

Anna Rutgersson, Jaak Jaagus, Frederik Schenk, Martin Stendel, Lars Barring, Agrita Briede, Björn Claremar, Inger Hanssen-Bauer, Jari Holopainen, Anders Moberg, Øyvind Nordli, Egidijus Rimkus, and Joanna Wibig

---

### Abstract

This chapter describes observed changes in atmospheric conditions in the Baltic Sea drainage basin over the past 200–300 years. The Baltic Sea area is relatively unique with a dense observational network covering an extended time period. Data analysis covers an early period with sparse and relatively uncertain measurements, a period with well-developed synoptic stations, and a final period with 30+ years of satellite data and sounding systems. The atmospheric circulation in the European/Atlantic sector has an important role in the regional climate of the Baltic Sea basin, especially the North Atlantic Oscillation. Warming has been observed, particularly in spring, and has been stronger in the northern regions. There has been a northward shift in storm tracks, as well as increased cyclonic activity in recent decades and an increased persistence of weather types. There are no long-term trends in annual wind statistics since the nineteenth century, but much variation at the (multi-)decadal timescale. There are also no long-term trends in precipitation, but an indication of longer precipitation periods and possibly an increased risk of extreme precipitation events.

---

A. Rutgersson (✉) · B. Claremar  
Department of Earth Sciences, Uppsala University,  
Uppsala, Sweden  
e-mail: anna.rutgersson@met.uu.se

J. Jaagus  
Institute of Ecology and Earth Sciences, University of Tartu,  
Tartu, Estonia

F. Schenk  
Department of Mechanics, KTH Royal Institute of Technology,  
Stockholm, Sweden

M. Stendel  
Danish Climate Centre, Danish Meteorological Institute,  
Copenhagen, Denmark

L. Barring  
Rossby Center, Swedish Meteorological and Hydrological  
Institute, Norrköping, Sweden

A. Briede  
Faculty of Geography and Earth Sciences, University of Latvia,  
Riga, Latvia

---

I. Hanssen-Bauer  
Norwegian Centre for Climate Services,  
Norwegian Meteorological Institute, Oslo, Norway

J. Holopainen  
Department of Geosciences and Geography,  
University of Helsinki, Helsinki, Finland

A. Moberg  
Department of Physical Geography and Quaternary Geology,  
Stockholm University, Stockholm, Sweden

Ø. Nordli  
Research and Development Department, Norwegian  
Meteorological Institute, Oslo, Norway

E. Rimkus  
Department of Hydrology and Climatology,  
Vilnius University, Vilnius, Lithuania

J. Wibig  
Department of Meteorology and Climatology,  
University of Lodz, Lodz, Poland

## 4.1 Introduction

This chapter reports on trends and variability in atmospheric parameters over the past 200–300 years. The focus is on large-scale atmospheric circulation and its changes, as well as on observed changes in surface variables such as wind, temperature and precipitation. Situated in the extra-tropics of the Northern Hemisphere, the Baltic Sea basin is under the influence of air masses from the Arctic to the subtropics. It is therefore a region of very variable weather conditions. From a climatological point of view, the region is controlled by two large-scale pressure systems over the north-eastern Atlantic Ocean—the Icelandic Low and the Azores High—and a thermally driven pressure system over Eurasia (high pressure in winter, low pressure in summer). In general, westerly winds predominate, although any other wind direction is also frequently observed. As the climate of the Baltic Sea basin is to a large extent controlled by the prevailing air masses, atmospheric conditions will therefore be controlled by global climate as well as by regional circulation patterns. The atmospheric parameters are strongly interlinked (i.e. the circulation influences the wind, temperature, humidity, cloudiness and precipitation patterns, and the radiation and cloudiness influence surface temperature).

## 4.2 Large-Scale Circulation Patterns

The atmospheric circulation in the European/Atlantic sector plays an important role in the regional climate of the Baltic Sea basin (Hurrell 1995; Slonosky et al. 2000, 2001; Moberg and Jones 2005; Achberger et al. 2007). The Baltic Sea region is influenced in particular by the North Atlantic Oscillation (NAO; Hurrell 1995). The NAO influences northern and central Europe and the north-east Atlantic and therefore also the climate in the Baltic Sea basin. The impact of the NAO is most pronounced during the winter season, November to March (Hurrell et al. 2003). While the NAO is defined in relation to conditions within the European/Atlantic sector, it is in fact part of a hemispheric circulation pattern, the Arctic Oscillation (AO; e.g. Thompson and Wallace 1998). See Box 4.1.

### Box 4.1 North Atlantic Oscillation

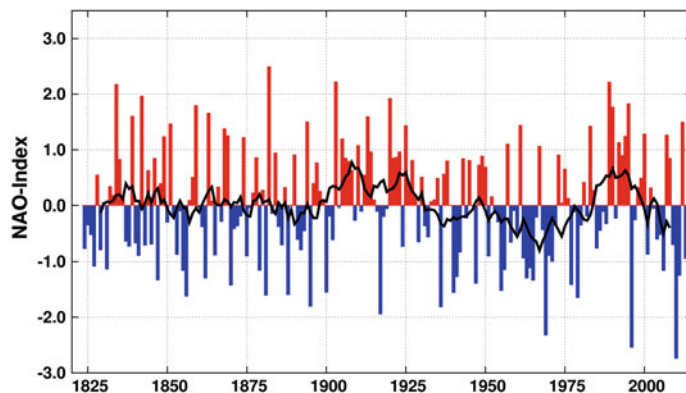
The NAO is the dominant mode of near-surface pressure variability over the North Atlantic and neighbouring land masses, accounting for roughly

one-third of the sea level pressure (SLP) variance in winter. In its positive (negative) phase, the Icelandic Low and the Azores High are enhanced (diminished), resulting in a stronger (weaker) than normal westerly flow (Hurrell 1995). For strongly negative NAO indices, the flow can even reverse when there is higher pressure over Iceland than over the Azores.

There is no unique way to define the spatial structure of the NAO. One approach uses one-point correlation maps (Hurrell et al. 2003). These can be used to identify the NAO as regions of maximal negative correlation over the North Atlantic (e.g. Wallace and Gutzler 1981). Points identified by this procedure are situated near or over Iceland and over the Azores extending to Portugal, respectively. Other approaches use principal component analysis, in which the NAO is identified by the eigenvectors of the cross-correlation matrix which is computed from the temporal variation of the grid point values of SLP, scaled by the amount of variance they explain (e.g. Barnston and Livezey 1987) or clustering techniques (e.g. Cassou and Terray 2001a, b). A third option uses latitudinal belts. An index defined this way yields higher correlations with air temperature and precipitation in the eastern Baltic Sea region (e.g. Li and Wang 2003).

The NAO is the first mode of a principal component analysis of winter SLP. The second mode is called the east Atlantic pattern (Wallace and Gutzler 1981) and represents changes in the north–south location of the NAO (Woolings et al. 2008). It is characterised by an anomaly in the north-eastern North Atlantic Ocean, between the NAO centres of action. Negative values mean a southward displacement of the NAO centres of action and lower temperatures (Moore and Renfrew 2012), positive values correspond to more zonal winds over Europe and expected higher temperatures. The third dominant mode is the Scandinavian pattern, also called the Eurasian (Wallace and Gutzler 1981) or blocking pattern (Hurrell and Deser 2009), which in its positive phase is characterised by a high-pressure anomaly over Scandinavia and a low-pressure anomaly over Greenland. This indicates an east–west shift of the northern centre of variability defining the NAO.

As shown in Fig. 4.1, the strongly positive NAO phase in the 1990s can be seen as a component of multi-decadal variability comparable to conditions at



**Fig. 4.1** NAO index for boreal winter (DJFM) 1823/1824–2012/2013 calculated as the difference between the normalised station pressures of Gibraltar and Iceland (Jones et al. 1997). Updated via [www.cru.uea.ac.uk/~timo/datapages/naoi.htm](http://www.cru.uea.ac.uk/~timo/datapages/naoi.htm) and renormalised for the period 1824–2013

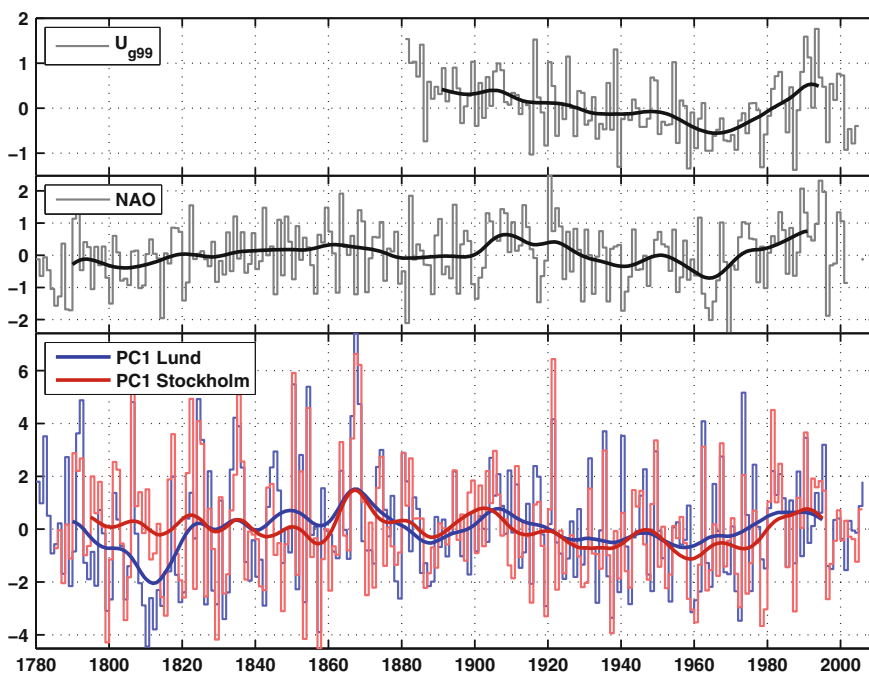
the beginning of the twentieth century rather than as part of a trend towards more positive values.

The long-term annual variations in the NAO are in good agreement with 99th percentile wind speeds (Wang et al. 2011) over western Europe and the first principal component (PC1) calculated over eight different pressure-based storm indices over Scandinavia (Bärring and Fortuniak 2009), showing large multi-(decadal) variations in atmospheric circulation and related wind climates (Fig. 4.2 and further discussed in Sect. 4.3.2).

#### 4.2.1 Circulation Changes in Recent Decades

From a long-term perspective, the behaviour of the NAO is irregular. However, for the past five decades, specific periods are apparent. Beginning in the mid-1960s, a positive trend has been observed, that is towards more zonal circulation with mild and wet winters and increased storminess in central and northern Europe, including the Baltic Sea area (e.g. Hurrell et al. 2003). After the mid-1990s, however, there was a trend towards more negative NAO indices, in other words a more meridional circulation. These circulation changes are apparently independent of the exact definition of

**Fig. 4.2** Time evolution of the 99th percentiles of the geostrophic wind index (Alexandersson et al. 1998, 2000, *top*), a reconstructed NAO index (Luterbacher et al. 2002, *centre*) and the first principal components of the Lund and Stockholm storminess indices (PC1) over the Baltic Sea region. *Thick curves* are filtered with a Gaussian filter ( $\sigma = 4$ ) to focus on inter-decadal variations (Bärring and Fortuniak 2009)



the NAO (see also Jones et al. 1997; Slonosky et al. 2000, 2001; Moberg et al. 2005).

Kyselý and Huth (2006, see Fig. 4.3) discussed the intensification of zonal circulation, especially that during the 1970s and 1980s. The stronger zonal circulation does not appear isolated, but coincides with changes in other atmospheric modes. In recent winters, the authors noted an intensification of cyclonic activity over Fennoscandia along with more frequent blocking situations over the British Isles. At the same time, less cyclonic activity is observed over the Mediterranean. While there is a general increase in the zonality of the flow in winter, the opposite appears to occur in summer (Kaszewski and Filipiuk 2003; Wang et al. 2009a).

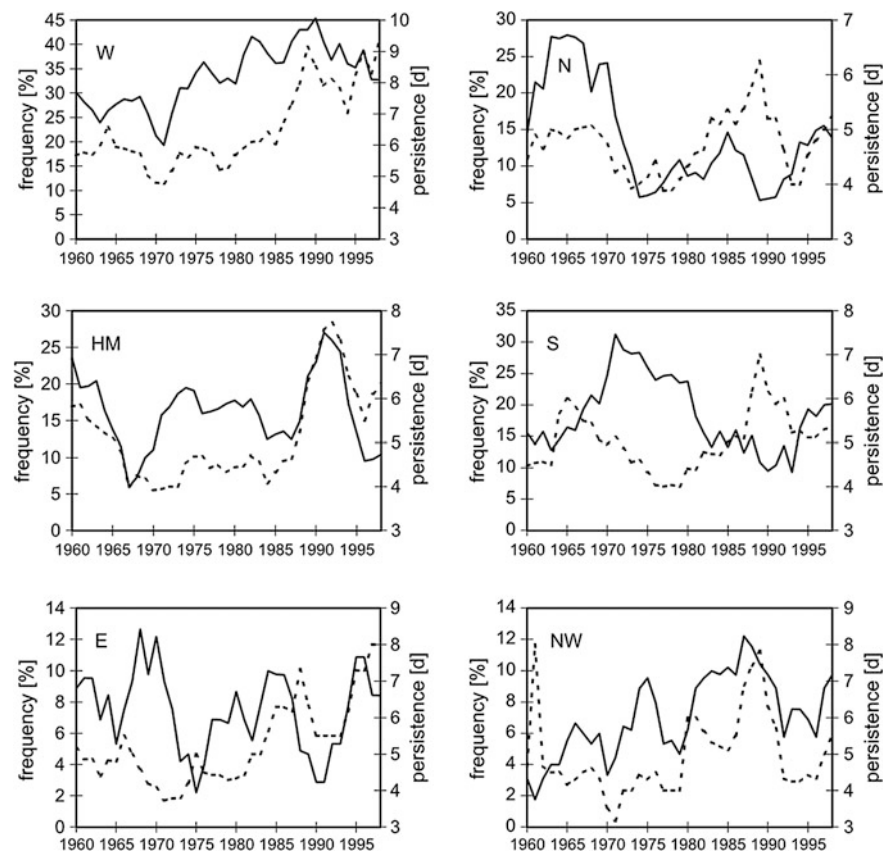
There are also indications (Kyselý 2000; Werner et al. 2000; Kyselý 2002; Kyselý and Huth 2006) that weather types (as defined, for example, by Hess and Brezowsky 1952) are more persistent than in earlier decades. For all weather types (zonal, meridional or anticyclonic), an increase in persistence of the order of 2–4 days is found from the 1970s to the 1990s. This increase in persistence may be reflected in the increase in the occurrence of extreme events.

Getzlaff et al. (2011) and Lehmann et al. (2011, Fig. 4.4) showed intensified cyclonic circulation and stronger westerlies for the 1990s and 2000s compared to the 1970s and 1980s.

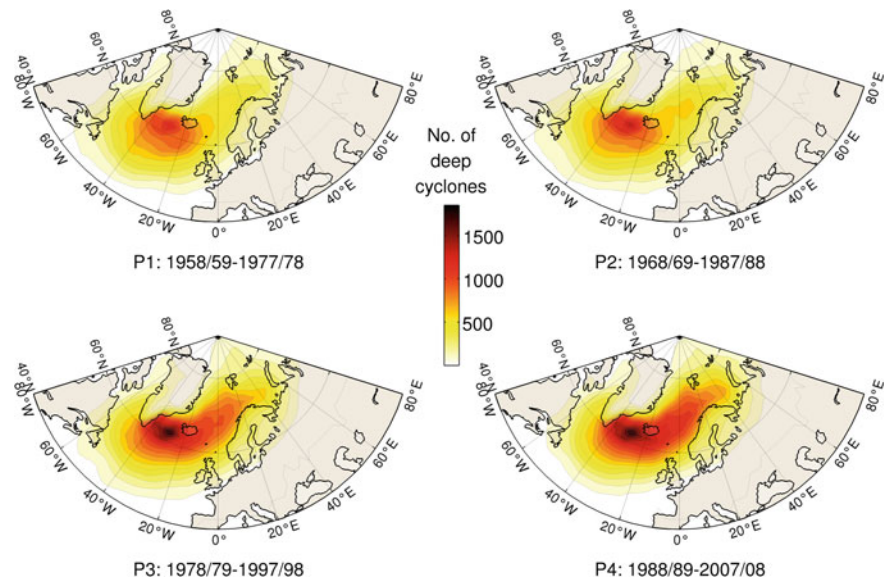
Interpretation of circulation changes must be done with care, and reanalysis products are often used (such as the reanalysis from the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) NCEP/NCAR, or the reanalysis of the European Centre of Medium Range weather forecasts; ERA). Despite inhomogeneities in the NCEP/NCAR reanalysis data, both before and after the introduction of satellites as a source of environmental monitoring data in late 1978 (the same holds for ERA products), the results in Fig. 4.4 probably mirror real changes. Lack of data over ocean areas before the introduction of satellites might not introduce major problems since several Ocean Weather Ships (OWS) were on duty after the Second World War in the north-east Atlantic. It appears probable that deep cyclones were identified in particular by OWS ‘C’ (south of Greenland) or OWS ‘M’ (east of Greenland). For the Barents Sea region, inhomogeneities in the data cannot be completely ruled out. However, periods P3 and P4 (see Fig. 4.4 for definition), both occurring after the transition to satellites, should be directly comparable.

Jaagus (2006) investigated the large-scale circulation over Estonia during the second half of the twentieth century and found a general increase in westerlies, particularly in February and March with a decrease in May. Such an increase

**Fig. 4.3** Temporal changes in the relative frequencies of occurrence (in %; solid curve) and mean lifetime (in days; dashed curve) of groups of large-scale circulation patterns (‘Großwetterlagen’; GWL) in winter in the period 1958–2000. Five-year running means are shown. The capital letters indicate the circulation pattern: *W* (westerly), *N* (northerly), *S* (southerly), *E* (easterly), *NW* (north-westerly) and *HM* (anticyclonic; ‘Hoch Mitteleuropa’). GWL are defined in detail by Hess and Brezowski (1952) and Kyselý and Huth (2006)



**Fig. 4.4** Total number of deep (core pressure < 980 hPa) cyclones counted for four 20-year periods P1–P4, based on NCEP/NCAR reanalysis four times daily SLP data for winter (DJFM). Unit is number of deep cyclones, with an increment of 100 (Lehmann et al. 2011). See discussion of inhomogeneities in Sect. 4.2



may have caused additional coastal erosion along the eastern margin of the Baltic Sea (see Chap. 20), as well as changes in other parameters in the region (Klavinš et al. 2007, 2009; Valdmann et al. 2008; Draveniece 2009; Rivza and Brunina 2009; Avotniece et al. 2010; Klavinš and Rodinov 2010; Lizuma et al. 2010).

