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ORIGINAL PAPER

Homogenization of air temperature and its long-term trends in Poznań (Poland) for the period 1848–2016

Leszek Kolendowicz[1] · Bartosz Czernecki[1] · Marek Półrolniczak[1] · Mateusz Taszarek[1,2] · Arkadiusz M. Tomczyk[1] · Katarzyna Szyga-Pluga[1]

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Abstract

A long-term series of meteorological measurements will allow for a better understanding of the rate and nature of climate change. Such analysis presumes a historical knowledge of the particular place of measurements and changing measurement techniques, as well as a further evaluation of the quality of the available data. This research focuses on the city of Poznań and temperature measurements conducted from 1848 to 2016. By 1919, the location of meteorological stations had changed five times, causing time-series inhomogeneities. In 1921, meteorological measurements began to be carried out at the Poznań-Ławica airport, which have there been maintained to this day. The monthly means of air temperature for the period 1848–1919 clearly indicate a break in their homogeneity. For this reason, the main objective of this study is to reconstruct the 169-year long air temperature records in a homogeneous way so as to make it coherent with the surrounding series of long-term measurements. Data gaps are supplemented by the constant difference method based on the homogenized data series from the nearest stations. The monthly means are homogenized according to the Alexanderson's Standard Normal Homogeneity Test. In addition, evaluation of the annual, seasonal, and monthly temperature trends is also provided. An increasing long-term trend can be observed for the entire period of analysis. For the years 1848–2016, the air temperature grew at a rate of 1.1 °C per 100 years. As far as seasons go, the highest increase was observed in Winter (+ 1.5 °C/100 years) with the lowest in Summer (+ 0.6 °C/100 years). In the last 30 years, the pace of trend has increased to a rate of + 4.6 °C per 100 years, with the highest values recorded for Summer (+ 7.5 °C/100 years).

1 Introduction

The analyses of a long-term series exceeding two centuries (e.g., temperature measurements) allow for a better understanding of the rate and nature of climate change (Stocker et al. 2013), an issue that is most frequently analyzed due to the increase in air temperature. Since short-term measurement series may not be suited for an accurate evaluation of trends induced by global warming, studies based on a long-term series should be of particular interest. The local aspects of changes in air temperature have often become a hot topic in discussions among local researchers who are knowledgeable of the particular location's history, changes in the station's location, measurement techniques, the exposure of instruments, and their precision (Grigull 1986; Maciążek 2005). Local researchers are also the ones best acquainted with the available data and can thus provide reliable evaluation of its quality (Pospieszyńska and Przybylak 2018). Although Poland has a long-standing research tradition into multi-annual trends in temperature, it has suffered many wars and changes to its borders over the last 200 years. A rapid increase in urbanization has also been noted since the beginning of the industrial revolution around the 1850s (Davis 1955). All these factors may have a significant impact on the temperature records and should therefore be interpreted with caution. In the last 30 years, numerous researchers have addressed this problem and provided comprehensive analyses of temperature records for Poland, which will be discussed in the following paragraphs.

A standardized tree ring width-chronology of the Scots pine (*Pinus sylvestris* L.), along with different types of

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✉ Leszek Kolendowicz
leszko@amu.edu.pl

1 Department of Climatology, Institute of Physical Geography and Environmental Planning, Adam Mickiewicz University, Poznań, Poland

2 Skywarn Poland, Warsaw, Poland

documentary evidence (e.g., annals, chronicles, diaries, private correspondence, records of public administration, early newspapers), was used by Przybylak et al. (2005) to analyze temperature changes in Poland from the sixteenth to the twentieth century. According to the results, periods that include 1530–1590, 1656–1670, 1820–1850, 1910–1940, and even after 1985 featured a warm late Winter and early Spring. On the other hand, a cold Winter and early Spring occurred in 1600–1650, 1760–75, 1800–1815, 1880–1900, and 1950–1980. Significant upward trends for the temperature in Poland for March and May were also detected by Degirmendžić et al. (2004) who analyzed 51 stations for the period 1951–2000. The area mean air temperature and atmospheric precipitation totals in Poland covering a 100-year periods and 50 stations were also presented by Kożuchowski and Żmudzka (2003). The rising trend in temperature as well as a slightly decreasing trend in annual precipitation totals for Poland were detected.

Of the individual locations in Poland for which long-term temperature analyses in have been carried out, we may list Wrocław (period 1791–2007) presented by Bryś and Bryś (2010), Warsaw (1779–1998) by Lorenc (2000), and Cracow (1792–1995) by Trepińska (1997), Trepińska and Kowanetz (1997) and Piotrowicz (2007). Elaborations covering slightly shorter time-series concerning Gdańsk and Hel (1851–1995) by Miętus (1998) and Filipiak and Miętus (2010), Bydgoszcz (1851–1990) by Vízi et al. (2000), Poznań (1848–2009 and 1848–1997) by Nyćkowiak et al. (2014) and Tamulewicz (2000) respectively, Puławy (1871–1990) by Górski and Marciniak (1992), Śnieżka (1881–2010) by Migała et al. (2016), Łódź (1903–2000) by Wibig et al. (2004), and Toruń (1871–2010) by Pospieszyńska and Przybylak (2018). The aforementioned studies and their statistical trends are compatible with those observed in neighboring countries, e.g., Potsdam in Germany (Lehmann and Kalb 1993) and Prague in Czech Republic (Brázdil et al. 2012a, b).

In Poznań, the first systematic air temperature measurements started in January 1848. From that time until Poland regained its independence in 1919, measurements were made as part of the operational work of a meteorological network belonging to Prussia. By 1919, the location of thermometers and later the location of the meteorological stations had been changed five times within the administrative boundaries of the city of Poznań (Fig. 1, Table 1). In 1921, measurements started at the Poznań-Ławica airport, and they have since been maintained at that place to this day.

It is likely that frequent changes concerning measurements techniques and the location of instruments (in the period from 1848 to 1920) could have influenced the homogeneity of the obtained measurement time-series as well as the quality of the temperature data. Despite the fact that long-term monthly means of air temperature from 1848 to 2009 were studied for Poznań by Nyćkowiak et al. (2014) and a detailed analysis of the historical temperature data was conducted by Smosarski (1923, 1925), monthly means of air temperature from 1848 to 1919 clearly indicate a break in their homogeneity. For this reason, the main objective of this study is to arrive at a climatological reconstruction of the 169-year long data series of monthly mean temperatures for Poznań. We aim to restore the homogeneity of temperature records and present the most important long-term climatological statistics. Such a long and homogeneous series can contribute to already existing elaborations on the air temperature measurements performed over centuries, and may also help to better understand climate change within Central Europe. The homogenized data series of monthly temperature means is appended in full as supplementary material.

2 The history of meteorological observations in Poznań

The first systematic observations of air temperature in the Greater Poland Voivodeship are associated with the creation of a measurement network belonging to the Prussian Meteorological Institute in Berlin, which was established in 1847. Systematic temperature measurements in Poznań commenced on January 1, 1848 (Plenzler 1966). The first station was set up in the area of the upper town—the western part of Poznań lying on the floodplain (Fig. 1, Table 1). These measurements were significantly different from those currently performed. The height above ground level (AGL), upon which thermometers were initially installed, remains unknown. This was at a north-western wall of the building. The same thermometers were also used to measure extreme temperatures. This was the first meteorological station in Poznań to perform the measurements three times a day. In 1862, the thermometers were moved to Grobla St. 1 and set at 2.5 m AGL (i.e., about 64 m above sea level, ASL). Air temperature measurements at this site were conducted until 1885. In 1867, the observation site was relocated to today's Zielona St. 3, and had since remained there until 1873. The location was initially set up in August 1885 at Zielona St. 2 (65 m ASL). Thermometers without a shield were placed at 6.2 m AGL next to a window facing west towards a narrow courtyard surrounded by buildings on both sides (Plenzler 1966). Therefore, thermometers were not exposed to direct sunlight, but the neighborhood of several floor buildings could have significantly reduced the airflow and thus decreased the temporal variance of air temperature. The station at Zielona St. 2 operated until the end of 1910.

