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Observed changes and variability of atmospheric parameters in the Baltic Sea region during the last 200 years

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ABSTRACT: The Baltic Sea is located in Northern Europe and exhibits significant climate variability, with influence of air masses from arctic to subtropical origin. By updating and discussing results described in the framework of the BACC project (BALTEX Assessment of Climate Change for the Baltic Sea Basin), this study presents observed changes in atmospheric parameters during the last 200 yr. Circulation patterns show large decadal variability with a northward shift of storm tracks and increased cyclonic activity in recent decades with increased persistence of weather types. However, the wind climate shows no robust long-term trends, and is dominated by pronounced (multi-)decadal variability. Near-surface temperatures show continued warming, in particular during spring and winter; this is stronger over northern regions. Up to this point, no long-term trends are detectable for precipitation, although some regional indications exist for an increased length of precipitation periods, and possibly an increased risk of extreme precipitation events.

KEY WORDS: Climate change · Climate variability · Baltic Sea region · Observations · Historical climate

1. INTRODUCTION

The Baltic Sea is a brackish, semi-enclosed sea located between central and Northern Europe (53°–66° N and 10°–30° E). The drainage basin is roughly 4 times the surface area of the sea with land use ranging from densely populated agricultural areas in the south to sparsely populated forested regions in the north. Situated in the extratropics of the Northern Hemisphere, the Baltic Sea region can be under the influence of air masses from arctic to subtropical origin. It is therefore a region of very variable weather conditions and far reaching teleconnections. The region is dominated mainly by 2 large-scale pressure systems over the northeastern Atlantic, 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, there are westerly winds over the region, although any other wind direction is also observed frequently. The zonal pressure gradient over the North Atlantic and the position of the Icelandic Low and Azores High mainly influence variations of atmospheric parameters like wind, temperature and humidity in the region. The climate of the Baltic Sea shows a strong seasonal cycle, but also large inter-annual to multi-decadal variability. It is important to understand and describe potential long-term changes and variability of atmospheric parameters, as they have large impacts on hydrological, oceanographic and biogeochemical processes in the region. The mostly shallow and complex bathymetry of the semi-enclosed Baltic

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Sea makes the ecosystem very sensitive to any atmospheric changes. Here, the precipitation and temperature control the river runoff to the Baltic Sea with a well-known relation between atmospheric circulation patterns and sea-level, sea-ice, salinity and oxygen. The storm frequency clearly influences Baltic Sea mixing and marine ecosystems.

Here we present an updated summary of existing data and previous investigations done within the framework of the BACC (BALTEX Assessment of Climate Change for the Baltic Sea Basin) projects (BACC Author Team 2008, 2014). The data is extended to also cover 2013, as well as a brief analysis of the blocking feature and impact of Arctic ice reduction. We focus on the last 200 yr to rely on robust *in situ* measurements only. The Baltic Sea area is relatively unique in terms of long-term data, with a dense observational network covering an extended time period, although many national (sub-) daily observations still await digitization and homogenization.

A network of stations with continuous and relatively accurate measurements has been developed since the middle of the 19th century (few stations were established in the middle of the 18th century). Satellites were introduced in 1978, which significantly improved data coverage, providing higher resolution in space and time. Data that spans extended periods cannot be expected to be homogeneous in time. It is therefore important that conclusions concerning long-term trends are drawn from homogenized data. Also gridded data sets cannot be expected to be homogeneous as the density and quality of the assimilated data undergoes spatial and temporal changes. Temperature measurements cover relatively extended periods, and significant efforts have been made to homogenize station data and databases. It can thus be expected that trends in temperature are relatively robust, even though uncertainties are larger for earlier data (e.g. Brohan et al. 2006). Direct wind observations cover usually relatively short periods and suffer from strong inhomogeneities (e.g. WASA 1998), so that most studies rely on reanalysis data or on reconstructions based on pressure observations (see Feser et al. 2014 for a review). So far, pressure based reconstructions might yield more robust long-term trend analysis than reconstructions based on long-term reanalysis products over the Euro-Atlantic region since 1871 (Krueger et al. 2013, Dangendorf et al. 2014). The highly variable nature of precipitation with large local to regional differences together with the limited availability of data makes homogenisation of this quantity difficult.

It is during the latter part of the investigated period that the potential recent anthropogenic influence could be seen. As little long-term observations are available for many variables, it remains difficult to interpret recent changes in the context of the last 200 yr. The focus is here on physical parameters characterizing the atmosphere, like circulation patterns, wind, temperature, and precipitation, where reliable data allows such an analysis.

2. LARGE-SCALE CIRCULATION PATTERNS

The atmospheric circulation in the European/Atlantic sector plays an important role for the regional climate of the Baltic Sea basin (Hurrell 1995, Slonosky et al. 2000, 2001, Moberg & Jones 2005, Achberger et al. 2007). It can be described mainly by the North Atlantic Oscillation (NAO), the zonality of the atmospheric flow and the blocking frequency. The first mode of a principal component analysis (PCA) of winter sea-level pressure (SLP) variability is the NAO, which in winter shares a close correlation with atmospheric and marine state variables of the Baltic Sea region (where a positive index indicates mild and wet winters and a negative index indicates cold and dry winters). Fig. 1 shows the winter NAO index for 1823 to 2013. In a long term perspective, the behavior of the NAO is rather irregular. However, for the last 5 decades, specific periods are apparent. Beginning in the mid-1960s, a positive trend has been observed, i.e. toward 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 tendency towards more negative NAO indices, in other words, a more meridional circulation. The strongly positive NAO phase in the 1990s can be seen as part of a multi-decadal variation comparable to that at the beginning of the 20th century rather than a trend towards more positive values (Jones et al. 1997, Slonosky et al. 2000, 2001, Moberg et al. 2005).

