

Daily temperature and precipitation extremes in the Baltic Sea region derived from the BaltAn65+ reanalysis

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Abstract Daily 2-m temperature and precipitation extremes in the Baltic Sea region for the time period of 1965–2005 is studied based on data from the BaltAn65+ high resolution atmospheric reanalysis. Moreover, the ability of regional reanalysis to capture extremes is analysed by comparing the reanalysis data to gridded observations. The shortcomings in the simulation of the minimum temperatures over the northern part of the region and in the simulation of the extreme precipitation over the Scandinavian mountains in the BaltAn65+ reanalysis data are detected and analysed. Temporal trends in the temperature and precipitation extremes in the Baltic Sea region, with the largest increases in temperature and precipitation in winter, are detected based on both gridded observations and the BaltAn65+ reanalysis data. However, the reanalysis is not able to capture all of the regional trends in the extremes in the observations due to the shortcomings in the simulation of the extremes.

1 Introduction

Natural systems and human activities are strongly impacted by extreme climate events (e.g. Easterling et al. 2000), motivating research of these extremes. Alexander et al. (2006) show significant changes in the temperature and

precipitation extremes in many parts of the globe during the years 1951–2003. In general, both minimum and maximum temperatures have increased in relation to global warming, whereas minimum temperatures have increased more (Alexander et al. 2006). As for precipitation, a general trend of wetting occurs.

In Europe and in the different subregions within Europe, the temperature and precipitation extremes have previously been extensively studied based on station data by Klein Tank and Können (2003), Moberg and Jones (2005), Moberg et al. (2006), Zolina et al. (2009, 2010), Heino et al. (1999) and Yan et al. (2002). Klein Tank and Können (2003) show nearly equal warming of the minimum and maximum temperatures during the years 1946–1999 in Europe and a larger increase in the precipitation extremes than is expected from the increase in the mean precipitation amount. Moberg et al. (2006) also show nearly equal warming of the minimum and maximum temperatures in Europe during the years 1901–2000 but they did not detect disproportionately large increases in the extreme precipitation of this longer time period.

Research on the temperature and precipitation extremes that is based on station data, specifically in the Baltic Sea region and in the smaller subregions in the Baltic Sea area, is summarized by the BALTEX Second Assessment of Climate Change for the Baltic Sea Basin (BACC II Team 2015). In different countries in the Baltic Sea region, the minimum and maximum 2-m temperatures have become warmer, and precipitation extremes trend is toward wetter conditions, which is characteristic for Europe in general (BACC II Team 2015; Wibig and Glowicki 2002; Jaagus et al. 2014; Kažys et al. 2011; Avotniece et al. 2010; Rimkus et al. 2011; Päädam and Post 2011). During the winter, the warming of the minimum temperatures and the increase in

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the extreme precipitation during the period of 1960–1990 are related to changes in the North Atlantic Oscillation (BACC II Team 2015; Scaife et al. 2008).

In addition to observational station data, temperature and precipitation extremes can also be studied using atmospheric reanalysis. Global reanalysis are valuable meteorological data sets for atmospheric research, as they provide continuous and physically consistent data. Zolina et al. (2004) compare precipitation extremes from different global reanalysis datasets to station data over Europe. Kharin et al. (2005) compare near surface temperature and precipitation extremes from the Atmospheric Model Intercomparison Project (AMIP-2) simulations to global reanalysis and observations. Zolina et al. (2004) show significantly reduced intensities of extreme precipitation over Europe in the global reanalysis dataset compared to station data. Also, Kharin et al. (2005) present poor model simulations of the precipitation extremes compared to the observations. In terms of temperature extremes, there are considerable differences in the cold extremes, specifically in regions covered by snow or ice (Kharin et al. 2005).

The horizontal resolution of the global reanalysis is relatively coarse, and it is often beneficial to use regional reanalysis data with better spatial resolutions to study local details. In this paper, the spatial and temporal distributions of the precipitation and temperature extremes in the Baltic Sea region based on the regional BaltAn65+ reanalysis (Luhamaa et al. 2011) are compared to the extremes derived from the EOBS database (Haylock et al. 2008). Previously, Männik et al. (2015) compared the annual, seasonal and monthly mean temperatures and precipitation amounts from the BaltAn65+ reanalysis to the means from the EOBS database. They found that, for the mean temperatures, BaltAn65+ reanalysis is a reliable data source. However, for the precipitation amounts, rather large deviations were found compared to the EOBS database. It is important for the users of the BaltAn65+ dataset to know the quality of the simulated extremes as well as the quality of the means. In addition, analysis of the extremes helps to specify the model deficiencies for simulating temperature and precipitation.

The main goal of this paper is to study the spatial and temporal distributions of the daily temperature and precipitation extremes in the Baltic Sea region based on BaltAn65+ reanalysis data in the years 1965–2005 and to evaluate the ability of the reanalysis to capture the extremes compared to daily gridded observations. The BaltAn65+ reanalysis and EOBS dataset are described in Section 2. Results are presented in Section 3. A discussion on the temperature and precipitation extremes in the Baltic Sea region and the ability of the BaltAn65+ reanalysis to capture these is provided in Section 4. Conclusions are drawn in Section 5.

2 Data and methods

2.1 BaltAn65+ reanalysis

The BaltAn65+ reanalysis (Luhamaa et al. 2011) was compiled for the time period of 1965 to 2005 using the High Resolution Limited Area Model (HIRLAM) for the geographic area surrounding the Baltic Sea (Fig. 1). The configuration of the HIRLAM model used to compile the reanalysis is described by Luhamaa et al. (2011). The turbulence is parameterized by a prognostic turbulent kinetic energy scheme (Cuxart et al. 2000) with a diagnostic scale length. The Interaction Soil-Biosphere-Atmosphere (ISBA) scheme (Noilhan and Mahfouf 1996; Noilhan and Planton 1989) is used for the parametrization of surface processes.

The so-called STRACO scheme (Unden et al. 2002; Sass 2002) is used to parametrize cloud processes (both stratiform and convective condensation). Cloud condensate is a prognostic variable and is dynamically advected, and a semi-prognostic treatment of cloud fraction is used (Unden et al. 2002). Using the STRACO scheme, a smooth transition between the stratiform and convective regimes is achieved (Unden et al. 2002). In the STRACO scheme, the treatment of cloud microphysics follows Sundqvist (1993) and for convection moisture convergence closure is used (Unden et al. 2002). This parameterization of convection is resolution dependent (Unden et al. 2002). A case study of a convective event using the STRACO scheme at different horizontal resolutions was performed by Niemelä and Fortelius (2005). They found stronger overestimation of convective precipitation at grid spacings of 11 km (this grid spacing is also used for the BaltAn65+ reanalysis) than at 5.6 km grid spacing.

The BaltAn65+ reanalysis includes short (6 h) forecasts by the HIRLAM numerical weather prediction (NWP) model (Unden et al. 2002) and analysis fields from surface analysis and Three-Dimensional Variational (3DVAR) analysis for the upper air (Gustafsson et al. 2001; Lindskog et al. 2001), at the horizontal resolution of 11 km. The boundary fields from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-40 global reanalysis (Uppala et al. 2005) were used. The different observational data used in the data assimilation include upper air soundings (TEMP), aircraft reports (AIREP), pilot-balloon stations (PILOT), surface synoptic observations (SYNOP), synoptic observations from ships (SHIP) and drifting buoys (DRIBU) data (Luhamaa et al. 2011). The values of the used 2-m temperatures are the result of surface analysis at 00, 06, 12 and 18 UTC each day. Consequently, the 2-m temperature data are, to a large extent, constrained by the assimilated observations. The precipitation data together with the maximum and minimum temperatures were used from +6 h forecasts.

