Oceanographic regional climate projections for the Baltic Sea until 2100

H. E. Markus Meier1,2, Christian Dieterich3,*, Matthias Gröger1, Cyril Dutheil1, Florian Börgel1, Kseniia Safonova1, Ole B. Christensen1 and Erik Kjellström2
1Department of Physical Oceanography and Instrumentation, Leibniz Institute for Baltic Sea Research Warnemünde, Rostock, 18119, Germany
2Research and Development Department, Swedish Meteorological and Hydrological Institute, Norrköping, 601 76, Sweden
3Danish Climate Center, Danish Meteorological Institute, Copenhagen, Denmark

Correspondence to: H.E. Markus Meier (markus.meier@io-warnemuende.de)

Abstract. Recently performed scenario simulations for the Baltic Sea including marine biogeochemistry were analyzed and compared with earlier published projections. The Baltic Sea, located in northern Europe, is a semi-enclosed, shallow and tide-less sea with seasonal sea-ice cover in its northern sub-basins, and a long water residence time causing oxygendepletion in the bottom water of the southern sub-basins. With the help of a regional climate model, recently performed scenario simulations for the Baltic Sea including marine biogeochemistry were analyzed and compared with earlier published projections. Specifically, dynamical downscaling using a regional coupled atmosphere-ocean climate model was used to regionalize four global Earth System Models. As, however, the regional climate model does not include components for representing terrestrial and marine biogeochemistry, an additional catchment and a coupled physical-biogeochemical model for the Baltic Sea were unincorporated. In addition, Previous scenario simulations and scenarios taking into account the impact of various water levels were scenario not examined as well. According to the projections, compared to the present climate, suggest higher water temperatures, a shallower mixed layer with a sharper thermocline during summer, reduced sea-ice cover and intensified greater mixing in the northern Baltic Sea during winter, can be expected compared to present climate. Both the frequency and the duration of marine heat waves would increase significantly, in particular in the coastal zone of the southern Baltic Sea (except in regions with frequent upwelling). Nonetheless, due to the uncertainties in the projections of regarding the regional winds, the water cycle and the global sea-level rise, robust and statistically significant salinity changes could not be identified. The impact of a changing climate on biogeochemical cycling is predicted to be considerable but in any case smaller than the impact of that of plausible nutrient input changes. Implementing the proposed Baltic Sea Action Plan, a nutrient input abatement plan for the entire catchment area, would result in a significantly improved ecological status of the Baltic Sea, including reductions in the size of the hypoxic area also in a future climate, strengthening which in turn would increase the resilience of the Baltic Sea against anticipated future climate change. While our findings about regarding changes in variables of the heat cycle variables mainly confirm earlier scenario simulations, earlier projections for salinity and biogeochemical cycles they differ substantially from earlier projections of salinity and biogeochemical cycles, because of different due to differences in experimental setups and different on bioavailable nutrients input scenarios for bioavailable nutrients.
During the time in which preparation of this paper was prepared, shortly before its submission, Christian-Dieterich passed away (1961 – 2021). This sad event marked the end of the life of a distinguished oceanographer and climate scientist who made important contributions to the climate modelling of the Baltic Sea, North Sea and North Atlantic regions.

1 Introduction

The Baltic Sea is a shallow, semi-enclosed sea with a mean depth of 54 m located in northern Europe (Fig. 1). It has a mean depth of 54 m but due to the strongly varying bottom topography, the Baltic Sea can be divided into a number of several sub-basins, with limited transports between them (Sjöberg, 1992). In particular, the water exchange between the Baltic Sea and with the North Sea is hampered because of two shallow sills located in narrow channels connecting the Baltic Sea with the North Sea these two water bodies. Thus, large saltwater inflows occur only sporadically, on average once per year, mainly during the winter season but never during summer (Mohrholz, 2018). Furthermore, because the Baltic Sea is embedded within a catchment area that is about four times larger than the Baltic Sea surface, with a large annual freshwater input are large relative to the volume of the Baltic Sea (Bergström and Carlsson, 1994), causing large horizontal and vertical salinity gradients (Fonsoelius and Valderrama, 2003). The volume of the Baltic Sea is ~21,700 km^3 (Sjöberg, 1992) and the turnover time of the total freshwater supply (~16,000 m^3 s^-1) is 35 years (Meier and Kauker, 2003). These features contribute to strong horizontal and vertical salinity gradients in the Baltic Sea (Fonsoelius and Valderrama, 2003).

Moreover, due to its location and physical characteristics, especially such as the long water residence time, the Baltic Sea is vulnerable to external pressures, such as including eutrophication, pollution, and global warming (e.g., Jutterström et al., 2014). The volume of the Baltic Sea amounts to 21,700 km^3 (Sjöberg, 1992) and consequently the turnover time of the total freshwater supply of about 16,000 m^3 s^-1 is 35 years (Meier and Kauker, 2003) is about 40 years. Using Ocean circulation modelling, has shown that the time scale of the salinity response to changes in atmospheric and hydrological forcing was estimated at about 20 years (Meier, 2006).

In the early 21st century, about 85 million people, in 14 countries, currently were living in the catchment area of the Baltic Sea, representing a considerable anthropogenic pressure. The marine ecosystem is accordingly high (HELCOM, 2018). Insufficiently treated wastewater, emissions of pollutant emissions, overfishing, habitat degradation and intensive marine traffic, including such as oil transport, put place a heavy burden on the ecosystem of the Baltic Sea (Reckermann et al., 2021). One example consequence is the oxygen depletion of the Baltic Sea’s deep waters, with the consequence of dead areas that bottom areas lacking higher forms of life (e.g., Carstensen et al., 2014; Meier et al., 2018b). In 2018, the area of the dead bottoms was equal to the surface of the Republic of Ireland, with an area of about 73,000 km^2, which is about one sixth of the sea surface area of the Baltic Sea. Bottom oxygen depletion in the deeper parts of the Baltic Sea is activated because the accelerated oxygen consumption due to that accompanies the remineralisation of organic matter (Meier et
Projects of the Baltic Sea’s climate at the end of the 21st century were among the first to be made for coastal seas worldwide (Meier and Saraiva, 2020). Already at the beginning of the 2000s, the first scenario simulations based upon dynamical downscaling (Fig. 2) were carried out for selected time slices in present and future climates (e.g., Haapala et al., 2001; Meier, 2002a, b; Omstedt et al., 2000; Rummukainen et al., 2004). These initial findings of the first assessment of climate change in the Baltic Sea basin” (BACC Author Team, 2008). However, these first projections were based on scenarios consisting of a single global climate model (GCM) and a single greenhouse gas (GHG) concentration scenario (150% increase in equivalent CO₂ concentration in the atmosphere in the future climate compared to the historical climate) and only covered 10-year time slices. These initial attempts were therefore followed by more advanced scenario simulations using mini-ensembles (e.g., Döcher and Meier, 2004; Meier et al., 2004b; Meier et al., 2004a; Räisänen et al., 2004) and centennial-long simulations were carried out (e.g., Meier, 2006; Meier et al., 2006; Meier et al., 2015) and higher trophic levels (e.g., Bauer et al., 2019; Ehrnsten et al., 2020; Gogina et al., 2020; Holopainen et al., 2016; MacKenzie et al., 2012; Niiranen et al., 2013; Vuorinen et al., 2015; Weigel et al., 2015). The BACC II Author Team (2015) concluded that “recent studies confirm the findings of the first assessment of climate change in the Baltic Sea basin”. A detailed key message overview of that report was that “No clear tendencies in saltwater transport were found. However, the uncertainty in salinity projections is likely to be large due to biases in atmospheric and hydrological models. Although wind speed is projected to increase over sea, especially over areas with diminishing ice cover, no significant trend was found in potential energy …” (a measure of energy to homogenize the water column). “In accordance with earlier results, it was found that sea-level rise has greater

1https://helcom.fi/helcom-at-work/events/events-2021/ccfs-launch/
potential to increase surge levels in the Baltic Sea than does increased wind speed. In contrast to the first BACC assessment (BACC Author Team, 2008), the findings reported in this chapter are based on multi-model ensemble scenario simulations using several GHG emissions scenarios and Baltic Sea models. However, it is very likely that estimates of uncertainty caused by biases in GCMs are still underestimated in most studies” (BACC II Author Team, 2015).

Since the early 21st century, transient simulations for the period 1960–2100 using regional ocean (Holt et al., 2016; Pushpadas et al., 2015) and regionally coupled atmosphere–ocean models, so-called Regional Climate System Models (RCSMs; Bülow et al., 2014; Dieterich et al., 2019; Gröger et al., 2019; Gröger et al., 2021b) have also been available for the entire, combined Baltic Sea and North Sea system. An overview was given by Schrum et al. (2016) as part of the North Sea Region Climate Change Assessment Report (NOSCCA, Quante and Colijn, 2016) and by Gröger et al. (2021a) within the Baltic Earth Assessment Report (BEAR) project (this thematic issue).

There is a notable difference in the salinity projections between the first two assessments (BACC Author Team, 2008; BACC II Author Team, 2015) and recent scenario simulations (Meier et al., 2021). The first Baltic Sea scenario simulations, driven by nine RCSMs and five GCMs, showed a pronounced negative ensemble mean change in salinity because two of the modelled GCMs showed a significant increase in the mean west wind component (Meier et al., 2006). Then, these pronounced changes in the large-scale atmospheric circulation were not observed as a feature of later studies anymore (Saraiva et al., 2019a). However, note that as the natural variability was poorly sampled, and that this finding differences might be just by chance or may be coincidental.

The large spread in river discharge did not decrease between the various studies, ranging between −8% and to +26% (Meier et al., 2006; 2021). Since global sea level rise projections were corrected in more recent assessments the projected rates of global sea level rise (SLR) were revised upwards towards higher rates (e.g., IPCC, 2019a; Bamber et al., 2019), recent scenario simulations for the Baltic Sea also considered a rise in sea level rise (Meier et al., 2021). As a consequence of compensating effects of the competing drivers of salinity changes, i.e. wind, freshwater input and sea level, future salinity changes were predicted to be only small (Table 2).

The aim of this study is to provide an overview of the projections performed since 2013, i.e. after the last assessment of climate change for the Baltic Sea basin, and to compare recent results with previous findings by the BACC II Author Team (2015). We focus on projections for the marine environment, both-from both physical and biogeochemical perspectives. Among the analysed variables are temperature, salinity, oxygen, phosphate, nitrate, phytoplankton concentration, primary production, nitrogen fixation, hypoxic area and Secchi depth (measuring water transparency) are analysed. An accompanying study by Christensen et al. (2021) investigated atmospheric projections in the Baltic Sea region.

For an overview of the development of RCSMs and their applications, the reader is referred to Gröger et al. (2021a). For that, in our comparison, between of the various studied of scenario simulations, we analyse the only published data (Table 1), with a focus on the analysis on two recently generated sets of scenario simulations, henceforth called BalticAPP and CLIMSEA (Table 1, see Saraiva et al., 2019a, b; Meier et al., 2019a; 2021). These are, that we compared with the previous, henceforth called ECOSUPPORT scenario simulations (Meier et
al., 2014), which were assessed by the BACC II Author Team (2015). Efforts of investigating investigations of the impact of climate change on the Baltic Sea primary production in the Baltic Sea without utilizing a regional climate model did not utilise a RCM (Holt et al., 2016; Pushpadas et al., 2015) are not addressed in this study (herein). nor are also nutrient input reduction scenarios under present climate, e.g. as described by Friedland et al. (2021), are not considered. To our knowledge, further coordinated experiments aimed at projections for the coupled physical-biogeochemical system of the Baltic Sea after 2013 have not been published. Uncoordinated scenario simulations performed prior to 2013 (including Ryabchenko et al., 2016) and their uncertainties were previously discussed by Meier et al. (2018a; 2019b).

The paper is organized as follows. In Section 2, the dynamical downscaling method, the catchment and Baltic Sea models, the experimental setup and the analysis strategy are introduced. In Section 3, the historical and future climates results of the three sets of scenario simulations, ECOSUPPORT, BalticAPP and CLIMSEA, are compared. In Tables 1, 3 and 4, provide an overview about these (Tables 3 and 4) and other (Table 1) scenario simulations from the literature is provided. A consideration of knowledge gaps and a summary of our findings finalize conclude the study. Acronyms used in this study are explained in Table 5.

2 Methods

2.1 Regionalization of a changing climate

Dieterich et al. (2019) produced an ensemble of scenario simulations with a coupled RCSM, called RCA4-NEMO. RCA4-NEMO, which was introduced by Wang et al. (2015), Gröger et al. (2019; 2021b), and Dieterich et al. (2019) have validated and analyzed the different aspects of the RCA4-NEMO ensemble discussed herein. The atmospheric component, RCA4 (Rosby Centre Atmosphere model Version 4), was run at a resolution of 0.22 degrees and 40 vertical levels in the EURO-CORDEX domain (Jacob et al., 2014) and the coupled North Sea-Baltic Sea model NEMO (Nucleus for European Modelling of the Ocean) at a resolution of two nautical miles (3.7 km) and 56 levels. The two components of the RCSM are coupled by sending sea surface data of sea level pressure, energy, mass and momentum fluxes every three hours from the atmosphere to the ocean model. Conversely, the atmosphere model receives data of at the same frequency sea and ice surface temperatures and the sea-ice fraction and albedo at the same frequency.

This RCSM has been applied to downscale eight different Earth System Models (ESMs), each one driven by three Representative Concentration Pathways (RCPs). For the Baltic Sea projections, four ESMs (MPI-ESM-LR, EC-Earth, IPSL-CM5A-MR, HadGEM2-ES; see Gröger et al. (2019) with and references for the ESMs therein) and the GHG concentration scenarios RCP4.5 and RCP8.5 were selected (Table 3). The four ESMs were part of the Fifth Coupled Model Intercomparison Project (CMIP5; Taylor et al., 2012) and their results were assessed in the Fifth IPCC Assessment Report (AR5; IPCC, 2013).

Surface variables of the atmospheric component were saved at hourly to 6-hourly frequency to allow for an analysis of means and extremes in present and future climates. As RCA4-NEMO does not contain model
components for terrestrial and marine biogeochemistry, two additional models forced with the atmospheric surface fields of RCA4-NEMO, i.e. a catchment and a marine ecosystem model, were employed (Fig. 2).

For the ECOSUPPORT scenario simulations, dynamical downscaling was performed with the regional Rossby Centre Atmosphere Ocean (RCAO) model (Döscher et al., 2002). RCAO consists of the atmospheric component RCA3 (Samuelsson et al., 2011) and the oceanic component RCO (Meier et al., 2003; Meier, 2007), with horizontal grid resolutions of 25 km and six nautical miles (11.1 km), respectively. In the vertical, the ocean model has 41 levels with layer thicknesses ranging between 3 m close to the surface and 12 m at 250 m depth. The latter was the maximum depth in the model.

2.2 Catchment models

In BalticAPP/CLIMSEA and ECOSUPPORT, the catchment model E-HYPE (Hydrological Predictions for the Environment, http://hypeweb.smhi.se), a process-based, high-resolution multi-basin model applied for Europe (Hundecha et al., 2016; Donnelly et al., 2017), and a statistical hydrological model STAT (Meier et al., 2012c), respectively, were respectively applied to calculate river runoff and nutrient inputs under changing climate but without considering land surface changes. The statistical model calculates river runoff from precipitation minus evaporation over the catchment area; river-borne nutrient inputs are estimated as the product of a given nutrient concentration and the statistically derived volume flow (Gustafsson et al., 2011; Meier et al., 2012c).

In CLIMSEA, two nutrient input scenarios, defining plausible future pathways of nutrient inputs from rivers, point sources and atmospheric deposition, i.e. the BSAP and reference (REF) scenarios (Saraiva et al., 2019a; b), are used (Fig. 3). In BalticAPP, nutrient input scenarios followed BSAP, REF and Worst Case (WORST) scenarios (Saraiva et al., 2019a; b; Pihlainen et al., 2020). Finally, in ECOSUPPORT, instead of WORST a business-as-usual (BAU) scenario is applied (Gustafsson et al., 2011; Meier et al., 2012c).

In the BSAP scenario in CLIMSEA and BalticAPP, nutrient inputs linearly decrease from the actual current values in 2012 (i.e., the average for 2010–2012) to the maximum allowable input in 2020, defined by the mitigation plan. After that, nutrient inputs remain constant until the end of the century. A similar temporal evolution is defined in ECOSUPPORT but with a reference period of 1997–2003 (Gustafsson et al., 2011; their Fig. 3.1).

In the REF scenario, in CLIMSEA and BalticAPP, the nutrient inputs are calculated by using E-HYPE, which considers the impact of changing river flow on nutrient inputs but neglects land use or socioeconomic development. These inputs correspond on average approximately to the observed mean inputs during the period 2010–2012.

The two additional, above-mentioned scenarios on future projections, BAU and WORST, are not compared because the corresponding input assumptions differ (see Meier et al., 2018a). However, both are characterized by population growth and intensified agricultural practices such as land cover changes.
and fertilizer-use (HELCOM, 2007; Zandersen et al., 2019; Pihlainen et al., 2020), and are only discussed in this study. They are discussed only for the sake of completeness.

Comparing the historical (1980–2005) and future (2072–2097) periods reveals that the reductions in nutrient inputs under the BSAP scenario are smaller in ECOSUPPORT than in BalticAPP and CLIMSEA (Meier et al., 2018a; their Fig. 3). In ECOSUPPORT and BalticAPP/CLIMSEA using the same physical-biogeochemical model RCO-SCOBi, input changes of bioavailable phosphorus amount to ~11 ktons (Model A in Meier et al., 2018a) and ~34 ktons (Model C in Meier et al., 2018a), respectively (Table 6). Corresponding figures for input changes in bioavailable nitrogen are ~230 and ~269 ktons. In Table 6, also lists the calculated changes for the other two biogeochemical models in ECOSUPPORT, BALTSEM (Model F in Meier et al., 2018a) and MOM-ERGOM (Model D in Meier et al., 2018a), and for the REF scenarios are listed. A comparison confirms the considerable differences between ECOSUPPORT and BalticAPP/CLIMSEA scenario simulations. In the next section, the Baltic Sea models are introduced.