On January 1, 1911, temperature measurements started at the newly established station belonging to the Poznań University (Woś 2010). The station was located at a height of 78 m ASL within one of the buildings at today's Adam Mickiewicz University. According to Plenzler (1966), the

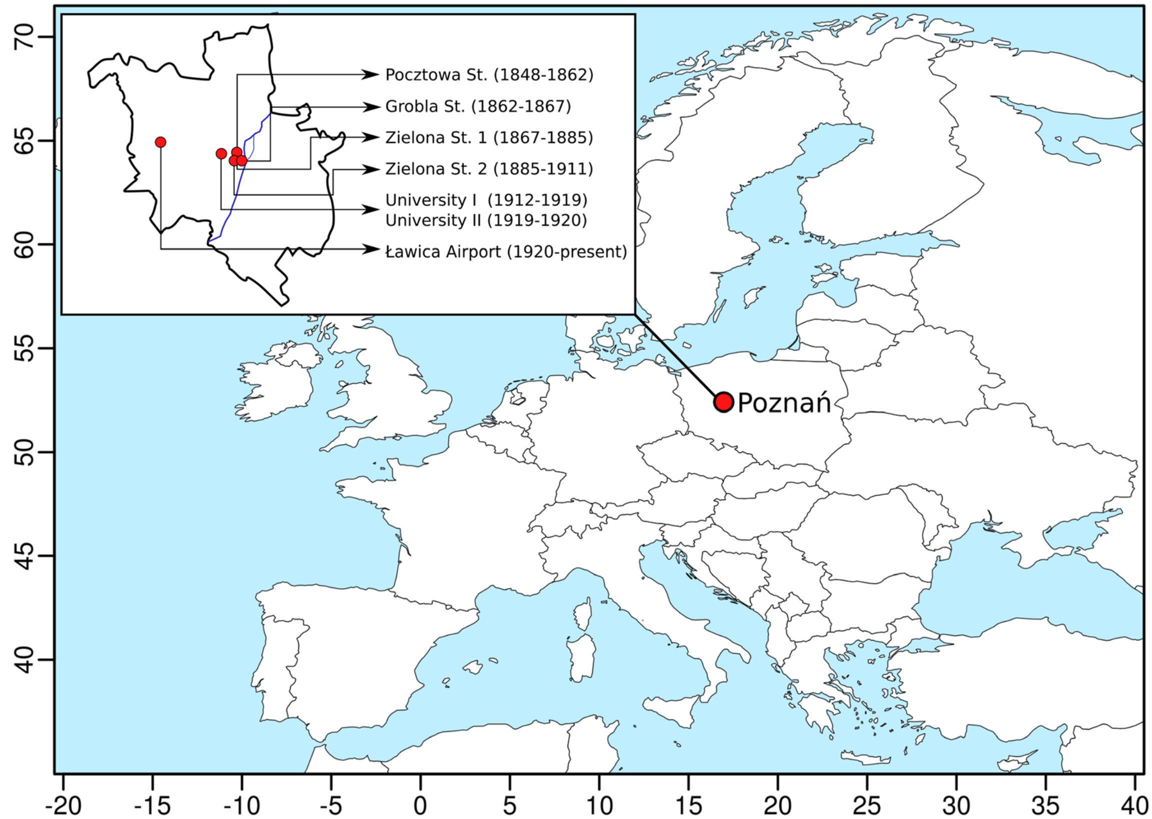


Fig. 1 Location of Poznań and measuring points

meteorological station was located in a 40 × 80 m botanical garden, neighboring railroad excavations (from the west) and buildings of the Collegium Minus (from the north, east and south). Initially, the meteorological shelter of the English type (in which the thermometers were placed) stood 12 m from the western wall of the Collegium Minus. It was then moved about 15 m further to the west, and in 1914, a thermograph was mounted in a shelter. Until December 1918, the observations were usually performed by a local physics teacher. After the outbreak of the Wielkopolska Uprising on December 27, 1918, patronage over the station was taken over by the Poznań University, which used its measurements for research purposes until July 31, 1935 (Plenzler 1966).

After World War I, a Regulation of the Council of Ministers of 28 April 1919 established the State Meteorological Institute. In 1921, the station at Poznań-Ławica started functioning and operated during the inter-war period as a military station at the airport. During World War II, the State Meteorological Institute was closed down. The continuity of meteorological observations during the war was only maintained by some meteorological stations in Poland including Poznań. However, even those stations which functioned during the Nazi occupation were almost completely destroyed during the last phase of hostilities on Polish lands (Farat 2004). As a consequence, parts of the measurements from the beginning of 1945 are missing. On March 8, 1945, the Council of Ministers passed a resolution which merged the hydrological and meteorological services into the National Hydrological and Meteorological Institute (PIHM). A PIHM branch in Poznań was established in May 1945, and since then a new observational network began its operational work. The Poznań-Ławica station resumed its operational activity on April 20 of that year but was transferred to the PIHM on January 11, 1946.

Air temperature measurements at the Poznań-Ławica station have been conducted up to this day, even though the meteorological shelter (Stevenson screen) has been moved within the airport area several times. Initially, due to the damage caused by the war, the station was moved further, south-east of the airport. Then in 1948, it was moved about 2 km towards the north-east. The current location (52° 25′ 02″ N, 16° 50′ 09″ E, 83 m ASL) is in a flat and open area near the airport's runway. In 1955, it was decided to relocate the shelter with the thermometers for a further 100 m to the south-west so as to move it away from buildings that could affect the results of the measurements. On November 15, 1956, the Airport Weather Office was established on the basis of an operating meteorological station belonging to PIHM. In 1971, PIHM was transformed into the Institute of Meteorology and Water Management (IMGW), and in 2010 renamed as the Institute of Meteorology and Water Management-National Research Institute (IMGW-PIB). The Poznań-Ławica meteorological

Table 1 Basic information concerning temperature measuring points in Poznań. Meters above sea level (ASL), meters above ground level (AGL), local time (LT)

Location	Height [m ASL]	Height [m AGL]	Thermometer site	Period	Hours [LT]	Mean annual correction within homogenization algorithm [°C]
Pocztowa St.	–	–	–	Jan 1848–March 1862	6, 14, 22	−0.47
Grobla St. 1	–	2.5	Outside the window without a shade	Apr 1862–Sep 1867	6, 14, 22	−0.70
ZielonaSt. 1	–	15	Outside the window without a shade	Oct 1867–Jul 1885	6, 14, 22	−0.59
Zielona St. 2	–	6.2	Outside the window without a shade	Aug 1885–Sep 1892	7, 14, 21	−0.60
Długa St. 3	58	8.6	Outside the window in the zinc box	Sep 1892–Dec 1911	7, 14, 21	−0.59
University I (Wały Wazów)	78	2.0	Bigger English instrumental shelter in the garden	Jan 1912–May 1919	7, 13, 21	−0.59
University II	78	2.0	Instrumental shelter in the garden	June 1919–December 1920	7, 13, 21	−0.42
Poznań-Ławica	83	2.0	Instrumental shelter next to the runway	January 1921–December 2016	Every hour	–

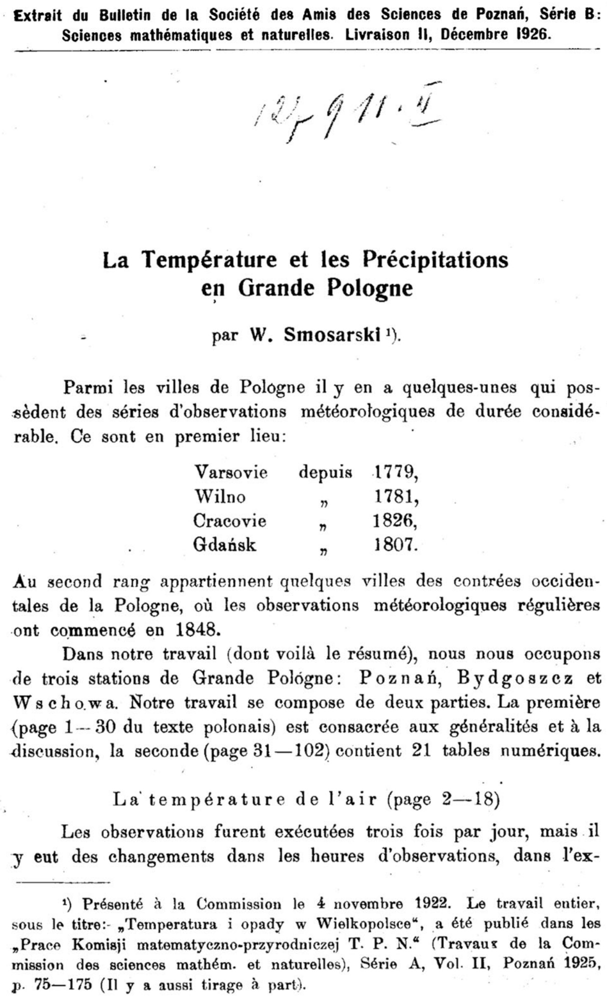
station is currently the only place where the longest systematic measurements of temperature for Poznań are available.