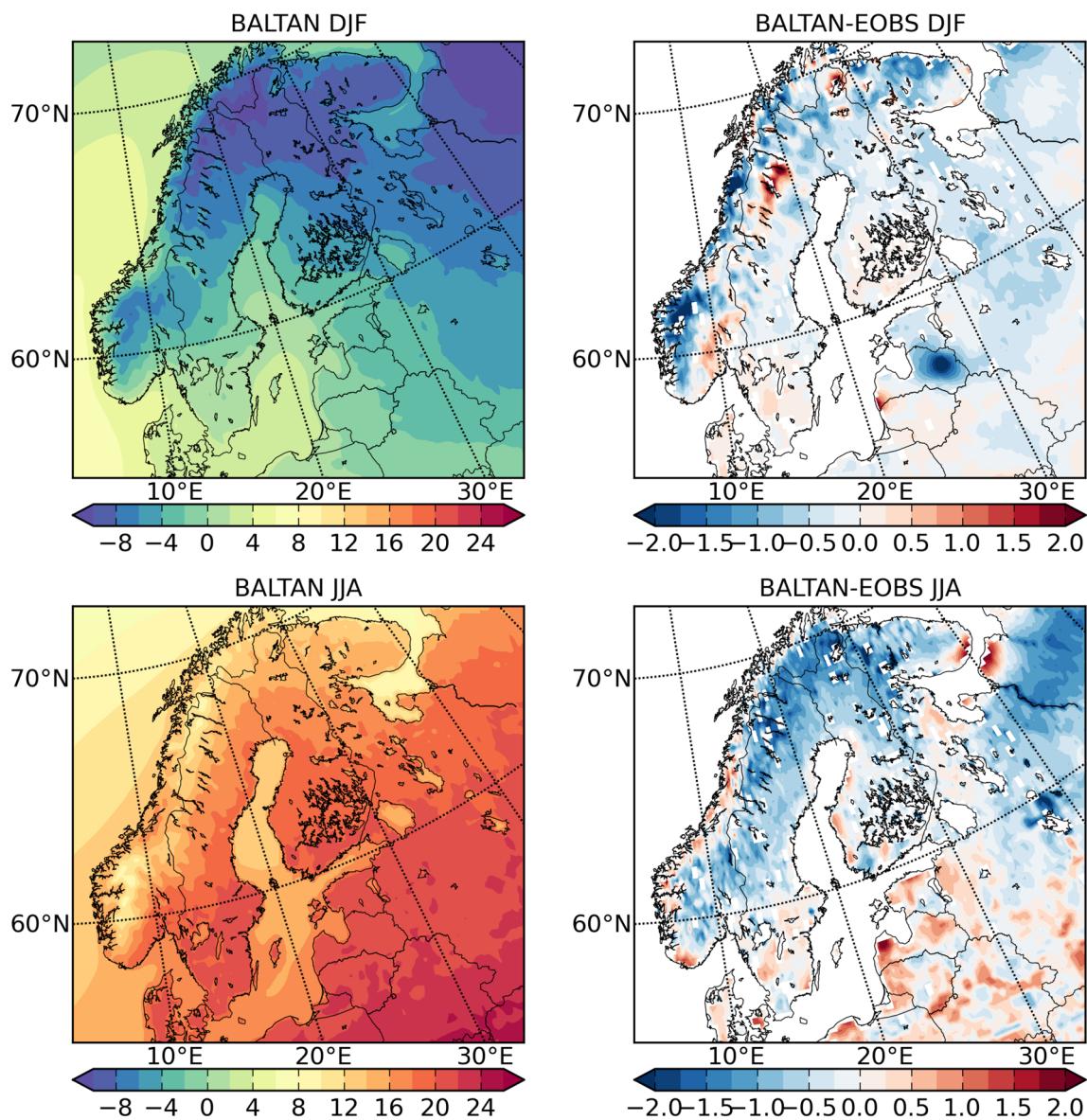


Fig. 1 Average daily maximum 2-m temperature ($^{\circ}\text{C}$) in the winter and summer from the BaltAn65+ reanalysis data, as well as the difference ($^{\circ}\text{C}$) from the EOBS average over land

2.2 EOBS dataset

The EOBS data are based on the observations of the daily precipitation and the minimum, maximum and mean surface temperatures collected during several research projects (Haylock et al. 2008), which have been spatially interpolated to compile a gridded dataset. The gridding is explained by Haylock et al. (2008): first, the interpolation of the monthly means was performed followed by the kriging of the daily anomalies. Gridded temperature and precipitation observations from across Europe at a horizontal resolution of 0.25° from the EOBS database version 11 are used in this paper. This dataset provides data over land only, thus

the precipitation and temperature data from the BaltAn65+ reanalysis over the Baltic sea cannot be compared to the EOBS data. There is an uneven spatial distribution of stations used for the EOBS data, with the best spatial coverage in the UK, the Netherlands and Switzerland (Haylock et al. 2008). For the study area surrounding the Baltic Sea, the station coverage is less dense over the Scandinavian Peninsula than the rest of the study area (Haylock et al. 2008).

Gridding introduces smoothing of the extremes compared to the original station data. Haylock et al. (2008) show a reduction in the intensities of the extremes in the EOBS data compared to station data. In addition, Hofstra et al. (2009) compared temperature and precipitation data

with other data sets over Europe and found larger errors in extremes of the EOBS dataset than of the mean values. According to Haylock et al. (2008), the gridding of the observations led to the difference in the 10-year return values with error magnitudes as large as 1.1 °C for the maximum temperature and 66% for the precipitation. However, they conclude that the extremes from the EOBS should be directly comparable with model data with a similar spatial resolution.

2.3 Analysis of the extremes

To directly compare the BaltAn65+ reanalysis and EOBS data, the reanalysis data are interpolated to the spatial grid

of the EOBS data (a 0.25° by 0.25° horizontal resolution) using area-weighted interpolation. All of the analysis has been done for each season (DJF, MAM, JJA, SON) to show the seasonal variability. The figures included in the manuscript show mostly data for the winter and summer to reduce the number of plots. The winter season is included in all plots as the strongest trends (together with considerable differences between the BaltAn65+ reanalysis and EOBS) are detected in the winter. The differences in the maximum and minimum temperatures over the lakes are the result of a lack of measurements over the lakes; thus, the lake areas have been masked in the plots showing the differences between the reanalysis and EOBS.

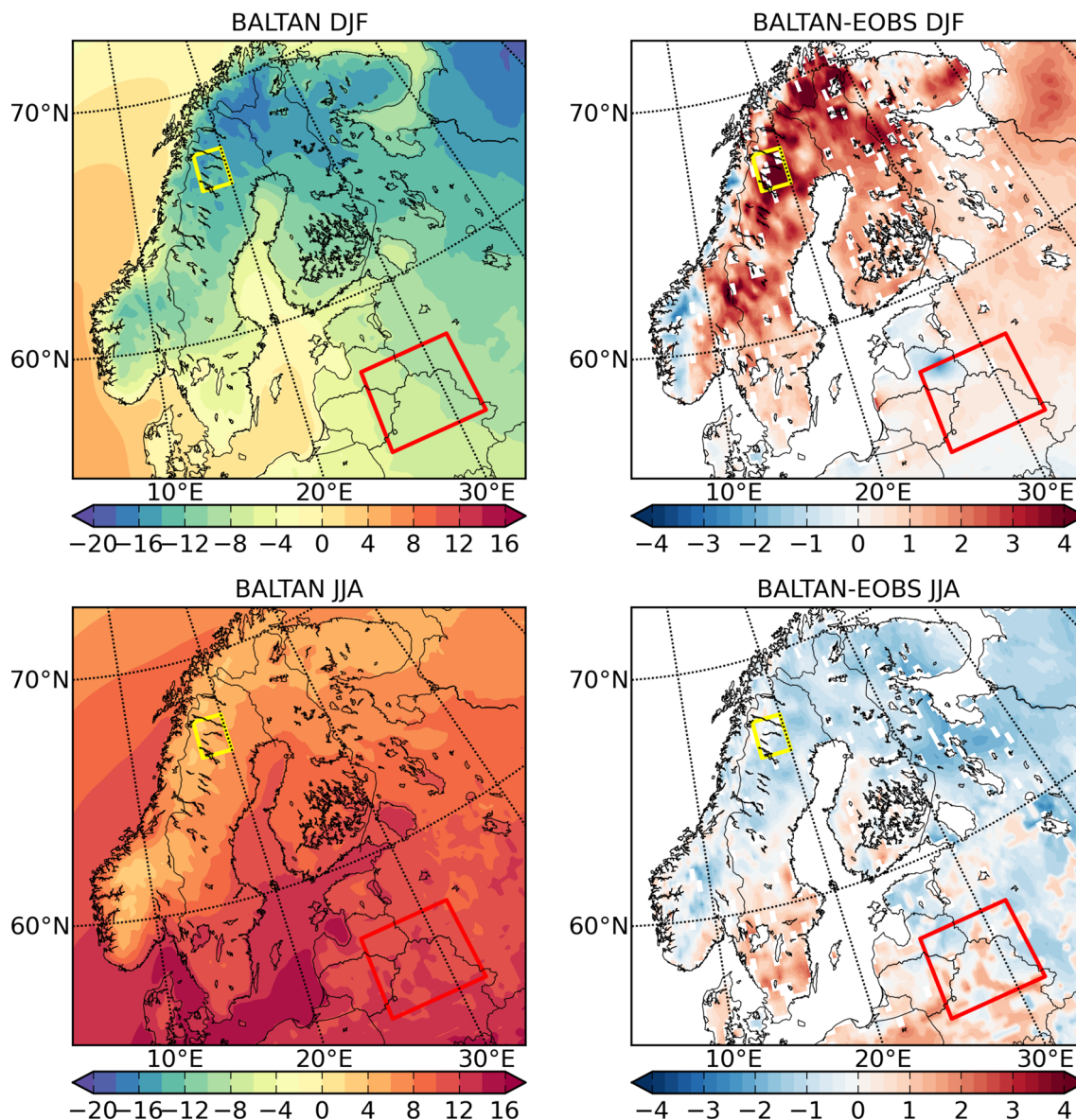
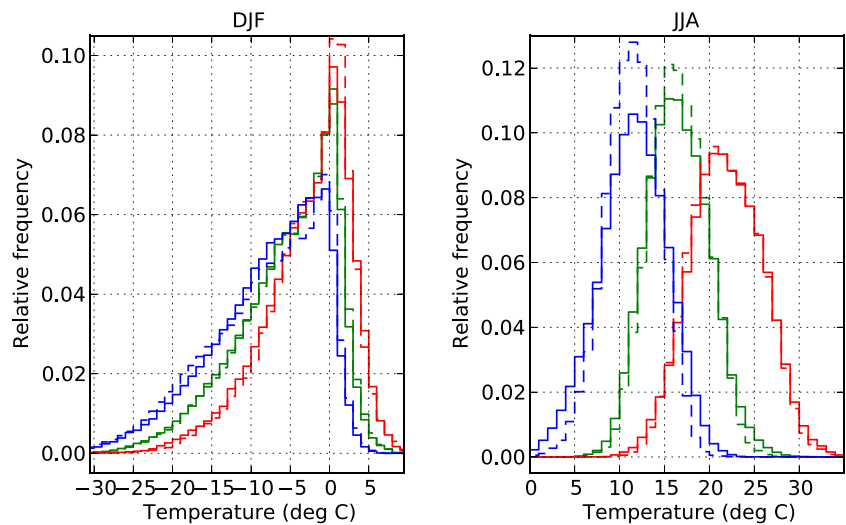