The second mode of the PCA is called the East Atlantic pattern (Wallace & Gutzler 1981) and represents changes in the north–south location of the NAO (Woollings et al. 2008). It is characterized by an anomaly in the northeastern North Atlantic, between the NAO centers of action. Negative values mean a southward displacement of the NAO centers of action and lower temperatures (Moore & Renfrew 2011); positive values correspond to more zonal winds over Europe and expected higher tempera-

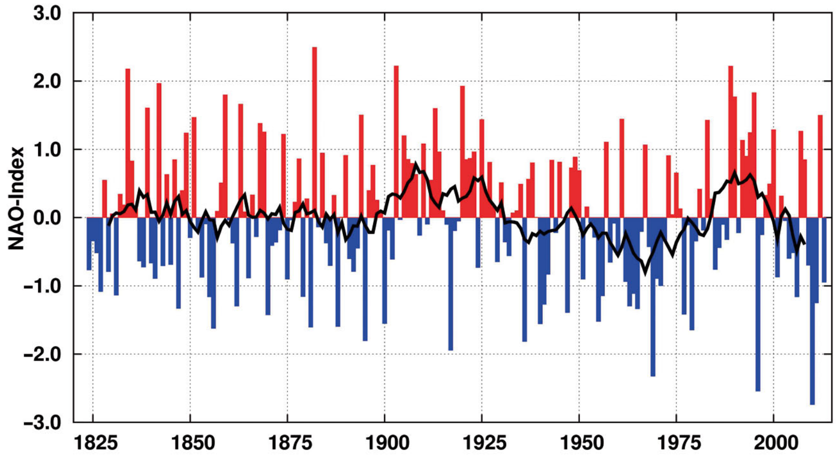

Fig. 1. NAO index for boreal winters (DJFM) of 1823–2013 (Jones et al. 1997). Updated via www.cru.uea.ac.uk/~timo/datapages/naoi.htm and re-normalized for the period 1824–2013. Black line: 11 yr running mean highlights decadal-scale variability. Bars: positive (red) and negative (blue) indices

tures. The third dominant mode is the Scandinavian pattern, also called the Eurasian (Wallace & Gutzler 1981) or blocking pattern (Hurrell & Deser 2009), which in its positive phase is characterized by a high pressure anomaly over Scandinavia and a low pressure anomaly over Greenland. This indicates an east–west shift of the northern center of variability defining the NAO. The corresponding negative phase is sometimes referred to as an Atlantic ridge.

Rimbu & Lohmann (2011) constructed a North Atlantic blocking index which also shows pronounced decadal variations with more frequent blocking in the 1910s, 1940s and 1960s as well as after 1995, and low blocking in particular in the 1920s, 1970s and early 1990s. Fig. 2 shows the blocking frequency for 1948 to 2012 using 3 definitions with some differences in the patterns. Together with the NAO, these large variations in blocking frequency are in very good agreement with the observed mean winter temperature (see Fig. 6b) and wind (see Fig. 5) anomalies and annual storminess variations (see Fig. 4) in the Baltic Sea region during the 20th century.

Kyselý & Huth (2006) show an intensification of zonal circulation in particular during the 1970s and 1980s, followed by intensified cyclonic activity over Fennoscandia along with more frequent blocking situations over the British Isles. While there is a general increase in the zonality of the flow in winter, the opposite takes place in summer (Kaszewski & Filipiuk 2003, Wang et al. 2009a, 2011). There are also indications (Kyselý 2000, 2002, Werner et al. 2000, Kyselý & Huth 2006) that weather types are more persistent than in earlier decades. For all weather types (zonal, meridional, or anticyclonic), an increase in persistence in the order of 2 to 4 d is found from the 1970s to the 1990s. This increase in persistence may contribute to an increase in the occurrence of extreme events.

Circulation changes in the Baltic Sea region may also be related to climate anomalies in other regions. Many authors discuss the cold temperatures of the winters 2009–2010 and 2010–2011 over large parts of Europe (including the Baltic Sea region). Overland & Wang (2010) point out a relationship of circulation changes in the Baltic Sea region to the loss of sea ice in the Arctic. For a reduction in Arctic summer sea ice, additional heat is stored in the Arctic Ocean due to the increase in late summer open water area, and contributes to an increase in the lower tropospheric relative topography (thickness of the layer between 500 and 1000 hPa surfaces). As a consequence, anomalous easterly winds are observed in the lower troposphere along 60° N in many regions. Petoukhov

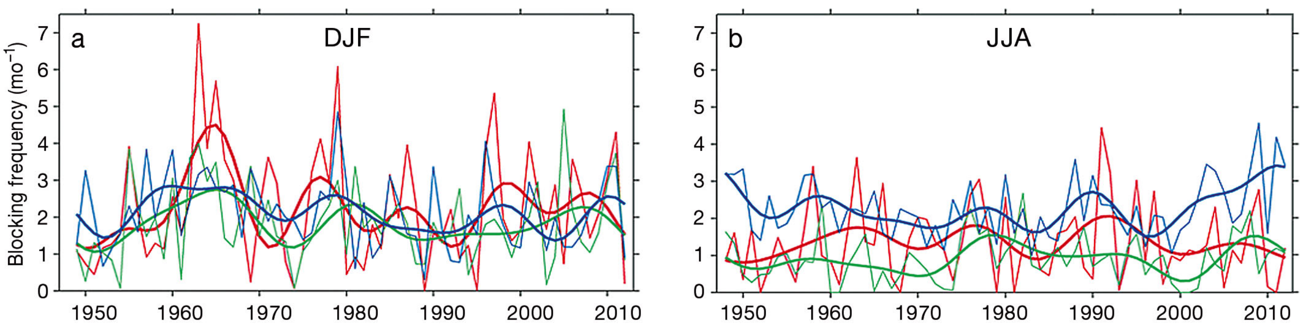

Fig. 2. Mean monthly blocking frequency in boreal (a) winter (DJF) and (b) summer (JJA) blocking over the North Atlantic (40°–80° N, 60° W–0°) in the NCEP reanalysis for 1948–2012 using 3 different definitions of blocking as described in Barnes et al. (2014). Thin blue, red and green lines for the 3 different indicies; thick lines: smoothed time series obtained using a Lanczos filter with a cutoff frequency of 10 yr

& Semenov (2010) performed a series of experiments with the ECHAM5 model, and found a dependence of central European winter temperatures on sea ice cover in the Barents and Kara (BK) Seas. A gradual decrease in sea ice from 100 % to ice-free conditions leads to a strong temperature increase 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. Yang et al. (2011), using the EC-Earth model (Hazeleger et al. 2012) with considerably higher resolution than Petoukhov & Semenov (2010), confirm a decrease in winter temperatures with decreasing BK sea ice, but in a more linear way than in Petoukhov & Semenov (2010).