3 Database and homogenization methodology

In the first research phase, the monthly means of the air temperature derived from Smosarski's publications (1923, 1925) were taken into considerations (Fig. 2). Professor Władysław Smosarski collected all available meteorological data concerning air temperature and precipitation for the Greater Poland Voivodeship for the period 1848–1922. Additionally, information about the meteorological station and detailed measurement techniques were also provided. Measurement values after 1922 were derived from the secondary sources (meteorological yearbooks) published by the German and Polish national meteorological services available at the archive of IMGW-PIB. As the temperature measurement techniques changed throughout the analyzed period, the same also happened to the methodology of determining the monthly means (e.g., the number and timing of daily measurements). This issue is a typical limitation for the historical data and has been discussed in many previous studies (e.g., Trepińska 1997; Lorenc 2000; Bryś and Bryś 2010; Pospieszyńska and Przybylak 2018). Although authors are aware of this disadvantage, it is generally considered that this issue should have a minimal effect on the results. In addition, homogenization algorithm should also minimize the negative aspect of this issue.

Data collected from the entire observational period was checked for quality control, while gaps were supplemented by the constant difference method (Pruchnicki 1987) based on the homogenized and spatially interpolated data series from the nearest stations. For Potsdam, data was derived from the website http://www.pik-potsdam.de; for Warsaw, we used a data compiled by Lorenc (2000), for Prague by Brázdil and Budíková (1999) and Kyselỳ (2002), for Wrocław by Bryś and Bryś (2010), for Gdańsk by Miętus (1998), for Śnieżka by Migała et al. (2016), for Szczecin by Jones et al. (2012), and for Cracow by Trepińska and Kowanetz (1997). All these stations were investigated in terms of their geographical distance to Poznań and correlation coefficients (Table 2). Based on this, it was decided that data series from Potsdam, Prague, Warsaw, Śnieżka, and Gdańsk would be implemented via the constant difference method. Despite the high correlations for Szczecin, Wrocław, and Cracow (Table 2, Fig. 4), and the relatively long observational periods, it was decided to skip these series from further analyses mainly due to a lack of homogeneity as pointed out by the Standard Normal Homogeneity Test (SNHT) proposed by Alexandersson (1986).

a)



Extrait du Bulletin de la Société des Amis des Sciences de Poznań, Série B: Sciences mathématiques et naturelles. Livraison II, Décembre 1926.

12/911.II

La Température et les Précipitations en Grande Pologne

par W. Smosarski [1]).

Parmi les villes de Pologne il y en a quelques-unes qui possèdent des séries d'observations météorologiques de durée considérable. Ce sont en premier lieu:

Varsovie	depuis	1779,
Wilno	„	1781,
Cracovie	„	1826,
Gdańsk	„	1807.

Au second rang appartiennent quelques villes des contrées occidentales de la Pologne, où les observations météorologiques régulières ont commencé en 1848.

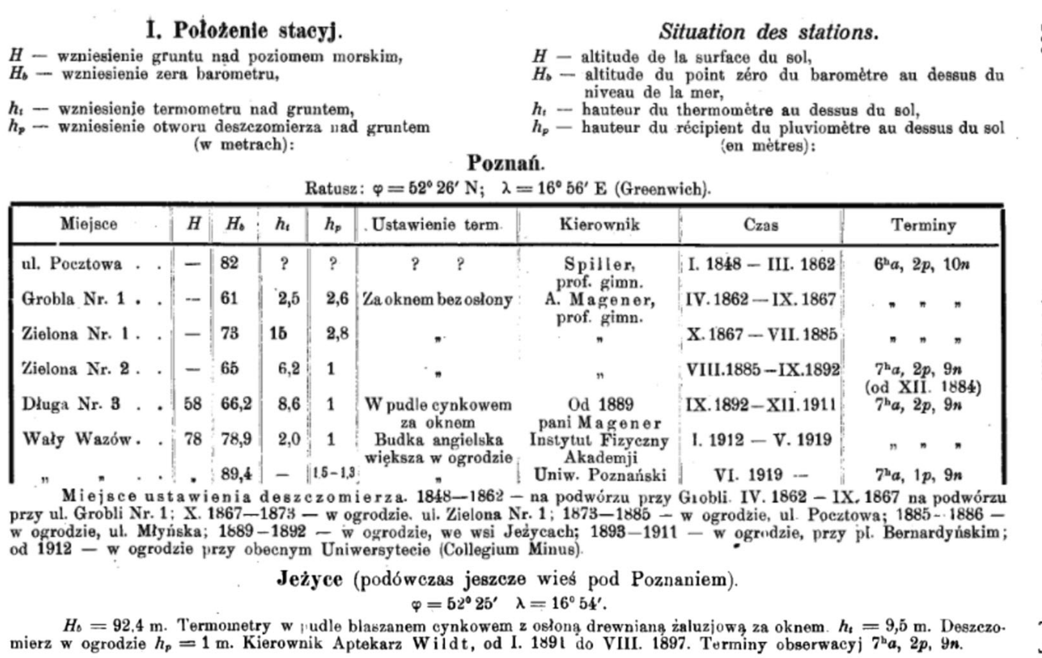
Dans notre travail (dont voilà le résumé), nous nous occupons de trois stations de Grande Pologne: Poznań, Bydgoszcz et Wschowa. Notre travail se compose de deux parties. La première (page 1—30 du texte polonais) est consacrée aux généralités et à la discussion, la seconde (page 31—102) contient 21 tables numériques.

La température de l'air (page 2—18)

Les observations furent exécutées trois fois par jour, mais il y eut des changements dans les heures d'observations, dans l'ex-

[1]) Présenté à la Commission le 4 novembre 1922. Le travail entier, sous le titre: „Temperatura i opady w Wielkopolsce", a été publié dans les „Prace Komisji matematyczno-przyrodniczej T. P. N." (Travaux de la Commission des sciences mathém. et naturelles), Série A, Vol. II, Poznań 1925, p. 75—175 (Il y a aussi tirage à part).

b)



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I. Położenie stacyj. / Situation des stations.

H — wzniesienie gruntu nad poziomem morskim,
H_b — wzniesienie zera barometru,
h_t — wzniesienie termometru nad gruntem,
h_p — wzniesienie otworu deszczomierza nad gruntem (w metrach):

H — altitude de la surface du sol,
H_b — altitude du point zéro du baromètre au dessus du niveau de la mer,
h_t — hauteur du thermomètre au dessus du sol,
h_p — hauteur du récipient du pluviomètre au dessus du sol (en mètres):

Poznań.

Ratusz: $\varphi = 52^\circ 26'$ N; $\lambda = 16^\circ 56'$ E (Greenwich).