Fig. 2 Average daily minimum 2-m temperature (°C) in the winter and summer from the BaltAn65+ reanalysis data, as well as the difference (°C) from the EOBS average over land

Fig. 3 The frequency distribution of the daily 2-m temperatures (°C) (daily minimum in blue, average in green and maximum in red) in the winter and summer from the BaltAn65+ reanalysis (solid lines) and EOBS (dashed lines) data for a subregion situated to the south-east of the Baltic Sea, shown by the red box in Fig. 2

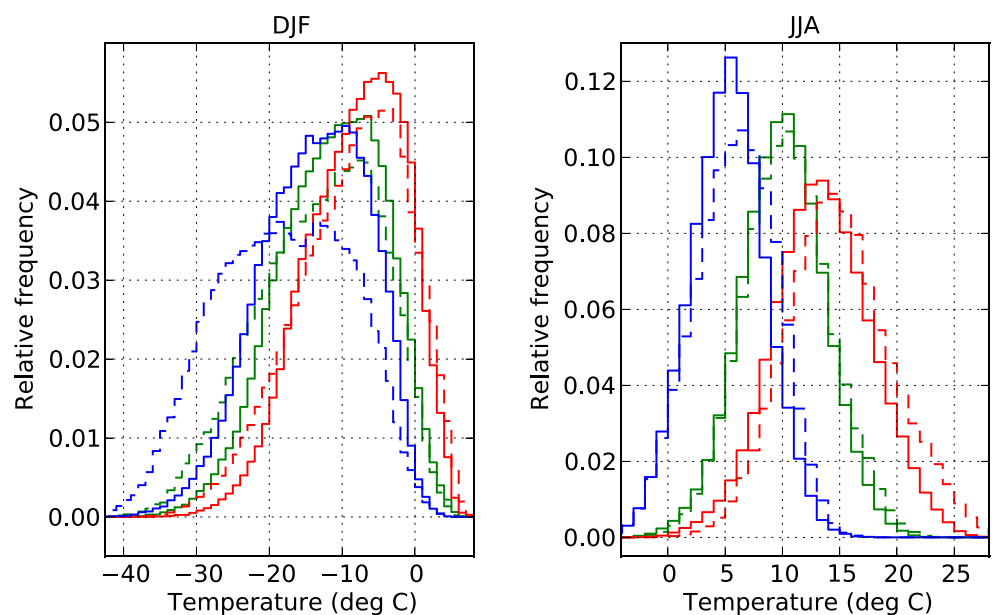


The spatial distributions of the selected seasonal percentile values of the daily precipitation amounts and the daily minimum and maximum 2-m temperatures from the BaltAn65+ reanalysis and EOBS dataset are compared. For seasonal data (especially in the spring and autumn), it is important to note that warmer/colder days mostly occur in specific months instead of equally throughout the season. To analyse the temporal trends in the occurrence of extremes, the days exceeding below the defined seasonal percentiles (characteristic for the whole study period 1965–2005) are counted at each grid point and a linear trend analysis is performed. For minimum temperature, the days with temperatures below the seasonal 10th percentile (cold nights) are counted and for maximum temperature the days with temperatures above the seasonal 90th percentile (warm days) are counted. In terms of precipitation, the days with

a precipitation amount exceeding the seasonal 95th percentile of the daily precipitation amount (very wet days) are counted. The 95th percentile of the precipitation amount was calculated using all days, not just wet days (i.e. days with precipitation amounts exceeding a certain threshold). These indexes follow Peterson et al. (2001). Comparing the daily values to certain percentile values at each grid point instead of a comparison to fixed thresholds helps to account for the regional variance, which is rather large for the area covered by the BaltAn65+ reanalysis.

Although the trends for the BaltAn65+ reanalysis are somewhat out of date (the last available year included is 2005), calculation of trends is useful for the evaluation of the quality of the simulated extremes. A least-squares regression method is used to calculate linear trends. The linear trends with p value smaller than 0.05 are assumed

Fig. 4 The frequency distribution of the daily 2-m temperatures (°C) (daily minimum in blue, average in green and maximum in red) in the winter and summer from the BaltAn65+ reanalysis (solid lines) and EOBS (dashed lines) data for a subregion in Scandinavia, shown by the yellow box in Fig. 2



to be statistically significant in this paper. Trends in the daily maximum and minimum temperatures in different seasons are analysed in a similar way to how Männik et al. (2015) analysed trends in daily average temperatures. The frequency distributions of the daily precipitation and temperature from the BaltAn65+ reanalysis and EOBS are presented for different subregions (daily data from all the grid points in the respective subregion are included) to analyse the differences in the temperature and precipitation distributions between the BaltAn65+ reanalysis and EOBS data. The specific subregions used for the analysis of the frequency distributions of temperature and precipitation were mostly selected due to the presence of large differences between the reanalysis and observations in these regions.

3 Results

3.1 Temperature extremes

Seasonal means of the daily maximum and minimum temperatures are shown in Figs. 1 and 2. In general, the maximum temperatures are too low and the minimum temperatures are too high in the BaltAn65+ reanalysis when compared to the EOBS data. The average 2-m temperature in the different seasons is better simulated (not shown) than the seasonal mean of the daily maximum and minimum temperatures in the BaltAn65+ reanalysis. Underestimation of the maximum temperatures is strongest in the summer (up to 1.5 °C) and overestimation of the minimum

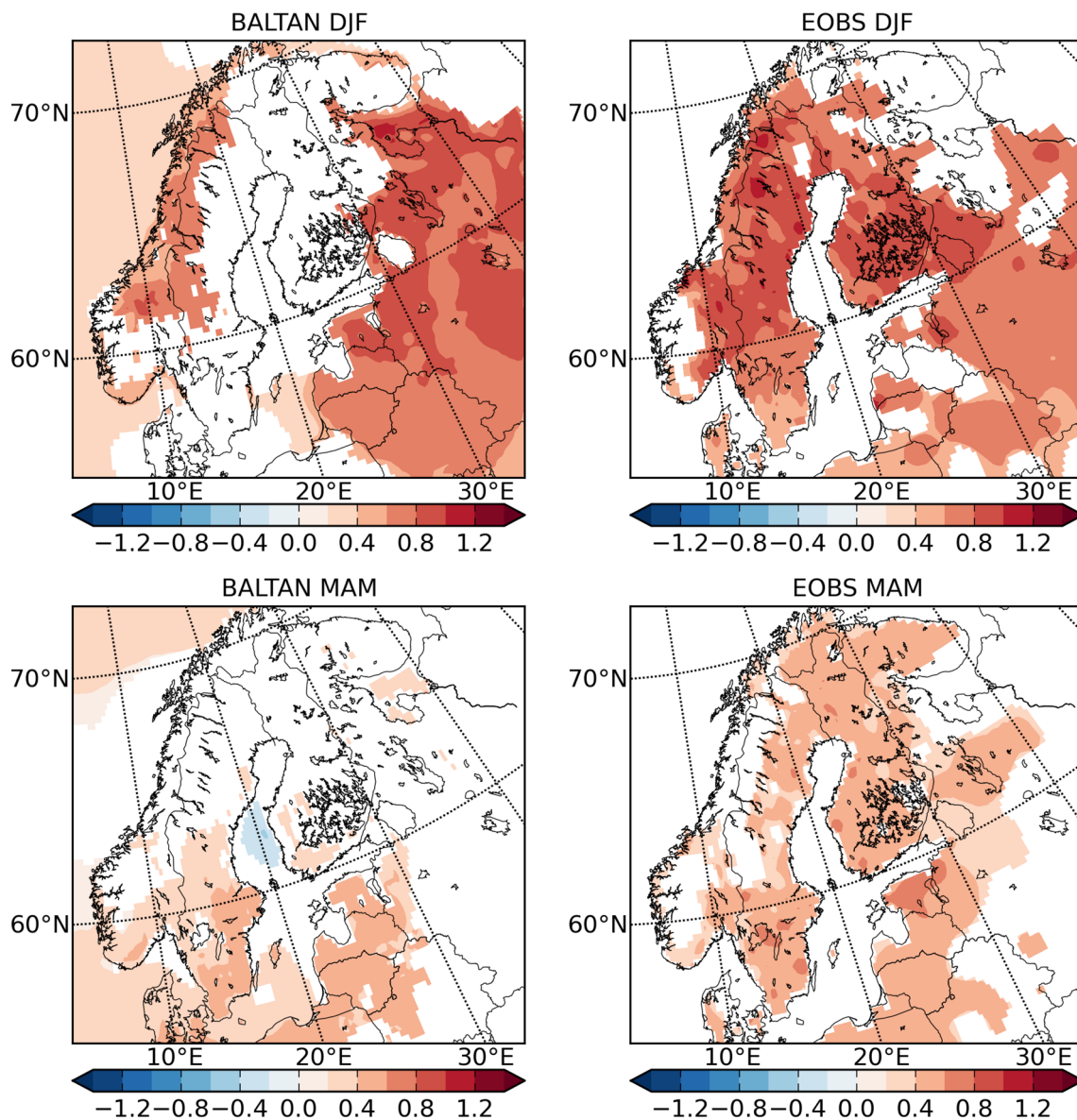


Fig. 5 Statistically significant linear trend of the average daily maximum 2-m temperature (°C/decade) in the winter and spring from the BaltAn65+ reanalysis and EOBS data over land

temperatures is strongest in the winter (regionally more than 4 °C). The minimum temperatures in the BaltAn65+ reanalysis data are also too high (regional overestimation up to 3 °C) in the spring (not shown).

