

RESEARCH ARTICLE

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Key Points:

- The Baltic Sea SST trend is mainly driven by SAT, which has been reinforced by the positive phase of the AMO since 1980
- Wind parallel to the coast and cloudiness are important for the SST in upwelling and offshore areas, respectively
- Changing stratification due to inflows from the North Sea do not affect long-term variability in the SST

Supporting Information:

- Supporting Information S1

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Temperature Variability of the Baltic Sea Since 1850 and Attribution to Atmospheric Forcing Variables

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Abstract The Baltic Sea is highly impacted by global warming and other anthropogenic changes and is one of the fastest-warming marginal seas in the world. To detect trends in water temperature and to attribute them to atmospheric parameters, the results of two different ocean circulation models driven by reconstructed atmospheric forcing fields for the period 1850–2008 were analyzed. The model simulations were analyzed at temporal and spatial scales from seasonal to centennial and from intrabasin to basin, respectively. The strongest 150-year trends were found in the annual mean bottom temperature of the Bornholm Deep (0.15 K/decade) and in summer mean sea surface temperature (SST) in Bothnian Bay (0.09–0.12 K/decade). A comparison of the time periods 1856–2005 and 1978–2007 revealed that the SST trends strengthened tenfold. An attribution analysis showed that most of the SST variability could be explained by the surface air temperature (i.e., sensible heat flux) and the latent heat flux. Wind parallel to the coast and cloudiness additionally explained SST variability in the coastal zone affected by the variations in upwelling and in offshore areas affected by the variations in solar radiation, respectively. In contrast, the high variability in stratification caused by freshwater and saltwater inflows does not impact the long-term variability in the SST averaged over the Baltic Sea. The strongest SST trends since the 1980s can be explained by the superposition of global warming and a shift from the cold to the warm phase of the Atlantic Multidecadal Oscillation.

1. Introduction

With a volume of 21,700 km³, including the Kattegat (BACC Author Team, 2008), and a salinity range from 3 to 12 g/kg (Fonselius & Valderrama, 2003), the Baltic Sea is one of the largest brackish seas in the world. Its physical characteristics such as salinity and temperature and also oxygen concentration are dominated by changes in the atmosphere, particularly temperature, sea level pressure, precipitation and river runoff, the cloudiness/radiation budget, wind, and nutrient inputs from rivers and the atmosphere. The Baltic Sea is connected to the open sea only by the narrow Danish straits. Moreover, its strong stratification prohibits vertical mixing due to a permanent halocline (Matthäus & Franck, 1992).

As climate change results in an increase in temperature as well as changes in circulation patterns, the Baltic Sea is also affected by increasing air and water temperatures (BACC II Author Team, 2015). Belkin (2009) analyzed reconstructed sea surface temperature (SST) trends of all large marine ecosystems between 1982 and 2006, collocating them by their trends. The Baltic Sea showed the largest temperature change of 1.35 K since 1982, followed by the North Sea, with a change of 1.31 K. Both changes were more than 7 times larger than the global rate. Coastal seas are known to be more sensitive to global climate change, as the absorption of sunlight at the surface of shallow and turbid waters is higher (Belkin, 2009), but also among coastal seas, the temperature rise in the Baltic Sea region is extreme. Considering a longer time period (1957–2006) produces different results because the local minimum in the 1980s was lower in the Baltic Sea than in other large marine ecosystems. Thus, the total temperature increase during the last 50 years was smaller than that during the last 30 years.

Hence, it is of special interest to investigate why the temperature change in the Baltic Sea was so strong during the last 30 years. The air temperature in the Baltic Sea catchment area rose by 0.4 K/decade during 1970–2008 (BACC II Author Team, 2015; Lehmann et al., 2011), while the values for the northern Baltic Sea were even larger. The global change amounts to 0.177 K/decade (IPCC AR4, 2007a).

Several publications have dealt with satellite-derived SST trends, considering different periods and spatial means of the Baltic Sea (Belkin, 2009; Gustafsson et al., 2012; Lehmann et al., 2011; Siegel et al., 2006). In addition, many publications reported the strongest SST trends during the summer months (Lehmann et al., 2011; Siegel et al., 2006; Stramska & Białogrodzka, 2015). With monitoring data from the southern Baltic Sea, MacKenzie and Schiedek (2007a) showed that the summer SST increased 2–5 times faster between 1985 and the early 2000s than the global rate over the same period of time. Belkin (2009), Siegel et al. (2006), Lehmann et al. (2011), and Stramska and Białogrodzka (2015) calculated similar annual Baltic Sea mean SST changes of approximately 0.56–0.57 K/decade during 1982–2006 and 1990–2004 and 0.5 K/decade during 1990–2008 and 1982–2013.

Although many publications (e.g., Lehmann et al., 2011; MacKenzie & Schiedek, 2007a; Stramska & Białogrodzka, 2015) have analyzed the general evolution of the hydrographic state of the Baltic Sea, particularly the SST, and reported exceptionally strong temperature trends in that region, very few studies have dealt with the temperature variability and its atmospheric drivers in detail. Lehmann et al. (2011) examined a large increase in air temperature but also a decrease in cloud cover, which could be an important factor warming the Baltic Sea surface water. There is also evidence for increasing warm summer inflow events during the last decades bringing warm surface water from the North Sea to deeper areas of the Baltic Sea (BACC II Author Team, 2015; Leppäranta & Myrberg, 2009; Meier et al., 2006; Mohrholz et al., 2006). Thus, in 100 years, the bottom temperature at Bornholm Deep increased exceptionally fast (Fonselius & Valderrama, 2003). A sensitivity test showed that higher absorption rates due to increased turbidity led to higher temperatures at the surface (Löptien & Meier, 2011). Eutrophication led to increased algal blooms and a remarkable decrease in Secchi depth during the last 100 years (Laamanen et al., 2004). However, the strong trends in summer SST since 1880 cannot be explained by increased algal blooms alone (Löptien & Meier, 2011). Stramska and Białogrodzka (2015) found higher annual variability in shallow coastal areas with large riverine nutrient inputs.

Many publications have also looked at the connection between the North Atlantic Oscillation (NAO; e.g., Hurrell, 1995; Visbeck et al., 2001) and SST changes, which is strongest in winter (Lehmann et al., 2011; Stramska & Białogrodzka, 2015). The NAO describes the strength of the dipole between the Icelandic low and Azores high pressure systems and plays an important role in the large-scale circulation pattern over Northern Europe. However, the NAO is not always the dominant pattern representing the atmospheric variability of the Baltic Sea region (Kauker & Meier, 2003; Meier & Kauker, 2003). The Atlantic Multidecadal Oscillation (AMO; Knight et al., 2006) is another important index of large-scale internal climate variability and is represented by the mean SST averaged over the North Atlantic (Knight et al., 2006). The associated atmospheric and oceanic circulation has an impact on the climate in the Northern Hemisphere, including Europe and the Baltic Sea. The AMO is related to variations in the transport of warm water toward Europe (Pohlmann et al., 2006; Sutton & Hodson, 2005) via the Gulf Stream and North Atlantic Current. This effect is more pronounced during the summer season. The northward heat transport in the Atlantic is the reason that Europe is warmer than North America, although they are located at the same latitudes (Pohlmann et al., 2006). Hence, in phases with a high AMO (anomalous high SST over the North Atlantic), there is increased heat transport toward Europe. Börgel et al. (2018) showed that the AMO also has an effect on the Baltic Sea salinity.

Temperature variability, especially at the surface, affects the ecosystems of the Baltic Sea. For instance, SST is an important factor for the onset and spatial distribution of cyanobacterial blooms (Kanoshina et al., 2003; Neumann et al., 2012) and for the populations of some fish species (MacKenzie & Köster, 2004). The complex system of the Baltic Sea has changed in different ways during the last 160 years since the first observations of temperature, salinity, and Secchi depth were recorded. Numerous studies concerning the long-term changes in the Baltic Sea using observations (Fonselius & Valderrama, 2003; Winsor et al., 2001) as well as simulations (Meier & Kauker, 2003; Schimanke et al., 2014) were performed during the last two decades. This study uses simulations of two models of the physical and biogeochemical evolution of the Baltic Sea from 1850 to 2008 with the same atmospheric forcing variables to understand the changes in temperature variability of the Baltic Sea. The advantage of model simulations over observational data sets is that the former are dynamically consistent and provide better spatial and temporal resolution. This study is, to the best of our knowledge, the first attempt to analyze temperature trends of the Baltic Sea with respect to seasonal and spatial differences with model simulations as well as several observational data sets and

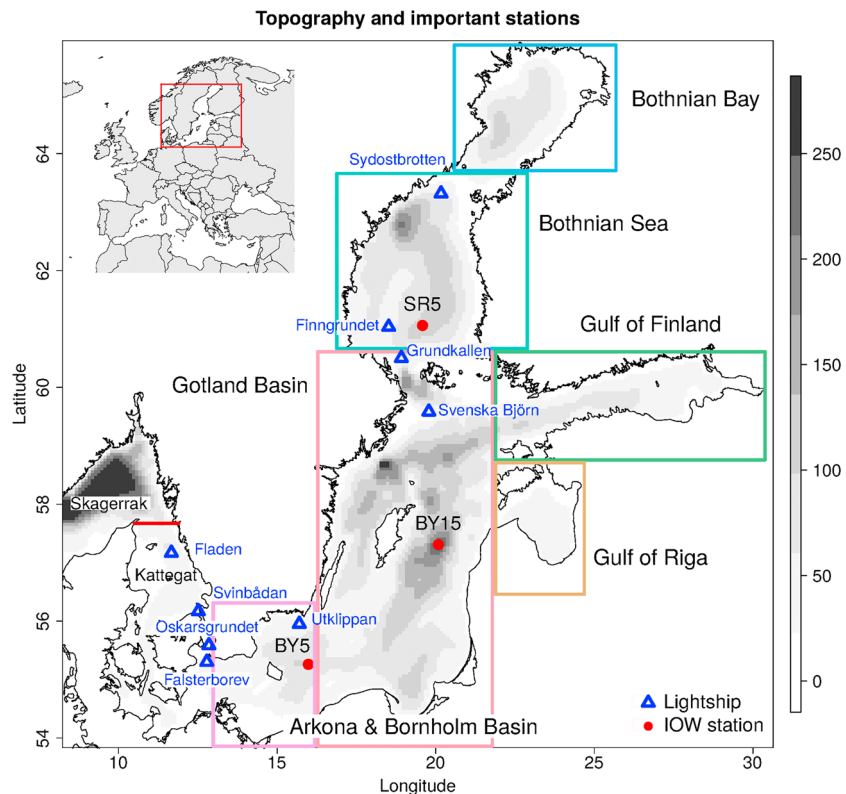


Figure 1. Bathymetry of the MOM setup with basins and stations (from the database of the Leibniz Institute for Baltic Sea Research IOW and lightships) used in this study. The red line between Kattegat and Skagerrak represents the boundary of the RCO model.

attribute the changes to variability in the atmosphere. We also provide a possible explanation of why the Baltic Sea warmed so quickly during 1982–2006.