Fig. 3 shows the variation in the August ice edge position (in degrees latitude) in the Barents Sea (Vinje 1998, 2001) and minimum sea ice volume determined using satellite data with the Pan-Arctic Ice-Ocean Modeling and Assimilation System (PIOMAS; Schweiger et al. 2011) and the mean DJF temperature anomaly in the northern part of the Baltic Sea region for the respective periods (see Section 4 for explanation of temperature data). The ice edge shifts northward (Fig. 3a shows a linear trend for the period 1851 to 1999), sea ice volume decreases (Fig. 3b shows a linear trend for the period 1979 to 2011), and the Baltic Sea winter temperature increases (Fig. 3c&d show linear trends for the respective periods). Table 1 shows the correlation of temperature and ice parameters (ice volume and ice extent respectively). There is no simple correlation between the ice parameters (ice edge or volume) and the DJF temperature. The correlation coefficient of the detrended ice and temperature time series (linear trends shown in Fig. 3 subtracted prior to the correlation) is larger for ice volume and temperature ($r_{detrended}$ = 0.3 giving an explained variance of 10 % for the period 1979 to 2012) than for the non-detrended data for 1979 to 2012. The ice data sets are not entirely comparable, as Barents Sea ice edge and total ice volume are only partly related. Thus, by using ice volume observations from the last 30 yr, only a weak signal of the reduced ice is seen in the winter temperatures in the Baltic Sea region. For the extended time period and the crude estimate of ice edge in the Barents Sea, no simple correlation with Baltic Sea winter temperatures exists. There is no correlation between the ice extent in the Barents Sea region and the Baltic Sea temperature for the period 1850 to 1998. However, this does not rule out a more complicated relation. In Yang et al. (2011) it was suggested that different cir-

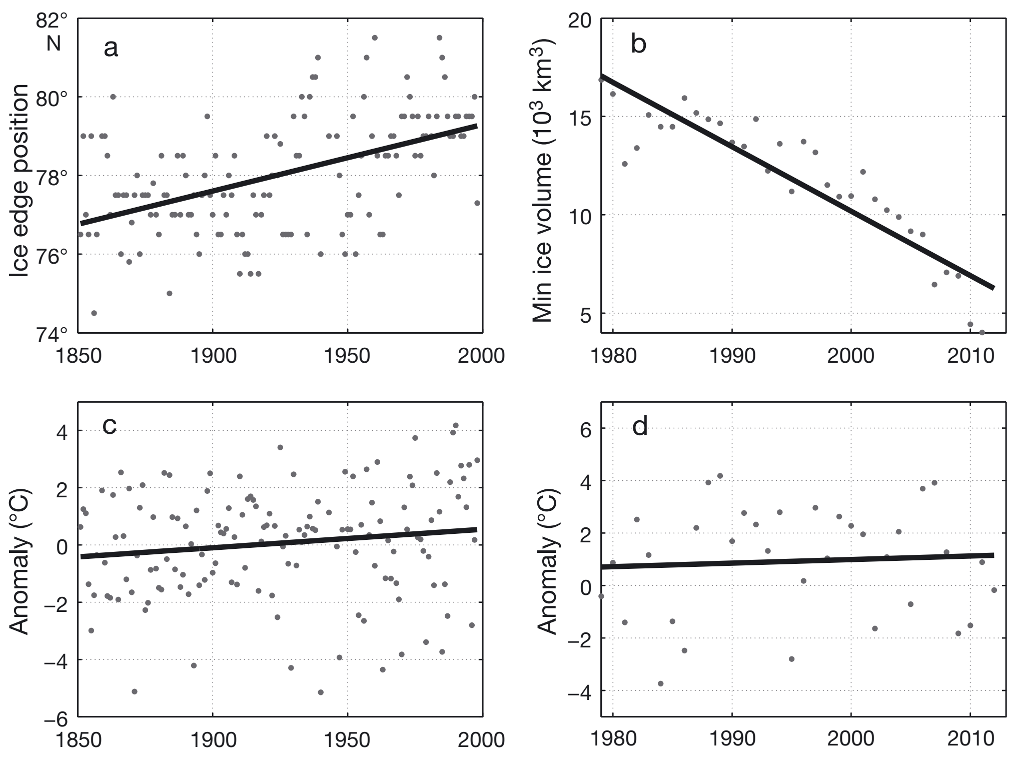

Fig. 3. (a) Position of ice edge during August in the Barents Sea for 1851–1998; (b) Minimum Arctic ice volume for 1979–2012; Temperature anomaly for the winter seasons (DJF) of (c) 1851–1999 and (d) 1979–2013. Annual values (dots) and linear trends (lines) for the respective periods

Table 1. Correlation coefficients between ice properties and temperature with (r) and without long-term trends ($r_{detrended}$) for the northern (>60° N) and southern (<60° N) Baltic Sea regions for periods 1850–1998 and 1979–2012

Data sets	1850–1998	1979–2012
r(Northern)	–0.03	–0.08
r(Southern)	0.13	0.07
$r_{detrended}$(Northern)	0.06	0.32
$r_{detrended}$(Southern)	0.07	0.31

culation regimes have different impacts on the relation between Arctic ice and European temperatures.

This finding is corroborated by Barnes et al. (2014) who investigate the connection of Northern Hemisphere blocking and Arctic sea ice retreat. Comparing 4 different reanalysis products and considering 3 different definitions of blocking (Barnes et al. 2012, Dunn-Sigouin et al. 2013, Masato et al. 2013), the authors find no clear evidence for robust trends in blocking frequency or onset. It should, however, be noted that this does not automatically imply that such trends do not exist, since the 4 investigated reanalyses show quite different results, even though they are essentially based on the same raw data. This may further complicate the detection of changes in blocking. In contrast, Francis & Vavrus (2012), Liu et al. (2012) and Tang et al. (2013) suggest a connection between sea ice retreat and the occurrence of blocking. More research is required to increase our understanding of the impact of declining sea ice on regional boreal climates like the Baltic Sea region.