In a subregion situated to the south-east of the Baltic Sea (shown by the red box in Fig. 2), the frequency distributions of the minimum, maximum and average 2-m temperatures agree well between the BaltAn65+ reanalysis and EOBS data (Fig. 3). The maximum of frequency distribution of the reanalysis' temperatures coincides with that of the EOBS for all three temperatures, but the BaltAn65+ temperatures have a larger variance than the EOBS inside the subregion. For the winter months, all three frequency

distributions are strongly asymmetric, skewed towards the lower temperatures.

The Scandinavian region was studied in more detail as this is where the largest differences are detected. The frequency distributions of the 2-m temperatures in a subregion in Scandinavia (denoted by the yellow box in Fig. 2) clearly show overly high minimum and average temperatures in the BaltAn65+ reanalysis compared to the EOBS data in the winter (Fig. 4) and spring (not shown). In the winter, the EOBS data has a larger variance in addition to the shift in the position of the maximum. In the summer (Fig. 4) and autumn (not shown), the agreement of the frequency distributions is better, but the reanalysis temperatures

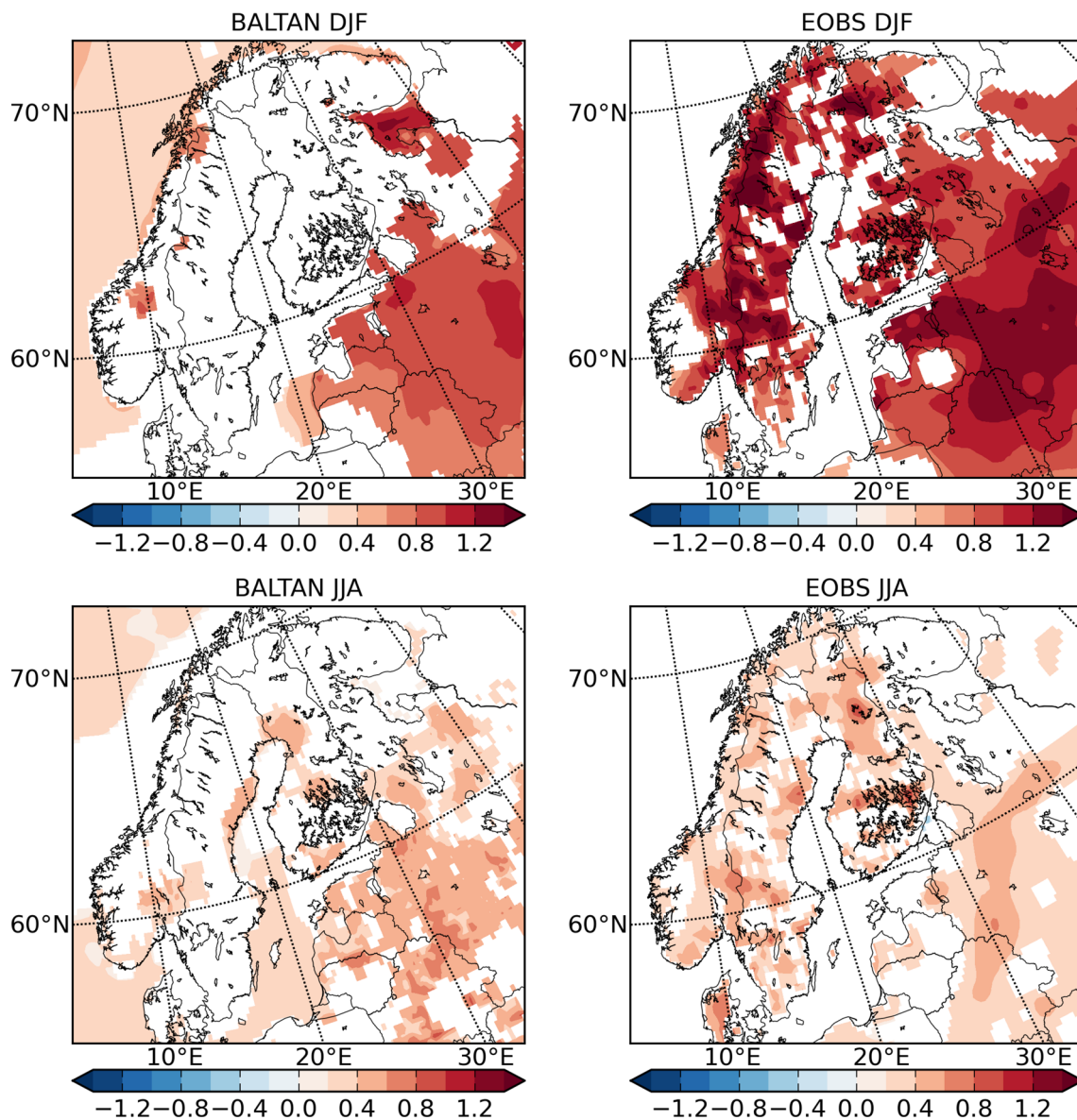


Fig. 6 Statistically significant linear trend of the average daily minimum 2-m temperature (°C/decade) in the winter and summer from the BaltAn65+ reanalysis and EOBS data over land

are slightly lower than the EOBS ones and have a lower variance.

At first, we follow how the extremes have changed through time by presenting the statistically significant linear trends of the average daily maximum and minimum 2-m temperatures in the different seasons (Figs. 5 and 6). The strongest trends are detected in the winter. The maximum temperatures are increased by up to 1 °C per decade in the winter and up to 0.6 °C per decade in the spring in both the BaltAn65+ reanalysis and the EOBS data. According to the BaltAn65+ reanalysis data, a statistically significant warming is characteristic for the area on the eastern flank of the Baltic Sea. However, according to the EOBS data,

warming is also characteristic for Scandinavia in the winter and spring.

In the winter, the minimum temperatures rise up to 1.4 °C per decade according to the linear trend based on the EOBS data and up to 1.2 °C per decade based on the BaltAn65+ reanalysis data. According to the EOBS data, there is a statistically significant warming of the minimum temperatures in the other seasons (up to 0.8 °C per decade) as well. As with the maximum temperatures, the statistically significant linear trends detected for Scandinavia in EOBS are not detected in the BaltAn65+ reanalysis data for the minimum temperatures. In general, the warming of the minimum temperatures in the winter is stronger than the warming of the