In section 2, the model simulations, observations, and reconstructions used for the evaluation as well as the statistical methods are introduced. Section 3 presents simulated temperature trends and their evaluation relative to observations. Our results are also compared with the results from previous publications, and the trends are attributed to atmospheric forcing parameters. In sections 4 and 5, the results are discussed, and the conclusions of this study are drawn, respectively.

2. Data and Methods

2.1. Models

Two models were used. The Modular Ocean Model coupled with the Ecological ReGional Ocean Model (MOM-ERGOM; Neumann, 2000) and the Rossby Centre Ocean circulation model coupled with the Swedish Coastal and Ocean Biogeochemical Model (RCO-SCOB; Eilola et al., 2009; Meier et al., 2003) were both forced with the same reconstructed High-Resolution Atmospheric Forcing Fields (HiResAFF) by Schenk and Zorita (2012). The model domains and bathymetry are shown in Figure 1. Both models use the same atmospheric forcing, river runoff, and bathymetry data. However, the latter data were interpolated to different grids with a different spatial resolution.

2.1.1. RCO-SCOB

The RCO model is a Bryan-Cox-Semnter-type ocean circulation model coupled to a Hibler-type sea ice model (Meier et al., 1999, 2003). The horizontal and vertical resolutions are 3.7 km and 3 m, respectively. The subgrid-scale mixing in the ocean is parameterized using a $k-\epsilon$ turbulence closure scheme with flux boundary conditions (Meier, 2001). A flux-corrected, monotonicity-preserving transport scheme is embedded without explicit horizontal diffusion (Meier, 2007). The model domain comprises the Baltic Sea and Kattegat with lateral open boundaries in the northern Kattegat. In the case of inflow temperature, salinity, nutrients (phosphate, nitrate, and ammonium), and detritus, the values are nudged toward observed

climatological profiles, and in the case of outflow, a modified Orlanski radiation condition is used (Meier et al., 2003). Daily sea level variations in the Kattegat at the open boundary of the model domain were calculated from the meridional sea level pressure gradient across the North Sea using a statistical model (Gustafsson et al., 2012). The SCOB model comprises the dynamics of nitrate, ammonium, phosphate, oxygen, hydrogen sulfide, three phytoplankton species (including nitrogen-fixing cyanobacteria), zooplankton, and detritus (Eilola et al., 2009). The sediment contains nutrients in the form of benthic nitrogen and benthic phosphorus. Processes including assimilation, remineralization, nitrogen fixation, nitrification, denitrification, grazing, mortality, excretion, sedimentation, resuspension, and burial are considered. With a simplified wave model, resuspension of organic matter is calculated (Almroth-Rosell et al., 2011). Fluxes of heat, incoming longwave and shortwave radiation, momentum, and matter between the atmosphere, ocean, and sea ice are parameterized using bulk formulae adapted to the Baltic Sea region (Meier, 2002). Inputs to the bulk formulae are state variables of the atmospheric planetary boundary layer, including 2-m air temperature, 2-m specific humidity, 10-m wind, cloudiness, and mean sea level pressure, and ocean variables such as SST, sea surface salinity (SSS), sea ice concentration, albedo, and water and sea ice velocities. A detailed description of the model setup can be found in Meier et al. (2018).

2.1.2. MOM-ERGOM

“The physical part of the model is based on the circulation model MOM (version 5.1) (Griffies, 2004) and has been adapted to the Baltic Sea with an open boundary condition to the North Sea and riverine freshwater input. The MOM is complemented with a sea ice model to estimate ice cover thickness and extent. The horizontal resolution of the model grid is approximately 5 km, while vertically, the model is resolved into 134 layers, with a layer thickness of 2 m” (Neumann et al., 2017).

Since the MOM is operated in an uncoupled manner (without an atmospheric model) in this application, the downward heat fluxes have to be prescribed. The longwave radiation is calculated according to Berliand and Berliand (1952) with an adjustment of the cloud coverage (Kondratyev, 1969). For shortwave radiation, we used the model by Bodin (1979).

Essentially, the ERGOM simulates the marine nitrogen and phosphorus cycles. Three functional phytoplankton groups are involved in primary production (large cells, small cells, and cyanobacteria). A dynamically developing bulk zooplankton variable provides grazing pressure on the phytoplankton. Dead particles accumulate in the detritus state variable. In the sedimentation process, a portion of the detritus is mineralized into dissolved ammonium and phosphate. Another portion reaches the sea bottom, where it accumulates as sedimentary detritus and is subsequently buried, mineralized, or resuspended into the water column, depending on the velocity of near-bottom currents. Under oxic conditions, some of the mineralized phosphate is bound by iron oxides and is thus retained in the sediment, becoming liberated when conditions become anoxic. Oxygen development in the model is coupled to biogeochemical processes via stoichiometric ratios, with oxygen levels in turn controlling processes such as denitrification and nitrification.

Additionally, we created a box model in the MOM (hereafter called MOMbox) by constructing a rectangular basin with 3×3 grid points and a flat bottom with a depth of 100 m. We positioned the box model in the Gotland Basin from 19.5°E to 20.5°E longitude and 57.0°N to 57.5°N latitude. To omit advectional processes, the horizontal ocean currents were set to 0. Since neither sporadic inflows through the Danish straits nor freshwater input from the rivers was considered in the 1-D model, the salinity profile had to be prescribed, while precipitation was maintained. In this manner, the box model was initialized each year with a new salinity profile to maintain the vertical stratification. We followed two approaches: One simulation used the same vertical salinity profile for each year, and the second used the salinity profile from the original simulation to meet the temporal variability in the salinity. The time series of SST, SSS, and bottom salinity of the box models are shown in the supporting information. The box model was driven by the same atmospheric forcing as in the previous simulations.

2.2. Forcing Data

The HiResAFF data set developed by Schenk and Zorita (2012) were used in this study. This data set was already used and evaluated in Gustafsson et al. (2012) and Meier et al. (2012). Schenk and Zorita (2012) applied the analogue method to assign regionalized reanalysis data to the few available observational stations in the early periods. In this manner, the authors obtained consistent multivariate forcing fields without artificial interpolation. Simulations of the Rossby Centre regional Atmosphere-Ocean (RCOA; Döscher et al., 2002) model with a $0.25^\circ \times 0.25^\circ$ spatial resolution and daily model output were performed, using

ERA40 reanalysis data (Uppala et al., 2005) during 1958–2007 as forcing variables. The fields for 2-m air temperature were taken from an atmosphere-only simulation with RCA3, which was driven by observed SSTs (Samuelsson et al., 2011). The generated pool of daily atmospheric forcing fields (analogue pool, 1958–2008) including air temperature, wind, relative humidity, total cloud cover, precipitation, and mean sea level pressure was assigned to available observations during 1850–1957 (reconstructed period) using the analogue method (Schenk & Zorita, 2012). This method has been tested using various settings of the analogue method and by comparing the results with reanalyzed data and observations, which indicated that the data set is reliable and robust. River runoff and riverine nutrient loads were reconstructed following Meier et al. (2012) and Gustafsson et al. (2012), respectively.

2.3. Observations

For model evaluation, long-term observations from various observational data sets were used. The in situ temperature and salinity observations from the Leibniz Institute for Baltic Sea Research Warnemünde (IOW) database (https://www.io-warnemuende.de/en_iowdb.html) provide profiles at the most important stations, while reconstructions such as the U.K. Meteorological Office Hadley Centre data set HadISST1 (Rayner et al., 2003; https://www.metoffice.gov.uk/hadobs/hadisst/data/HadISST_sst.nc.gz) and the Optimum Interpolation SST (OISST) Version 2 satellite data from the National Oceanic and Atmospheric Administration (NOAA; Reynolds et al., 2007; <http://monitor.cicsnc.org/obs4MIPs/data/OISST/Monthly/>) provided spatial information for the SST. The daily OISST (Reynolds et al., 2007; Stramska & Białogrodzka, 2015) data have a spatial resolution of $0.25^\circ \times 0.25^\circ$ but are only available since 1982. Many satellite data provide only sea skin temperature, but with the so-called optimum interpolation method (Reynolds et al., 2007) the data can be interpolated to real sea surface water temperatures; thus, the data can be compared directly with model results. The HadISST1 data set is a reconstruction of merchant ship measurements, in situ observations, and values from other sources (MacKenzie & Schiedek, 2007b; Rayner et al., 2003) and provides only monthly data with a resolution of $1^\circ \times 1^\circ$ but includes data collected since the 1870s. This data set has already been used for analyses in the Intergovernmental Panel on Climate Change (IPCC) report (IPCC AR5, 2013). Additionally, temperature measurements from Swedish lightships (Lindkvist & Lindow, 2006; <http://smhi.diva-portal.org/smash/record.jsf?pid=diva2%3A947588&dswid=-8586>) were used to verify simulations back to the 1860s. Sea ice data of the Baltic Sea were provided by the European Environment Agency (EEA; Baltic Sea ice data (FMI), 2017, <https://www.eea.europa.eu/data-and-maps/diviz/maximum-extent-of-ice-cover>).