3. WIND CLIMATE

Variations in the wind climate over the Baltic Sea region are on average closely linked to the atmospheric circulation and cyclonic activity over the North Atlantic. Based on NCEP/NCAR reanalysis data over the North Atlantic since 1958, the number of deep cyclones (core pressure <980 hPa) in winter (DJFM) reached a minimum in the early 1970s and clearly increased in the following decades, reaching their maximum around the last decade of the 20th century (Lehmann et al. 2011). At the same time, a continuous shift of North Atlantic storm tracks towards the north-east regionally increased the impact and number of storms over Northern Europe in winter and spring of recent decades, but decreased in autumn. Following the intensification of deep lows, a significant positive trend exists for storminess since the middle of the last century in reanalysis data over this region (Donat et al. 2011).

On a larger spatial scale, the pattern of increasing storm activity and wave heights over the northern North Atlantic, decreasing trends in lower mid-latitudes, and NE shift of storm tracks in boreal winter for 1955–2004 appears to be consistent with a combined influence of anthropogenic and natural forcing, while it is less likely that external forcing played an important role in the first half of the 20th century (Wang et al. 2009b). While the spatial trend pattern of the last 40 to 60 yr is consistent with scenario simulations of the 21st century under increased greenhouse gas concentrations (e.g. Ulbrich et al. 2009, Feser et al. 2014), the question about potential long-term trends in storminess is currently disputed, as no homogeneous wind observations are available on longer timescales.

As synoptic-scale storms are generally linked to the large-scale forcing over the pressure field, one possibility is to use pressure gradients to derive geostrophic wind speeds from triplets of surface pressure readings (Krueger & von Storch 2011). Based on high annual percentiles of geostrophic wind speeds calculated from a triangle of station pressure over the German Bight, Schmidt & von Storch (1993) did not find any long-term trend for the wind climate of 1876–1990. The absence of robust long-term trends was confirmed by numerous storm indices over the NE-Atlantic, North Sea, southern Baltic Sea region and central Europe (e.g. Alexandersson et al. 2000, Matulla et al. 2008, Bärring & Fortuniak 2009, Wang et al. 2009a) showing similar high storm levels during the 1880s as observed in the 1990s with a distinct minimum in the 1970s (see Feser et al. 2014 for a review).

While the previous storm indices present local to regional wind statistics, 2 novel datasets became available recently which try to construct physically consistent atmospheric fields on longer timescales. (1) By assimilating surface pressure records into a state-of-the-art global climate model, the 20th Century Reanalysis (20CRv2; Compo et al. 2011) suggests significant positive trends for storminess since 1871 over the Euro-Atlantic and to a less extent over the Baltic Sea region (Donat et al. 2011). The obviously inconsistent long-term trends relative to observations seem to be related to 20CRv2 assimilating fewer pressure observations back in time, which leads to spurious upward trends in 20CRv2 before ~1940 over the NE-Atlantic (Krueger et al. 2013) and before 1910 over the North Sea region (Dangendorf et al. 2014). The latter study confirms results from pressure-based storm indices showing no long-term trend since 1843, by using independent data of storm surges at Cuxhaven on the German North Sea coast. If the surges are derived through statistical regression using 20CRv2 as predictor, the comparison with the observed record suggests that 20CRv2 is locally consistent only after around 1910. To which extent 20CRv2 consistent over the Baltic Sea region needs to be further evaluated.

(2) Schenk & Zorita (2012) recently released a new reconstruction of HIgh RESolution Atmospheric Forcing Fields (HiResAFF) for Northern Europe that was extended for the period 1850–2009 (Gustafsson et al. 2012). Based on the pattern similarity between daily SLP station data in the past with SLP observations since 1958, historical atmospheric fields were reconstructed by taking the daily atmospheric fields of regionally downscaled ERA40 reanalysis for any day in the past for which the pattern similarity is maximized for an analogous day in the 1958–2007 period (Schenk & Zorita 2012). As shown in Fig. 4, the reconstructed 99th percentile of annual wind speeds from HiResAFF in the vicinity of Stockholm yield comparable results regarding long-term features of annual storminess derived from single-station proxies of Stockholm used by Bärring & Fortuniak (2009). Divergence of storm indices before 1850 (Fig. 4) are caused by non-regular observation times on a sub-daily scale where daily quantities (green line) provide a more robust measure.

While the previous studies analysed historical storminess on an annual basis, Wang et al. (2009a) repeated and updated (1874–2007) previous studies based on the 99th percentiles of geostrophic wind speed over the NE Atlantic, Northern and Central Europe, and focused more on seasonal and regional differences. They found that the maxima in the 1990s are due to winter storminess, while the high annual storm values in the 1880s are mainly due to summer storminess. For the period 1878–2007, Wang et al. (2011) found weak negative trends in the 99th percentiles over central Sweden and the southwestern Baltic Sea in winter (DJF) and a clear ($p < 0.05$) negative trend over the southwestern Baltic Sea in summer (JJA). As shown in Fig. 5, HiResAFF (Schenk & Zorita 2012) confirms decreasing seasonal mean wind speeds in summer as in Wang et al. (2011) and the peak in summer wind speeds in the 1880s (Wang et al. 2009a), i.e. over the western Baltic Sea region. According to HiResAFF, the peak in summer winds extends still further back in time to the 1850s. However, no increased summer windiness is reconstructed in the 1880s over the Northern and Eastern Baltic Sea, highlighting regional differences in the wind climate. While Wang et al. (2009a) attribute 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 western and central Baltic Sea in the 1880s.