2.3 Baltic Sea models

In this study, data from three different Baltic Sea models were used. The Swedish Coastal and Ocean Biogeochemical model coupled to the Rossby Centre Ocean model (RCO-SCOBi) is driven by the atmospheric surface field data calculated by either RCAO or RCA4-NEMO and by the river runoff and nutrient input scenarios derived from either STAT or E-HYPE projections and atmospheric deposition (Fig. 2). Atmospheric depositions are assumed to be constant at the observed levels during 2010–2012 or reduced as in the BSAP (Fig. 3). RCO is a Bryan-Cox-Semtner-type ocean circulation model with horizontal and vertical grid resolutions of 3.76 km and 3 m, respectively (Meier et al., 1999; 2003; Meier, 2001; 2007). SCOBi is a biogeochemical module of the nutrient-phytoplankton-zooplankton-detritus (NPZD) type, considering state variables such as phosphate, nitrate, ammonium, oxygen concentration, the phytoplankton concentrations of three algal types (diatoms, flagellates and others, cyanobacteria) and detritus (Elilola et al., 2009; Almroth-Rosell et al., 2011, 2015). RCO-SCOBi was used in many Baltic Sea climate applications (for an overview see Meier and Saraiva, 2020), evaluated with respect to measurements and compared with other Baltic Sea models (Elilola et al., 2011; Placke et al., 2018; Meier et al., 2018a).

Alfred The Ecological Regional Ocean Model (ERGOM, see www.ergom.net) is a marine biogeochemical model coupled with an ocean general circulation model and a Hilber-type sea-ice model (MOM, Griffies, 2004); it with about the same complexity is roughly the same as that of the RCO-SCOBi model. The horizontal resolution of the model is about 5.6 km and thus somewhat coarser than that of RCO-SCOBi but at least in the surface layer by far higher, i.e. 1.5 m in the upper 30 m and below that depth gradually increasing to up to was high as 5 m (Neumann et al., 2012).

The Baltic Sea Long-Term Large-Scale Eutrophication Model (BALTSEM) spatially resolves the Baltic Sea into 13 dynamically interconnected and horizontally averaged sub-basins with high vertical resolution (Gustafsson et al., 2012). For further details about these and other available Baltic Sea ecosystem models the reader is referred to Meier et al. (2018a).
2.4 Scenario simulations

In CLIMSEA, we have analysed the ensemble of 48 RCO-SCOBI scenario simulations for the period 1976–2098 (Table 3) that was produced following the dynamical downscaling approach described in Sections 2.1–2.3 (Fig. 2) and presented in Meier et al. (2021). Contrary to previous studies (Meier et al., 2014a; 2011b; Saraiva et al., 2019a), the CLIMSEA scenario simulations also consider various scenarios of global sea level rise (SLR). In the three SLR scenarios starting from the year 2005 that were applied by Meier et al. (2021) applied three SLR scenarios starting from the year 2005. In these scenarios, by the year 2100 the projected mean sea level changes relative to the seabed projected by the year 2100 were: (scenario 1) 0 m, (scenario 2) the ensemble mean of RCP4.5 (0.54 m) and RCP8.5 (0.90 m) IPCC projections (IPCC, 2019b; Hieronymus and Kalén, 2020) and (scenario 3) the 95th percentiles of the lowest case (1.26 m, here combined with RCP4.5) and highest case scenarios (2.34 m, here combined with RCP8.5) scenarios following Bamber et al. (2019; Table 3). A deepening of the water depth at all grid points every 10 years increases the relative sea level linearly. The spatially varying land uplift was not considered. For details, the reader is referred to Meier et al. (2021).

The CLIMSEA ensemble simulations were compared with earlier ensemble scenario simulations by Meier et al. (2014a; 2011b; 2012c) and Neumann et al. (2012) using called ECOSUPPORT, and by Saraiva et al. (2019a, b) and Meier et al. (2019a) called BalticAPP. Both sets of scenario simulations, ECOSUPPORT and BalticAPP, applied a similar downscaling approach similar to that used in the CLIMSEA projections (Fig. 2). However, the scenario simulations of ECOSUPPORT were based upon different global and regional climate models, three coupled physical-biogeochemical models for the Baltic Sea and previous GHG emission scenarios as detailed by the Fourth IPCC Assessment Report (AR4; Table 1). Compared to BalticAPP, the CLIMSEA ensemble was enlarged by three SLR scenarios (Table 3) whereas previous projections assumed that no change in the mean sea level relative to the seabed will occur. The need for including SLR scenarios is based upon the finding that the relative sea level above the sills in the entrance area limits the transport and controls salinity in the entire Baltic Sea (Meier et al., 2017). As the relative SLR during the period 1915–2014 was estimated to be 0–1 mm year$^{-1}$, resulting from the net effect of past eustatic SLR and land uplift (Madsen et al., 2019), a lowest-case optimistic scenario for the future would be an unchanged relative sea level above the sills that is relatively unchanged (Meier et al., 2021). In CLIMSEA, mean and highest case scenarios follow the median values of the RCP4.5 and RCP8.5 ensembles reported by Oppenheimer et al. (2019) and the 95th percentiles of the lowest and highest case scenarios of Bamber et al. (2019; Table 3).

2.5 Analysis

Evaluation of the historical period

To evaluate the model results of the BalticAPP and CLIMSEA scenario simulations during the historical period, we calculated the annual and seasonal mean biases during the historical period between observed with RCO-SCOBI simulations and reanalysis data (Liu et al., 2017) and calculated Liu et al. (2017) utilised the Ensemble Optimal Interpolation (EnOI) method to assimilate observed profiles of
temperature, salinity and the concentrations of oxygen, ammonium, nitrate and phosphate determined by the Swedish environmental monitoring program into the RCO-SCOBI model. As reanalysis data are available for the period 1971–1999, we limited the our bias calculations to 1976–1999, the overlap period between the historical period of the scenario simulations and the reanalysis data. Model data of historical periods of BalticAPP and ECOSUPPORT scenario simulations were evaluated by Saraiva et al. (2019a, b) and Meier et al. (2011a, 2011b, 2012c, d), respectively.

**Mixed-layer depth**

The mixed-layer depth (MLD) was calculated following de Boyer Montégut et al. (2004), using a threshold value for the difference between the near-surface water temperature at 10 m depth and the temperature at the MLD of $\Delta T = 0.2^\circ C$.

**Secchi depth**

Secchi depth ($S_D$) is a measure of water transparency and is calculated from $S_D = 1.7/k(PAR)$, where $k(PAR)$ is the coefficient of underwater attenuation of the photosynthetically available radiation (Kratzer et al., 2003). Factors controlling $k(PAR)$ in the RCO-SCOBI model were the concentrations of phytoplankton and detritus. In addition, salinity was used in one of the other Baltic Sea models (MOM-ERGOM) of the ECOSUPPORT scenario simulations as a proxy of the spatio-temporal dynamics of coloured dissolved organic matter (CDOM) or yellow substances.

**Trends**

First, the monthly average of SST was computed from the model output every 48 hours. Then, the linear trend was calculated using the Theil-Sen estimator (Theil, 1950; Sen, 1968). The trend computed with this method was the median of the slopes determined by all pairs of sample points. The advantage of this computationally expensive method is that it is much less sensitive to outliers. The significance of the SST trends was evaluated from a Mann-Kendall non-parametric test with a threshold of 95%. The SST trends were computed by season and annually. In this last case, the annual cycle was removed before computing the linear trend was computed.

Following Kniebusch et al. (2019), we performed a ranking analysis to determine the atmospheric drivers others than air temperature that are most important for the monthly variability of SST in each ESM forcing of the CLIMSEA data set and in both the RCP scenarios, RCP4.5 and RCP8.5. The SST trend is dominated by the trend in air temperature. Thus, to partly eliminate the air temperature effect on SST, the differences between residuals in the SSTs and from a linear regression model fitting between the SSTs and the surface atmospheric temperature (SAT) were calculated and subtracted from the SST. Then, this was followed by applying a cross-correlation analysis of the residual SSTs to determine the main factor driving the SST trend. For each grid point and variable (i.e. cloudiness, latent heat flux, and u-v wind components), the explained variance was calculated and the variable explaining the most variance was identified.

**Marine heat waves**
During the past recent decades, the Baltic Sea region has warmed up faster than either the global mean warming (Rutgersson et al., 2015; Kniebusch et al., 2019) and/or any other coastal sea (Belkin, 2009), making the region prone to marine heat waves (MHWs). Indeed, short periods of abnormally high water temperatures have recently been documented for the Baltic Sea (Suursaar, 2020). MHWs can be defined with reference to the mean climatology (e.g. the 90th, 95th, 98th percentile temperature) or by temperatures exceeding absolute temperature thresholds, re-defined with respect to the end-user applications (Hobday et al., 2018). In most cases, MHWs are defined by the number of periods, their intensity, and their duration and for the specific purposes (Hobday et al., 2018). In this study, we here only focus on the general impact of climate change addressing the sensitivity of ecosystem dynamics. Hence, since an appropriate definition of metrics for MHWs suitable for the Baltic is lacking. In the following, MHWs are re-defined herein as periods of consecutive days with an SST \( \geq 20^\circ C \) lasting for at least 10 consecutive days to better reflect the sensitivity of ecosystem dynamics. For comparison, we showed also MHWs defined as periods of SST exceeding the 95th percentile of the SST distribution also lasting for at least 10 consecutive days.

3 Results

3.1 Historical period

3.1.1 Water temperature

The climate of the Baltic Sea region varies considerably due to maritime and continental weather regimes. For the period 1970–1999, the annual mean SST amounts to about \( -7.8^\circ C \) (Fig. 4). The mean seasonal cycle of the SST is pronounced, and thus, every winter, the northern Baltic Sea, including the Bothnian Bay, Bothnian Sea and the eastern Gulf of Finland, is characterized by sea ice covered every winter (not shown). Due to its large latitudinal extension, the Baltic Sea is characterized during all seasons throughout the year by a distinct SST difference between the colder northern and warmer southern sub-basins (Fig. 4). In the southern Baltic Sea, there is also a pronounced west–east temperature gradient, mainly during summer and autumn, which reflects the large-scale cyclonic circulation that transports warmer, and more saline southern waters along the eastern coast and colder, less saline northern waters of northern origin along the western side (see Gröger et al., 2019, their Suppl. Mat. S1; Fig. 4).

On average, during the historical period 1976–2005, the climate in the CLIMSEA climate simulations is warmer are warmer compared to the climate according to the reanalysis data (Fig. 4). In particular, During spring and summer, the shallow coastal zone of the northern and eastern Baltic Sea is too warm. The spatially averaged biases during winter, spring, summer, and autumn are in the annual mean amounting to 0.8, 0.9, 0.8, 1.0 and 0.9°C. The reason for the warm bias is likely a bias of the RCM. If driven by the reanalysis data ERA-40 (Uppala et al., 2005), RCA4-NEMO systematically overestimates water temperatures and underestimates sea-ice cover in the Baltic Sea during the historical period 1976–2005 (Gröger et al., 2019; their Suppl. Mat. S1).

In the ECOSUPPORT scenario simulations, there is also a systematic warm bias of the RCAO driven by GCMs at the lateral boundaries, particularly resulting in too warm such that winter water temperatures are too warm and
three applied Baltic Sea models (Table 3) forced with the RCSM atmospheric surface fields, in the simulations driven by regionalised-regionalised reanalysis data (ERA-40) showed smaller the mean biases are smaller (Eilola et al., 2011).

3.1.2 Mixed-layer depth

Figure 5 shows the seasonal MLD cycle calculated after de Boyer Montégut et al. (2004). A deeper MLD with pronounced west-east gradients is seen over the characterises the open ocean, with pronounced west-east gradients. This is related to the predominant south-westerly wind regime, with the larger wind fetches and higher significant wave heights in the eastern Gotland Basin causing wave-induced vertical mixing. Furthermore, a positive sea-air temperature contrast favours higher wind speeds (positive winter thermal feedback loop: Gröger et al., 2015; 2021b). In spring, a weakening wind regime, which lowers reduces heat exchange (thereby turning from a shift from heat loss to heat gain), and together with the increased solar irradiance leads to a thinner MLD in the southern Baltic Sea while in the northern part-melting sea ice and subsequent thermal convection and wind-induced mixing still maintain MLDs > 50 m in the sea’s northern part.

During summer, the when atmosphere-ocean dynamics are weakest, leading to a pronounced thermocline develops and shallowest-MLDs are shallowest (the so-called summer thermal short circuit: Gröger et al., 2021b). During autumn, the atmosphere cools faster than the Earth’s surface and land masses cool faster than the open sea areas. Because of the increased thermal contrasts, differences result in a stronger, the large-scale wind regime strengthens with a positive feedback on the MLD.

The ensemble model mean in CLIMSEA reproduces these dynamics and the spatial pattern relatively well. During the cold season, however, the MLD is somewhat shallower in the simulations relative to the reanalysis data of Liu et al. (2017). This may be the result of the air-sea coupling. Gröger et al. (2015, 2021b) have demonstrated that the complex thermal air-sea feedbacks in winter are less well represented by stand-alone ocean models do not very well than by represent the complex thermal air-sea feedbacks in winter as fully coupled ocean-atmosphere GCMs. This can result in SST biases and a too-shallow MLD (Gröger et al., 2015; Figure 7a therein; Gröger et al., 2021b). However, the real reasons of for the underestimated winter MLD are unknown.

In the literature, MLDs in the ECOSUPPORT scenario simulations have not been analysed.

3.1.3 Marine heat waves

Baltic Sea MHWs are here defined herein as periods of >10 days duration during which 1) the SST higher than 20°C and 2) the SST exceeds the 95th percentile temperature. Figure 6 compares the CLIMSEA climate model ensemble mean with the reanalysis data set generated by the same model are compared in Figure 6 (Liu et al., 2017).

The index for MHW index uses a fixed threshold focusing more on what emphasises the environmental impact of the heat waves. In particular, diazoo trophic nitrogen fixation becomes effective at higher temperatures. The
spatial pattern of such MHWs is strongly related to the simulated SST. Figure 6a shows that such periods of MHWs are mostly absent in the open sea of the Baltic proper and further north in the Gulf of Bothnia, but they are most highly abundant in shallow marginal bays like such as the Gulf of Finland and Gulf of Riga as well as along the coasts. The RCO ensemble mean produces the MHWs produced by the RCO ensemble mean are generally more frequent and of longer duration than those of the reanalysis data set. Furthermore, the coastal signature of high abundance extends further offshore (Fig. 6a). In case of For the Belt Sea and Bay of Lübeck, this leads to considerable deviations from the reanalysis data set.

The second index is based on a reference climatology, which is taken as that of 1976–1999. The number of MHWs (Fig. 6c) correlates negatively with their average duration (Fig. 6d). This is somewhat more pronounced in the reanalysis data set. In general, the patterns obtained with the reanalysis data and the RCO show similar patterns but the amplitude of spatial variance is higher in the reanalysis data. The duration of MHWs in the RCO (Fig. 6d) is highest in the open sea, their interruption likely due to the vertical mixing induced by wind events by induced vertical mixing.

Since MHWs are predominantly a summer phenomenon in the Baltic Sea, the stability of the seasonal thermocline is likely a key element in their dynamics of MHWs and such that processes related to summer vertical mixing can be considered a benchmark in the models ability to simulate MHWs and their simulation by the models. Given that mixing is highly parameterised in current ocean models, the RCO reproduces the spatial patterns of MHW reasonably well.

In the literature, MHWs in the ECOSUPPORT scenario simulations have not been analysed.

3.1.4 Salinity

The annual mean sea surface salinity (SSS) distribution shows a large north–south gradient mirroring both the input of freshwater from rivers, mostly located in the northern catchment area, and saltwater inflows from the North Sea (Fig. 7). The SSS drops from about 20 g kg⁻¹ in the Kattegat to < 2 g kg⁻¹ in the northern Bothman Bay and eastern Gulf of Finland. For the period 1970–1999, the annual mean SSS of the Baltic Sea including the Kattegat amounts to about 7.3 g kg⁻¹. Occasionally large inflows of heavy saltwater from the Kattegat occasionally ventilate the bottom water of the Baltic Sea, filling its deeper regions (Fig. 7). Due to almost absent tides are almost absent, mixing is limited and such that the water column is characterised by a pronounced vertical gradient in salinity, and consequently also in density, between the sea surface and the bottom. Probably due to differences in the data of the hydrological model (E-HYPE) data compared to observations, in the CLIMSEA climate models SSS in the coastal zone and in the Kattegat is on average lower in the CLIMSEA climate models compared to the reanalysis data by Liu et al. (2017) (Fig. 7). The spatially averaged,
annual mean bias amounted to about \( 0.4 \text{ g kg}^{-1} \). In the climate models, bottom salinities in the Belt Sea, Great Belt area and the Gotland Basin (most pronounced especially in the northwestern part) are considerably higher and in the Bornholm Basin considerably lower than in the reanalysis data (Fig. 7). The spatially averaged, annual mean bias amounted to about \( 0.3 \text{ g kg}^{-1} \). Hence, the vertical stratification in the Belt Sea, Great Belt area and the Gotland Basin is also larger in the climate models than in the reanalysis data, because the difference between surface and bottom salinity salinities is a good proxy for the vertical stratification.

In the ECOSUPPORT scenario simulations, in the entire Baltic Sea SSS was overestimated in the entire Baltic Sea, in particular in the northern and eastern Baltic Sea regions (Meier et al., 2011b, 2011c). In the northern and eastern Baltic Sea, both also the ensemble mean bottom salinity and vertical stratification were are also overestimated while the bottom salinity in the eastern Gotland Basin was well reproduced/simulated (Meier et al., 2012c).

