	*	3.4	3.9	1.5
1834	2.4	2.7	4.3	*	3.4	3.6	1.1	***–0.1***	0.4	1.3	*	0.9	1.3	–1.4
1835	–2.0	–0.9	–1.3	*	–0.4	–0.4	–2.7	–3.2	–3.0	–1.1	*	–2.2	–1.4	–4.7
1836	1.3	1.3	2.5	*	1.7	2.5	0.2	1.0	0.6	2.3	*	0.9	1.6	–0.7
1837	3.4	3.6	4.4	*	4.0	4.2	1.4	–2.5	–1.9	–1.6	*	–1.4	–1.4	–4.1
1838	0.6	1.4	2.1	*	*	*	–0.9	–2.0	–1.4	–1.0	*	*	*	–3.4
1839	4.9	5.3	5.9	*	*	*	3.6	–1.6	–1.9	–1.3	*	*	*	–1.6
1840	6.0	5.7	6.8	*	*	*	4.7	–7.6	–8.3	–7.7	*	*	*	–11.7
1841	4.3	4.0	5.2	*	*	*	3.4	3.1	3.2	3.8	*	*	*	0.6
1842	0.7	0.6	1.6	*	*	*	–0.9	1.9	2.1	3.4	*	*	*	–0.1
1843	2.8	3.3	4.3	*	*	*	*	2.4	2.8	3.3	*	*	*	*
1844	4.4	4.5	***5.3***	*	*	*	*	–5.8	–4.7	–4.4	*	*	*	*
1845	6.1	5.6	***6.7***	*	*	*	*	1.6	1.3	***1.9***	*	*	*	*
1846	2.4	1.9	2.7	*	*	*	*	–3.3	–2.9	–2.5	*	*	*	*
1847	4.1	3.5	5.0	*	*	*	*	–0.7	–1.0	0.2	*	*	*	*
1848	3.2	3.3	4.0	*	*	*	*	0.6	0.7	0.2	*	*	*	*
1849	*	3.1	3.5	*	*	*	*	*	–5.0	–5.0	*	*	*	*
1850	*	*	5.2	*	*	*	*	*	*	0.8	*	*	*	*
1851	*	*	*	*	*	*	*	*	*	*	*	*	*	*

Explanation: Głu = Głubczyce (Leobschutz), Klucz = Kluczbork (Kreuzburg), Nysa (Neisse), Szas = Szaszorowice (Zapplau), Syc = Syców (Polnisch Wartenberg), M.Ksg. = Księginice Małe (Klein–Kniegnitz), N.Rud. = Nowa Ruda (Neurode); bold italics indicate corrected or interpolated values; * lack of measurements. Other explanations as in Table 25.2

The observations carried out by Lorenz, a construction master, on an estate in Szaszorowice (Zapplau) near Góra (Gurhau) for a period of over 5 years differed significantly from the measurement regime applied at the other stations in Silesia. From January 1819 to March 1825, three daily temperature readings were taken in the morning, noon/early afternoon and late evening, though not at set times. Depending on the season and situation (and the changing rhythm of other activities and household chores), the morning observation occurred between 3h and 9h, the noon observation took place between 12h and 15h, and the evening one between 21h and 24h. Hence the mean monthly values for Zapplau calculated by Büttner are questionable for these years and they can represent real values only in approximation. However, the Tp values from April 1825 to the end of March 1830 are reliable as the measurements during that period were taken at strictly defined times: 6h, 14h and 22h for the spring–summer months (March–September) and 7h, 14h and 22h for the autumn–winter months (October–February).

Meteorological observations were also conducted in Sudetenland.[12] One from the longest Tp series (1822–1847) is from Nowa Ruda (Neurode)[13] and includes monthly values for the period January 1823–October 1843, calculated by Günther (Galle 1857). The Tp measurements (except for an interval from September 1823 to April 1825), and the unpublished periods of 1822 and November 1843–1847, have only two gaps, that is, August–September 1828 and March 1831. Observations and measurements were conducted by Rohde, a shift master at a coal mine, and the pharmacist Lauterbach. In the years 1823–1831 measurements were taken at 7h, 14h and 22h, and then, beginning in 1832, at 6h, 14h and 21h. The values were used in the paper only for comparisons and an additional verification some Tp data from Wrocław.

