Detection and attribution studies of climate related changes in the Baltic Sea since 1850

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"Did they ever fit together?"

Al Gore - An inconvenient truth

Contents

Acknowledgement **VII**

Abbreviations **IX**

Abstract **XI**

Zusammenfassung **XIII**

Publications **XV**

1 Introduction **1**

2 The Baltic Sea **3**
- 2.1 Important large-scale modes of climate variability . . . 3
- 2.2 Salinity dynamics . . . 5
- 2.3 Temperature variability and sea ice . . . 6
- 2.4 Biogeochemistry . . . 8

3 Data and methods **11**
- 3.1 Model simulations . . . 11
- 3.2 Observational data . . . 14
- 3.3 Evaluation of the model results . . . 14
  - 3.3.1 Physical parameters . . . 14
  - 3.3.2 Biogeochemical parameters . . . 17
- 3.4 Statistical methods . . . 18

4 Results of the detection and attribution studies in the Baltic Sea **19**
- 4.1 Temperature . . . 19
  - 4.1.1 Detection of SST and bottom temperature trends . . . 19
  - 4.1.2 Attribution to atmospheric forcing variables . . . 20
  - 4.1.3 Why was the Baltic Sea warming so fast during 1982-2006? . 22
- 4.2 Salinity . . . 23
  - 4.2.1 Detection of long-term variability in SSS . . . 24
  - 4.2.2 Attribution to wind and river runoff . . . 25
- 4.3 Biogeochemistry . . . 26

4.3.1 Experimental approach 27
4.3.2 Attributing oxygen depletion to nutrient loads and climate variability 28

5 Discussion and Conclusion **33**
5.1 Uncertainties of the model simulations and the statistical approaches 33
5.2 Summary and discussion of the results 33
5.3 Relevance of the study 35

References **37**

A CV **45**

B Declaration of my contributions to the publications **47**
B.1 Temp-Paper (Kniebusch et al., 2019a) 47
B.2 Salt-Paper (Kniebusch et al., 2019b) 47
B.3 Sensitivity-Paper (Meier et al., 2018) 48

C Publications **49**
C.1 Temp-Paper: Temperature Variability of the Baltic Sea Since 1850 and Attribution to Atmospheric Forcing Variables 51
C.2 Salt-Paper: Changing salinity gradients in the Baltic Sea as a consequence of altered freshwater budgets 73
C.3 Sensitivity-Paper: Disentangling the impact of nutrient load and climate changes on Baltic Sea hypoxia and eutrophication since 1850 85

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Abbreviations

AMO	**A**tlantic **M**ultidecadal **O**scillation
AMSIcE	**A**nnual **M**aximum **S**ea **Ic**e **E**xtent
BED	**B**altic **E**nvironmental **D**atabase
BHDC	**B**ALTEX **H**ydrological **D**ata **C**enter
CO_2	Carbon dioxide
DIN	**D**issolved **I**norganic **N**itrogen
DIP	**D**issolved **I**norganic **P**hosphorus
H_2S	Hydrogen sulfide
ICES	**I**nternational **C**ouncil for the **E**xploration of the **S**ea
IOW	Leibniz Institute for Baltic Sea Research Warnemünde
HadISST1	**Had**ley Centre Sea **I**ce and **S**ea **S**urface **T**emperature data set
HiResAFF	**Hi**gh **Res**olution **A**tmospheric **F**orcing **F**ields
IPCC	**I**ntergovernmental **P**anel on **C**limate **C**hange
MOM	**M**odular **O**cean **M**odel
NAO	**N**orth **A**tlantic **O**scillation
N_2	Molecular nitrogen
$NH_4{}^+$	Ammonium
$NO_2{}^-$	Nitrite
$NO_3{}^-$	Nitrate
O_2	Molecular oxygen
OISST	**O**ptimal **I**nterpolated **S**ea **S**urface **T**emperature data set
$PO_4{}^{3-}$	Phosphate
RCO	**R**ossby **C**entre **O**cean model
REF	**Ref**erence simulation
SAT	**S**urface **A**ir **T**emperature
SLP	**S**ea **L**evel air **P**ressure
SSS	**S**ea **S**urface **S**alinity
SST	**S**ea **S**urface **T**emperature

Abstract

This thesis follows the approach of detection and attribution in order to find out how the Baltic Sea and its ecosystem have changed since the first systematic observations started around 1850 and what caused these changes. Therefore, coupled atmosphere-ocean models including marine biogeochemical processes were forced with a reconstructed data set for the period 1850-2008 and the model results as well as various observational data sets were analysed. For the attribution of changes in the Baltic Sea to atmospheric and other forcings different approaches were applied following either statistical or experimental strategies.

Variations in sea surface temperature (SST) are mainly driven by the heat fluxes (sensible, latent, radiative). Only in coastal areas wind parallel to the coast, which causes upwelling, plays a more important tole. Although the strong vertical stratification of the Baltic Sea is highly variable on multidecadal time scales, it has no significant impact on the long-term variability of the Baltic Sea SST. The often reported strong SST trend during 1982-2006 can be explained by the switch from the negative to the positive phase of the Atlantic Multidecadal Oscillation (AMO), an important mode of large-scale climate variability for the northern hemisphere, which enhanced the effect of global warming.

A systematic long-term drift towards a higher latitudinal gradient in the sea surface salinity (SSS) was found, which is partly masked by high multidecadal variability. The multidecadal variability of SSS and its North-South gradient is driven by both forcing variables wind and freshwater supply and, thus, by large-scale weather patterns. In contrast, the positive trend in the North-South gradient is caused by locally increasing river runoff in the northern basins.

The increase in the spatial expansion of water masses with low oxygen concentrations, so-called hypoxic area, can mainly be attributed to anthropogenically induced changes in riverborne nutrient loads and atmospheric deposition. Although

physical parameters like temperature are also important factors for the variability of hypoxia, it would not have occurred if nutrient conditions had remained at levels from 1850.

This work emphasizes that analysing climatic changes requires to also consider the internal variability of the climate system, since it can mask or enhance long-term changes during time periods of several decades.

Zusammenfassung

Diese Arbeit folgt der Methode "Detection and Attribution" (deutsch: Erkennung und Zuordung), bei der im Allgemeinen langfristige Veränderungen des Klimasystems bestimmt und ihren Ursachen zugeordnet werden. Das Ziel ist es hier, herauszufinden, wie sich die Ostsee und ihr Ökosystem seit Beginn der ersten systematischen Beobachtungen um 1850 verändert haben und was diese Veränderungen verursacht hat. Dazu wurden gekoppelte Atmosphären-Ozean-Modelle, welche auch marine biogeochemische Prozesse einbeziehen, mit rekonstruierten atmosphärischen und Flusseintragsdaten für den Zeitraum 1850-2008 angetrieben und die Modellergebnisse sowie verschiedene Beobachtungsdatensätze analysiert. Um die Veränderungen in der Ostsee ihren Ursachen, z.B. in der Atmosphäre, zuzuordnen, wurden sowohl statistische als auch experimentelle Ansätze verfolgt.

Die Variabilität in der Oberflächentemperatur (SST) wird hauptsächlich durch die Wärmeflüsse (fühlbare und latente Wärme sowie Wärmestrahlung) verursacht. Nur in Küstengebieten spielt der küstenparallele Wind eine wichtigere Rolle, da dieser zu Auftrieb führt. Obwohl die starke vertikale Schichtung der Ostsee auf multidekadischen Zeitskalen hohe Schwankungen aufweist, hat sie keinen signifikanten Einfluss auf die langfristige Variabilität der Oberflächentemperatur der Ostsee. Der starke SST-Trend in den Jahren 1982-2006 erklärt sich durch den Wechsel von der negativen zur positiven Phase der atlantischen multidekadischen Oszillation (AMO), einem wichtigen Modus der großräumigen Klimavariabilität für die nördliche Hemisphäre, der die Auswirkungen der globalen Erwärmung in diesem Zeitraum zusätzlich verstärkt hat.

Des Weiteren wurde eine systematische langfristige Zunahme im Nord-Süd-Gradienten des Oberflächensalzgehalts der Ostsee festgestellt, die durch eine hohe multidekadische Variabilität überlagert ist. Die langzeitliche Variabilität des Oberflächensalzgehalts und seines Nord-Süd-Gradienten wird sowohl vom Wind als auch durch

den Süßwassereintrag der Flüsse und somit durch großflächige Wettermuster bestimmt. Der positive Trend im Salzgradienten wird hingegen nur durch lokal zunehmenden Frischwassereintrag der Flüsse in den nördlichen Becken verursacht.

Die Ausbreitung der Wassermassen mit niedriger Sauerstoffkonzentration, den so genannten hypoxischen Gebieten, ist vor allem auf anthropogen induzierte Veränderungen der Nährstoffbelastung in den Flüssen und der Atmosphäre zurückzuführen. Obwohl physikalische Parameter wie z.B. die Wassertemperatur auch wichtige Faktoren für die Variabilität der Hypoxie sind, wäre sie nicht aufgetreten, wenn die Nährstoffbedingungen auf dem Niveau von 1850 geblieben wären.

Diese Arbeit betont, dass bei der Analyse von Klimaveränderungen die interne Variabilität des Klimasystems nicht vernachlässigt werden darf, da sie langfristige Veränderungen über einen Zeitraum von mehreren Jahrzehnten verschleiern oder verstärken kann.

Publications

Publications for the cumulative dissertation

"Temp-Paper"

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Temperature variability of the Baltic Sea since 1850 and attribution to atmospheric forcing variables

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"Salt-Paper"

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Climate Dynamics 53: 1145-1166 | `https://doi.org/10.1007/s00382-018-4296-y`

Other peer-reviewed publications

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Assessment of uncertainties in scenario simulations of biogeochemical cycles in the Baltic Sea | Frontiers in Marine Science Vol. 6 No. 46 | https://doi.org/10.3389/fmars.2019.00046

Radtke H., F. Börgel, S.-E. Brunnabend, A. Eggert, **M. Kniebusch**, H.E.M. Meier, D. Neumann, T. Neumann and M. Placke (2019)
Validator - a Web-Based Interactive Tool for Validation of Ocean Models at Oceanographic Stations | Journal of Open Research Software Vol. 7 No. 18 | https://doi.org/10.5334/jors.259

Neumann T., H. Siegel, M. Moros, M. Gerth, **M. Kniebusch** and D. Neumann (in review)
Ventilation of the Northern Baltic Sea | Ocean Science Discussion | https://doi.org/10.5194/os-2019-48

Conferences

Kniebusch M., H.E.M. Meier, H. Radtke

Changing salinity gradients in the Baltic Sea as a consequence of changing runoff in Northern Europe

Poster | EGU General Assembly 2019 | Vienna, Austria | 12.04.2019

Kniebusch M., H.E.M. Meier, T. Neumann

Temperature variability of the Baltic Sea since 1850 in model simulations and observations and attribution to variability in the atmosphere

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Poster | Baltic Sea Science Congress 2017 | Rostock, Germany | 15.06.2017

1 Introduction

It is generally accepted that the global earth system including climate and weather as well as biodiversity and natural habitats is significantly perturbed by humans (Stott et al., 2010). At the latest since the growth of the ozone hole has been dammed by reducing ozone-depleting substances in air conditioning and cosmetic utensils (Kuttippurath and Nair, 2017; Rockström et al., 2009), it was proven that humans can significantly perturb the composition of the atmosphere and that these changes can have fatal consequences. Nowadays, climate change, plastic pollution and particulate matter pollution in the cities are anthropogenically induced threats towards the global ecosystem and hence our own habitat. Researchers all over the world focus on how greenhouse gases affect the climate system on regional as well as on global scale. Understanding and predicting the underlying processes are important if greenhouse gas emissions are not reduced considerably and global warming continues. One important aspect of climate research are detection and attribution studies in order to understand the cause-and-effect chains and to disentangle internal climate variability and anthropogenic changes (Bindoff et al., 2013).

In the course of climate change, not only the temperature is rising, but complex modifications occur, e.g., regarding circulation patterns, the length of the seasons and the occurrence of extreme events (Field et al., 2012). Hence, also precipitation, cloudiness, sea level pressure and humidity is changing. Additionally, the climate system is non-linear with huge differences between regions and considered time periods, hence the causes of specific changes are not easily to be determined. Regional trends in air temperature vary between slightly negative trends in the southern mid latitudes up to 1.2 K/decade during 1981-2012 in higher northern latitudes (IPCC AR5, 2013). Although regional climate variability is mainly driven by large-scale atmospheric variability it is highly perturbed by local effects due to topography and landcover, while land masses and higher latitudes show higher variability and sensitivity than other regions (Manabe and Stouffer, 1980).

The approach of detection and attribution studies according to the Intergovernmental Panel on Climate Change (IPCC AR4, 2007; IPCC AR5, 2013) is, first, to identify systematic changes in a variable that is linked to climate, and secondly, to explain the transition by changes in other relevant factors using statistical methods or model simulations giving a plausible physical explanation (Bindoff et al., 2013). Generally, this is applied when changes in the climate are attributed to anthropogenic forcing. In this work, changes in the Baltic Sea (physical as well as biogeochemical) are attributed to corresponding changes in atmospheric and other external forcing variables like nutrient input from rivers. The atmosphere-ocean interaction in the Baltic Sea is additionally discussed under the aspect of anthropogenic induced changes.

The temporal climate variability shows various fluctuations including the daily and annual cycles characterized by day and night and the seasons, respectively. Additionally, there are long-term internal variations on interannual to multidecadal time scales. In this manner, it is very important to have a look at the temporal resolution and considered period before analysing climate-related time series.

From the mathematical point of view there is a long-term trend (i.e. global warming) superimposed by long-term variability (oscillations of several years or decades) which is again superimposed by annual and daily cycles. In order to address the long-term variability and trends, allocatable low-frequency variability could be removed in order to make the changes visible (e.g., Wilks, 2011). Talking about temperature trends in the mid latitudes for instance, annual (or seasonal) mean temperatures should be used in order to remove the strong intraannual variability, which is larger than the long-term signal and, thus, can mask long-term changes.

When the signal, effects and timing of internal climate variability are known, their influence on a specific time series can be discussed as well. Often, large-scale drivers dominate the climate of a region. Hence, identifying and disentangling the influence of large-scale internal climate variability on a regional climate system can expose the regional processes.

2 The Baltic Sea

Being a semi-enclosed sea with limited exchange with the open ocean, the Baltic Sea is highly influenced by the regional climate, hydrology and human impacts in the catchment area. With a total area of about 420 000 km^2 (including the Kattegat and the Danish straits, cf. Fig. 2.1) it is one of the largest marginal seas on earth. At the same time it is one of the best monitored and analysed coastal regions, which is why it is often used as a laboratory for accelerated changes due to human impacts (Conley, 2012; Reusch et al., 2018).

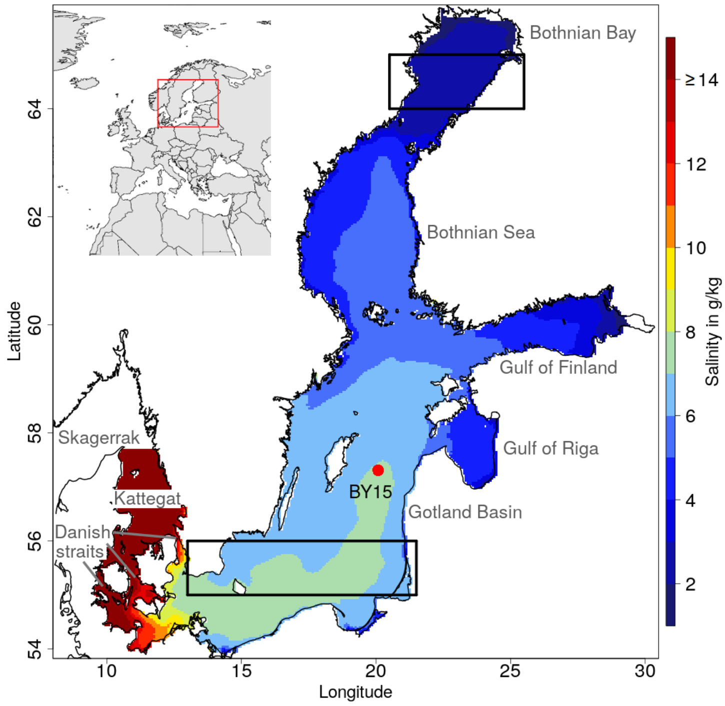

Fig. 2.1 Mean sea surface salinity in g/kg during 1850-2008 simulated by the regional ocean model RCO. The two black boxes represent the areas for the calculation of the North-South gradient. The station BY15 (Gotland Deep) is the location for the observations representative of the Baltic Sea mean salinity anomalies.

2.1 Important large-scale modes of climate variability

The most important modes of climate variability for northern Europe and, thus, the Baltic Sea region are the so-called North Atlantic Oscillation (NAO, Hurrell et al., 2003) and Atlantic Multidecadal Oscillation (AMO, Knight et al., 2006).

The North Atlantic Oscillation can be described by the NAO index, which quantifies the dipole between the Icelandic low and the Azores high pressure system. A positive NAO index means that both pressure systems are very strong leading to a strong pressure gradient and, thus, to strong westerly winds. In contrast, negative NAO phases lead to reduced westerly winds and stable meteorological situations over central Europe. For the Baltic Sea region, phases with positive NAO are dominated by increased precipitation and mild temperatures and negative NAO by extreme temperatures (hot during summer, cold during winter) and less precipitation (Hurrell et al., 2003). The link between the NAO index and weather over Northern Europe is more pronounced during winter, which is why the winter (DFJ) NAO index is mainly used for the attribution (Visbeck et al., 2001). The NAO shows high temporal variability on annual to subdecadal time scales. There are mainly two different methods, how the NAO index is calculated. In the past, measurements of sea level pressure (SLP) at Reykjavik and Gibraltar were substracted to get the approximated difference between the two pressure systems. This method bears a lot of uncertainties, but is the only way to determine the index back to 1800 when the measurements started. More modern methods use statistical approaches like empirical orthogonal functions or principal component analyses (Thompson and Wallace, 1998) in order to take the whole spatial distribution of the pressure systems into account. Since this method needs fully resolved SLP maps over the North Atlantic, good reanalysis data are needed, which is why these time series are comparatively short. The NAO is closely related to the Arctic Oscillation (AO), while the latter not as relevant for the northern hemisphere as the NAO (Ambaum et al., 2001).

The Atlantic Multidecadal Oscillation describes variations in the mean temperature state of the North Atlantic and reflects the heat transport towards Northern Europe via the Gulf Stream. In the data set provided by the Royal Netherlands Meteorological Institute (KNMI) Climate Explorer (Trenberth and Shea, 2005; Kennedy et al., 2011, `https://climexp.knmi.nl/data/iamo_hadsst_ts.dat`) the AMO index is defined as the mean sea surface temperature (SST) of the North Atlantic between 0°W to 80°W and 0°N to 60°N, with the long-term trend substracted and low-pass filtered with a cut-off period of 10 years. The AMO shows high variability on long periods with cycles of about 60-90 years. In this manner, the climate of the whole northern hemisphere, particularly Europe, is affected by this multidecadal oscillation. Years with a positive AMO index exhibit higher temperatures and increased precipitation in northern Europe (Börgel et al., 2018).

There are many other internal modes of climate variability that are important for northern Europe, e.g. the Scandinavian and the East-Atlantic (EA) pattern (Barnston and Livezey, 1987). The Great Salinity Anomalies (GSA) also cause temperature anomalies in the northern North Atlantic on multidecadal timescales which influence the temperature over northern Europe (Dickson et al., 1988), while they can be caused by two different mechanisms and are therefore not easy to address (Belkin et al., 1998). Since NAO and AMO are the most important modes

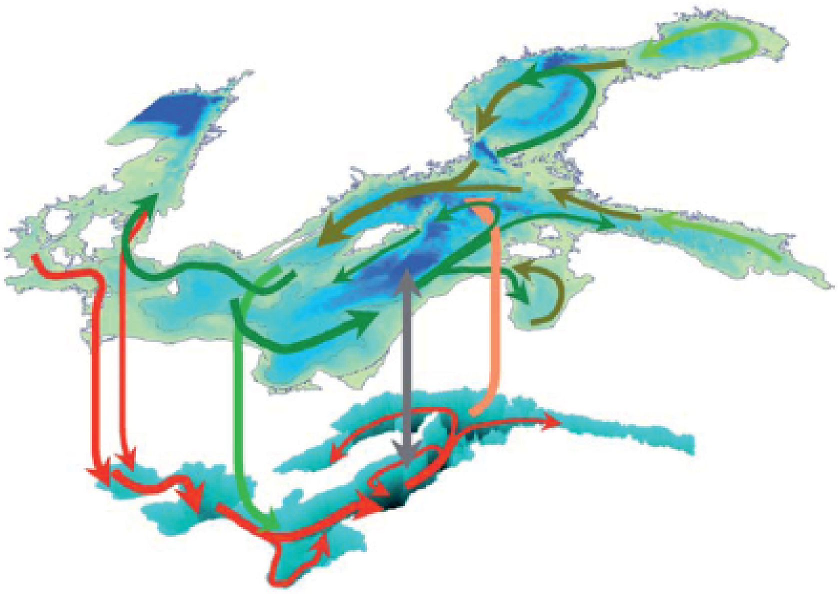

Fig. 2.2 Schematic illustration of the water circulation in the Baltic Sea. Red arrows refer to high saline water below the halocline, green to fresh surface water and vertical (light green, beige and grey) arrows denote entrainment and diffusion. Source: BACC Author Team (2008).

with explicit influences on the temperature in northern Europe and long time series available that have often been used in the literature, only these two were considered in this work.