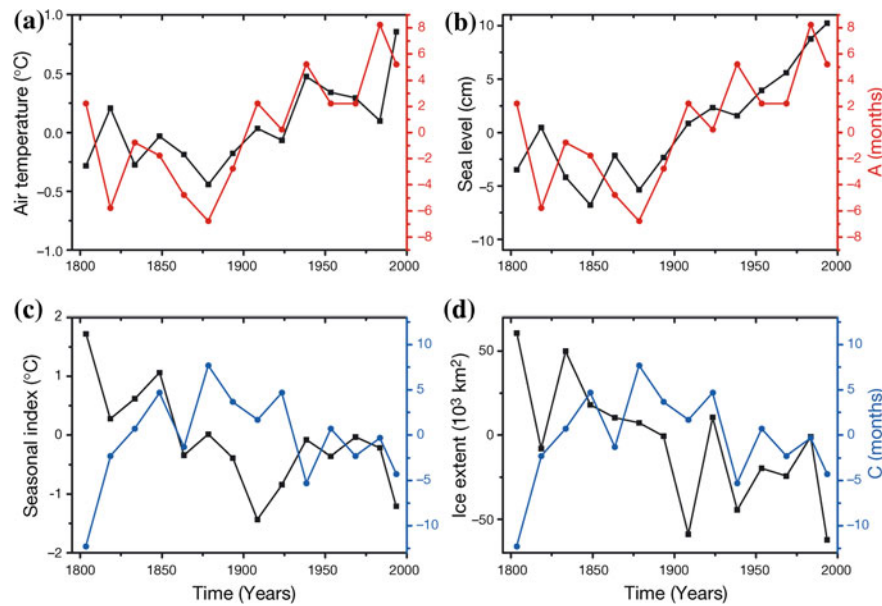
#### 4.2.2 Long-Term Circulation Changes

There are a large number of studies discussing the influence of long-term change in atmospheric circulation on surface characteristics of the Baltic Sea region. Early publications, for example, by Tinz (1996), Chen and Hellström (1999), Koslowski and Glaser (1999), Jevrejeva (2001), Omstedt and Chen (2001) and Andersson (2002) agreed that there has been a north-eastward shift in low-pressure tracks, which is consistent with a more zonal circulation over the Baltic Sea basin and the observed trend of a more positive NAO index, at least up to the 1990s (Trenberth et al. 2007). A northward shift in low-pressure tracks is also consistent with model projections of anthropogenic climate change, as pointed out by Leckebusch and Ulbrich (2004), Bengtsson et al. (2006), Leckebusch et al. (2006), Pinto et al. (2007) and, more recently, Lehmann et al. (2011).

Jacobeit et al. (2001, 2003) and Hurrell and Folland (2002) discussed the strong temporal variability in the relationship between the general circulation of the atmosphere and surface climate characteristics over the past 300 years. Their studies suggested that the increased frequency of both anticyclonic circulation and westerly wind types result in a warmer climate with reduced sea-ice cover and a reduced seasonal amplitude in temperature. Their studies concluded that long-term (multi-decadal) climate change in the Baltic

Sea region is at least partly related to changes in atmospheric circulation.

Omstedt et al. (2004) made a thorough investigation of the past 200 years of climate variability and changes based on the long Stockholm time series of temperature and sea level as well as ice cover and circulation types based on pressure data (Fig. 4.5; see also Chap. 9 for further discussion). Over the entire period, the authors found positive trends in temperature and sea level, increased frequencies in both westerlies and anticyclonic circulation and negative trends for the amplitude of the seasonal temperature cycle and sea-ice cover. Increased westerlies indicate a stronger than normal zonal flow with a positive NAO index, whereas anticyclonic circulation indicates a north-eastward movement of the low-pressure tracks. This is consistent with the observed upward trend in the NAO index (Hurrell and Folland 2002) and circulation changes as reported by Jacobeit et al. (2003). Eriksson et al. (2007) and Eriksson (2009) extended the analysis of Omstedt et al. (2004) by examining the covariability of long time series from the Baltic Sea region over different timescales during boreal winter. Over a period of 500 years, 15 periods with a clearly distinct climatic signature with respect to circulation patterns, inter-annual variability and the severity of winters were identified (see Chap. 3, Fig. 3.10). The onsets of these periods appear to have been mainly driven by internal perturbations, although volcanic activity and solar variability may also have played a role at certain times. The analysis indicates a clear increase in mean and maximum temperatures beginning at the end of the nineteenth century. The seasonal index (i.e. the magnitude of the annual temperature amplitude) shows a negative trend. Further inspection reveals that the frequency of both westerlies and anticyclonic circulation is considerably higher in the twentieth century than in the nineteenth century.



**Fig. 4.5** Anomalies in the Stockholm climate record together with the circulation types that describe the vorticity of the atmospheric circulation. *Red* indicates anticyclonic circulation and *blue* cyclonic circulation. **a** Air temperature and anticyclonic circulation, **b** sea level and anticyclonic circulation, **c** seasonal index, defined as the difference

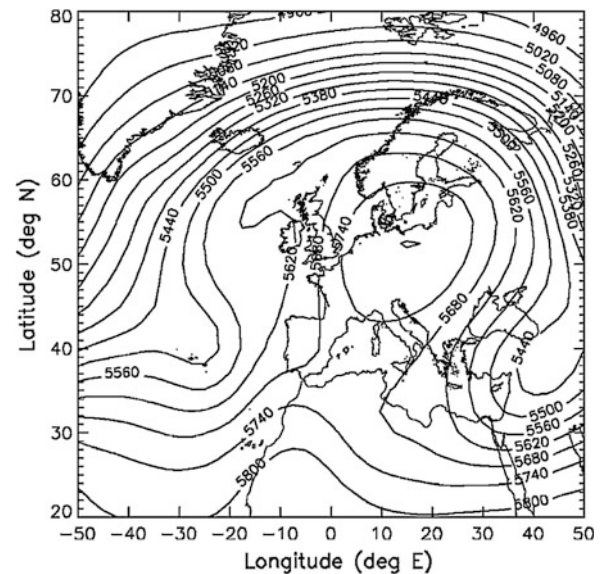
between summer (JJA) and winter (DJF) seasonal temperatures, and cyclonic circulation, and **d** ice cover and cyclonic circulation. 15-year averages for 1800–1815, 1811–1825, 1826–1840..., 1961–1975, 1976–1990, 1986–2000 (Omstedt et al. 2004)

Sepp (2009) examined the increase in cyclonic activity and the frequency of westerlies over the Baltic Sea basin during the twentieth century and the tendency for increased cyclogenesis. In recent years, an increase in the percentage of deep cyclones has been observed, while the total number has not changed. There is also a dependence on the NAO: during its positive phase, less, but stronger cyclones form over the Baltic Sea region.

### 4.2.3 NAO and Blocking

Blocking of the atmospheric flow is frequently observed in the Baltic Sea region. Since blocking situations, once they have developed, are often quasi-stationary and can persist for extended periods, they are often responsible for extreme weather events and have quite early raised the interest of scientists (for example Namias 1947; Rex 1950b; Green 1977). Figure 4.6 gives an example of a blocking pattern over central Europe.

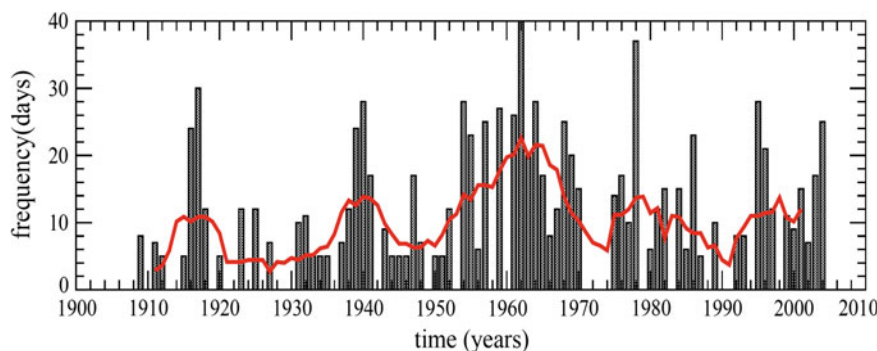
Rex (1950a) subjectively defined a blocking event as a quasi-persistent (more than 10 days) split of the mid-tropospheric flow over more than  $45^\circ$  in longitude. Numerous authors have suggested modifications to this definition, including objective measures based on meridional height gradients. These approaches were reviewed by Barriopedro et al. (2006). Vial and Osborn (2012) discussed the poor performance of models with respect to simulating number,



**Fig. 4.6** The 500 hPa height field on 6 March 1948, showing a typical blocking situation (Barriopedro et al. 2006)

frequency and spatial extent of blocking situations, a problem that had persisted for many years (d'Andrea et al. 1998).

Rimbu and Lohmann (2011) used south-western Greenland temperature measurements and stable isotope records from ice cores as a proxy for North Atlantic atmospheric blocking and found that in winter, warm (cold) conditions over south-western Greenland were related to high (low)



**Fig. 4.7** Blocking index (bars) and its decadal variation (seven-year running mean; *red*) for boreal winter (DJF) 1908–2005. The blocking index takes into account spatial aspects and persistence, and it is defined as the number of blocked days per winter in the sector 80°–

10°W. The blocking condition must be satisfied for an interval of at least 12.5° for at least five consecutive days (persistence criteria), Rimbu and Lohmann (2011)

blocking activity and a negative (positive) phase of the NAO. For summer, however, the authors found the opposite, that warm (cold) conditions over south-western Greenland were related to low (high) blocking activity and a positive (negative) phase of the NAO, even though a significant part of the North Atlantic blocking variability was not directly related to NAO variability, but rather to the exact position of the centre of blocking, which, in turn, did show dependence on the NAO phase. Furthermore, it is well known (e.g. Luo and Wan 2005; Barriopedro et al. 2006) that the frequency of blocking exhibits considerable inter-decadal variation. Rimbu and Lohmann (2011) constructed a North Atlantic blocking index (Fig. 4.7) which shows pronounced decadal variations with frequent blocking in the 1910s, 1940s and 1960s as well as after 1995, and low blocking particularly in the 1920s, 1950s, 1970s and early 1990s, in good agreement with the observed temperature anomalies in the Baltic Sea region during the twentieth century. The relationship, first discussed by van Loon and Rogers (1978), also holds further back in time; very mild south-western Greenland winter temperatures during the Late Maunder Minimum (late seventeenth and early eighteenth centuries, see Chap. 3, Sect. 3.5) coincides with above normal blocking frequency over Europe, cold winters and above (below) normal pressure over northern (southern) Europe (Luterbacher et al. 2001) and above normal sea ice (Koslowski and Glaser 1999). It has also been possible to simulate these changes in blocking frequency in reconstructed (Casty et al. 2005) and model data (Stendel et al. 2006).

#### 4.2.4 Distant Controls of Circulation Changes

There are also indications that circulation changes in the Baltic Sea region are related to climate anomalies at further distances. Several authors have addressed the question

whether the NAO is influenced by ENSO (El Niño/Southern Oscillation). Since there is no significant correlation between the two indices, the effects seem to be small (e.g. Rogers 1984; Pozo-Vázquez et al. 2001; Sutton and Hodson 2003). However, it can be expected that the influence of ENSO on the European climate is nonlinear and so should be analysed in terms of composites of strong anomalies of ENSO (Brönnimann et al. 2007). In this way, in periods of pronounced La Niña or El Niño, the European climate can be indirectly influenced by ENSO through teleconnections via a downstream propagation of tropical disturbance from the Pacific to the North Atlantic (Fraedrich 1994) to the stationary Rossby waves. Another indirect link exists via the effect of ENSO on tropical North Atlantic temperatures (e.g. Chiang et al. 2002). Jevrejeva et al. (2003) discussed the influence of the Arctic Oscillation (of which the NAO can be regarded as the European/North Atlantic part) and of ENSO on ice conditions in the Baltic Sea and found a weak, but non-negligible contribution from the latter. García-Serrano et al. (2011) applied a principal component analysis to the North Atlantic/European winter 200 hPa stream function and found a discernible El Niño signature. In contrast, von Storch (1987) did not find a robust ENSO signal in winter. Thus, many different mechanisms for controlling European climate have been suggested, but with little predictive skill.

Graf and Zanchettin (2012) discussed the effects of El Niño on North Atlantic/European climate. Distinguishing between ‘central Pacific’ and ‘east Pacific’ El Niños, they found a teleconnection via a ‘tropospheric bridge’ between the latter and cold European winters. Seager et al. (2010) related positive snowfall anomalies in the Arctic to excess moisture due to anomalously warm conditions in the preceding summer and autumn and stated that most models are unable to capture this wintertime cooling due to their poor representation of snow cover variability. Stroeve et al. (2011) and Jaiser et al. (2012) showed from ERA-Interim

data that low ice concentrations over the Arctic Ocean lead to an increase in heat released into the atmosphere and, as a consequence, to a reduction in vertical static stability, leading to circulation anomalies over Europe in winter that resemble the negative phase of the NAO. In contrast, Ineson et al. (2011) related weaker winter westerlies and a negative NAO phase-like pattern to a minimum in solar ultraviolet (UV) irradiance. If this finding proves correct, it implies that low solar activity drives a cold winter in northern Europe and the United States.

Overland and Wang (2010) found a relationship between changes in atmospheric circulation in the Baltic Sea region and the loss of sea ice in the Arctic. Triggered by a reduction in Arctic summer sea ice caused by anomalous meridional flow, the resulting additional heat stored in the Arctic Ocean due to the increase in late summer open water area contributed to an increase in the lower tropospheric relative topography (500/1000 hPa), but not necessarily to changes in SLP. As a consequence, anomalous easterly winds were observed in the lower troposphere along 60°N in many regions, including northern Europe and the Baltic region. This is in contrast to early findings by Glowienka-Hense and Hense (1992), who concluded that Arctic sea-ice variability may have an effect on mid-latitude circulation through synoptic transient eddy forcing.

More specifically, Petoukhov and Semenov (2010) performed a series of experiments with the ECHAM5 model at low resolution (T42, i.e. approximately 300-km grid point spacing with 19 vertical levels) and found a dependence of central European winter temperatures from sea-ice cover in the Barents and Kara Seas. A gradual decrease in sea-ice cover from 100 % to ice-free conditions led to a strong temperature increase, and via a nonlinear relationship between convection over the ice-free parts and baroclinic effects triggered by changes in temperature gradients near the surface heat source, this resulted in a warming, then a cooling and at very low ice cover, again a warming over central Europe. Yang et al. (2011), using the EC-Earth model (Hazeleger et al. 2012) with considerably higher resolution (T159, i.e. approximately 80 km between grid points, with 31 vertical levels), confirmed a decrease in winter temperature with decreasing sea ice in the Barents and Kara Seas, but in a more linear way than by Petoukhov and Semenov (2010). In the light of the record, low Arctic ice cover and recent cold winters over Europe, these are interesting findings. As a consequence, transitions between different regimes of the atmospheric circulation in the sub-polar and polar regions may be very likely. Mesquita et al. (2010) even found a connection to positive sea-ice anomalies in the Sea of Okhotsk via a westward shift in cyclois and the build-up of a pattern resembling the negative phase of the NAO over the North Atlantic.

Many other authors have also discussed the low temperatures of the 2009/2010 and 2010/2011 winters over large

parts of Europe (including the Baltic Sea region). Taws et al. (2011) observed a tripole pattern in sea-surface temperature (SST) anomalies related to a negative NAO phase. Guirguis et al. (2011) and Cattiaux et al. (2010) argued that only parts of Europe, Russia and the United States experienced cold anomalies, while extreme warm events were observed at several other locations in the Northern Hemisphere, thus providing a consistent picture of a regional cold event under global warming conditions. Cattiaux et al. (2010) and Ouzeau et al. (2011) highlighted the importance of an adequate representation of the stratosphere in the ARPEGE model for reproducing the cold anomalies over Europe. Cohen et al. (2010) related stratospheric temperature anomalies and their interaction with the troposphere. On the other hand, Jung et al. (2011) stated that internal atmospheric dynamic processes were responsible for the extended negative NAO phase in 2009/2010. Stroeve et al. (2011) argued that negative AO indices and corresponding low sea-ice volumes at the beginning of the melt season result in the summer melt of much of the multi-year sea ice due to ice transport into warmer southerly waters related to the atmospheric circulation anomalies. Some studies also suggest a link between autumn snow cover in Eurasia and Northern Hemisphere winter circulation (see Chap. 6).

#### 4.2.5 Controls of the NAO

A spectral analysis of the NAO time series revealed little evidence for the NAO index to vary on any preferred timescales (Hurrell and Deser 2009). There were large changes from winter to winter and even within a season, but a decadal signal was also visible. For example, high NAO index values prevailed during the 1920s, while the 1960s were characterised by low values. Very high values were observed in the 1990s, together with a north-eastward displacement of the centres of action (Hurrell and van Loon 1997). Whether this is related to anthropogenic climate change or to what extent the NAO might change in the future due to global warming is still a matter of conjecture. The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) (Meehl et al. 2007) stated that ‘... the most consistent results from the majority of the current generation of models show, for a future warmer climate, a poleward shift of storm tracks in both hemispheres...’. Ulbrich et al. (2009) concluded that most models agree that there are fewer, but more intense cyclones in many parts of the extra-tropics, including the North Atlantic/European region. They also noted that this conclusion can only be drawn when ‘extreme’ is defined as a function of core pressure, whereas no such increase (actually, a slight decrease in several models) is found when ‘extreme’ is instead defined from pressure gradients.



### 4.2.6 Circulation Changes in Contrast to Global Warming

In two recent articles, Bhend and von Storch (2008, 2009) presented a method to compare the consistency of observed trends with climate change projections, even if no estimates of natural variability exist. They found that anthropogenic forcing can explain a large part of the observed changes in temperature and precipitation over the Baltic Sea region and that this correlation is unlikely to be occurring by chance. However, it cannot fully explain the observed trends. Since, due to its stochastic nature, a relatively large part of the NAO could be unrelated to anthropogenic climate change, the NAO signal was removed and the analysis was repeated. The results indicate that the climate change signal in temperature and precipitation is robust with respect to the removal of the NAO for long-term means, whereas seasonal as well as spatial variability is underestimated. This may be due to additional forcing mechanisms not included in their model set-up (e.g. the indirect aerosol effect) or to a general underestimate of the model response to anthropogenic forcing (see Chap. 10 as well as Chaps. 23–25).

### 4.3 Surface Pressure and Winds

The wind climate, described through the statistics of near-surface wind speed and direction, has a strong impact on human activities and the Baltic Sea ecosystem. Extreme wind speeds are a direct threat to life and property and an indirect threat through wind waves, storm surges (Chap. 9) and coastal erosion (Chap. 20) leading to high economic loss. However, on the European scale at least, no trends were found for storm losses adjusted for inflation and changes in population and wealth in the period 1970–2008 (Barredo 2010). Nilsson et al. (2004) calculated a storm damage index for Sweden for the period 1901–2000 based on storms sufficient to cause forest damage. Although the 1980s suffered most extreme storm events in terms of windthrow, the authors noted several factors other than wind that increased or decreased storm damage. Widespread and severe damage usually relates to severe winter storms. A positive NAO index is generally associated with an increased number of extreme cyclones although they can also occur at negative phases of the NAO (Pinto et al. 2009). Among others, typical examples of severe winter storms causing widespread damage in the last decade have been Gudrun/Erwin on 8/9 January 2005 (Haanpää et al. 2006; Suursaar et al. 2006) and Kyrill on 18/19 January 2007 (Fink et al. 2009). Negative economic effects can also result from unusually calm

conditions, especially for activities with an increasing dependence on wind energy.