### 3.1.5 Sea level

Due to the seasonal cycle in wind speed, with wind directions predominantly from the southwest, the sea level in the Baltic Sea varies considerably throughout the year, with the highest sea levels of about 40 cm being measured relative to the Kattegat, occurring during winter at the northern coasts of the Bothnian Bay and at the eastern coast of the Gulf of Finland (Fig. 7). For the period 1976–1999, the annual mean sea level in the Nordic height system 1960 (N1960) as determined by Ekman and Mäkinen (1996) amounted to about 16 cm, with a horizontal north–south difference of about 35 cm (not shown). This sea level slope was explained by the lighter brackish water in the northeastern Baltic Sea compared to that in the Kattegat and by the mean wind coming from the southwesterly direction, which pushes the water to the north and east (Meier et al., 2004a).

The differences in the mean sea level between the CLIMSEA climate models and the reanalysis data are small (Fig. 7) and the spatially averaged, winter mean bias amounted only about 0.6 cm. Sea levels in some parts of the coastal zone such as the western Bothnian Sea are higher in the climate models compared to that in the reanalysis data, probably due to lower salinities. The negative sea level bias in the eastern Gotland Basin suggests an intensified, basin-wide cyclonic gyre. The seasonal cycle of the ensemble mean sea level is relatively well simulated, but with an overestimated sea level in early spring and an underestimated sea level in summer at all investigated tide gauge locations compared to both observations and hindcast simulations driven by regionalised ERA40 data (Fig. 8).

In the ECOSUPPORT scenario simulations, sea levels were not systematically analyzed. In one of the three models (RCO-SCOBi), seasonal mean biases were comparable to the biases in the CLIMSEA scenario simulations found (Meier et al., 2011a).

### 3.1.6 Oxygen concentration and hypoxic area

Since the 1950s, nutrient inputs into the Baltic Sea have increased due to population growth and intensified fertilizer fertilizer use in agriculture (Gustafsson et al., 2012, Fig. 3). Nutrient inputs reached their peak in the 1980s and have steadily declined thereafter until the early 21st century as a consequence of following the
implementation of nutrient input abatement strategies. Nonetheless, since the 1960s, the bottom water of the Baltic Sea below the permanent halocline has been characterized by oxygen depletion and large-scale hypoxia (Figs. 9 and 22).

Following Consistent with the stratification biases in the deeper sub-basins of the Baltic Sea, summer bottom oxygen concentrations in the Bornholm Basin are higher and those in the Gotland Basin in CLIMSEA/BalticAPP climate simulations are higher and lower, respectively, in the CLIMSEA/BalticAPP climate simulations compared to than in the reanalysis data (Liu et al., 2017) (Fig. 9). Hence, The stronger vertical stratification, especially at the halocline depth, hampers vertical fluxes of oxygen, causing prolonged residence times and lower bottom oxygen concentrations, especially at the halocline depth of the Gotland Basin. Spatially averaged biases during winter, spring, summer, and autumn and in the annual mean are small but systematic; and amount to \(-0.6, -0.7, -0.7, -0.5\) and \(-0.6 \text{ mL L}^{-1}\) respectively.

In the ECOSUPPORT scenario simulations, the ensemble mean deep-water oxygen concentrations in the eastern Gotland Basin and in the Gulf of Finland were slightly higher (but within the range of natural variability) and that in the Gulf of Finland significantly lower than determined from observations (Meier et al., 2011a, 2011b; 2012d).

3.1.7 Nutrient concentrations

Nutrients (i.e., phosphorus and nitrogen) content in the surface layer during winter is a good indicator of the intensity of the following spring bloom. Highest Sea surface mean winter concentrations of winter mean of phosphate and nitrate are found are highest in the coastal zone, in particular close to the mouths of the large rivers in the southern Baltic Sea that transport elevated inputs of nutrients into the sea (Fig. 9).

During For the historical period of 1976–1999, winter surface phosphate concentrations in accordance with the climate simulations are relatively close to those of the reanalysis data (Fig. 9). The considerably different concentrations are only differ substantially found only in those coastal regions influenced by large rivers probably due to differing inputs. Such regions are, for instance, such as the coastal zones affected by the discharges of the Odra, Vistula and Pärnu rivers. Spatially averaged biases are largest during summer and autumn, with an average bias of in summer amounted to \(+0.2 \text{ mmol P m}^{-2}\) in summer.

Similarly, Likewise, simulated winter surface nitrate concentrations in the simulations are close to those in the reanalysis data but differ in coastal regions they differ due to differences in their inputs from large rivers (Fig. 9). This is exemplified by, in particular, larger differences are found in the Gulf of Riga and in the eastern Gulf of Finland, where the large differences between them are due to inputs from hydrographic from the Neva River. Spatially averaged biases during winter, spring, summer, and autumn and in the annual mean are rather small but systematic; and amount to \(-1.1, -1.3, -0.5, -0.7\) and \(-0.9 \text{ mmol N m}^{-2}\) respectively.

In the ECOSUPPORT scenario simulations, the simulated profiles of phosphate, nitrate and ammonium are within the range of observations during for 1978–2007, except for in the case of phosphate in the Gulf of Finland.
3.1.8 Phytoplankton concentrations

During the period 1976–1999, high concentrations of dense phytoplankton blooms were confined to the coastal zone, i.e., the area with the highest nutrient concentrations (Fig. 10). Water transparency, measured by Secchi depth, is lower in the Baltic Sea compared to the open ocean (Fleming-Lehtinen and Laamanen, 2012), and for the period 1970–1999, the annual mean Secchi depth averaged for the entire Baltic Sea, including the Kattegat, amounts to about 6.6 m only. In the coastal zone, the Secchi depth is also much smaller in the coastal zone than in the open Baltic Sea (Fig. 10), and also in the northern Baltic Sea, Secchi depth is smaller than in the Gotland Basin, due-attributable to yellow substances originating from land (Fleming-Lehtinen and Laamanen, 2012).

Following due to nutrient concentration biases, the simulated annual mean surface phytoplankton concentrations of the simulations are close to those of the reanalysis data of Liu et al. (2017), but they deviated in coastal regions (Fig. 10). Spatially averaged biases during winter, spring, summer, and autumn and in the annual mean are relatively small, and amounts to ~0.02, ~0.1, ~0.009, +0.06 and ~0.008 mg chlorophyll (Chl) m$^{-2}$, respectively. Note that in the reanalysis hindcast data of Liu et al. (2017), assimilated nutrient and oxygen concentrations were assimilated but not chlorophyll data.

Similar results are also found for the mean biases in the simulated Secchi depths (Fig. 10). Furthermore, Secchi depths in climate simulations, Secchi depths in climate simulations, Secchi depths are systematically deeper in the regions south of Gotland Island and in the entrance to the Gulf of Finland (northeastern Gotland Basin) than elsewhere in the Baltic Sea. Spatially averaged biases during winter, spring, summer and autumn and in the annual mean amount to 0.2, 0.4, 0.06, +0.1 and +0.2 m, respectively.

Compared to the Secchi depth data from HELCOM (HELCOM, 2013; their Table 4.3) and Savchuk et al. (Savchuk et al. 2006; their Table 3), the CLIMSEA climate simulations underestimate the Secchi depth in the southwestern and northern Baltic Sea, respectively, while in the Gotland Basin the model results well fit the observations well (Meier et al., 2019a).

In the ECOSUPPORT scenario simulations, Secchi depth has not been analysed relative to compared with observations.

3.1.9 Biogeochemical fluxes

An evaluation of biogeochemical fluxes, such as primary production and nitrogen fixation, is difficult because of lacking observations are lacking. An exception is the study by Hieronymus et al. (2021), who compared in which historical simulations were compared with in situ observations of nitrogen fixation. The RCO-SCOBI model includes, including a cyanobacteria life cycle (CLC) model (Hense and...
Beckmann, 2006; 2010) driven by reconstructed atmospheric and hydrological data and combined with in situ observations of nitrogen fixation. Hieronymus et al. (2021) The authors found a satisfactory agreement, with the results mainly within the uncertainty range of the observations. However, simulated monthly mean nitrogen fixation during 1999–2008 showed a prolonged peak period in July and August whereas according to the observations showed the peak was more mostly confined to July. However, it should be noted that the RCO-SCOBi version that has been used differed in the scenario simulations discussed here (e.g., Saraiva et al., 2019a) did not contain a CLC model.

3.2 Future period

3.2.1 Water temperature

Annual and seasonal mean changes

In Figures 11 and 12 and Table 7, annual and seasonal mean SST changes between 1976–2005 and 2069–2098 in RCO-SCOBi are depicted and quantified, respectively. The maximum seasonal warming signal propagates between winter and summer from the Gulf of Finland via the Bothnian Sea into the Bothnian Bay (Fig. 11). Maximum warming occurs during summer in the Bothnian Sea and Bothnian Bay. Comparing the seasonal patterns of RCP4.5 and RCP8.5, seasonal patterns are similar although the warming is greater in RCP8.5 compared to RCP4.5. The latter As The SLR has almost no impact on SST changes. Hence, BalticAPP and CLIMSEA scenario simulations yield similar results are similar (not shown). The warming level according to ECOSUPPORT is in between that predicted by CLIMSEA/BalticAPP RCP4.5 and RCP8.5 results because the GHG emissions of the A1B scenario, which forces the ECOSUPPORT ensemble, are in between those of the RCP4.5 and RCP8.5 scenarios.

In the CLIMSEA/BalticAPP RCSM projections, the annual mean SST changes in the Baltic Sea driven by four ESMs, i.e. MPI-ESM-LR, EC-EARTH, IPSL-CM5A-MR, HadGEM2-ES, under the RCP8.5 scenario amount were +2.32°C, +3.7a, +3.52 and +4.67°C respectively (Gröger et al., 2019). Thus, the ensemble mean change is +3.54°C. The corresponding ensemble mean change in the RCO-SCOBi scenario simulations is smaller, and amount to +2.92°C. Different MLDs, vertical stratification and sea-ice cover in the two ocean models, RCO-SCOBi and NEMO, may explain the different responses. Indeed, the comparison of the MLD between the two models reveals a systematic shallower MLD in the RCSM compared to RCO-SCOBi (not shown), which would argue for a higher sensitivity of the RCSM to climate warming.

While the spatial patterns of the SST changes in the scenario simulations of ECOSUPPORT (e.g., Meier et al., 2012c) and CLIMSEA (e.g., Saraiva et al., 2019b) scenario simulations are similar. However, the uncertainties due to the applied global (Meier et al., 2011a, 2011b) or regional (Meier et al., 2012b) model might vary in some cases considerable. In particular, of note is the summer ensemble range caused by the various GCMs is

One of the scenario simulations of ECOSUPPORT was driven by the generally warmer A2 scenario which due to higher GHG emissions compared was generally warmer than the A1B scenario. However, this particular simulation of the ECHAM5–MPIOM GCM is exceptional and at the end of the 21st century the temperature is not much warmer than that obtained with the corresponding run based on the same model under the A1B scenario.
notable (Meier et al., 2014; 2011a). The differences in the magnitude of the warming are explained by the various GHG concentration scenarios (shown in Fig. 12).

Trends

Since SLR and nutrient input scenarios have a negligible impact on SST changes, only a comparison between the RCP4.5 and RCP8.5 scenarios in CLIMSEA/BalticAPP has been done. The multi-model mean of the annual mean SST trends averaged over the Baltic Sea is about $0.18$ °C decade$^{-1}$ and $0.35$ °C decade$^{-1}$ in the RCP4.5 and RCP8.5 scenarios, respectively. At the Baltic Sea scale, seasonal SST trends based on annual values vary only slightly ($\pm0.01$ °C decade$^{-1}$ in both scenarios). However, at the sub-basin scale, seasonal variations are much stronger, reaching $\pm0.05$ °C decade$^{-1}$ in the northern Baltic Sea, with a maximum in summer (Fig. 13). This summer maximum in the northern Baltic Sea can likely be explained by the projected decline in sea-ice cover as in the recent summer, as occurred during the period 1850–2008 period (Kniebusch et al., 2019).

As seen in Figure 14, the relative SST trends indicate that faster warming of the northern Baltic Sea will warm faster than the southern Baltic Sea ($0.02$ °C decade$^{-1}$ and $0.04$ °C decade$^{-1}$ in the RCP4.5 and RCP8.5 scenarios, respectively), with the largest trends, calculated over the entire period 2006–2099, reaching $-0.24$ °C decade$^{-1}$ and $-0.45$ °C decade$^{-1}$ in RCP4.5 and RCP8.5, respectively. However, a calculation of the SST trends by 30-year slice periods every 10 years over the entire period shows that annual SST trends are variable over time (not shown). The natural variability appears to modulate these trends, with successive periods of increasing and decreasing SST trends with a period of about 30 years. For example, in the RCP8.5 scenario, SST trends gradually increase over the first 50 years of the period, reaching a maximum of $0.5$ °C decade$^{-1}$ over the period between 2046 and 2075, before declining slightly from 2060 onwards. As in the RCP4.5 scenario, this is a result of the pronounced natural variability in this scenario as well. Despite the robustness of the spatial pattern of the SST trends, spatial patterns (p value < 0.05 everywhere), the analysis of SST trends for the four ESM forcings reveals an important dependency of SST trends on atmospheric forcings, with a spread of $\pm0.06$ °C decade$^{-1}$ decade$^{-1}$ from the multi-model mean in all of both scenarios (not shown).

At an annual timescale, it is well known that the variability of the air temperature, through the sensible heat fluxes, is the main driver of the Baltic Sea’s SST (Kniebusch et al., 2019), as illustrated here by the high variance of SST explained by air temperature between of these two variables (between 0.85 and 0.95, Fig. 15). The minimum of variance explained is located in the Bothnian Bay, where the sea-ice cover isolates seawater from the air in winter.

To analyze the processes responsible for the SST trends, were analyzed using a rank analysis of atmospheric variables (i.e. latent heat fluxes, cloud cover, and u-v wind components) performed following Kniebusch et al. (2019; Fig. 16). The second parameter (after SAT) explaining the variability of in the SST differs according to the location and ESM. Nevertheless, in all ESMs and in both RCP scenarios, zonal and meridional wind components are the variables most correlated with SST along most of the coastal areas, probably because of upwelling. In the open sea of the Baltic proper and in the Bothnian Bay, the second most important variable is cloudiness. This is also the case in the Bothnian Sea under the RCP4.5 scenario. However,
in the RCP 8.5 the second most important variable is at this location in the latent heat flux. The difference might be explained by perhaps due to the absence of complete melting of the sea ice under RCP 8.5, amplifying and therefore the amplified air-sea exchange under RCP 8.5.

In the vertical, temperature trends are largest in the surface layer compared to the Baltic Sea winter water of the Baltic Sea above the halocline, thus causing a more intense seasonal thermocline (see Section 3.2.2) with in which the largest trends are largest in spring and summer (not shown). Elevated trends are also found in the also characterise deep water, due to the influence of saltwater inflows that will be warmer in a future climate because the inflows originate from the shallow entrance area and occur mainly in winter. Hence, the deep water below the halocline in these sub-basins that are sporadically ventilated by lateral saltwater inflows, such as the Bornholm Basin and the Gotland Basin, the deep water below the halocline will warm more than the overlaying intermediate layer water.

In the literature, trends in ECOSUPPORT scenario simulations have not been analysed.

### 3.2.2 Mixed-layer depth

In Figure 17 shows the changes in the MLD are shown. During winter, reduced sea-ice cover in the Bothnian Sea and Bothnian Bay favours a widespread deepening of the MLD, in the Bothnian Sea and Bothnian Bay, likely caused by wind-induced mixing, favours a widespread deepening of their MLDs. In spring, the most pronounced feature is a strong shallowing of the MLD in the Bothnian Sea, probably likely caused by the radiative fluxes that warm the surface layer and less thermal convection (Hordoir and Meier, 2012). During the historical period, water temperatures are between 2.0 and 3.0°C in this area were between 2.0 and 3.0°C (Fig. 4). Thus, in the future, surface water warming between 1.6 and 2.4°C (Fig. 11) may hamper thermal convective mixing, in future.

The changes during summer are less pronounced. Contrary to winter, there is an overall shallowing in the entire Baltic Sea is found. This is in agreement with a shallower, and more intense thermocline in warming scenarios, as suggested by Gröger et al. (2019), and it is a common feature among the projections, because the changes in wind speed are small (Christensen et al., 2021). The Autumn is primarily characterized by a prolongation of the thermal stratification, leading to an overall shallower MLD compared to the autumn during the historical period.

While Hordoir et al. (2018; 2019) speculated that these changes in thermocline depth during summer might have a significant impact on the vertical overturning circulation (Hordoir et al., 2018; 2019). However, the meridional overturning circulation in the Baltic proper does not show a clear signal but a northward expansion of the main overturning cell (Gröger et al., 2019). Indeed, the effect is expected to be small (Placke et al., 2021).
3.2.3 Marine heat waves

Figure 18 shows the number of MHWs within climatological 30-year time slices is shown in Figure 18. Under conditions of the historical climate, MHWs are virtually absent in open ocean areas. They are most frequent in shallow regions and more abundant along the eastern (Baltic States) compared to the western (Swedish) coast, which may reflect that the greater frequency of coastal upwelling events occur more frequent along the western compared to the eastern Baltic Sea coasts of the Baltic Sea. Even already under the RCP4.5 scenario, wide areas of the Baltic proper are affected by MHWs -coughly once a year. The strongest response is projected for the high-emission RCP8.5 scenario, and specifically in marginal basins like such as the Gulf of Riga or the Gulf of Finland, where the ensemble mean MHWs would occur 2-3 two or three times per year in the future.

Not only the frequency but also the average duration of the MHWs will increase with climate warming. Under RCP8.5, even in the open Gulf of Bothnia MHWs of ~20 days duration would occur, even in the open Gulf of Bothnia future (Fig. 18). The increase in MHWs in the Baltic Sea is likewise linked to an increased frequency of tropical nights in the Baltic Sea (Meier et al., 2019a; Gröger et al., 2021b).