2.2 Salinity dynamics

Due to the limited exchange with high saline water from the open sea and a positive freshwater budget, the Baltic Sea is dominated by brackish water and characterised by an estuarine circulation (BACC Author Team, 2008). The saltwater flowing from the North Sea through the Danish straits accumulates at the bottom of the Baltic Sea (Matthäus and Franck, 1992; Schinke and Matthäus, 1998) and flows from basin to basin following the topography (cf. Fig. 2.2). In contrast, the freshwater from the rivers mainly stays at the surface, flows southwards and leaves the Baltic Sea through the Danish straits into the North Sea. The ocean circulation driven by saltwater inflow through the Danish straits and river discharge is affected by the Coriolis force leading to cyclonic flow patterns (Döös et al., 2004). As a result, the Baltic Sea has high salinity gradients in both horizontal and vertical direction leading to a strong halocline in about 60-80m depth, which reduces vertical mixing via diffusion and advection. The spatial distribution of the mean sea surface salinity (SSS) can be seen in Figure 2.1.

Inflow activities of high saline water are either baroclinically or barotropically driven (Mohrholz, 2018). The small inflow events, so called baroclinic events, occur due to the salinity difference between the Kattegat and the Baltic Sea. In contrast, barotropic events occur due to sea level differences in that region caused by long lasting easterly wind conditions (Franck et al., 1987). When the wind turns towards West again, huge water masses are pushed into the Baltic Sea. Extreme barotropic inflow events are called major Baltic inflows (MBIs) and bring huge amounts of high saline and oxygen-rich water within a few days. Long-term observations and reconstructions of MBI events by Fischer and Matthäus (1996) showed decreasing frequency of these events since the 1980s. However, Mohrholz (2018) revised the time series taking into account that after 1991 a new observation station at a different location was used for the detection of MBI events and adding additional observations for the time period 1976-1991 when there was a lack of appropriate observations. This analysis revealed that the statistics of MBIs (now referred to as large barotropic events) have not changed since 1887 while there is a clear multidecadal variability with a period of 25-30 years. In total, barotropic inflow events provide 50% of the saltwater transport into the Baltic Sea (Mohrholz, 2018). Although large barotropic events contribute only 20% to the total saltwater transport, these are the only sources for deepwater ventilation in the stratified Baltic Sea.

Apart from that, freshwater supply from the rivers explains about 50% of the variability of the Baltic Sea mean salinity (Meier and Kauker, 2003b). The total river runoff to the Baltic Sea without the Kattegat amounts to 450 km^3 per year. There were no long-term changes in the total river runoff during the past century (Meier and Kauker, 2003b), while some rivers show significant positive trends (Lindström and Bergström, 2004; BACC II Author Team, 2015). The freshwater supply due to net precipitation (precipitation-evaporation) is about ten times smaller than the river runoff.

2.3 Temperature variability and sea ice

Since the Baltic Sea is located in the mid-latitudes between 53°N and 66°N, the seasonal variability of temperature is very high. While at least the northern basins are frozen during winter, in summer the SST in the South can reach over 20°C. A map of the simulated mean SST during 1850-2008 can be seen in Figure 2.3.

With air temperatures below the freezing point during winter, the seasonal sea ice cover in the Baltic Sea shows high variability from year to year. The annual maximum sea ice extent (AMSIcE) is reached in March, while during late summer the Baltic Sea is completely ice free. The northern basins Bothnian Bay, Bothnian Sea and the Gulf of Finland are at least partly frozen every winter. The observed AMSIcE of the Baltic Sea varies between 12% (50 000 km^2) and 100% (Baltic Sea ice data (FMI), 2017). The maximum annual ice volume of the entire Baltic Sea

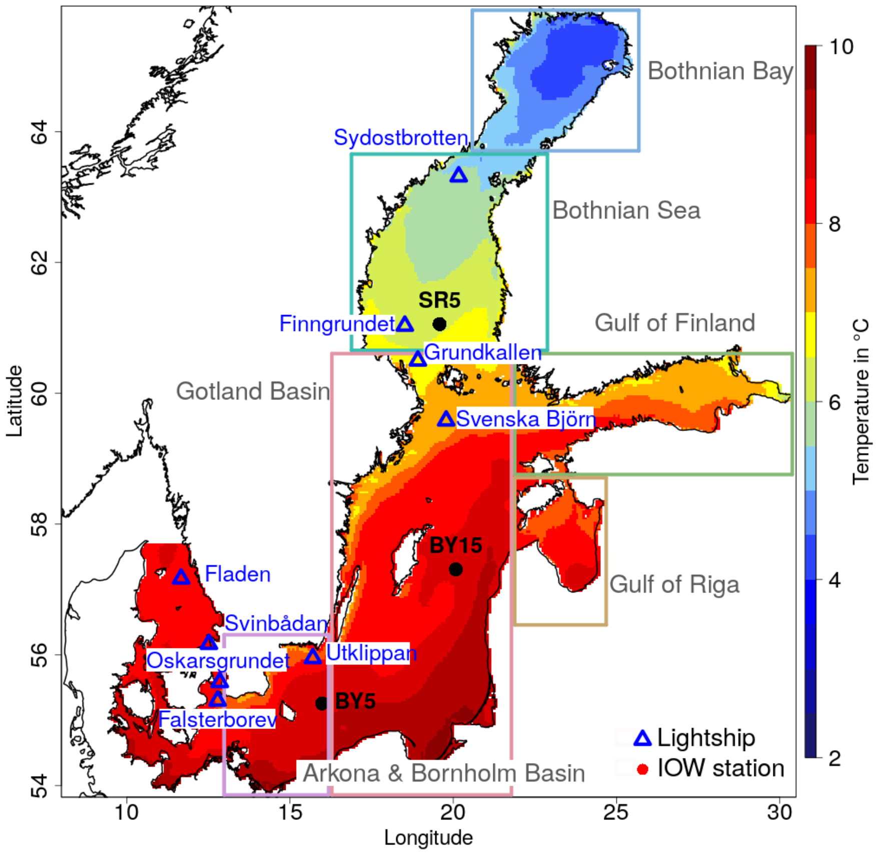

FIG. 2.3 Mean sea surface temperature in °C during 1850-2008 simulated by the regional ocean model RCO and basin boundaries for the analysis (cf. Figure 4.2). Considered stations of the IOW database and lightship sites are shown by black dots and blue triangles, respectively.

decreased significantly during the last 100 years (Ronkainen, 2013) aand also the length of the ice season is becoming shorter (Jevrejeva et al., 2004).

Wind-induced coastal upwelling is an important aspect regarding the SST distribution of the Baltic Sea. If wind is blowing parallel to the coast and the coast is located on the left side of the wind direction (on the northern hemisphere), the Coriolis force pushes water masses away from the coast and water masses from deeper areas move up. During summer, these events often lead to cool water conditions within a few days, because colder deep water is brought to the surface (Lehmann and Myrberg, 2008). Areas which are regularly affected by upwelling show relatively low mean SST values, like along the eastern Swedish coast (cf. Fig. 2.3).

Many publications report very fast rising temperatures in the Baltic Sea area (Belkin, 2009; Lehmann et al., 2011) with temperature trends which are about 2-5 times higher than those on the global scale (MacKenzie and Schiedek, 2007). Since the absorption of sunlight at the surface of shallow and turbid waters is higher in marginal seas such as the Baltic Sea (Belkin, 2009), these areas are generally more sensitive to global warming than the open ocean. However, also among coastal seas, the temperature rise in the Baltic Sea region was extreme during 1982-2006 and the water turbidity could not explain the strong SST trends (Löptien and Meier, 2011).

2.4 Biogeochemistry

Eutrophication is the most important hazard to the Baltic Sea marine ecosystem. It is primarily caused by increased anthropogenic nutrient inputs since the 1950s (Gustafsson et al., 2012). Among others, the sources are increasing agricultural and farming activities and insufficient wastewater treatment. An oversupply of nutrients causes increased growth of phytoplankton, higher accumulation of dead organic material (detritus) at the sea floor and, thus, excessive consumption of oxygen leading to the spread of oxygen minimum zones in the deeper parts of the Baltic Sea. When the dissolved oxygen concentrations fall below 2 ml/l researchers speak of hypoxic conditions, because higher forms of life are impossible. Areas with zero oxygen concentration are called anoxic. In these areas, the biogeochemical proccesses change completely. Organisms at higher trophic levels die or migrate and the chemical decomposition and mineralisation of detritus changes. Although hypoxia is not solely caused by anthropogenic nutrient inputs and exists in marginal seas and estuarine systems all over the world (Diaz, 2001), the well-monitored Baltic Sea is a good example how rapidly humans can affect a marine ecosystem. A brief comparison of the biogeochemical processes of the normal and eutrophied Baltic Sea is illustrated in Figure 2.4 and is explained in the following.

The growth of phytoplankton is called primary production because higher trophic levels depend on it. For the formation of organic material carbon, nitrogen and phosphorus is needed and oxygen (O_2) is produced. Since there is enough carbon available in the form of CO_2, the ratio between dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) controls the primary production and, thus, the whole ecosystem of the region. Molecular nitrogen (N_2) can only be consumed by some cyanobacteria species, which are, thus, not limited to DIN.

Generally, DIN summarizes Nitrate (${NO_3}^-$), Nitrite (${NO_2}^-$) and Ammonium (${NH_4}^+$) and DIP mainly consists of phosphate (${PO_4}^{3-}$). If one of these nutrients is lacking, the primary production is limited to the missing element following approximately the Redfield ratio (Redfield, 1934).

In this manner, eutrophication leads to increased primary production and, hence, more detritus and higher oxygen consumption at the bottom. At some point of eutrophication the oxygen consumption exceeds the input of oxygen from the phytoplankton and from physical ventilation and hypoxia occurs. Through the strong stratification in the Baltic Sea with a steep halocline the oxygen from the surface is kept away from the bottom zones leading to hypoxia or even anoxia in the deeper layers. The only way to ventilate the anoxic and hypoxic zones

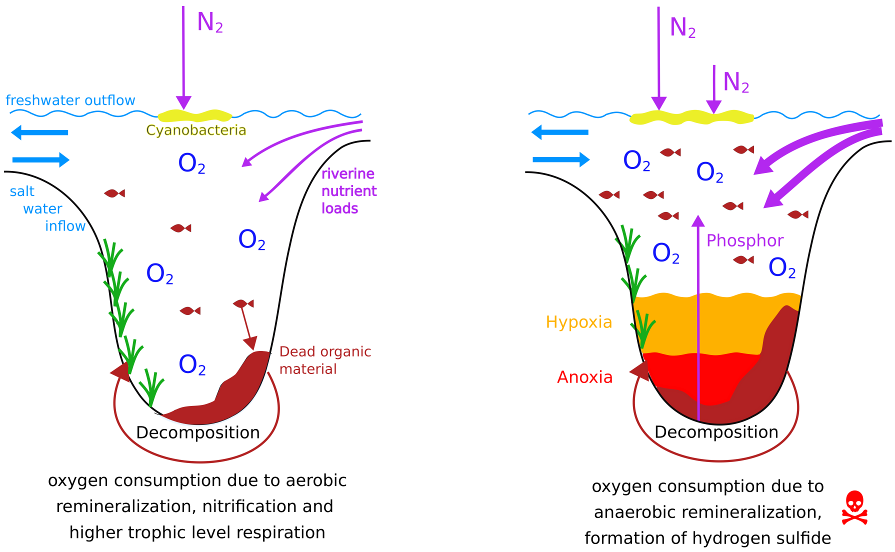

FIG. 2.4 Schematic sketch of the environmental status of the Baltic Sea under normal conditions (left) and eutrophication (right).

are the major Baltic inflows bringing heavy saline and oxygen-rich surface water to the bottom zones of the Baltic Sea. However, these events only have short-term effects. In fact, Meier et al. (2018c) found out that the oxygen consumption rates increased during the last decades and that hypoxia occurs faster after each ventilation event.

In anoxic and hypoxic water, the processes of decomposing dead material change. Under oxic conditions, the low energy consuming oxygenation takes place using O_2 and producing CO_2. Parallel to this, denitrification takes place consuming nitrate and producing N_2. If oxygen concentration is low, the second process becomes more important. Additionally, under hypoxia phosphate fluxes from the sediment into the water column increase. Both processes lead to a lower DIN/DIP ratio in the whole water column. With decreasing nitrate concentration, a third process takes place. Using sulfate from the water column, the toxic hydrogen sulfide (H_2S) is produced. A reduced DIN/DIP ratio favours the growth of some cyanobacteria species, since they are able to fix N_2 from the atmosphere directly taking benefit from the high availability of phosphorus. Dead material from phytoplankton including cyanobacteria sinks downward and accumulates at the bottom. Thus, increased primary production in the surface layer due to eutrophication enhances the oxygen consumption in deeper parts. Additionally, the release of phosphorus from the sediment (Meier et al., 2019) under hypoxia leads to increased nitrogen fixation by cyanobacteria making it available for other phytoplankton species leading to even more N_2 in the water column. This is a positive feedback to eutrophication creating a vicious cycle (Vahtera et al., 2007).

The vicious cycle is additionally enhanced by increasing summer temperatures due to global warming, because cyanobacteria blooms only occur in water with temperatures higher than 16°C. Hence, harmful algae blooms significantly increased in the central Baltic Sea in the course of climate change (Neumann et al., 2012).

Additionally, brackish water in general represents hard conditions for flora and fauna, since species are either adapted to marine or to freshwater conditions. Vuorinen et al. (2015) reported about a minimum in species diversity in the Baltic Sea at the so-called horohalinicum, a salinity around 7 g/kg, which is mainly located in the northern part of the Gotland Basin. Since the salinity in the Baltic Sea is very variable on multidecadal time scales, the location of the horohalinicum is varying with a range of several 100 km from North to South. Hence, flora and fauna have to migrate or adapt to the new conditions in order to survive. Vuorinen et al. (1998) additionally found a decrease in fish biomass since the 1970s, presumably caused by the decrease in SSS during the same time period.

Changing river runoff does not only impact the salinity of the Baltic Sea but also controls the nutrient inputs from the rivers enhancing or decreasing the eutrophication. Other factors like fishery and invasive species are additional threats for the ecosystem of the Baltic Sea, while ocean acidification due to increased uptake of CO_2 does not yet have a clear effect (Havenhand, 2012). Since these aspects are not (yet) part of most regional climate models, these aspects are not analysed in this work.

The combined effects of limited water exchange with the open ocean, strong vertical stratification, high salinity gradients, rapidly rising temperatures, high river-born nutrient inputs and corresponding oxygen limitation represent difficult living conditions for a marine ecosystem. The combination of the hydrographic characteristics and eutrophication is the reason why especially the Baltic Sea is threatened by hypoxia. It is still unclear, what the most important drivers are and if a good environmental status can be restored.

Coupled atmosphere-ocean models including marine biogeochemical processes are valuable tools for analysing and understanding the nonlinear dynamics of the Baltic Sea and its ecosystem. In this manner, this work addresses the impact of atmospheric variables, of hydrographic parameters and of eutrophication on the physical and biogeochemical processes.

3 Data and methods

In this thesis, the results of two models simulating the coupled physical-biogeochemical processes of the Baltic Sea using the same atmospheric forcing data set for the period 1850-2008 were analysed. In order to detect systematic changes, various statistical methods have been applied, which were chosen with respect to the considered variable. For the attribution of the long-term variability to the underlying changes in the atmosphere, freshwater or nutrient supply, either statistical approaches or sensitivity simulations were used.

In order to improve the readability, in the following the three publications considered for the cumulative dissertation are referred to as Temp-Paper (Kniebusch et al., 2019a), Salt-Paper (Kniebusch et al., 2019b) and Sensitivity-Paper (Meier et al., 2018b). In the order of appearance they can be found in the Appendix C.

3.1 Model simulations

In all publications, results of the Rossby Centre Ocean circulation model coupled with the Swedish Coastal and Ocean Biogeochemical model (RCO-SCOBI, Meier et al., 2003; Eilola et al., 2009) are shown. Kniebusch et al. (2019a) additionally studied results of the Modular Ocean Model coupled with the Ecological Regional Ocean Model (MOM-ERGOM, Neumann, 2000). Basic information about the model setups are given in Table 3.1.

Both models numerically solve the primitive equations in order to simulate the ocean circulation. Sub-grid processes and thermodynamical processes (e.g. heat fluxes and sea ice) are parameterized using different approaches from the literature. In-depth descriptions of the models can be found in the three publications (cf. Appendix C) and the corresponding publications therein. However, there are some basic differences in the heat flux parameterization, which should be mentioned in order to understand the differences in the results.

In RCO, the bulk formulae calculating heat, momentum and matter fluxes (Meier, 2002) are solved using state variables of the atmospheric planetary boundary layer including 2 m air temperature, 2 m specific humidity, 10 m wind, cloudiness, net precipitation and SLP as well as ocean variables like SST, SSS, sea ice cover,

	RCO-SCOBI	MOM-ERGOM
horizontal resolution	3.7 km	5 km
vertical resolution	3 m	2 m
temporal resolution of the output	2-daily	monthly
maximum depth	247.5 m	268 m
simulation area	including Kattegat	including Skagerrak

TABLE 3.1 Basic characteristics of the applied model setups for RCO-SCOBI and MOM-ERGOM

albedo and velocities of water and sea ice. In contrast, MOM uses prescribed heat fluxes from atmospheric variables only. Additionally, the parameterizations of sea ice and turbulence differ.

Both ocean models are coupled with a biogeochemical model including nutrient loads, primary production and deoxygenation in order to address hypoxia related processes in the Baltic Sea. However, in this work only results of the the coupled RCO-SCOBI model are shown. The model includes all processes described in Section 2.4 and other important processes like sedimentation and resuspension (Eilola et al., 2009; Almroth-Rosell et al., 2011).

For the initialisation of the models the same atmospheric forcing, river runoff, nutrient loads and bathymetry data were used, while the data were interpolated to the corresponding model grids (cf. Table. The reconstructed high-resolution atmospheric forcing fields (HiResAFF) by Schenk and Zorita (2012) provide three-hourly fields of air temperature, wind, sea level pressure, cloudiness, precipitation and humidity for the period 1850-2008 for the whole Baltic Sea region. HiResAFF is based on simulation results for the period 1958-2008 (analogue-period) which were used as a pool of analogues for the reconstruction of the period 1850-1957 when only few observations were available. River runoff data were reconstructed combining different observational data sets. Detailed information about the forcing data can be found in Meier et al. (2018b).

In the Salt-Paper and the Sensitivity-Paper, sensitivity experiments using RCO-SCOBI have been performed in order to find out, which atmospheric driver is more important for the evolution of the oceanographic and biogeochemical parameters. In this manner, the long-term variability of some forcing variables such as air temperature, wind and nutrient input have been removed or the values have been increased or decreased. Details about the corresponding sensitivity experiments are given in Section 4.2 and Section 4.3.

Data set	Variable	Data type	Time
OISST (Reynolds et al., 2007)	SST	Analysis combining satellite, buoys and ship data (0.25° x 0.25°, daily)	1982-today
HadISST1 (Rayner et al., 2003)	SST	reconstruction (1° x 1°, monthly)	1870-today
IOW database (`www.io-warnemuende.de/en_iowdb.html`)	T, S,...	in situ measurements	1860-today
ICES Database (2018)	T, S,...	in situ measurements	1900-today
Stockholm air temperature (Moberg et al., 2002)	SAT	monthly mean of in situ measurements	1750-today
lightships (Lindkvist and Lindow, 2006)	SST and SSS	in situ measurements	1860-1970
NAO (Jones et al., 1997)	NAO index	SLP difference Reykjavik-Gibraltar (monthly)	1901-today
AMO (`https://climexp.knmi.nl/data/iamo_hadsst_ts.dat`)	AMO index	detrended mean SST over 0°W-80°W and 0°N-60°N (monthly)	1870-today
BHDC river runoff (Bergström and Carlsson, 1994)	river runoff	monthly amount	1950-1998
BED (`http://nest.su.se/bed`)	T, S, O_2, PO_4^{3-}, NO_3^-	monthly mean values	1900-today

Table 3.2 Basic information about observational and reconstructed data sets used for the evaluation of the model results. T - Temperature, S - Salinity; A list of abbreviations can be found on page IX.