Storms are also an essential factor for ventilation and mixing of the strongly stratified Baltic Sea. Inflow events from the North Sea importing salt and oxygen into the Baltic Sea basin are highly dependent on the wind climate and atmospheric pressure differences (Lass and Matthäus 1996; Gustafsson and Andersson 2001) and have a strong impact on the Baltic Sea ecosystem (see also Chap. 7). Warm water inflows into the Baltic Proper in summer indicate that pressure systems and wind conditions in summer also play a vital role (Feistel et al. 2004).

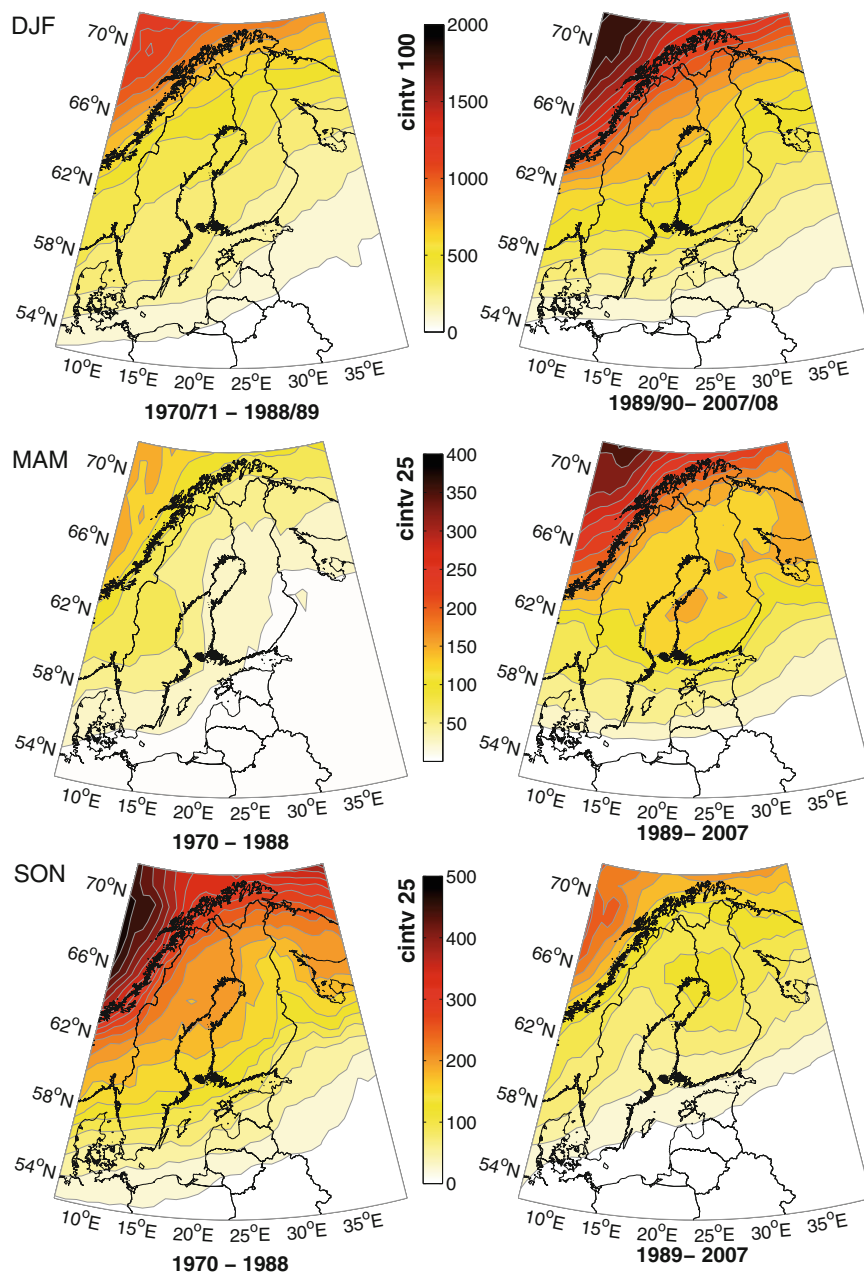
#### 4.3.1 Wind Climate in Recent Decades

The temporal and spatial covariance of the wind climate is generally related to large-scale variations in atmospheric circulation over the North Atlantic and in winter to the NAO. Hence, changes in the synoptic-scale wind climate over the Baltic Sea region are closely related to variability in atmospheric circulation, baroclinic activity and changes in the North Atlantic storm tracks.

During the latter half of the twentieth century, the wind climate over the north-east Atlantic and northern Europe underwent large changes. Based on NCEP/NCAR reanalysis data (Kalnay et al. 1996; Kistler et al. 2001), the number of deep cyclones (core pressure < 980 hPa) in winter (DJFM) reached a minimum in the early 1970s and increased over the following decades peaking around the last decade of the twentieth century (Lehmann et al. 2011, Fig. 4.4). At the same time, a continuous north-eastward shift in the storm tracks regionally increased the impact and number of storms over northern Europe and thus the Baltic Sea in winter and spring, although there was a decrease in autumn (Fig. 4.8).

Consequently, a strong increase in storminess in the 1980s and 1990s across the North Sea (e.g. Carter and Draper 1988; Hogben 1994) raised public concern about the possible impact of increased greenhouse gas concentrations on the rougher wave and storm climate (Schmidt and von Storch 1993). Based on high-resolution meteorological data from SMHI for the period 1970–2007, regional changes were also found in the wind climate over the Baltic Sea region (Lehmann et al. 2011). Although wind speeds returned to average values by the last decade of the investigated period, there was a clear increase in mean geostrophic wind speed of  $1.5 \text{ ms}^{-1}$  for the period 1989–2007 compared to 1970–1988 in the southern and central Baltic Sea region in winter (DJF). This coincided with an increase in the number and spatial extent of deep lows (Fig. 4.8) over

**Fig. 4.8** Changes in the number of deep cyclones (core pressure < 980 hPa) between 1970–1988 and 1989–2008 over the Baltic Sea region for winter (DJF), spring (MAM) and autumn (SON) from SMHI data (Lehmann et al. 2011). Note different scales and contour intervals for the different seasons. Scale (contour interval, cintv) refers to the number of cases below 980 hPa



the Baltic Sea region. While the increase in mean geostrophic wind speeds in winter over the Bothnia Bay was only  $0.5 \text{ ms}^{-1}$  over this period, a general increase of  $0.5\text{--}1 \text{ ms}^{-1}$  took place over most areas in spring (MAM) together with a change to more westerly than south-westerly winds.

Comparable shifts for early spring were also reported for Finland by Keevallik and Soomere (2008) and Keevallik (2011) from the 1960s to 1990s with changes to more westerly than north-westerly winds. For the period 1966–2011, Jaagus and Kull (2011) also found a clear change in the main wind direction over Estonia in winter changing from south-east in the 1970s to south-west in the last decade. A general tendency towards more zonal and less meridional

flow in winter is also confirmed for the easternmost Baltic Sea region for the period 1961–2003 accompanied by increasing variability (Khokhlova and Timofeev 2011).

In contrast, wind speeds in autumn (SON) decreased over the western and central Baltic Sea (by  $1.5\text{--}2 \text{ ms}^{-1}$ ) and the Bothnia Bay (by  $0.5 \text{ ms}^{-1}$ ) explained by a general decrease in the number and spatial extent of deep lows in 1989–2007 compared to 1970–1988 (Fig. 4.8). Over the Kiel Bight, this change in strong wind speeds ( $>13.9 \text{ ms}^{-1}$ ) is accompanied by a marked change in the frequency distribution of wind direction with a decrease in south-westerly and an increase in the easterly component of the winds (Lehmann et al. 2011).

The increase in mean wind speed since the 1960s and 1970s is accompanied by a relative increase in the frequency of storms over the southern North Sea and Baltic Sea ( $\sim 1\text{--}2\%$  per year) in the period 1958–2001 based on numerically downscaled NCEP/NCAR reanalysis data (Weisse et al. 2005). Including also the Norwegian Sea, the positive trends in storm frequency were found to be statistically significant ( $p < 0.05$ ). Although high annual geostrophic wind speeds (above the 99th percentile) returned to average or calm conditions over the north-east Atlantic, central Europe, the North Sea and the Baltic Sea at the end of the twentieth century (Matulla et al. 2008), there has been an upward trend in winter storminess for the past 50 years over northern Europe (Donat et al. 2011). Whether this trend is likely to persist over the longer term or is due to large (multi-)decadal variability is addressed in the following section.

### 4.3.2 Long-Term Wind Climate

Long data series of direct wind observations are sparse, and most measurements even in recent decades suffer from potential inhomogeneities due to changes in the environment (growing trees or new buildings in the vicinity, station relocation, etc.) or changes in methodology (different instruments, number of measurements per day, etc.) as discussed by the group ‘*Waves and Storms in the North Atlantic*’ (WASA 1998; von Storch and Weisse 2008; Lindenberg et al. 2012). Also, cyclone detection and tracking algorithms to derive the frequency and intensity of deep lows as a proxy for storminess from historical pressure fields face the problem of lower data density and quality back in time (Smits et al. 2005), possibly leading to an apparent increase in high-latitude cyclone activity that is actually due to higher data density (see Sect. 4.3.4).

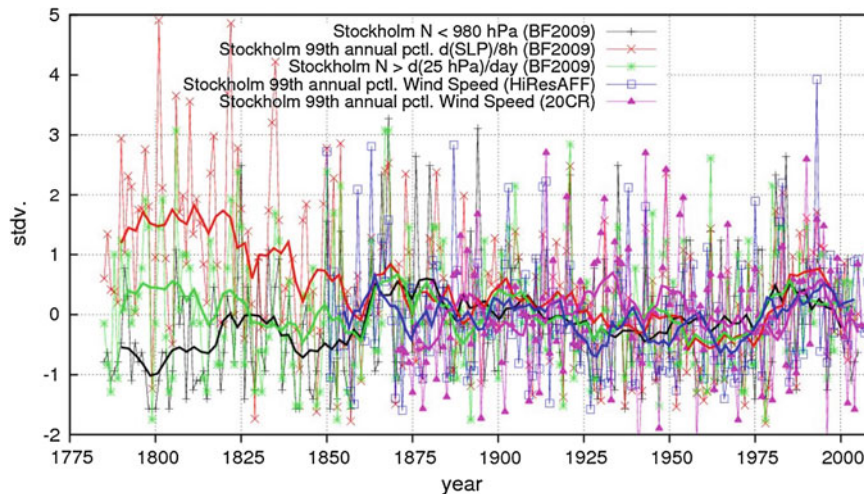
As synoptic-scale storms are generally linked to large-scale forcing over the pressure field, pressure gradients can be used to derive geostrophic wind speeds based on surface pressure readings (Krueger and von Storch 2011). A first study based on geostrophic wind speeds calculated from a triangle of station pressure over the German Bight by Schmidt and von Storch (1993) showed no long-term trend for the wind climate of 1876–1990. High annual wind speeds in the 1990s appeared to be comparable to high wind speeds in the 1880s as well as in the early and mid-twentieth century. Kaas et al. (1996) found no overall trends but considerable decadal variability. This was further confirmed by studies from the WASA group (WASA 1998), Alexandersson et al. (2000) and Matulla et al. (2008) using different pressure triangles over Europe, mainly the North Sea. For Finland, Suvilampi (2010) found a slight decrease in annual

geostrophic wind speeds since 1884 and a weak but non-significant upward trend for the past 50 years. The tendency for a long-term decrease in annual wind speeds is also confirmed by Wern and Barring (2009) for southern Sweden based on geostrophic wind speeds derived from pressure triangles. For the period 1901–2008, the authors found statistically significant negative trends in annual potential wind energy and mean and extreme ( $>25\text{ ms}^{-1}$ ) geostrophic wind speeds. For the shorter period, 1951–2008, a tendency to negative trends in mean wind speeds was found for northern Sweden, while weak non-significant trends of both signs were found for central and southern Sweden. In general, the authors concluded that (multi-)decadal scale variations dominate rather than any long-term trends.

While the decrease in storminess from a peak around the 1880s happened quite suddenly in central Europe, there was a gradual slow-down over a period of decades in northern Europe until the 1960s (Figs. 4.8 and 4.9 in DJF). Matulla et al. (2008) found the increase in storminess starting in the late 1970s was most pronounced in NW Europe and more steady in central Europe. They also found general agreement between storminess over central Europe and NW Europe despite some difference in timing and/or magnitude. Barring and Fortuniak (2009) also showed a correlation between inter-decadal variations over southern Scandinavia and similar variations over NW Europe.

Another way to estimate historical storminess is by using pressure-based single-station proxies such as different pressure tendencies per unit time, mean or low percentiles of surface pressure or, for example, the annual number of deep lows. Based on different storm indices derived from single-station pressure readings for Lund and Stockholm, Barring and von Storch (2004) and Barring and Fortuniak (2009) found no robust signs of any long-term trend in southern Sweden for the period 1780/1800 to 2005. Hanna et al. (2008) found similar results based on a daily pressure variability index calculated as absolute 24 h pressure differences, that is  $\Delta p = |p_{t+24} - p_{t+0}|$ , for the British Isles since 1830 and for Denmark since 1874 confirming increased storminess at the end of the nineteenth century and the 1980s to 1990s, with the 1880s being the stormiest decade. The informational value of five different pressure-based storminess indices including those used by Barring and von Storch (2004) and Hanna et al. (2008) was evaluated by Krueger and von Storch (2012). The authors confirmed the general usefulness of the indices as storminess proxies, with absolute pressure tendencies per six or eight hours containing the highest informational value.

Schenk and Zorita (2011) released a new reconstruction of High RESolution Atmospheric Forcing Fields (HiRe-sAFF) for northern Europe for the period 1850–2009



**Fig. 4.9** Storminess indices of the annual number of deep lows ( $N < 980$  hPa), the 99th percentile of pressure tendency per 8 h, the annual number of days exceeding a pressure tendency of 25 hPa for the Stockholm station 1785–2005 (Barring and Fortuniak 2009) compared to the reconstructed annual 99th percentile of wind speeds in the

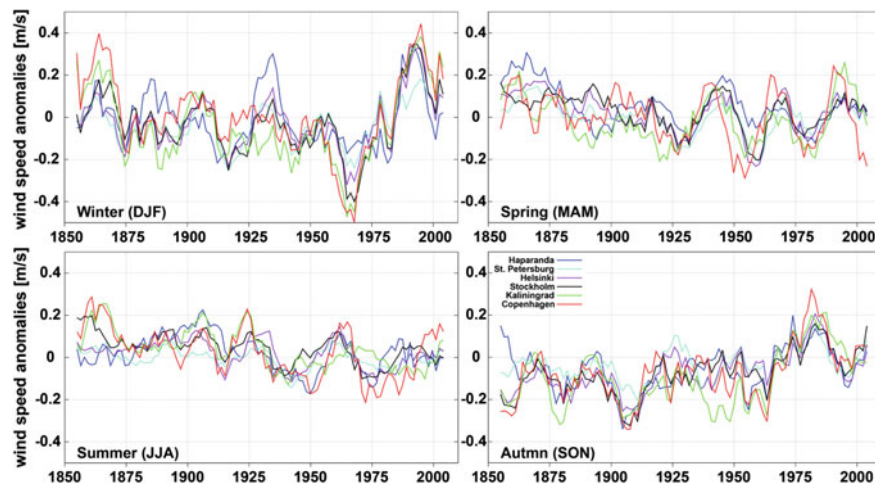
vicinity of Stockholm 1850–2009 from HiResAFF (Schenk and Zorita 2011, 2012). Data normalised with respect to the period 1958–2005. Bold lines represent the 11-year running mean to highlight decadal variability

including wind. Based on the pattern similarity between daily SLP station data starting in 1850 and SLP observations since 1958, Schenk and Zorita (2012) reconstructed historical atmospheric fields by taking the daily atmospheric fields of regionally downscaled ERA reanalysis for any day for which the pattern similarity is maximised for an analogous day in 1958–2007. As shown in Fig. 4.9, the reconstructed 99th percentile of annual wind speeds from HiResAFF in the vicinity of Stockholm gives comparable results regarding long-term features of annual storminess derived from single-station proxies of Stockholm used by Barring and Fortuniak (2009). The different storminess measures agree in showing increased annual wind speeds in the 1880s and 1990s and an unusually calm period around the 1960s to 1970s and a return to average conditions in recent years although the number of deep lows does not indicate calm conditions. Figure 4.9 also confirms the gradual decline in wind speeds since the end of the nineteenth century as reconstructed by Matulla et al. (2008) for northern Europe.

As discussed by Barring and Fortuniak (2009), up to eight different proxies for storminess calculated from single-station pressure data represent different aspects related to storminess. Estimating the covariance over all indices, the derived first principal component (PC1) shows good agreement with the 99th percentiles of the geostrophic wind index from Trenberth et al. (2007) and the reconstructed NAO index from Luterbacher et al. (2002) with respect to long-term variability (see Fig. 4.1). In contrast to the number of deep lows ( $N < 980$  hPa) in Fig. 4.9, the PC1 over all eight

indices captures the calm period of the 1960s and 1970s indicating that it is better to use a number of different indices rather than relying on only one. The highest correlation between HiResAFF annual extreme wind speeds and single-station proxies was achieved for the pressure tendency over 8 h ( $r = 0.50$ ) confirming the work of Krueger and von Storch (2012). Remarkably high values for the 8-h pressure tendencies on the one hand and very low values for the number of deep lows on the other hand indicate low confidence in the data before around 1850 probably due to irregular pressure readings. As irregular sub-daily observations hamper the detection of deep lows or pressure changes over 6 h, the estimate using annual numbers of days exceeding a pressure change of 25 hPa per 24 h in Fig. 4.9 (green line) is likely to be more reliable prior to around 1850 as only one observation per day is required. Also, the large differences between the Stockholm and Lund time series in the early historical period should be noted with care (Barring and von Storch 2004).

While the previous studies analysed historical storminess on an annual basis only, Wang et al. (2009a) repeated and updated (1874–2007) previous studies based on the 99th percentiles of geostrophic wind speed over the NE Atlantic, and northern and central Europe and focused more on seasonal and regional differences. They found that the maxima in the 1990s were due to winter storminess, while the high annual storm values in the 1880s were mainly due to summer storminess. For the period 1878–2007, Wang et al. (2011) found weak negative trends in the 99th percentiles



**Fig. 4.10** Sliding decadal (11-year) mean seasonal wind speed anomalies for the Baltic Sea region for 1850–2009. Anomalies are calculated by subtracting the mean for 1958–2007. Time series are

drawn from the gridded fields of HiResAFF (Schenk and Zorita 2011, 2012). Grid points are selected in the closest vicinity of Haparanda, St Petersburg, Helsinki, Stockholm, Kaliningrad and Copenhagen

over central Sweden and the south-western Baltic Sea in winter (DJF) and a significant ( $p < 0.05$ ) negative trend over the south-western Baltic Sea in summer (JJA).