Another way to analyse MHWs is to calculate an also be analysed by calculating them with respect to the 95th percentile temperature of the historical reference climate (Fig. 19). For the historical climate, the average duration of such periods MHWs occur in most regions less than 20–30 days, although in the southern Baltic Sea, especially west of the Baltic proper, they MHWs are more frequent. However, the climate change signal is characterized by more frequent MHWs that are both more frequent and of longer duration. Already in RCP4.5, MHWs in the Baltic Sea occur at least every year. The strongest increase in frequency is near the coasts, whereas the average duration increases less compared to the open sea (Fig. 19). This is probably related to repeated cold-water entrainments from the open sea that interrupt warm periods because of the greater frequency of coastal upwelling events compared to the open sea. In addition, with their lower heat storage capacity, shallow areas are due to their lower heat storage, more sensitive to cold weather events and the associated oceanic heat loss.

3.2.4 Salinity

In the CLIMSEA ensemble, salinity changes are not robust, i.e. the ensemble spread is larger than the signal (Meier et al., 2021). Under both RCP4.5 and RCP8.5, the ensemble mean salinity change signal is small compared to the ensemble spread because the impact on salinity of the projected increase in total river runoff from the entire catchment (Fig. 3) on salinity is approximately compensated by the impact of larger saltwater inflows due to the projected SLR (Table 9 not shown). The results would be about the same if only the IPCC mean SLRs are considered. Hence, compared to previous studies such as those by Meier et al. (2014; 2015; ECOSUPPORT) and Saraiva et al. (2019a; BalticAPP: Fig. 12), the ensemble mean salinity changes in CLIMSEA are much smaller (Table 9 not shown) and it is impossible to judge whether these changes will be positive or negative. In idealized sensitivity experiments performed with the RCO-SCOBI model for the period 1850–2008 (Meier et al., 2017; 2019d), it was suggested that the change in the average Baltic Sea salinity (1988–2007) linearly increased linearly with sea-level rise SLR and at a rate of about 1.4 g kg m$^{-2}$ (Table 9).
3.2.5 Sea level

Following global sea level changes, SLR in the Baltic Sea will accelerate in future (Hünicke et al., 2015; Church et al., 2013; Bamber et al., 2019; Oppenheimer et al., 2019; Weisse and Hünicke, 2019), albeit at a somewhat slower rate than the global mean because of the remote impact of the melting Antarctic ice sheet (Grinsted, 2015). Changes in SLR in the North Atlantic (and the Baltic Sea) would not be larger resulting from in response to the melting of the Antarctic ice sheet compared to than to the melting of Greenland, due to gravitational effects. For a mid-range scenario, Baltic SLR in the Baltic Sea is projected to be ~87% of the global mean (Pellikka et al., 2020). Eustatic Land uplift will partly compensate for the eustatic SLR, in particular in the northern Baltic Sea (e.g., Hill et al., 2010). In RCP2.6 and RCP8.5, the global mean sea level in 2100 is 43 cm and 84 cm higher, respectively, compared to during the period 1986–2005 (Oppenheimer et al., 2019). For these two scenarios, likely ranges amount were 29–59 cm and 61–110 cm, respectively. Assessing the ice sheet dynamics in more detail, Bamber et al. (2019) assessed ice sheet dynamics in detail and subsequently estimated for low- and high-case scenarios global median SLRs in 2100 of 69 cm and 111 cm for low- and high-case scenarios in 2100, respectively. They found Likely ranges according to the authors of were 49–98 cm and 79–174 cm and very likely ranges of 36–126 cm and 62–238 cm.

In BalticAPP and CLIMSEA scenario simulations, sea level changes are small (Fig. 12, Table 3). On the other hand, sea level changes whereas in ECOSUPPORT scenario simulations they are larger, particularly in spring, because one member of the multi-model ensemble considers Archimedes’ principle (not shown). Note that in Figure 12 the sea level changes shown in Figure 12 consider only changing river runoff, changing wind, and melting sea ice as affecting the sea level (according to Archimedes’ principle (only in the ECOSUPPORT ensemble). As whereas neither the global mean SLR and nor land uplift are not included, and they have to be added (e.g., Meier, 2006; Meier et al., 2004a).

In CLIMSEA, there are no statistically significant nonlinear seasonal changes rather than the SLR does not exist (Fig. 20). In both GHG concentration scenarios, the largest changes are only about ±5 cm were found. According to these results, confirm that systematic changes in the regional wind field are small (Christensen et al., 2021) and nonlinear effects are negligible as well, i.e., mean sea level changes do not significantly differ between various SLR scenarios (not shown). Instead, in the projections, the mean absolute sea level in the Baltic Sea simply follows the mean sea level in the North Atlantic. However, the spatially inhomogeneous isostatic adjustment considerably will considerably alter patterns of sea level changes relative to the sea floor.

Due in response to the global mean SLR, the sea level extremes in the Baltic Sea that are rare today will become more common in the future (e.g., Hieronymus and Kalén, 2020). However, changes in sea level extremes relative to the mean sea level are statistically will not be statistically significant because wind velocities are projected to remain unchanged (Christensen et al., 2021). Exceptions are areas with sea ice decline because the planetary boundary will get less stable and wind speeds will increase (Meier et al., 2011b). The exceptions are areas with sea ice decline since they are linked to a decrease in atmospheric stability accompanied by increased wind velocities, which follows from the result of increased temperature and increased turbulent fluxes (Meier et al., 2011b). These increases will mostly translate as changes from calm to light
wind conditions change the stable atmospheric boundary layer and becomes less stable. For stronger wind conditions related to high sea level extremes, the impact of stratification effects on mixing is small. In addition, open water areas after sea-ice loss have a smaller surface roughness compared to than ice-covered areas, also with the reduced surface friction leading to an increase in wind velocities because of reduced surface friction.

As sea level extremes also depend on the path of low-pressure systems (Lehmann et al., 2011; Suursaar and Sooäär, 2007), which do not show systematic changes in. In a future climate, do not show systematic changes (Christensen et al., 2021), changes in sea level extremes relative to the mean sea level are not expected. In addition, a large internal variability at low frequencies prevents the detection of climate-warming-related changes in sea level extremes (Lang and Mikołajewicz, 2019).

### 3.2.6 Oxygen concentration and hypoxic area

**Bottom oxygen concentration**

Projected changes in bottom oxygen concentrations differ considerably between ECOSUPPORT and BalticAPP/CLIMSEA scenario simulations, as illustrated for summer (Fig. 21, Table 10), whereas the differences between the BalticAPP (SLR = 0 cm) and CLIMSEA (SLR > 0 cm) scenarios are relatively smaller (Meier et al., 2021). The differences between the ECOSUPPORT and BalticAPP ensembles mainly reflect the different experimental setups of the simulations and the different nutrient input scenarios (Meier et al., 2018a). While in the shallow regions without a pronounced halocline future bottom oxygen concentrations decrease in all scenario simulations, due to the decreased lower oxygen saturation concentrations, in the deeper offshore regions with a halocline, changes in bottom oxygen concentration depend largely on the applied nutrient input scenario (Fig. 21).

In ECOSUPPORT scenario simulations, the future bottom oxygen concentration decreases significantly in all scenarios except under the BSAP, where the bottom oxygen concentrations in the deeper regions at changes only slightly change on average (see Meier et al., 2014a, 2011b). By contrast, in the BalticAPP projections, bottom oxygen concentrations under the BSAP decrease in the deeper regions increase considerably, regardless of the degree of warming (see Saraiva et al., 2019a; Meier et al., 2014a, 2011b). Under RCP4.5, bottom oxygen concentrations increase even under the nutrient inputs of REF and WORST nutrient inputs, whereas RCP8.5 predicts slight reductions in the Bothnian Sea and southwestern Baltic Sea, in particular under WORST. These results are explained by the historical nutrient input reductions and the slow response of the Baltic Sea. Similar results were also calculated for the CLIMSEA ensemble (Meier et al., 2021).

The differences in the oxygen concentration changes between the ECOSUPPORT and BalticAPP/CLIMSEA ensembles can be explained as follows. In ECOSUPPORT, nutrient input changes in nutrient input relative to the historical period 1961–2006, including the observed nutrient inputs averaged from the period 1995–2002, were applied (Gustafsson et al., 2011; Meier et al., 2011ab). During this period, the observed nutrient inputs were lower than in BalticAPP/CLIMSEA scenario simulations because in the latter the observed monthly nutrient inputs, including the pronounced decline from the peak in the 1980s until the much lower recent values, were used as the forcing (Meier et al., 2018a). Furthermore, in ECOSUPPORT, future nutrient
inputs under the BSAP scenario were calculated as relative changes, resulting in higher future inputs than in
BalticAPP/CLIMSEA, in which applied absolute values of the BSAP were applied.

Hence, in ECOSUPPORT under the BSAP, the reductions nutrient input reductions between future and historical
nutrient inputs are smaller in ECOSUPPORT under the BSAP than in BalticAPP/CLIMSEA (Table 6) and
resulting in a smaller response of the biogeochemical cycling. We argue that the more realistic historical
simulation, including a spin-up since 1850, based on observed or reconstructed nutrient inputs as used for
the BalticAPP and CLIMSEA ensembles would result in a more realistic model response that is more realistic
compared to that of the ECOSUPPORT scenario simulations.

3.2.7 Nutrient concentrations

In ECOSUPPORT, the hypoxic area is projected to increase under REF and BAU nutrient input scenarios (Meier
et al., 2011a, 2011b). Only under BSAP, is there a slight decrease compared to the early 2000s as found.

In CLIMSEA under REF, the hypoxic area is projected to slightly decrease slightly until about 2050, as a delayed
response to nutrient input reductions, and then increase again towards the end of the century, likely presumably
in response to increased nutrient inputs increase and warming (Fig. 22). Larger hypoxic areas are calculated under
RCP8.5 than under RCP4.5. Under BSAP, the hypoxic area is projected to considerably decrease. At the end of
the century, the size of the hypoxic area is expected to be 22-37% larger compared to when the average size of during the period 1976-2005. This green-range denotes represents the results of the various
scenario simulations ensemble members.

In accordance with previous studies, such as Saraiva et al. (2019b) and Meier et al. (2021), it was found that the
impact of warming (reduced oxygen solubility, increased internal nutrient cycling, increased riverine inputs) and
of increasing stratification (decreased ventilation) may amplify oxygen depletion of oxygen, enlarging that enlarges the hypoxic area in the Baltic Sea and partially counteracting nutrient input abatement
strategies such as the BSAP. However, in all available scenarios the impact of climate change is smaller than the
impact of nutrient input changes.

While in ECOSUPPORT scenario simulations of future climate the projected winter surface phosphate
concentrations in winter increase in future climate under all three nutrient input scenarios (except in the Gulf of
Finland in BSAP), in BalticAPP projections winter the surface phosphate concentrations in winter decrease almost
everywhere (except in the Odra Bight and adjacent areas in REF and WORST) (not shown). In contrast to the
spatial pattern of nearly ubiquitous changes in the surface phosphate concentration changes, larger nitrate
concentration changes are usually confined to the coastal zone, showing and differ in their varying signs of the
changes. In ECOSUPPORT projections, the increases in winter surface nitrate concentrations in REF and BAU
increase in particular are largest in the Gulf of Riga, the eastern Gulf of Finland, and along the eastern coasts of the
Baltic proper in REF and BAU (not shown). In BalticAPP projections, the increases in in REF and WORST winter
surface nitrate concentrations in REF and WORST increase in particular are largest in the Bothnian Bay and the Odra Bight while concentrations decrease in the Gulf of Riga and the Vistula lagoon. Nitrate concentrations decrease in the Gulf of Riga and the Vistula lagoon. Overall, the differences in surface nutrient concentrations between the two sets of scenario simulations are considerable (not shown) and these can be differences can be explained by largely differing nutrient inputs from land. Thus, while in ECOSUPPORT the projected changes in inputs in ECOSUPPORT refer to the average inputs during 1995–2002, in BalticAPP scenario simulations the observed past historical changes including include the decline in nutrient inputs since the 1980s are considered (Meier et al., 2018a).

3.2.8 Phytoplankton concentrations

Annual mean changes in surface phytoplankton concentration (expressed as chlorophyll concentration) follow the changes in nutrient concentrations and are confined to the productive zone along the coasts (Fig. 23). In ECOSUPPORT projections, annual mean Secchi depths are decreasing in all scenario simulations (see Fig. 24 and Table 11). On the other hand, in the BalticAPP projections, the area-averaged Secchi depths generally increase, except in the combination of combined RCP8.5 and BAU scenarios (Table 11), indicating a general improvement of the water quality in future compared to the present climate. The most striking changes occur in the BSAP scenario, showing in which the Secchi depth increases by up to 2 m in the coastal zone of the eastern Baltic proper. Changes in stratification (illustrated by the differences between BalticAPP and CLIMSEA ensembles and between the CLIMSEA ensemble mean and high SLR scenarios) have only a minor impact on the water transparency response (Table 11). The overwhelming driver of Secchi depth changes in the Secchi depth are nutrient input scenarios (illustrated by the differences between ECOSUPPORT and BalticAPP/CLIMSEA ensembles and highlighted by in some cases, even contradictory signs in the changes).

3.2.9 Biogeochemical fluxes

In CLIMSEA under the BSAP, primary production and nitrogen fixation are projected to considerably decrease in a future climate (Fig. 22). According to this scenario, the interannual variability would decline. Under REF, nitrogen fixation is projected to slightly decrease until about 2050, as a delayed response to nutrient input reductions, and then to increase towards the end of the century, likely in response to increased nutrient inputs increase and warming. At the end of the century, both primary production and nitrogen fixation will be at the same level as under current conditions. The impact of warming is larger under high than under low nutrient conditions (Saraiva et al., 2019b).

3.2.10 Relation to the large-scale atmospheric circulation

The dominant large-scale atmospheric pattern controlling the climate in the Baltic Sea region during winter is the North Atlantic Oscillation (NAO; Hurrell, 1995). However, this relationship is not stationary but depends on other modes of variability, such as the Atlantic Multidecadal Oscillation (AMO; Börger et al., 2020). During the past climate, the relationship between the NAO index and regional climate variables in the Baltic Sea region, such as SST, changed over time (Vihma and Haapala, 2009; Omstedt and Chen, 2001; Hunicke and Zorita, 2006; Chen and Hellström, 1999; Meier and Kauker, 2002; Beranová and Huth, 2008).
Figure 25 shows the calculated ensemble mean winter (December through February) NAO index for the period 2006–2100. For the RCP4.5 emission scenario, it is found that the NAO shows high interannual variability. By applying a wavelet analysis, it is found that the calculated NAO index contains some decadal variability, which differs for every model (not shown). By a comparison of comparing RCP4.5 and with the high-emission scenario RCP8.5, it can be seen that the spread of the ensemble increases with increasing greenhouse gas GHG concentrations. Furthermore, Figure 25 also shows the running correlation between the NAO index and the area-averaged SST. Indeed, the correlation remains positive but it is not constant in time. By comparing, it is found that there are no systematic changes between in both the two emission scenarios. However, although for RCP8.5, the ensemble spread is slightly larger, ensemble spread is found.

4 Knowledge gaps

In the largest set of scenario simulations of this study, the CLIMSEA ensemble, only four ESMs were regionalised, using only one RCSM; consequently, the CLIMSEA ensemble is still too small to estimate the uncertainties caused by ESM and RCSM differences. It should be noted that while recently, ensemble modules for terrestrial and marine biogeochemistry (Gröger et al., 2021b) such that these simulations were therefore, we have not considered these simulations in our assessment.

Furthermore, in this study the uncertainties related to unresolved physical and biogeochemical processes in the Baltic Sea and on land were not considered, because only one Baltic Sea and one catchment model were used. Although the CLIMSEA ensemble is larger than the ensembles in previous studies, it is still too small to estimate all sources of uncertainty.

In addition to the uncertainties related to global and regional climate and impact models, the unknown pathways of GHG and nutrient emissions are thus far unknown and the role of natural variability versus anthropogenic forcing is not well understood (Meier et al., 2018a; 2019b; 2021). Recent studies suggested that the impact of natural variability such as the low-frequency AMO, is larger than hitherto estimated. For instance, it was shown that in paleoclimate simulations the AMO affects Baltic Sea salinity on time scales of 60–180 years (Börgel et al., 2018), which is longer than the simulation periods of available scenario simulations. Furthermore, the AMO may also influence the centres of action of the NAO (Börgel et al., 2020). The Lateral tilting of the positions of the Icelandic Low and Azores High explains the changes in the correlation; changes between the NAO and regional variables such as water temperature, sea-ice cover and river runoff in the Baltic Sea region (Börgel et al., 2020). Although there are indications that the AMO is affected by various climate states such as the Medieval Climate Anomaly and the Little Ice Age (Wang et al., 2017; Börgel et al., 2018), it is unknown how future warming would affect these modes of climate variability is unclear.

We have not analyzed Changes in sea-ice cover were not analyzed in this study because in the recent scenario simulations of the CLIMSEA ensemble sea-ice cover is systematically underestimated. However, we found that
The future sea-ice cover is projected to be considerably reduced, with an on-average ice-free Bothnian Sea and western Gulf of Finland. Recent results by Högland et al. (2017) confirmed earlier results by Meier (2002b) and Meier et al. (2011; 2014), see BACC Author Team (2008).

Most noticeable are the differences in projected biogeochemical variables between ECOSUPPORT and BalticAPP/CLIMSEA ensembles. In ECOSUPPORT, nutrient input changes relative to the historical period 1961-2006 with prescribed observed nutrient inputs from the period 1995-2002 were applied (Gustafsson et al., 2014; Meier et al., 2014a). During the historical period 1980-2002, these inputs were lower than in BalticAPP/CLIMSEA scenario simulations, because in the latter the observed monthly nutrient inputs including the pronounced decline from the peak in the 1980s until the much lower recent values were prescribed (Meier et al., 2018a). Hence, in ECOSUPPORT the nutrient input reductions under the BSAP between future and historical inputs are smaller than in BalticAPP/CLIMSEA resulting in a smaller response of the biogeochemical cycling. We argue that the more realistic historical simulation including a spinup since 1850 under observed or reconstructed nutrient inputs as used for the Baltic-APP and CLIMSEA ensembles would give a more realistic model response compared to the ECOSUPPORT scenario simulations. However, not exactly known current and completely unknown future bioavailable nutrient inputs from land and atmosphere were classified as one of the biggest uncertainties (Meier et al., 2019b).