To quantify the variability in surface air temperature (SAT), a long record of air temperature measurements in Stockholm collected at the old astronomical observatory since the 1750s was considered (Moberg et al., 2002; https://bolin.su.se/data/stockholm/homogenized_monthly_mean_temperatures.php).

In addition, time series of the large-scale NAO and AMO climate indices were used to attribute the Baltic Sea mean SST variability to external drivers. Long-term observations of the sea level pressure differences between Reykjavik, Iceland, and Gibraltar, Spain, constitute the NAO index, which is available from the Climatic Research Unit, University of East Anglia (Jones et al., 1997; <https://crudata.uea.ac.uk/cru/data/nao/nao.dat>). The AMO index is defined as the mean SST over -80°E to 0°E and 0°N to 60°N detrended by the global mean SST change and shows a periodicity of approximately 60 years, oscillating between high and low mean SST values. A time series of the AMO index based on the HadISST1 data set is available from the Royal Netherlands Meteorological Institute (KNMI) Climate Explorer (Kennedy et al., 2011; Trenberth & Shea, 2005, https://climexp.knmi.nl/data/iamo_hadsst_ts.dat).

2.4. Statistical Methods

The analysis of the data mentioned above was performed using either the Climate Data Operators (CDO, 2015) or the statistical program R (R Core Team, 2015), while many figures were created using the package “ggplot2” (Wickham, 2009).

In this paper, anomalies were calculated relative to the period 1981–2008 because of the shortest observational data set (OISST). Baltic Sea mean temperatures refer to areas east of 13°E longitude (Figure 1). In the figures, time series of temperature are low-pass filtered with a cutoff frequency of 10 years to visualize the long-term variability. However, the linear and multilinear regression analyses were performed using the unfiltered annual or seasonal (winter, December to February [DJF]; spring, March to May [MAM]; summer, June to August [JJA]; and autumn, September to November [SON]) mean. The linear regression analysis was performed using the general least square fit method by maximum likelihood, taking the autocorrela-

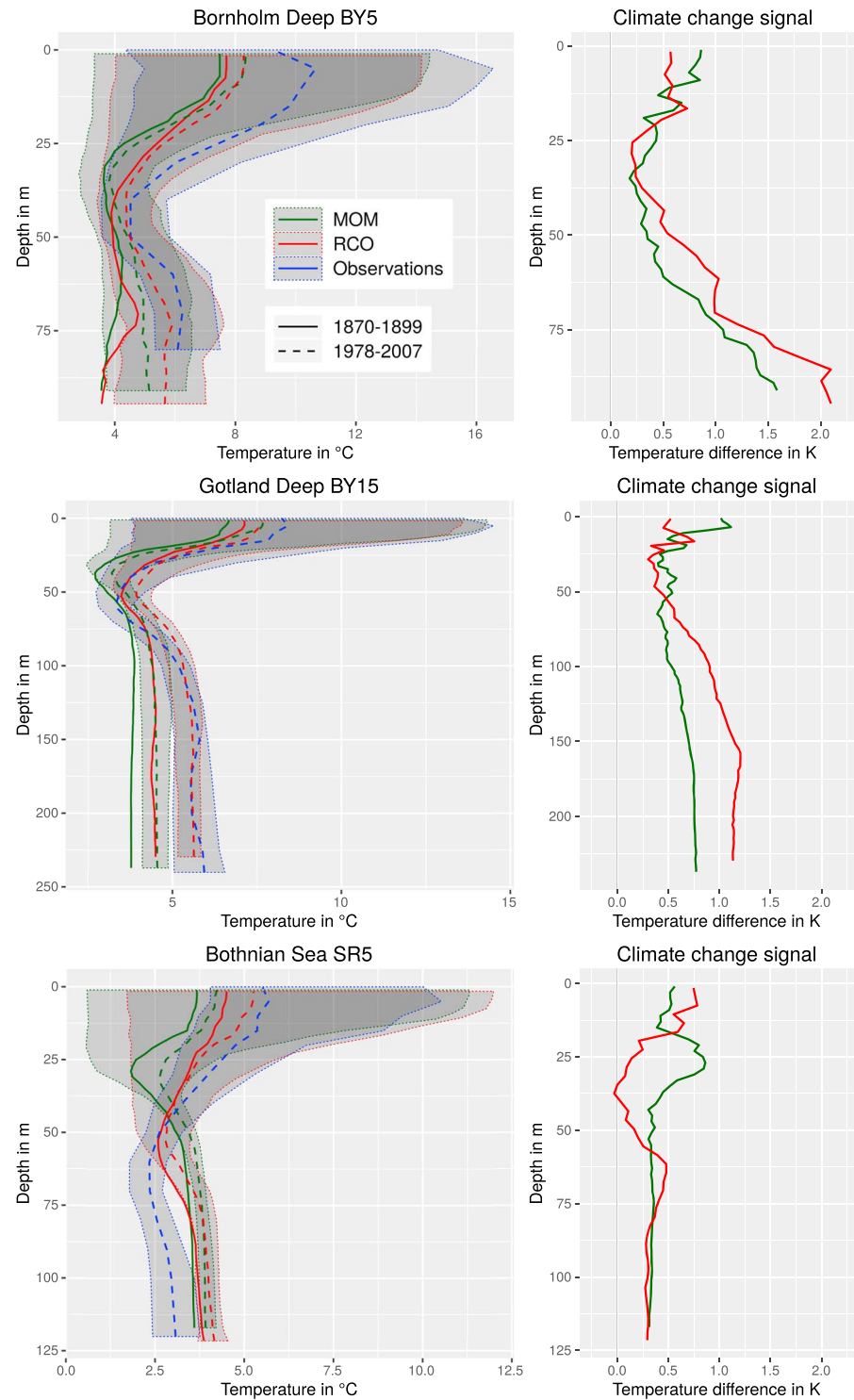


Figure 2. Profiles of simulated and observed temperatures in the Bornholm Deep (BY5), Gotland Deep (BY15), and Bothnian Sea (SR5). In the left column, for both simulations and observations, dashed and dotted lines show the median and the 25th and 75th percentiles during 1978–2007, respectively. In addition, the solid lines show median temperatures in the simulations during 1870–1899. In the right column, the simulated climate change signal in temperatures for the periods 1870–1899 and 1978–2007 is shown.

Table 1

Mean Annual Maximum Ice Extent in Observations and Simulations (in 10^6 m²), Root-Mean-Square Error (RMSE), and Correlation (Cor) of Simulations Compared to Observations for the Whole Simulated Period (1850–2008), the Reconstructed Period (1850–1957), and the Period of the Analogue Pool (1958–2008)

Time	Mean			RMSE		Cor	
	Obs	RCO	MOM	RCO	MOM	RCO	MOM
1850–2008	198.5	165.8	293.9	74.8	117.1	0.79	0.79
1850–1957	205.4	172.5	301.8	83.5	123.3	0.76	0.76
1958–2008	183.8	151.7	277.0	52.0	102.9	0.88	0.89

tion at a time lag of 1 (alpha) into account, which is a measure of the internal variability and important for calculating realistic confidence intervals (Ribes et al., 2016). To determine alpha, the first 50 years of each time series were used, while for shorter time series such as the OISST or lightship data, the value for alpha of the corresponding time series in the model simulations was used. For the regression analysis, the R package “Linear and nonlinear effect models” (Pinheiro et al., 2016) was applied. The interpretation of significance levels based on the p value and the corresponding thresholds was carried out according to Box 1.1 (“Treatment of Uncertainties in the Working Group I”) in the IPCC AR4 (2007a), while the null hypothesis was that no trend existed. Furthermore, the considered period for long-term trends (1856–2005) was chosen according to IPCC AR4 (2007a), while the short-term trends were calculated for the last 30 years in the simulation (1978–2007) without the record year 2008 (cf. Figure 12).

The correlation coefficient was calculated using Pearson's correlation, while its squared value was used to indicate the explained variance (Wilks, 2011).

Lastly, a ranking analysis was performed to determine which atmospheric drivers are most important for the variability in the Baltic Sea SST. Since air temperature explains most of the variability in the SST and is not stationary, the SST was subtracted by the residuals from a linear model fitting the SST to the SAT. The trend in air temperature dominated the time series of SST and thus masked other effects, which is why it was removed. To identify the second and third most important drivers of the SST, a cross-correlation analysis was applied because the effects of wind on the SST in upwelling areas is delayed by several days. For each grid point and variable (cloudiness, latent heat flux, and both wind components), the explained variance with a maximum time lag of 30 days was calculated. Finally, the variable explaining the most and second most variance was identified for each grid point.

3. Results

3.1. Evaluation of the Model Results

In situ observations from the IOW database were used to validate the temperature profiles at three exemplary stations from south to north (Bornholm Deep [BY5], Gotland Deep [BY15], and Bothnian Sea [SR5]; cf. Figure 1).

In Figure 2, the vertical mean temperature profiles for the period 1978–2007 show good agreement at the selected stations, which represent different vertical temperature gradients. The SST is underestimated in both models but is still within the standard deviation of the observations, except for the MOM in the Bothnian Sea. Simulated profiles are also shown for the period 1870–1899. The difference between the two periods in the model results represents the climate change signal and is shown in the right column. The change in temperature at every station and depth is positive. The largest changes occurred at Bornholm Deep with differences between 1.7 and 2 K. Toward the north, the changes become smaller for both the surface and deeper layers. In general, the changes at and below the thermocline are the smallest. In the deeper layers of the Gotland and Bornholm basins, saltwater inflows dominate the variability in water masses, with higher temperature changes than in the surface layer.