As shown in Fig. 4.10, HiResAFF confirms decreasing seasonal mean wind speeds in summer (Wang et al. 2011) and the peak in summer wind speeds in the 1880s (Wang et al. 2009a), that is over the southern Baltic Sea region. However, no increased summer winds are reconstructed for the 1880s over the northern and eastern Baltic Sea region highlighting regional differences in the wind climate. While Wang et al. (2009a) attributed high annual storminess in the 1880s mainly to higher storminess in summer, HiResAFF shows higher mean wind speeds in all seasons except autumn over the southern and central Baltic Sea region in the 1880s.

So far, all long-term reconstructions of the wind climate discussed here have been derived from (sub-)daily pressure observations relying on physical (triangle method) and empirical (analogue-upscaling) methods or from pressure tendencies and the number of deep lows as indirect storminess indices. While the reconstructions show good agreement in terms of a dominance of (multi-)decadal variability rather than robust long-term trends in wind speed, a recent study by Donat et al. (2011) differs in showing a significant long-term increase in winter storminess since 1871 for Europe based on the twentieth-century reanalysis (20CR) data (Compo et al. 2011). The model used for 20CR is very similar to those used for NCEP/NCAR reanalysis but uses a different data assimilation technique. Unlike NCEP/NCAR, 20CR uses only daily station SLP monthly SST and sea ice for data assimilation of historical observations since 1871. As the density of stations with daily SLP increases strongly over time, potential users of 20CR should be cautious about

whether the 20CR trend is in fact an artefact caused by the lower station density in earlier times (e.g. Krueger et al. 2013) similar to other long-term trends found in reanalysis data subsequently identified as spurious (see Sect. 4.3.4).

### 4.3.3 Long-Term Trends Versus Decadal Variability

The findings of reconstructions based on geostrophic wind speeds derived from pressure triangles, different storminess proxies using single-station pressure indices and field reconstructions using analogue-upscaling, are in good agreement showing large decadal variability rather than robust trends in storminess over northern Europe since 1850. The 1880s and 1990s show maxima in annual mean and extreme wind speeds, while the 1970s were unusually calm. The past decade shows a return to average conditions, and only the summer wind climate over the southern Baltic Sea region shows a slight negative long-term trend. Studies analysing the wind climate of the past 40–60 years detect large changes in the recent past (Sect. 4.3.1) that are characterised by the rebound from very calm conditions in the 1960s at the beginning of many observational time series for wind, followed by the very stormy 1990s. Hence, while positive trends in this period indeed describe a dramatic change in wind state, the return to average conditions in the past decade and the long-term analysis of the wind climate over more than 150 years clearly commute the decadal trend into (multi-)decadal variability.

The physical explanation for these large changes from the 1970s to the 1990s relates to dynamical changes in the large-scale atmospheric circulation over the North Atlantic and the

NAO. Over this period, the NAO index switched from strongly negative to unprecedentedly high positive values highlighting the strong correlation of storminess with the NAO (Sect. 4.2). The NE shift of the NAO together with the increased pressure gradient over the North Atlantic extended the geographical influence and numbers of deep lows towards the Baltic Sea region (Fig. 4.8, Wang et al. 2006; Lehmann et al. 2011), explaining upward trends in annual and winter to spring storminess from the 1960s to 1990s. However, this relation depends on the region and time period (Matulla et al. 2008), where recent decades show a very high influence of the NAO (Alexander et al. 2005) with a weaker link in previous times (Alexandersson et al. 1998).

Regarding atmospheric circulation and weather type, there is a corresponding change from calm anticyclonic conditions towards more active cyclonic conditions at the end of the twentieth century for the winter season (Hurrell et al. 2003). In addition, the remarkably calm period during 1960s and 1970s coincides with a period of very high Euro-Atlantic atmospheric blocking frequency in winter (e.g. Rimbu and Lohmann 2011, Fig. 4.7) relative to the period 1908–2005, preventing or weakening zonal (westerly) flow and leading to low wind speeds and fewer storms over Scandinavia. In contrast, the 1990s show low blocking and high wind speeds.

The long-term negative trend in the wind climate for summer (Wang et al. 2009a, 2011) over the southern Baltic Sea region agrees with the findings of Kaszewski and Filipiuk (2003). Based on weather type classifications over central Europe for summer 1881–1998, they found a tendency towards less zonal and increased meridional flow which could explain the decreasing wind speeds in summer.

Whether external forcing over the past half century has influenced trends in atmospheric circulation and storminess is difficult to identify due to the large natural variability over the North Atlantic and northern Europe. According to Wang et al. (2009b), combined anthropogenic and natural forcing have had a detectable influence on the pattern of atmospheric circulation during boreal winter showing an upward trend in storminess and ocean wave heights in the high northern latitudes and a decreasing trend in the lower northern latitudes for 1955–2004. Further analysis for the first half of the twentieth century suggests that external forcing is less likely to have been an important factor for surface pressure and storminess (see Chaps. 23–25 for attribution). From the different long-term reconstructions of storminess based on surface pressure observations covering more than 150 years, the wind conditions of recent decades seem not to be unusual and to fall within the large range of natural variations which are to a large extent explained by the NAO.

#### 4.3.4 Potential Inconsistencies in Long-Term Trends

As direct wind observations usually cover limited time periods and/or suffer from strong inhomogeneities in the data (Sect. 4.3.2), many studies rely either on reanalysis data or on different reconstructions derived from pressure observations. As previously discussed, the different pressure-based reconstructions show good overall agreement regarding long-term variations in storminess independent of the method used. The conclusion drawn from these studies—that northern European storminess is dominated by large multi-decadal variations rather than long-term trends—appears robust given that Krueger and von Storch (2011, 2012) also confirmed the informational value of most reconstruction methods used.

The analysis by Donat et al. (2011), however, does not agree with the previous reconstructions in suggesting a significant long-term increase in winter storminess since 1871 for Europe based on the 20CR data (Compo et al. 2011). Assimilating only daily station SLP monthly SST and sea ice from historical observations since 1871, the density of stations with daily SLP strongly increases over time in the 20CR model. As the discrepancy in 20CR compared to other reconstructions reduces in parallel to the increase in number of stations, increasing storminess with time could be an artefact due to the changing station density (Krueger et al. 2013) comparable to other spurious long-term trends found in reanalysis data (cf. Trenberth and Smith 2005 and Hines et al. 2000 in case of the of SLP, Bengtsson et al. 2004; Paltridge et al. 2009; Dessler and Davis 2010). At least average or higher wind speeds in the 1880s (in contrast to what is suggested by 20CR) are supported by direct observations for western Europe (Clarke and Rendall 2011) such as sand dune studies in southern Wales (Higgins 1933) and severe storm analysis by Lamb and Frydendahl (1991). Furthermore, Omstedt et al. (2004) found an unusually high frequency of cyclonic circulation at the end of the nineteenth century with a pronounced peak in cyclonic weather types in 1871–1885 relative to 1800–2000. According to historical weather records of gale days for Scotland, remarkably high values were recorded for 1884–1900 (Dawson et al. 2002) which contrasts with very low storm activity in the 1880s derived from the 20CR model data.

To what extent reanalysis products like ERA40 and NCEP/NCAR might also be compromised by similar problems regarding spurious long-term trends in pressure and wind needs further investigation. In general, variables derived from reanalysis data (wind speeds, pressure etc.) are assumed to be closely co-related to observations through

data assimilation into state-of-the-art climate models. Even though reanalysis datasets are often referred to as ‘observations’, several studies highlight the possibility of detecting spurious long-term trends in reanalysis data caused, for example, by a regionally changing density of assimilated stations over time. As an example, Smits et al. (2005) found no trend in observed storminess over the Netherlands for 1962–2002, in contrast to the trend seen in NCEP/NCAR reanalysis data.

In addition to issues with data assimilation, there is also a resolution issue with the relatively coarse gridded NCEP/NCAR and ERA reanalysis. As might be expected (see Raible et al. 2008), this is more of a problem with NCEP/NCAR (triangular truncation of T62, approximately 1.9° in latitude and longitude) than ERA (for ERA40; T106, approximately 1.1°). Analysing storm tracks over the Euro-Atlantic sector (Trigo 2006) and the cyclone lifetime characteristics of the Northern Hemisphere (Löptien et al. 2008) in NCEP/NCAR and ERA, the results are comparable, or the summer season for the two different reanalysis products. Apart from spatial resolution issues, differences in dynamics, physical parameterisations of the models and assimilation of observations may also play a role in the quality of the data (see Ulbrich et al. 2009 and references therein).

## 4.4 Surface Air Temperature

### 4.4.1 Long-term Temperature Climate

Earlier studies detected a significant increase in surface air temperature in the Baltic Sea region during 1871–2004 (BACC Author Team 2008). Rather than showing a steady increase, however, temperature showed large (multi-)decadal variations dividing the twentieth century into three main phases: warming until the 1930s, followed by cooling until the 1960s and then another distinct period of warming during the final decades of the time series. Linear trends of the annual mean temperature anomalies during 1871–2011 were 0.11 °C per decade north of 60°N and 0.08 °C per decade south of 60°N in the Baltic Sea basin (Table 4.1). This is greater than for the trend in global mean temperature, which is about 0.06 °C per decade for 1861–2005 (IPCC 2007). All seasonal trends are positive and significant at the 95 % level, except winter temperature north of 60°N (lower significance due to the large variability). The largest trends are observed

in spring (and winter south of 60°N) and the smallest in summer. The seasonal trends are also larger in the northern area, than the southern area. The annual and seasonal time series of surface mean air temperature for the Baltic Sea basin presented by the BACC Author Team (2008) have been updated and are shown in Fig. 4.11. The warming has continued over the past few years during spring and summer in the southern area and in autumn and spring in the northern area, and the winters of 2009/2010 and 2010/2011 were relatively cold.

Similar features are also evident in the long Stockholm temperature series (Fig. 4.12). Based on the same period (1871–2011), the trends and significance resemble those in the Baltic Sea basin north of 60°N.

Long-term variations and trends in the Baltic Sea basin are similar to those for European mean air temperature (Casty et al. 2007). A number of studies show similar warming trends for areas of the Baltic Sea basin and its vicinity: Finland (Tietäväinen et al. 2009), Sweden (Hellström and Lindström 2008, see Chap. 5, Fig. 5.18), Norway (Hanssen-Bauer et al. 2009), Czech Republic (Brázdil et al. 2009), Latvia (Lizuma et al. 2007; Klavinš and Rodinov 2010), Estonia (Kont et al. 2007, 2011; Russak 2009) and for the three Baltic countries together (Kriauciuniene et al. 2012). Long and homogeneous time series of spatial mean air temperature were created for Finland covering 1847–2008 (Tietäväinen et al. 2009). Trends were calculated for three periods: 1909–2008, 1959–2008 and 1979–2008. An increase in annual mean temperature was significant at  $p < 0.05$  level for all three periods. Tietäväinen et al. (2009) found significant warming in winter (1959–2008 and 1979–2008), spring (1909–2008 and 1959–2008), summer (1909–2008 and 1979–2008) and autumn (1979–2008). The increase in annual mean air temperature for Finland during 1909–2008 was 0.09 °C per decade. The annual mean temperature time series for Finland agrees with the results in Fig. 4.11. The most significant warming in Finland was typical for spring where the trend value was 0.15 °C per decade during 1847–2004 (Linkosalo et al. 2009).

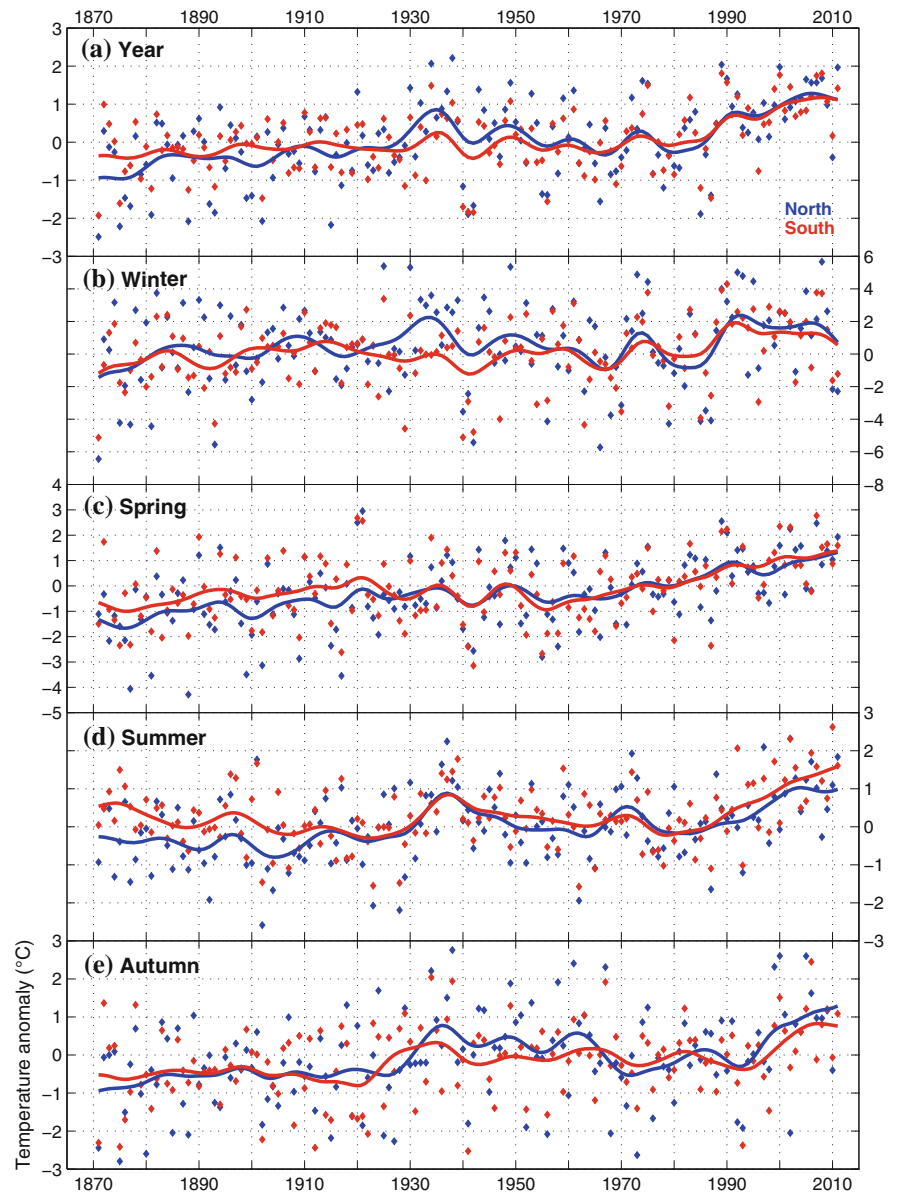
Temperature increased in south-eastern Norway during the twentieth century and the first decade of the twenty-first century by an average of 0.07 °C per decade (Hanssen-Bauer et al. 2009). However, the long-term temperature trend has varied throughout the century, starting with relatively low temperatures, followed by the well-known increase in the

**Table 4.1** Linear surface air temperature trends (°C per decade) for 1871–2011 in the Baltic Sea basin

Datasets	Annual	Winter	Spring	Summer	Autumn
Northern area (north of 60°N)	<b>0.11</b>	0.10	<b>0.15</b>	<b>0.08</b>	<b>0.10</b>
Southern area (south of 60°N)	<b>0.08</b>	<b>0.10</b>	<b>0.10</b>	<b>0.04</b>	<b>0.07</b>

Trends shown in *bold* are significant at the  $p < 0.05$  level. The trends were also tested by the nonparametric Mann–Kendall test. The results were consistent with the linear trend test. Data from the CRUTEM3v dataset (Brohan et al. 2006)

**Fig. 4.11** Annual and seasonal mean surface air temperature anomalies (relative to 1960–1991) for the Baltic Sea basin 1871–2011, calculated from 5° by 5° latitude, longitude box average taken from the CRUTEM3v dataset (Brohan et al. 2006) based on land stations (from *top* to *bottom*: **a** annual, **b** winter (*DJF*), **c** spring (*MAM*), **d** summer (*JJA*), **e** autumn (*SON*). *Blue* comprises the Baltic Sea basin north of 60°N and *red* south of 60°N. The dots represent individual years and the smoothed curves (Gaussian filter,  $\sigma = 3$ ) highlight variability on timescales longer than 10 years



1920s, referred to as ‘the early twentieth-century warming’, which ended in the 1930s. After this warm decade, temperature then decreased until the 1980s after which there has been a still ongoing rapid increase. The first decade of the twenty-first century has been the mildest of the series. In terms of seasonal trends, the trend for summer is weaker than for the other seasons. The strongest trend is for spring (Hanssen-Bauer et al. 2009).

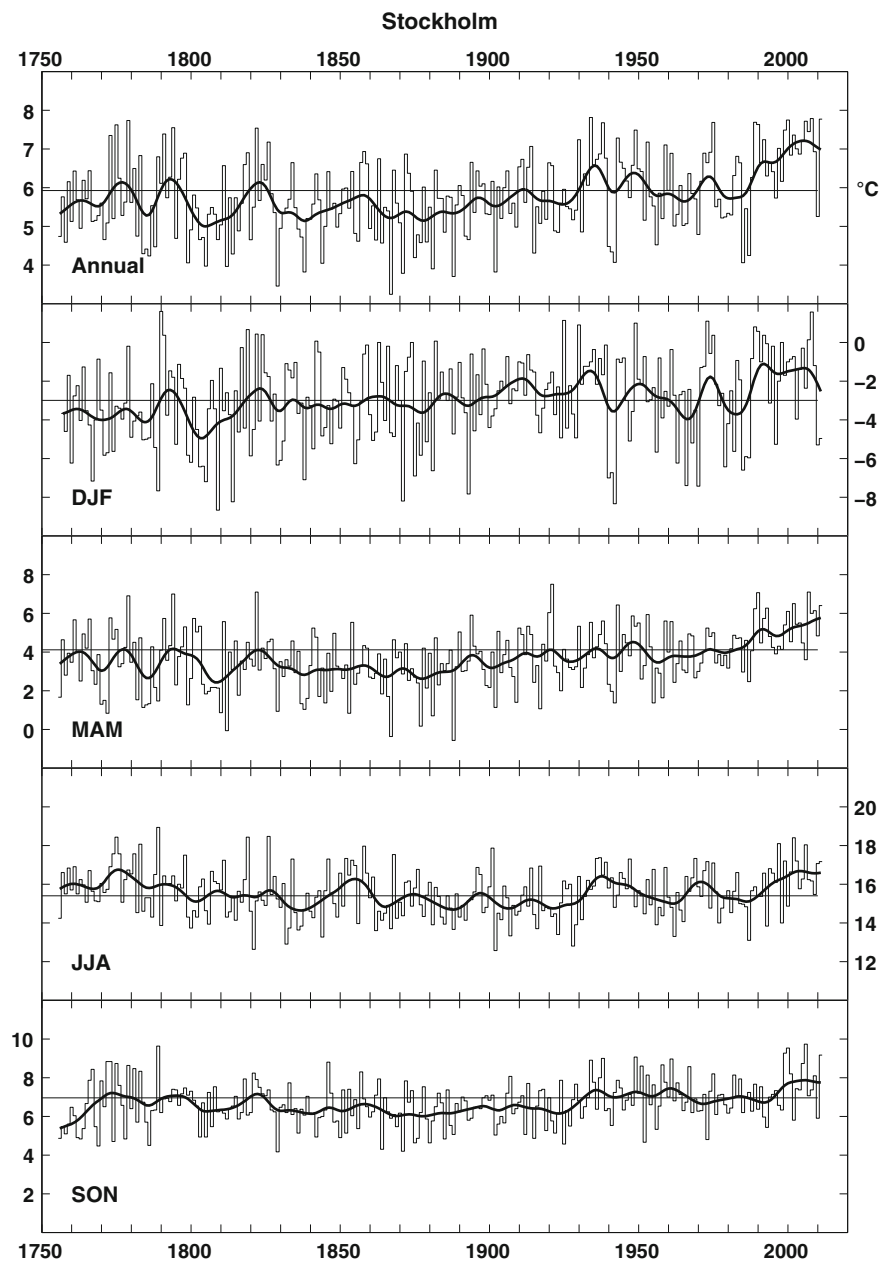
The strong warming during spring is also supported by the work of Nordli et al. (2007). Using a composite series for February–April temperature based on ice break-up records on Lake Randsfjorden (1758–1874) and instrumental observation since 1875 (Fig. 4.13), these authors found that

the high temperatures in spring and late winter between 1989 and 2011 were unprecedented since 1758.