The various ensembles of the scenario simulation sets have in common that plausible nutrient input changes have a bigger impact on changes in biogeochemical variables, such as nutrients, phytoplankton and oxygen concentrations, concentrations than of either the projected changes in climate, such as warming, or changes in vertical stratification. The latter would be caused by increased freshwater inputs, SLR or changes in regional wind fields, assuming RCP4.5 or RCP8.5 scenarios. Long-term simulations of past climate supported these results. Although historical warming had an impact on the size of the present-day hypoxic area, model results suggested that the main reason for hypoxia in the Baltic Sea was best explained by the increase in nutrient inputs due to population growth and intensified agriculture since 1950 (Gustafsson et al., 2012; Carstensen et al., 2014; Meier et al., 2012a; 2019c, d). Hypoxia was also observed during a feature of the Medieval Climate Anomaly (Zillén and Conley, 2010). However, a preliminary attempt to simulate the past 1000 years paleoclimate modeling could not explain such low oxygen conditions without substantial increases in nutrient inputs (Schimanke et al., 2012). Thus, the sensitivity of state-of-the-art physical-biogeochemical models to various drivers might be questioned and, apparently, it is clear that the models do not reproduce all important processes correctly.

As outlined in previous assessments, current and future bioavailable nutrient inputs from land and atmosphere are unknown and were consequently classified as one of the biggest uncertainties (Meier et al., 2019b). For a more detailed discussion of uncertainties in Baltic Sea projections, the reader is referred to Meier et al. (2018a; 2019b; 2021).
5 Summary

As shown in Section 3, the latest published scenario simulations confirm the findings of the first and second assessments of climate change in the Baltic Sea region (BACC Author Team, 2006; BACC II Author Team, 2015), namely that, in all projections driven by RCP4.5 and RCP8.5 and driven by four selected ESMs of CMIP5, water temperature is projected to increase and sea-ice cover to decrease significantly. In the two RCP4.5 concentration scenarios, the ensemble mean annual SST changes in SST between 1978–2007 and 2069–2098 amount to are 2°C and 3°C, respectively. Warming would enhance the stability across the seasonal thermocline and cause a shallower mixed layer depth (MLD) during summer, would be shallower. During winter, however, the mixed layer in the northern Baltic Sea would be deeper, probably because of the declining sea-ice cover and the associated intensification of wind speed, waves and vertical mixing. Both the frequency and the duration of marine heat waves (MHWs) would increase significantly, in particular south of 60°N and in particular in the coastal zone (except in regions with frequent upwelling).

The projected spatial patterns of seasonal SST trends projected during for 2006–2099 are similar compared to those of historical reconstructions during of the period 1850–2008, although in most regions the magnitude of the trends was larger. The largest trends were found in summer in the northern Baltic Sea (Bothnian Sea and Bothnian Bay) and thus in regions where under a warmer climate, on average under a warmer climate sea ice would melt earlier or would even have disappeared completely due to the ice-albedo feedback. This implies that, with increasing warming, SST trends in the northern Baltic Sea will become larger relative to SST trends than those in the southern Baltic Sea. It follows accordingly, that in contrast to the present climate, wherein which mean SSTs considerably decline from south to north, in a future climate the north-south temperature gradient will weaken in future climate.

Contrary to previous scenario simulations, recent scenario simulations considered the impact of the global mean SLR on Baltic Sea salinity, causing which for the ensemble mean salinity would be more or less completely compensated for the effects of the projected increasing river runoff. However, as future changes in all three drivers of salinity (wind, runoff and SLR) are highly uncertain, the spread in the salinity projections solely caused by the various ESMs is larger than any signal.

In agreement with the earlier assessments, we conclude that SLR has a greater potential to increase surge levels in the Baltic Sea than does changing wind speed or changed wind direction. For the latter, there have been no statistically significant changes during the 21st century thus far more observed.

In agreement with earlier studies, nutrient inputs—changes in nutrient input according to the BSAP or REF scenarios would have a larger impact on biogeochemical cycling in the Baltic Sea than will a changing climate driven by RCP4.5 or RCP8.5 scenarios. Furthermore, the impact of climate change would be more pronounced under higher than under lower nutrient conditions. Hence, without further nutrient input reductions, as suggested by the BSAP, eutrophication and oxygen depletion will worsen. However, the response determined in recent studies differs considerably from the results of the responses reported in previous studies, considerably because of more plausible assumptions on regarding historical and future nutrient inputs, resulting, for instance, sometimes in some cases this has led to opposite signs in the response of bottom oxygen concentrations. The new
scenarios suggest the implementation of the BSAP would lead to a significant improvement in the ecological status of the Baltic Sea regardless of the applied RCP scenario.

However, as a new driver, global SLR was recently identified as a new global driver. Depending on the combination of SLR and RCP scenario, a significant impact on the bottom oxygen concentration was found to be significant. A higher mean sea level relative to the seabed at the sills would cause increased saltwater inflows, a stronger vertical stratification in the Baltic Sea and a larger hypoxic area. The relationship between vertical stratification and the size of the hypoxic area was confirmed by historical measurements. Nevertheless, recent studies suggested that the difference in future nutrient emissions between the BSAP and REF scenarios is a more important driver of than the projected changes in climate with respect to changes in hypoxic area, phytoplankton concentration, water transparency (expressed by Secchi depth), primary production and nitrogen fixation than projected changes in climate.

The currently available ensembles of scenario simulations are now larger than in previous studies. Consequently, the uncertainty range covered by the assessed ESMs is larger resulting in a larger and, in turn, the spread of the results are also larger. It was shown that the uncertainty caused by ESM differences became now larger. However, the ensemble size might still be too small and the model uncertainty is very likely underestimated. Moreover, natural variability might be a more important source of uncertainty than previously considered for applications in the Baltic Sea.

In the present climate, the climate variability of the Baltic Sea region during winter is dominated by the impact of the NAO. However, during the past twentieth century, the correlation between the NAO and regional variables such as water temperature or sea ice varied in time. These low-frequency changes in correlation were projected to continue and systematic changes in the influence of the large-scale atmospheric circulation on regional climate and in the NAO itself could not be detected, although a northward shift in the mean summer position of the westerlies at the end of the twenty-first century compared to the twentieth century was reported earlier (Gröger et al., 2019). The projected changes in this correlation were projected to continue. Furthermore, systematic changes in the influence of the large-scale atmospheric circulation on regional climate and on the NAO itself could not be detected. However, a northward shift in the mean summer position of the westerlies at the end of the twenty-first century compared to the twentieth century was reported earlier (Gröger et al., 2019). This conclusion was drawn based upon a limited set of simulations with a few ESMs.

Acknowledgements

During the preparation of this paper, shortly before its submission, our co-author, Christian Dieterich, passed away (1964–2021). This sad event marked the end of the life of a distinguished oceanographer and climate scientist who made important contributions to climate modelling for the Baltic Sea, North Sea and North Atlantic regions.

This study belongs to the series of Baltic Earth Assessment Reports (BEARs) of the Baltic Earth Program (Earth System Science for the Baltic Sea Region). The work was financed by the Copernicus Marine Environment Monitoring Service through the CLIMSEA project (Regionally downscaled climate projections for the Baltic and...
North seas, CMEMS 66-SE-CALL2: LOT4) and by the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (Formas) through the ClimeMarine project within the framework of the National Research Programme for Climate (grant no, 2017-01949). Regional climate scenario simulations have been conducted on the Linux clusters Krypton, Bi, Triolith and Tetralith, all operated by the National Supercomputer Centre in Sweden (NSC, http://www.nsc.liu.se/). Resources on Triolith and Tetralith were funded by the Swedish National Infrastructure for Computing (SNIC) (grants SNIC 002/12-25, SNIC 2018/3-280 and SNIC 2019/3-356). Furthermore, we thank Berit Recklebe (Leibniz Institute for Baltic Sea Research Warnemünde, IOW) for technical support and Dr. Boris Chubarenko and Dr. Vladimir Ryabchenko for very good comments that helped to improve an earlier version of the manuscript.
Figure 1: Bottom topography of the Baltic Sea (depth in m). The Baltic proper comprises the Arkona Basin, Bornholm Basin and Gotland Basin. The border of the analyzed domain of the Baltic Sea models is shown as a black line in the northern Kattegat. In addition, the tide gauges Klagshamn (55.522°N, 12.894°E), Landsort (58.742°N, 17.865°E), Hamina (60.563°N, 27.179°E), and Kalix (65.697°N, 23.096°E) are also depicted.
Figure 2. Dynamical downscaling approach for the Baltic Sea region. In Section 2, the models for the various components of the Earth System are explained (Source: Meier et al., 2021).
Figure 3. Projections of river discharge and nutrient inputs from land and atmosphere into the entire Baltic Sea in m³ s⁻¹ using a cut-off period of 30 years of four regionalised regionalised Earth System models (ESMs; illustrated by different line types) under RCP4.5 (green) and RCP8.5 (red) scenarios. Lower panels: Bioavailable phosphorus (in 10⁶ kg P year⁻¹, left panels) and nitrogen inputs (in 10⁹ kg N year⁻¹, right panels) from land (upper panels) and the atmosphere (lower panels) under RCP4.5, BSAP (blue), RCP4.5, REF (green), RCP8.5, BSAP (orange) and RCP8.5, REF (red) scenarios. Nutrient inputs during the historical period are depicted in black. The nutrient input scenario WORST of the BalticAPP scenario simulations (Saraiva et al., 2019a; their Fig. 4) is not displayed, and neither are the ECOSUPPORT nutrient input scenarios (Gustafsson et al., 2011; their Fig. 3.1) are not displayed here. (Source: Meier et al., 2021)
Figure 4: Upper panels: Annual and seasonal mean sea surface temperature (SST in °C) in a reanalysis of data during 1970–1999 (Liu et al., 2017). Lower panels: Difference between the climatologies of the ensemble mean of the regionalized ESMs used in BalticAPP (Saraiva et al., 2019a) and CLIMSEA (Meier et al., 2021) during the historical period (1976–2005) and those of the reanalysis data. From the left to the right panels: winter (December–February, DJF), spring (March–May, MAM), summer (June–August, JJA), autumn (September–November, SON) and annual (ANN) mean SSTs or SST differences.
Figure 5: Mixed-layer thickness calculated according to the $0.03 \text{ kg m}^{-3}$ criterion following de Boyer Montégut et al. (2004). a) Reanalysis data (Liu et al., 2017). b) Ensemble mean over the four models (Saraiva et al., 2019a). Shown are the averages during 1976–1999.
Figure 6: a) Number of >10-day periods where the sea surface temperature (SST) exceeds 20°C. b) Average duration of the periods displayed in a). c) Number of 10-day periods where the SST exceeds the 95th percentile. d) Average duration of the periods displayed in c). Left column: reanalysis data (Liu et al., 2017). Right column: ensemble mean of the scenario simulations driven by four ESMs (Saraiva et al., 2019a). The analysis period is 1976–1999. Note the different colour scales used in c) and d).
Figure 7: Upper panels: Annual mean sea surface salinity (SSS) and bottom salinity (BS) (in g kg$^{-1}$) and the winter (December–February) mean sea level (SL; in cm) in the reanalysis data during 1971–1999 (Liu et al., 2017; from left to right). Note that the model results of sea level are given in the Nordic height system NH60 (Ekman and Mäkinen, 1996). Lower panels: Difference between the climatologies of the ensemble mean of the regionalised ESMs used in BalticAPP (Saraiva et al., 2019a) during the historical period (1976–2005) and those of the reanalysis data.
Figure 8: Monthly mean sea level of according to a hindcast (driven by a regionalized regionalised reanalysis of atmospheric surface fields, i.e. RCA4 driven by ERA-40; Hindcast 888), reanalysis with the data assimilation by of Liu et al. (2017) (Hindcast 888) and four climate simulations following (Saraiva et al., 2019a) (Run_A001, Run_D001), the ensemble mean and observations for the historical period 1976–2005 at the sea level stations Klagshamn, Landsort, Hamina and Kalix (for the locations, see Figure 1). The 95% confidence interval of the observations is shown as a grey shaded area.
Figure 9: Upper panels: Summer (June–August) mean bottom dissolved oxygen (DO) concentrations (in mL L$^{-1}$), winter (December–February) mean surface phosphate (PO4) concentrations (in mmol P m$^{-3}$) and winter (December–February) mean surface nitrate (NO3) concentrations (in mmol N m$^{-3}$) in the reanalysis data during 1976–1999 (Liu et al., 2017). Negative oxygen concentration equivalents denote hydrogen sulphide concentrations, with 1 mL H$_2$S L$^{-1}$ = −2 mL O$_2$ L$^{-1}$. Nutrient concentrations are vertically averaged for the upper 10 m. Lower panels: Difference between the climatologies of the ensemble mean of the ESMs (Saraiva et al., 2019a) and those of the reanalysis data during of the historical period (1976–2005).
**Figure 10:** Upper panels: Annual mean phytoplankton concentrations (CHL; in mg Chl m$^{-3}$) and annual mean Secchi depth (SD; in cm) in of the reanalysis data during for 1976–1999 (Liu et al., 2017). Phytoplankton concentrations are vertically averaged for the upper 10 m. Since for in the calculation of the Secchi depth as background only one value for the concentration of yellow substances per sub-basin is available, artificial borders between sub-basins become visible. Lower panels: Difference between the climatologies of the ensemble mean of the ESMs (Saraiva et al., 2019a) and those of the reanalysis data during for the historical period (1976–2005).
Figure 11. Changes in seasonal mean sea surface temperatures (SST) as simulated by the CLIMSEA ensemble (Meier et al., 2021). From left to right, mean SST changes (in °C) in winter (December, January and February; DJF), spring (March, April and May; MAM), summer (June, July and August; JJA) and autumn (September, October and November; SON) are shown. Mean sea surface temperature changes (in °C) between 1976–2005 and 2069–2098 under RCP4.5 (upper panels) and RCP8.5 (lower panels) are shown.
Figure 12: From left to right, changes of the mean SST (°C) in summer (June–August), the mean sea surface temperature (SST; °C), annual mean sea surface salinity (SSS; g kg⁻¹), annual mean bottom salinity (BS; g kg⁻¹ kg⁻¹), and winter (December–February) mean sea level (SL; cm) between 1978–2007 and 2069–2098 are shown.

From top to bottom, the results of the ensembles ECOSUPPORT (white background, Meier et al., 2011a, 2011b), BalticAPP RCP4.5 (grey background, Saraiva et al., 2019a) and BalticAPP RCP8.5 (grey background, Saraiva et al., 2019a) are depicted.
Figure 13: Multi-model mean (MMM) of annual (panels a, d, f, k) and seasonal (panels b, c, e, g, j, l, o) surface temperature (SST$_t$) trends (in $^\circ$C decade$^{-1}$) computed for the period 1850–2008 (top), 2006–2099 in RCP4.5 (middle) and RCP8.5 (bottom) scenario. Hatched areas represent the regions where the trend is statistically significant (p-value < 0.05, Mann-Kendall test). Data sources for historical reconstructions and projections are from Meier et al. (2019d) and Saraiva et al. (2019a), respectively.
Figure 14: Multi-model mean (MMM) of the annual sea-surface temperature (SST) trends relative to the spatial average (in °C decade$^{-1}$) for a) RCP4.5 and b) RCP8.5 scenario simulations. (Data source: Saraiva et al., 2019a)
Figure 15: Multi-model mean (MMM) explained variance (in percent) between the monthly mean sea surface temperature SST and the forcing air temperature over the period 2006–2099 in the a) RCP4.5 and b) RCP8.5 scenario simulations. (Data source: Saraiva et al., 2019a)
Figure 16: Results of the cross-correlation analysis of the detrended sea surface temperature (SST) (monthly mean) with the wind components, latent heat flux, and cloudiness. Maps of the atmospheric drivers with the highest cross-correlations in the RCP4.5 (top) and RCP8.5 (bottom) scenarios for various GCM forcings (Saraiva et al., 2019a). From left to right: MPI-ESM-LR, EC-EARTH, IPSL-CM5A-MR, HadGEM2-ES.
Figure 17. Mixed-layer depth calculated after according to the $0.03 \text{ kg m}^{-3}$ criterion of de Boyer Montégut et al. (2004). Shown are the ensemble average changes of four different ESMs between 1976–2005 and 2069–2098 with the mean sea-level rises a) 0.90 m (RCP8.5) and b) 0.54 m (RCP4.5). (Data source: Meier et al., 2021)
Figure 18. a) Number of heat waves (defined as the number of periods in which the water temperature is ≥ 20°C) for historical (1976–2005), and future (2069–2098) climates. b) Average duration of the heat waves. Note that no temperature bias adjustment was done prior to the analysis. Shown are the ensemble averages of four different ESMs with the mean sea level rises a) 0.54 m (RCP4.5) and b) 0.90 m (RCP8.5). (Data source: Meier et al., 2021)
Figure 19. Same as in Figure 18 but for heat waves defined as periods of $\geq 10$ days during which the water temperature exceeded the 95th percentile of the historical reference temperature. (Data source: Meier et al., 2021)
Figure 20: Monthly mean sea level changes between 1976–2005 and 2069–2098 at Klagshamn, Landsort, Hamina and Kalix and Kattegat (for the locations, see Figure 1) for RCP4.5 (left panel) and RCP8.5 (right panel). Shown are the changes relative to the mean sea level rise a) 0.54 m (RCP4.5) and b) 0.90 m (RCP8.5). Shaded areas in white to dark grey denote +/- two standard deviations at Klagshamn to Kalix respectively. The chosen model approach does not indicate any non-linear effects for scenarios with a larger sea level rise in sea level scenarios. (Data source: Meier et al., 2021)
Figure 21: a) Ensemble mean changes in the summer (June–August) bottom dissolved oxygen concentration (mL L$^{-1}$) in summer (June–August) between 1978–2007 and 2069–2098. From left to right, the results of the nutrient input scenarios of the Baltic Sea Action Plan (BSAP), Reference (REF) and Business-As-Usual (BAU) are shown. From top to bottom, the results of the ensembles ECOSUPPORT (white background; Meier et al., 2011a, 2011b), BalticAPP RCP4.5 (grey background; Saraiva et al., 2019a) and BalticAPP RCP8.5 (grey background; Saraiva et al., 2019a) are depicted. b) As in panel a) but for CLIMSEA RCP4.5 (upper panels) and CLIMSEA RCP8.5 (lower panels) under the high SLR-sea level rise scenario, i.e., 1.26 m (RCP4.5) and 2.34 m (RCP8.5). Left and right columns show the BSAP and REF scenarios, respectively. (Source: Meier et al., 2021)
Figure 22: From top to bottom: hypoxic area (in km²), volume-averaged primary production (in kg C year⁻¹) and volume-averaged nitrogen fixation (in kg N year⁻¹) for the entire Baltic Sea, including the Kattegat (see Figure 1) in the historical (until 2005, black lines) and scenario simulations (after 2005, coloured lines) simulations driven by four regionalised ESMs (illustrated by different line types) under RCP4.5, BSAP (blue), RCP4.5, REF (green), RCP8.5, BSAP (orange) and RCP8.5, REF (red) scenarios. A spin-up simulation since 1850 was performed, as illustrated by the evolution of hypoxia. (Source: Meier et al., 2021)
Figure 23: As in Figure 21a but for annual mean surface phytoplankton concentration changes (mg Chl m\(^{-3}\)). Concentrations are vertically averaged for the upper 10 m. (Source: Meier et al., 2011a, 2011b; Saraiva et al., 2019a)
Figure 24. As in Fig. 21a but for changes in the annual mean Secchi depth change (m). (Source: Meier et al., 2011a, 2011b; Saraiva et al., 2019a)
Figure 25. Ensemble 10-year running mean North Atlantic Oscillation (NAO) index (upper panels) and 10-year running correlation between the NAO and area averaged sea surface temperature (SST) in the Baltic Sea (lower panels) under RCP4.5 (left panels) and RCP8.5 (right panels) scenarios. Depicted are winter (December - February) mean, median, minimum, maximum and 15th and 85th percentiles. (Data source: Meier et al., 2021)
### Table 1. Selected ensembles of the scenario simulations for the Baltic Sea carried out in international projects