The current knowledge about the long-term evolution of the wind and storm climate is far from complete, both on a regional scale and regarding extreme cyclone developments like the one in January 2007 (Fink et al. 2009). This implies that a detailed analysis of extreme cyclones on a synoptical scale is limited to the last decades, with little direct information on longer timescales. Station pressure-based reconstructions of long-term wind and storm statistics indicate quasi-stationary conditions with prominent (multi-) decadal variations (Feser et al. 2014). These results are consistent with externally forced Atmosphere–Ocean General Circulation Models for the last millennium (e.g. Fischer-Bruns et al. 2005, Xia et al. 2013) showing no response in Northern Hemispheric storm characteristics related to changes in external forcing. Only under strongly increasing greenhouse gas (GHG) conditions is a NE shift of storm tracks proposed over the North Atlantic (Fischer-Bruns et al. 2005, Ulbrich et al. 2009). It remains open if the currently observed NE shift of storm tracks since the 1960s (Lehmann et al. 2011) is a harbinger of already increased GHG concentrations, as suggested by Wang et al. (2009b), based on the period since 1900, because the conditions around the 1880s appear to be similar to the 1990s regarding the magnitude and frequency of storm activity.

4. SURFACE AIR TEMPERATURE

Earlier studies have detected quite a significant surface air temperature increase in the Baltic Sea region during 1871–2004 (BACC Author Team 2008). The warming has partly continued up to the present (during summer in the southern parts and during autumn in the north), although some winters during the last decade have been relatively cold (Fig. 6).

The temperature increase is not monotonous but accompanied by large (multi-) decadal variations dividing the 20th century into 3 main phases: (1) warming in the beginning of the century until the 1930s; (2) cooling until 1960s; and (3) another distinct warming during the last decades of the time series. Linear trends of the annual mean temperature anomalies during 1871–2013 were 0.10 K decade^{-1} north of 60° N and 0.08 K decade^{-1} south of 60° N in the Baltic

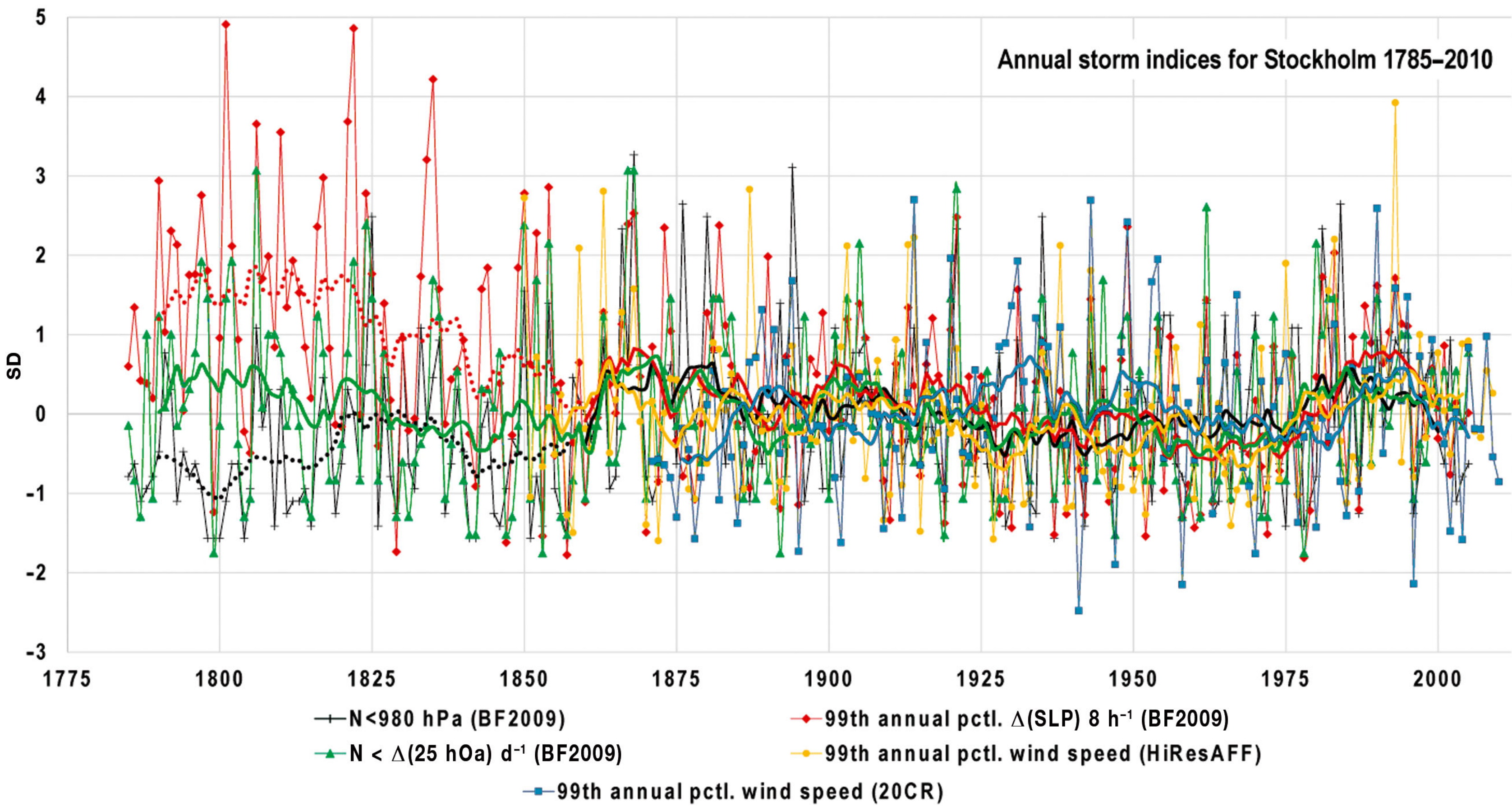

Fig. 4. Storminess over the central Baltic Sea region (~60° N, ~18° E). Storm indices of the annual number (N) of deep lows (<980 hPa), the 99th percentile of sea level pressure (SLP) tendency per 8 h, and the annual number of days exceeding a pressure tendency of 25 hPa for the station of Stockholm 1785–2005, from Bärring & Fortuniak (2009) (BF2009), compared to the reconstructed annual 99th percentile of daily wind speeds in the vicinity of Stockholm 1850–2009 from the HIgh RESolution Atmospheric Forcing Fields (HiResAFF; Schenk & Zorita 2012) and the 20th Century Reanalysis (20CR; Compo et al. 2011). Data normalized relative to the period 1871–2008. Bold lines: 11 yr running means to highlight decadal variations. Dotted lines: uncertain data quality due to irregular or unknown subdaily sampling hours