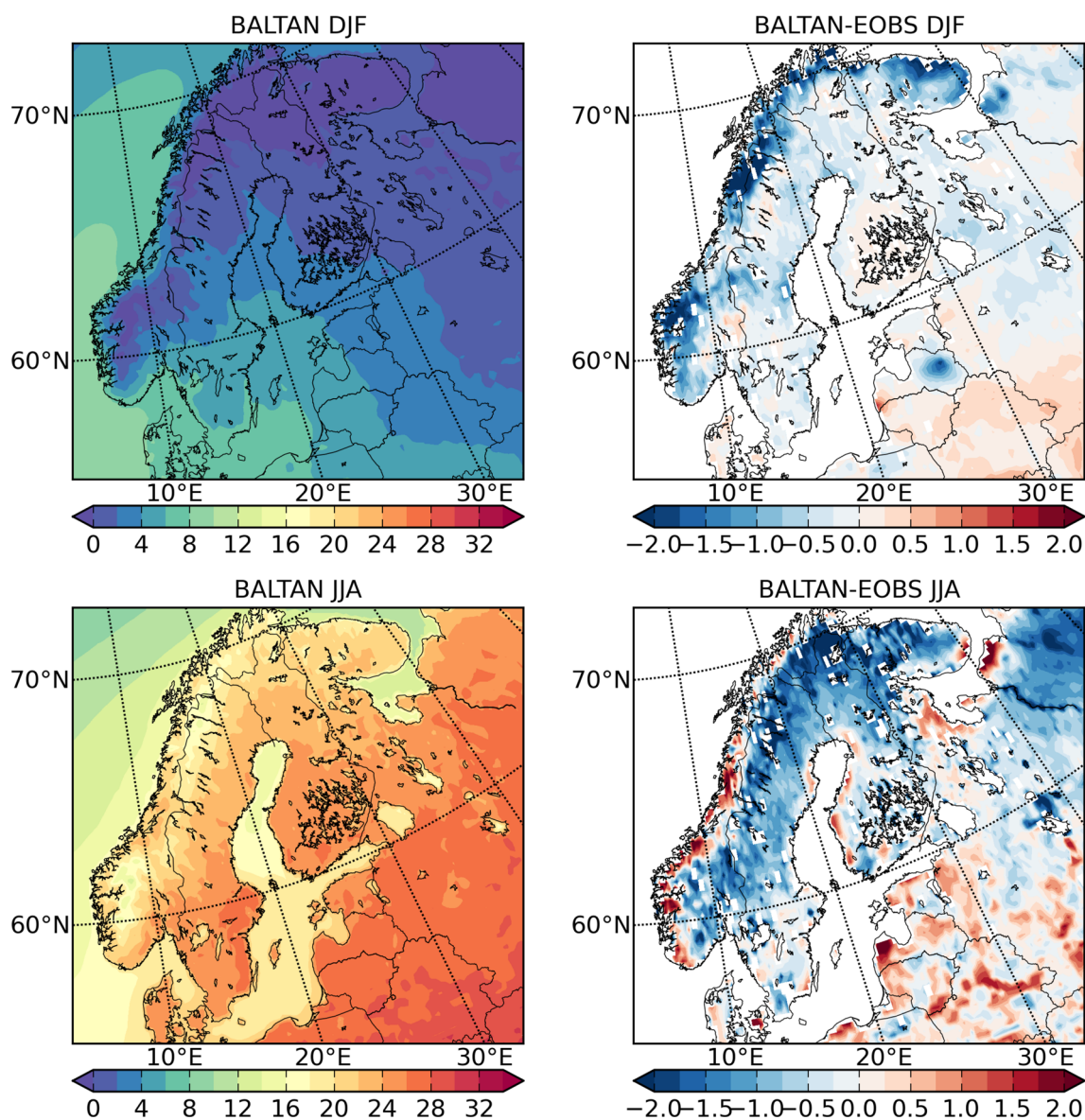


Fig. 7 90th percentile of the daily maximum 2-m temperature (°C) in the winter and summer from the BaltAn65+ reanalysis data, as well as the difference (°C) from EOBS over land

maximum temperatures, which leads to a decrease in the diurnal temperature range.

The 90th percentile of the daily maximum 2-m temperature in the different seasons and the 10th percentile of the daily minimum 2-m temperature are presented in Figs. 7 and 8, respectively. The BaltAn65+ reanalysis extremes are less extreme than the EOBS ones over remarkably large areas. The 90th percentile of the daily maximum 2-m temperature is more than 2 °C lower in the BaltAn65+ reanalysis compared to the EOBS data in the spring (not shown) and summer. The opposite is true for the 10th percentile of the daily minimum 2-m temperature, which is up to 6 °C higher for large areas of Scandinavia in the spring (not shown) and winter in the BaltAn65+ reanalysis.

The linear trends of the number of days per season with maximum (minimum) 2-m temperatures above (below) the 90th (the 10th) percentile in the summer and winter during the time period of 1965–2005 are shown in Figs. 9 and 10, respectively. In the winter, there is a tendency for the number of days over the selected warm day threshold to increase over time while the number of days below the cold night threshold decreases. Both rates are approximately 3 days per decade over a large area. In terms of the minimum temperatures in the winter, the negative linear trend over large parts of Scandinavia detected in the EOBS data is not detected by the BaltAn65+ reanalysis (Fig. 10). There are also some statistically significant trends in other seasons, but their magnitude are lower and they occur in smaller areas.

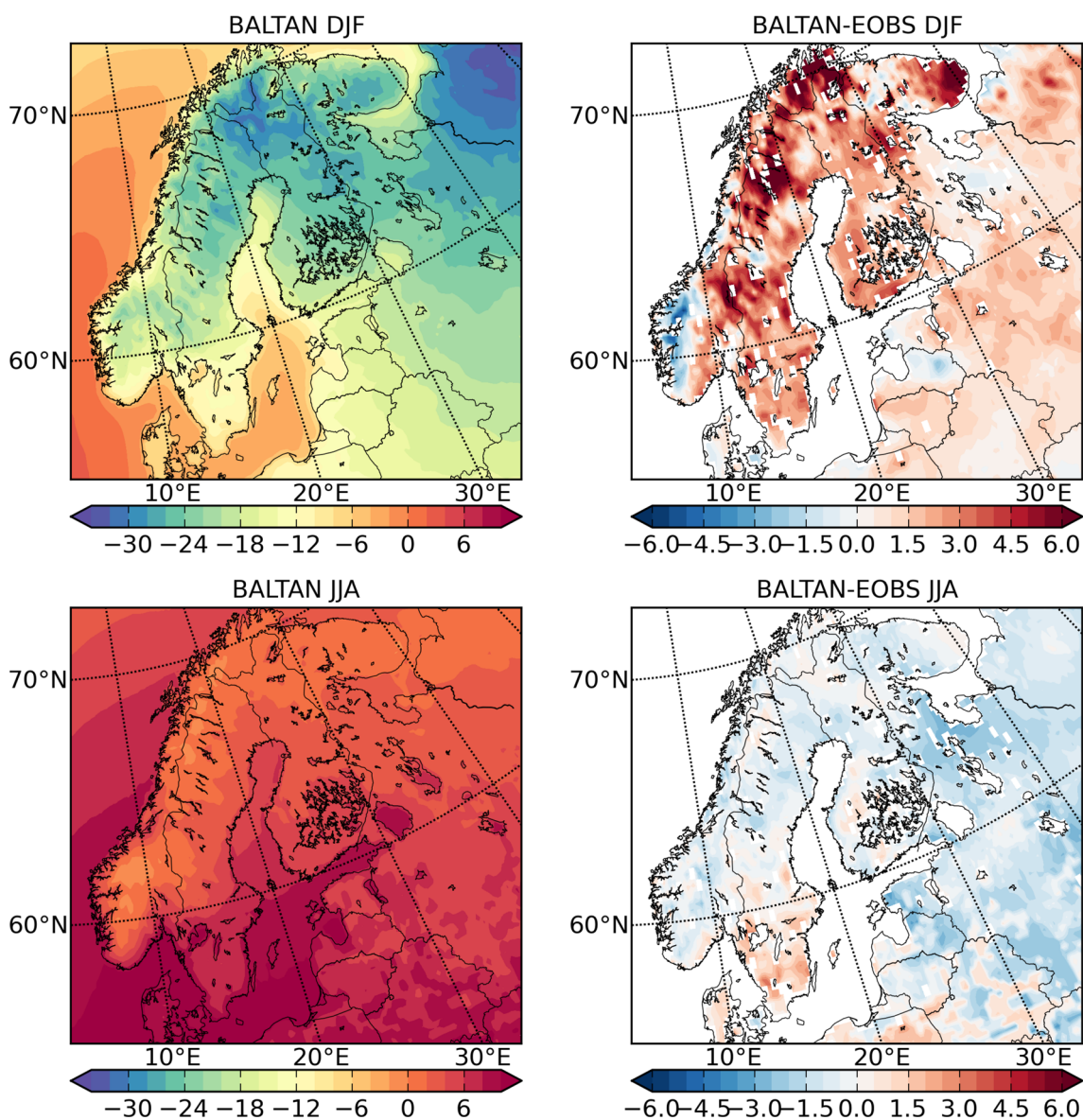


Fig. 8 10th percentile of the daily minimum 2-m temperature (°C) in the winter and summer from the BaltAn65+ reanalysis data, as well as the difference (°C) from EOBS over land