| Project summaries | Acronym | GCM | RCSM | Ocean model | Period(s) | Ocean model |
|-------------------|---------|-----|------|-------------|-----------|-------------|
| Swedish Regional Climate Modeling/Modelling Program | SWECLIM | AR3 | RCA4 | One physical Baltic Sea model | 1961–1990 and 2071–2100 | One physical biogeochemical Baltic Sea model |
| | ECOSUPPORT | AR4 | RCAO | Three physical-biogeochemical Baltic Sea models | 1961–2099 and 950–1800 AD | See ECOSUPPORT, Schimanke and Meier, 2016 |
| | INFLOW | AR4 | RCAO | Three physical-biogeochemical Baltic Sea models including the carbon cycle | 1960–2100 | See INFLOW, Omstedt et al., 2012 |
| | Baltic-C | AR4 | RCA | One physical-biogeochemical Baltic Sea model | 1976–2100, improved initial conditions | One physical-biogeochemical Baltic Sea model including focus on the Baltic Sea and North Sea regions and one physical-biogeochemical ocean model |
| | BalticAPP | AR4 | RCA4-NEMO | Two physical regional models | 1961–2099 | Two physical regional models with focus on the Baltic Sea and North Sea regions and one physical-biogeochemical ocean model |
| | KLIWAS | AR4 | REMO-MPIOM, REMO-HAMSOM, RCA4-NEMO | One physical-biogeochemical Baltic Sea model | 1976–2100 | One physical-biogeochemical Baltic Sea model |
| | CLIMHEA | AR4 | RCA4-NEMO | | | |

Table 1.

| Formatiert: Deutsch (Deutschland) | Formatiert: Schwedisch (Schweden) | Formatiert: Englisch (Großbritannien) |
|-----------------------------------|-----------------------------------|-----------------------------------|
Table 2. Salinity projections assessed by the BACC Author Team (2008), BACC II Author Team (2015) and BEAR (this study). Salinity changes depend on the changes in the wind field (in particular, the west wind component), river discharge and sea-level rise (SLR).

|                | West wind    | River discharge (%) | Sea-level rise SLR | Salinity              |
|----------------|--------------|---------------------|-------------------|-----------------------|
| BACC (2008)    | Large increase | -8 to +26%          | 0                 | 0 to −3.7 g kg⁻¹     |
| BACC II (2015) | Small increase | +15 to +22%         | 0                 | −1 to −2 g kg⁻¹      |
| BEAR (this study) | No significant change | +2 to +23%       | Medium SLR +0.54 to +0.90 m | No robust change, with a considerable spread |
Table 3. List of scenario simulations of three ensembles. From left to right, the columns show the Earth System Model (ESM), the Regional Climate System Model (RCSM), the Baltic Sea Ecosystem Model, the greenhouse gas (GHG) emission or concentration scenario, the nutrient input scenario, the sea-level rise (SLR) scenario and the simulation period, including historical and scenario periods. The four nutrient input scenarios were Baltic Sea Action Plan (BSAP), Reference (REF), Business-As-Usual (BAU) and Worst Case (WORST) scenario. For the three SLR scenarios in the CLIMSEA ensemble, the mean sea level changes at the end of the century are given in meters.

ECOSUPPORT (28 scenario simulations, Meier et al., 2011a, 2011b)

| ESM          | RCSM     | Baltic Sea Model | GHG scenario | Nutrient input scenario | SLR scenario | Period    |
|--------------|----------|-------------------|--------------|-------------------------|--------------|-----------|
| HadCM3       | RCAO     | BALTSEM           | A1B          | BSAP/REF/BAU            | 0            | 1961–2099 |
| ECHAM5-MPI-OM-1 | RCAO    | BALTSEM           | A1B          | BSAP/REF/BAU            | 0            | 1961–2099 |
| ECHAM5-MPI-OM-3 | RCAO    | BALTSEM           | A1B          | BSAP/REF/BAU            | 0            | 1961–2099 |
| ECHAM5-MPI-OM-1 | RCAO    | BALTSEM           | A2           | BSAP/REF/BAU            | 0            | 1961–2099 |
| HadCM3       | RCAO     | MOM-Ergom         | A1B          | BSAP/REF                | 0            | 1961–2099 |
| ECHAM5-MPI-OM-1 | RCAO    | MOM-Ergom         | A1B          | BSAP/REF                | 0            | 1961–2099 |
| HadCM3       | RCAO     | RCO-SCOBI         | A1B          | BSAP/REF/BAU            | 0            | 1961–2099 |
| ECHAM5-MPI-OM-1 | RCAO    | RCO-SCOBI         | A1B          | BSAP/REF/BAU            | 0            | 1961–2099 |
| ECHAM5-MPI-OM-3 | RCAO    | RCO-SCOBI         | A1B          | BSAP/REF/BAU            | 0            | 1961–2099 |
| ECHAM5-MPI-OM-1 | RCAO    | RCO-SCOBI         | A2           | BSAP/REF/BAU            | 0            | 1961–2099 |

BalticAPP (21 scenario simulations, Saraiva et al., 2019a)

| ESM          | RCSM     | Baltic Sea Model | GHG scenario | Nutrient input scenario | SLR scenario | Period    |
|--------------|----------|-------------------|--------------|-------------------------|--------------|-----------|
| MPI-ESM-LR   | RCA4-NEMO | RCO-SCOBI      | RCP4.5       | BSAP/REF/WORST          | 0            | 1976–2099 |
| MPI-ESM-LR   | RCA4-NEMO | RCO-SCOBI      | RCP8.5       | BSAP/REF/WORST          | 0            | 1976–2099 |
| Model | Scenario | Climate Model | GCM | RCP | BSAP/REF/WORST | Start | End |
|-------|----------|---------------|------|-----|----------------|-------|-----|
| EC-EARTH | RCA4-NEMO | RCO-SCOBI | RCP4.5 | BSAP/REF/WORST | 0 | 1976-2099 |
| EC-EARTH | RCA4-NEMO | RCO-SCOBI | RCP8.5 | BSAP/REF/WORST | 0 | 1976-2099 |
| IPSL-CM5A-MR | RCA4-NEMO | RCO-SCOBI | RCP4.5 | BSAP/REF/WORST | 0 | 1976-2099 |
| HadGEM2-ES | RCA4-NEMO | RCO-SCOBI | RCP4.5 | BSAP/REF/WORST | 0 | 1976-2099 |
| HadGEM2-ES | RCA4-NEMO | RCO-SCOBI | RCP8.5 | BSAP/REF/WORST | 0 | 1976-2099 |
| CLIMSEA (48 scenario simulations, Meier et al., 2021) |
| MPI-ESM-LR | RCA4-NEMO | RCO-SCOBI | RCP4.5 | BSAP/REF | 0.00/0.54/1.26 | 1976-2099 |
| MPI-ESM-LR | RCA4-NEMO | RCO-SCOBI | RCP8.5 | BSAP/REF | 0.00/0.90/2.34 | 1976-2099 |
| EC-EARTH | RCA4-NEMO | RCO-SCOBI | RCP4.5 | BSAP/REF | 0.00/0.54/1.26 | 1976-2099 |
| EC-EARTH | RCA4-NEMO | RCO-SCOBI | RCP8.5 | BSAP/REF | 0.00/0.90/2.34 | 1976-2099 |
| IPSL-CM5A-MR | RCA4-NEMO | RCO-SCOBI | RCP4.5 | BSAP/REF | 0.00/0.54/1.26 | 1976-2099 |
| IPSL-CM5A-MR | RCA4-NEMO | RCO-SCOBI | RCP8.5 | BSAP/REF | 0.00/0.90/2.34 | 1976-2099 |
| HadGEM2-ES | RCA4-NEMO | RCO-SCOBI | RCP4.5 | BSAP/REF | 0.00/0.54/1.26 | 1976-2099 |
| HadGEM2-ES | RCA4-NEMO | RCO-SCOBI | RCP8.5 | BSAP/REF | 0.00/0.90/2.34 | 1976-2099 |
**Table 4:** Summary of the characteristics of the ECOSUPPORT, BalticAPP and CLIMSEA scenario simulations discussed in this study. For further details, the reader is referred to Tables 1 and 3. Acronyms are explained defined in Table 5.

| Acronym | Atmospheric forcing | GHG emission or concentration scenario | Hydrological forcing | Nutrient input scenario | Special features |
|---------|---------------------|---------------------------------------|----------------------|------------------------|------------------|
| ECOSUPPORT | Regionalized CMIP3 data, two GCMs | SRES A1B, A2 | STAT | BSAP, REF, BAU | Three Baltic Sea models |
| BalticAPP | Regionalized CMIP5 data, four ESMs | RCP4.5, 8.5 | E-HYPE | Revised scenarios BSAP, REF, WORST | Four ESMs |
| CLIMSEA | Regionalized CMIP5 data, four ESMs | RCP4.5, 8.5 | E-HYPE | Revised scenarios BSAP, REF | SLR is considered |
| Acronym | Explanation/Definition | Comment | Reference |
|---------|------------------------|---------|-----------|
| AMO     | Atlantic Multidecadal Oscillation | Mode of climate variability | Knight et al. (2005) |
| BACC    | Assessment of climate change for the Baltic Sea basin | Regional climate change assessment | BACC Author Team (2008), BACC II Author Team (2015) |
| BalticAPP | Well-being from the Baltic Sea - applications combining natural science and economics | Climate modelling project for the Baltic Sea | Saraiva et al. (2019a) |
| BEAR    | Baltic Earth assessment reports | Regional climate change assessment | https://baltic.earth |
| BSAP    | Baltic Sea Action Plan | Nutrient load abatement strategy for the Baltic Sea | HELCOM (2013b) |
| BSAP, REF, BAU, WORST | Baltic Sea Action Plan, Reference, Business-As-Usual and WORST | Nutrient load scenarios | Meier et al. (2012a), Saraiva et al. (2019b) |
| CLC     | Cyanobacteria Life Cycle Model | Advanced biogeochemical model including a cyanobacteria life cycle | Hense and Beckmann (2006, 2010) |
| CLIMSEA | Regionally downscaled climate projections for the Baltic and North Seas | Climate modelling project for the Baltic Sea | Meier et al. (2021) |
| CMIP    | Coupled Model Intercomparison Project of the World Climate Research Programme (WCRP) | In this study, GCM/ESM results from CMIP3 and CMIP5 were assessed | https://www.wcrp-climate.org/wgcm-cmip |
| EC-EARTH | European Countries Earth System Model | ESM, CMIP5 | https://www.knmi.nl/home |
| ECHAMS  | Max Planck Institute Global Climate Model | GCM, CMIP5 | Roeckner et al. (2006), Jungclaus et al. (2006) |
| ECOSUPPORT | Advanced modelling tool for scenarios of the Baltic Sea ECOxstem to SUPPORT decision making | Climate modelling project for the Baltic Sea | Meier et al. (2014) |
| E-HYPE  | Hydrological Predictions For The Environment applied for Europe | Process-based multi-basin model for the land surface | https://hypeweb.smhi.se/ |
| Acronym | Description | Notes |
|---------|-------------|-------|
| ERA-40 | 40-year reanalysis of the European Centre for Medium Range Weather Forecast | Reanalysis data used, e.g. for instance as atmospheric forcing for ocean models (Uppala et al. 2005) |
| ESM | Earth System Model | Model applied for global climate simulations including the carbon cycle (Heavens et al. 2013) |
| EURO-CORDEX | Coordinated Downscaling Experiment—European Domain | High-resolution climate change projections for European impact research (Jacob et al. 2014) |
| GCM | General Circulation Model | Model applied for global climate simulations (Meckel et al. 2004) |
| GHG | Greenhouse gas | Emission or concentration scenarios (Nakićenović et al. 2000; Moss et al. 2010; van Vuuren et al. 2011) |
| HadCM3 | Hadley Centre Global Climate Model | GCM, CMIP3 (Gordon et al. 2000) |
| HadGEM2-ES | Hadley Centre Global Environment Model version 2—Earth System | ESM, CMIP5 (http://www.metoffice.gov.uk) |
| HELCOM | Helsinki Commission | Consists of the Baltic Sea countries and the European Union (https://helcom.fi) |
| IOW | Leibniz Institute for Baltic Sea Research Warnemünde | German research institute (http://io-warnemuende.de) |
| IPCC | Intergovernmental Panel of Climate Change | Generated assessment reports (AR) of past and future changes in 1990, 1995, 2001, 2008, 2013 inter alia based upon CMIP results (http://www.ipcc.ch) |
| IPSL-CM5A-MR | Institut Pierre Simon Laplace Climate Model—Medium Resolution | ESM, CMIP5 (http://ecm.ipsl.fr/) |
| MPI-ESM-LR | Max Planck Institute Earth System Model—Low Resolution | ESM, CMIP5 (https://www.mpimet.mpg.de) |
| NAO | North Atlantic Oscillation | Mode of climate variability (Hurrel 1995) |
| NOSCA | North Sea Region Climate Change Assessment Report | Regional climate change assessment (Quante and Colijn 2016) |
| RCA3 | Rossby Centre Atmosphere Model version 3 | Regional climate model (Samuelsson et al. 2011) |
| **RCA4-NEMO** | Rossby Centre Atmosphere model Version 4: Nucleus for European Modelling of the Ocean | Coupled atmosphere-ocean model applied to the Baltic Sea and North Sea | Dieterich et al. (2013), Wang et al. (2015), Kupiainen et al. (2014), Madec (2016) |
| **RCAO** | Rossby Centre Atmosphere Ocean Model | Regional climate model | Döscher et al. (2002) |
| **RCM** | Regional Climate Model | Regional atmosphere or coupled atmosphere-ocean model applied to the dynamical downscaling of a changing climate | Giorgi (1990), Rummukainen (2010, 2016a), Rummukainen et al. (2015), Feser et al. (2011), Rockel (2015), Schrum (2017) |
| **RCO-SCOBI, BALTSEM, MOM-ERGOM** | Model abbreviations | Coupled physical, biogeochemical models for the Baltic Sea | Meier et al. (2018a), their Tables 1 and 2 and references therein |
| **RCP** | Representative Concentration Pathway | Greenhouse gas concentration scenario | Moss et al. (2010), van Vuuren et al. (2011) |
| **RCSM** | Regional Climate System Model | Regional coupled atmosphere–sea ice–ocean–wave–land surface–atmospheric chemistry–marine ecosystem model | Giorgi and Gao (2018) |
| **SRES** | Special Report on Emission Scenarios | Described greenhouse gas emission scenarios, e.g. A1B, A2 | Nakicenović et al. (2000) |
| **STAT** | Hydrological model | Statistical model for river runoff calculated from precipitation and evaporation over land | Meier et al. (2012a) |
Table 6. Projected ensemble mean changes in (total land and atmosphere) bioavailable annual phosphorus ($\Delta P$) and nitrogen ($\Delta N$) inputs (in ktons) into the Baltic Sea between historical (1980–2005) and future (2072–2097) climates under the scenarios REF and BSAP (in ktons). (Source: Meier et al., 2018a; their Fig. 3).