3.2 Observational data

For the validation of the model results (cf. Section 3.3) and the attribution to large-scale climate modes in the Temp-paper, several observational and reconstructed data sets have been used. An overview of the utilised data is given in Table 3.2. Detailed descriptions of the data sets can be found in the publications and the corresponding references and web pages.

3.3 Evaluation of the model results

In order to verify if the results of the model simulations are appropriate for the purpose of detection and attribution studies of long-term changes in the Baltic Sea, the model results have to be compared to independent observations. Hence, the simulations have been thoroughly evaluated in Meier et al. (2018b) and Kniebusch et al. (2019a) using the observational and reconstructed data sets described in Table 3.2. With regard to the purpose of the study, the evaluation mainly considers the vertical distribution and the long-term variability of the considered variables. Furthermore, the applied forcing data were evaluated in other publications before (Schenk and Zorita, 2012; Gustafsson et al., 2012) and are very likely the most reliable reconstructed forcing data for northern Europe available back to 1850. However, there are some shortcomings in the data set and the model results which should be discussed.

In Figure 3.1 the simulated mean vertical profiles of temperature, salinity and dissolved oxygen for 1978-2008 are compared to observations from the IOW database giving a good overview of the variables in general. Similar results are shown in Figure 2 in the Temp-Paper and Figure 10 in the Sensitivity-Paper.

3.3.1 Physical parameters

The vertical stratification with a steep halocline is reproduced well by both models, while RCO performs better than MOM, especially in the northern basins. Since observations during winter are scarce, they may overestimate annual mean temperatures especially in the northern basins explaining the relatively low SST values in the model results.

Long-term variability in SSS and SST was evaluated using the longest measurement time series available (cf. Table 3.2). Correlations between simulated SSS and lightship data are relatively low with values between 0.54 and 0.67 in RCO. However, comparing observations at Gotland Deep from the ICES database with the simulated mean SSS of the Baltic Sea, the correlation is very high for RCO

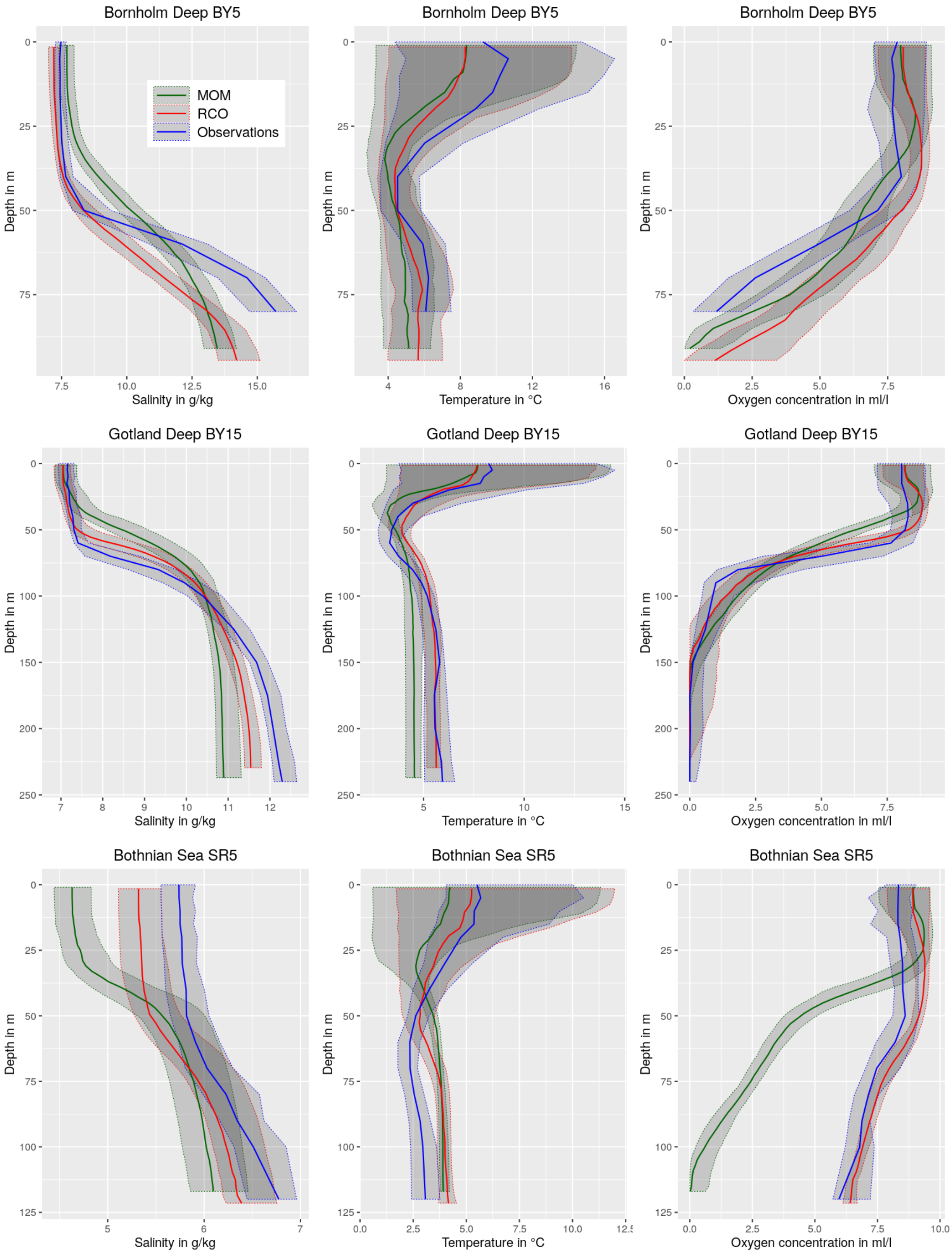

FIG. 3.1 Simulated and observed annual mean profiles of salinity, temperature and dissolved oxygen at the stations Bornholm Deep, Gotland Deep and Bothnian Sea (BY5, BY15 and SR5 in Fig. 2.3). Full and dotted lines show the median, the 25th and 75th percentiles during 1978-2007, respectively.

with 0.91 (cf. Fig. 2 in the Salt-Paper). In fact, salinity measurements from lightships are assumed to be biased due to different measurement techniques (Meier et al., 2018b).

The forcing river runoff data have been evaluated in the Sensitivity-Paper and in the supplementary material of the Salt-paper. As there is no consistent river runoff data set since 1850 available, several observational data sets and simulations have been post-processed and merged in order to get homogeneous forcing data (Meier et al., 2018b). Though there are only few observations of river runoff available, the long-term variability of Baltic Sea mean SSS, which is mainly driven by freshwater supply from the rivers (Meier and Kauker, 2003b), is reproduced well during the last 100 years. Hence, we can assume that the river runoff data are reliable.

A comparison of lightship data with simulated SST revealed that long-term (cf. Fig. 3 in the Temp-Paper) as well as intraannual (cf. Fig. 6 in the Sensitivity-Paper) SST variability is reproduced well in the models. Long-term correlations of simulated SST with the different observational data are high with values between 0.8 and 0.98 in both models. However, trends in simulated SST and reconstructed SAT are slightly underestimated.

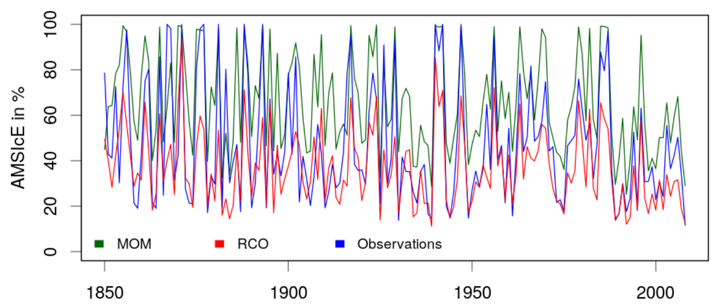

Fig. 3.2 Simulated and observed maximum annual sea ice extent as the percentage of the Baltic Sea area.

Due to the differences between the models in simulated SST, also the amount of sea ice is affected. In Table 1 in the Temp-paper and Table 3 in the Sensitivity-Paper, the annual maximum sea ice extent (AMSIcE) in the models is compared with observations from the Finnish Meteorological Institute (FMI, Baltic Sea ice data (FMI), 2017). In the Sensitivity-Paper, the 2-daily model output has been used to calculate the AMSIcE, while for the Temp-paper we used the monthly model output in order to make the results from MOM and RCO comparable. This explains, why the values for RCO are different in both tables. The temporal evolution of AMSIcE in both models and the observations are shown in Figure 3.2. The observed AMSIcE during 1850-2008 amounts to 198.5 x 10^6 m^2, which is approximately 50% of the Baltic Sea area, while the interannual variability is very high with a range between 10% and 100%. During the whole simulation time, RCO slightly underestimates and MOM overestimates the amount of sea ice. According to the observations, for about nine times the sea ice cover exceeded 95% of the area of the Baltic Sea (cf. Fig. 3.2). In comparison, in RCO 95% have only been reached once and in MOM the Baltic Sea has been frozen for over 30 times. Since these values are calculated on monthly time scales, AMSIcE may be underestimated in the simulation results.

Thus, MOM does not reproduce sea ice realistically. The underestimated AMSIcE and SST in RCO can be explained by overestimated temperatures in the forcing, since the analogues used for the reconstruction originate from a period that is already affected by a warmer climate. In this manner, very low temperatures before 1958 cannot be reproduced. The comparison of the simulated sea ice of the reconstructed (1850-1957) and the analogue-pool period (1958-2008) supports this assumption. This leads to the conclusion, that the forcing data may not be able to reproduce the high temporal variability of temperature in the Baltic Sea. Among others, this can be seen in Figure 4 & 5 in the Temp-paper and Figure 8 in the Sensitivity-Paper. Nevertheless, the qualitative trend estimates depending on the region or considered time period are correct.

Regarding heat fluxes and sea ice the models are parameterized differently leading to the discrepancies in simulated SST and sea ice. Moreover, MOM uses conservative temperature as model output, whiles in RCO it is the potential temperature, which is close to the in situ temperature in a shallow basin like the Baltic Sea. However, the difference between the two definitions of temperature amounts to only 0.5 K (IOC, 2010).

3.3.2 Biogeochemical parameters

For the analysis of the biogeochemical parameters, only the results of RCO-SCOBI were used. Since the general conclusions from both models are the same, the amount of simulation time for sensitivity experiments could be reduced by using only one model.

The simulated nitrogen, phosphate, oxygen and hypoxic area were compared to observations from the observational data base Baltic Environmental Database (BED, cf. Fig. 9 in the Sensitivity-Paper). In contrast to temperature and salinity, observations in nitrate and phosphate are scarce and earliest continuous observations began in the 1960s. The temporal variability of simulated surface nitrate, phosphate and oxygen generally follows the observations, while phosphate is overestimated during the last decades, when riverine nutrient loads were already diminished. The same applies for the integrated DIN and DIP pools. However, since nutrients are under-sampled, real amounts of nitrate and phosphate in the Baltic Sea are not well observed.

Figure 3.1 shows that the vertical stratification of dissolved oxygen characterised by oxygen-rich water at the surface and lower oxygen concentration towards the bottom is reproduced well by RCO in all basins. However, oxygen concentrations are slightly overestimated.

Another important variable is the hypoxic area representing the area with bottom layer oxygen concentrations lower than 2 ml/l. In RCO-SCOBI, the onset of hypoxic area occurred around 1950. Unfortunately, observational data are only available after 1960, but since the rapid increase in the 1960s is well reproduced in the model (cf. Fig. 11 in the Sensitivity-Paper), we can assume that RCO-SCOBI is able to reproduce the occurrence of hypoxic area. After 1970, hypoxic area is overestimated in the model, but the variability of periods with decreasing and increasing hypoxia is satisfactorily simulated. The same can be seen in the temporal variability of the oxygen concentration at 200 m depth at Gotland Deep (Fig. 9e in the Sensitivity-Paper). Oxygen concentration is generally decreasing and hydrogen sulfide occurs in the 1970s. The decadal variability in O_2 caused by the saltwater inflows bringing oxygen-rich surface water to the deeper regions of the Baltic Sea is well reproduced as well.

In summary, though the forcing data as well as the simulation results are not perfect, the long-term variability of the SST and SSS as well as the oxygen depletion are simulated quite well. In this manner, the results are suitable for detection and attribution studies of long-term variability of the Baltic Sea and its ecosystem.

3.4 Statistical methods

For the processing of the model and observational data, the *climate data operators* (CDO, 2015) and the statistical program *R* (R Core Team, 2015) were used. Many figures were prepared using the package *ggplot2* (Wickham, 2016).

For the detection of trends the *R* package *nlme* was applied (Pinheiro et al., 2016). Due to different statistical characteristics of the considered parameters, two advanced significance tests were chosen. Regarding temperature, a linear regression taking the auto correlation at time lag 1 into account was used following Ribes et al. (2016). Since freshwater related processes in the Baltic Sea show large multidecadal variabilities with periods of about 20-30 years (Mohrholz, 2018; Winsor et al., 2001), the Phase Scrambling Fourier Transform (PSFT) bootstrap method (Theiler and Prichard, 1996) was used for the analysis of the salinity. Using this method, the significance of an estimated trend is calculated separating the signal (trend) and the noise (including the multidecadal variability) and testing, if there is still a trend apparent if the noise was artificially created maintaining the statistical characteristics. This has been done 1000 times and the quantiles are used as confidence intervals and for the estimation of p-values.

The attribution of the variability in salinity, temperature and biogeochemical variables to the forcing was done using either Pearson's correlation coefficients (R) and explained variances (R^2) or the sensitivity experiments with RCO-SCOBI.

4 Results of the detection and attribution studies in the Baltic Sea

4.1 Temperature

During 1982-2006 the SST of the Baltic Sea showed the strongest positive trends of the earth (Belkin, 2009). The fact that the Baltic Sea is warming relatively fast has been repeatedly mentioned in different publications (e.g. BACC Author Team, 2008; Lehmann et al., 2011; MacKenzie and Schiedek, 2007). However, already the supplementary material of Belkin (2009) considering a longer time period (1957-2006) revealed that the Baltic Sea was not always the fastest warming marine ecosystem.

In this manner, the Temp-Paper analysed the temperature variability of the Baltic Sea in different temporal and spatial dimensions in order to explain why the Baltic Sea was warming so fast during that specific period. Using two model setups with differing heat flux and sea ice parameterizations and numerous observational data sets for the evaluation (cf. Section 3.3), the study is a unique and reliable analysis of temperature variability of the Baltic Sea since the first available measurements in 1850.

4.1.1 Detection of SST and bottom temperature trends

First, the spatial distribution of temperature trends at the surface and at the bottom were analysed for the periods 1856-2005 and 1978-2007 (cf. Fig. 6 and 7 in the Temp-Paper). The choice of the time periods follows the IPCC AR4 (2007). The highest trends occur at the bottom of the Bornholm Basin, which is confirmed by results based on observations and former publications. During 1856-2005 the bottom water temperature at Bornholm Deep increased with 0.13-0.15 K/decade. In contrast, the bottom temperature trends of the short time period (1978-2007) are not consistent and often not significant. On short time scales the effect of the MBI events is too dominant which is why there is no clear trend during that period.

The highest trends in annual mean SST during 1856-2005 are located in the south-western part of the Baltic Sea around the Swedish coast with values around 0.5 K/decade. During 1978-2007 the trends around the Swedish coast are smallest and the highest SST trends can be found in the northern basins, while trends are more evenly distributed over the whole Baltic Sea area. Comparing both time intervals, the SST trends have increased 10-fold, while the increase in the North was highest.

4.1.2 Attribution to atmospheric forcing variables

The bottom temperature trends were mainly attributed to inflow events since the trends follow the topography. In contrast, the SST trends have been analysed in more detail, because the connection with the atmosphere is stronger and more complex.

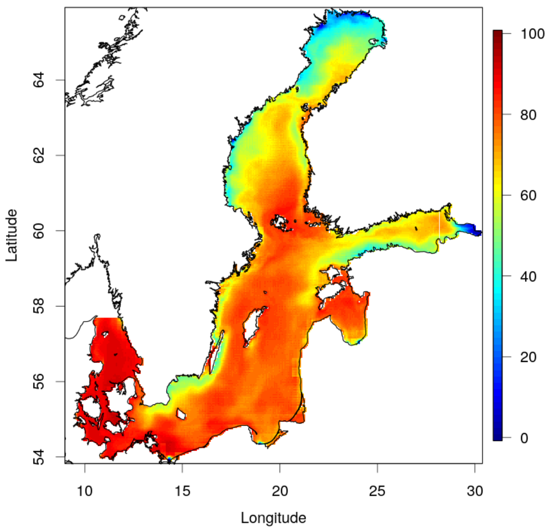

FIG. 4.1 Explained variance in % between the simulated annual mean SST (RCO) and the forcing SAT (HiResAFF) over the whole simulation time. Source: Kniebusch et al. (2019a).

The variability of the SST in the Baltic Sea was mainly attributed to the forcing air temperature. On the one hand this has been done statistically with explained variances around 90% (Fig. 4.1) and on the other hand using an additional 1D-simulation which shows that the general evolution of the SST would not change if horizontal advection is omitted. Moreover, several publications support this assumption (Meier et al., 2018b; Omstedt and Rutgersson, 2000). Since the variability of the SAT is very high and, thus, dominates the SST variability, it was important to show the strong connection between both in order to statistically filter the SAT signal (including the trend) from the SST. This has been done subtracting the residuals from a linear model fitting the SST to the SAT. The filtered time series was then used to find other atmospheric drivers of the SST since there are also areas with lower explained variances.

In Figure 4.2, the SST and SAT trends were split to the four seasons and the six basins (cf. Fig. 2.3) in order to analyse and explain the spatial and temporal differences.

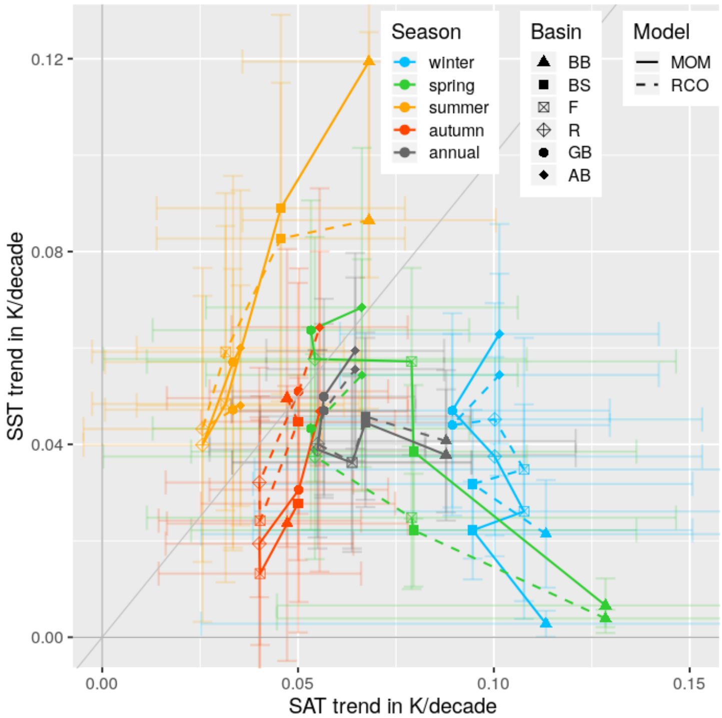

FIG. 4.2 Scatter plot of seasonal and regional (basins, cf. Fig. 2.3) trends in simulated SST over reconstructed air temperature with 90% confidence intervals; the grey line represents the direct relation between SAT and SST. Basins: Bothnian Bay (BB), Bothnian Sea (BS), Gulf of Finland (F), Gulf of Riga (R), Gotland Basin (GB) and Arkona Basin and Bornholm Basin (AB). Seasons: winter (DJF), spring (MAM), summer (JJA), autumn (SON). Source: Kniebusch et al. (2019a).

Most important is the disconnection of the SST and the SAT during winter and spring due to freezing. The trends in SST generally follow those in SAT during summer and autumn, but during winter and spring, when sea ice is present, the trends in SST are close to zero, although corresponding trends in SAT are strongest. In this manner, lower explained variances of the SST related to the SAT in the northern basins can mainly be attributed to the presence of sea ice, which is basically a side-effect of the SAT. Figure 10 in the Temp-Paper additionally shows the annual cycle of the difference between SST and SAT as a measure for the sensible heat flux. During summer, when SST trends were strongest, the sensible heat flux is directed into the water. Together with decreasing length in the ice period (Jevrejeva et al., 2004), the very strong SST trends during summer (which are exceeding corresponding SAT trends) can be explained.