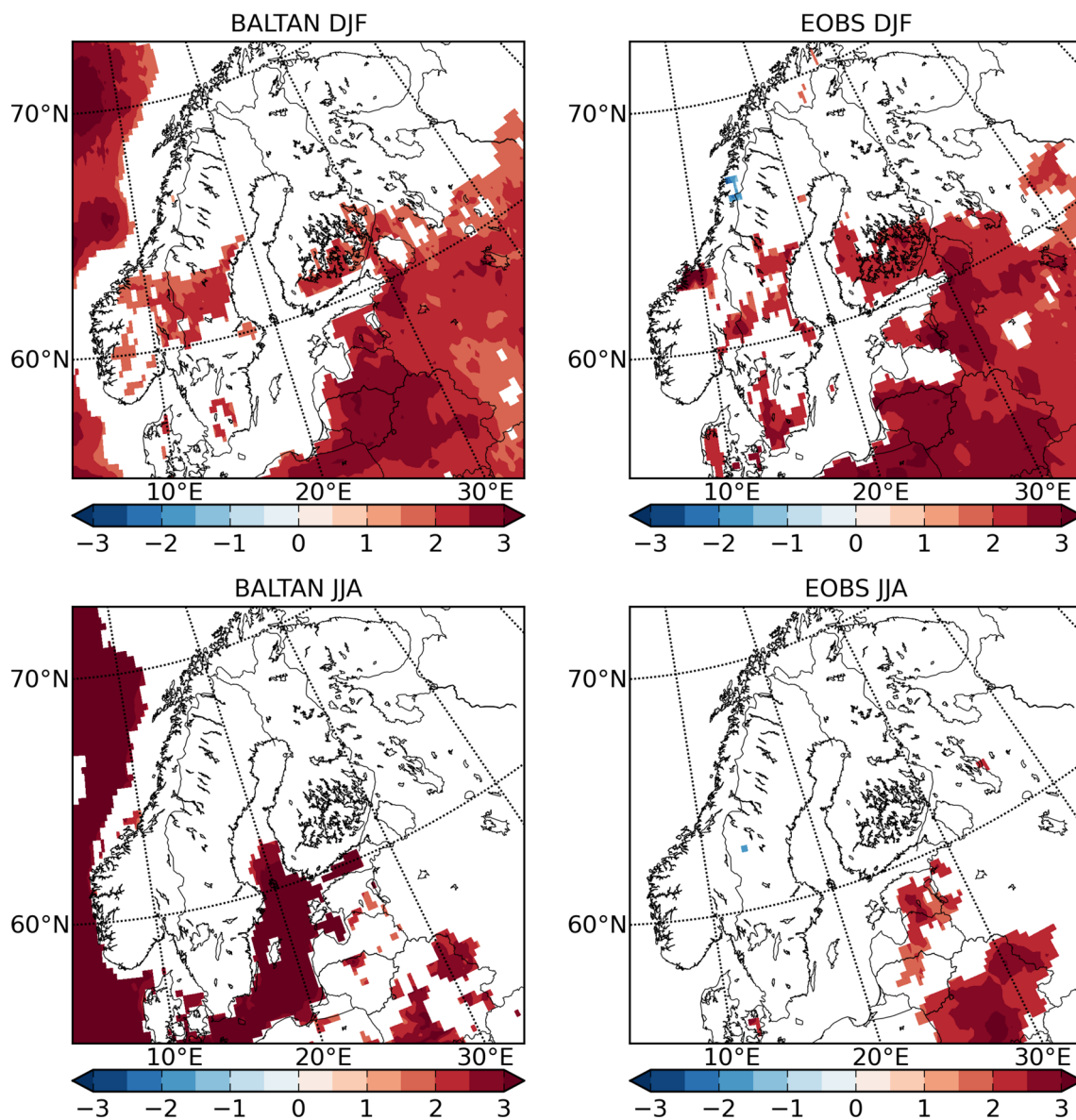


Fig. 9 Statistically significant linear trend (seasonal number of days per decade) of the number of days with 2-m maximum temperatures exceeding the 90th percentile from the BaltAn65+ reanalysis (over the entire area) and EOBS data (over land)

According to the BaltAn65+ reanalysis, there are also seasonal statistically significant linear trends in the number of days above/below the selected percentile thresholds over the Baltic Sea.

3.2 Precipitation extremes

The variability of the 95th percentile of the daily precipitation over the whole region is very large (Fig. 11), both in the winter and summer. The largest differences in the 95th percentile of precipitation between the BaltAn65+ reanalysis and EOBS are over the Scandinavian mountains. The deviations are twofold: over the extensive mountainous areas, BaltAn65+ shows greater than 6 mm higher percentiles

than EOBS and, right at the Atlantic coast, the percentiles in the reanalysis are more than 6 mm lower than in the EOBS data. We look at these differences in more detail using the cumulative distribution functions (CDF) of the daily precipitation for the subregions denoted with the yellow and green boxes in Fig. 11. In the northern part of Scandinavia (yellow box in Fig. 11), the proportion of the high precipitation events in the reanalysis is greater than in EOBS in all seasons and especially in the winter (Fig. 12). Even in winter, more than 5% of the precipitation sums stay above 15 mm per day, what is too high for these high latitudes. In addition, for the days with the lowest daily precipitation amounts, the values are overestimated by 1 to 2 mm in the reanalysis compared to the EOBS data in this region. In the western part

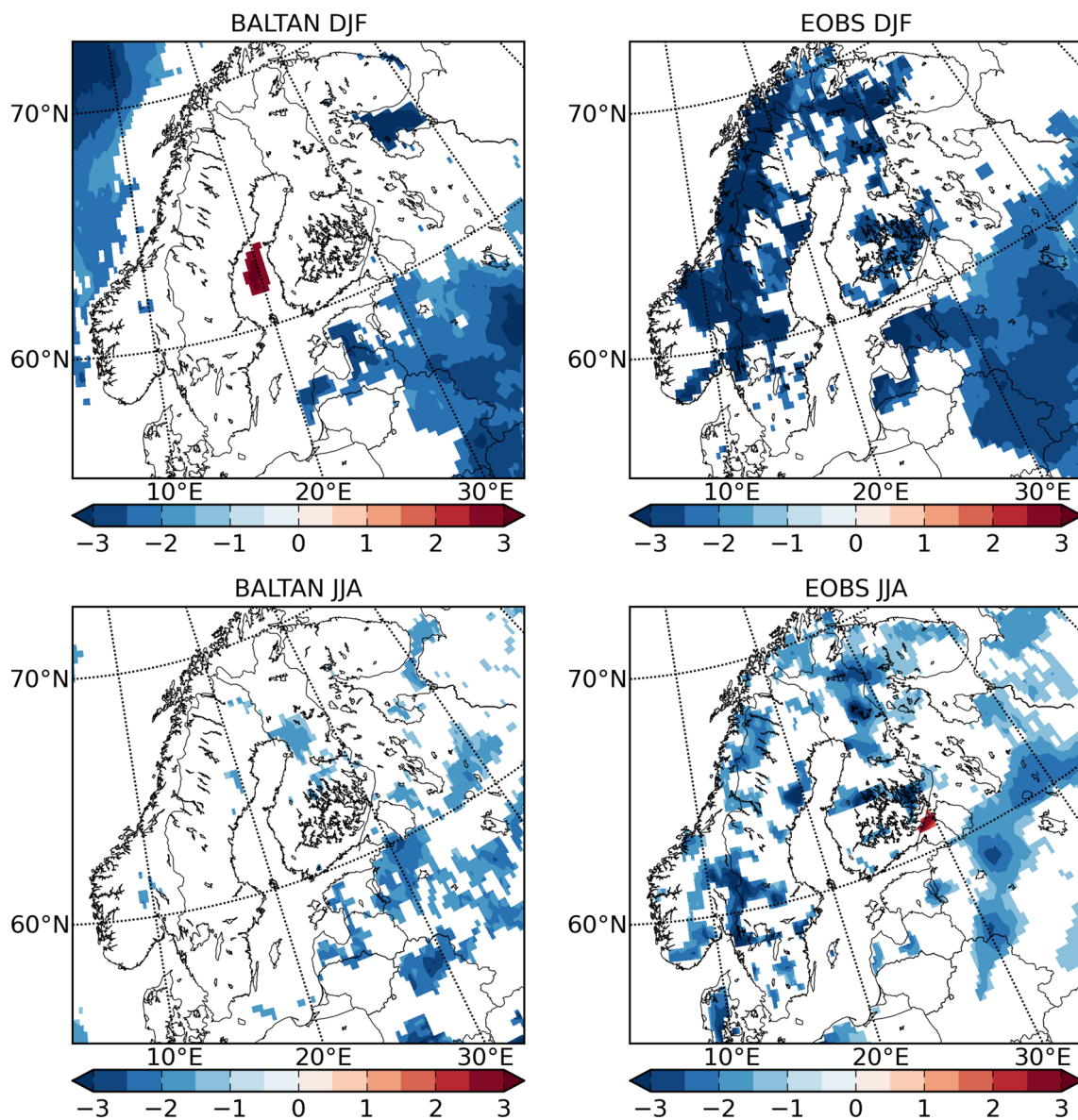


Fig. 10 Statistically significant linear trend (seasonal number of days per decade) of the number of days with 2-m minimum temperatures below the 10th percentile from the BaltAn65+ reanalysis (over the entire area) and EOBS data (over land)

of Scandinavia, next to the Atlantic Ocean, in a very narrow region (green box in Fig. 11), the extreme precipitation amounts are underestimated in the reanalysis compared to EOBS in various seasons. Figure 13 presents the CDF for the winter and, compared to Fig. 12, the positions of the blue and red curve are reversed. In general, there is less heavy precipitation in the reanalysis data compared to the EOBS data for the areas in Scandinavia close to the Atlantic and more heavy precipitation further away from the coast.

One more region of obvious overestimation of precipitation (and overestimated extreme precipitation) in the BaltAn65+ reanalysis is in the summer in the Baltic countries and Belarus (red box in Fig. 11), which may result from the overestimation of convective precipitation in this region.

From the CDF of the daily precipitation for this region in the summer (in Fig. 14), the overestimation of the frequency of heavy precipitation is clearly visible. There is generally very good agreement between the precipitation distributions of the reanalysis and EOBS (not shown) over most of the region in other seasons.

The linear trends of the seasonal number of days with the precipitation amounts above the 95th percentile in the winter and summer are shown in Fig. 15. In the winter, there are 1.5 more days per decade when the 95th percentile threshold is exceeded over a large area in EOBS. In the BaltAn65+ reanalysis, this kind of statistically significant trend in the winter is characteristic over a notably smaller area than in EOBS.