Since sea ice is a very important factor for the temperature variability in the Baltic Sea, in Table 1, the simulated maximum ice extent is compared with observations (Baltic Sea ice data (FMI), 2017). In this study, the total area of all grid points with a monthly mean sea ice concentration larger than 10% was summarized (Meier & Kauker, 2003). According to the observations, this was performed for the whole simulation area, while the RCO was corrected by 6.4% due to the data missing from the Skagerrak. The observed mean annual maximum ice extent during 1850–2008 amounts to 198.5×10^6 m², while the MOM produces a mean of

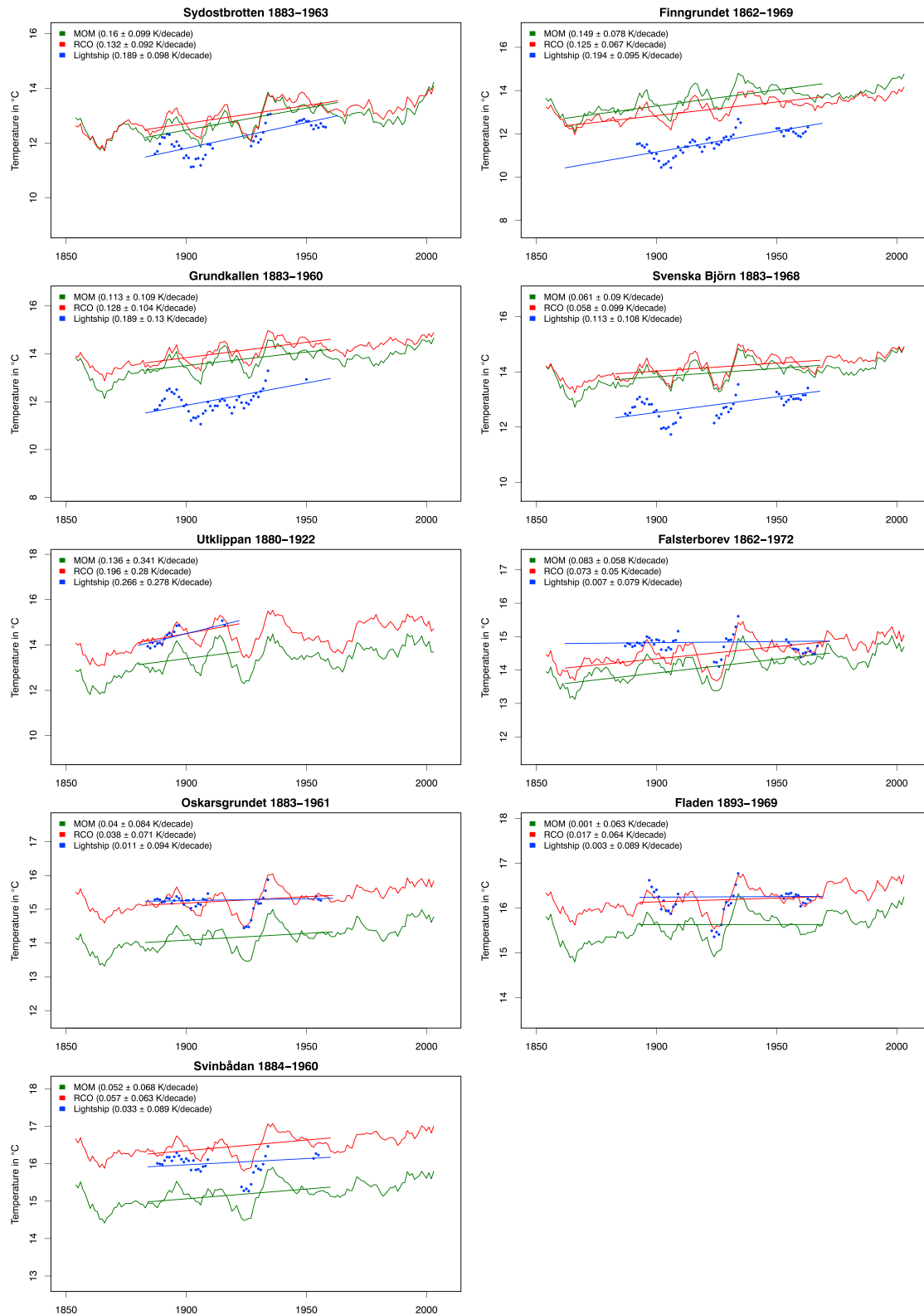


Figure 3. Simulated and observed 10-year running mean summer sea surface temperatures at lightship sites (cf. Figure 1) and corresponding linear trends during time periods with lightship observations.

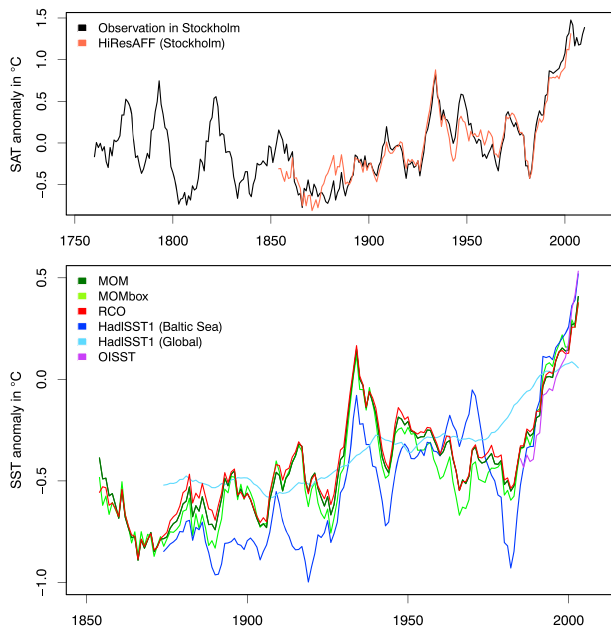


Figure 4. Ten-year running mean of simulated and observed time series. (top) SAT anomalies in Stockholm. (bottom) Baltic Sea mean and Gotland Deep SST anomaly. SAT = surface air temperature; SST = sea surface temperature.

$293.9 \times 10^6 \text{ m}^2$ and the RCO produces a mean of $165.8 \times 10^6 \text{ m}^2$, with root-mean-square errors of 117.1×10^6 and $74.8 \times 10^6 \text{ m}^2$, respectively. In addition, the variability in the annual maximum ice extent is underestimated in both models, while the MOM reproduces years with a completely ice-covered sea surface but overestimates the absolute mean, whereas the RCO result is closer to the observations but underestimates the mean sea ice extent.

Hereafter, mainly SST will be considered because the effects of the atmospheric forcing are most obvious for this variable. If measurements are available, these data sets (HadISST1 and OISST) will be included in the graphs to verify the detected long-term trends and variability.

To evaluate the long-term SST variability back to the 1860s, Figure 3 compares the 10-year running mean lightship measurements (Lindkvist & Lindow, 2006) with the corresponding simulated temperature at the closest model grid points. Since winter measurements during that time are very sparse, especially in the northern Baltic Sea, only the summer months (JJA) are considered.

The temperature variability is well reproduced by both models at all stations, while the mean error differs spatially. At the most northern station, Sydostbrotten, and in the southern areas (Utklippan and Falsterborev), the time series show good agreement, especially for the RCO in southern areas. However, in areas around the Archipelago Sea (Finngrundet, Grundkallen and Svenska Björn), the models show a large positive bias of 2–3 K. Nevertheless, at all stations, the variability in the measurements

and simulations shows very good agreement. The estimated trends for periods when observations are available show qualitative agreement. All time series exhibit the highest trends at Utklippan and the lowest at Fladen. Due to the different time periods of measurements at each lightship, conclusions about the spatial distribution of trends cannot be made. With respect to missing values and long periods with gaps in the measurements, we conclude that the variability in summer SST is well reproduced by both simulations. Figure 3 emphasizes the differences between the models. In northern areas, the MOM simulates slightly higher (or almost identical) temperatures than the RCO model. However, the more south the station is, the less the simulated SST of the MOM follows the observations and the lower it is below the observations, while the RCO values and observations are very close.

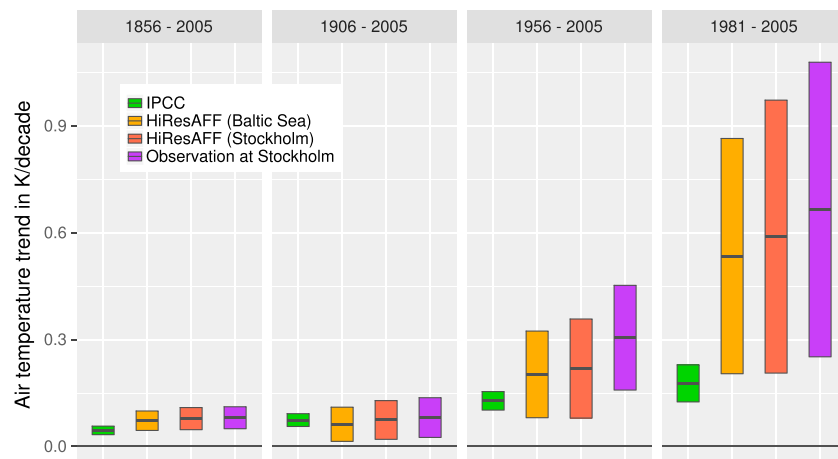


Figure 5. Trends in global (IPCC AR4, 2007a) and Baltic Sea annual mean surface air temperature in different periods. The global trends are taken from Table TS.6 of IPCC AR4 (2007b).