Miejsce	H	H_b	h_t	h_p	Ustawienie term.	Kierownik	Czas	Terminy
ul. Pocztowa . .	—	82	?	?	? ?	Spiller, prof. gimn.	I. 1848 — III. 1862	$6^h a$, $2p$, $10n$
Grobla Nr. 1 . .	—	61	2,5	2,6	Za oknem bez osłony	A. Magener, prof. gimn.	IV. 1862 — IX. 1867	„ „ „
Zielona Nr. 1 . .	—	73	15	2,8	„	„	X. 1867 — VII. 1885	„ „ „
Zielona Nr. 2 . .	—	65	6,2	1	„	„	VIII. 1885 — IX. 1892	$7^h a$, $2p$, $9n$ (od XII. 1884)
Długa Nr. 3 . .	58	66,2	8,6	1	W pudle cynkowem za oknem	Od 1889 pani Magener	IX. 1892 — XII. 1911	$7^h a$, $2p$, $9n$
Wały Wazów . .	78	78,9	2,0	1	Budka angielska większa w ogrodzie	Instytut Fizyczny Akademji	I. 1912 — V. 1919	„ „ „
„ „ . . .	„	89,4	—	1.5 – 1.3	„	Uniw. Poznański	VI. 1919 —	$7^h a$, $1p$, $9n$

Miejsce ustawienia deszczomierza. 1848—1862 — na podwórzu przy Grobli. IV. 1862 — IX. 1867 na podwórzu przy ul. Grobli Nr. 1; X. 1867—1873 — w ogrodzie. ul. Zielona Nr. 1; 1873—1885 — w ogrodzie, ul. Pocztowa; 1885—1886 — w ogrodzie, ul. Młyńska; 1889—1892 — w ogrodzie, we wsi Jeżycach; 1893—1911 — w ogrodzie, przy pl. Bernardyńskim; od 1912 — w ogrodzie przy obecnym Uniwersytecie (Collegium Minus).

Jeżyce (podówczas jeszcze wieś pod Poznaniem).

$\varphi = 52^\circ 25'$ $\lambda = 16^\circ 54'$.

$H_b = 92{,}4$ m. Termometry w pudle blaszanem cynkowem z osłoną drewnianą żaluzjową za oknem. $h_t = 9{,}5$ m. Deszczomierz w ogrodzie $h_p = 1$ m. Kierownik Aptekarz Wildt, od I. 1891 do VIII. 1897. Terminy obserwacyj $7^h a$, $2p$, $9n$.

W. SMOSARSKI

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Fig. 2 Samples of pages from Smosarski's book (1925)

It is also important to highlight that historical thermometers suffered from an instable position of the zero point which showed a gradual rise over some years after manufacturing (Middleton 1966). For example, Winkler (2009) showed for the station of Hohenpeißenberg that the correction of this secular rise of the zero position may influence the trend calculation of the temperature. However, around 1885, a new composition of a stable thermometer glass was found and only thermometers produced thereafter gave reliable results. This effect was known to the organizers of the meteorological network. According to the instruction for the observers of the Prussian meteorological service were requested to control the zero point every year and to communicate any change to the central bureau and to apply a corresponding corrections. The measurements in Poznań up to 1918 were conducted according to the Prussian regulations and by this time instrumental records probably share the same biases as other stations located on the Prussian territory which were used for the calibration purposes (e.g. Potsdam, Gdańsk, Toruń).

The monthly means of air temperature data from Poznań were homogenized according to the SNHT algorithm using the CLIMATOL version 3.0 package (Guijarro and Guijarro 2016; Guijarro 2017) for the R programming language (R Core Team Core Team 2018). Dates at which inhomogeneities were detected were also manually confronted against changes in the location and type of measuring instruments used (Section 2, Fig. 3). The calculation based on the CLIMATOL R package was meant to prove whether a potential loss of homogeneity was evident in the defined time ranges. In case of a positive answer, the corrections were applied as suggested by the algorithm on a monthly basis. In the period between September and December of 1939 and at the beginning of 1945, no observations were available due to military activities related to World War II. For these cases, reconstruction was also based on the CLIMATOL software calculation, which is basically a regression function weighted by the distances to the nearest stations (with a dataset). The mean temperature corrections applied within the use of homogenization algorithm for each period with a station relocation are presented in Table 1. Up to 1920, the average correction was on the level of 0.5–0.6 °C while after the station was moved to Poznań-Ławica airport, it was below 0.01 °C. It is also worth mentioning that the previously described historical dataset derived from Smosarski's publications (Smosarski 1923; Smosarski 1925) required a manual correction to a few obvious typographical errors (e.g., lack of negative sign).

Of the statistical methods used for climatological analysis, we use methods such as the Pearson correlation coefficients (for estimating the strength of the relation between datasets; Wilks 2011), linear regression (for establishing the long-term trends), and the Student's *t* test (for estimating statistical significance of calculated trends). Then, for estimating optimal breaks in the long-time series trend (1848–2016), i.e., years indicating a change in the direction or intensity of the trend in shorter periods, we used the "strucchange" R package (Zeileis et al. 2002) where the procedure proposed by Bai and Perron (1998) was applied. In this methodology, testing or assessing deviations from stability in the classical linear regression model is used on the base of RSS (residual sum of squares) and BIC (Bayesian information criterion). Details of this algorithm are described in Zeileis et al. (2003). In addition, the percentile classification that is operationally used by the Polish Institute of Meteorology and Water Management-National Research Institute in climate monitoring (Czernecki and Miętus 2011) is also applied in our dataset. This classification is based on the percentiles that are calculated for monthly (separately from each other) and annual mean values, taking into consideration thresholds of: 5, 10, 20, 30, 40, 60, 70, 80, 90 and 95 percentiles. The 11 classes established in this way (5 for warm, 5 for cold, and 1 for normal) are calculated for the reference period of 1961–1990, and then adopted to create a heat map.

Table 2 Pearson correlation coefficients of monthly air temperature between monthly air temperatures in Poznań and locations used as reference

	Potsdam	Warsaw	Prague	Wrocław	Cracow	Szczecin	Gdańsk	Śnieżka
J	0.982	0.960	0.927	0.984	0.929	0.989	0.952	0.773
F	0.978	0.965	0.931	0.979	0.938	0.966	0.947	0.791
M	0.966	0.961	0.922	0.972	0.919	0.982	0.940	0.857
A	0.924	0.931	0.899	0.965	0.811	0.959	0.890	0.916
M	0.919	0.921	0.889	0.964	0.878	0.960	0.927	0.920
J	0.914	0.867	0.805	0.912	0.832	0.943	0.874	0.910
J	0.909	0.902	0.824	0.895	0.818	0.964	0.865	0.924
A	0.908	0.909	0.842	0.921	0.790	0.934	0.865	0.905
S	0.922	0.921	0.884	0.944	0.831	0.946	0.881	0.902
O	0.932	0.931	0.891	0.965	0.853	0.958	0.899	0.799
N	0.952	0.956	0.900	0.970	0.915	0.964	0.921	0.725
D	0.974	0.946	0.900	0.970	0.922	0.982	0.913	0.720