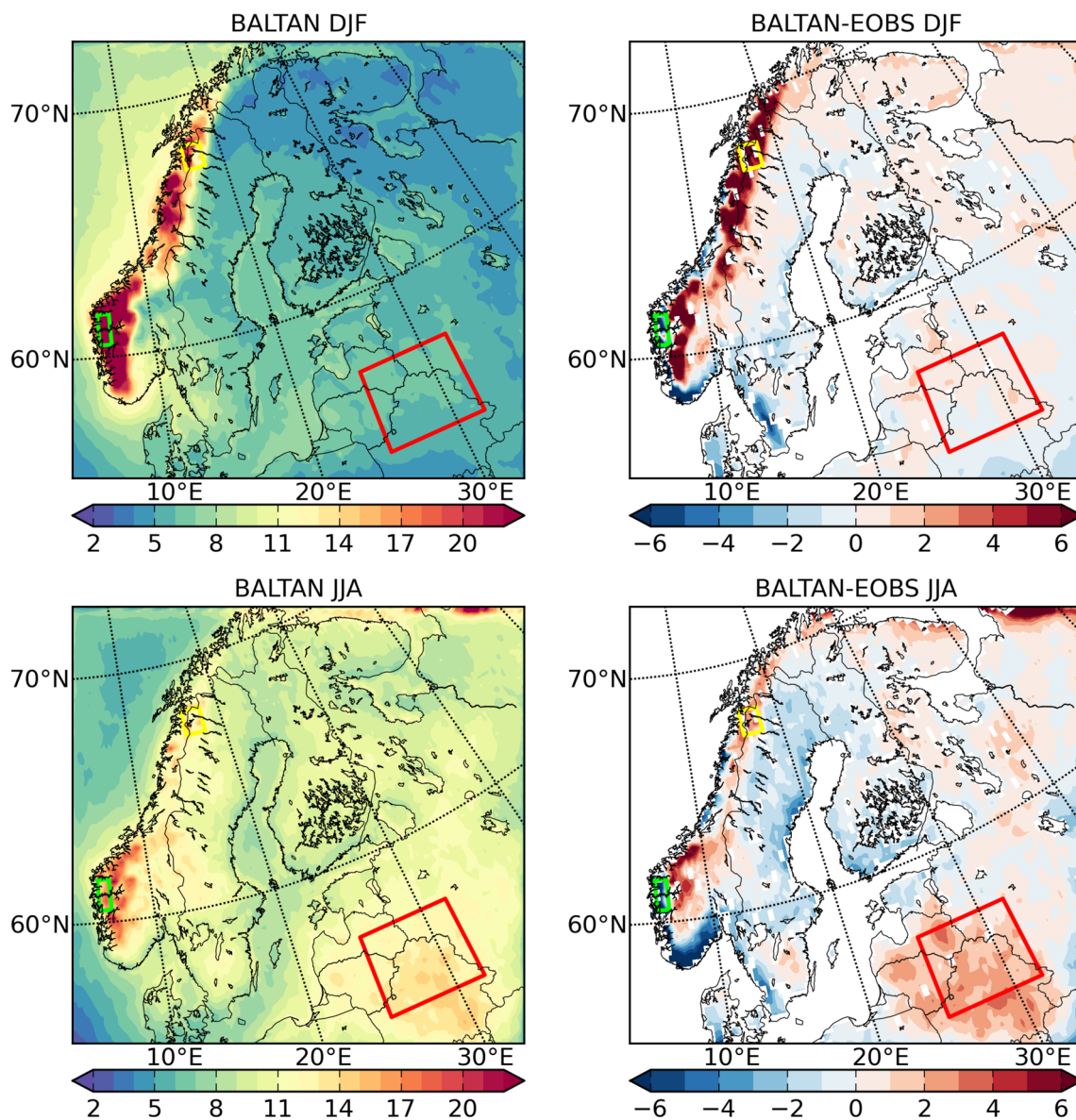


Fig. 11 95th percentile of the daily precipitation (mm) in the winter and summer from the BaltAn65+ reanalysis data, as well as the difference (mm) from EObs over land

4 Discussion

There are shortcomings in the simulation of precipitation extremes and in the simulation of minimum temperatures, especially in the winter and spring, in the BaltAn65+ reanalysis compared to EObs data. This behaviour is similar to previous studies analysing temperature and precipitation extremes from the model data (e.g. Kharin et al. 2005).

Männik et al. (2015) showed that the seasonal differences in the mean 2-m temperature between the BaltAn65+ reanalysis and EObs are largest in the winter. Our study explains that the overestimation of the average 2-m temperature in the BaltAn65+ reanalysis for a large part of Scandinavia in the winter is associated with overestimated

minimum temperatures in this area (Fig. 2) since, the maximum temperatures are similar to the EObs data in the winter (Fig. 1).

Additionally, the deviations in the average 2-m temperature in the spring can, to a large extent, be explained by the overestimated minimum temperatures in the BaltAn65+ reanalysis. The errors in the winter and spring result from poor simulation of temperatures during very stable atmospheric conditions in the cold periods, when large areas of the study domain are covered by snow. Atlaskin and Vihma (2012) showed a warm bias in the 2-m temperature forecast of different NWP models (including the HIRLAM model used to compute the BaltAn65+ reanalysis) for stable boundary layers in the winter over Finland and Europe.

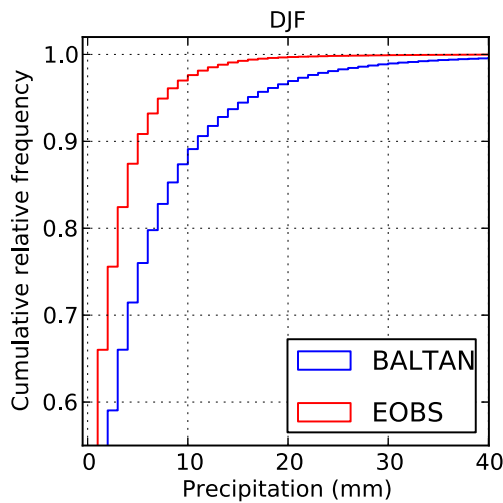


Fig. 12 Cumulative frequency distributions of the daily precipitation amounts (mm) in the winter from the BaltAn65+ reanalysis and EOBS data for a subregion of Scandinavia, shown by the *yellow box* in Fig. 11

Additionally, Järvenoja (2005) highlighted the strong positive bias in HIRLAM temperature forecasts for Northern Europe in the winter, with the bias increasing with the lower temperatures.

The strongest linear trends in the seasonal average maximum and minimum 2-m temperatures in the BaltAn65+ reanalysis are detected in the winter for a large part of the study area, but the area with statistically significant trends is larger in the EOBS data. The statistically significant trends over an extensive area of Scandinavia that are detected in the EOBS data are missing from the BaltAn65+ reanalysis. A similar lack of significant trends, but in the seasonal average 2-m temperature, was detected by Männik

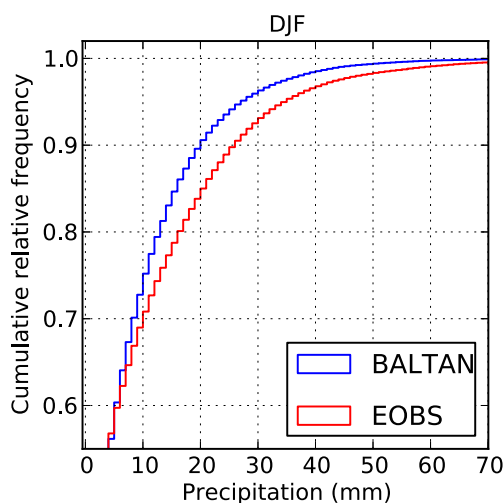


Fig. 13 Cumulative frequency distributions of the daily precipitation amounts (mm) in the winter from the BaltAn65+ reanalysis and EOBS data for a subregion of Scandinavia, shown by the *green box* in Fig. 11

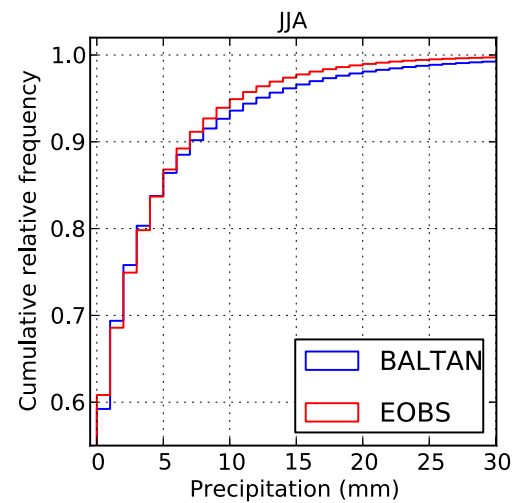


Fig. 14 Cumulative frequency distributions of the daily precipitation amounts (mm) in the summer from the BaltAn65+ reanalysis and EOBS data for a subregion situated to the south-east of the Baltic Sea, shown by the *red box* in Fig. 11

et al. (2015). Furthermore, the statistically significant linear trends in the annual number of days with 2-m minimum temperatures below the 10th percentile in multiple seasons over Scandinavia, which are detected in the EOBS data, are not detected in the BaltAn65+ reanalysis. This can also be explained by the poor simulation of the minimum temperatures over Scandinavia. In addition, there is a downward trend in the minimum temperature in the reanalysis data over the Bothnian Sea area.

In general, the trends in the number of days exceeding the selected temperature thresholds agree well between the EOBS and BaltAn65+ reanalysis data, except for the minimum temperatures over Scandinavia. The trends in the minimum temperature extremes in the winter in the EOBS data agree with Scaife et al. (2008), who explained that the changes were associated with the variability in the atmospheric circulation expressed as variability of the North Atlantic Oscillation. There are also statistically significant linear trends in the minimum temperature extremes in both the EOBS and BaltAn65+ reanalysis data in the other seasons, but the spatial distribution of these trends is patchy.