Furthermore, a statistical ranking analysis was performed in order to find the second and third most important atmospheric driver of the SST depending on their explained variances. A cross-correlation analysis between the 2-daily model output of RCO comparing the filtered SST with each forcing variable at each grid point was applied. Since wind-induced coastal upwelling shows a time lag of around seven days, it is included in the analysis using a maximum time lag of 30 days. For the analysis, the latent heat flux, both wind components and cloudiness were used. The latent heat flux was calculated with a bulk formula using relative humidity, SAT and total wind speed and is dominated by the relative humidity and wind speed with mean explained variances of 28% and 31%, respectively. Sea level pressure and net precipitation are highly correlated with cloudiness and have no direct impact on the SST and, thus, were omitted in the analysis.

The results of the ranking analysis indicate that at all grid points the second most important factor next to the SAT is the latent heat flux with 30-50% explained variance. Hence, the sensible and the latent heat fluxes dominate the SST variability of the Baltic Sea. Considering the three remaining parameters, cloudiness (as a measure for the shortwave radiation), the meridional and the zonal wind component, the third most important driver depends on the location as can be seen in Figure 4.3. At most of the western and northern coasts, wind parallel to the coast is more important than cloudiness. These areas are well known to be affected by wind-induced upwelling bringing mainly colder water from deeper layers to the surface. In Figure 4.1, upwelling areas show lower explained variances between SST and SAT. Moreover, the SST is generally lower in those areas (cf. Fig. 2.3). In contrast, in most offshore areas, cloudiness, i.e. the radiative heat flux, is more important.

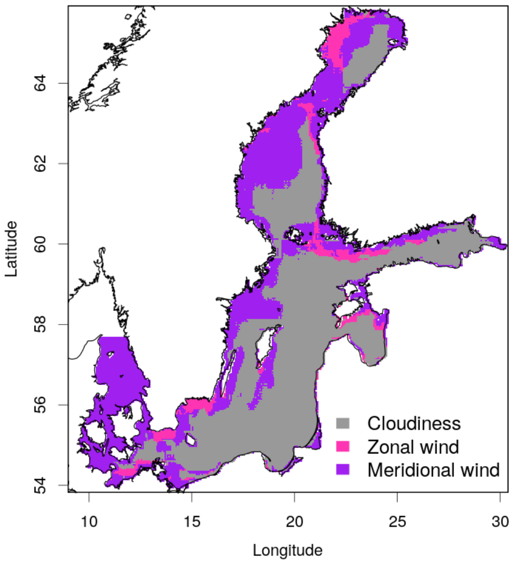

Fig. 4.3 Map showing the third most important driver for each grid point on the basis if the ranking analysis. Adapted from: Kniebusch et al. (2019a).

The spatial distribution of SST trends in Figure 6 and 7 in the Temp-Paper show very different results in the upwelling area comparing both periods. This could be either due to changes in the upwelling events, i.e. wind, or due to changes in the water masses brought up from the deeper parts. In the long-term the trends along the Swedish coasts are very high compared to the whole Baltic Sea, while they are low and not significant in the short-term. During 1856-2005 the trends at the bottom of the Baltic Sea are very high. Hence, the warmer bottom water brought up to the surface during upwelling events could be an explanation for the strong SST trends at the Swedish coast during that period. In contrast, during 1978-2007 SST trends in these areas are smaller. As has been discussed before, short-term bottom water trends are not statistically significant and highly affected by the variability of MBI events.

4.1.3 Why was the Baltic Sea warming so fast during 1982-2006?

Since the SST is mainly affected by SAT and the trend would vanish if the trend in SAT is removed (cf. Fig. 11 in the Sensitivity-Paper) and also the North Sea shows comparatively high SST trends during that period (Belkin, 2009), the high

SAT trends over Northern Europe (IPCC AR4, 2007) caused the rapid increase in SST in the Baltic Sea. The most important modes of climate variability for Northern Europe affecting SAT are the NAO and AMO (cf. Section 2.1).

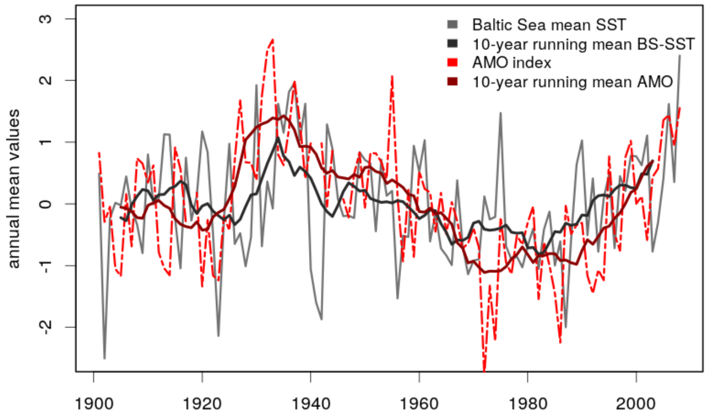

Fig. 4.4 Detrended and normalized time series of the Baltic Sea annual mean SST and the Atlantic Multi-decadal Oscillation (AMO). Adapted from: Kniebusch et al. (2019a).

Figure 12 in the Temp-Paper compares the connection between the two climate indices and the Baltic Sea mean SST on annual and decadal time scales. While the winter NAO influences the Baltic Sea mean SST on annual time scales with an explained variance of 14%, the AMO is the dominating factor on decadal time scales with an explained variance of 60% (cf. Fig. 4.4). In this manner, the switch from the negative phase of the AMO during the 1980s to the positive phase peaking around 2008 explains the exceptional high SST trends in this region during that period and why other periods show different results (Supplement in Belkin (2009)). In fact, since 2008 SAT and SST in the Baltic Sea region slightly decreased again supporting this finding. Unfortunately, the forcing data HiResAFF are only available until 2008, thus, it could not have been shown with our data.

Furthermore, the Baltic Sea is a semi-enclosed basin located in the higher latitudes and is characterized by strong stratification. These characteristics may have additionally enhanced the SST trends of the Baltic Sea compared to the North Sea.

4.2 Salinity

In the Salt-Paper, the long-term variability of the sea surface salinity (SSS) of the Baltic Sea is analysed. Since salinity in the Baltic Sea is about equally affected by both freshwater supply from the rivers and saltwater inflows through the Danish straits (Meier and Kauker, 2003a,b; Winsor et al., 2001), the processes are more complicated than those affecting the SST. Moreover, the vertical mixing due to diffusion and advection is so far not completely understood.

The processes related to the Baltic Sea salinity are complex, because the two important drivers, wind (causing barotropic saltwater inflows) and river runoff,

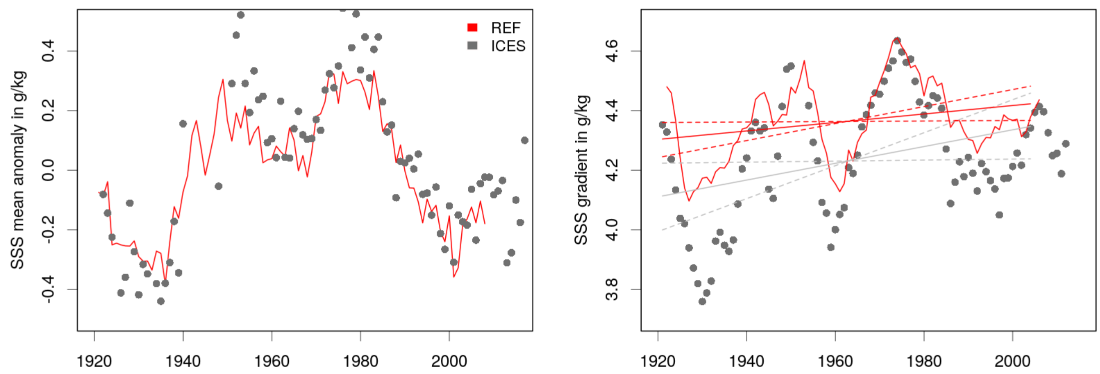

Fig. 4.5 Annual Baltic Sea mean SSS anomaly and 4-year running mean North-South gradient in SSS in the REFerence simulation and observations of the ICES database (cf. Tab. 3.2). Right: The solid lines show the linear trends and dashed lines the 66% confidence intervals. Adapted from: Kniebusch et al. (2019b).

are highly correlated due to the large-scale circulation patterns (Zorita and Laine, 2000). Hence, a statistical approach to attribute changes in the salinity to the corresponding forcing variable would be insufficient. In this manner, sensitivity experiments with the regional model RCO were performed in order to eliminate or enhance the impact of the two main parameters, wind and river runoff, in order to find out, which parameter is important for which kind of variability.

Over the year, 510 km^3 freshwater enters the Baltic Sea, of which the total annual river discharge of about 450 km^3/year contributes over 86%. Precipitation and river runoff are highly correlated which is why it is sufficient to address the influence of the more important river runoff in the sensitivity experiments.

4.2.1 Detection of long-term variability in SSS

In addition to the Baltic Sea mean SSS, the difference between the South and the North is considered, hereafter referred to as the gradient. In Figure 2.1 it can be seen that the SSS is decreasing towards North, since the only connection towards the saline open ocean is located in the Danish straits. The mean difference during the past 100 years amounts to about 4.2 g/kg over approximately 1000km. Thus, the difference between the SSS in the South and in the North is a good measure for the spatial distribution of the salinity in the Baltic Sea.

Since the river runoff data are a combination of different observational data sets, only the results after 1920 are considered in order to minimize the uncertainty which is considerably larger before 1920.

Figure 4.5 shows the temporal evolution of SSS and its gradient between 1921 and 2004 in the model simulation and observations. SSS in the Baltic Sea exhibits high

Experiment	Wind	River runoff	Comment
WIND	1904	REF	wind conditions from 1904 repeated
FRESH	REF	1.2*REF	increased river runoff maintaining long-term variability
constRUNOFF	REF	mean(REF)	no long-term variability in runoff

Table 4.1 Overview of the sensitivity experiments analysed in the Salt-Paper. Under wind and river runoff, the applied forcing is shown, while REF means that the forcing is like in the reference simulation and the year 1904 means that the forcing from this year is repeated every year.

multidecadal variability with a period of about 20-30 years. Although there is an increase in annual mean SSS during 1921-2004, it is not statistically significant due to the strong multidecadal variability. In contrast, the observed North-South gradient shows a slightly significant positive trend with 66% confidence between 1921 and 2004, though there is also multidecadal variability. Considering a longer time period (1900-2004), the significance in the model results increases and confidence amounts to 90%. Considering the fact that it can be seen in both the simulations and the observations, one can assume that the drift towards higher latitudinal differences is systematic.

4.2.2 Attribution to wind and river runoff

In order to find out which atmospheric variable causes the drift towards higher gradients on the one hand and the multidecadal variability on the other hand, three sensitivity experiments were performed with RCO. A brief overview is given in Table 4.1. The sensitivity experiments follow different approaches lowering or increasing the forcing variables and/or keeping them constant. The same experiments and many more following the same approach are introduced in the Sensitivity-Paper. As has been discussed before, there are two variables mainly affecting the SSS in the Baltic Sea: freshwater supply by the rivers and wind (causing barotropic inflows and blocking of the outflow of brackish water in the surface layer in case of west wind). In WIND, the wind conditions from 1904 were repeated and, thus, the variability in barotropic saltwater inflows is modified. The experiment FRESH does not remove the long-term variability, but increases the river runoff by 20%, while constRUNOFF uses the climatological mean runoff.

The results of the sensitivity experiments reveal that both atmospheric forcing variables equally contribute to the multidecadal variability, but only the river runoff causes the long-term drift in the North-South gradient in SSS (cf. Fig. 2d in the Salt-Paper).

The trend in the gradient can be attributed to regional increase in river runoff in the northern basins (cf. Fig. 3 in the Salt-Paper). However, the detailed underlying processes are complicated. The Baltic Sea mean SSS was increasing during the last century, though the trend is not significant. This trend contradicts the future projections predicting a freshening of the Baltic Sea (BACC II Author Team, 2015). This can have two plausible explanations. On the one hand, this might depend on shortcomings of the lateral boundary conditions in both the historical reconstruction and in the projections. Rising global sea levels would result in increasing saltwater inflows. On the other hand, it could be due to internal variability longer than 160 years and the recent increase in river runoff in the northern basins was not enough to reverse the trend, as it may be the case in the future. However, in the northern basins the positive trend is almost reversed since the trend there is about three times smaller than in the South during 1921-2004. As a conclusion, the freshening of the Baltic Sea already takes places in the North, where the increase in freshwater supply is predicted for the future. The combination of both effects, increasing salinity in the South and increasing freshwater supply in the North leads to the significant positive trend in the latitudinal gradient in SSS.

This is further supported by the results of the sensitivity experiment FRESH. The positive trends in both SSS and its gradient are not as high as in REF. In this manner, we can assume that the current situation characterized by a switch from increasing to decreasing SSS in the Baltic Sea leads to higher gradients. This may be temporary as indicated by the lower trend in the gradient in FRESH.

In the Salt-Paper, the possible causes for the multidecadal variability affecting both wind and freshwater supply are discussed. There were several publications, where the multidecadal variability with a period of 20-30 years was found, e.g. in the major Baltic inflows (Mohrholz, 2018) and precipitation (BACC II Author Team, 2015; Lindström and Bergström, 2004). However, neither NAO with sub-decadal variability nor AMO with periods between 60-90 years could explain this multidecadal variability. Hence, further research is needed in the future.

4.3 Biogeochemistry

The Sensitivity-Paper addresses the effects of the atmospheric forcing and eutrophication on the environmental status of the Baltic Sea. As has been mentioned before, eutrophication due to increasing riverine nutrient input and atmospheric deposition as well as physical processes like warming temperatures and the variability of major Baltic inflows have impacts on hypoxia and cyanobacteria blooms in the Baltic Sea. So far, the individual impacts of the different forcing variables have not been disentangled using coupled physical-biogeochemical circulation models.

Figure 4.6 shows the temporal evolution of the nutrient loads in the Baltic Sea (DIN and DIP) and the hypoxic area. Since the timing of the increase in hypoxia is directly related to the increase in both DIN and DIP, the question is if hypoxia would have occurred without increased external nutrient loads and how variability in physical parameters like temperature and stratification affect hypoxia and harmful algae blooms.

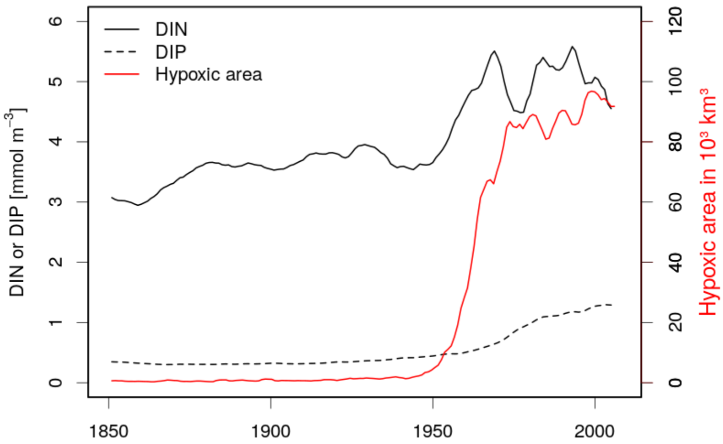

FIG. 4.6 Four-year running mean of simulated (REFerence simulation) dissolved inorganic nitrogen (DIN) and phosphorus (DIP) and hypoxic area.

4.3.1 Experimental approach

Following the same approach for sensitivity experiments as in the Salt-Paper, in total 13 sensitivity experiments were performed. An overview of the main characteristics and the outcome of the experiments can be seen in Table 4 in the Sensitivity-Paper. However, in this thesis the main results of the publication are summarized showing the results of only six sensitivity experiments. Furthermore, only the impact on oxygen concentration, cyanobacteria concentration and hypoxic area will be discussed, while the publication also analyses DIN/DIP ratio, phytoplankton concentration and Secchi depth.

An overview of the shown sensitivity simulations is presented in Table 4.2. In TAIR1 and TAIR2, the variability in the annual mean temperature and relative humidity is suppressed by repeatedly using the annual cycle from 1904 (cold year) and 2008 (warm year), respectively. Hence, TAIR2 is approximately 2 K warmer than TAIR1 and REF during the first 50 years. In addition to TAIR1, CONST also repeatedly applies the annual cycle of wind and cloud conditions from 1904. Due to a higher mixed layer depth in CONST this experiment represents unfavorable conditions for cyanobacteria. In these three simulations, there is no long-term variability, i.e. trend, in temperature, but the temporal evolution of freshwater supply as well as nutrient input is maintained. In this manner, the impact of the climatological variability on the biogeochemistry of the Baltic Sea can be determined.

Experiment	Climate	Nutrient loads	Comment
TAIR1	Temp 1904	REF	cold climate
TAIR2	Temp 2008	REF	warm climate
CONST	1904	REF	cold climate
LOW	REF	1850	pristine conditions
HIGH	REF	1985	highest loads ever recorded
CYANO	2008	1850	cyanobacteria favoring climate conditions

Table 4.2 Overview of the sensitivity experiments used for Figure 4.7. Under the columns "Climate" and "nutrient loads", the years are listed, of which temperature, relative humidity, cloudiness and wind conditions or nutrient loads in the rivers and the atmospheric deposition are repeated, respectively. In TAIR1 and TAIR2 only temperature and humidity were set constant. REF means that the forcing is like in the reference simulation.

The sensitivity experiments LOW and HIGH follow the oppposite approach maintaining the climate variability and using constant low (from 1850 - pristine conditions) and high (from 1985 - highest nutrient input ever recorded) amounts of riverine nutrient loads and atmospheric deposition.

CYANO combines both experimental strategies representing TAIR2-climate under LOW nutrient conditions. Hence, CYANO favors cyanobacteria blooms from a physical point of view, since 2008 was characterized by a record-high cyanobacteria bloom (Kahru and Elmgren, 2014). In this manner, it can be studied if hypoxia and increased cyanobacteria blooms would have occurred in the course of climate change without reinforced external nutrient loads.

The other sensitivity experiments in the Sensitivity-Paper were performed considering the impact of river runoff (cf. Section 4.2) and sea level. However, these experiments address other research questions and, thus, are omitted for this thesis.

4.3.2 Attributing oxygen depletion to nutrient loads and climate variability

In Figure 4.7, the results of the simulations are shown as volume averaged mean values for the whole Baltic Sea including Kattegat and low-pass filtered with a cut-off period of 4 years in order to address the long-term changes.

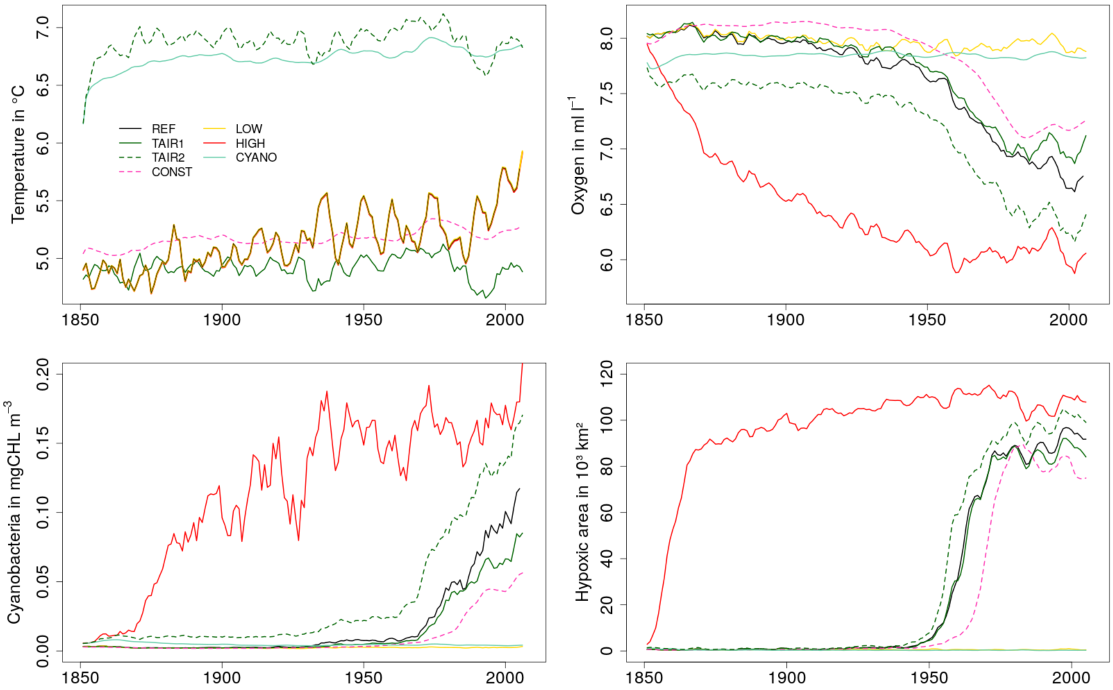

Fig. 4.7 Four-year running mean of simulated volume averaged annual temperature, dissolved oxygen concentration, cyanobacteria concentration and hypoxic area in the simulations REF, TAIR1, TAIR2, CONST, LOW, HIGH and CYANO. Although the number of sensitivity experiments is reduced, the colours and linetypes are the same as in Figure 12 in the Sensitivity-Paper. Adapted from: Meier et al. (2018b).