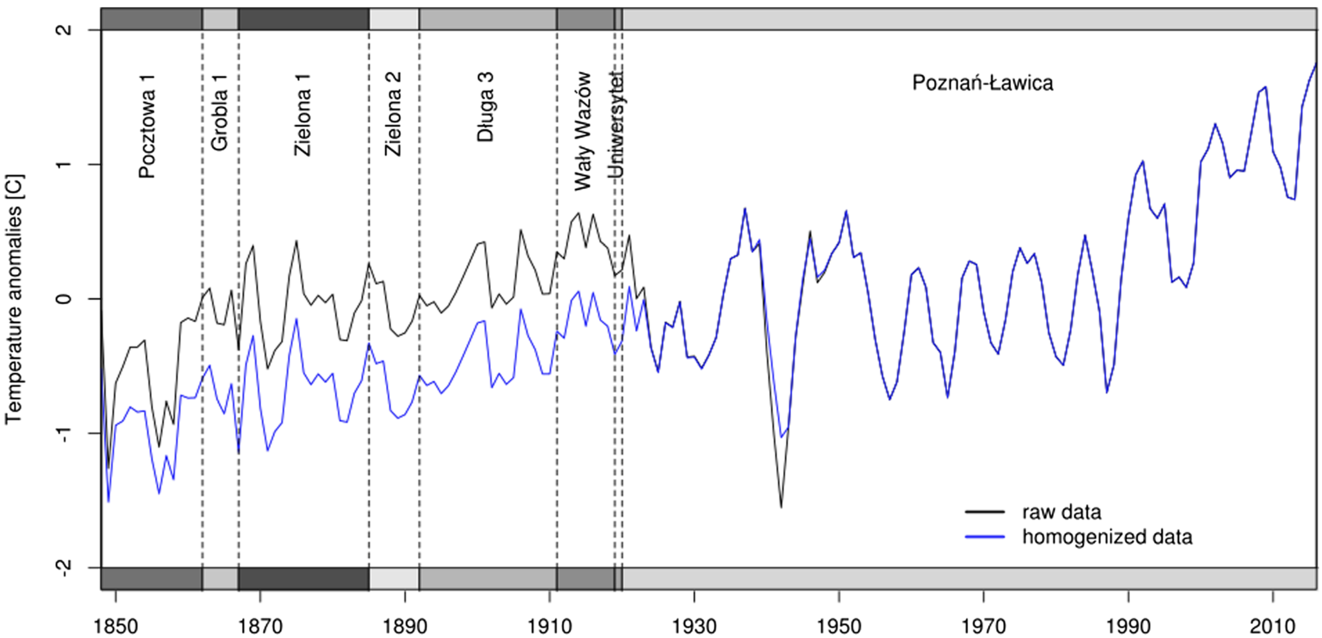

Fig. 3 The homogenized annual air temperature time series (blue line) and raw data anomalies in Poznań, 1848–2016. The dashed lines indicate the time range and locations of measurements according to Table 1

The raw and homogenized air temperature for Poznań from the period 1848–2016 with respect to measurement locations is presented in Fig. 3. The most problematic period concerns the years 1848 to 1920, and is characterized by frequent changes in the location of the measurement site (Section 2). It is also the period in which the biggest differences between the in situ measurements and values obtained after applying homogenization algorithms are observed. This can be explained by the location of the thermometer which was usually outside a window and close to a building's wall. Not without significance is also the fact that until 1892 the measurements were made in the absence of a thermometer shield. Since that time, the thermometer was first placed in a zinc box and later in the meteorological shelter (Table 1). The next issue was the height at which the thermometer was located. It varied from 2.5 to even 15 m AGL. After the aforementioned period, the reconstructed data mostly coincide with measurements performed in the current location of the IMGW-PIB station at Poznań-Ławica airport. The only exception is the World War II period (1939–1945). At that time, gaps in data are observed, particularly due to military operations from September to December 1939 and at the beginning of 1945.

The multi-year courses of the annual air temperature (5-year moving mean) for the finally homogenized Poznań series are compared with other locations in Fig. 4. Despite the clear difference between the values obtained after homogenization and the initial ones defined by Smosarski (1923, 1925), the high similarity between the temperatures in Poznań (both series) compared to other stations is noticeable. The analysis of trend variability in the shorter terms revealed that three sub-periods featuring different characteristics in temperature trends (1848–1902, 1902–1987, 1987–2016) can be defined (Fig. 5). This issue is going to be discussed in detail in the latter part of this paper.

4 Annual and monthly variability

On the basis of a newly constructed and homogenized series of monthly air temperature, an attempt is made to analyze its long-term climatological aspects for Poznań. Patterns in the annual cycle are typical for Central Europe within the transition zone of a marine to continental climate. Monthly temperature means are predominantly affected by the solar angle and atmospheric circulation (Slonosky et al. 2001; Sepp and Jaagus 2002; Degirmendžić et al. 2004; Ustrnul 2006; Wibig et al. 2009; Ustrnul et al. 2010). As a consequence, the area of Greater Poland is characterized by a high variability of monthly temperature means from year to year (Figs. 6 and 7). The biggest deviations occur mainly during winter months (December, January, February), while the lowest fall is found in late Summer (July, August, September). It is noticeable that the highest spread between 5 and 25 percentiles applies to winter months (Fig. 6).

A relatively high standard deviation (0.96 °C) shows that the average values of air temperature for particular years are also widely spread around the long-term mean (Figs. 5 and 7). A very hot year can occur right after a very cold one and vice versa. The same pattern can also be observed for the monthly variability. The annual average air temperature for the period 1848–2016 was 8.1 °C but extreme values for

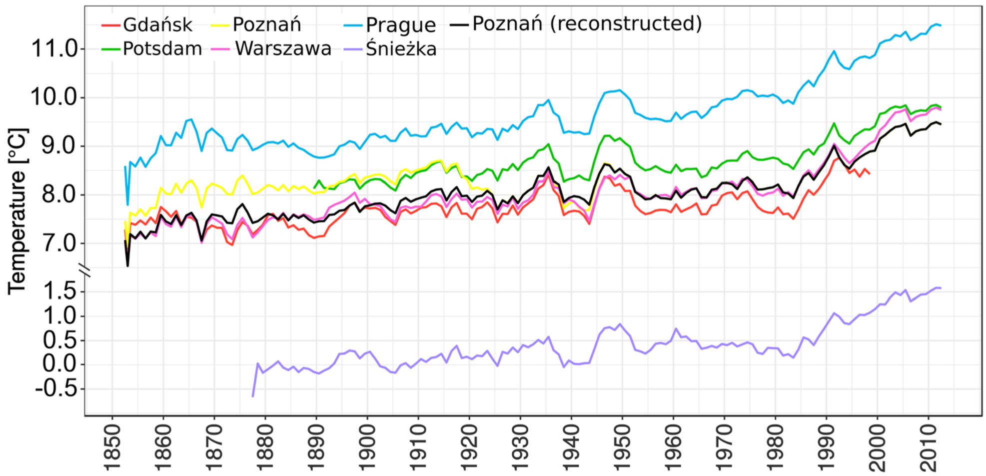

Fig. 4 A 5-year moving mean air temperature for Gdańsk, Potsdam, Prague, Śnieżka, Warsaw, and Poznań (before and after homogenization)

individual years ranged from 5.5 to 10.5 °C in 1871 and 2014, respectively (Figs. 5 and 7, Table 3). The top 10 coldest years are dominated by cases from the nineteenth century while the warmest are supplemented every year by new records. The same pattern is noticeable even when extreme monthly values are considered. The most recent coldest monthly temperature on record comes from 1979 and concerns a mean temperature in July of 15.22 °C. The rest of the records fall mainly on the breakthrough of the nineteenth and twentieth centuries (Table 4). Although the warmest monthly temperature records are dominated by recent years (January, March, July, August, December), some of them are dated back to even 1889 when exceptionally hot May and June occurred. The warmest October was in 1907, April in 1918, September in 1947, November in 1963, and February in 1990 (Table 4).

5 Long-term trends

Despite year-to-year oscillations in the monthly mean temperature, an increasing long-term trend can be observed. From 1848 to 2016, the air temperature grew at a rate of + 1.1 °C per 100 years (Fig. 5, Table 5) with a similar trend noted in the other European sites if similar periods of analysis are taken into account (Rebetez and Reinhard 2008; Dobrovolnỳ et al. 2009; Leijonhufvud et al. 2010; Mikkonen et al. 2015; Niedźwiedź et al. 2015; Pospieszyńska and Przybylak 2018). As to the seasons, the highest increase is observed in Winter (Fig. 8, Table 5) with + 1.5 °C per 100 years (peak in December + 1.7) and the lowest in Summer (+ 0.6) with a monthly minimum in June (+ 0.3). Spring and Autumn are characterized by an increasing trend of + 1.4 and + 0.9, respectively.