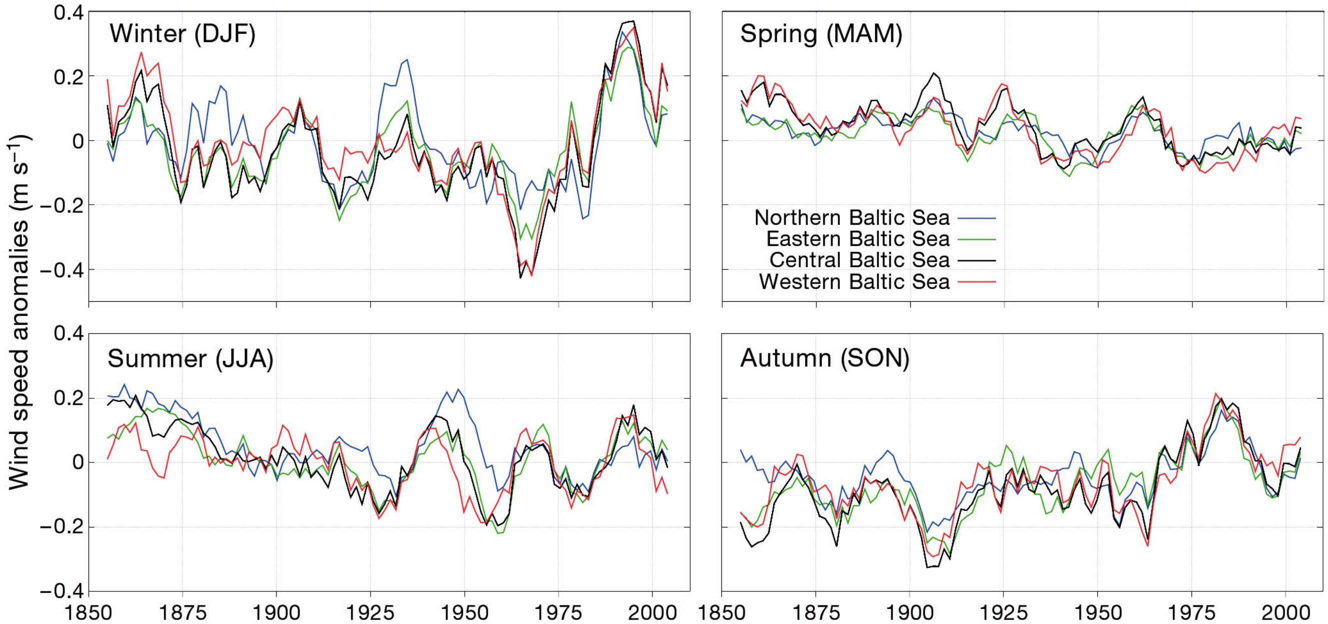

Fig. 5. Sliding decadal (11 yr) mean seasonal wind speed anomalies for the Baltic Sea regions for 1850–2009 relative to the mean of 1958–2007. Time series are drawn from the gridded fields of HIgh RESolution Atmospheric Forcing Fields (HiResAFF; Schenk & Zorita 2012). Grid points are selected in the closest vicinity of Haparanda, Saint Petersburg, Helsinki, Stockholm, Kaliningrad and Copenhagen

Sea region (Table 2). This is larger than the global mean temperature trend, which is about 0.06 K decade^{-1} for the period 1871–2005 (IPCC 2007). All seasonal trends are positive and significant at the 95% level, except winter temperature north of 60° N (because of the large variability). The largest trends are observed in spring and the smallest in summer, with higher seasonal trends in the northern area compared to the south. The annual and seasonal time series of surface mean air temperature for the Baltic Sea basin, separately for its northern and southern parts, are shown in Fig. 6, sharing more or less similar variations and trends to those of the European mean air temperature (Casty et al. 2007).

For the more recent decades, an analysis of temperature trends from 1970 to 2008 in the Baltic Sea area showed the strongest increase in the Gulf of Bothnia in autumn and winter (0.5 to 0.6 K decade^{-1}), while significant changes occurred during spring and summer in the central and southern parts of the Baltic Sea area (an increase of 0.2 to 0.3 K decade^{-1}) (Lehmann et al. 2011). Large temperature changes over the northern Baltic Sea in winter and spring are very likely related to a reduction of ice seen during the same period (BACC Author Team 2014).

Results of studies on regional temperature changes agree with these general results. The increase in annual mean air temperature for Finland during 1909–2008 was 0.09 K decade^{-1} (Tietäväinen et al. 2010). In the southeastern part of Norway it was 0.07 K decade^{-1} for the same period. The trend value 0.09 K decade^{-1} was found for Riga, Latvia, in the period 1851–2006 (Lizuma et al. 2007). During the second half of the 20th century, the trend values were much larger: approximately 0.3 K decade^{-1} for annual mean temperature was observed in Estonia in 1950–2009 (Russak 2009, Kont et al. 2011). Temperature fluctuations have been coherent in all 3 Baltic states (Kriauciuniene et al. 2012).

The daily temperature cycle is also changing, with both the mean minimum and mean maximum temperature in the Baltic Sea area increasing over the past century. The mean maximum temperature has increased more rapidly in the latter part of spring (April and May), while the mean minimum temperature has increased more than the maximum temperature in much of the winter (BACC Author Team 2008, Avotniece et al. 2010, Jaagus et al. 2013). Consequently, the diurnal temperature range has increased in spring and decreased in winter. No changes in the annual mean diurnal temperature range were detected in the Baltic countries (Jaagus et al. 2013).