Long-term series of annual mean air temperature in Rīga, Latvia, indicate a significant warming since 1850 of 1.4 °C (Lizuma et al. 2007). For the shorter period (1948–2006), statistically significant trends ( $p < 0.05$ ) were found at all five stations studied in Latvia (Klavinš and Rodinov 2010). The highest temperature increase occurred in spring and winter. During the whole observation period (1795–2007), mean air temperature at Rīga-University Meteorological Station increased by 1.9 °C in winter, 1.3 °C in spring, 0.7 °C in autumn and 1.0 °C for the year as a whole (Klavinš and Rodinov 2010).



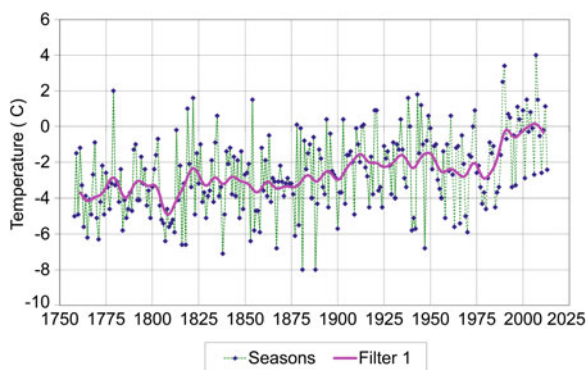
**Fig. 4.12** Annual and seasonal mean surface temperatures (°C) in Stockholm 1756–2011, calculated from the homogenised daily mean temperature series by Moberg et al. (2002) after a correction for a suspected positive bias in summer temperature before 1859 (Moberg et al. 2003). The correction is the same as used by Moberg et al. (2005). Smoothed curves (Gaussian filter,  $\sigma = 3$ ) highlight variability on timescales longer than 10 years



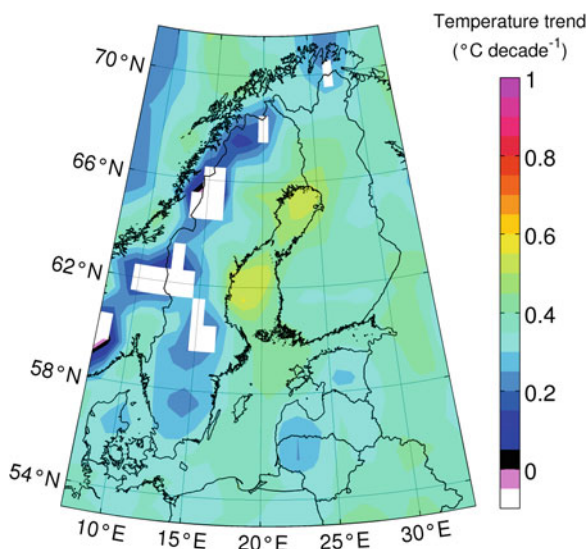
#### 4.4.2 Temperature Trends in Recent Decades

The reanalysis data compiled from the mesoscale analysis system (MESAN) and ERA40 dataset indicated that during the period 1990–2004, all years except one, 1996, had a mean temperature above normal for most of Europe (Jansson et al. 2007). Lehmann et al. (2011) showed a warming trend in annual mean temperature of 0.4 °C per decade over the Baltic Sea basin with the strongest change in its northern part using the SMHI database with a  $1^\circ \times 1^\circ$  horizontal resolution and 3 h time step during 1970–2008 (Fig. 4.14). The strongest trend in the Gulf of Bothnia occurred in

autumn and winter (0.5–0.6 °C per decade), while in the central and southern part of the Baltic Sea region, significant changes occurred in spring and summer (0.2–0.3 °C per decade). This is in agreement with annual mean surface air temperature at coastal stations in Estonia having increased by about 0.3 °C per decade during 1950–2009 (Russak 2009; Kont et al. 2011) and the Russian part of the Baltic Sea drainage basin, where temperatures increased by 0.4 °C per decade during 1976–2006 (Chap. 6). In terms of seasonal change, statistically significant warming occurred in winter, spring and summer, but not autumn, and in terms of months during the first half of the year (JFMAM) with the greatest change in March and April.



**Fig. 4.13** Late winter/early spring (FMA) temperature for south-eastern Norway (Austlandet) based on ice break-up data from Lake Randsfjorden (1758–1874) and instrumental observations (1875–2011), updated from Nordli et al. (2007). Filter 1 means 10-year moving average series of original data



**Fig. 4.14** Linear trend in annual mean surface air temperature during 1970–2007 based on the SMHI dataset. Trends in the light-shaded areas (as over parts of the Scandinavian mountains) are statistically non-significant at the  $p < 0.05$  level (Lehmann et al. 2011)

#### 4.4.3 Daily Cycle and Seasonality

Not only are the annual mean and seasonal mean temperatures changing, but the daily temperature cycle, which is reflected in the daily maximum and minimum temperatures, is also changing. Previous studies have shown that the daily minimum temperature has increased much more than the daily maximum causing a decreasing trend in diurnal temperature amplitude (BACC Author Team 2008). In Rīga, the mean minimum temperature increased by 1.9 °C during 1913–2006, while the mean maximum temperature increased by 1.7 °C. The mean maximum temperature increased most rapidly in the later part of spring (April–May), while the

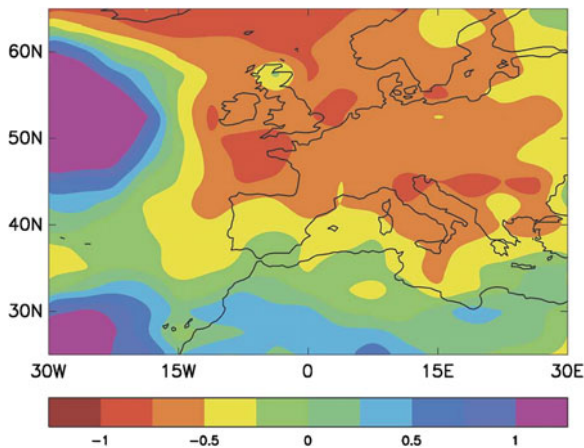
minimum temperature increased most in winter (Lizuma et al. 2007). Consequently, the daily temperature range has decreased (Avotniece et al. 2010).

Climate change is expressed not only in time series of climatic parameters but also in changes in seasonality. The length of the growing season and the sums of positive degree-days have previously been shown to increase, whereas the length of the cold season and the frost days have decreased (BACC Author Team 2008). Trends in start dates and duration of climatic seasons were analysed for Tartu, Estonia, during 1891–2003 by Kull et al. (2008). Some statistically significant changes ( $p < 0.05$ ) were detected. The start of late autumn (i.e. the end of the growing season, indicated by a continuous drop in daily mean air temperature below 5 °C) became 8 days later and the start of winter (indicated by the formation of a permanent snow cover) 17 days later. The duration of summer increased by 11 days and of ‘early winter’ by 18 days, while the duration of winter proper has decreased by 29 days. Here, ‘early winter’ means the transition period with unstable weather conditions with the forming and melting of snow cover before the beginning of winter proper, which is defined by the presence of a permanent snow cover. The length of the growing season (defined by a daily mean air temperature permanently above 5 °C) increased by 13 days (Kull et al. 2008). In Poland, the number of ice days ( $T_{\max} \leq 0$  °C) and frost days ( $T_{\min} \leq 0$  °C) decreased by 2 and 3 days per decade, respectively, while the mean monthly minimum and maximum temperatures and the frequency of warm days ( $T_{\max} \geq 25$  °C) generally increased during 1951–2006. A warming trend occurred in winter, spring and mid- and late summer, but not in June or autumn (Wibig 2008a).

#### 4.4.4 Temperature Extremes

Changes in temperature extremes may influence human activity much more than changes in average temperature. There have been a number of projects and studies on changes in temperature extremes over the past decade. Examples of projects investigating extremes of relevance for the Baltic Sea region include the following: European Climate Assessment (Klein Tank and Können 2003), Statistical and Regional dynamical Downscaling of Extremes for European regions (STARDEX; Haylock and Goodess 2004), European and North Atlantic daily to MULTidecadal climate variability (EMULATE; Moberg et al. 2006) as well as several national projects. A large number of indices describing extremes have been elaborated (BACC Author Team 2008).

Using ensembles of simulations from a general circulation model (HadCM3), large changes in the frequency of 10th percentile temperature events over Europe in winter



**Fig. 4.15** Fractional change in the frequency of very low daily minima in winter surface temperature. The fractional change in occurrence of below-10th percentile daily minimum temperature events is plotted between the winters 1964/1965–1968/1969 and 1990/1991–1994/1995. The 10th percentile is defined over the former period for each ensemble and at each grid point. In order that the existing dataset could be used, percentiles are calculated over 1961–1990. All daily values for the model were pooled together over the December–February (DJF) period to calculate both percentile thresholds and changes in frequency (Scaife et al. 2008)

appear mainly explained by related changes in the NAO from the 1960s to 1990s (Scaife et al. 2008). A decreasing tendency in the frequency of very low daily minima in winter surface temperatures has been present across most of Europe including the Baltic Sea region over the past 50 years (Fig. 4.15). The number of frost days between the winters 1964/1965–1968/1969 and 1990/1991–1994/1995 decreased by 20–30 days in that region (Scaife et al. 2008).

Nine temperature indices were used for analysing weather extremes at 21 stations in Poland during 1951–2006 (Wibig 2008a). The indices are based on daily maximum and daily minimum temperatures. A statistically significant increase was detected for the annual numbers of days with daily maximum temperature above both 25 and 30 °C, while a statistically significant decrease was observed in the length of the frost season and in the annual number of frost days (daily minimum below 0 °C) and ice days (daily maximum below 0 °C). Positive trends in monthly temperature indices were observed from February to May and from July to September (Wibig 2008a).

Changes in temperature extremes were also observed in Latvia using daily data from two stations for the period 1924–2008 and three stations for the period 1946–2008 (Avotniece et al. 2010). The Mann–Kendall test indicates statistically significant positive trends in the number of tropical nights ( $T_{\min} \geq 20$  °C) and of summer days ( $T_{\max} \geq 25$  °C) and negative trends in the number of frost days ( $T_{\min} \leq 0$  °C) and of ice days ( $T_{\max} \leq 0$  °C). The number of hot days and nights increased in Lithuania during

1961–2010 particularly in July and August and in 1998–2010 (Kažys et al. 2011). Abnormally warm or cold weather conditions over several consecutive days can be used as an alternative to studying temperature extremes. An analysis of extremely warm and cold days in Łódź, Poland, during 1931–2006 was undertaken by Wibig (2007). A particular day was included in a warm (cold) period if its daily mean temperature was higher (lower) than 1.28 (–1.28) standard deviations for this particular calendar day, which corresponds to the 90 % (10 %) percentile in the case of a normal distribution. The duration of extremely mild periods has increased significantly in winter, while the number of heat waves has increased in summer as well as during the year as a whole. Accordingly, the length of cold waves has decreased significantly in winter. The annual number of cold days decreased by 0.87 days per decade (Wibig 2007). In spite of general warming, the frequency of cold periods in Poland has not decreased significantly (Wibig et al. 2009). Time series of the number of days with  $T_{\min} \leq 15$  °C,  $T_{\min} \leq 20$  °C and  $T_{\max} \leq 10$  °C show a significant trend at only one of the nine stations (Zakopane) during 1951–2006. An increase in the frequency of heat waves occurred in the Czech Republic in 1961–2006 (Kyselý 2010). Owing to the increase in mean summer temperature, the probability of very long heat waves in the Czech Republic has risen by an order of magnitude over the past 25 years (Kyselý 2010).

Changes in surface air temperature are determined mostly by large-scale atmospheric circulation. As this influences large geographical areas, it is not surprising that temperature studies focusing on different areas show similar fluctuations and trends. Nevertheless, data quality is also very important in trend analysis, and thus, time series based on data from different sources and might contain significant inhomogeneities.

## 4.5 Precipitation

### 4.5.1 Long-Term Precipitation Climate

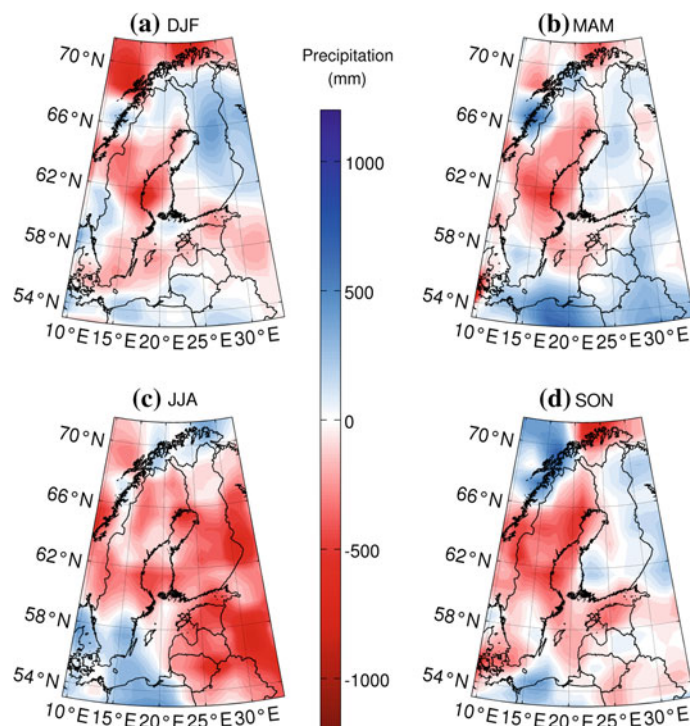
Change in precipitation during the twentieth century in the Baltic Sea basin has been more variable than for temperature. There have been regions and seasons of increasing precipitation as well as those of decreasing precipitation (BACC Author Team 2008). Time series of European mean precipitation is characterised by large inter-annual and inter-decadal variability and with no long-term trends apparent for 1766–2000 (Casty et al. 2007). There were no clear trends in Latvia during 1922–2003 (Briede and Lizuma 2007). Variations in annual precipitation with a periodicity of 26–30 years were detected for all three Baltic countries during 1922–2007 (Kriauciuniene et al. 2012). The periodicity varied by season: spring (24–32 years), summer (21–

33 years), autumn (26–29 years) but with no periodicity evident in winter. Summer precipitation in Finland during 1908–2008 showed a positive trend (Ylhäisi et al. 2010). A statistically significant trend in south-western Finland was detected in June and in north-eastern Finland in May, July and for the whole summer period (MJJAS). An increase in precipitation was detected in south-eastern Norway where annual precipitation increased by about 15–20 % during 1900–2010, with a higher increase in autumn and winter and a lower increase in spring and summer (Hanssen-Bauer et al. 2009). There has been no trend in autumn precipitation over the past 30 years in this area but a marked increase in winter precipitation (Hanssen-Bauer et al. 2009).

#### 4.5.2 Precipitation Climate in Recent Decades

A general increase in precipitation during winter is typical for northern Europe over the past few decades. The greatest increase has been observed in Sweden and on the eastern Baltic Sea coast, while southern Poland has on average received less precipitation. A tendency of increasing precipitation in winter and spring was detected during the latter half of the twentieth century. Benestad et al. (2007) compared downscaled and modelled precipitation at 27 stations in Fennoscandia for 1957–1999. Only a few locations exhibited trends that were statistically significant at the 5 % error level.

**Fig. 4.16** Change in total precipitation between 1994–2008 and 1979–1993 by season based on SMHI data (Lehmann et al. 2011)

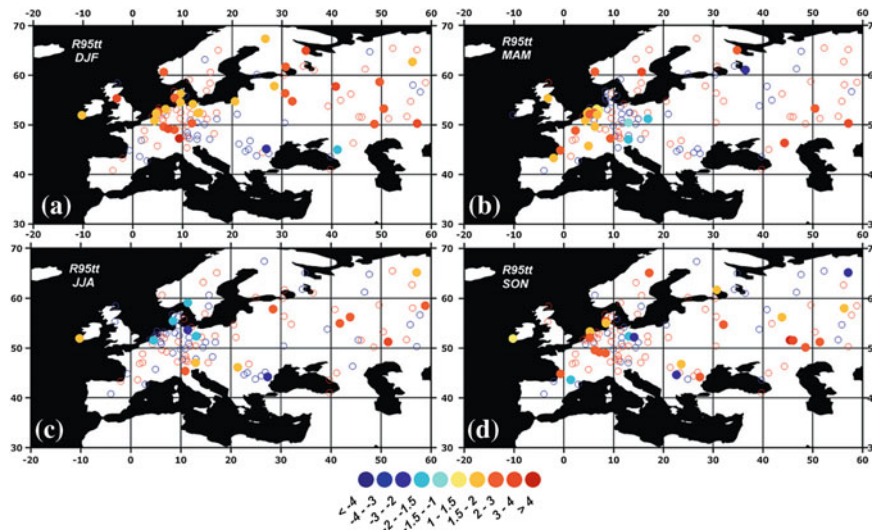


A comparison of annual mean precipitation for 1994–2008 with that for 1979–1993 showed less precipitation in the northern and central Baltic Sea region and more in the southern region (Lehmann et al. 2011). The pattern also varied by season (Fig. 4.16). Spatial distribution and trends in precipitation related to large-scale atmospheric circulation and local landscape factors were analysed for the three Baltic countries (Jaagus et al. 2010). A statistically significant positive trend for 1966–2005 was detected only for eastern Estonia, eastern Latvia and Lithuania as a whole in winter and for western Estonia in summer. A detailed study of summer precipitation data for Helsinki during 1951–2000 did not indicate any trends (Kilpeläinen et al. 2008).