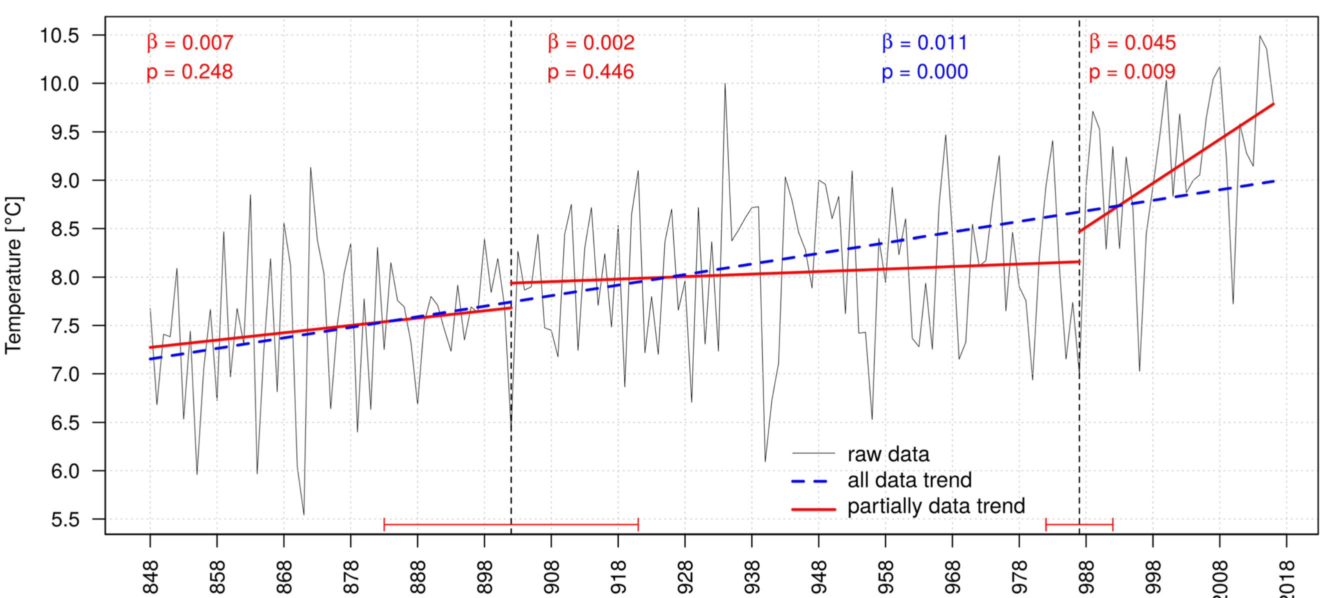

Fig. 5 Mean annual air temperature and linear trend according to three sub-periods (1848–1902, 1902–1987, 1987–2016), featuring different characteristics in temperature trends

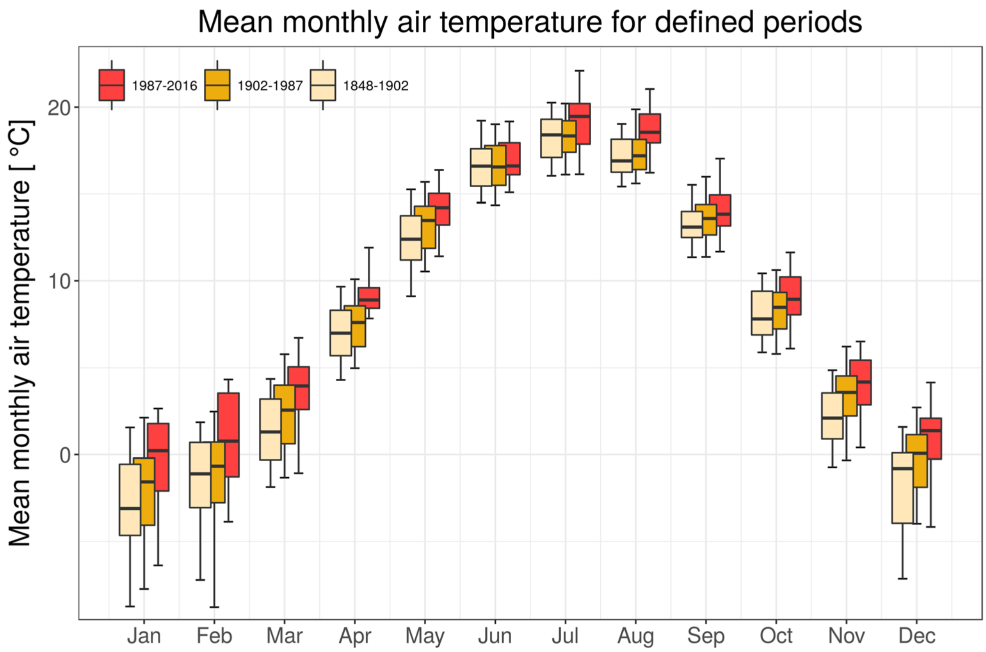

Fig. 6 Box-and-whisker plots representing the monthly means of air temperature for Poznań in the three sub-periods. The median is denoted as a horizontal line inside the box, the edges of the box represent the 25th and 75th percentiles, and whiskers represent the 10th and 90th percentiles

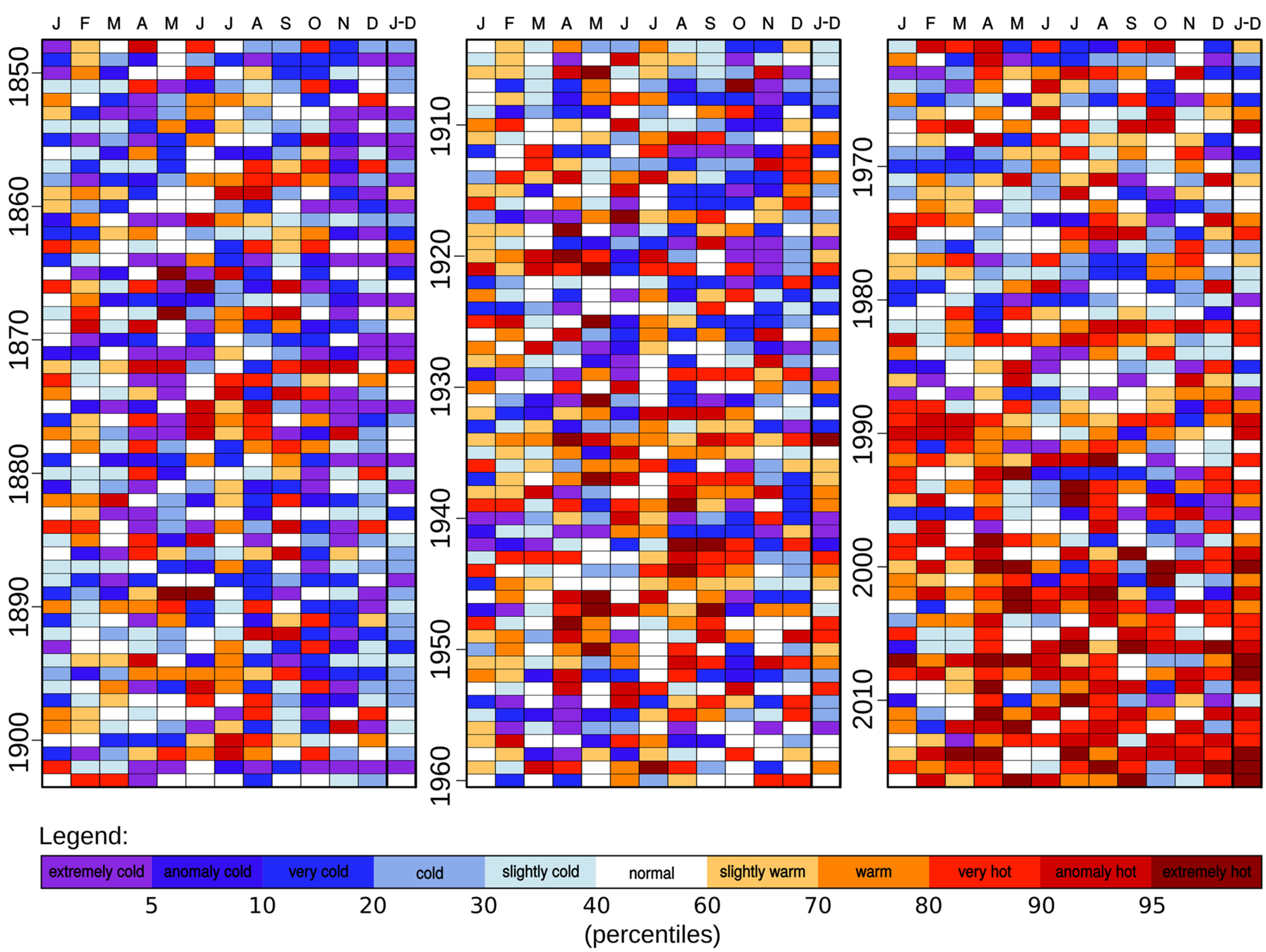

Fig. 7 The percentile classification of the monthly mean temperature. Thresholds of 5, 10, 20, 30, 40, 60, 70, 80, 90 and 95 percentile denote 11 classes (described in legend). Classes were calculated for the reference period of 1961–1990. For further details, see Czernecki and Miętus (2011)