The long-term variability of the physical parameters temperature and salinity is indistinguishable between LOW, HIGH and REF. RCO does not simulate a long-term feedback from reduced/increased nutrients on the volume averaged water temperature, presumably because the effects on SST and the temperature of deeper layers are contradicted and cancel each other out (Löptien and Meier, 2011). Also in experiments affecting salinity and stratification (only shown in the Sensitivity-Paper) the volume averaged temperature does not change. This supports the results of a 1D-simulation with a different model in the Temp-Paper which shows that the long-term variability of SST is not significantly affected by the variability in the stratification.

Since the water temperature is mainly driven by the surface air temperature (cf. Temp-Paper) in TAIR1, TAIR2, CONST and CYANO no long-term trend in the volume averaged water temperature is apparent. However, also in CONST and CYANO there is still a little decadal variability left which can possibly be caused by unchanged parameters like precipitation or the open boundary conditions in the Kattegat.

During the whole simulation time, cyanobacteria as well as phytoplankton concentration (not shown) show largest amounts in HIGH and smallest in LOW. Consequently, also hypoxic area is largest in HIGH accompanied with lowest oxygen concentrations. In contrast, sensitivity simulations with low nutrient concentrations (LOW, CYANO) simulate almost no cyanobacteria concentration or hypoxic area. This leads to the conclusion that the reinforced external nutrient loads were crucial for the development of hypoxia in the Baltic Sea.

The increase in the cyanobacteria concentration in HIGH is more or less linear with high subdecadal variability, while hypoxic area increases fast during 1850-1870 up to an area of about 90 000 km^3 and slower until the end of the simulation reaching its maximum in the 1970s with 110 000 km^3. After 1970 there is a slight decrease in hypoxic area, while it is not changing significantly. Also in cyanobacteria concentration, the increase is faster during the first 30 years, while the difference is not as high as for hypoxic area. During 2008, a year with record high cyanobacteria blooms in the Baltic Sea, their concentration is almost doubled in HIGH compared to REF.

Experiments with reference nutrient loads show that physical parameters do have impacts on the amounts as well as the onset of hypoxia and cyanobacteria blooms. In TAIR2, hypoxia occurs approximately 5 years earlier than in REF, while in CONST it is 10 years later. Hence, under eutrophied conditions, as we will still have to deal with in the near future (Saraiva et al., 2019), the air temperature is still an important driver for the severity of cyanobacteria blooms and hypoxic area. Comparing TAIR1 and TAIR2, in 2008 the cyanobacteria concentration is twice as high in the warm than in the cold climate and is almost as high as in HIGH. Similar results can be seen in the oxygen concentration and hypoxic area.

Under climatically unfavorable conditions (CONST), cyaonobacteria concentration is significantly reduced. Since salinity is decreased due to lower wind conditions, stratification of the Baltic Sea is lower. Additionally, the low water temperatures worsen the living conditions of cyanobacteria. Consequently, under cold and lower stratified conditions also harmful algae blooms would be reduced.

In contrast, CYANO represents climate conditions favorable for cyanobacteria blooms. The results indicate that the vicious cycle would not have occurred if no increased nutrient input into the Baltic Sea had happened. Although in CYANO the cyanobacteria concentrations are higher than in LOW, there is no hypoxia. However, this result can also be due to shortcomings in the model. The burial of nutrients in the sediment may be overestimated leading to less available phosphorus. With a phosphorus pool that is large enough, randomly occurring anoxic conditions could have started sufficient release of phosphorus from the sediment to support the production of cyanobacteria (Warden et al., 2017). This may have caused higher areas of hypoxia due to the vicious cycle. Unfortunately, the model does not support this scenario and it is still an open question, if this could have occurred without increased external nutrient loads. If we could have shown that this scenario was possible during the last 160 years, it could it could have been an explanation for hypoxia in the former past like the medieval warm period (Zillén et al., 2008).

In summary, anthropogenic nutrient loads and atmospheric deposition were crucial for the expansion of hypoxic area during the last century. However, physical parameters like water temperature and stratification caused by saltwater inflows have impact on the timing and the dimensions. If the external nutrient loads are as high in future as under present conditions (e.g. Meier et al., 2019), the temperature rise due to global warming will be important. However, according to the model results, the occurrence of hypoxia cannot be caused by increasing temperature alone, although cyanobacteria concentration would also have increased without increased external nutrient loads.

5 Discussion and Conclusion

5.1 Uncertainties of the model simulations and the statistical approaches

The analysed models MOM and RCO apply different heat flux and sea ice parameterization approaches leading to differences in absolute SST values and sea ice formation. Additionally, MOM uses the conservative and RCO the potential temperature as model output. Furthermore, the parameterizations of sub-scale processes are different as well. Validating the model results against observations regarding various variables, RCO generally performs better than MOM.

Beside the uncertainties in the models, the forcing data set is another source of uncertainty. The results indicate, that severe winters are missing in the analogue pool for the reconstructed period back to 1850 which leads to an overestimation of air temperature during the first 100 years of the forcing data and hence to an underestimation of the variability in temperature. However, the qualitative comparison of trends shows good agreement with respect to the observations. Moreover, the fact that both models lead to the same conclusions despite the uncertainties and different strategies of heat flux and sea ice parameterizations makes the results of the study robust and reliable. The differences between the models can be seen as a rough estimate for the model uncertainty.

The results discussed throughout this thesis were significant, often with p-values lower than 0.01. The low statistical significance of the trend in the North-South gradient in SSS was discussed in more detail in the Salt-Paper.

5.2 Summary and discussion of the results

The Baltic Sea SST is mainly driven by the heat fluxes (sensible, latent and radiative), while in coastal areas wind-induced upwelling plays a larger role than cloudiness, i.e. the radiative heat flux. The long-term SST variability is not significantly affected by variations in stratification, caused by river runoff and saltwater inflows from the North Sea, and eutrophication processes. The record high temperature trend during 1982-2006 was attributed to the shift from a negative to a positive phase of the AMO which enhanced global warming during that period over the whole northern hemisphere. Since the Baltic Sea is shallow, surrounded by land and located in higher latitudes it was probably more sensitive to the high temperature trends during that period.

The SSS in the Baltic Sea shows high multidecadal variability caused by the two forcing variables wind and river runoff. This variability was found in many other variables connected to large-scale atmospheric circulation patterns over Europe (Mohrholz, 2018; BACC II Author Team, 2015; Lindström and Bergström, 2004). Although the high multidecadal variability lowered the significance, a systematic trend towards a higher North-South gradient in SSS was found. In contrast to the variability of SSS, the trend in the gradient is only driven by local changes in the river runoff which was increasing in the northern basins of the Baltic Sea. Global warming intensifies the hydrological cycle in humid areas (IPCC AR5, 2013). Hence, these local changes can also be explained by climate change.

The sensitivity experiments performed with RCO-SCOBI revealed that human induced increasing nutrient loads and atmospheric deposition were crucial for the formation of hypoxic area in the Baltic Sea during the past 100 years. However, physical parameters, especially temperature, affect the timing and the extent of the hypoxic area and cyanobacteria blooms. Hence, in a 2008-world, as in the sensitivity experiment TAIR2, the cyanobacteria concentrations were twice as high as under the reference conditions. However, in another publication we showed that despite global warming the Baltic Sea could still be put back into a good environmental status (Meier et al., 2018a) .

Nevertheless, there are still a number of open questions. With regard to the temperature of the Baltic Sea, the disentangled impacts of the stratification and being a semi-enclosed sea is still unclear. The 1D-simulation with MOM showed that the variability in the stratification has no significant effect on the long-term variability in SST, but the general effect of the stratification on the SST is still unclear. Would the trend have been smaller if the Baltic Sea was vertically well mixed? Additionally, the causes of the multidecadal variability in the salinity, runoff and wind are still unclear. Furthermore, the sensitivity experiments with RCO unfortunately did not support the assumption that the vicious cycle could have happened due to climate forcing only; without increasing nutrient loads. Hence, it is still unclear what were the causes for hypoxia in the past, e.g. during the medieval warm period (Conley et al., 2009; Zillén et al., 2008). Although the reconstruction shows satisfactory results, the mentioned shortcoming of this reconstruction, e.g. the overestimation of temperatures during severe winters before 1958, illustrate the importance of further research in this area.

5.3 Relevance of the study

The present work addresses the dynamics of the Baltic Sea and its ecosystem driven by complex physical as well as biogeochemical processes sine 1850, when regular monitoring observations started. The detailed understanding of long-term impacts of changes in nutrient loads, temperature and river runoff helps to develop plausible future projections of the Baltic Sea considering more processes such as greenhouse gas scenarios, aerosol processes and other related changes, which increase the degrees of freedom and hence the uncertainty of the simulations. The approach of detection and attribution is a good tool to disentangle the combined processes affecting variables that are dependent on several other variables and on large-scale internal climate modes.

Earlier studies used shorter time periods mainly due to lack of an appropriate forcing data set (Meier and Kauker, 2003b). Gustafsson et al. (2012) applied the HiResAFF data set for the first time forcing a coupled physical-biogeochemical model dividing the Baltic Sea into 13 sub-basins. In recent studies, only simplified oxygen consumption models were used in order to find out how e.g. changes in the amount of river runoff and the mineralisation rate amplify oxygen depletion (Gustafsson and Omstedt, 2009) or what the temporal and spatial variability of hypoxic area looks like (Lehmann et al., 2014). Carstensen et al. (2014) followed a statistical approach by quantifying nutrient release and recycling processes.

In this manner, this work is the first attempt to use fully coupled regional climate models including a more complex biogeochemical model for the simulation of the Baltic Sea from 1850 until 2008 using a suitable forcing data set. The studied period reaches back to a time which was not yet affected by high anthropogenic impacts like global warming and increased nutrient loads. Moreover, the results of the reconstruction were sufficient for a detection and attribution study that disentangled the internal variability from anthropogenic induced changes in physical as well as biogeochemical parameters.

This work emphasizes that systematic changes in the climate system can be masked or enhanced by internal modes of variability for a limited period of time, mainly decades. However, all systematic long-term changes detected in this study, the increasing temperature, the drift towards a higher North-South gradient in SSS as well as the occurrence of hypoxia and the increase in cyanobacteria concentration, were attributed to anthropogenic induced changes causing the exceptional high changes in the Baltic Sea during the last 160 years.

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Education

2013–2015 **Master of Science**, *Institute of Meteorology*, Free University Berlin, *grade – 1.5*.

02/2013 **Master thesis**, Evaluation of the urban climate model MUKLIMO_3 for Berlin and simulation of mitigation strategies for the urban heat island, supervisors: Prof. Dr. Sahar Sodoudi, Prof. Dr. Ulrich Cubasch, *final grade – 1.3*.

2009–2013 **Bachelor of Science**, *Institute of Meteorology*, Free University Berlin, *final grade – 2.3*.

02/2013 **Bachelor thesis**, *Auswirkungen der Klimaänderung auf die atmosphärische Anregung der Polbewegung (engl.: Climate change signal in atmospheric polar motion)*, supervisors: Univ.-Prof. Dr. Uwe Ulbrich, Dr. Henning Rust, *final grade – 1.5*.

Experience

2017 **MathDACC Summer School**, *CNRS center, Aussois, France*, Mathematics for Climate Change Detection and Attribution.

2017 **3rd Baltic Earth International Summer School**, *Askö Laboratory, Trosa, Sweden*, Climate of the Baltic Sea region.

since 2016 **PhD candidate**, *Leibniz Institute for Baltic Sea Research Warnemünde, Department of Physical Oceanography and Instrumentation*.

2011–2015 **Student assistant**, *Institute of Meteorology*, Free University Berlin.
- 2013-2015 in research group urban climate and health
- 2011-2013 in research group for Climate Diagnostics and Extreme Meteorological Events

2012 **Internship**, *Helmholtz Centre Potsdam, German Research Centre for Geosciences (GFZ), Department of "Earth System Modelling"*, Application of a new clustering algorithm on SST data of the Agulhas stream in the South Atlantic..

2009 **English School**, *Embassy CES Cambridge*, three weeks.
language level achieved: 6(7) – advanced

2007 **participation at "Jugend Forscht"**, *Berlin*, title: "Golfstrom".
Replication of the gulf stream in a little aquarium.

2006 **practical school training**, *Institute of Meteorology*, Free University Berlin, two weeks during the holidays.

2005 **practical school training**, *MeteoGroup Deutschland GmbH*, Berlin, two weeks during school time.

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B Declaration of my contributions to the publications

B.1 Temp-Paper (Kniebusch et al., 2019a)

My first main author paper "Temperature variability of the Baltic Sea since 1850 and attribution to atmospheric forcing variables" is the result of my first one and a half years of analysing long-term changes of different variables in the two model simulations.

The main part of the concept and writing (90%) and the analysis of the data and preparation of the figures (100%) of this paper was done by myself, while the model simulations were performed by my co-authors. During brainstorming meetings with my supervisor and co-author, where I showed my latest results, we narrowed the results for writing the paper.

For the methods I went to an international Summer School on "Mathematics for Climate Change Detection and Attribution" (MathDACC) in Aussois, France. There I learned how to deal with long-term trends if the autocorrelation is relatively high and decided on the applied trend analysis.

Except of the model descriptions in the methods, the writing of the manuscript was done by myself. The manuscript has been reviewed by my supervisor and Thomas Neumann. They only provided notes and comments, so that in the end I did the revision myself. Only a few sentences were completely formulated by my supervisor.

B.2 Salt-Paper (Kniebusch et al., 2019b)

In my second main author paper "Changing salinity gradients in the Baltic Sea as a consequence of altered freshwater budgets", my co-authors provided slightly more support because due to the limited word count and number of figures in GRL the manuscript had to be more concise. However, the concept and writing (80%) and the data analysis and figure preparation (90%) was mainly done by myself.

Because the salinity dynamics of the Baltic Sea have high multidecadal variability, my statistical approach had to be changed. Hence, the PTSF method was used, which was implemented by Hagen Radtke. He provided an R-script for the trend analysis of any time series.

B.3 Sensitivity-Paper (Meier et al., 2018)

Preparing this publication, I was directly involved in the main concept and helped to define the setup of the sensitivity simulations and the analysis of their results.

The analysis of the sensitivity simulations and the preparation of Figure 12 and Figure 13 was done by me. Additionally, I helped writing and editing the manuscript.

C Publications

The following publications are included in the appendix in the order of appearance:

Kniebusch et al. (2019a): Temperature Variability of the Baltic Sea Since 1850 and Attribution to Atmospheric Forcing Variables
Supplementary information are attached

Kniebusch et al. (2019b): Changing salinity gradients in the Baltic Sea as a consequence of altered freshwater budgets
Supplementary information are attached

Meier et al. (2018): Disentangling the impact of nutrient load and climate changes on Baltic Sea hypoxia and eutrophication since 1850

JGR Oceans

RESEARCH ARTICLE
10.1029/2018JC013948

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 km^3, 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

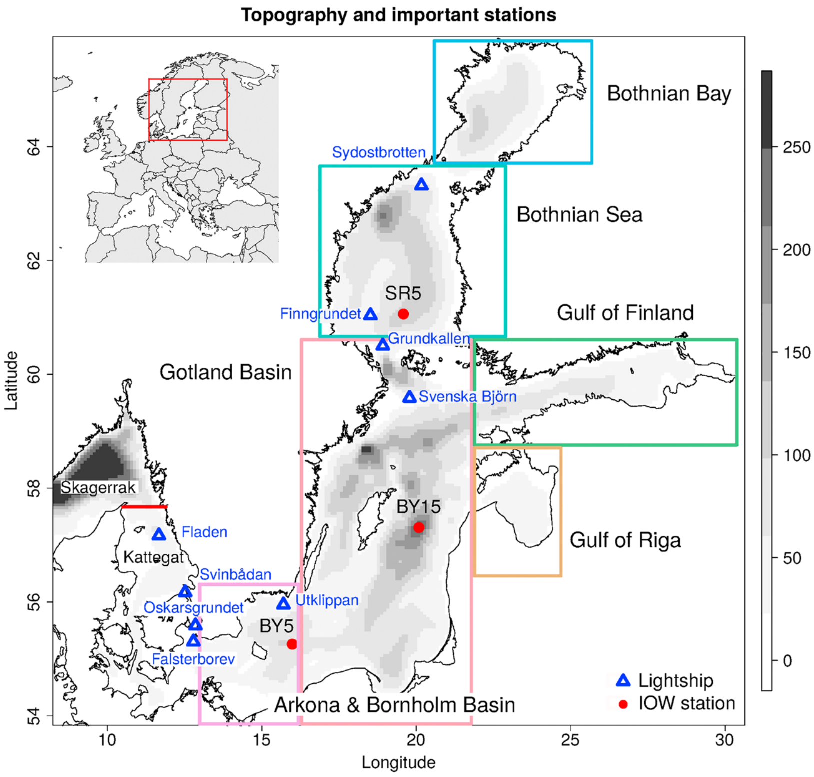

Figure 1. Bathymetry of the MOM setup with basins and stations (from the database of the Leibniz Institute for Baltic Sea Research IOW and lightships) used in this study. The red line between Kattegat and Skagerrak represents the boundary of the RCO model.

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-SCOBI; 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-SCOBI

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-ϵ 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 SCOBI 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 predescribed, 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 (RCAO; Döscher et al., 2002) model with a $0.25° \times 0.25°$ 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° × 0.25° 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° × 1° 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/daviz/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-

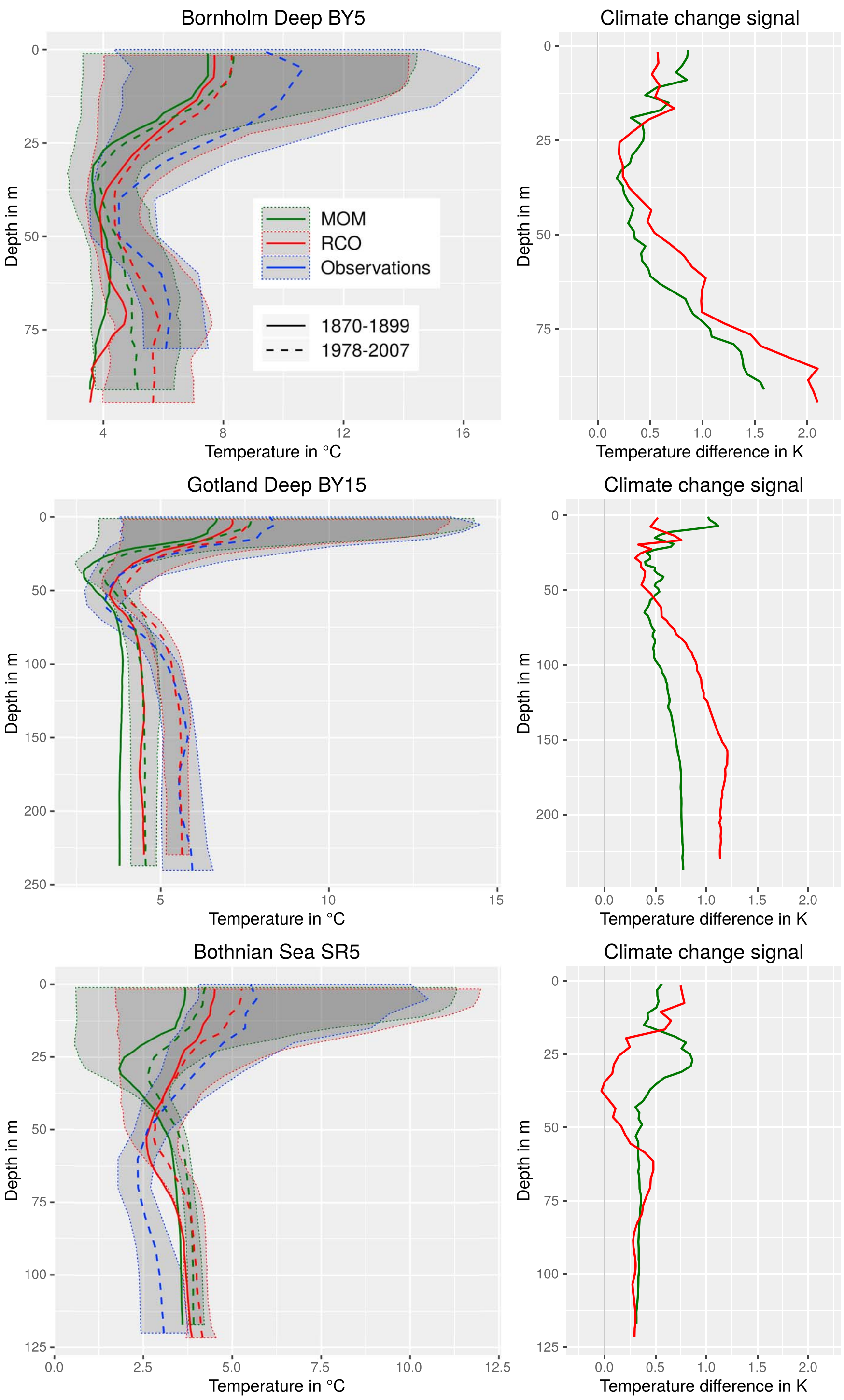

Figure 2. Profiles of simulated and observed temperatures in the Bornholm Deep (BY5), Gotland Deep (BY15), and Bothnian Sea (SR5). In the left column, for both simulations and observations, dashed and dotted lines show the median and the 25th and 75th percentiles during 1978–2007, respectively. In addition, 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 m^2), 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)