#### 4.5.3 Precipitation Extremes

According to the BACC Author Team (2008) and more recent studies, precipitation increase in northern Europe is associated with an increase in the frequency and intensity of extreme precipitation events. The climatology of extreme precipitation events is usually described by several indices of heavy precipitation. Zolina et al. (2009) showed mostly positive trends in daily precipitation and precipitation totals at 116 stations across Europe, including the Baltic Sea region, during 1950–2000. Although most of the trends are not statistically significant, some positive trends were identified for winter and spring, while negative trends mostly

**Fig. 4.17** Linear trends (% per decade) in the R95tt index (fraction of total precipitation above 95th percentile of rain-day amounts) for **a** winter, **b** spring, **c** summer and **d** autumn for the period 1950–2000. *Open circles* show all trend estimates and *closed circles* denote locations where the trends are significant at 95 %. *Blue* indicates negative trends and *red* indicates positive trends (Zolina et al. 2009)



occurred in summer and, in some cases, in autumn (Fig. 4.17).

Using ensembles of simulations from a general circulation model (HadCM3), Scaife et al. (2008) found large changes in the frequency of 90th percentile precipitation events over Europe in winter, which are related to changes in the NAO from the 1960s to 1990s. This relationship is likely to have led to an increased occurrence of heavy precipitation events over northern Europe and a decreased occurrence over southern Europe and extratropical North Africa during high NAO periods.

The duration of wet periods with daily precipitation exceeding 1 mm increased by 15–20 % across most of Europe during 1950–2008 (Zolina et al. 2010). The increased duration of wet periods was not caused by more wet days, but by short rain events having been regrouped into prolonged wet spells. Becoming longer, wet periods in Europe are now characterised by heavier precipitation. Heavy precipitation events during the past two decades have become more frequently associated with longer wet spells, and precipitation is now heavier than during 1950s and 1960s (Zolina 2011).

Wibig (2009) used daily data at five stations in Poland during the latter half of the twentieth century to analyse the number of days with precipitation exceeding given thresholds, the duration of wet and dry spells and precipitation amount in a single event. A positive trend was detected in the number of wet spells and days with precipitation and a negative trend in mean precipitation during any given spell.

Very few changes were detected at a number of stations in Poland during 1951–2006 (Wibig 2008a; Łupikasza 2010). Only the number of days with precipitation increased significantly. Positive as well as negative trends in indices of precipitation extremes were detected (Fig. 4.18). Decreasing trends dominated in summer, while increasing trends were

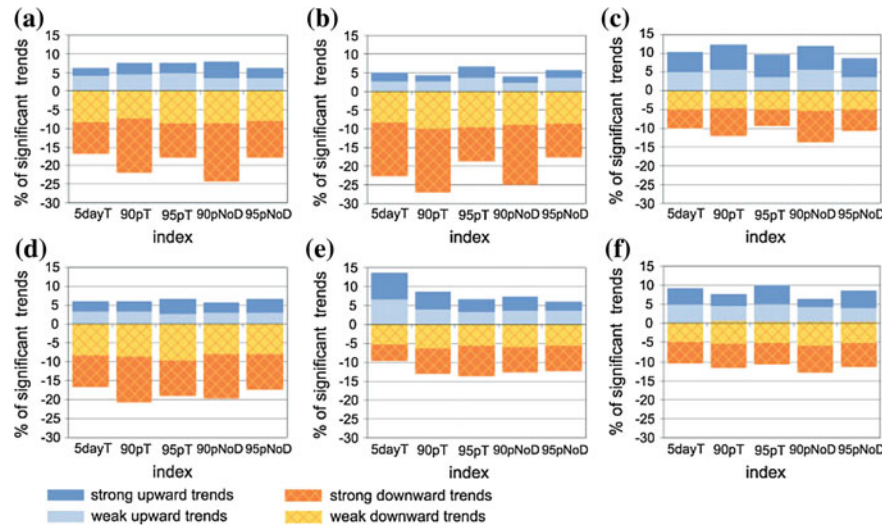
more pronounced in spring and autumn. In summer and winter, decreasing trends were more spatially coherent in southern Poland (Łupikasza 2010). A similar result (i.e. lack of significant trends in extended precipitation time series) was found in Łódź for 1904–2000 (Podstawczyńska 2007); the only trends were an increase in dryness indices in February, April and August.

Trends in extreme precipitation in western Germany during 1950–2004 were analysed by Zolina et al. (2008). Only the northernmost part of the territory belongs to the Baltic Sea basin. Increasing trends in the 95th and 99th percentiles were detected in winter, spring and autumn and with a negative trend occurring in summer in northern Germany.

Kažys et al. (2009) and Rimkus et al. (2011) analysed long-term changes in heavy precipitation events in Lithuania during 1961–2008. They found increasing trends for the number of days with heavy precipitation (above 10 mm) and for heavy precipitation as a percentage of total annual precipitation (Fig. 4.19).

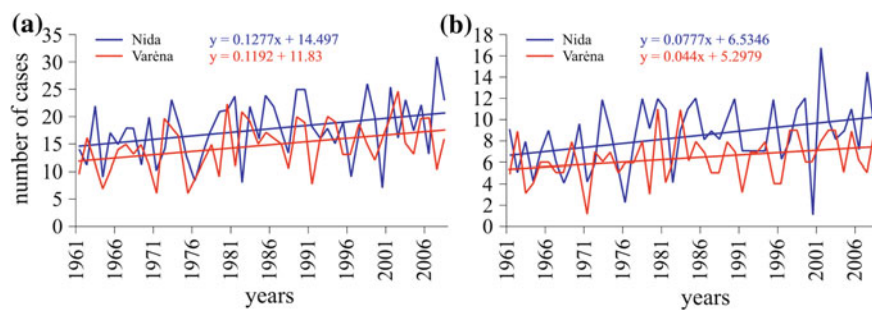
Mean values of daily heavy precipitation as a percentage of the annual total range from 33 to 44 % in Lithuania and in some years can be close to 60 %. In summer and autumn, the percentage of heavy precipitation is much higher than during the rest of the year. Analysis showed positive but mostly non-significant tendencies across large parts of Lithuania during the study period. This means that the temporal variability of precipitation has increased. This tendency is especially clear in summer when an increase in precipitation extremes can be observed in spite of neutral or negative tendencies in the total summer precipitation (Rimkus et al. 2011).

Valiukas (2011) analysed long-term fluctuations and trends in the occurrence of dry periods for Vilnius, Lithuania, during 1891–2010. Two indices—the Standardized



**Fig. 4.18** Percentage of statistically significant trends in extreme precipitation indices calculated for each station and for each of the 30-year moving periods within 1951–2006 in Poland. **a** cool half-year, **b** summer, **c** spring, **d** warm half-year, **e** winter, **f** autumn. Weak trends—significant at  $0.1 < p \leq 0.2$ , and strong trends—significant at  $p \leq 0.1$ .

The number of possible cases was counted by multiplying the number of stations by number of 30-year moving periods (26 stations with data covering the period 1951–2000 multiplied by 21 time series or 21 stations with data covering the period 1951–2006 multiplied by 27 time series) (Łupikasza 2010)



**Fig. 4.19** Number of days with heavy precipitation **a**  $>10$  mm per day and **b**  $>20$  mm in three consecutive days in Nida (western Lithuania) and Varėna (south-eastern Lithuania) in 1961–2008. All trends are

statistically significant according to a Mann–Kendall test (Rimkus et al. 2011)

Precipitation Index (SPI) for different time steps and the Selyaninov Hydrothermic Coefficient (HTC—ratio of precipitation and sum of daily mean temperatures divided by 10)—were used for identifying drought. Statistically significant trends were not detected. A small decrease in dryness was observed, however. A significant increase in the number of days with heavy precipitation ( $\geq 10$  mm) was observed in Latvia during 1924–2008 (Avotniece et al. 2010). Analysis of extreme precipitation and drought events in Estonia using moving averages of daily precipitation revealed an increase in the occurrence of extreme events (Tammets 2007, 2010). During the period 1957–2006, the sum of wet and dry days has grown considerably in Estonia. The main cause was two extremely dry summers, 2002 and 2006. An increase in the number of wet and dry days and persistence of precipitation

events could be due to the increase in persistence of weather patterns discussed in Sect. 4.2.

Przybylak et al. (2007) used the climate extreme index (CEI) according to Karl et al. (1996) to determine the variability of all climate extremes together for Poland over 1951–2005. Using gridded data from the NCEP/NCAR reanalysis, they found that CEI was at a maximum in the 1990s with a non-significant upward trend for the period as a whole. Increasing trends was seen for annual mean number of days with  $T_{\max}$  and  $T_{\min}$  above the 90th percentile and for percentage changes in areas of Poland where the precipitation minus potential evapotranspiration is considerably below normal. A decreasing trend was found for percentage changes in area of Poland with precipitation minus potential evapotranspiration considerably above normal, spatially

averaged frequency of extreme 1-day precipitation totals above 15 mm and a considerably greater than normal mean number of days with precipitation (Przybylak et al. 2007).

## 4.6 Cloudiness and Solar Radiation

### 4.6.1 Cloudiness

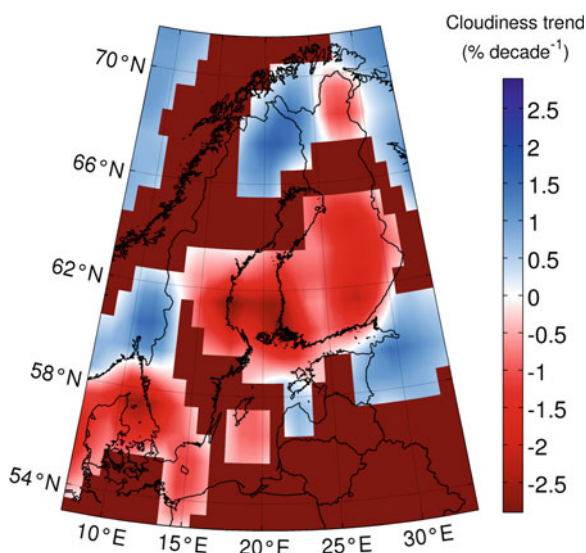
Records of cloudiness and solar radiation are generally shorter than for temperature and precipitation. There were remarkable long-term fluctuations in mean cloudiness and sunshine duration over the Baltic Sea basin during the twentieth century. The trends were of almost opposite sign between the northern (Estonia) and southern (Poland) parts of the study region (BACC Author Team 2008). From the 1950s until the 1990s, total cloud cover decreased over Poland, while the amount of low-level clouds increased over Estonia. The trends were reversed in the 1990s. Fluctuations in sunshine duration were more or less of opposite sign compared to cloudiness. There is a trend of decreasing cloud cover over the Baltic Sea basin of 1 % per decade for 1970–2008 (Fig. 4.20), mostly in spring and autumn (Lehmann et al. 2011). However, cloud cover increased over parts of the mountainous regions of Scandinavia and the south-eastern Gulf of Finland, mainly during winter and summer.

Filipiak and Miętus (2009) undertook a detailed study of spatial and temporal variability in cloudiness at 41 stations in Poland for 1971–2000. Positive as well as negative changes in cloudiness were detected, mainly related to local variability; only a few were statistically significant. Time series of cloudiness in Łódź, Poland, for 1951–2000 indicate some

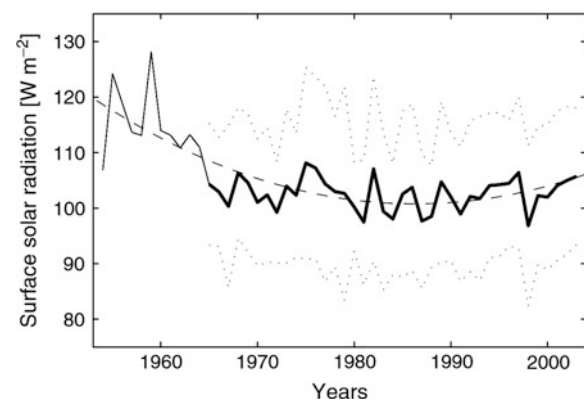
trends in the frequency of specific cloud types (Wibig 2008b). Total cloud cover significantly decreased, while low-level clouds increased during the warm season. Strati-form clouds became less frequent and convective clouds more frequent. An increasing trend in high-level clouds was also observed (Wibig 2008b). A clear decrease in cloudiness after the 1980s was recorded in Lund, Luleå, Sodankylä and Hamburg, that is in the Baltic Sea region (Stjern et al. 2009) mainly in March and September. An increase in annual mean low-level clouds was reported at Tartu-Tõravere, Estonia, from the 1960s to 1980s, and a rapid decrease since 1990s (Russak 2009).

### 4.6.2 Sunshine Duration and Solar Radiation

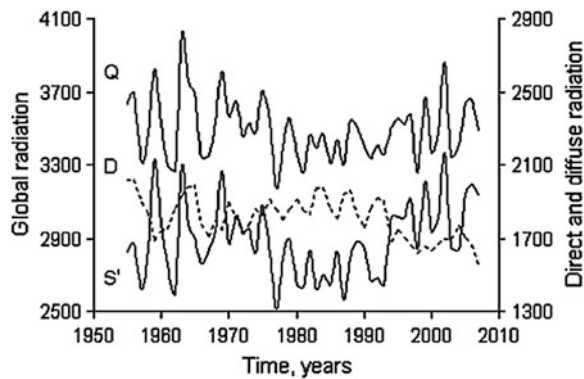
Stjern et al. (2009) presented surface solar radiation data from 11 stations in north-western Europe and the European Arctic within the context of the ongoing discussion on global dimming and global brightening. They compared the records to records of cloud cover and to qualitative information on aerosol concentrations and atmospheric circulation patterns. The authors found a decrease in solar radiation of 18.3 % or 21.5 W m<sup>2</sup> during 1955–2003 (Fig. 4.21), while the 1983–2003 period showed a 4.4 % increase. The earlier part of the time series (before 1965) contains data from only two stations (Hamburg, Copenhagen) and so is less reliable. After 1965, no trend can be distinguished. Similar results on change in solar radiation were obtained for the Tartu-Tõravere Meteorological Station in Estonia during 1955–2007 (Russak 2009). A decrease in global and direct radiation occurred from the 1950s until the end of the 1980s (Fig. 4.22). After that an increasing trend is evident. The



**Fig. 4.20** Linear trend of total cloud cover during 1970–2008 based on meteorological data obtained from SMHI (Lehmann et al. 2011)



**Fig. 4.21** Mean surface solar radiation at 11 stations. *Solid line* indicates where the mean comprises more than three stations and the *dotted line* an envelope of  $\pm 1$  standard deviation. The *dashed line* represents a second-degree regression fit (Stjern et al. 2009)



**Fig. 4.22** Time series of global ( $Q$ ), diffuse ( $D$ ) and direct radiation incident on a horizontal surface ( $S'$ ) at Tartu-Tõravere meteorological station, Estonia. Unit is  $\text{MJ m}^{-2}$  (Russak 2009)

trend in solar radiation is opposite to that in low-level cloud cover.

Changes in global solar radiation based on the NCEP/NCAR dataset were analysed by Uscka-Kowalkowska et al. (2007) for central Europe during 1951–2005. The study area had 35 grid points and covered Poland, eastern Germany, Czech Republic, Slovakia, western Ukraine and Belarus, Lithuania and southern Sweden, areas which mostly belong to the Baltic Sea basin. A general increase in solar radiation was detected during the study period. The strongest trends were found in April, May, November and December, while little change was detected in March and October. Higher trend values are characteristic for the northern part of the study area (Uscka-Kowalkowska et al. 2007). Net radiation and net long wave radiation show a significant positive trend in Tartu-Tõravere, Estonia, during 1961–2002 (Fig. 4.22) (Russak 2009). Variability in the individual components of the radiation budget for the Baltic Sea region was discussed by the BACC Author Team (2008). No new evidence is available.

The studies mentioned here generally indicate negative trends in cloudiness and coincident positive trends in sunshine duration and solar radiation in the major parts of the Baltic Sea basin over recent decades. The number of investigations to date is not sufficient to enable more detailed and reliable conclusions.

## 4.7 Conclusion

Variations and trends of atmospheric parameters in the Baltic Sea region during the last 200–300 years can be summarised as follows. A northward shift in storm tracks and increased cyclonic activity have been observed in recent decades with an increased persistence of weather types. No long-term trend have been observed in annual wind statistics

since the nineteenth century, but considerable variations on (multi-)decadal timescales have been observed. An anthropogenic influence cannot be excluded since the middle of the twentieth century. The pattern in wind and wave heights over the Northern Hemisphere with a NE shift of storm tracks appears to be consistent with combined natural and external forcing. Continued warming has been observed, particularly during spring and is stronger over northern regions (polar amplification) than southern. Bhend and von Storch (2009) detected that the significant warming trends over the Baltic Sea region are consistent with future climate projections under increased greenhouse gas concentrations. No long-term trend was observed for precipitation, but there is some indication of an increased duration of precipitation periods and possibly an increased risk of extreme precipitation events.

**Open Access** This chapter is distributed under the terms of the Creative Commons Attribution Noncommercial License, which permits any noncommercial use, distribution, and reproduction in any medium, provided the original author(s) and source are credited.