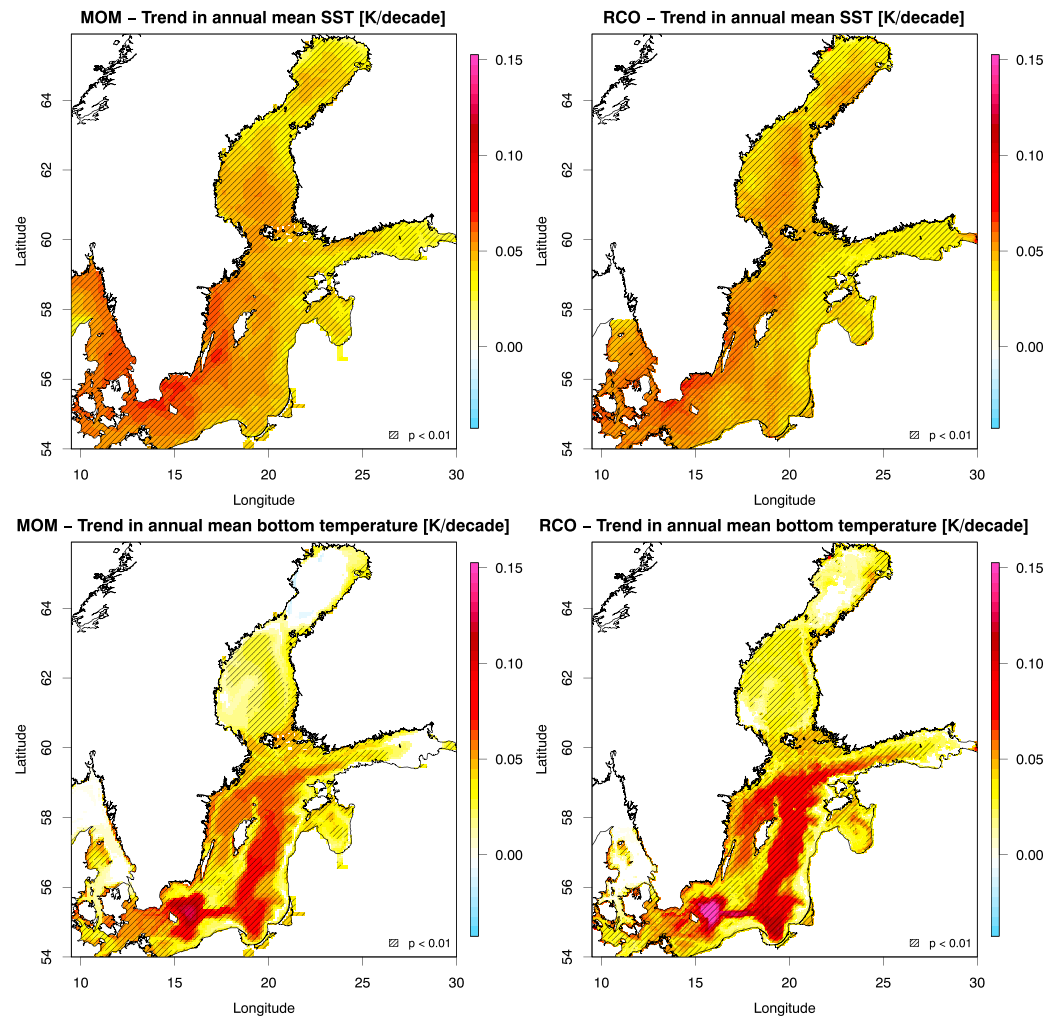


Figure 6. Maps of simulated 150-year linear SST (top row) and bottom temperature (bottom row) trends in Kelvin per decade for the MOM (left column) and RCO model (right column) during 1856–2005. Areas with a high significance level are hatched (p values lower than 0.01), and areas with no significance (p values larger than 0.33) are excluded (white). SST = sea surface temperature.

3.2. Detection of SST and Bottom Temperature Trends

Figure 4 shows the temperature development of both SAT (top panel) and SST (bottom panel) anomalies in the Baltic Sea region. The temperature variability in the forcing fits well with the long-term temperature measurement in Stockholm (Moberg et al., 2002). The correlation on a monthly scale amounts to 0.9. Additionally, the warm periods in the 1930s and 1990/2000s, which were repeatedly reported in recent studies (BACC II Author Team, 2015; IPCC AR4, 2007a), are clearly visible. The temperature after 2000 exceeded the highest values ever measured since 1756.

In the bottom panel of Figure 4, the results of both model simulations and observations from the Baltic Sea mean SST show good agreement, with correlations between 0.8 for the HadISST1 data set and 0.85 for the OISST data set. The mean error of the simulated SST amounts to -0.4 K for the MOM and $+0.1$ K for the RCO model, while the errors differ spatially, as seen in Figures 2 and 3. Nevertheless, the correlations between measurements and simulations are very high, which allows us to assess the temperature variability from continuous simulations since 1850.

Figure 5 summarizes Baltic Sea mean air temperature trends in different periods and data sets as well as the global trend reported in Table TS.6 by the IPCC AR4 (2007b). The temperature trends are consistently higher in the Baltic Sea than at the global scale. Especially during the last 25 years, the trends in the Baltic Sea were 3 times higher. The observations in Stockholm show even higher values. The error bars of the Baltic Sea air

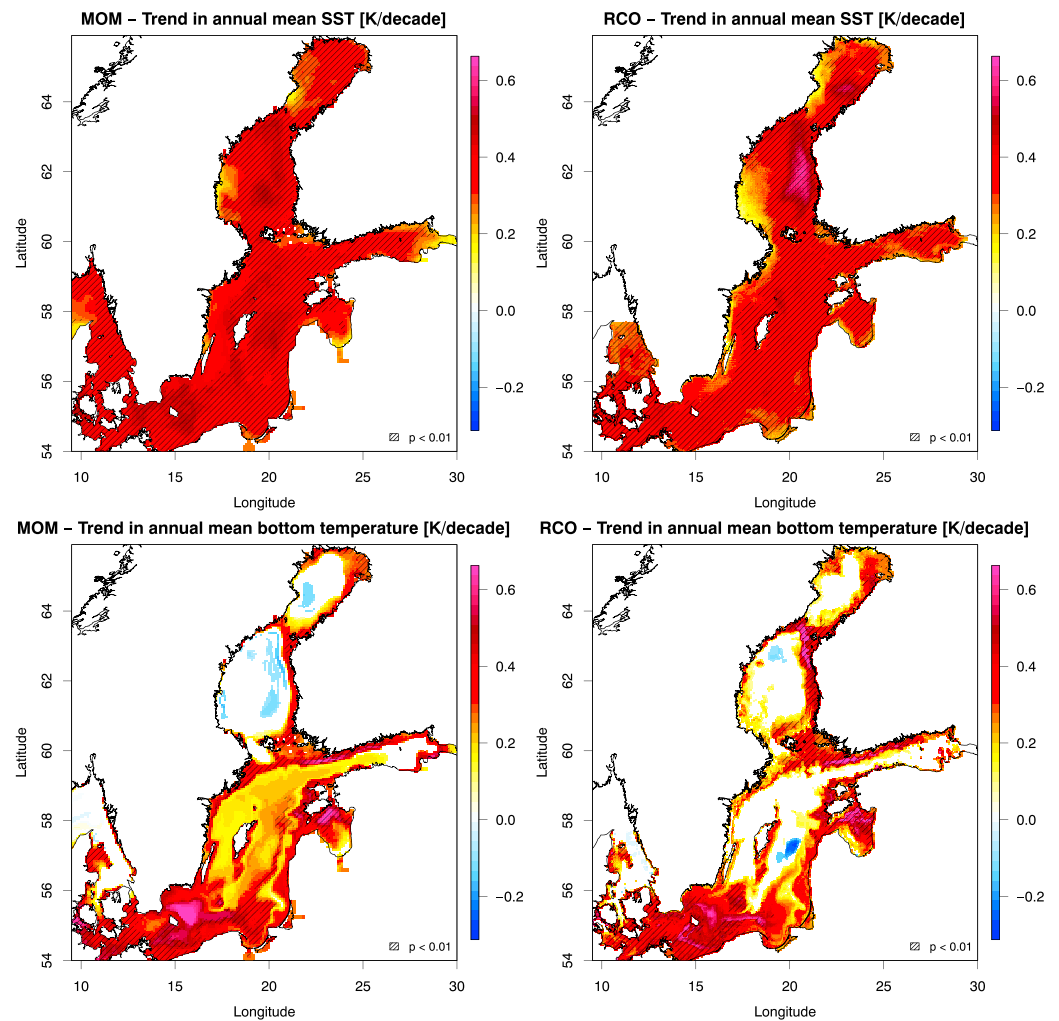


Figure 7. Maps of simulated 30-year linear SST (top row) and bottom temperature (bottom row) trends in Kelvin per decade for the MOM (left column) and RCO model (right column) during 1978–2007, as in Figure 6. SST = sea surface temperature.

temperature trends are much taller than those for the global trends due to the higher variability in the former (Figure 4). However, the overlap of the confidence intervals of global and Baltic Sea trends during the last period is very small or lacking (Stockholm observations), which shows that the increase in temperature in the Baltic Sea region during recent decades has been significantly larger than the global rate. However, the trends are underestimated in the forcing data.

The spatial distributions of the sea surface and bottom temperature trends during 1856–2005 with a significance level higher than 66% are shown in Figure 6. The models show comparable results regarding the spatial distribution, although the MOM simulated slightly stronger SST trends, especially in western areas, and the RCO model simulated stronger bottom temperature trends in the deeper parts of the Baltic Sea. The increase in the bottom temperature during 1856–2005 generally followed the bathymetry of the Baltic Sea. Most striking is the strong trend at Bornholm Deep, which amounts to almost 0.15 K/decade in the RCO model and 0.13 K/decade in the MOM and is comparable to the results in Figure 2.