	Mean			RMSE		Cor	
Time	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 m^2, while the MOM produces a mean of

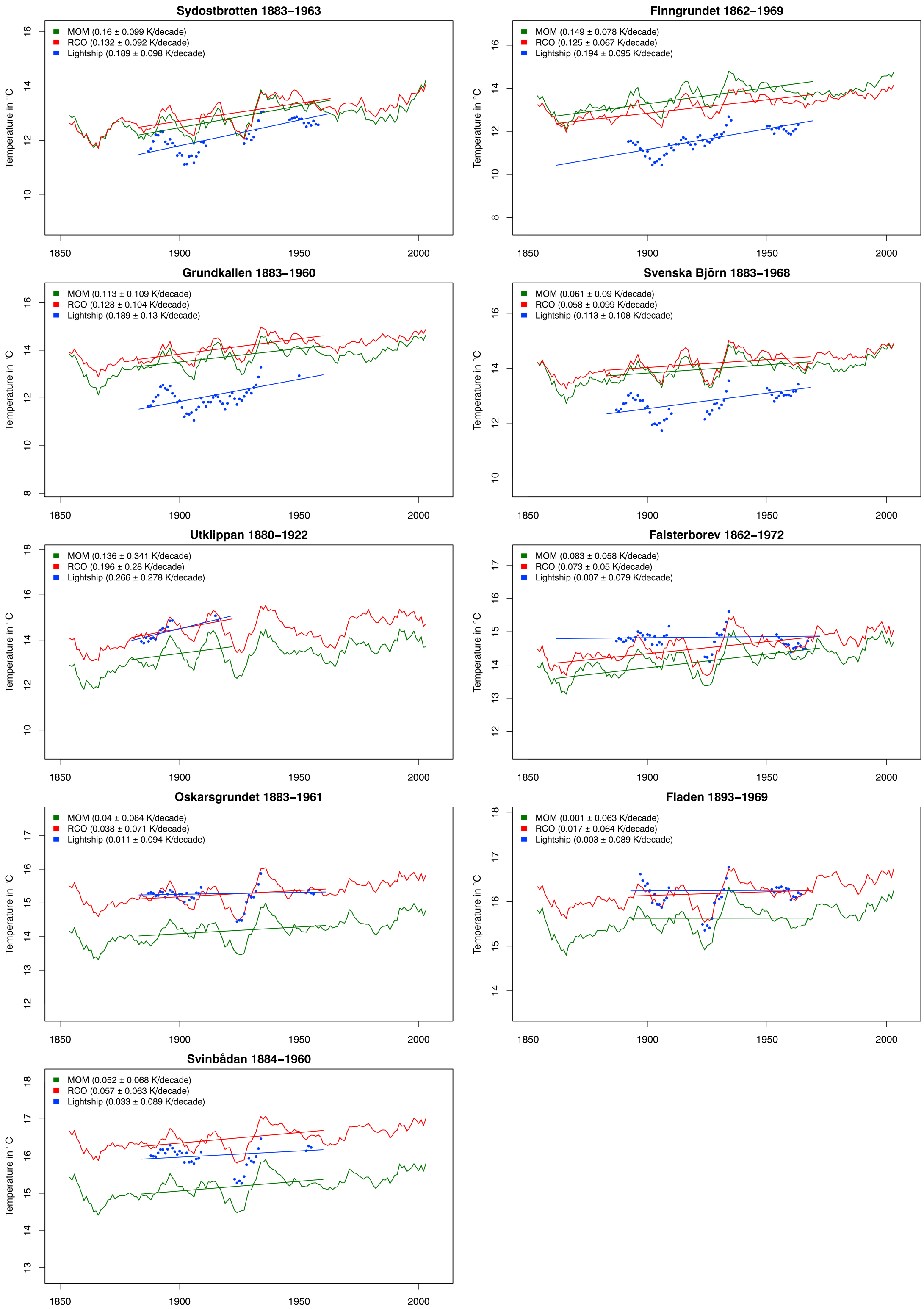

Figure 3. Simulated and observed 10-year running mean summer sea surface temperatures at lightship sites (cf. Figure 1) and corresponding linear trends during time periods with lightship observations.

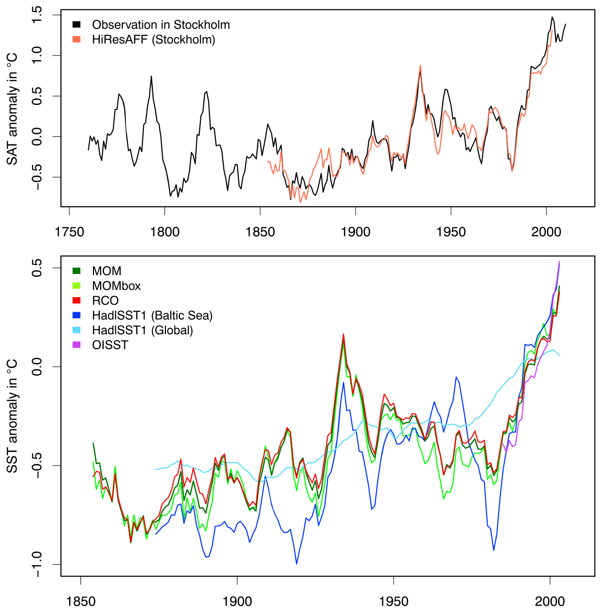

Figure 4. Ten-year running mean of simulated and observed time series. (top) SAT anomalies in Stockholm. (bottom) Baltic Sea mean and Gotland Deep SST anomaly. SAT = surface air temperature; SST = sea surface temperature.

293.9×10^6 m^2 and the RCO produces a mean of 165.8×10^6 m^2, with root-mean-square errors of 117.1×10^6 and 74.8×10^6 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.

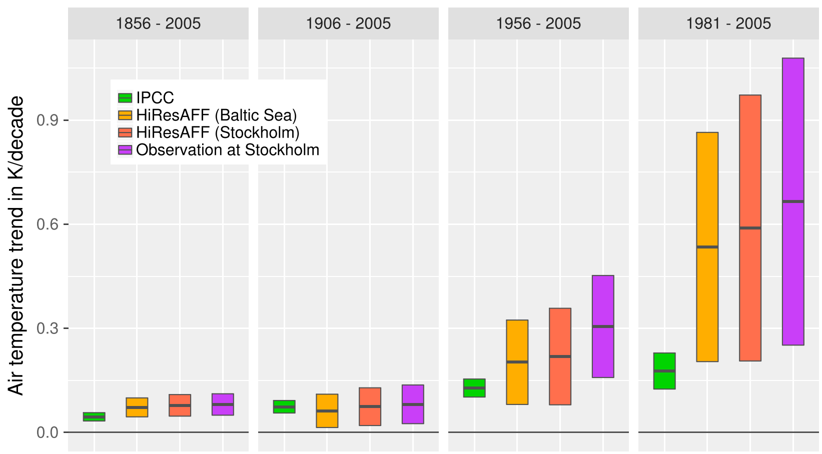

Figure 5. Trends in global (IPCC AR4, 2007a) and Baltic Sea annual mean surface air temperature in different periods. The global trends are taken from Table TS.6 of IPCC AR4 (2007b).

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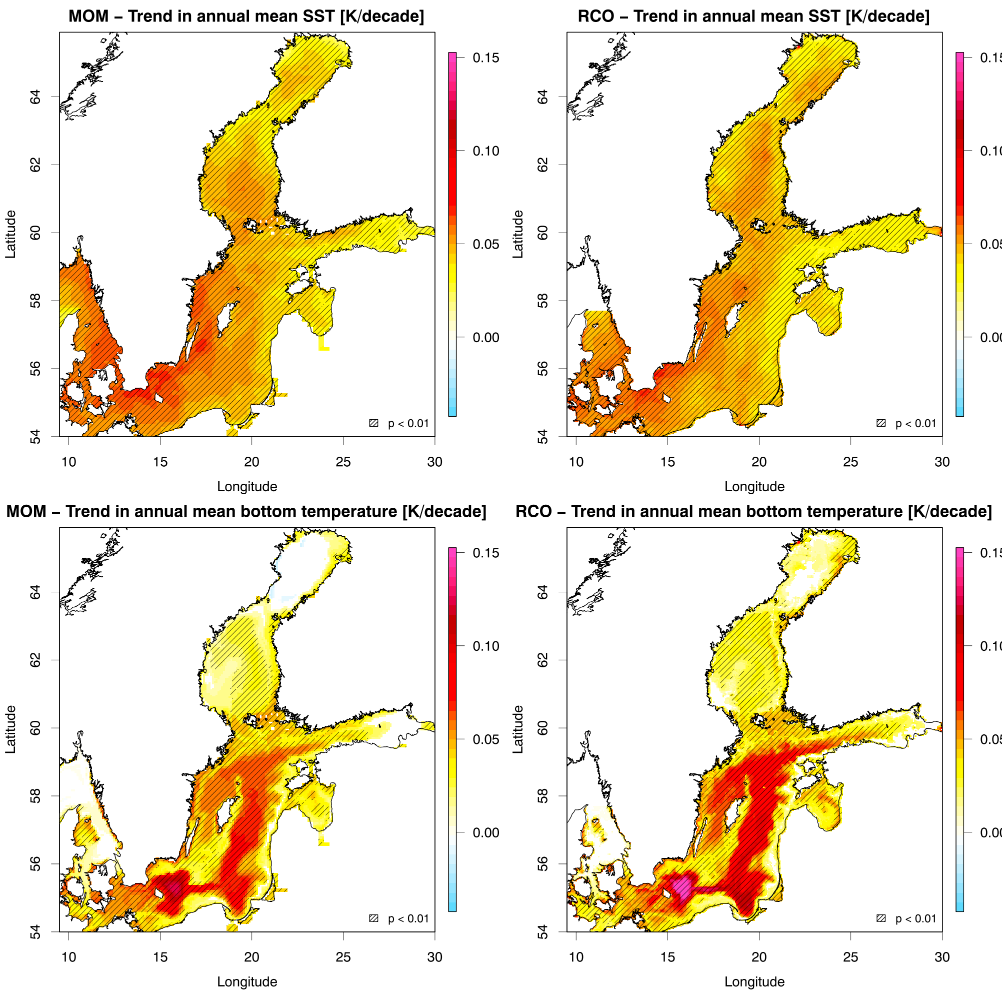

Figure 6. Maps of simulated 150-year linear SST (top row) and bottom temperature (bottom row) trends in Kelvin per decade for the MOM (left column) and RCO model (right column) during 1856–2005. Areas with a high significance level are hatched (*p* values lower than 0.01), and areas with no significance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

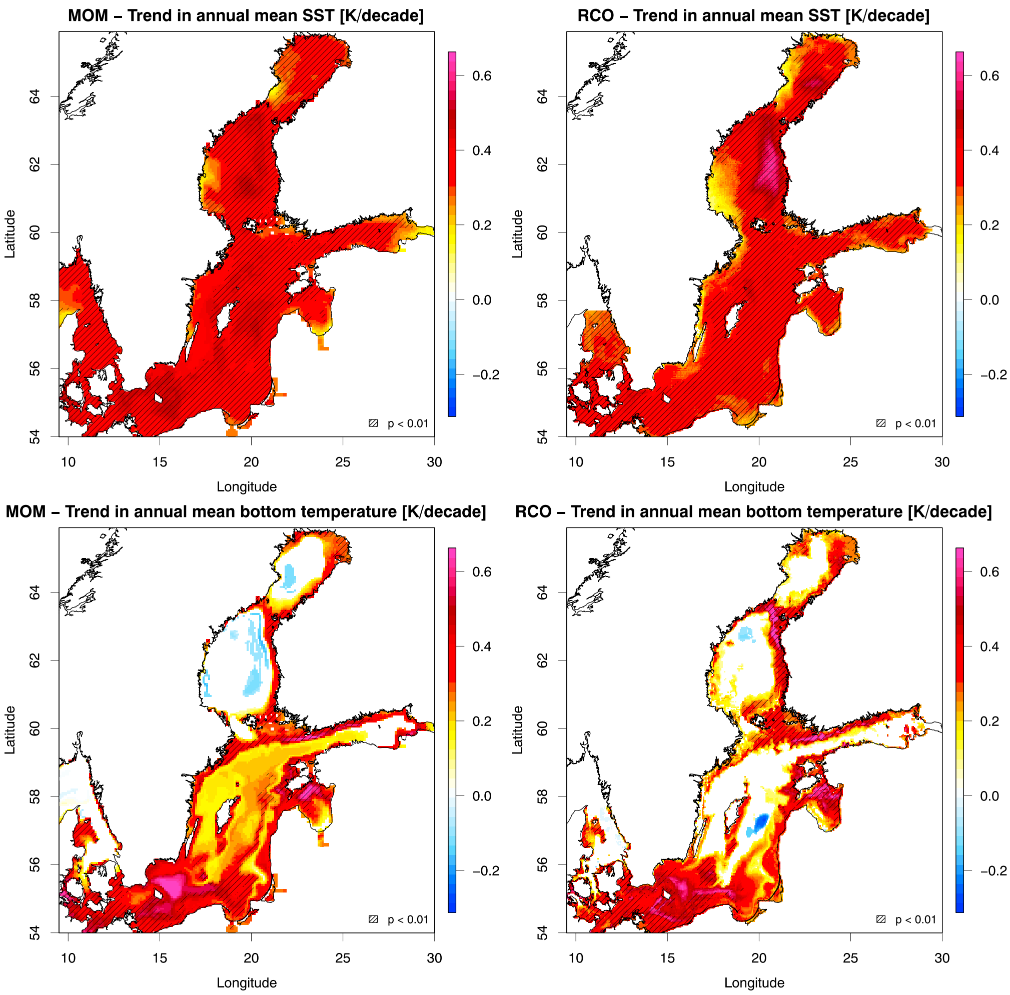

Figure 7. Maps of simulated 30-year linear SST (top row) and bottom temperature (bottom row) trends in Kelvin per decade for the MOM (left column) and RCO model (right column) during 1978–2007, as in Figure 6. SST = sea surface temperature.

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

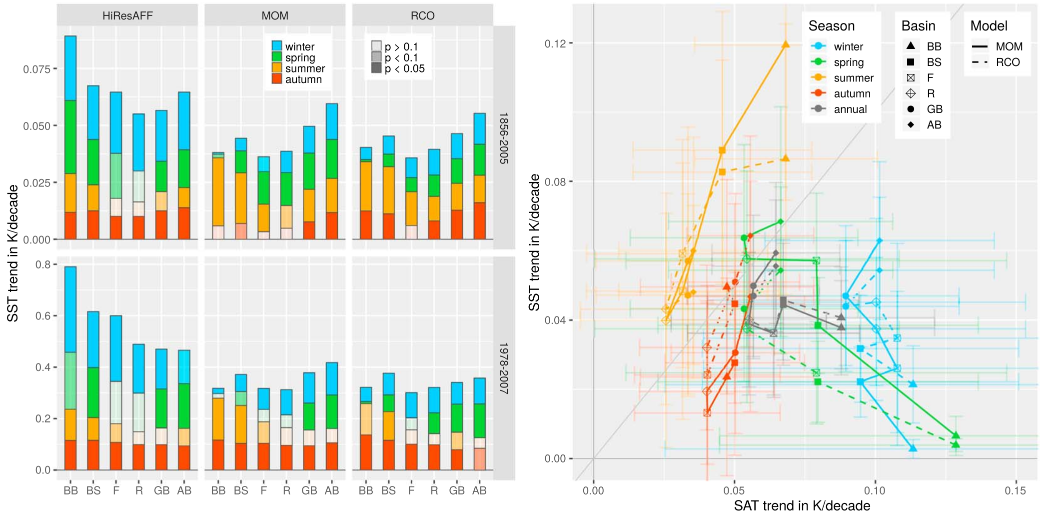

Figure 8. Seasonal and regional (basins, cf. Figure 1) trends in simulated SST and reconstructed air temperature. (left) The height of the bars represents the trend in the annual mean SST for two time periods (1856–2005 and 1978–2007). The height of the colored bars shows one quarter of the seasonal 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.

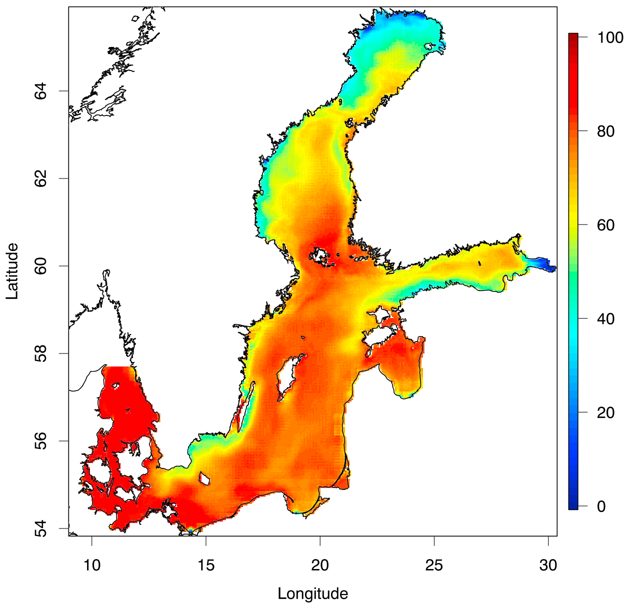

Figure 9. Explained variance (in percent) between the simulated annual mean sea surface temperature (RCO) and the forcing air temperature (HiResAFF) over the whole simulated period.

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.

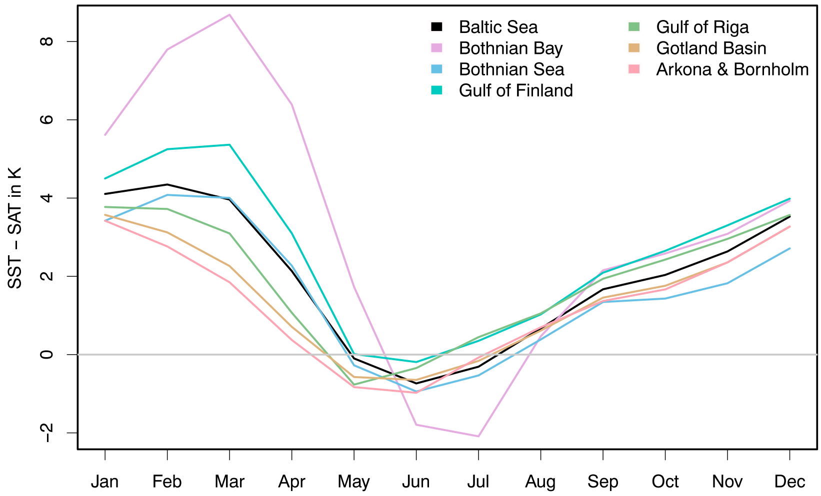

Figure 10. Annual cycle of the mean difference during 1850–2008 between SAT and SST in Kelvin for all basins and the whole Baltic Sea. The temperature difference between water and air is a measure of the sensible heat flux. SST = sea surface temperature; SAT = surface air temperature.

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 advectional 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.