In addition to an increase in mean temperatures, there has been an increase in temperature extremes. For example, in Poland a statistically significant increase in the annual number of days with daily max-

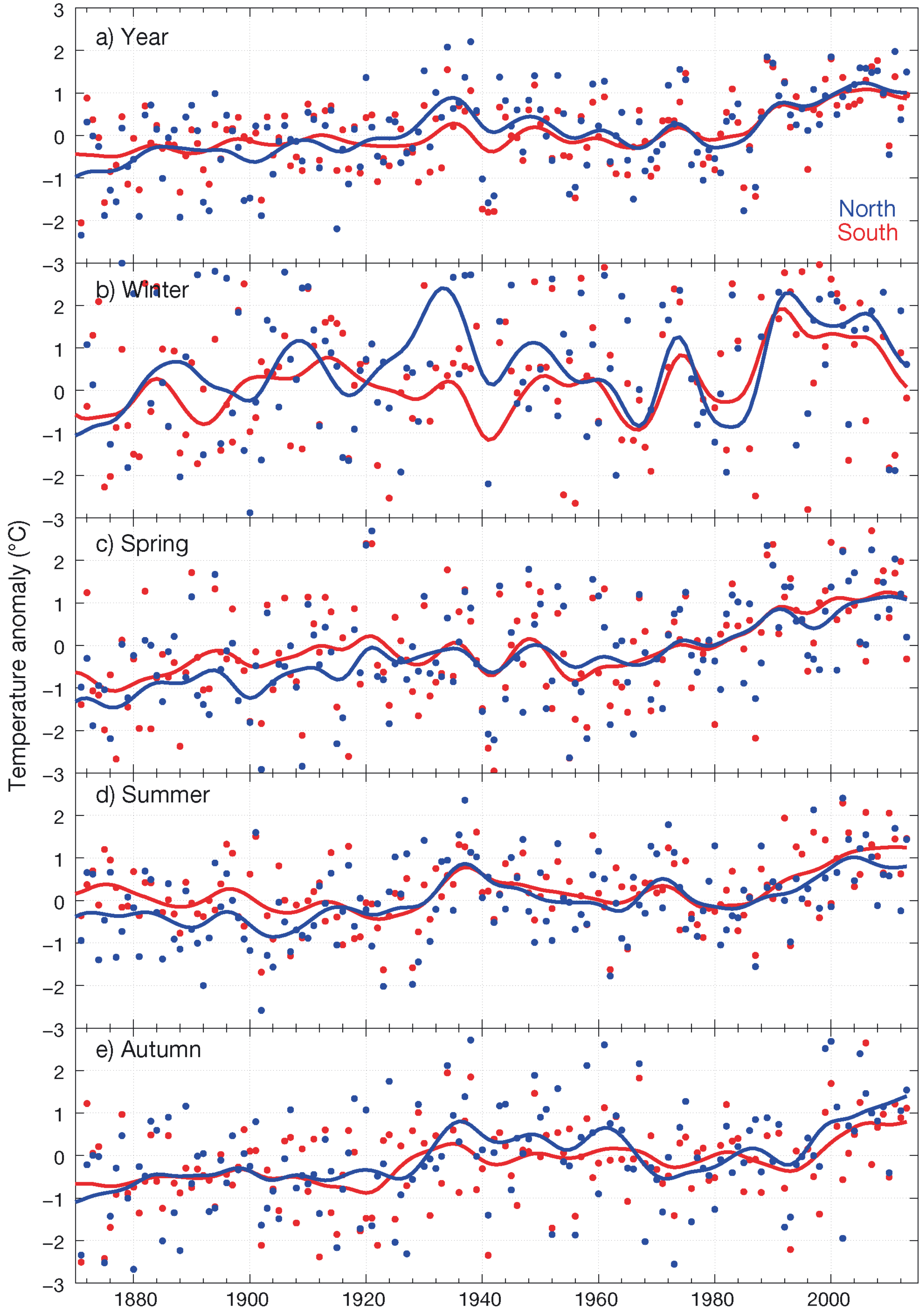

Fig. 6. Annual and seasonal mean near-surface air temperature anomalies for the Baltic Sea Basin for 1871–2013, taken from the CRUTEM3v dataset (Brohan et al. 2006). Blue, red: Baltic Sea basin region north and south, respectively, of 60° N. Dots: individual years. Smoothed curves: variability on timescales longer than 10 yr

Table 2. Linear surface air temperature trends (K decade^{-1}) for the period 1871–2013 over the northern (>60° N) and southern (<60° N) Baltic Sea basin. **Bold**: significance at $p < 0.05$. Data from the updated CRUTEM3v dataset (Brohan et al. 2006)

	Annual	Winter	Spring	Summer	Autumn
Northern area	**0.10**	0.08	**0.14**	**0.08**	**0.10**
Southern area	**0.08**	**0.09**	**0.11**	**0.05**	**0.08**

imum temperature above 25°C (also the number of days with maximum temperature above 30°C) was observed for the period 1951–2006 (Wibig 2008), while a 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). Furthermore, the duration of extremely mild periods increased significantly in winter, and the number of heat waves increased in summer (Scaife et al. 2008, Wibig 2008, Kysely 2010).

These changes are also resulting in seasonality changes: the length of the growing season has increased, whereas the length of the cold season has decreased. The number of days by which autumn and winter are delayed differs from south to north and east to west, but as an example in Tartu, Estonia, the number of deep winter days (with snow cover) has decreased by 29 d over the past century while the growing season has increased by 13 d in this period (Kull et al. 2008).

5. PRECIPITATION

The amount of precipitation in the Baltic Sea area during the past century has varied between regions and seasons, with both increasing and decreasing precipitation and no general trend during the period 1766–2000 (Casty et al. 2007). A tendency of increasing precipitation in winter and spring was detected during the second half of the 20th century (Zolina et al. 2009). Comparing downscaled and modelled precipitation from 27 stations in Fennoscandia during 1957–1999, a trend analysis was performed (Benestad et al. 2007) which found only few locations exhibiting trends that were statistically significant at the 5% level.