Apart from the above-mentioned stations situated in Silesia in the first half of the nineteenth century, there were over ten other meteorological stations operating

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[12] The beginnings of meteorological observations in Sudetenland can most probably be traced back to a brief measurement episode of about 6 months (the data was never published), which took place in Wałbrzych (Waldenberg) from July to December 1821. The next year saw the beginning of long-term observations in Kłodzko (Glatz), Nowa Ruda (Neurode) and Duszniki Zdrój (Reinerz). The latter ones lasted from October 1822 until the end of 1833, but they were neither compiled nor published. Matters were different in Kłodzko – meteorological observations performed there were interrupted for several years from the year 1822 to 1847 (Galle 1857).

[13] Long-term meteorological observations in Sudetenland were also conducted in Bystrzyca Kłodzka (Habelschwerdt) in the years 1823–1849, but the results were probably not published. From among the stations outside the Kłodzko region, Galle (1857) presented the results of observations in Kamienna Góra (Landshut) lasting from 1836 to 1847, as well as the results of observations from 1836 to 1850 in Miedzianka (Kupferberg) and in Rudawy Janowickie (Landeshuter Kamm). Galle's monograph also contained a 5 year record (August 1836 – March 1842) of the monthly Tp values and other meteorological observations performed in Złoty Stok (Reichenstein). The first measurements taken high in the mountains on the peak of Śnieżka (Schneekoppe) in the Karkonosze Mountains (Riesengebirge) are important in the history of the Sudetenland measurements. They were recorded in different summer months in the years 1824–1834 by Sibenhaar. These observations, also including results of air temperature measurements, were compiled by Günther (Galle 1857).

for periods of a couple of years to more than 10 years at a time (Galle 1857). Those stations which were important for the reconstruction of the Silesian climate were located at Zittau (the measurements from 1828), Görlitz (from 1836), Legnica (Liegnitz) (1836–1844), Opole (Oppeln) (1837–1848), Racibórz (Ratibor) (1842). However the data from these stations are unpublished. Only some of these stations continued their activity (sometimes with short intervals) into the second half of the nineteenth century or into the twentieth century. Apart from Wrocław, these were Görlitz and Racibórz (Hellmann 1887; Körber 1997), but such continuous activity was very often connected with location changes of the original station.

Whether the data and information published in this compilation will result in a better future reconstruction of the climatic changes in Lower Silesia, especially in the spatial and long-term secular dimension, is open to discussion. This depends to a large extent on the results of further archival research and the outcome of searches for lost original materials. Difficulties arise from the fact that many archives as well as collections of old Silesian prints were destroyed or stolen either in the course of the war or shortly thereafter.

25.7 Conclusions

The reconstruction that was carried out in this work, of the 100 year period (1791–1890) of the Wrocław Tp series, taking into consideration relations with the other Silesian stations (Fig. 25.3), constitutes an essential starting point for the reconstruction of the series in its entirety (i.e., up to 2007) which is the subject of a separate study (Bryś and Bryś 2009). This study discussed the reconstruction difficulties related to the lack of homogeneity of the measurements in the nineteenth century. Lack of access to original materials in the form of observation diaries makes it impossible to achieve a more precise and accurate verification of the existing data. This is of particular relevance with reference to daily data. Various uncertainties remain that are connected with location changes and observation times, though these are insignificant for the data reconstructed in the form of mean monthly values. Possible errors in the notation of the Tp monthly values for Wrocław should not exceed the value of plus or minus 0.2°C.

It would be worthwhile investigating, a partial reconstruction of some longer or episodic temperature series from various Silesian stations (including those in Sudetenland) published by Galle (1857). This further reconstruction, feasible only if further sources are located in the archives, would not only be helpful in terms of recreating the climatic background of the areas surrounding Wrocław, but in the future would allow researchers to reconstruct widespread climate changes in the region of Lower Silesia and its outskirts in a longer dimension than the secular one. This would be of great significance for the construction of more reliable climatic models as well as climatic change scenarios.

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