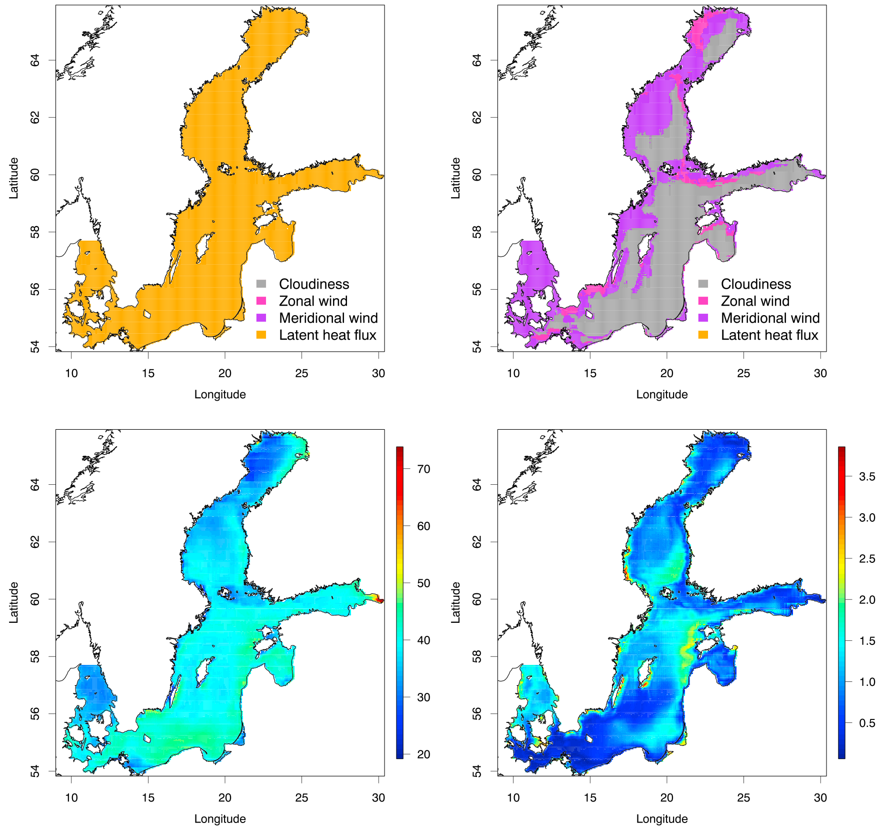

Figure 11. Results of the cross-correlation analysis of the detrended sea surface temperature (2-day output of the RCO model is used) with the wind components, latent heat flux, and cloudiness. Maps of atmospheric drivers (top row) with the highest (left column) and second highest (right column) cross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

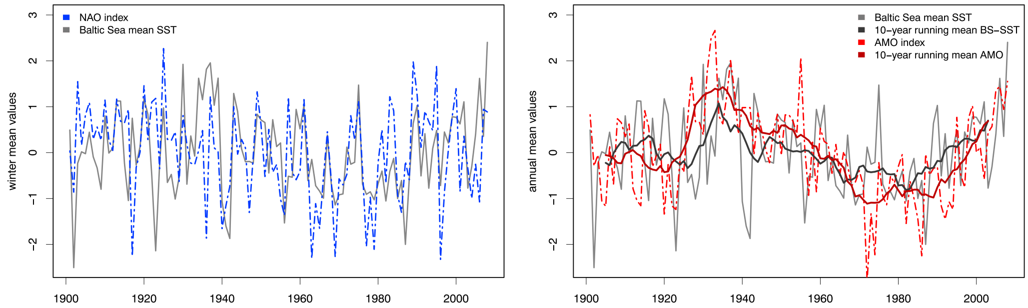

Figure 12. Detrended and normalized time series of the Baltic Sea annual mean SST and two climate indices. (left) Winter (December–February) mean NAO. (right) Annual and 10-year running mean AMO and SST. SST = sea surface temperature; NAO = North Atlantic Oscillation; AMO = Atlantic Multidecadal Oscillation.

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

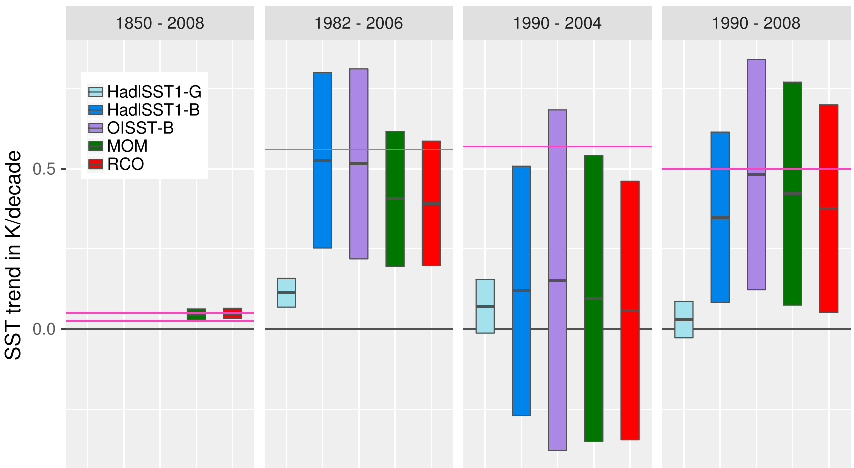

Figure 13. SST trends of the Baltic Sea in different data sets and publications (pink lines, from left to right: Gustafsson et al., 2012, Belkin, 2009, Siegel et al., 2006, and Lehmann et al., 2011). SST = sea surface temperature.

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

10.1029/2018JC013948

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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Supporting Information for
"Temperature variability of the Baltic Sea since 1850 and attribution to atmospheric forcing variables"

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Additional Supporting Information about the box simulations

The figures of the Supplementary material compare the results of the reference MOM simulation as used in the publication (MOM (original)) with results of the two box simulations. MOMBox is the simulation shown in Figure 4 in the paper and uses constant salinity profiles from 1850 for each year. MOMBox2 uses time-dependent annual salinity profiles. Figure S1 shows the temporal evolution of SSS in all simulations at Gotland Deep and Figure S2 shows a scatter plot of the SST of the box simulations over the original simulation for Gotland Deep.

Since the initialization profile from 1850 shows lower SSS, MOMBox generally has lower SSS values. However, the different initializations regarding the salinity profile do not change the simulated SST significantly.

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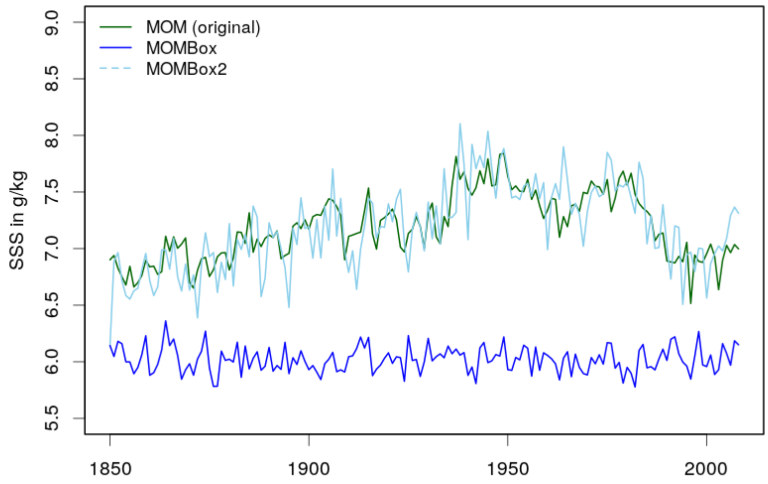

Figure S1. Annual mean of simulated SSS at the station Gotland Deep (lon: 20E, lat: 57.3N) from MOM, MOMBox and MOMBox2

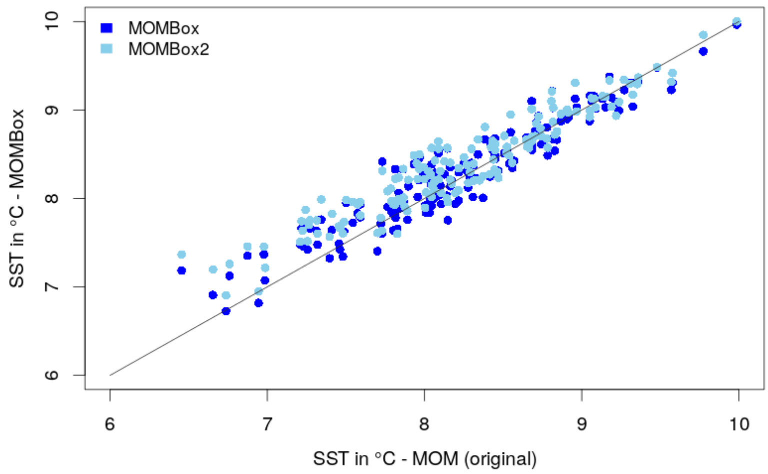

Figure S2. Annual mean of simulated SST at the station Gotland Deep (lon: 20E, lat: 57.3N) from MOM, MOMBox and MOMBox2

Geophysical Research Letters

RESEARCH LETTER
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Changing Salinity Gradients in the Baltic Sea As a Consequence of Altered Freshwater Budgets

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Key Points:
- The latitudinal gradient in the Baltic Sea surface salinity (SSS) has increased during the last century
- Climate variability of the Baltic Sea water cycle (including SSS) is dominated by low-frequency variations on about 30-year time scale
- The long-term change in SSS gradient can be attributed to increasing river runoff in the northern Baltic Sea drainage area

Supporting Information:
- Supporting Information S1

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Abstract Climate change is expected to enhance the hydrological cycle in northern latitudes reducing the salinity in the Baltic Sea, a land-locked marginal sea with a large catchment area located in northern Europe. With the help of ocean simulations forced by historical atmospheric and hydrological reconstructions and local observations, we analyzed long-term changes in the sea surface salinity of the Baltic Sea as well as its latitudinal gradient. The variability of both is dominated by multidecadal oscillations with a period of about 30 years, while both atmospheric variables, wind and river runoff, contribute to this variability. Centennial changes show a statistically significant positive trend in the North-South gradient of sea surface salinity for 1900–2008. This change is mainly attributed to increased river runoff from the northernmost catchment indicating a footprint of the anthropogenic impact on salinity with consequences for the marine ecosystem and species distributions.

1. Introduction

The sea surface salinity (SSS) is an important variable for the marine ecosystem because most species are either adapted to marine or freshwater conditions. Hence, high spatial and temporal variability have high impacts on primary production and fish biomass. Although the Baltic Sea ecosystem is highly productive, it has low biodiversity due to low salinity values.

In the salinity range between 5 and 7 g/kg, the so-called horohalinicum, a minimum number of species, is found, since most species are not specifically adapted to brackish conditions (Vuorinen et al., 2015). In the present climate, the horohalinicum is located in the center of the Baltic Sea and a future freshening due to climate change (Meier et al., 2006) would be an additional threat for halophilic fish populations and other marine species. Indeed, since the 1970s, fish biomass in the Baltic Sea has declined due to the decreasing SSS emphasizing the important role of changes in the regional water cycle for the marine environment (Vuorinen et al., 1998).

The Baltic Sea has often been used as a laboratory for global climate and environmental changes since it is well observed due to long-term marine and land-based monitoring programs (Conley, 2012; Reusch et al., 2018). Following this approach, we analyze long-term salinity records to detect changes in the water cycle in the catchment area. The Baltic Sea is one of the biggest brackish seas in the world with limited exchange with the open sea through the Danish straits. The salinity of the Baltic Sea east of 13°E ranges between 13 g/kg at the bottom in the central Baltic Sea and 2 g/kg at the surface in the Bothnian Bay (cf. Figure 1). The Baltic Sea salinity is driven by freshwater supply due to river runoff and net precipitation and the exchange with saline water from the North Sea. Due to its higher density, new saline water accumulates mainly at the bottom of the Baltic Sea and reaches the surface via vertical advection, entrainment, and turbulent diffusion (BACC Author Team, 2008). Most of the salt is transported into the Baltic Sea during so-called major Baltic inflows (Franck et al., 1987; Mohrholz, 2018). These events happen sporadically, mainly during winter, with a maximum of a few times a year. Since 1887, frequency and intensity of major Baltic inflows did not change systematically although a pronounced multidecadal variability with a main period of 25–30 years was found (Mohrholz, 2018). Hence, long-term changes in salinity are likely driven by changes in wind and river runoff (Meier & Kauker, 2003a). Based on 4-year annual mean values, accumulated freshwater supply by the rivers explains about 50% of the decadal variability of the Baltic Sea mean salinity (Meier & Kauker, 2003a, 2003b; Winsor et al., 2001).

The river flow in northern Europe is well monitored (Stahl et al., 2010) and serves as a good database for detection and attribution studies in a warming climate. Under global warming, an intensification of the

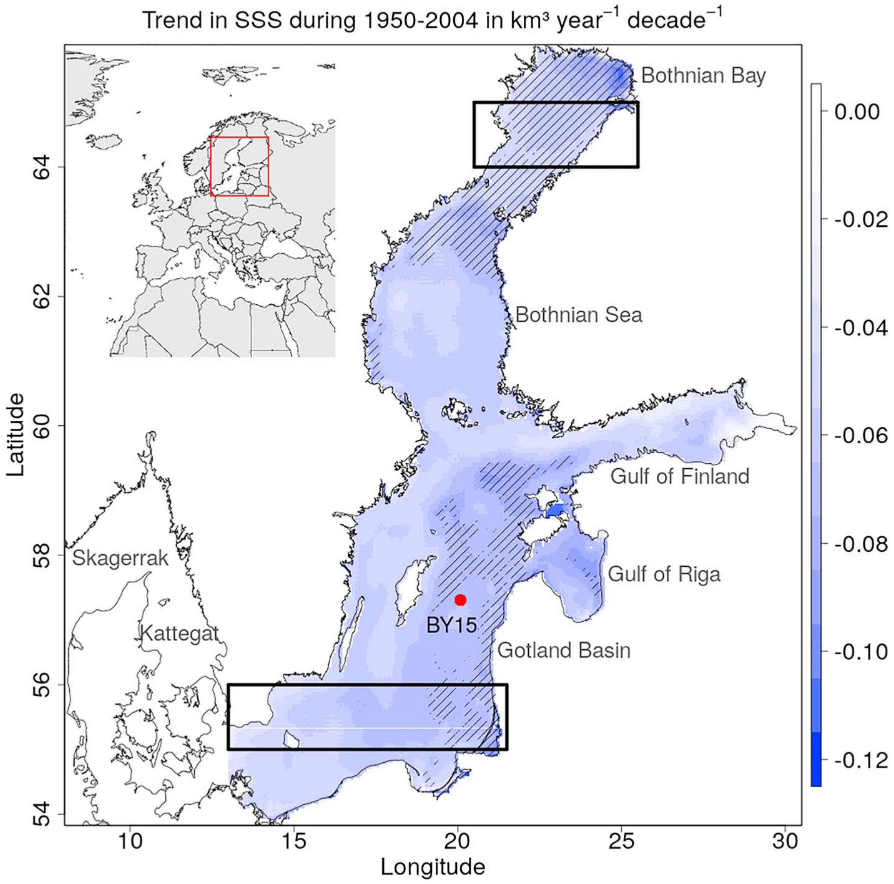

Figure 1. Trends in SSS during 1950–2004 with hatched 95% significance. The two black boxes depict the areas for the North-South gradient calculation, and the station BY15 (Gotland Deep) is the location for the observations representing the Baltic Sea mean salinity anomalies. SSS = sea surface salinity.

global hydrological cycle is projected. Although the total annual mean river flow in the Baltic Sea catchment area was rather stable since 1920, a few rivers showed increasing trends (BACC II Author Team, 2015; Hisdal et al., 2010; Lindström & Bergström, 2004). Since the 1970s, the total winter mean river flow increased and the summer flow decreased, maybe partly because many of the rivers are regulated since the 1970s (Carlsson & Sanner, 1994). However, the observed seasonal changes agree well with future projections under climate change (e.g., Graham, 2004). When averaged over the land areas of the midlatitudes (30°N to 60°N) of the Northern Hemisphere, all data sets of precipitation show an increase in precipitation on 66% probability with medium confidence since 1901 and high confidence after 1951 (IPCC AR5, 2013).

Salinity in the surface layer of the Baltic Sea is well mixed and serves as a low-pass filter of the atmospheric and hydrological forcing, that is, wind, river runoff, and precipitation, indicating long-term changes in regional climate. While long-term trends in salinity observations since the start of measurements in the late nineteenth century are statistically not significant (Fonselius & Valderrama, 2003; Winsor et al., 2001), SSS decreased since the 1970s (Samuelsson, 1996; Vuorinen et al., 1998) although volume-averaged salinities remained unchanged indicating an intensification of the vertical stratification (Meier & Kauker, 2003a).

In this study, long-term variability of SSS since 1900 is investigated and the changes are attributed to changing river runoff and wind over the Baltic Sea basin.

2. Data and Methods

Results of the Rossby Centre Ocean model (Meier et al., 2003) were used to analyze spatially and temporally consistent time series of SSS. Sensitivity experiments were carried out to investigate the role of wind and river runoff for salinity changes. The circulation model is based on the primitive equations and has a spatial resolution of 3.7 km in the horizontal and 3 m in the vertical dimension.

The model is forced for the period 1850–2008 with the high-resolution atmospheric forcing fields HiResAFF by Schenk and Zorita (2012) which were used before to address long-term climate variability of the Baltic Sea region (Gustafsson et al., 2012; Kniebusch et al., 2019; Meier et al., 2018).

The river runoff in the simulation consists of multiple observational data sets which were merged in order to get a homogeneous river runoff data set (Meier et al., 2018). Reconstructions for 1850–1900 by Hansson et al. (2011), for 1901–1920 by Cyberski et al. (2000), and for 1921–1949 by Mikulski (1986) were used. Observations from the BALTEX Hydrological Data Center (BHDC; Bergström & Carlsson, 1994) were available from 1950 to 1998 and extended and replenished by hydrological model results from Graham (1999). Due to the low quality of the early reconstructions and to avoid discontinuities in interannual and decadal variabilities of river runoff, only the results after 1920 are used. Since Meier et al. (2018) postprocessed the runoff observations of the BHDC, the original data of the period 1950–1998 (Bergström & Carlsson, 1994) are additionally used to verify the results (see supporting information).

In this study, the reference simulation (REF) applying the forcing data as described above and three sensitivity experiments from Meier et al. (2018) affecting the salinity are analyzed. In WIND, the wind fields of the year 1904 are repeatedly applied as forcing. In constRUNOFF, river runoff was set to climatological monthly mean runoff of the period 1850–2008 and in FRESH, the river runoff was increased by 20%, while the relative interannual variability was retained. In all experiments, the annual cycle and the interannual variations of the other atmospheric forcing variables were left unchanged compared to REF.

The model, the sensitivity experiments, and the river runoff data used in this study are thoroughly described and evaluated by Meier et al. (2018). The spatial and temporal comparison with several observational data sets (in situ monitoring data and historical lightship data) revealed that long-term variabilities of temperature and salinity are well reproduced (Kniebusch et al., 2019; Meier et al., 2018).

The study area including important stations and regions is shown in Figure 1. In this study, only the Baltic Sea east of 13°E is considered due to the large spatial gradients in the Danish straits. The latitudinal difference in SSS (hereafter called “gradient”) is expressed as the annual mean North-South salinity difference between the boxes shown in Figure 1. Divided by the distance between the box centers of about 1,000 km, the gradient in our study would refer to a horizontal gradient in 10^{-3} g·kg^{-1}·km^{-1}. We investigate the gradient because area-averaged SSS trends are statistically not significant on centennial time scales.

To evaluate the simulated SSS, measurements from ICES Database (2018) are used. Since the availability of data from the first half of the twentieth century is limited in general and in northern areas in particular, available data from large regions (cf. Figure 1) are averaged. For the evaluation of the simulated Baltic Sea mean salinity, measurements from a 2° × 2° grid box around Gotland Deep (BY15) are used since salinity anomalies at this station represent anomalies of the mean salinity averaged over the entire Baltic Sea (Winsor et al., 2001).

We calculated linear trends during different periods from time series of annual mean salinity and river runoff. However, due to a high decadal variability in river runoff and salinity, an estimation of the significance level of these trends is not straightforward. The decadal variability causes a long-range temporal autocorrelation in the records, which needs to be taken into account. Hence, for significance tests the Phase Scrambling Fourier Transform bootstrap method (Theiler & Prichard, 1996) was applied. The method has recently been used for trend analysis in decadal hydrological (Zanchettin et al., 2007) and large-scale circulation patterns (Thejll et al., 2003). The method works as follows: In the first step, the signal (in this case the linear trend) and the noise are separated. In the second step, the noise is Fourier analyzed, and a large ensemble of artificial noise time series is generated by randomizing the Fourier phases but keeping the amplitudes. This means that the surrogate time series have the same autocorrelation properties as the original noise. The artificial noise is added to the signal, and the linear trend estimation is repeated. From this ensemble of trend estimates, which in our case contained 1,000 members, we derived quantiles and used them as p values and confidence intervals.

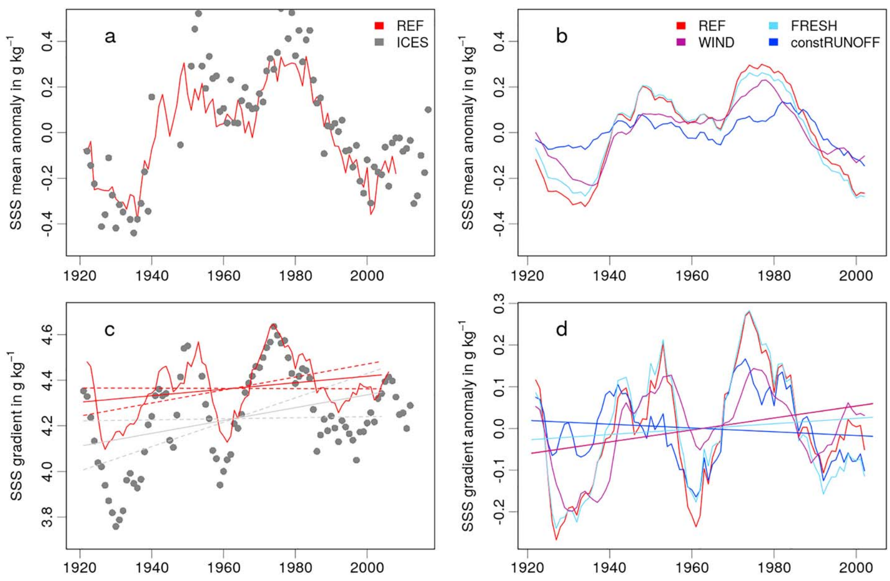

Figure 2. (a) Annual mean and (b–d) 4-year running mean time series of anomalies of the Baltic Sea mean SSS (a and b) and the North-South gradient in the SSS (c and d). (left column) Reference simulation and observations of the ICES database (cf. Figure 1). (right column) Anomalies in the reference simulation and sensitivity experiments. The solid lines in (c) and (d) show the linear trends of the corresponding annual time series. In (b) the 66% confidence intervals of the trends are also shown by the dashed lines. SSS = sea surface salinity; REF = reference simulation; ICES = International Council for the Exploration of the Sea.