Because the rate of global warming has increased in recent decades (cf. Figure 5), it is interesting to examine whether the spatial distribution changed. Figure 7 shows the same results as Figure 6 but for the period 1978–2007. Regions with relatively strong SST trends expanded to northern areas, while the RCO model simulates higher values than the MOM. In contrast, the SST trends at the Swedish coastline are weaker than those throughout the whole Baltic Sea, especially in the RCO simulation. The bottom temperature trends in deeper parts of the Baltic Sea are different from those shown in Figure 6. In deeper parts below 60 m, the

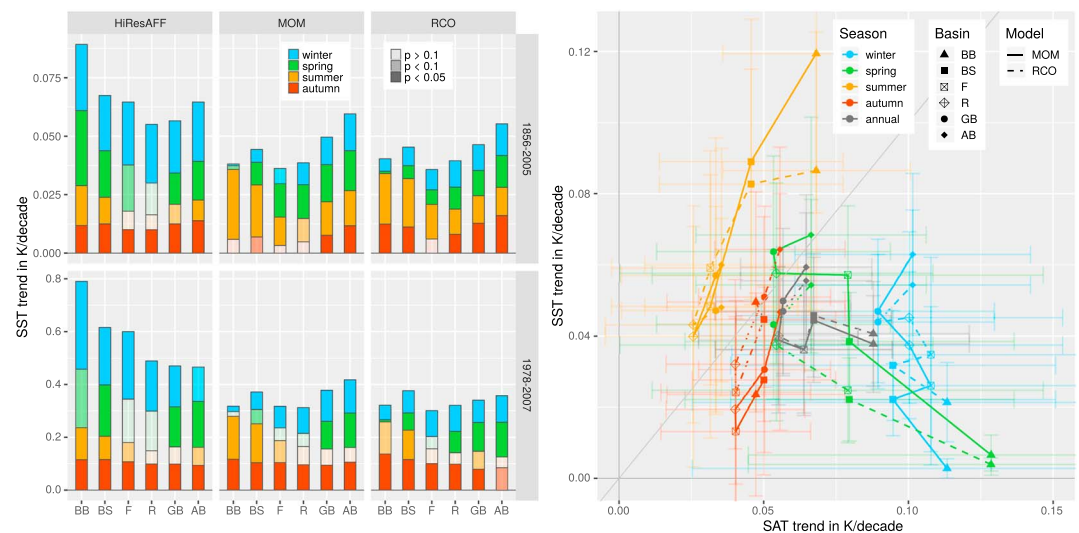


Figure 8. Seasonal and regional (basins, cf. Figure 1) trends in simulated SST and reconstructed air temperature. (left) The height of the bars represents the trend in the annual mean SST for two time periods (1856–2005 and 1978–2007). The height of the colored bars shows one quarter of the seasonal trends, representing the proportion of the seasons. (right) Scatter plot of SST over SAT trends with 90% confidence intervals; the gray line represents the direct relation between SAT and SST. Basins: BB = Bothnian Bay; BS = Bothnian Sea; F = Gulf of Finland; R = Gulf of Riga; GB = Gotland Basin; AB = Arkona Basin and Bornholm Basin. Seasons: DJF = winter; MAM = spring; JJA = summer; SON = autumn. SST = sea surface temperature; SAT = surface air temperature.

differences between the models are quite large, and most of the trends are not significant; in fact, even the signs of the trends differ. In shallow areas (up to a 50 m depth), the surface layer is well mixed, and the SST trends of this layer are homogeneous with depth, which can be seen for both models.

3.3. Seasonal Variability in SST and SAT

For a closer look at the seasonal and spatial variations of the SST and SAT trends, Figure 8 shows simulated and reconstructed trends in different seasons and subbasins (cf. Figure 1) of two different periods (150 and 30 years, cf. Figures 6 and 7). The significance levels are represented by the transparency of the colors,

but strong trends mainly have a significance level higher than 90%. The bar plot (left column) shows both periods in direct comparison, while the height and the color of the bars represent the annual trend and the proportion of the seasonal trend (since all trends are positive), respectively. The trends during the last three decades are approximately 10 times stronger than those since 1856, which can also be seen in Figures 6 and 7.

In addition, the scatter plot on the right-hand side of Figure 8 compares the trends in SST and air temperature during 1856–2005 directly, while the gray line represents the direct relation between them. Points above this line mean that the water temperature rises faster than the air temperature, and vice versa. The simulations show similar results, with small differences in the magnitude of the temperature increase between subbasins and seasons. The temperature trends show very high seasonal and regional variability. The strongest seasonal SST trends can be found in Bothnian Bay during summer, which are stronger than equivalent trends in the forcing air temperature (Figure 8), while the strongest SAT trends occur during winter and spring. The increase in air temperature is larger in northern than in southern areas in all seasons except autumn, especially in Bothnian Bay during winter and spring. Except in summer, the trends in SST are weaker than those in the SAT. The differences between SST and SAT are not significant, except in the northern basins (Bothnian Sea and Bothnian Bay) during summer (at least in the MOM), winter, and spring, with 90% confidence.

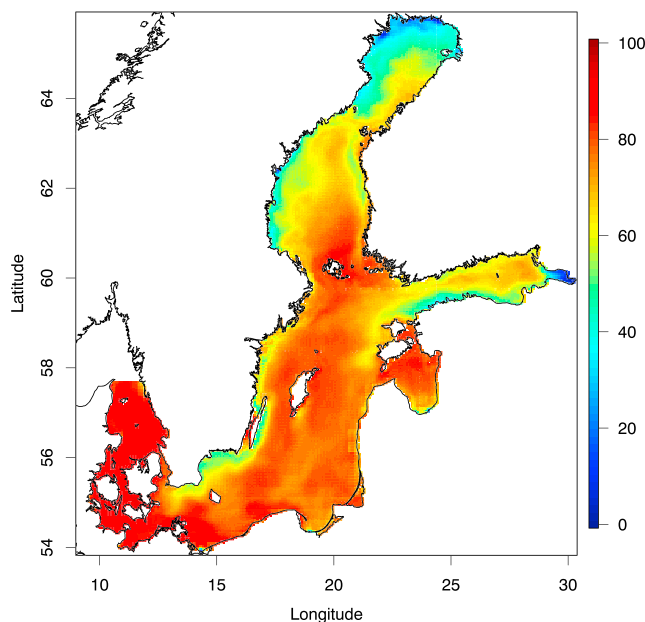


Figure 9. Explained variance (in percent) between the simulated annual mean sea surface temperature (RCO) and the forcing air temperature (HiResAFF) over the whole simulated period.

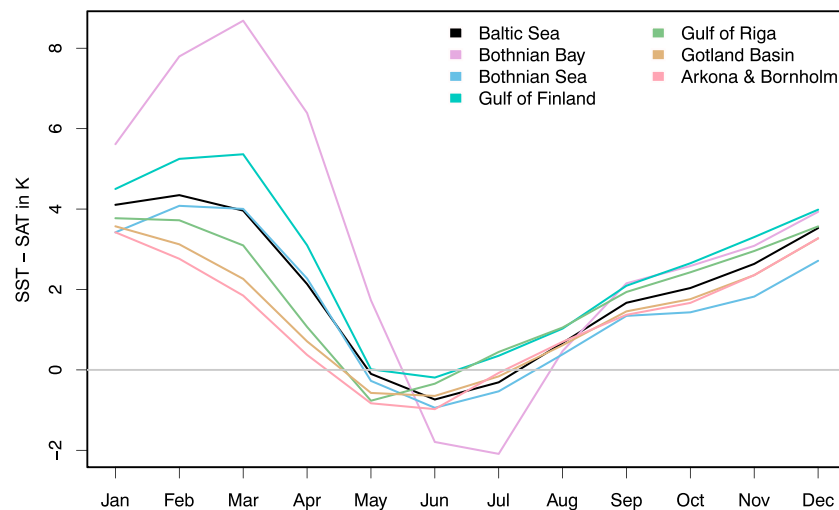


Figure 10. Annual cycle of the mean difference during 1850–2008 between SAT and SST in Kelvin for all basins and the whole Baltic Sea. The temperature difference between water and air is a measure of the sensible heat flux. SST = sea surface temperature; SAT = surface air temperature.

3.4. Attributing the SST Trends to the Atmospheric Forcing and Oceanographic Variables

The main driver of SST is the variability in the air temperature, with the highest explained variances on an annual scale of between 80% and 93% in the RCO model in the central areas of the Baltic Sea (Figure 9). The 1-D simulation of the MOMbox confirms this result (cf. bottom panel of Figure 4) because the long-term temporal variability does not change considerably when advective processes are omitted. Furthermore, a sensitivity analysis by Meier et al. (2018) showed that the long-term trends in SST vanish if the interannual variability in the forcing SAT is removed. Already shown by Omstedt and Rutgersson (2000), the Baltic Sea thermodynamically behaves like a closed ocean basin, and heat fluxes through the Danish straits are small. Hence, the attribution is confirmed, and we can apply the statistical approach of removing the induced variability in the air temperature to identify other important atmospheric variables, which was not previously possible because the variability in the air temperature was too dominant.

However, the link between SST and SAT is not always apparent. As shown in Figures 8 and 9, SST trends show different behaviors among seasons and regions. Indeed, Figure 9 shows lower explained variances in coastal areas, river mouths, the Bothnian Sea, Bothnian Bay, and the Gulf of Finland. To explain the discrepancies between SAT and SST during the different seasons, Figure 10 shows the mean difference between air and water temperature, which is a measure of the sensible heat flux according to the applied bulk formula (Meier, 2002; Meier et al., 1999). In most of the seasons, the difference is positive, which means that the water is warmer than the air. Only at the end of spring and in early summer is the heat flux directed toward the water, while the difference is largest in Bothnian Bay, where the strongest SST trends can be found.

The other atmospheric variables affecting the SST are both wind components, the latent heat flux and cloudiness (representative of the radiation budget). Precipitation and air pressure are highly correlated with cloudiness and have no direct impact on the SST.

The results of the ranking analysis are presented in Figure 11. The 2-day simulation output of the RCO model is used because the effects of wind cannot be detected on a monthly scale as provided by the MOM since upwelling only occurs over time periods from several days to weeks (Lehmann & Myrberg, 2008). All results show high significance with p values less than 0.01.

The latent heat flux is the second most important factor after the SAT at all grid points, while the explained variances in the detrended SST amount to 30–50%. The third most important atmospheric variable explaining the SST variability differs spatially. The wind component parallel to the coastline is important in most of the coastal areas. These areas are known to be affected by wind-induced coastal upwelling. The other areas, mainly located in the open sea and in eastern areas, are dominated by cloudiness, that is, solar radiation. However, the variances explained by wind and cloudiness are very small (below 4%), while that explained by upwelling areas is the largest.