Table 3 Ten coldest and warmest years in the analyzed period (1848–2016) according to the annual mean air temperature

	Ten coldest years [°C]		Ten warmest years [°C]	
1.	1871	5.54	2014	10.49
2.	1855	5.96	2015	10.36
3.	1864	5.97	2008	10.17
4.	1870	6.04	2007	10.04
5.	1940	6.09	2000	10.03
6.	1879	6.40	1934	10.00
7.	1902	6.40	2016	9.80
8.	1956	6.53	1989	9.71
9.	1853	6.53	2002	9.67
10.	1881	6.63	2006	9.66

The analysis of trend variability in the shorter terms revealed that three sub-periods featuring different characteristics in long-term temperature trends can be defined according to the algorithm suggested by Bai and Perron (1998) (Fig. 5). The first one consists of the years 1848 to 1902, and has a statistically insignificant trend at a rate of + 0.7 °C per 100 years (peak in Winter (+ 1.8) and minimum in Autumn (+ 0.1)). Interestingly, some months (June, August, October) indicate a decreasing albeit non-significant trend with − 0.3, − 0.2 and − 1.9 °C per 100 years, respectively. The next period covering the years 1901–1987 indicates a lack of any significant trends in temperature according to the obtained T test's p values (Fig. 5, Table 5). A yearly increase in air temperature has trend of + 0.2 °C per 100 years with maximum in Autumn (1.2) and minimum with decreasing trend in Winter (− 0.3). With extreme monthly values, February features a decreasing trend with − 1.7 °C per 100 years while November has an increasing trend of + 2.1 °C per 100 years.

The last period involving recent years (1987–2016) shows a strong and statistically significant trend at a rate of + 4.6 °C per 100 years (Fig. 5, Table 5). A strong increase is evident especially during Summer (+ 7.5 °C) and Autumn (+ 6.1 °C) with lower values for Spring (+ 4.6 °C) and Winter (+ 0.5 °C). November and July seem to experience the highest increase at a rate of + 9.7 and + 8.3 °C, respectively. All mentioned values regarding recent decades are statistically significant at a level of 1-α = 0.05. Negative trends are observed only for January (− 2.1 °C) and February (− 3.0 °C), where both slopes of the coefficients are non-significant. Trend analysis indicates that although the highest increases in temperature occurred in Winter (when considering the entire observational period), a sharp increase in the last 30 years has been caused mainly by Summer and Autumn (Fig. 8, Table 5). However, it is worth noting that compared to summertime period, Winter months are characterized by the biggest variability in air temperature (Figs. 6, 7 and 8), and thus any results regarding trends should be summarized with caution, which is confirmed by a lack of statistical significance according to T-test values (Table 5).

Similar but slightly different conclusions can be drawn when analysis of a box-plot chart is included (Fig. 6). Percentile distributions for most months indicate a progressive growth in temperature for the subsequent periods being studied. The median temperature in recent years is above the 75th percentile for almost every month except June, September, October and November. The largest deviation is observed in April and August when the 25th percentile from recent years is at the level of the 75th percentile from previous periods. A very sharp increase is also evident in the 5th percentile during winter months, and in the 95th percentile in February and July. The smallest differences among the analyzed periods occur in June which have not changed much during the considered period. Very similar results are obtained when LOESS

Table 4 Coldest and warmest months in the analyzed period (1848–2016)

	Coldest		Warmest	
	Year	Mean temperature [°C]	Year	Mean temperature [°C]
January	1848	− 11.3	2007	4.5
February	1929	− 13.4	1990	5.3
March	1853	− 3.5	2014	7.0
April	1929	3.2	1918	12.4
May	1864	7.9	1889	17.6
June	1923	12.5	1889	20.5
July	1979	15.2	2006	24.0
August	1864	14.5	2015	22.7
September	1912	9.1	1947	17.2
October	1922	4.7	1907	12.7
November	1858	− 3.0	1963	7.1
December	1870	− 7.8	2015	5.7

Table 5 Slope of linear regression for selected periods on a monthly and seasonal basis

Period	1848–2016	1848–1902	1903–1986	1987–2016
January	0.014*	0.026	− 0.004	− 0.021
February	0.011*	0.003	− 0.017	− 0.030
March	0.015*	0.021	0.000	0.034
April	0.014*	0.010	− 0.001	0.060*
May	0.012*	0.012	− 0.002	0.045
June	0.003	− 0.003	0.004	0.070*
July	0.007*	0.010	− 0.006	0.083*
August	0.010*	− 0.002	0.010	0.072*
September	0.006*	0.003	0.002	0.075*
October	0.006*	− 0.019	0.012	0.013
November	0.016*	0.020	0.021*	0.097*
December	0.017*	0.010	0.009	0.049
Spring (MAM)	0.014*	0.014	− 0.001	0.046
Summer (JJA)	0.006*	0.002	0.002	0.075*
Autumn (SON)	0.009*	0.001	0.012*	0.061*
Winter (DJF)	0.015*	0.018	− 0.003	0.005
Year	0.011*	0.007	0.002	0.046*

*Statistically significant trend estimate for p value < 0.05

regression (locally weighted scatterplot smoothing) is applied on a seasonal basis (Fig. 8). Although a continuously increasing trend has been observed for Spring since the 1960s, for Summer since the 1980s, and for Autumn since the 1990s, Winter is characterized by a stronger variance over the last 30 years.

A detailed multi-annual trend analysis is also presented in Fig. 9 which makes it possible to distinguish trends for any possible configuration of a given timeframe (i.e., of at least 30 years). Trends determined in this way confirm that the most prominent increase in air temperature has become evident in recent decades, especially after the 1960s (from + 2 °C up to more than + 4 °C per 100 years). From the 1930s to the 1980s, a decrease in trend can be observed. This period coincides with the commonly known air temperature drop in Europe, which took place between the 1950s and the 1980s (Stocker et al. 2013).