3. Results

3.1. Detection of Changes in Salinity

The left column of Figure 2 shows the evolution of the measured and simulated Baltic Sea annual mean SSS anomaly and its low-pass filtered North-South gradient for 1921–2004. The model-observation comparison shows good agreement with correlation coefficients of 0.91 for the mean salinity and 0.77 for the gradient, while the observations in each case show a higher amplitude in the long-term variability.

Figure 2 indicates low-frequency periodic variations with a period of about 30 years in both mean salinity and its gradient, while both are correlated (0.59 in the Rossby Centre Ocean model and 0.61 in observations). Low (high) salinities are accompanied by a small (high) North-South gradient. The negative trend in SSS since the 1970s, which can be seen in Figures 2a and 1 as well as in former publications (Samuelsson, 1996; Vuorinen et al., 1998), seems to be part of the long-term oscillation and is not a systematic change in salinity on centennial time scale. Since the 2000s, the salinity is increasing again. The low-frequency variability with a period of about 30 years can also be seen in the freshwater supply of the model forcing (Meier et al., 2018, their Figure 3).

The trend analysis of the North-South gradient in salinity was done for the period 1921–2004. The observed salinity gradient shows a significant trend (66% confidence) with 0.028 $g \cdot kg^{-1} \cdot decade^{-1}$, while the simulated gradient increases with 0.014 $g \cdot kg^{-1} \cdot decade^{-1}$ and is not significant. However, considering a longer period, for example, until 2006, when the last peak of the low-frequency oscillation is reached, the trend becomes significant at the 66% confidence level, too. Considering the period 1900–2008, the simulated trend becomes significant at 90% confidence. Since the drift toward a higher gradient can also be seen in the observations, we conclude that this result is not a model artifact; hence, we will investigate the causes of an increasing North-South gradient in SSS with time.

3.2. Attribution to Atmospheric Forcing

The salinity of the Baltic Sea and thus its North-South gradient is mainly dependent on the two atmospheric forcing variables wind (driving the water exchange with the North Sea) and freshwater supply. On long-term, river runoff and net precipitation are considerably correlated (Meier & Kauker, 2003a). Hence, it is sufficient to examine runoff only to attribute long-term salinity changes since the total runoff (14,000 m^3/s) is much higher than the total net precipitation (precipitation-evaporation = 1,000 … 2,000 m^3/s) for the whole Baltic Sea area (Meier & Kauker, 2003a; Meier et al., 2018).

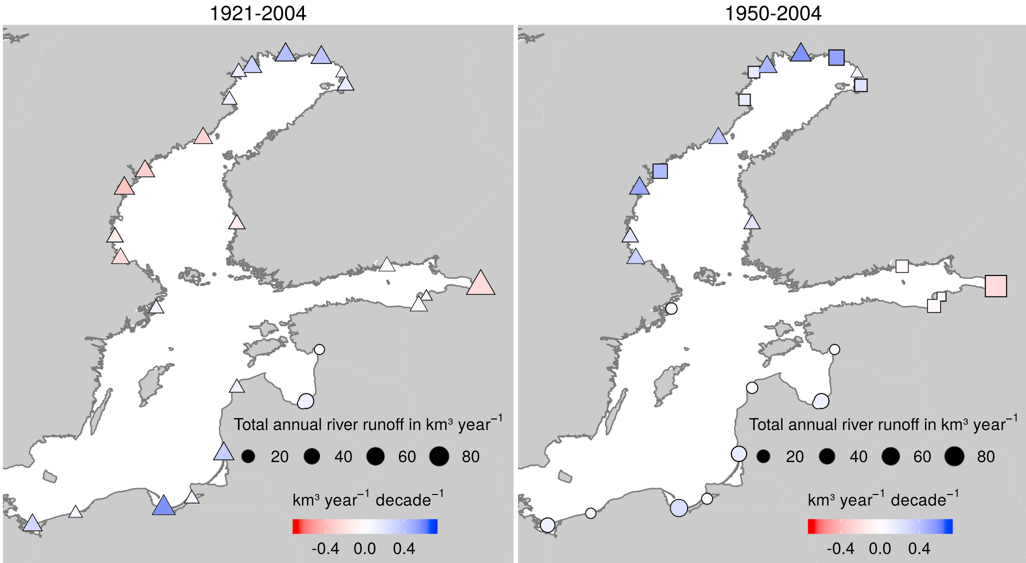

Figure 3. Annual river runoff trends during 1921–2004 (left) and 1950–2004 (right) in cubic kilometers per year per decade. The size of the symbols refers to the total annual river runoff of the corresponding river in the corresponding time period, and the shape refers to the significance (circle—not significant, triangle—66%, and square—90%).

The right column in Figure 2 shows the anomalies in SSS (b) and the gradient (d) for the simulations REF, WIND, constRUNOFF, and FRESH. In all simulations, the low-frequency oscillations of both SSS and the gradient are evident. However, the amplitudes of the oscillations are smaller in both WIND and constRUNOFF, while constRUNOFF explains 66% (67%) and WIND 54% (86%) of the variance in the annual mean gradient (SSS) in the reference simulation. The variance of the gradient in REF amounts to 0.027 g^2/kg^2. In the sensitivity simulations constRUNOFF and WIND, the variance is much lower with 0.013 and 0.01 g^2/kg^2; for the SSS anomaly the differences are even larger. In contrast, FRESH reproduces the long-term variability of the SSS anomaly and gradient very well.

The trend estimates of the SSS gradient show substantially different results in the sensitivity experiments. WIND shows about the same trend as REF, while the trend is smaller in FRESH and even negative in constRUNOFF. Hence, river runoff is crucial for the drift in the North-South gradient in Figure 2c.

Since there was no significant change in the annual freshwater supply to the Baltic Sea during 1902–1998 (Meier & Kauker, 2003a), the spatial distribution of trends in total annual river runoff (hereafter called "annual runoff") for two periods is shown in Figure 3. Both periods show spatially differing trends in annual runoff. During 1921–2004, there is significantly increasing river runoff in southeastern and most northern areas and negative trends in the Bothnian Sea and the Gulf of Finland. During 1950–2004, positive trends spread from the Bothnian Bay to the Bothnian Sea following long-term trends in precipitation patterns (BACC Author Team, 2008). Trends in the Gulf of Finland and in the southern Baltic Sea are negative or around zero and not significant, respectively.

In Figure 1, the simulated trends in SSS are shown for the period 1950–2004. It can be seen that significant changes in the SSS can be found in the northern areas and the eastern Gotland Basin. In the northernmost areas of the Bothnian Bay, where the highest increase in annual runoff was found, the highest changes in SSS are located causing the drift toward a higher gradient in salinity.

4. Discussion

4.1. Long-Term Trends in Salinity, Its Gradient, and the River Runoff

The underlying mechanism of the increasing North-South gradient is complex. The Baltic Sea mean SSS was increasing during 1921–2004 (cf. Figure 2), though not significantly. In this manner, also, the gradient increased since they are correlated directly. Since the amplitude of the variability is small in the northern (fresher) basins, the variability and amount of the gradient are dominated by the SSS in the southern (salty) regions. In contrast, the sensitivity experiments show that the trend in the gradient is independent from wind, that is, the salt inflows and thus the SSS variability in the South. Hence, it is important to discuss how river runoff causes the increasing latitudinal gradient on centennial time scales. During 1921–2004, there were local significant positive trends in the river runoff in the North. At the same time, the positive trends in SSS in the northern basins were 3 times smaller than those in the South (not shown). In this manner, the locally changing river runoff dominated the centennial trends in the North-South gradient, although the multidecadal variability is dominated by SSS variability in the South.

Increasing river runoff in the northern basins can either be caused by increasing precipitation or the melting of glaciers in the catchment area due to higher temperatures. However, the total volume of Swedish glaciers is rather small and has no impact on the river runoff (Bergström, 1993). In contrast to this, precipitation trends could explain increasing river runoff (Stahl et al., 2010). In Sweden, total precipitation has increased continuously since measurements started in 1860 (Alexandersson, 2002, 2004; Hellström & Lindström, 2008), which may have caused the increased river runoff in the northern basins (cf. Figure 3). However, precipitation trends in Sweden are likely influenced by the increase in the number of measurements (Hellström & Lindström, 2008). Nevertheless, precipitation is expected to increase in higher latitudes with climate change which is consistent with patterns in recent runoff trends (Stahl et al., 2010).

In contrast to the river runoff, the long-term positive trends in salinity during the past contradicts future projections of the Baltic Sea which show a freshening of the Baltic Sea until the end of the 21st century (Meier et al., 2006). This can have several reasons. On the one hand, the inflow statistics in the future simulations might not be correct leading to an underestimation of saltwater inflows. For instance, most available scenario simulations do not consider the global mean sea level rise (Meier et al., 2019). On the other hand, the projected runoff trends in the North may be high enough to turn the small positive trends in SSS toward negative values. In fact, FRESH in Figure 2b already shows a lower trend in SSS than REF and WIND supporting this assumption. However, there could also be internal variability on longer time scales longer than 160 years.

4.2. Causes of the 30-Year Variability

In addition to the Baltic Sea mean SSS and the gradient, the pronounced variability with a time scale of about 30 years is found in precipitation at selected stations (e.g., BACC II Author Team, 2015, their Figure 5.8) or averaged over Sweden (e.g., Hellström & Lindström, 2008, their Figure 3), total river runoff in the Baltic Sea basin (e.g., Meier & Kauker, 2003a, their Figure 3), barotropic saltwater inflows (Mohrholz, 2018, his Figure 3), and volume mean salinity of the Baltic Sea (e.g., Winsor et al., 2001, their Figure 15; Meier & Kauker, 2003a, their Figure 8). Also, wind has a variability on the multidecadal time scale (e.g., BACC II Author Team, 2015).

Barotropic saltwater inflows contribute approximately half to the total salt import into the Baltic Sea (Mohrholz, 2018). According to measurements, changes in Skagerrak deep water salinity are small and likely not a source of long-term changes in Baltic Sea salinity (not shown). Moreover, sensitivity experiments showed that surface layer salinity at the open boundary in Kattegat is not important for saltwater dynamics of the Baltic Sea (Meier & Kauker, 2003b). In this manner, the causes for the multidecadal variability lie either in the wind conditions or the river runoff. The results of the sensitivity experiments indicate that both variables contribute to the multidecadal variability of the Baltic Sea salinity.

The variability in wind and river runoff is mainly explained by variations in large-scale circulation patterns (Hansson et al., 2011; Meier & Kauker, 2003a) which are highly correlated with large-scale climate variability indices like the North Atlantic Oscillation (Hurrell et al., 2003) and the Atlantic Multidecadal Oscillation (Knight et al., 2006). Changes in precipitation over the Baltic Sea basin are caused by atmospheric circulation changes (BACC II Author Team, 2015). Hence, multidecadal variations of the large-scale atmospheric circulation would explain the multidecadal variations in salinity (cf. Börgel et al., 2018). However, neither the Atlantic Multidecadal Oscillation (periods of 60–90 years) nor the North Atlantic Oscillation (subdecadal variability) show a periodicity of about 30 years. Frankcombe et al. (2010) assumed that the 20- to 30-year cycles are induced by the internal variability of the Atlantic Meridional Overturning Circulation. Furthermore, the Scandinavian pattern (originally Eurasian pattern in Barnston and Livezey (1987)) could explain

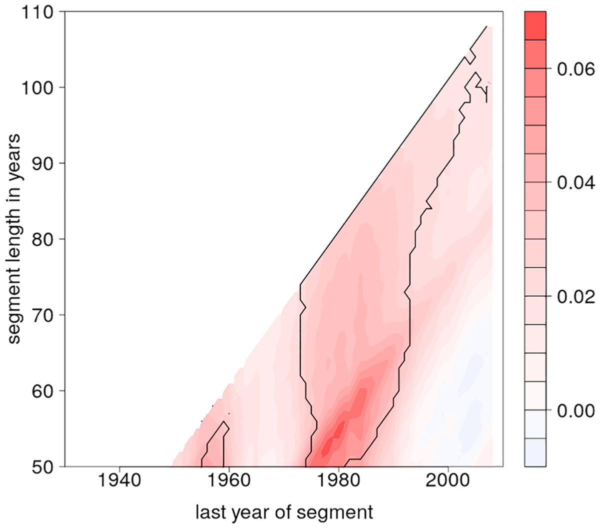

Figure 4. Trend of the simulated North-South gradient in sea surface salinity (cf. Figure 2) in grams per kilogram per decade as a function of the length of the time segment and ending year of the calculation period. The minimum segment length is 50 years due to the low-frequency variability. Areas within the black line are statistically significant at 90% confidence.

the low-frequency oscillations as well. To find out where the internal variability originates will be part of further research.

4.3. Uncertainties

Since the time series is relatively short compared to the time scales of the high multidecadal variability, the significance of trend in the gradient during 1921–2004 is only likely (66% confidence). However, the salinity gradient since 1900 increased on 90% confidence, which is a common level of significance for changes in precipitation (IPCC AR4, 2007; IPCC AR5, 2013). Trends in precipitation and thus freshwater budgets in general are less confident than changes in temperature at the same time, which is why 66% (likely) and 90% (very likely) confidence intervals are often used. The fact that the trend in the North-South gradient becomes more significant with longer time series supports our finding. Figure 4 shows the trends of the gradient in the reference simulation in all periods longer than 50 years following Liebmann et al. (2010). Among them, 80% are positive and 50% significant at 90% confidence. The few slightly negative trends were found after 1970, when the low-frequency oscillation of the salinity turned from its maximum to its minimum. In this manner, although the significance for the considered time period is low, the changes are systematic on long-term perspectives.

Sources of uncertainty mainly arise from the database of the river discharges. As a homogeneous data set for the entire period 1850–2008 does not exist, the model forcing is a combination of several different runoff data sets (Meier et al., 2018) leading to possible inhomogeneities. To narrow this uncertainty, only simulation results after 1921 are used (two data sets for river runoff) and results are compared to the period with a consistent observational data set (1950–2004). Additionally, the original river runoff data from the BHDC without preprocessing were analyzed in the supporting information. The trend estimates for the five biggest rivers of the northern Baltic Sea during 1950–1997 of the original data set by the BHDC and the postprocessed forcing data are presented and compared. Though the trends differ in amount and significance, all trends are positive leading to a higher freshwater supply in the Bothnian Sea and the Bothnian Bay. An impact of river regulation is also possible, although hydrological model results suggest that after the regulation of many of the large rivers in the 1970s in northern Scandinavia the annual mean runoff of Swedish rivers did not change significantly compared to the period before the 1970s (Carlsson & Sanner, 1994).

Another uncertainty might be caused by the choice of the location of the northern and southern areas for the calculation of the latitudinal gradient. Especially the observations are very sensitive to the choice of the considered area. The definition of the areas in Figure 1 represents a compromise between sufficiently many continuous observations (which would not be the case in the most northern part of the Bothnian Bay) and the location close to the big rivers in the North to get the full range of the salinity difference. Following Fonselius and Valderrama (2003), measurements from different seasons were used for addressing long-term variability of salinity in the Baltic Sea. However, the long-term trend is small compared to the seasonal variability in the southern Baltic Sea. Hence, the higher trend in the observed North-South gradient compared to the simulated trend might be caused by temporally increasing observations in the North. Nevertheless, changing the areas and seasons for the calculation of the simulated North-South gradient did not change the trend estimation considerably (not shown). Moreover, after 1950 observations from almost every month in every year were available. Considering only observations from the most frequently observed month (July) did not change the results either.

5. Conclusions

Low-frequency oscillations with a period of about 30 years dominate the variability of the Baltic Sea salinity since 1850. The short-term trend in SSS since the 1970s is mainly explained by this variability. Sensitivity experiments showed that the low-frequency oscillations in SSS were caused by corresponding oscillations in both runoff and wind. The low-frequency variability in SSS is also well correlated with the North-South gradient in SSS.

There is a significant long-term trend in the SSS gradient during 1900–2004 (90% confidence). Our sensitivity simulations revealed that this trend will vanish if the annual mean river runoff is kept constant, indicating that the increase in SSS gradient is caused by local changes in river runoff. A detailed analysis of long-term trends in river runoff showed that at least since 1921, freshwater fluxes in the Bothnian Bay, the northernmost Baltic Sea basin, have increased. Positive runoff trends spread southward and include the rivers of the Bothnian Sea during 1950–2004.

In summary, the SSS in the Baltic Sea was increasing during the last 100 years, though the multidecadal variability caused by large-scale precipitation and wind fields prevented any significance. Since the North-South gradient is dominated by the more saline and variable southern regions, it increased with increasing SSS, too. However, the regionally increasing river runoff in the northern basins additionally increases the difference between North and South leading to a significant positive trend on centennial time scales.

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Supporting Information for "Changing salinity gradients in the Baltic Sea as a consequence of altered freshwater budgets"

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Evaluation of the river runoff in the hydrological forcing and the impact of river regulations

Table 1 compares the annual mean river runoff and its trend during 1950-1997 of the observations by BHDC and the hydrological forcing data set of the six largest rivers in the northern Baltic Sea and two smaller rivers in the Bothnian Bay. The database of BHDC is only available from 1950-1998, while some rivers do not have values for 1998 and closely located rivers are often combined.

The observations are constantly lower than the forcing data because they have been fitted to the total river runoff to the Baltic Sea taking ungauged runoff into account. However, the relative amount of each river is consistent between both data sets. Though there are differences between the trend estimates and not all trends are statistically significant, all trends are positive. The time series of the observations by Bergström and Carlsson (1994) are too short to get significant estimates. The river Kemijoki had a regime shift in the observed river runoff, which was not seen in any of the neighboring rivers. Hence, we have not included its observed trend estimate.

In order to investigate the impact of river regulations, three closely located rivers (one unregulated and two regulated) have been compared. From the rivers in Table 1, the Piteälven (below the line) is one of the few rivers which is not regulated by dam building. The two closest rivers (Lule & Raneälven and Skellefteälven) are regulated. A comparison of the anomalies of the rivers revealed that there are neither regime shifts in river runoff nor differences in temporal variability (not shown). The correlations between all rivers are moderate (> 0.55), while for the two small rivers (the unregulated Piteälven and the regulated Skellefteälven) the correlation amounts to 0.87. Hence, we assume that river regulation do not change the total annual river runoff considerably, which is also supported by the findings of Carlsson and Sanner (1994).

The comparison of river runoff of the hydrological forcing and observations and the evaluation of the impact of river regulation support the conclusions of our study.

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			Forcing data			BHDC data		
Lon	Lat	Name	Total	trend	l.o.s.	Total	trend	l.o.s.
23.33	65.81	Kalix- & Torneälven	26.72	0.51	66%	21.94	0.24	66%
24.60	65.74	Kemijoki	24.61	0.47	66%	20.26	NA	NA
17.58	62.43	Indalsälven & Ljungan	22.13	0.39	no	18.43	0.40	no
22.12	65.51	Lule & Raneälven	20.98	0.40	66%	17.29	0.59	90%
18.31	62.87	Ångermanälven	19.10	0.34	no	15.95	0.54	no
20.39	63.70	Umeälven & Sävarån	17.01	0.30	no	14.18	0.41	90%
21.66	65.37	Piteälven (unregulated)	7.17	0.14	66%	5.85	0.23	90%
21.32	64.67	Skellefteälven	6.59	0.12	66%	5.40	0.19	no

Table 1. Trends in total annual mean river runoff during 1950-1997 of the six largest rivers and two others (below the line) of the northern Baltic Sea in the original data from the BHDC and the model forcing. Total = total annual mean river runoff in km^3; trend = trend in total annual mean river runoff in km^3 decade^{-1}; l.o.s. = level of significance

C.3 Sensitivity-Paper: Disentangling the impact of nutrient load and climate changes on Baltic Sea hypoxia and eutrophication since 1850

The original publication is available at https://link.springer.com/article/10.1007/s00382-018-4296-y