In the winter, the minimum temperatures have warmed more than the maximum temperatures, which coincides with the conclusion of the BACC II Team (2015) about the minimum temperature changes in the Baltic Sea region. This leads to a decrease in the diurnal temperature range. Jaagus et al. (2014) present evidence of this kind of change in the Baltic countries, which overlaps with the significant trend regions in our study. However, the minimum temperatures of the reanalysis have not warmed as much as those in the EOBS data. The greater increase in the minimum temperatures in the winter (than in the maximum and average temperature) is possibly related to changes in cloud cover.

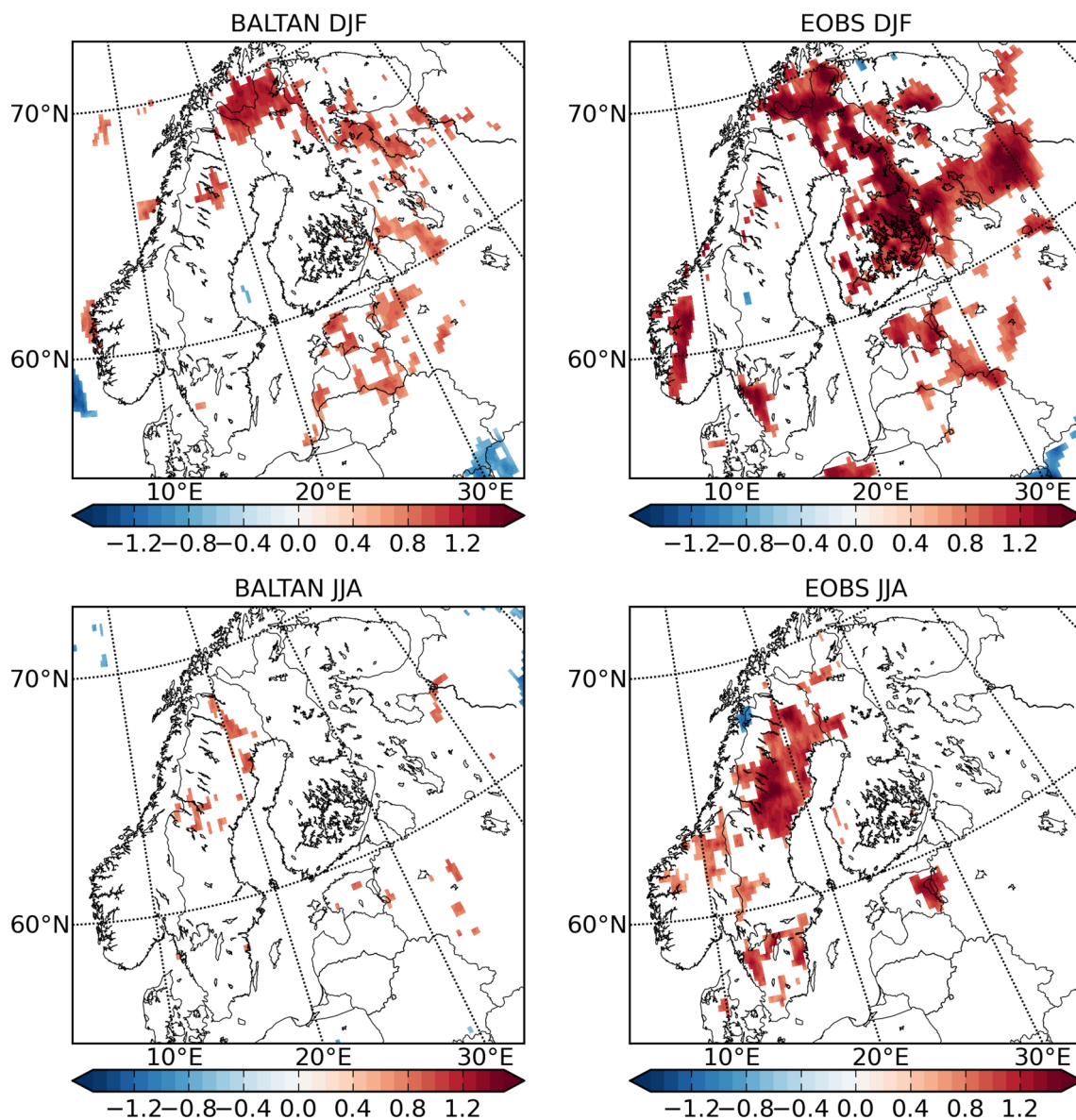


Fig. 15 Statistically significant linear trend (seasonal number of days per decade) of the number of days with precipitation amounts exceeding the 95th percentile from the BaltAn65+ reanalysis (over the entire area) and EOBS data (over land)

For example, Karl et al. (1993) revealed that the cloud cover and the amount of low clouds have increased in regions where the minimum temperatures have increased at a faster rate than the maximum temperatures. In addition, changes in the surface conditions may play an important role. The number of annual snow cover days decreased in the most of the area surrounding the Baltic Sea during the study period (BACC II Team 2015), which might influence the maximum and minimum temperatures differently.

We find several strong trends in the temperature over the Baltic Sea and, to evaluate them, we would need data sources other than EOBS, as the EOBS data are available only over land. The strong positive trends of the temperatures

over the central and southern parts of the sea in Fig. 9 are not in accordance with the results of Lehmann et al. (2011) or Høyer and Karagali (2016), who find the largest trends of SST in the northern and eastern basins of the sea. However, their trends are valid for the annual mean and could easily be associated with the shortening of the ice-season over these basins. Until now, very few papers have been devoted to the temperature extremes over the Baltic Sea. The paper by Bradtke et al. (2010) investigates the seasonal patterns of the SST data from satellites for the time period of 1986–2006. Their conclusions about the mean annual temperatures coincide with others, but they also study the temporal changes in the duration of the extremely hot periods in summer.

Their results about the prolonging of the length of the hot periods being greatest in the central and southern basins of the sea, confirm our results. They also note, that there is a tendency for the summer season to start earlier, which brings along a warming of the whole season.

Regarding precipitation, Männik et al. (2015) showed large differences in the seasonal precipitation sums over the Scandinavian mountains from the BaltAn65+ reanalysis and EOBS, such that the reanalysis overestimated the seasonal precipitation amount by up to 300 mm. There is also a strong disagreement in the daily precipitation extremes in this area between the two datasets. The analysis of the precipitation distribution frequencies showed overestimations of precipitation in the BaltAn65+ reanalysis of 1 to 2 mm for days with low daily precipitation amount and an overestimation of over 5 mm for days with heavy precipitation over a large part of the Scandinavian mountains. This may result from the poor representation of the influence of the complex topography in this region due to the limited resolution in the reanalysis and from the characteristics of the microphysical parametrization leading to too much precipitation in general.

The largest increase in heavy precipitation also occurs in the winter. The spatial distributions of the linear trends in the number of days with precipitation amounts exceeding 95th percentile in the different seasons are very similar to spatial distributions of the linear trends in the seasonal total precipitation shown by Männik et al. (2015). This is true for the BaltAn65+ reanalysis and EOBS in the winter and for EOBS in the summer. The linkage between the temporal trends in the total and heavy precipitation in Northern Europe is also highlighted by BACC II Team (2015).

The regional and seasonal atmospheric circulation strongly influence the mean weather, and the influence of the North Atlantic Oscillation mode on the winter climate of Northern Europe is now well established (BACC II Team 2015). The North Atlantic Oscillation index is highly variable and its long-term behaviour is irregular. However, from the mid-sixties to the end of the nineties and into the twentieth century, a positive trend towards more zonal circulation occurred. This period mostly coincides with our study period; therefore, strong unidirectional trends in the winter precipitation extremes and minimum temperature are in accordance with the North Atlantic Oscillation related changes (Scaife et al. 2008). At the same time, there are further interrelations, as the increase in the extreme precipitation in the winter is also caused by higher temperatures, which means that the winter precipitation has a higher probability of being rain instead of snow. The shift of the winter storm tracks to the northeast in the North Atlantic European region (Bengtsson et al. 2006; Lehmann et al. 2011) could also be related to the changes in winter precipitation.

5 Conclusions

Daily temperature and precipitation extremes in the Baltic Sea region over the time period of 1965–2005 were studied using the BaltAn65+ reanalysis and EOBS data. The disagreements in the simulated minimum temperatures and in the precipitation extremes of the two datasets were detected and analysed. Scandinavia is a region where the data of the BaltAn65+ reanalysis should be treated with care. The minimum temperatures in the winter and spring are too high in the reanalysis, and the extreme precipitation is poorly simulated over Scandinavia, which is seen when the data are compared to EOBS in different seasons. The extreme precipitation distributions from the BaltAn65+ reanalysis and EOBS data agree in the eastern part of the Baltic Sea region, and the extreme temperatures agree in the southern part of the Baltic Sea region.

The strongest trends in extreme temperature and precipitation were detected in the winter over a large part of the study domain. There are more warm days, i.e. there are 3 more days each decade when maximum temperatures are above the 90th percentile. Similarly, there are fewer cold nights, i.e. there are 3 fewer days each decade when the minimum temperatures are below the 10th percentile. As the minimum temperatures have warmed more in the EOBS data than the maximum temperatures, the diurnal temperature range has decreased. In addition, there are more very wet days, i.e. there are 1.5 more days each decade when the precipitation amount exceeds the 95th percentile.

The analysis of the extremes has helped to analyse the strengths and weaknesses of the HIRLAM numerical weather prediction model and the BaltAn65+ reanalysis, which should be carefully considered by the users of this dataset.

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