Trends in precipitation in particular countries depend very much on time frames, seasons and locations. An increase in precipitation was detected in southeastern Norway (Hanssen-Bauer et al. 2009). Annual precipitation has increased about 15 to 20% during 1900–2010, which has been higher in autumn and winter, and lower in spring and summer. Summer precipitation in Finland during 1908–2008 shows a positive trend (Ylhäisi et al. 2010). Statistically significant trends in south-western Finland were detected in June and in northeastern Finland in May, July and for the whole summer period (MJJAS). There were no clearly expressed trends in Latvia during the longer period 1922–2003 (Briede & Lizuma 2007). During the last decades a statistically significant increasing trend was detected in southeastern Norway (Hanssen-Bauer et al. 2009), Lithuania, eastern Latvia and eastern Estonia (Jaagus et al. 2010). Comparing annual mean precipitation during 1994–2008 with that of 1979–1993, less precipitation was observed in the northern and central Baltic Sea, and more precipitation in southern region (Lehmann et al. 2011).

The increase in precipitation in Northern Europe is also associated with an increase in the frequency and intensity of extreme precipitation events; the number of extreme precipitation days per year and the seasons in which they occur vary for the different catchment areas of the Baltic Sea. Wet periods with daily precipitation exceeding 1 mm have become longer over most of Europe by about 15 to 20% during 1950–2008 (Zolina et al. 2010). The lengthening of wet periods was not caused by an increase of the total number of wet days. Becoming longer, wet periods in Europe are now characterized by an increase in heavy precipitation. Heavy precipitation events during the last 2 decades have become much more frequently associated with longer wet spells and have intensified in comparison with the 1950s and 1960s (Zolina 2011).

The number of days with precipitation exceeding given thresholds, lengths of wet and dry spells, and precipitation amounts in single spells were analysed using daily data from 5 stations in Poland during the second half of the 20th century (Wibig 2009). A positive trend was detected for the number of wet spells and days with precipitation, while a negative trend was found for mean precipitation during a given spell. Positive as well as negative trends in indices of precipitation extremes were detected in Poland for 1951–2006, but the highest number of decreasing trends was in summer, especially in southern Poland, whereas the number of increasing trends was more pronounced in spring and autumn (Łupikasza 2010). The number of heavy precipitation events has increased in all Baltic states: Lithuania, 1951–2006 (Rimkus et al. 2011); Latvia, 1924–2008 (Avotniece et al. 2010); and Estonia, 1957–2009 (Tammets & Jaagus 2013).

6. OPEN QUESTIONS

There are a number of open questions related to changes in atmospheric parameters during the last 200 yr, for which continued research is required to understand and describe climate change/variability. Of particular interest are the distant controls of circulation changes. Is there a relation between reduced ice in the Arctic and low winter temperatures in the northern European regions, as suggested by Overland & Wang (2010)? As the reduction of Arctic sea ice seems to continue, a potential effect on circulation patterns over the Baltic Sea region would be of crucial importance for Baltic Sea climate. Although the global warming signal is clearly reflected in mean temperature change, altered circulation patterns would most likely have a larger impact on several state variables.

Although Bhend & von Storch (2009) detected a clear long-term temperature change over the Baltic Sea region, the separation of natural and anthropogenic signals requires more research. As an example, the Atlantic Multidecadal Oscillation (AMO) originates in the Atlantic and is defined from patterns in the SST variability. Several studies have shown that AMO can force European climate (e.g. Rodwell et al. 1999, Kushnir et al. 2002, Sutton & Hodson 2005, Semenov et al. 2010). These signals may superimpose long-term trends and be an indication of the impact of the ocean on the European climate on a multidecadal scale. Such variations are likely associated with natural rather than anthropogenically forced variability (Gulev et al. 2013). The relation to climate variability in the Baltic Sea region is, however, not clear.

Persistence of circulation types has increased during the last century and might be also related to the reduction of Arctic ice. The persistence of weather types can explain the increase in frequency and intensity of extreme precipitation events. For extreme events however, current studies rely on a rather small amount of data covering usually relatively short time scales, and it is difficult to draw any statistically significant conclusions. For reliable trend estimates there is a need for more homogenised, unbiased data. This is particularly important when evaluating trends of rarely occurring extreme events with large local differences.

As the anthropogenic GHG emissions are most significant during the last decades, human induced climate change signals should dominate during this period. The Baltic Sea (as a semi-enclosed sea basin) could be considered as a modulator for global climate change signals, but the region can also generate its own signals. On the regional level, the discrimination of anthropogenic and natural signals, and the differentiation between locally forced changes and globally imposed ones still remain an open question. The Baltic Sea region has relatively unique long-term data, and there is strong motivation for further research in this region (Meier et al. 2014).

The past 200 yr have the advantage of *in situ* measurements with relatively high accuracy. We would, however, like to point out the need for extension of long-term reanalyses and the homogenisation of such products. The long-term temperature and, to some extent, wind trends, are relatively reliable, but long term trends using existing data of precipitation and extreme events are significantly less reliable. There is a need for an extension and a homogenisation of existing reanalysis products (like 20CR and ERA) which would be valuable for continued analysis. For precipitation in the more recent decades, the Global Precipitation Climatology Project (GPCP; Adler et al. 2003) and similar products exist. These have, however, limitations in the Baltic Sea region.

7. CONCLUSIONS

Variations and trends of atmospheric parameters in the Baltic Sea region during the last 200 yr can be summarized as follows. (1) Atmospheric circulation: northward shift of storm tracks and increased cyclonic activity in recent decades, with increased persistence of weather types. (2) Wind: no long-term trend in annual wind statistics since the 19th century, but considerable variations on a (multi-)decadal timescale. Nevertheless, an anthropogenic influence cannot be excluded since the middle of the 20th century. The trend 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 (Wang et al. 2009b). (3) Temperature: continued warming, particularly during spring, and stronger over northern regions (polar amplification). Bhend & 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. (4) Precipitation: no long term trend, but an indication for an increased length of precipitation periods and possibly an increased risk of extreme precipitation events. No clear link to anthropogenic climate change visible for precipitation (Bhend & von Storch 2008).

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