| Nutrient input scenario | REF $\Delta P$ | REF $\Delta N$ | BSAP $\Delta P$ | BSAP $\Delta N$ |
|-------------------------|----------------|----------------|------------------|-----------------|
| ECOSUPPORT BALTSEM      | $+2$           | $-17$          | $-15$            | $-208$          |
| ECOSUPPORT MOM-ERGOM    | $+4$           | $-13$          | $-8$             | $-180$          |
| ECOSUPPORT RCO-SCOB1     | $+4$           | $+22$          | $-11$            | $-240$          |
| BalticAPP/CLIMSEA RCO-SCOB1 (RCP4.5) | $-18$ | $-129$ | $-34$ | $-269$ |
Table 7. Ensemble mean changes in sea surface temperature (SST; in °C) in the ECOSUPPORT, BalticAPP RCP4.5, BalticAPP RCP8.5, CLIMSEA RCP4.5 and CLIMSEA RCP8.5 scenario simulations averaged for the Baltic Sea including the Kattegat (data sources: Meier et al., 2011a, 2011b, 2021; Saraiva et al., 2019a). (DJF = December, January, February, MAM = March, April, May, JJA = June, July, August, SON = September, October, November)

| Δ SST          | Winter (DJF) | Spring (MAM) | Summer (JJA) | Autumn (SON) | Annual mean |
|---------------|--------------|--------------|--------------|--------------|-------------|
| ECOSPPORT SRES A1B | -2.5         | +2.8         | +2.8         | +2.5         | +2.6        |
| BalticAPP RCP4.5 | +1.7         | +1.9         | +2.0         | +1.8         | +1.8        |
| BalticAPP RCP8.5 | +2.9         | +3.2         | +3.3         | +3.0         | +3.1        |
| CLIMSEA RCP4.5  | +1.7         | +1.9         | +2.0         | +1.9         | +1.9        |
| CLIMSEA RCP8.5  | +2.8         | +3.0         | +3.0         | +2.9         | +2.9        |
| Annual/winter changes | ECOSUPPORT A1B/A2 | BalticAPP RCP4.5 | BalticAPP RCP8.5 | CLIMSEA RCP4.5 mean | CLIMSEA RCP4.5 high | CLIMSEA RCP8.5 mean | CLIMSEA RCP8.5 high |
|-----------------------|------------------|------------------|------------------|---------------------|---------------------|---------------------|---------------------|
| Δ SSS                 | −1.5             | −0.7             | −0.6             | −0.3                | +0.2                | −0.2                | +0.6                |
| Δ BS                  | −1.6             | −0.6             | −0.6             | −0.0                | +0.6                | −0.0                | +1.1                |
| Δ SL                  | +5.5             | +0.4             | +3.7             | +0.2                | +0.1                | +3.4                | +3.2                |

Table 8. Ensemble mean changes in annual mean sea surface salinity (SSS; in g kg$^{-1}$), annual mean bottom salinity (BS; in g kg$^{-1}$) and winter mean sea level (SL) relative to the global mean sea level (SL) (in cm) in ECOSUPPORT, BalticAPP RCP4.5, BalticAPP RCP8.5, CLIMSEA RCP4.5 and CLIMSEA RCP8.5 scenario simulations averaged for the Baltic Sea including the Kattegat. For CLIMSEA, both the ensemble mean and the high sea level scenarios are listed. In ECOSUPPORT and BalticAPP/CLIMSEA, the changes between 1978–2007 and 2069–2098 and between 1976–2005 and 2069–2098 were calculated, respectively. (Data sources: Meier et al., 2011a, 2011b; Saraiva et al., 2019a)
Table 9. Salinity changes averaged for the Baltic Sea in 1988–2007 relative to 1850 as a function of sea-level rise (SLR). In the reference simulation, the mean salinity amounts to 7.42 g kg\(^{-1}\). In method 1, the increase in the water level was added to the first vertical grid box of the RCO-SCOBI model, while in method 2 the increase in the water level was evenly divided between the first and second grid boxes.

| SLR (in m) | -0.24 | -0.5 | +1.0 | +1.5 (method 1) | +1.5 (method 2) |
|------------|-------|------|------|----------------|----------------|
| Salinity (in g kg\(^{-1}\)) | -0.35 | -0.71 | +1.41 | +2.10 | +2.03 |

Table 10. As in Table 8, but showing the ensemble mean changes in the summer mean bottom oxygen concentration (in mL L\(^{-1}\)) in ECOSUPPORT, BalticAPP RCP4.5, BalticAPP RCP8.5, CLIMSEA RCP4.5 and CLIMSEA RCP8.5 scenario simulations averaged for the Baltic Sea including the Kattegat. The project of changes depend on the nutrient input scenario: Baltic Sea Action Plan (BSAP), Reference (REF), Business-As-Usual (BAU) or Worst Case (WORST). (Data sources: Meier et al., 2011a,b, 2021; Saraiva et al., 2019a)

| Summer changes | ECOSUPPORT A1B/A2 | BalticAPP RCP4.5 | BalticAPP RCP8.5 | CLIMSEA RCP4.5 mean | CLIMSEA RCP4.5 high | CLIMSEA RCP8.5 mean | CLIMSEA RCP8.5 high |
|----------------|-------------------|------------------|------------------|---------------------|--------------------|--------------------|--------------------|
| BSAP           | -0.1              | +0.6             | +0.5             | +0.6                | +0.5               | +0.4               | +0.3               |
| REF            | -0.6              | +0.1             | -0.2             | +0.0                | -0.1               | -0.2               | -0.4               |
| BAU/WORST      | -1.1              | -0.1             | -0.5             | -0.5                | -0.5               | -0.5               | -0.5               |
| WORST          | -                | -0.1             | -0.5             | -0.5                | -0.5               | -0.5               | -0.5               |
As in Table 8, but showing the ensemble mean changes in the annual Secchi depth (in m) in the ECOSUPPORT, BalticAPP RCP4.5, BalticAPP RCP8.5, CLIMSEA RCP4.5 and CLIMSEA RCP8.5 scenario simulations averaged for the Baltic Sea including the Kattegat. The project ed changes depend on the nutrient input scenario, Baltic Sea Action Plan (BSAP), Reference (REF), and Business As Usual (BAU) or Worst Case (WORST) (Data sources: Meier et al., 2011a, 2011b, 2021; Saraiva et al., 2019a).

| Annual changes | ECOSUPPORT A1B/A2 | BalticAPP RCP4.5 | BalticAPP RCP8.5 | CLIMSEA RCP4.5 mean | CLIMSEA RCP4.5 high | CLIMSEA RCP8.5 mean | CLIMSEA RCP8.5 high |
|----------------|--------------------|------------------|------------------|---------------------|---------------------|---------------------|---------------------|
| BSAP           | -0.3               | +0.6             | +0.5             | +0.6                | +0.6                | +0.6                | +0.6                |
| REF            | -0.6               | +0.2             | -0.1             | +0.2                | +0.1                | +0.1                |                     |
| BAU/WORST      | -0.1               |                 |                  |                     |                     |                     |                     |
| WORST          | -0.1               |                 |                  |                     |                     |                     |                     |

References

Almroth-Rosell, E., Eilola, K., Hordoir, R., Meier, H. E. M., and Hall, P. O. J.: Transport of fresh and resuspended particulate organic material in the Baltic Sea - a model study, J. Mar. Syst., 87, 1-12, https://doi.org/10.1016/j.jmarsys.2011.02.005, 2011.

Almroth-Rosell, E., Eilola, K., Kuznetsov, I., Hall, P. O. J., and Meier, H. E. M.: A new approach to model oxygen dependent benthic phosphate fluxes in the Baltic Sea, J. Mar. Syst., 144, 127-141, https://doi.org/10.1016/j.jmarsys.2014.11.007, 2015.

Arheimer, B., Dahne, J., and Donnelly, C.: Climate change impact on riverine nutrient load and land-based remedial measures of the Baltic Sea Action Plan, Ambio, 41, 600-612, https://doi.org/10.1007/s13280-012-0323-0, 2012.

Bacc Author Team: Assessment of climate change for the Baltic Sea basin, Regional Climate Studies, Springer Science & Business Media, Berlin, Heidelberg, 473 pp., 2008.

BACC II Author Team: Second Assessment of Climate Change for the Baltic Sea Basin, Regional Climate Studies, Springer International Publishing, Cham, 2015.

Baltic Earth – Earth System Science for the Baltic Sea Region: https://www.baltic-earth.org, access: 13-10-2021.

Bamber, J. L., Oppenheimer, M., Kopp, R. E., Aspinall, W. P., and Cooke, R. M.: Ice sheet contributions to future sea-level rise from structured expert judgment, P. Natl. Acad. Sci. USA, 116, 11195, https://doi.org/10.1073/pnas.1817205116, 2019.

Bauer, B., Gustafsson, B. G., Hyttinen, K., Meier, H. E. M., Müller-Karulis, B., Saraiva, S., and Tomczak, M. T.: Food web and fisheries in the future Baltic Sea, Ambio, https://doi.org/10.1007/s13280-019-01229-3, 2019.

Belkin, I. M.: Rapid warming of large marine ecosystems, Prog. Oceanogr., 81, 207-213, https://doi.org/10.1016/j.pocean.2009.04.011, 2009.

Bergström, S., and Carlsson, B.: River runoff to the Baltic Sea – 1950-1990, Ambio, 23, 280-287, 1994.
Börgel, F., Frauen, C., Neumann, T., Schimanke, S., and Meier, H. E. M.: Impact of the Atlantic Multidecadal Oscillation on Baltic Sea Variability, Geophys. Res. Lett., 45, 9880-9888, https://doi.org/10.1029/2018GL078943, 2018.

Börgel, F., Frauen, C., Neumann, T., and Meier, H. E. M.: The Atlantic Multidecadal Oscillation controls the impact of the North Atlantic Oscillation on North European climate, Environ. Res. Lett., https://doi.org/10.1088/1748-9326/ab9025, 2020.

Bülow, K., Dietrich, C., Elizalde, A., Gröger, M., Heinrich, H., Hüttl-Kabos, S., Klein, B., Mayer, B., Meier, H. E. M., and Mikolajewicz, U.: Comparison of three regional coupled ocean atmosphere models for the North Sea under today's and future climate conditions (KLIWAS Schriftenreihe; KLIWAS-27/2014), Bundesanstalt für Gewässerkunde, 2014.

Christensen, J., Andersen, J. H., Gustafsson, B. G., and Conley, D. J.: Deoxygenation of the Baltic Sea during the last century, P. Natl. Acad. Sci. USA, 111, 5628-5633, https://doi.org/10.1073/pnas.1323156111, 2014.

Christensen, O. B., Kjellström, E., Dieterich, C., Gröger, M., and Meier, H. E. M.: Atmospheric regional climate projections for the Baltic Sea Region until 2100, Earth Syst. Dynam., 2021.

Church, J. A., Clark, P. U., Cazenave, A., Gregory, J. M., Jevrejeva, S., Levermann, A., Merrifield, M. A., Milne, G. A., Nerem, R. S., Nunn, P. D., Payne, A. J., Pfeffer, W. T., Stammer, D., and Unnikrishnan, A. S.: Sea Level Change, in: Climate Change 2013 – The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, Cambridge, UK, New York, USA, 1137-1216, https://doi.org/10.1017/CBO9781107415324, 2013.

de Boyer Montégut, C., Madec, G., Fischer, A. S., Lazar, A., and Iudicone, D.: Mixed layer depth over the global ocean: An examination of profile data and a profile-based climatology, J. Geophys. Res-Oceans, 109, https://doi.org/10.1029/2004jc002378, 2004.

Donnelly, C., Arheimer, B., Capell, R., Dahne, J., and Strömqvist, J.: Regional overview of nutrient load in Europe—challenges when using a large-scale model approach, E-HYPE, Proceedings of the H04, IAHS-IAPSO-IASPEI Assembly, 4, 49-58, 2013.

Donnelly, C., Gremli, W., Andersson, J., Gerten, D., Piscanec, G., Roudier, P., and Ludwig, F.: Impacts of climate change on European hydrology at 1.5, 2 and 3 degrees mean global warming above preindustrial level, Clim. Change, 143, 13-26, https://doi.org/10.1007/s10584-017-1971-7, 2017.

Dösscher, R., Meier, H. E. M.: Simulated sea surface temperature and heat fluxes in different climates of the Baltic Sea, Ambio, 33, 242-248, https://doi.org/10.1579/0044-7447-33.4.242, 2004.

Ehrnström, E., Norkko, A., Müller-Karulis, B., Gustafsson, E., and Gustafsson, B. G.: The meagre future of benthic fauna in a coastal sea—Benthic responses to recovery from eutrophication in a changing climate, Global Change Biol., 26, 2235-2250, https://doi.org/10.1111/gcb.15014, 2020.
Grinsted, A.: Projected Change - Sea Level, in: Second Assessment of Climate Change for the Baltic Sea Basin, edited by: BACC II Author Team, Regional Climate Studies, Springer International Publishing, Cham, 253-263, https://doi.org/10.1007/978-3-319-16006-1_14, 2015.

Gröger, M., Dieterich, C., Meier, H. E. M., and Schimanke, S.: Thermal air-sea coupling in hindcast simulations for the North Sea and Baltic Sea on the NW European shelf. Tellus A, 67, 26911, 2015.

Gröger, M., Arneborg, L., Dieterich, C., Höglund, A., and Meier, H. E. M.: Summer hydrographic changes in the Baltic Sea, Kattegat and Skagerrak projected in an ensemble of climate scenarios downscaled with a coupled regional ocean–sea ice–atmosphere model. Clim. Dyn., https://doi.org/10.1007/s00382-019-04908-9, 2019.

Gröger, M., Dieterich, C., Ho-Hagemann, H. T. M., Hagemann, S., Jakacki, J., May, W., Meier, H. E. M., Miller, P. A., Rutgersson, A., and Wu, L.: Coupled regional Earth system modelling in the Baltic Sea region, Earth Syst. Dyn. Discuss., 1-50, https://doi.org/10.5194/esd-2021-14, 2021a.

Gröger, M., Dieterich, C., and Meier, H. E. M.: Is interactive air sea coupling relevant for simulating the future climate of Europe?, Clim. Dyn., 56, 491-514, https://doi.org/10.1007/s00382-020-05489-8, 2021b.

Gustafsson, B. G., Savchuk, O. P., and Meier, H. E. M.: Load scenarios for ECOSUPPORT, Technical Report No. 4, Baltic Nest Institute, Stockholm, Sweden, 18, 2011.

Gustafsson, B. G., Schenck, F., Blenckner, T., Eilola, K., Meier, H. E. M., Müller-Karulis, B., Neumann, T., Ruoho-Airola, T., Savchuk, O. P., and Zorita, E.: Reconstructing the development of Baltic Sea eutrophication 1850-2006, Ambio, 41, 534-548, https://doi.org/10.1007/s13280-012-0318-x, 2012.

Haapala, J., Meier, H. E. M., and Rinne, J.: Numerical investigations of future ice conditions in the Baltic Sea, Ambio, 30, 237-244, https://doi.org/10.1579/0044-7447-30.4.237, 2001.

Heavens, N. G., Ward, D. S., and Natalie, M. J.: Studying and projecting climate change with earth system models, Nature Education Knowledge, 4, 4, 2013.

HELCOM: Towards a Baltic Sea unaffected by eutrophication - HELCOM Overview 2007, Krakow, Poland, HELCOM Ministerial Meeting, 35, 2007.

HELCOM: Approaches and methods for eutrophication target setting in the Baltic Sea region, Helsinki, Finland, Baltic Sea Environment Proceedings No. 133, 138pp, 2013.

HELCOM: HELCOM Copenhagen Ministerial Declaration - Taking Further Action to Implement the Baltic Sea Action Plan - Reaching Good Environmental Status for a healthy Baltic Sea, Copenhagen, Denmark, HELCOM Ministerial Meeting, 2014.

HELCOM: State of the Baltic Sea - Second HELCOM holistic assessment 2011-2016, Helsinki, Finland, Baltic Sea Environment Proceedings No. 155, 155pp, 2018.

HELCOM – Baltic Marine Environment Protection Commission: https://helcom.fi/, access: 13-10-2021.

Hense, I., and Beckmann, A.: Towards a model of cyanobacteria life cycle—effects of growing and resting stages on bloom formation of N2-fixing species, Ecol. Model., 195, 205-218, https://doi.org/10.1016/j.ecolmodel.2005.11.018, 2006.

Hense, I., and Beckmann, A.: The representation of cyanobacteria life cycle processes in aquatic ecosystem models, Ecol. Model., 221, 2330-2338, https://doi.org/10.1016/j.ecolmodel.2010.06.014, 2010.

Hieronymus, J., Eilola, K., Olafsson, M., Hense, L, Meier, H. E. M., and Almroth-Rosell, E.: Modeling cyanobacteria life cycle dynamics and historical nitrogen fixation in the Baltic Sea, Biogeosciences Discuss., 2021, 1-27, https://doi.org/10.5194/bg-2021-156, 2021.

Hieronymus, M., and Kalén, O.: Sea-level rise projections for Sweden based on the new IPCC special report: The ocean and cryosphere in a changing climate, Ambio, https://doi.org/10.1007/s13280-019-01313-8, 2020.
Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O. B., Bouwer, L. M., Braun, A., Colette, A., Déqué, M., Georgievski, G., and others: EURO-CORDEX: new high-resolution climate change projections for European impact research. Reg. Environ. Change, 14, 563-578, https://doi.org/10.1007/s10113-013-0499-2, 2014.

Janneclauss, J. H., Koenlive, N., Botzel, M., Haak, H., Luo, J.-J., Latif, M., Marotzke, J., Mikołajewicz, U., and Rosecker, E.: Ocean circulation and tropical variability in the coupled model ECHAM5/MPI-OM. J. Climate, 19, 3953-3972, https://doi.org/10.1175/JCLI3827.1, 2006.

Jutterström, S., Andersson, H. C., Omstedt, A., and Malmaeus, J. M.: Multiple stressors threatening the future of the Baltic Sea - Kattegat marine ecosystem: Implications for policy and management actions, Mar. Pollut. Bull., 86, 468-480, https://doi.org/10.1016/j.marpolbul.2014.06.027, 2014.