## References

- Achberger C, Box JE, Chen D (2007) Nordic region. *Bull Amer Met Soc* 88:S104-S106
- Alexander LV, Tett SFB, Jónsson T (2005) Recent observed changes in severe storms over the United Kingdom and Iceland. *Geophys Res Lett* 32:10.1029/2005GL022371
- Alexandersson H, Schmith T, Iden K, Tuomenvirta H (1998) Long-term variations of the storm climate over NW Europe. *Glob Atmos Ocean Syst* 6:97-120
- Alexandersson H, Tuomenvirta H, Schmith T, Iden K (2000) Trends of storms in NW Europe derived from an updated pressure data set. *Clim Res* 14:71-73
- Andersson HC (2002) Influence of long-term regional and large-scale atmospheric circulation on the Baltic sea level. *Tellus A* 54:76-88
- Avotniece Z, Rodinov V, Lizuma L, Briede A, Kļaviņš M (2010) Trends in the frequency of extreme climate events in Latvia. *Baltica* 23:135-148
- BACC Author Team (2008) Assessment of Climate Change for the Baltic Sea Basin. *Regional Climate Studies*, Springer Verlag, Berlin, Heidelberg
- Barnston AG, Livezey RE (1987) Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. *Mon Weather Rev* 115:1083-1126
- Barredo JI (2010) No upward trend in normalized windstorm losses in Europe: 1970-2008. *Nat Hazards Earth Syst Sci* 10:97-104
- Bärring L, Fortuniak K (2009) Multi-indices analysis of southern Scandinavian storminess 1780–2005 and links to interdecadal variations in the NW Europe–North Sea region. *Int J Climatol* 29:373-384
- Bärring L, von Storch H (2004) Scandinavian storminess since about 1800. *Geophys Res Lett* 31:L20202. doi:10.1029/2004GL020441
- Barriopedro D, Garcia-Herrera R, Lupo AR, Hernandez E (2006) A climatology of northern hemisphere blocking. *J Clim* 19:1042-1063
- Benestad RE, Hanssen-Bauer I, Førland EJ (2007) An evaluation of statistical models for downscaling precipitation and their ability to capture long-term trends. *Int J Climatol* 27:649-665



- Bengtsson L, Hagemann S, Hodges KI (2004) Can climate trends be calculated from reanalysis data? *J Geophys Res* 109:D11111. doi:[10.1029/2004JD004536](https://doi.org/10.1029/2004JD004536)
- Bengtsson L, Hodges KI, Roeckner E (2006) Storm tracks and climate change. *J Clim* 19:3518-3543
- Bhend J, von Storch H (2008) Consistency of observed winter precipitation trends in northern Europe with regional climate change projections. *Clim Dynam* 31:17-28
- Bhend J, von Storch H (2009) Is greenhouse gas warming a plausible explanation for the observed warming in the Baltic Sea catchment area? *Boreal Environ Res* 14:81-88
- Brázdil R, Cromá K, Dobrovolný P, Tolasz R (2009) Climate fluctuations in the Czech Republic. *Int J Climatol* 29:223-242
- Briede A, Lizuma L (2007) Long-term variability of precipitation in the territory of Latvia. In: Kļaviņš M (ed), *Climate change in Latvia*, p 35-44
- Brohan P, Kennedy JJ, Harris I, Tett SFB, Jones PD (2006) Uncertainty estimates in regional and global observed temperature changes: a new dataset from 1850. *J Geophys Res* 111:D12106. doi:[10.1029/2005JD006548](https://doi.org/10.1029/2005JD006548)
- Brönnimann S, Xoplaki E, Casty C, Pauling A, Luterbacher J (2007) ENSO influence on Europe during the last centuries. *Clim Dynam* 28:181-197
- Carter DJT, Draper L (1988) Has the northeast Atlantic become rougher? *Nature* 322:494
- Cassou C, Terray L (2001a) Oceanic forcing of the wintertime low-frequency atmospheric variability in the North Atlantic European sector: a study with the ARPEGE model. *J Clim* 14:4266-4291
- Cassou C, Terray L (2001b) Dual influence of Atlantic and Pacific SST anomalies on the North Atlantic/Europe winter climate. *Geophys Res Lett* 28:3195-3198
- Casty C, Handorf D, Raible CC, González-Rouco JF, Weisheimer A, Xoplaki E, Luterbacher J, Dethloff K, Wanner H (2005) Recurrent climate winter regimes in reconstructed and modelled 500 hPa geopotential height fields over the North Atlantic/European sector 1659-1990. *Clim Dynam* 24:809-822
- Casty C, Raible CC, Stocker TF, Wanner H, Luterbacher J (2007) A European pattern climatology 1766-2000. *Clim Dynam* 29:791-805
- Cattiaux J, Vautard R, Cassou C, Yiou P, Masson-Delmotte V, Codron F (2010) Winter 2010 in Europe: A cold extreme in a warming climate. *Geophys Res Lett* 37:[10.1029/2010GL044613](https://doi.org/10.1029/2010GL044613)
- Chen D, Hellström C (1999) The influence of the North Atlantic Oscillation on the regional temperature variability in Sweden: spatial and temporal variations. *Tellus A* 51:505-516
- Chiang JCH, Kushnir Y, Zebiak SE (2002) Deconstructing Atlantic ITCZ variability: Influence of the local cross-equatorial SST gradient and remote forcing from the eastern equatorial Pacific. *J Geophys Res* 107:148-227
- Clarke ML, Rendell HM (2011) Atlantic storminess and historical sand drift in Western Europe: implications for future management of coastal dunes. *J Coast Conservat* 15:227-236
- Cohen J, Foster J, Barlow M, Saito K, Jones J (2010) Winter 2009–2010: A case study of an extreme Arctic Oscillation event. *Geophys Res Lett* 37:[10.1029/2010GL044256](https://doi.org/10.1029/2010GL044256)
- Compo GP, Whitaker JS, Sardeshmukh PD et al (2011) The Twentieth Century Reanalysis Project. *Q J Roy Meteorol Soc* 137:1-28
- d'Andrea F, Tibaldi S, Blackburn M, Boer G, Déqué M, Dix M, Dugas B, Ferranti L, Iwasaki T, Kitoh A, Pope V, Randall D, Roeckner E, Straus D, Stern W, van den Dool H, Williamson D (1998) Northern hemisphere atmospheric blocking as simulated by 15 atmospheric general circulation models in the period 1979-1988. *Clim Dynam* 4:385-407
- Dawson AG, Hickey K, Holt T, Elliott L, Dawson S, Foster IDL, Wadhams P, Jonsdottir I, Wilkinson J, McKenna J, Davis NR, Smith DE (2002) Complex North Atlantic Oscillation (NAO) index signal of historic North Atlantic storm-track changes. *The Holocene* 12:363-369
- Dessler AE, Davis SM (2010) Trends in tropospheric humidity from reanalysis systems. *J Geophys Res* 115:D19127. doi:[10.1029/2010JD014192](https://doi.org/10.1029/2010JD014192)
- Donat M, Renggli D, Wild S, Alexander L, Leckebusch G, Ulbrich U (2011) Reanalysis suggests long-term upward trends in European storminess since 1871. *Geophys Res Lett* 38:L14703. doi: [10.1029/2011GL047995](https://doi.org/10.1029/2011GL047995)
- Draveniece A (2009) Detecting changes in winter seasons in Latvia: the role of arctic air masses. *Boreal Environ Res* 14:89-99
- Eriksson C (2009) Characterizing and reconstructing 500 years of climate in the Baltic Sea basin. Ph.D. thesis, Göteborgs universitet, Sweden
- Eriksson C, Omstedt A, Overland JE, Percival DB, Mofjeld HO (2007) Characterizing the European sub-arctic winter climate since 1500 using ice, temperature and atmospheric circulation time series. *J Clim* 20:5316-5334
- Feistel R, Nausch G, Heene T, Piechura J, Hagen E (2004) Evidence for a warm water inflow into the Baltic Proper in summer 2003. *Oceanologica* 46:581-598
- Filipiak J, Miętus M (2009) Spatial and temporal variability of cloudiness in Poland, 1971-2000. *Int J Climatol* 29:1294-1311
- Fink AH, Brücher T, Ermert V, Krüger A, Pinto JG (2009) The European storm Kyrill in January 2007: synoptic evolution, meteorological impacts and some considerations with respect to climate change. *Nat Hazards Earth Syst Sci* 9:405-423
- Fraedrich K (1994) An ENSO impact on Europe? *Tellus A* 46:541-552
- García-Serrano J, Losada T, Rodríguez-Fonseca B (2011) Extratropical atmospheric response to the Atlantic Niño decaying phase. *J Clim* 24:1613-1625
- Getzlaff K, Lehmann A, Harlaß J (2011) The response of the general circulation of the Baltic Sea to climate variability. *BALTEX Newsletter* April 2011, p 13-16
- Glowienka-Hense R, Hense A (1992) The effect of an Arctic polynya on the Northern Hemisphere mean circulation and eddy regime: a numerical experiment. *Clim Dynam* 7:155-163
- Graf H, Zanchettin D (2012) Central Pacific El Niño, the “subtropical bridge”, and European climate. *J Geophys Res* 117:[10.1029/2011JD016493](https://doi.org/10.1029/2011JD016493)
- Green J (1977) The weather during July 1976: some dynamical considerations of the drought. *Weather* 32:120-126
- Guirguis K, Gershunov A, Schwartz R, Bennett S (2011) Recent warm and cold daily winter temperature extremes in the Northern Hemisphere. *Geophys Res Lett* 38:[10.1029/2011GL048762](https://doi.org/10.1029/2011GL048762)
- Gustafsson BG, Andersson HC (2001) Modeling the exchange of the Baltic Sea from the meridional atmospheric pressure difference across the North Sea. *J Geophys Res* 106:19731-19744
- Haanpää S, Lehtonen S, Peltonen L, Talockaite E (2006) Impacts of winter storm Gudrun of 7<sup>th</sup> – 9<sup>th</sup> January 2005 and measures taken in the Baltic Sea Region. [www.astra-project.org/sites/download/ASTRA\\_WSS\\_report\\_final.pdf](http://www.astra-project.org/sites/download/ASTRA_WSS_report_final.pdf)
- Hanna E, Cappelen J, Allan R, Jónsson T, de Blanco F, Lillington T, Hickey K (2008) New insights into North European and North Atlantic surface pressure variability, storminess and related climate change since 1830. *J Clim* 21:6739-6766
- Hanssen-Bauer I, Drange H, Hisdal IH, Førland EJ, Lawrence D, Nesje A, Roald L, Sandven S, Sundby S, Vasskog K, Ådlandsvik B (2009) *Climate in Norway 2100*. Norsk klimasenter (in Norwegian)
- Haylock MR, Goodess CM (2004) Interannual variability of European extreme winter rainfall and links with large-scale circulation. *Int J Climatol* 24:759-776
- Hazeleger W, Wang X, Severijns C, Ștefănescu S, Bintanja R, Sterl A, Wyser K, Semmler T, Yang S, van den Hurk B, van Noije T, van der Linden E, van der Wiel K (2012) *EC-Earth V2.2: Description*

- and validation of a new seamless Earth system prediction model. *Clim Dynam* 39:2611-2629
- Hellström S, Lindström G (2008) Regional analys av klimat, vattentillgång och höga flöden. SMHI Rapport Hydrologi 110
- Hess P, Brezowsky H (1952) Katalog der Großwetterlagen Europas. Ber Dt Wetterdienstes in der US-Zone, No. 33
- Higgins LS (1933) An investigation into the problem of the sand dune areas on the south Wales coast. *Archaeol Cambrensis* 88:26-67
- Hines KM, Bromwich DH, Marshall GJ (2000) Artificial surface pressure trends in the NCEP-NCAR reanalysis over the Southern Ocean and Antarctica. *J Clim* 13:3940-3952
- Hogben N (1994) Increases in wave heights over the North Atlantic: A review of the evidence and some implications for the naval architect. *Trans Roy Inst Naval Arch W* 5:93-101
- Hurrell JW (1995) Decadal trends in the North Atlantic Oscillation and relationships to regional temperature and precipitation. *Science* 269:676-679
- Hurrell JW, Deser C (2009) North Atlantic climate variability: The role of the North Atlantic Oscillation. *J Mar Syst* 78:28-41
- Hurrell JW, Folland CK (2002) A change in the summer atmospheric circulation over the North Atlantic. *Exchange* 25:1-3
- Hurrell JW, van Loon H (1997) Decadal variations in climate associated with the North Atlantic Oscillation. *Clim Change* 36:301-326
- Hurrell JW, Kushnir Y, Ottersen G, Visbeck M (2003) An overview of the North Atlantic Oscillation. *The North Atlantic Oscillation: climatic significance and environmental impact. Geophys Monogr* 134:1-36
- Ineson S, Scaife AA, Knight JR, Manners JC, Dunstone NJ, Gray LJ, Haigh JD (2011) Solar forcing of winter climate variability in the Northern Hemisphere. *Nature Geosci* 4:753-757
- IPCC (2007) *Climate Change 2007*. In: Solomon SD, Qin M, Manning Z Chen, M Marquis, KB Averyt, M Tignor, Miller HL (eds), *The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge
- Jaagus J (2006) Climatic changes in Estonia during the second half of the 20th century in relationship with changes in large-scale atmospheric circulation. *Theor Appl Climatol* 83:77-88
- Jaagus J, Kull A (2011) Changes in surface wind directions in Estonia during 1966–2008 and their relationships with large-scale atmospheric circulation. *Est J Earth Sci* 60:220-231
- Jaagus J, Briede A, Rimkus E, Remm K (2010) Precipitation pattern in the Baltic countries under the influence of large-scale atmospheric circulation and local landscape factors. *Int J Climatol* 30:705-720
- Jacobeit J, Jönsson P, Barring L, Beck C, Ekström M (2001) Zonal indices for Europe 1780-1995 and running correlations with temperature. *Clim Change* 48:219-241
- Jacobeit J, Wanner H, Luterbacher J, Beck C, Philipp A, Sturm K (2003) Atmospheric circulation variability in the North Atlantic-European area since the mid-seventeenth century. *Clim Dynam* 20:341-352
- Jaiser R, Dethloff K, Handorf D, Rinke A, Cohen J (2012) Impact of sea ice cover changes on the Northern Hemisphere atmospheric winter circulation. *Tellus A* 64:11595. doi:10.3402/tellusa.v64i0.11595
- Jansson A, Persson C, Strandberg G (2007) 2D meso-scale re-analysis of precipitation, temperature and wind over Europe – ERAMESAN. SMHI Reports Meteorology and Climatology 112
- Jevrejeva S (2001) Severity of winter seasons in the northern Baltic Sea between 1529 and 1990: reconstruction and analysis. *Clim Res* 17:55-62
- Jevrejeva S, Moore JC, Grinsted A (2003) Influence of the Arctic Oscillation and El Niño-Southern Oscillation (ENSO) on ice conditions in the Baltic Sea: The wavelet approach. *J Geophys Res* 108:4677-4687
- Jones PD, Jónsson T, Wheeler D (1997) Extension to the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and South-West Iceland. *Int J Climatol* 17:1433-1450
- Jung T, Vitart F, Ferranti L, Morcrette J-J (2011) Origin and predictability of the extreme negative NAO winter of 2009/10. *Geophys Res Lett* 38:10.1029/2011GL046786
- Kaas E, Li TS, Schmith T (1996) Statistical hindcast of wind climatology in the North Atlantic and Northwestern European region. *Clim Res* 7:97-110
- Kalnay E, Kanamitsu M, Kistler R et al (1996) The NCEP/NCAR 40-year reanalysis project. *Bull Amer Meteorol Soc* 77:437-471
- Karl TR, Knight RW, Easterling DR, Quayle RG (1996) Indices of climate change for United States. *Bull Am Met Soc* 77:279-292
- Kaszewski BM, Filipiuk E (2003) Variability of atmospheric circulation in Central Europe in the summer season 1881-1998 (on the basis of the Hess-Brezowski classification). *Meteorol Z* 12:123-130
- Kažys J, Rimkus E, Bukantis A (2009) Gauskrituliai Lietuvoje 1961–2008 metais (Heavy precipitation events in Lithuania in 1961–2008). *Geografija* 45:44-53 (in Lithuanian with English summary)
- Kažys J, Stankūnavičius G, Rimkus E, Bukantis A, Valiukas D (2011) Long-range alternation of extreme high day and night temperatures in Lithuania. *Baltica* 24:71-82
- Keevallik S (2011) Shifts in meteorological regime of the late winter and early spring in Estonia during recent decades. *Theor Appl Climatol* 105:209-215
- Keevallik S, Soomere T (2008) Shifts in early spring wind regime in north-east Europe. *Clim Past* 4:147-152
- Khokhlova AV, Timofeev AA (2011) Long-term variations of wind regime in free atmosphere over the European territory of Russia. *Russ Meteorol Hydrol* 36:229-238
- Kilpeläinen T, Tuomenvirta H, Jylhä K (2008) Climatological characteristics of summer precipitation in Helsinki during the period 1951–2000. *Boreal Environ Res* 13:67-80
- Kistler R, Kalnay E, Collins W, Saha S, White G, Woolen J, Chelliah M, Ebisuzaki W, Kanamitsu M, Kousky V, van den Dool H, Jenne R, Fiorino M (2001) The NCEP-NCAR 50 year reanalysis. *Bull Am Meteorol Soc* 82:247-267
- Klavins M, Rodinov V (2010) Influence of large-scale atmospheric circulation on climate in Latvia. *Boreal Environ Res* 15:533-543
- Klavins M, Rodinov V, Draveniece A (2007) Large-scale atmospheric circulation processes as driving force in the climatic turning points and regime shifts in the Baltic region. In: Klavins M (ed) *Climate Change in Latvia*, University of Latvia, p 45-57
- Klavins M, Briede A, Rodinov V (2009) Long term changes in ice and discharge regime of rivers in the Baltic region in relation to climatic variability. *Clim Change* 95:485-495
- Klein Tank AMG, Können GP (2003) Trends in indices of daily temperature and precipitation extremes in Europe, 1946-99. *J Clim* 16:3665-3680
- Kont A, Endjärv E, Jaagus J, Lode E, Orviku K, Ratas U, Rivis R, Suursaar Ü, Tõnisson H (2007). Impact of climate change on Estonian coastal and inland wetlands – a summary with new results. *Boreal Environ Res* 12:653-671
- Kont A, Jaagus J, Orviku K, Palginnõmm V, Ratas U, Rivis R, Suursaar Ü, Tõnisson H (2011) Natural development and human activities on Saaremaa Island (Estonia) in the context of climate change and integrated coastal zone management. In: Schernewski G, Hofstede J, Neumann T (eds) *Global change and Baltic coastal zones*. Berlin, Springer, p 117-134
- Koslowski G, Glaser R (1999) Variations in reconstructed winter severity in the western Baltic from 1501 to 1995 and their