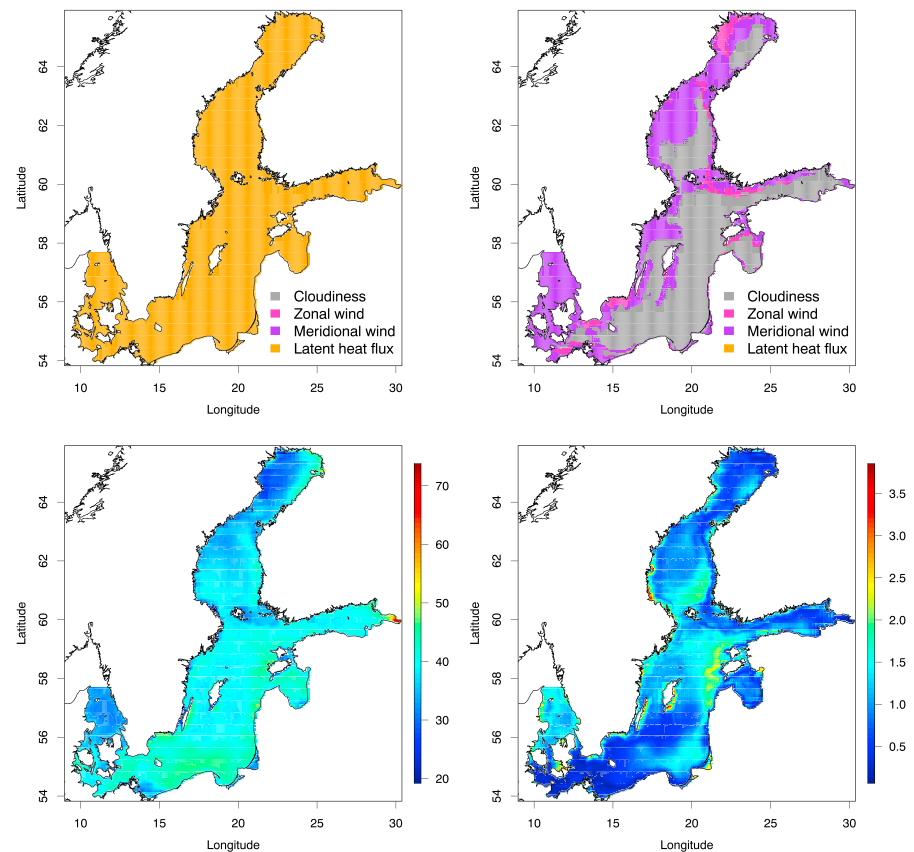


Figure 11. Results of the cross-correlation analysis of the detrended sea surface temperature (2-day output of the RCO model is used) with the wind components, latent heat flux, and cloudiness. Maps of atmospheric drivers (top row) with the highest (left column) and second highest (right column) cross correlations and related explained variances (in percent; bottom row).

3.5. Attribution to the NAO and AMO Climate Indices

In Figure 12, detrended and normalized time series for Baltic Sea mean SST (simulated by the RCO model) and the NAO and AMO climate indices are shown for 1901–2008. Since the winter NAO is the most prominent large-scale circulation pattern for Northern Europe (Lehmann et al., 2011), winter mean values (DJF) are considered. The main conclusions for the AMO are the same for the winter and annual means; hence, the annual mean values are considered for the AMO. Unfortunately, the AMO time series has many missing values before 1901, which is the reason the shorter time period is used. The explained variance amounts to 14% for the winter NAO index, while that for air temperature is much higher (25%). At an annual scale, the explained variance of AMO is quite small (5%). However, considering the long-term variability using the low-pass-filtered time series with a cutoff frequency of 10 years, 58% of the variability in the Baltic Sea mean SST can be explained by the AMO, while the NAO explains only 7%.

4. Discussion

4.1. Evaluation of SAT and SST

Comparing reconstructed and observed trends in Stockholm air temperature (Figure 5), we conclude that HiResAFF provide a good reconstructed air temperature over the Baltic Sea region but fails to resolve the high variability and slightly underestimates the trends in air temperature. We assume that the forcing data underestimate severe winters before 1958, as the analogues for the whole simulation period originate from a period that is already affected by a warmer climate. Thus, forcing fields for cold winters are scarce in the analogues. This assumption is supported by Table 1, which shows that the root-mean-square errors for simulated sea ice as well as the correlation are much better for the analogue pool period (1958–2007) than for the reconstructed period (1850–1957). Hence, the temperature variability and trends are presumably underestimated in the atmospheric forcing.

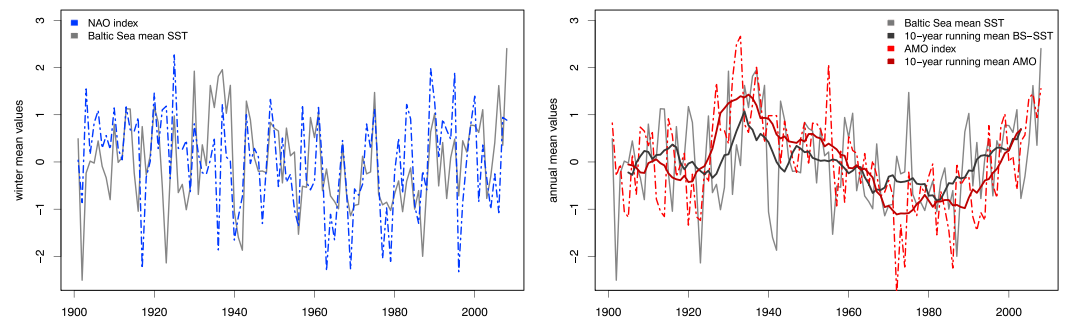


Figure 12. Detrended and normalized time series of the Baltic Sea annual mean SST and two climate indices. (left) Winter (December–February) mean NAO. (right) Annual and 10-year running mean AMO and SST. SST = sea surface temperature; NAO = North Atlantic Oscillation; AMO = Atlantic Multidecadal Oscillation.

The differences in simulated SST and sea ice can be explained by the different heat flux parameterizations and ice albedo values used in the models. Calculating the annual maximum sea ice extent using monthly mean values is an additional source of uncertainty because the observed time series is based on real-time observations with a higher temporal resolution (daily sea ice charts during winter; Baltic Sea ice data (FMI), 2017). Additionally, it should be mentioned that the models use different temperature outputs. The RCO model uses potential temperature, which is comparable to the in situ temperature in a shallow basin such as the Baltic Sea. In this simulation, the MOM applies the conservative temperature leading to a constant offset in comparison to the RCO model. Nonetheless, the correlation between measured air temperatures and reconstructed air temperatures is quite high, and the simulated SST trends fit quite well to the observations. In this manner, the simulations used in this study can be used to analyze the long-term variability in water temperature.

The profiles in Figure 2 show that both models mainly reproduce the vertical structure of temperature but do not meet the exact location and strength of the thermocline, especially in the Bothnian Sea. In addition, the SST is underestimated, presumably due to lack of observations in the winter.

Trend estimates from different publications using satellite SST data in different periods and spatial means of the Baltic Sea are reproduced with our data and compared in Figure 13. Generally, the simulated trends are consistent with the trends in the observations and in former publications, except for in the period 1990–2004 (Siegel et al., 2006). The trends of recent decades are generally slightly underestimated by both models. In Figure 4, higher variability in the HadISST1 data can be seen, which leads to lower temperatures during the colder period in approximately 1980 and higher temperatures in 2008. Since the forcing is not able to reproduce the large temporal variability, the large temperature increase since the 1980s is underestimated. In the

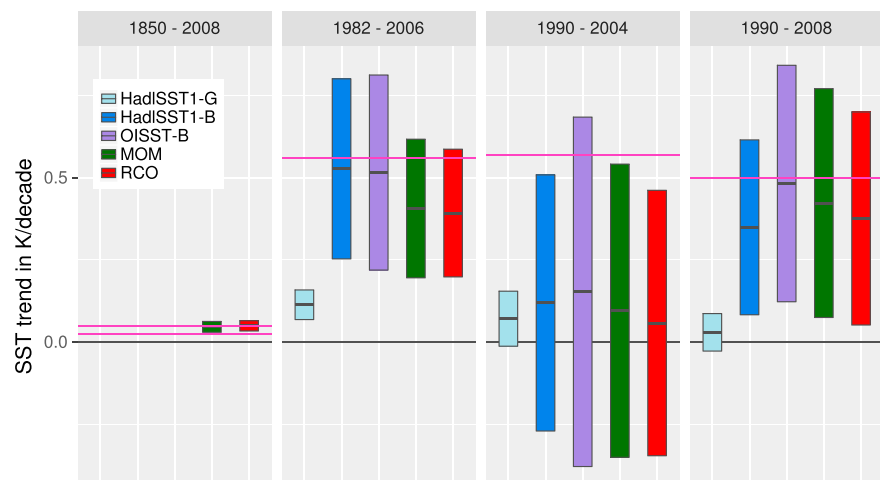


Figure 13. SST trends of the Baltic Sea in different data sets and publications (pink lines, from left to right: Gustafsson et al., 2012, Belkin, 2009, Siegel et al., 2006, and Lehmann et al., 2011). SST = sea surface temperature.

bottom panel of Figure 4, the global SST variability is additionally shown, emphasizing that the Baltic Sea follows the global trend but exhibits much higher variability, that is, stronger trends but also higher uncertainties. The periods of several previous studies were relatively short (15–30 years), although temperature trends in a varying system such as the Baltic Sea are very sensitive to the chosen start and end year. Regarding the high variability, small changes in the time period can lead to large differences in trend estimates, for example, results from the time period 1987–2001 fit well to the results of Siegel et al. (2006). All publications used different areas of the Baltic Sea, for example, Siegel et al. (2006) included Kattegat and Skagerrak, which could lead to different results. This assumption is confirmed by the comparison of OISST and HadISST1, which show similar results compared to the simulations performed in this study in all periods. In this manner, the analysis in this study is based on consistent basin boundaries and focuses on longer time periods of at least 30 years to increase the reliability of the results. Estimates from MacKenzie and Schiedek (2007a) were based on local observations, including observations from the North Sea, and therefore are not comparable to our results.