Kniebusch, M., Meier, H. E. M., Neumann, T., and Borgel, F.: Temperature Variability of the Baltic Sea Since 1850 and Attribution to Atmospheric Forcing Variables, J. Geophys. Res-Oceans, 124, 4168-4187, https://doi.org/10.1029/2019j0013948, 2019.

Knight, J. R., Allan, R. J., Folland, C. K., Vellinga, M., and Mann, M. E.: A signature of persistent natural thermohaline circulation cycles in observed climate, Geophys. Res. Lett., 32, https://doi.org/10.1029/2005gl024233, 2005.

Koninklijk Nederlands Meteorologisch Instituut – Ministerie van Infrastructuur en Waterstaat: https://www.knmi.nl/home, access: 13-10-2021.

Kotilainen, A. T., Arppe, L., Dobosz, S., Jansen, E., Kabel, K., Karhu, J., Kotilainen, M. M., Kuipers, A., Loughheed, B. C., Meier, H. E. M., Moros, M., Neumann, T., Porsche, C., Poulsen, N., Rasmussen, P., Ribeiro, S., Risebrobakken, B., Ryabchuk, D., Schimanke, S., Snowball, I., Spiridonov, M., Virtasalo, J. J., Weckström, K., Witkowski, A., and Zhmouida, V.: Echoes from the Past: A Healthy Baltic Sea Requires More Effort, Ambio 43, 60-68, https://doi.org/10.1007/s13280-013-0477-4, 2014.

Kratzer, S., Håkansson, B., and Charlotte, S.: Assessing Secchi and Photic Zone Depth in the Baltic Sea from Satellite Data, Ambio, 32, 577-585, 2003.

Kupiainen, M., Jansson, C., Samuelsson, P., Jones, C., Willén, U., Hansson, U., Ullerstig, A., Wang, S., and Düssler, B.: Rossby Centre regional atmospheric model, RCA4, Rossby Center News Letter, SMHI, Norrköping, Sweden, 2014.

Kuznetsoy, L. and Neumann, T.: Simulation of carbon dynamics in the Baltic Sea with a 3D model, J. Mar. Syst., 111-112, 167-174, https://doi.org/10.1016/j.jmarsys.2012.10.011, 2013.

Lang, A., and Mikołajewicz, U.: The long-term variability of extreme sea levels in the German Bight, Ocean Sci., 15, 651-668, 2019.

Lehmann, A., Getzlaff, K., and Harlafi, J.: Detailed assessment of climate variability in the Baltic Sea area for the period 1958 to 2009, Clim. Res., 46, 185, https://doi.org/10.3354/cr00876, 2011.

Leibniz-Institut für Ostseeforschung Warnemünde: https://www.io-warnemuende.de/, access: 13-10-2021.

Liu, Y., Meier, H. E. M., and Eilola, K.: Nutrient transports in the Baltic Sea – results from a 30-year physical–biogeochemical reanalysis, Biogeoosciences, 14, 2113-2131, https://doi.org/10.5194/bg-14-2113-2017, 2017.

MacKenzie, B. R., Meier, H. E. M., Lindegren, M., Neuenfeldt, S., Eero, M., Blencoecker, T., Tomczak, M. T., and Niiranen, S.: Impact of Climate Change on Fish Population Dynamics in the Baltic Sea: A Dynamical Downscaling Investigation, Ambio 41, 626-636, https://doi.org/10.1007/s13280-012-0325-y, 2012.

Madsen, K. G., Høyer, J. L., Søruaa, Ù., She, J., and Knudsen, P.: Sea Level Trends and Variability of the Baltic Sea From 2D Statistical Reconstruction and Altimetry, Front. Earth Sci., 7, https://doi.org/10.3389/feart.2019.00243, 2019.
Meier, H. E. M.: The Baltic Sea in the late twenty-first century, SMHI, Norrköping, Sweden, 2002a.

Meier, H. E. M., and Kauker, F.: Simulating Baltic Sea climate for the period 1902-1998 with the Rossby Centre coupled ice-ocean model, SMHI, Norrköping, Sweden, 2002.

Meier, H. E. M., Döscher, R., and Faxén, T.: A multiprocessor coupled ice-ocean model for the Baltic Sea: Application to salt inflow, J. Geophys. Res-Oceans, 108, 3273, https://doi.org/10.1029/2000JC000521, 2003.

Meier, H. E. M., and Kauker, F.: Modeling decadal variability of the Baltic Sea: 2. Role of freshwater inflow and large-scale atmospheric circulation for salinity, J. Geophys. Res-Oceans, 108, 2003.

Meier, H. E. M.: Regional ocean climate simulations with a 3D ice–ocean model for the Baltic Sea. Part 2: results for sea ice, Clim. Dyn., 19, 255-266, https://doi.org/10.1007/s00382-001-0225-5, 2002a.

Meier, H. E. M.: Regional ocean climate simulations with a 3D ice-ocean model for the Baltic Sea. Part 1: model experiments and results for temperature and salinity, Clim. Dyn., 19, 237-253, https://doi.org/10.1007/s00382-001-0224-6, 2002b.

Meier, H. E. M., and Kauker, F.: Simulating Baltic Sea climate for the period 1902-1998 with the Rossby Centre coupled ice-ocean model, SMHI, Norrköping, Sweden, 2002.

Meier, H. E. M., Döscher, R., and Faxén, T.: A multiprocessor coupled ice-ocean model for the Baltic Sea: Application to salt inflow, J. Geophys. Res-Oceans, 108, 3273, https://doi.org/10.1029/2000JC000521, 2003.

Meier, H. E. M., and Kauker, F.: Modeling decadal variability of the Baltic Sea: 2. Role of freshwater inflow and large-scale atmospheric circulation for salinity, J. Geophys. Res-Oceans, 108, 2003.

Meier, H. E. M.: The Baltic Sea in the late twenty-first century: a dynamical downscaling approach using two global models and two emission scenarios, Clim. Dyn., 27, 39-68, https://doi.org/10.1007/s00382-006-0124-x, 2006.

Meier, H. E. M., Kjellström, E., and Graham, L. P.: Estimating uncertainties of projected Baltic Sea salinity in the late 21st century, Geophys. Res. Lett., 33, L15705, https://doi.org/10.1029/2006GL026488, 2006.

Meier, H. E. M.: Modeling the pathways and ages of inflowing salt-and freshwater in the Baltic Sea, Estuar. Coast. Shelf Sci., 74, 610-627, https://doi.org/10.1016/j.ecss.2007.05.019, 2007.

Meier, H. E. M., Andresen, H., Dieterich, C., Eliola, K., Gustafsson, B., Høgeland, A., and Schimanke, S.: Transient scenario simulations for the Baltic Sea Region during the 21st century, SMHI, Norrköping, Sweden, 2011.

Meier, H. E. M., Döscher, R., Coward, A. C., Nylander, J., and Döös, K.: RCO – Rossby Centre regional Ocean biogeochemical model of the Baltic Sea, Clim. Res., 48, 31-55, https://doi.org/10.3354/cr00968, 2011c.
Meier, H. E. M., Höglund, A., Döscher, R., Andersson, H., Löptien, U., and Kjellström, E.: Quality assessment of atmospheric surface fields over the Baltic Sea from an ensemble of regional climate model simulations with respect to ocean dynamics, Oceanologia, 53, 193-227, https://doi.org/10.5697/oc-53-1-te.193, 2011.

Meier, H. E. M., Andersson, H. C., Arheimer, B., Blenchner, T., Chubarenko, B., Donnelly, C., Eilola, K., Gustafsson, B. G., Hansson, A., Havenhand, J., and others: Comparing reconstructed past variations and future projections of the Baltic Sea ecosystem—first results from multi-model ensemble simulations, Environ. Res. Lett., 7, 34005, https://doi.org/10.1088/1748-9326/7/3/034005, 2012a.

Meier, H. E. M., Eilola, K., Gustavsson, B. G., Kuznetsov, I., Neumann, T., and Savchuk, O. P.: Uncertainty assessment of projected ecological quality indicators in future climate, SMHI, Norrköping, Sweden, 2012b.

Meier, H. E. M., Hordoir, R., Andersson, H. C., Dieterich, C., Eilola, K., Gustafsson, B. G., Höglund, A., and Schimanke, S.: Modeling the combined impact of changing climate and changing nutrient loads on the Baltic Sea environment in an ensemble of transient simulations for 1961–2099, Clim. Dyn., 39, 2421-2441, https://doi.org/10.1007/s00382-012-1359-7, 2012c.

Meier, H. E. M., Müller-Karulis, B., Andersson, H. C., Dieterich, C., Eilola, K., Gustafsson, B. G., Höglund, A., Hordoir, R., Kuznetsov, I., Neumann, T., and others: Impact of climate change on ecological quality indicators and biogeochemical fluxes in the Baltic Sea: a multi-model ensemble study, Ambio, 41, 558-573, https://doi.org/10.1007/s13280-012-0320-3, 2012d.

Meier, H. E. M., Andersson, H. C., Arheimer, B., Donnelly, C., Eilola, K., Gustafsson, B. G., Kotwicki, L., Niset, T.-S., Niiranen, S., Pwowarczyk, J., Savchuk, O. P., Schenk, F., Weslawski, J. M., and Zorita, E.: Ensemble modeling of the Baltic Sea ecosystem to provide scenarios for management, Ambio, 43, 37-48, https://doi.org/10.1007/s13280-013-0475-6, 2014.

Meier, H. E. M., Höglund, A., Eilola, K., and Almroth-Rosell, E.: Impact of accelerated future global mean sea level rise on hypoxia in the Baltic Sea, Clim. Dyn., 49, 163-172, https://doi.org/10.1007/s00382-016-3333-y, 2017.

Meier, H. E. M., Edman, M. K., Eilola, K. J., Placke, M., Neumann, T., Andersson, H. C., Brunnabend, S.-E., Dieterich, C., Frauen, C., Friedland, R., Gröger, M., Gustafsson, B. G., Gustafsson, E., Isaev, A., Kuznetsov, I., Müller-Karulis, B., Neumann, T., and Schimanke, S.: Projected Oceanographical Changes in the Baltic Sea until 2100, Oxford Research Encyclopedia of Climate Science, https://doi.org/10.1093/acrefore/9780190228620.013.699, 2020.
society and climate on nutrient loading to the Baltic Sea, Sci. Total Environ., 138935, https://doi.org/10.1016/j.scitotenv.2020.138935, 2020.

Placke, M., Meier, H. E. M., Gräwe, U., Neumann, T., Frauen, C., and Liu, Y.: Long-Term Mean Circulation of the Baltic Sea as Represented by Various Ocean Circulation Models, Front. Mar. Sci., 5, https://doi.org/10.3389/fmars.2018.00287, 2018.

Placke, M., Meier, H. E. M., and Neumann, T.: Sensitivity of the Baltic Sea Overtturning Circulation to Long-Term Atmospheric and Hydrological Changes, J. Geophys. Res.-Oceans, 126, e2020JC016079, https://doi.org/10.1029/2020JC016079, 2021.

Pushpadas, D., Schrum, C., and Daewel, U.: Projected climate change impacts on North Sea and Baltic Sea: CMIP3 and CMIP5 model based scenarios., Biogeosci. Discuss., 12, https://doi.org/10.5194/bgd-12-12229-2015, 2015.

Quante, M., and Colijn, F.: North Sea region climate change assessment, Regional Climate Studies, SpringerOpen, Cham, 2016.

Räisänen, J., Hansson, U., Ullerstig, A., Döscher, R., Graham, L. P., Jones, C., Meier, H. E. M., Samuelsson, P., and Willén, U.: European climate in the late twenty-first century: regional simulations with two driving global models and two forcing scenarios, Clim. Dyn., 22, 13-31, https://doi.org/10.1007/s00382-003-0365-x, 2004.

Reckermann, M., Omststed, A., Soomere, T., Aigars, J., Akhtar, N., Beldowski, J., Brauwer, C. P.-S. d., Cronin, T., Czub, M., Eero, M., Hyttiäinen, K., Jalkanen, J.-P., Kiessling, A., Kjellström, E., Larsén, X. G., McCrackin, M., Meier, H. E. M., Oberbeckmann, S., Poska, A., Saarinen, J., Szymczycha, B., Underman, E., Vitasalo, M., Wörman, A., and Zoriža, E.: Human impacts and their interactions in the Baltic Sea region, Earth Syst. Dynam. Discuss., 1-127, https://doi.org/10.5194/esd-2021-54, 2021.

Reece, B.: The regional downscaling approach: a brief history and recent advances, Curr. Clim. Chang. Rep., 1, 22-29, https://doi.org/10.1007/s40641-014-0001-3, 2015.

Roeckner, E., Brokopf, R., Esch, M., Giorgetta, M., Hagemann, S., Kornblueh, L., Manzini, E., Schlese, U., and Schulzweida, U.: Sensitivity of simulated climate to horizontal and vertical resolution in the ECHAM5 atmosphere model, J. Climate, 19, 3771-3791, https://doi.org/10.1175/JCLI3724.1, 2006.

Rummukainen, M., Räisänen, J., Bringfelt, B., Ullerstig, A., Omststed, A., Willén, U., Hansson, U., and Jones, C.: A regional climate model for northern Europe: model description and results from the downscaling of two GCM control simulations, Clim. Dyn., 17, 339-350, https://doi.org/10.1007/s003820000109, 2001.

Rummukainen, M., Bergström, S., Persson, G., Rodhe, J., and Tjernström, M.: The Swedish Regional Climate Modelling Programme, SWECCLIM: A Review, Ambio 33, 176-182, 177, 2004.

Rummukainen, M.: State-of-the-art with regional climate models, Wires. Clim. Change, 1, 82-96, https://doi.org/10.1002/wcc.5, 2010.

Rummukainen, M., Roeck, B., Bärring, L., Christensen, J. H., and Reckermann, M.: Twenty-first-century challenges in regional climate modeling, Bull. Amer. Meteor. Soc. 96, ESTER-ESTER, https://doi.org/10.1175/BAMS-D-14-00214.1, 2015.

Rummukainen, M.: Added value in regional climate modeling, Wires. Clim. Change, 7, 145-159, https://doi.org/10.1002/wcc.318, 2016.

Rutgersson, A., Jaagus, J., Schenk, F., Stendel, M., Bärring, L., Briede, A., Claremarlunger, B., Hanssen-Bauer, Holopainen, J., Moberg, A., Nordli, Ø., Rimkus, E., and Wibig, J.: Recent Change - Atmosphere, in: Second Assessment of Climate Change for the Baltic Sea Basin, edited by: BACC II Author Team, Regional Climate Studies, Springer International Publishing, Cham, 69-97, https://doi.org/10.1007/978-3-319-16006-1_4, 2015.

Ryabchenko, V. A., Karlin, L. N., Isaev, A. V., Vankevich, R. E., Eremina, T. R., Molchanov, M. S., and Savcluk, O. P.: Model estimates of the eutrophication of the Baltic Sea in the contemporary and future climate, Oceanology+, 56, 36-45, https://doi.org/10.1134/S0001437016010161, 2016.
van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hertter, G. C., Kram, T., Krey, V., Lamarque, J.-F., Matsui, T., Maunder, M., Nakicenovic, N., Smith, S. J., and Rose, S. K.: The representative concentration pathways: an overview, Clim. Change, 109, 5, https://doi.org/10.1007/s10584-011-0148-z, 2011.

Vihma, T., and Haapala, J.: Geophysics of sea ice in the Baltic Sea: A review, Prog. Oceanogr., 80, 129-148, https://doi.org/10.1016/j.pocean.2009.02.002, 2009.

Vuorinen, I., Hänninen, J., Rajasilia, M., Laine, P., Eklund, J., Montesino-Pouzols, F., Corona, F., Junker, K., Meier, H. E. M., and Dippner, J. W.: Scenario simulations of future salinity and ecological consequences in the Baltic Sea and adjacent North Sea areas – implications for environmental monitoring, Ecol. Indic., 50, 196-205, https://doi.org/10.1016/j.ecolind.2014.10.019, 2015.

Wang, J., Yang, B., Ljungqvist, F. C., Luterbacher, J., Osborn, Timothy J., Briffa, K. R., and Zorita, E.: Internal and external forcing of multidecadal Atlantic climate variability over the past 1,200 years, Nat. Geosci., 10, 512-517, https://doi.org/10.1038/ngeo2962, 2017.

Wang, S., Dietrich, C., Dösscher, R., Höglund, A., Hordoir, R., Meier, H. E. M., Samuelsson, P., and Schimanke, S.: Development and evaluation of a new regional coupled atmosphere-ocean model in the North Sea and Baltic Sea, Tellus A, 67, 24284, https://doi.org/10.3402/tellusa.v67.24284, 2015.

WCRP – World Climate Research Programme: WCRP Coupled Model Intercomparison Project (CMIP); https://www.wcrp-climate.org/wcm-cmip, access: 13-10-2021.

Weigel, B., Andersson, H. C., Meier, H. E. M., Blenckner, T., Snickars, M., and Bonsdorff, E.: Long-term progression and drivers of coastal zoobenthos in a changing system, Mar. Ecol. Prog. Ser., 528, 141-159, https://doi.org/10.3354/meps11279, 2015.

Weisse, R., and Hänicke, B.: Baltic Sea Level: Past, Present, and Future, Oxford Research Encyclopedia of Climate Science, Oxford University Press, 2019.

Zandersen, M., Hyytiäinen, K., Meier, H. E. M., Tomczak, M. T., Bauer, B., Haapasaari, P. E., Olesen, J. E., Gustafsson, B. G., Refsgaard, J. C., Fridelli, E., Pihlainen, S., Le Tissier, M. D. A., Komenius, A.-K., and Van Vuuren, D. P.: Shared socio-economic pathways extended for the Baltic Sea: exploring long-term environmental problems, Reg. Environ. Change, 19, 1073-1086, https://doi.org/10.1007/s10113-018-1453-0, 2019.

Zillén, L., and Conley, D. J.: Hypoxia and cyanobacteria blooms—are they really natural features of the late Holocene history of the Baltic Sea?, Biogeosciences, 7, 2367, https://doi.org/10.5194/bg-7-2567-2010, 2010.