- implications from the North Atlantic Oscillation. *Clim Change* 41:175-191
- Kriauciuniene J, Meilutyte-Barauskiene D, Reihan A, Koltsova T, Lizuma L, Sarauskiene D (2012) Variability in temperature, precipitation and river discharge in the Baltic States. *Boreal Environ Res* 17:150-162
- Krueger O, von Storch H (2011) Evaluation of an air pressure based proxy for storm activity. *J Clim* 24:2612-2619
- Krueger O, von Storch H (2012) The informational value of pressure-based single-station proxies for storm activity. *J Atmos Ocean Tech* 29:569-580
- Krueger O, Schenk F, Feser F, Weisse R (2013) Inconsistencies between long-term trends in storminess derived from the 20CR reanalysis and observations. *J Clim* 26:868-874
- Kull A, Kull A, Jaagus J, Kuusemets V, Mander Ü (2008) The effects of fluctuating climatic and weather events on nutrient dynamics in a narrow mosaic riparian peatland. *Boreal Environ Res* 13:243-263
- Kyselý J (2000) Changes in the occurrence of extreme temperature events. PhD Thesis, Faculty of Mathematics and Physics, Charles University, Prague (in Czech, with English summary)
- Kyselý J (2002) Temporal fluctuations in heat waves at Prague-Klementinum, the Czech Republic, from 1901-1997 and their relationships to atmospheric circulation. *Int J Climatol* 22:33-50
- Kyselý J (2010) Recent severe heat waves in central Europe: how to view them in long-term prospect? *Int J Climatol* 30:89-109
- Kyselý J, Huth R (2006) Changes in atmospheric circulation over Europe detected by objective and subjective methods. *Theor Appl Climatol* 85:19-36
- Lamb HH, Frydendahl K (1991) *Historic storms of the North Sea, British Isles and Northwest Europe*. Cambridge University Press, Cambridge
- Lass HU, Matthäus W (1996) On temporal wind variations forcing salt water inflows into the Baltic Sea. *Tellus A* 48:663-671
- Leckebusch GC, Ulbrich U (2004) On the relationship between cyclones and extreme windstorms over Europe under climate change. *Glob Planet Change* 44:181-193
- Leckebusch GC, Koffi B, Ulbrich U, Pinto JG, Spanghehl T, Zacharias S (2006) Analysis of frequency and intensity of winter storm events in Europe on synoptic and regional scales from a multimodel perspective. *Clim Res* 31:59-74
- Lehmann A, Getzlaff K, Harlaß J (2011) Detailed assessment of climate variability in the Baltic Sea area for the period 1958 to 2009. *Clim Res* 46:185-196
- Li J, Wang J (2003) A new North Atlantic Oscillation index and its variability. *Adv Atmos Sci* 20:661-676
- Lindenberg J, Mengelkamp H-T, Rosenhagen G (2012) Representativity of near surface wind measurements from coastal stations at the German Bight. *Met Z* 21:99-106
- Linkosalo T, Häkkinen R, Terhivuo J, Tuomenvirta H, Hari P (2009) The time series of flowering and leaf bud burst of boreal trees (1846-2005) support the direct temperature observations of climatic warming. *Agr Forest Meteorol* 149:453-461
- Lizuma L, Kļaviņš M, Briede A, Rodinovs V (2007) Long-term changes of air temperature in Latvia. In: Kļaviņš M (ed) *Climate change in Latvia*, p 11-20
- Lizuma L, Briede A, Kļaviņš M (2010) Long-term changes of precipitation in Latvia. *Hydrol Res* 41:241-252
- Löptien U, Zolina O, Gulev S, Latif M, Soloviev V (2008) Cyclone life cycle characteristics over the Northern Hemisphere in coupled GCMs. *Clim Dynam* 31:507-532
- Luo D, Wan H (2005) Decadal variability of wintertime North Atlantic and Pacific blockings: A possible cause. *Geophys Res. Lett* 32: L23810. [10.1029/2005GL024329](https://doi.org/10.1029/2005GL024329)
- Lupikasza E (2010) Spatial and temporal variability of extreme precipitation in Poland in the period 1951–2006. *Int J Climatol* 30:991-1007
- Luterbacher J, Rickli R, Xoplaki E, Tinguely C, Beck C, Pfister C, Wanner H (2001) The Late Maunder Minimum (1675-1715) – a key period for studying decadal scale climatic change in Europe. *Clim Change* 49:441-462
- Luterbacher J, Xoplaki E, Dietrich D, Jones PD, Davies TD, Portis D, Gonzalez-Rouco JF, von Storch H, Gyalistras D, Casty C, Wanner H (2002) Extending North Atlantic Oscillation reconstructions back to 1500. *Atmos Sci Lett* 2:114-124
- Matulla C, Schoener W, Alexandersson H, von Storch H, Wang XL (2008) European storminess: Late 19th century to present. *Clim Dynam* 31:125-130
- Meehl GA, Stocker TF, Collins WD et al (2007) Global climate projections. In: Solomon S, Qin D, Manning M, Chen Z and others (eds), *Climate change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, p 749-844
- Mesquita MDS, Hodges KI, Atkinson DA, Bader J (2010) Sea-ice anomalies in the Sea of Okhotsk and the relationship with storm tracks in the Northern Hemisphere during winter. *Tellus A* 63:312-323
- Moberg A, Jones PD (2005) Trends in indices for extremes in daily temperature and precipitation in central Europe. *Int J Climatol* 25:1149-1171
- Moberg A, Bergström H, Kringsman JR, Svanered O (2002) Daily air temperature and pressure series for Stockholm (1756–1998). *Climatic Change* 53:171-212
- Moberg A, Alexandersson H, Bergström H, Jones PD (2003) Were the southern Swedish summer temperatures before 1860 as warm as measured? *Int J Climatol* 23:1495-1521
- Moberg A, Tuomenvirta H, Nordli Ø (2005) Recent climatic trends. In: Seppälä M (ed), *The Physical Geography of Fennoscandia*. Oxford Regional Environments Series, p 113-133
- Moberg A, Jones PD, Lister D et al (2006) Indices for daily temperature and precipitation extremes in Europe analysed for the period 1901–2000. *J Geophys Res* 111:D22106. Doi:[10.1029/2006JD007103](https://doi.org/10.1029/2006JD007103)
- Moore, GWK, Renfrew IA (2012) Cold European winters: interplay between the NAO and the East Atlantic mode. *Atmos Sci Lett* 13:1-8
- Namias J (1947) Characteristics of the general circulation over the northern hemisphere during the abnormal winter 1946–47. *Mon Weather Rev* 75:145-152
- Nilsson C, Stjernquist I, Barring L, Schlyter P, Jönsson AM, Samuelsson H (2004) Recorded storm damage in Swedish forests 1901-2000. *Forest Ecol Manag* 199:165-173
- Nordli Ø, Lundstad E, Ogilvie AEJ (2007) A late winter-early spring temperature reconstruction for southeastern Norway from 1758 to 2006. *Ann Glaciol* 46:404-408
- Omstedt A, Chen D (2001) Influence of atmospheric circulation on the maximum ice extent in the Baltic Sea. *J Geophys Res* 106:4493-4500
- Omstedt A, Pettersen C, Rodhe J, Winsor P (2004) Baltic Sea climate: 200 yr of data on air temperature, sea level variations, ice cover and atmospheric circulation. *Clim Res* 25:205-216
- Ouzeau G, Cattiaux J, Douville H, Ribes A, Saint-Martin D (2011) European cold winter 2009–2010: How unusual in the instrumental record and how reproducible in the ARPEGE-Climat model? *Geophys Res Lett* 38:[10.1029/2011GL047667](https://doi.org/10.1029/2011GL047667)
- Overland JE, Wang M (2010) Large-scale atmospheric circulation changes are associated with the recent loss of Arctic sea ice. *Tellus A* 62:1-9

- Paltridge G, Arking A, Pook M (2009) Trends in middle- and upper-level tropospheric humidity from NCEP reanalysis data. *Theor Appl Climatol* 98:351-359
- Petoukhov V, Semenov VA (2010) A link between reduced Barents-Kara sea ice and cold winter extremes over northern continents, *J Geophys Res* 115:D21111. doi:10.1029/2009JD013568
- Pinto JG, Ulbrich U, Leckebusch GC, Spanghel T, Reyers M, Zacharias S (2007) Changes in storm track and cyclone activity in three SRES ensemble experiments with the ECHAM5/MPI-OM1 GCM. *Clim Dynam* 29:195-210
- Pinto JG, Zacharias S, Fink AH, Leckebusch GC, Ulbrich U (2009) Environmental factors contributing to the development of extreme cyclones and their relationship with NAO. *Clim Dynam* 32:711-737
- Podstawczyńska A (2007) Okresy suche i wilgotne w Łodzi w XX wieku (Dry and wet periods in Łódź in the XXth century). *Acta Universitatis Lodzianensis, Folia Geographica Physica* 8:9-25
- Pozo-Vázquez D, Esteban-Parra MJ, Rodrigo FS, Castro-Díez Y (2001) The association between ENSO and winter atmospheric circulation and temperature in the North Atlantic region. *J Clim* 14:3408-3420
- Przybylak R, Vízi Z, Arazny A, Kejna M, Maszewski R, Uscka-Kowalkowska J (2007) Poland's climate extremes index, 1951-2005. *Geogr Polonica* 80:47-58
- Raible CC, Della-Marta PM, Schwierz C, Wernli H, Blender R (2008) Northern Hemisphere extratropical cyclones: A comparison of detection and tracking methods and different reanalyses. *Mon Weather Rev* 136:880-897
- Rex DF (1950a) Blocking action in the middle troposphere and its effect upon regional climate. Part I: An aerological study of blocking action. *Tellus* 2:196-211
- Rex DF (1950b) Blocking action in the middle troposphere and its effect upon regional climate. Part II: The climatology of blocking action. *Tellus* 2:275-301
- Rimbu N, Lohmann G (2011) Winter and summer blocking variability in the North Atlantic region – evidence from long-term observational and proxy data from southwestern Greenland. *Clim Past* 7:543-555
- Rimkus E, Kažys J, Bukantis A, Krotovas A (2011) Temporal variation of extreme precipitation events in Lithuania. *Oceanologia* 53:259-277
- Rivza P, Brunina L (2009) Problem of the Baltic coastal erosion in Latvia. *Econ Sci Rural Dev* 19:52-57
- Rogers JC (1984) The association between the North Atlantic Oscillation and the Southern Oscillation in the Northern Hemisphere. *Mon Weather Rev* 112:1999-2015
- Russak V (2009) Changes in solar radiation and their influence on temperature trend in Estonia (1955–2007). *J Geophys Res* 114:D00D01. doi:10.1029/2008JD010613
- Scaife AA, Folland CK, Alexander LV, Moberg A, Knight JR (2008) European climate extremes and the North Atlantic Oscillation. *J Clim* 21:72-83
- Schenk F, Zorita E (2011) New dataset of high resolution atmospheric forcing fields since 1850. *Baltex Newsletter* 14:10-13
- Schenk F, Zorita E (2012) Reconstruction of high resolution atmospheric fields for Northern Europe using analog-upscaling. *Clim Past* 8:1681-1703
- Schmidt H, von Storch H (1993) German Bight storms analyzed. *Nature* 365:791
- Seager R, Kushnir Y, Nakamura J, Ting M, Naik N (2010) Northern Hemisphere winter snow anomalies: ENSO, NAO and the winter of 2009/10. *Geophys Res Lett* 37:10.1029/2010GL043830
- Sepp M (2009) Changes in frequency of Baltic Sea cyclones and their relationship with NAO and Climate in Estonia. *Boreal Environ Res* 14:143-151
- Slonosky VC, Jones PD, Davies TD (2000) Variability of the surface atmospheric circulation over Europe, 1774-1995. *Int J Climatol* 20:1875-1897
- Slonosky VC, Jones PD, Davies TD (2001) Atmospheric circulation and surface temperature in Europe from the 18th century to 1995. *Int J Climatol* 21:63-75
- Smits A, Klein Tank AMG, Können GP (2005) Trends in storminess over the Netherlands, 1962–2002. *Int J Climatol* 25:1331-1344
- Stendel M, Mogensen IA, Christensen JH (2006) Influence of various forcings on global climate in historical times using a coupled atmosphere–ocean general circulation model. *Clim Dynam* 26:1-15
- Stjern CW, Kristjánsson JE, Hansen AW (2009) Global dimming and global brightening – an analysis of surface radiation and cloud cover data in northern Europe. *Int J Climatol* 29:643-653
- Stroeve JC, Maslanik J, Rigor I, Meier W, Fowler C (2011) Sea ice response to an extreme negative phase of the Arctic Oscillation during winter 2009/2010. *Geophys Res Lett* 38:10.1029/2010GL045662
- Sutton RT, Hodson DLR (2003) Influence of the ocean on North Atlantic climate variability 1871-1999. *J Clim* 16:3296 -3313
- Suursaar Ü, Kullas T, Otsmann M, Saaremäe I, Kuik J, Merilain M (2006) Cyclone Gudrun in January 2005 and modeling its hydrodynamic consequences in the Estonian coastal waters. *Boreal Environ Res* 11:143-159
- Suvilampi E (2010) Voimakkaiden geostrofisten tuulten alueellisuus ja muutokset Suomessa vuosina 1884–2100. Pro-gradu tutkielma, Maantiede, Turun yliopisto, Turku
- Taws SL, Marsh R, Wells NC, Hirschi J (2011) Re-emerging ocean temperature anomalies in late-2010 associated with a repeat negative NAO. *Geophys Res Lett* 38:10.1029/2011GL048978
- Tammets T (2007) Distribution of extreme wet and dry days in Estonia in last 50 years. *Proc Estonian Acad Sci Eng* 13:252-259
- Tammets T (2010) Estimation of extreme wet and dry days through moving totals in precipitation time series and some possibilities for their consideration in agrometeorological studies. *Agron Res* 8:433-438
- Thompson DWJ, Wallace JM (1998) The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. *Geophys Res Lett* 25:1297-1300
- Tietäväinen H, Tuomenvirta H, Venäläinen A (2009) Annual and seasonal mean temperature in Finland during the last 160 years based on gridded temperature data. *Int J Climatol* 30:2247-2256
- Tinz B (1996) On the relation between annual maximum extent of ice cover in the Baltic Sea and sea level pressure as well as air temperature field. *Geophysica* 32:319-341
- Trenberth KE, Smith L (2005) The mass of the atmosphere: A constraint on global analyses. *J Clim* 18:864-875
- Trenberth KE, Jones PD, Ambenje P, Bojariu R, Easterling D, Klein Tank A, Parker D, Rahimzadeh F, Renwick JA, Rusticucci M, Soden B, Zhai P (2007) Observations: surface and atmospheric climate change. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge
- Trigo IF (2006) Climatology and interannual variability of storm-tracks in the Euro-Atlantic sector: a comparison between ERA-40 and NCEP/NCAR reanalyses. *Clim Dynam* 26:127-143
- Ulbrich U, Leckebusch GC, Pinto JG (2009) Extra-tropical cyclones in the present and future climate: a review. *Theor Appl Climatol* 96:117-131

- Uscka-Kowalkowska J, Przybylak R, Vizi Z, Arazny A, Kejna M, Maszewski R (2007) Variability to global solar radiation in Central Europe during the period 1951-2005 (on the basis of data from NCEP/NCAR reanalysis project). *Geographia Polonica* 80:59-68
- Valdmann A, Käärd A, Kelpšaitė K, Kurennoy D, Soomere T (2008) Marine coastal hazards for the eastern coasts of the Baltic Sea. *Baltica* 21:3-12
- Valiukas D (2011) Sausringi laikotarpiai Vilniuje 1891–2010 m (Dry periods in 1891-2010 in Vilnius) *Geography* 47:9-18 (in Lithuanian with English summary)
- van Loon H, Rogers HJ (1978) The seesaw in winter temperature between Greenland and northern Europe. Part I: General description. *Mon Weather Rev* 106:296-310
- Vial J, Osborn TJ (2012) Assessment of atmosphere-ocean general circulation model simulations of winter northern hemisphere atmospheric blocking. *Clim Dynam* 39:95-112
- von Storch H (1987) A statistical comparison with observations of control and El Niño simulations using the NCAR CCM. *Beitr Phys Atmos* 60:464-477
- von Storch H, Weisse R (2008) Regional storm climate and related marine hazards in the Northeast Atlantic. *Climate Extremes and Society*. Diaz HF, Murnane RJ (eds) Cambridge University Press, p 54-73
- Wallace JM, Gutzler DS (1981) Teleconnections in the geopotential height field during the Northern Hemisphere winter. *Mon Weather Rev* 109:784-812
- Wang XL, Swail VR, Zwiers FW (2006) Climatology and changes of extratropical storm tracks and cyclone activity: Comparison of ERA-40 with NCEP/NCAR reanalysis for 1958–2001. *J Clim* 19:3145-3166
- Wang XL, Zwiers FW, Swail VR, Feng Y (2009a) Trends and variability of storminess in the Northeast Atlantic region, 1874–2007. *Clim Dynam* 33:1179-1195
- Wang XL, Swail VR, Zwiers FW, Zhang X, Feng Y (2009b) Detection of external influence on trends of atmospheric storminess and northern oceans wave heights. *Clim Dynam* 32:189-203
- Wang XL, Wan H, Zwiers FW, Swail VR, Compo GP, Allan RJ, Vose RS, Jourdain S, Yin X (2011) Trends and low-frequency variability of storminess over western Europe, 1878-2007. *Clim Dynam* 37:2355-2371
- WASA (1998) Changing waves and storms in the Northeast Atlantic? *Bull Am Meteorol Soc* 79:741-760
- Weisse R, von Storch H, Feser F (2005) Northeast Atlantic and North Sea storminess as simulated by a regional climate model 1958-2001 and comparison with observations. *J Clim* 18:465-479
- Wern L, Barring L (2009) Sveriges vindklimat 1901-2008 - Analys av förändring i geostrofisk vind. SMHI report Meteorologi 138
- Werner PC, Gerstengarbe F-W, Fraedrich K, Oesterle H (2000) Recent climate change in the North Atlantic/European sector. *Int J Climatol* 20:463-471
- Wibig J (2007) Fale ciepła i chłodu w Środkowej Polsce na przykładzie Łódzi (Waves of warmth and coldness in Central Poland on the example of Łódź). *Acta Universitatis Lodziensis, Folia Geographica Physica* 8:27-61
- Wibig J (2008a) Variability of weather extremes in Poland in the period 1951-2006. In: Sigro Rodriguez J, Brunet India M, Aguilar Anfrons E (eds.) *Cambio climatico regional y sus impactos*. Publicaciones de la Asociacion Espanola de Climatologia A6:469-479
- Wibig J (2008b) Cloudiness variations in Łódź in the second half of the 20th century. *Int J Climatol* 28:479-491
- Wibig J (2009) Variability of daily precipitation totals in Poland (1951-2000). *Geographia Polonica* 82:21-32
- Wibig J, Podstawczyńska A, Rzepa M, Piotrowski P (2009) Coldwaves in Poland – frequency, trends and relationships with atmospheric circulation. *Geographia Polonica* 82:47-59
- Woolings T, Hoskins BJ, Blackburn ML, Berrisford P (2008) A new Rossby wave-breaking interpretation of the North Atlantic Oscillation. *J Atmos Sci* 65:609-625
- Yang S, Christensen JH, Stendel M, Hansen AW (2011) Arctic sea ice reduction and the extreme cold winters in Europe revisited. Poster TH102A, Session C39 at WCRP Conference, 24-28 October 2011, Denver, CO, USA,
- Ylhäisi JS, Tietäväinen H, Peltonen-Sainio P, Venäläinen A, Eklund J, Räisänen J, Jylhä K (2010) Growing season precipitation in Finland under recent and projected climate. *Nat Hazards Earth Syst Sci* 10:1563-1574
- Zolina OG (2011) Changes in the duration of synoptic rainy periods in Europe from 1950 to 2008 and their relation to extreme precipitation. *Dokl Earth Sci* 436:690-695
- Zolina O, Simmer C, Kapala A, Bachner S, Gulev S, Maechel H (2008) Seasonally dependent changes of precipitation extremes over Germany since 1950 from a very dense observational network. *J Geophys Res* 113:D06110. doi:10.1029/2007JD008393
- Zolina O, Simmer C, Belyaev K, Kapala A, Gulev S (2009) Improving estimates of heavy and extreme precipitation using daily records from European rain gauges. *J Hydrometeorol* 10:701-716
- Zolina O, Simmer C, Gulev S, Kollet S (2010) Changing structure of European precipitation: longer wet periods leading to more abundant rainfalls. *Geophys Res Lett* 37:L06704. doi:10.1029/2010GL042468