4.2. Processes Affecting Bottom Temperature

In contrast to the SST, the temperature variability at the bottom of the deeper parts of the Baltic Sea is mainly driven by inflowing water from the North Sea and mixing with upper layers. The strongest SST trends can be found in the shallow Danish straits in the southwestern part of the Baltic Sea (cf. Figure 6). The water in this area arrives at the bottom of the Baltic Sea during inflow events. Since the Danish straits are very shallow, the strong SST trends are projected to the deeper parts of the Baltic Sea. The inflows follow the bathymetry of the Baltic Sea, spread out from subbasin to subbasin, and accumulate at the bottom of the Baltic Sea. Presumably, due to mixing in the relatively shallow Arkona Basin, the trends in the Bornholm Basin are stronger.

Since there are only a few major Baltic inflows (MBIs) bringing surface water to the bottom of the Baltic Sea, the bottom water temperature changes abruptly during these events. During stagnation periods, mixing occurs mainly with the cold intermediate water layer (cf. Figure 2), and the bottom water temperature slowly decreases until the next MBI occurs. In this manner, the choice of the period for trend estimation is crucial and could lead to artificial temperature trends during relatively short time periods, which is why the bottom temperature trends in Figure 7 are different in the simulations.

4.3. Processes Affecting SST

The SST in the Baltic Sea is mainly driven by the air temperature, that is, the sensible heat flux. The smaller explained variances in Figure 9 can be explained by wind-induced upwelling and the seasonal formation of sea ice.

In Figure 6, the trends in annual mean SST during 1856–2005 show higher values in the southwestern parts of the Baltic Sea, with maxima along the Swedish coastline. This is a well-known upwelling area, which leads to the assumption that either the upwelling decreases due to changes in wind or the upwelled water from deeper layers (not necessarily from the bottom) is warmer. In this manner, the strong bottom temperature trends during 1856–2005 could explain the strong SST trends in the upwelling area. In contrast, the bottom temperature trends were weaker during 1978–2007 and could explain the weaker SST trends in the coastal upwelling area along the Swedish coast during 1978–2007 (Figure 7). The effect of the cold water brought from deeper layers to the sea surface leads to lower annual mean SST values in the affected coastal areas (not shown). In addition, the autocorrelation of SST in upwelling areas was quite high (not shown), which led to less accuracy in the statistical analyses. This analysis was performed for the whole time series; therefore, periods without upwelling were included and may have altered the results and reduced the explained variance.

The weaker SST trends and lower explained variances due to SAT in the northern areas can be explained by sea ice cover, which isolates the water column during winter, when the increase in air temperature is greatest. This result can also be seen in Figure 8. In winter and spring, when the water is frozen, the large increase in air temperature has no effect on the SST as long as the water temperature is still at the freezing point. However, the variability in the annual maximum sea ice extent can be explained by local winter mean values of the air temperature (Tinz, 1996).

The difference between SAT and SST, as a measure of the sensible heat flux, is decreasing with climate change in most seasons and basins (not shown). Presumably less sea ice cover and the shortening of the

sea ice season led to a closer relation between the atmosphere and ocean because the decoupling of their variabilities due to the freezing point vanishes with global warming. In accordance with the ice-albedo feedback, the effects are greatest in the melting season (JJA in Bothnian Bay, cf. Figure 8). As the sea ice vanishes earlier in the year, the SST in summer can increase faster than before because the time when radiative and sensitive heat fluxes are both directed to the ocean (cf. Figure 10) is extended. This mechanism explains the strong summer SST trends (cf. Figure 8) as well as the faster strengthening of annual SST trends in the northern basins (cf. Figures 6 and 7).

The MOM generally simulates higher SST trends than the RCO model. It has been discussed before that the sea ice extent is larger in the MOM than in the RCO model, leading to weaker trends in SST toward north in winter. This effect was also observed here, although the effect was reversed in summer. Nevertheless, the qualitative conclusions that could be drawn from the models are the same.

Furthermore, the 1-D simulation in Gotland Deep (MOMBox) without horizontal advection and a constant salinity profile (presented in Figure 4) shows that the long-term variability in SST is not affected by inflows from the North Sea and corresponding changes in stratification. Differences in Figure 4 are caused by the use of different spatial means (whole Baltic Sea and Gotland Deep). Since the vertical stratification of the Baltic Sea is highly variable, an additional simulation using time-dependent salinity profiles from the fully resolved simulation was performed. Figures S1 and S2 in the supporting information compare the box simulations to the original simulation.

Figure 12 attributes the SST variability of the Baltic Sea to the large-scale climate variability indices NAO and AMO. The variance explained by the NAO index is greater on an annual scale (winter mean) than that explained by the AMO. Hence, in the short term, the NAO is the dominant climate index explaining the Baltic Sea mean SST, especially in winter. It was previously shown that the winter NAO describes 40–50% of the sea level pressure patterns over the Baltic Sea area (Lehmann et al., 2011) and 27% of the annual maximum ice extent (Omstedt & Chen, 2001; Tinz, 1996). In this manner, the explained variances in the winter SAT and SST of 40% and 14%, respectively, seem reasonable since the correlation between SST and SAT is weaker during winter due to sea ice cover. In contrast, the AMO explains less than 10% of the variability in both SST and SAT on an annual scale but almost 60% on longer time scales. Analysis of the low-pass-filtered time series suggests that the high SST values in the 1930s and the low SSTs during the 1980s can be explained by the AMO. Variations in heat transport via ocean currents are much slower than atmospheric oscillations such as the NAO (Peixoto & Oort, 1992, scale analyses on pages 37–40). This difference is why the NAO exhibits strong correlations on an annual scale and the AMO exhibits strong correlations on a longer time scale with low-pass-filtered data with a cutoff period of 10 years.

As we have shown, air temperature is the most important forcing variable of SST in the Baltic Sea and thus leads to similar strong trends in water temperature. In this manner, the shift toward a positive phase in the AMO index since the 1980s enhanced the effect of the changing climate over Northern Europe and led to the strongest air temperature trends observed there during 1978–2005 (IPCC AR4, 2007b). Presumably, the trends will weaken when the AMO mode turns negative again. This weakening may already have been the case before the 1980s since the short-term temperature trends during the 1940s–1980s were negative. Unfortunately, the HiResAFF forcing data are only available until 2009; therefore, the following years, with a slight decrease in the rate of global warming, were not included, and the results of this study could not be compared with those in the latest IPCC report. However, a comparison with the prolonged time series ending in 2012 in the IPCC AR5 (2013) reveals that the strongest air temperature trends are no longer in Northern Europe. This result could indicate that the global warming hiatus is also caused by the AMO.

Belkin (2009) identified the North Sea, which is located in the same region in Northern Europe as the Baltic Sea, as the second fastest warming coastal sea worldwide. This identification emphasizes that the warming in this region was generally enhanced and supports our hypothesis that the AMO has an impact on the warming of the region. In comparison with the North Sea, the Baltic Sea is quite shallow, stratified, and almost completely surrounded by land, where global warming is generally more pronounced. In addition, higher latitudes have a higher sensitivity to a warming climate due to polar amplification (Holland & Bitz, 2003; Manabe & Stouffer, 1980). The combination of these factors may have enhanced the heating of the Baltic Sea even more.

4.4. Uncertainties

Sources of uncertainty include deficiencies in the analogue data due to biases of the used regional climate model and discontinuities due to the daily resolution and changing climate not represented by the observations used as analogue data. The impact of advection on temperature trends might be biased due to the coarse grid resolution of the models. In addition, we discussed saltwater inflows from the North Sea as a possible factor affecting bottom water temperature variability but did not analyze the effect of MBIs and small saltwater inflows statistically. In this study, it was assumed that the long-term variability in in situ and satellite measurements and model simulations were comparable.

5. Conclusions

From our results, we can draw the following conclusions:

1. The reconstructed annual mean SAT over the Baltic Sea during 1856–2005 increased by 0.06 and 0.08 K/decade in the central Baltic Sea and in Bothnian Bay, respectively. The strongest trends were identified during winter, including 0.09 K/decade in southwestern and 0.13 K/decade in northeastern basins.
2. During 1856–2005, the simulated (by both the MOM and the RCO model) Baltic Sea annual mean SST increased by 0.03 and 0.06 K/decade in northeastern and southwestern areas, respectively. In comparison to 1856–2005, during 1978–2007, the annual mean SST trends strengthened tenfold, with a mean value of 0.4 K/decade, while the trends in northeastern areas strengthened faster than those in southwestern areas. The strongest SST trends during 1856–2005 were found in the summer season in Bothnian Bay, including 0.09 and 0.12 K/decade in the RCO and MOM model, respectively. These trends exceed the corresponding trends in air temperature.
3. For 1856–2005, the strongest bottom temperature trends were found in Bornholm Basin, where the trends amounted to 0.13 and 0.15 K/decade in the MOM and RCO model, respectively.
4. The seasonal sea ice cover plays an important role in the Baltic Sea as it decouples the variability of the ocean and the atmosphere during winter and spring. Hence, in winter, the strong trends in air temperature were not recognized by the SST because the air temperature was below the freezing point. In contrast, during summer, the ice-albedo feedback led to stronger SST than SAT trends because the length of the warming period of the SST was extended.
5. The most important driver of the Baltic Sea SST variability during 1850–2008 was the SAT, with explained variances between 80% and 93% in the central areas of the Baltic Sea, directly followed by the latent heat flux, with 30–50% explained variances for the detrended SST. The third most important factors were wind-induced upwelling in coastal areas and cloud cover over the open sea. The long-term variability in the Baltic Sea SST was not affected by variability in stratification.
6. The strong SST trends since the 1980s can be explained by the superposition of global warming and a change from the cold to the warm phase of the AMO, while the polar amplification and higher sensitivity of shallow coastal seas enclosed by land may also have contributed to the stronger SST trends.

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