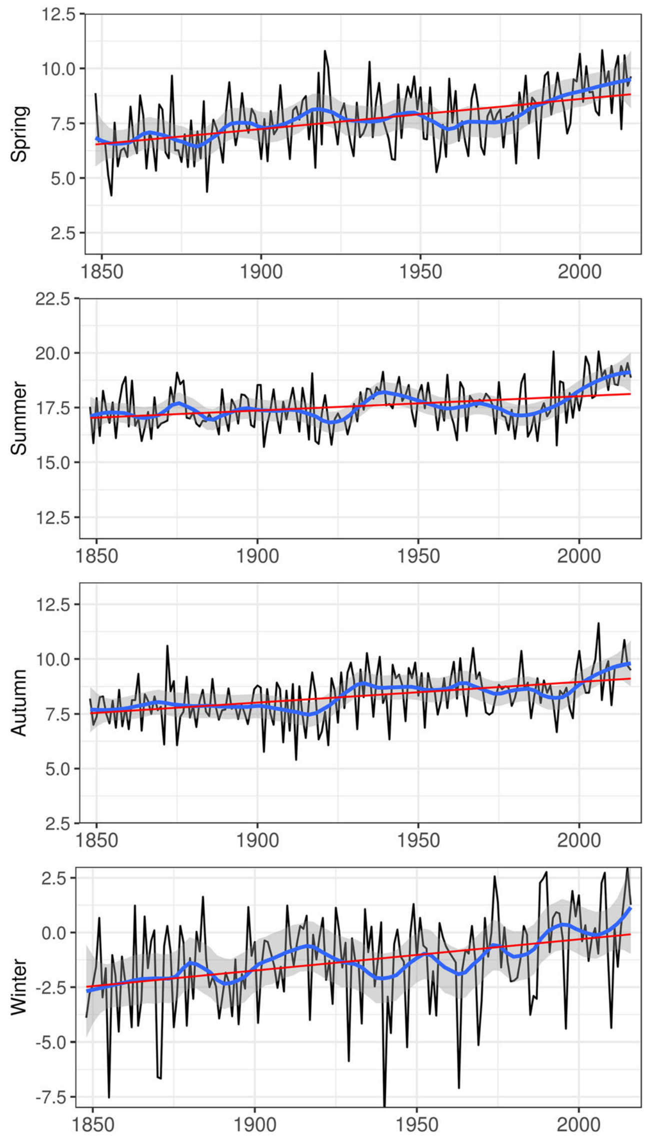

Fig. 8 Mean annual air temperature and linear trend according to seasons (Spring—MAM, Summer—JJA, Autumn—SON, Winter—DJF). Red line denotes linear regression trend. Blue line denotes LOESS (locally weighted smoothing by local regression) with a span value set at 0.2

6 Summary and concluding remarks

Poznań is located in Central Europe, and is characterized by a moderate transition zone between oceanic and continental climate. The topography of this part of Europe promotes the zonal flow of air masses from both western and eastern directions, which is one of the main causes of climate transitionality. In such conditions, atmospheric circulation and especially its anomalies significantly modulate air temperature and thus the monthly and annual means.

This research focuses on air temperature measurements that were conducted in Poznań between 1846 and 2016. Both rich meteorological data and available weather descriptions were collected and evaluated on the basis of other available datasets. The first systematic measurements started in Poznań in January 1848. By 1919, the location of thermometers, and later the location of the meteorological stations, had changed five times. In 1921, measurements began at the Poznań-Ławica airport which have been maintained on that location to this day. The monthly means of air temperature from 1848 to 1919 clearly indicate a break in their homogeneity. For this reason, the main objective of this study was to reconstruct the 169-year-long records so as to make them coherent with the surrounding climatological dataset.

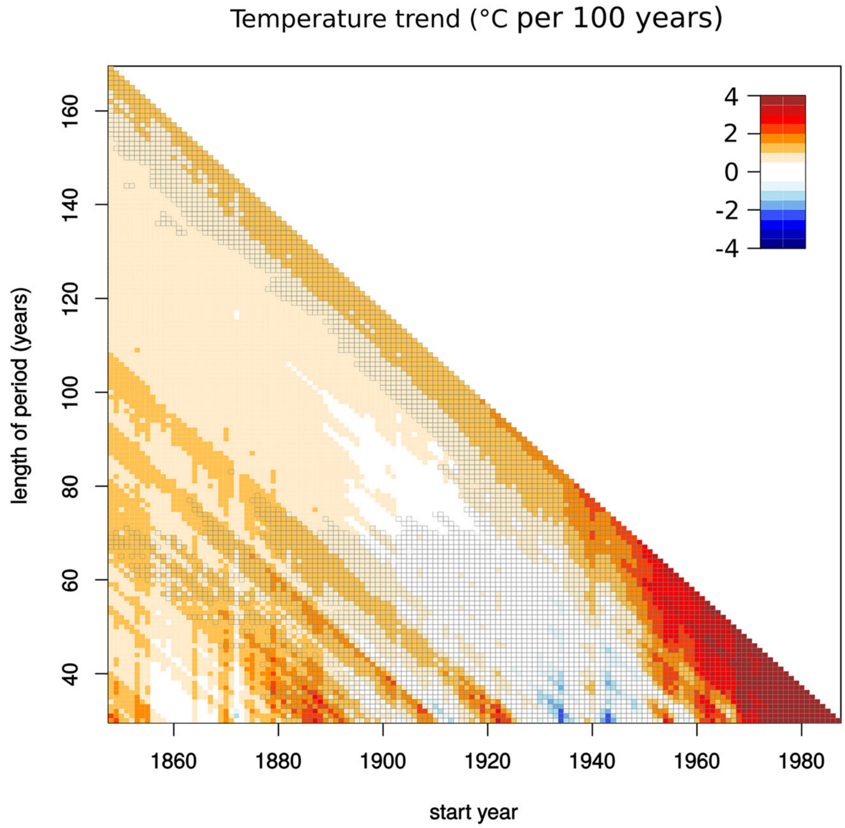

Fig. 9 Air temperature trends computed for different starting years and lengths of the data series (1848–2016). Black squares indicate a statistically significant trend at the level of 1-α = 0.05

Data gaps were supplemented by the constant difference method based on the homogenized data series from the nearest stations (Gdańsk, Potsdam, Prague, Śnieżka, Warsaw). The average monthly means in air temperature were homogenized according to the Standard Normal Homogeneity Test. The evaluation of the annual, seasonal, and monthly temperature variability and trends was additionally calculated. The obtained results provide an interesting insight into the inter-annual changes in the mean monthly temperature in Poznań in response to a globally warming climate. They were corroborated by similar analyses performed for other Polish and central European sites. The most important findings are presented as follows:

- The area of Greater Poland is characterized by a high variability in the mean monthly temperature from year to year. The biggest deviations occur mainly during Winter, with the lowest in late Summer.
- The mean air temperature values for particular years were widely spread around the long-term mean. A very hot year can occur right after a very cold one and vice versa. The same pattern can be observed for the monthly variability.
- The annual average air temperature for the period 1848–2016 is estimated at 8.1 °C but extreme values for individual years range from 5.5 to 10.5 °C in 1871 and 2014, respectively. The10 most coldest years are dominated by cases from the nineteenth century, while the warmest are supplemented each year by new records. The same pattern is also found for monthly values.
- An increasing long-term trend can be observed. From 1848 to 2016, the air temperature grew at a rate of 1.1 °C per 100 years. As to seasons, the highest increase was observed in Winter (1.5) and the lowest in Summer (0.6). In the last 30 years, the pace of the trend has increased to a rate of 4.6 °C per 100 years. A strong increase is especially evident during Summer (7.5 °C) and Autumn (6.1 °C), with lower values for Spring (4.6 °C) and Winter (0.5 °C).
- From the 1930s to the 1980s, a temporary decrease in the trend can be observed. This period coincides with the commonly known air temperature drop in Europe which took place between 1950s and 1980s.

The results of our analysis are in agreement with those obtained for other stations located in Central Europe. A long-term increasing trend of approximately 1 °C per 100 years was also obtained by Rebetez and Reinhard (2008), Dobrovolnỳ et al. (2009), Leijonhufvud et al. (2010), Mikkonen et al. (2015), Niedźwiedź et al. (2015), Pospieszyńska and Przybylak (2018). Breaks in the long-term trend for Poznań are comparable with Warsaw (Lorenc 2000), Cracow (Trepińska and Kowanetz 1997), Wrocław

(Bryś and Bryś 2010), and Toruń (Pospieszyńska and Przybylak 2018). A rapid increase in air temperature over the last three decades for Polish stations is part of a similar trend observed on a global scale and described in the IPCC report (Stocker et al. 2013). Considering the entire analyzed period (1848–2016), the highest increases in temperature are most evident during winter and smallest during summer, which is also the case for Potsdam, Prague, Warsaw, Cracow, Toruń, Wrocław, and Łódź. A very similar pattern in the course of the annual and monthly temperature in Poznań is also found in Łódź (Wibig et al. 2004) and Toruń (Pospieszyńska and Przybylak 2018). Similar to Poznań, those stations are characterized by a strong temperature variability on a yearly and monthly basis.

The analysis of the mean monthly temperature for Poznań and for the years 1848–2016 mostly confirms the results of other authors involved in the analysis of a long-term temperature series in Central Europe. It also provides an interesting overview of the changing local climate in the Greater Poland Lowland.

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