https://doi.org/10.5194/esd-2021-68
Preprint. Discussion started: 4 August 2021

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Oceanographic regional climate projections for the Baltic Sea until 2100

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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 residence time causing oxygen depletion in the bottom water of the southern sub-basins. With the help of dynamical downscaling using a regional coupled atmosphere-ocean climate model, four global Earth System Models were regionalized. As the regional climate model does not include components for the terrestrial and marine biogeochemistry, an additional catchment and coupled physical-biogeochemical model for the Baltic Sea were used. In addition to previous scenario simulations, the impact of various water level scenarios was examined as well. The projections suggest higher water temperatures, a shallower mixed layer with sharper thermocline during summer, reduced sea ice cover and intensified mixing in the northern Baltic Sea during winter compared to present climate. Both frequency and 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). Due to the uncertainties in projections of the regional wind, water cycle and global sea level rise, robust and statistically significant salinity changes cannot be identified. The impact of changing climate on biogeochemical cycling is considerable but in any case smaller than the impact 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 and reduced hypoxic area also in future climate, strengthening the resilience of the Baltic Sea against anticipated future climate change. While our findings about changes in variables of the heat cycle mainly confirm earlier scenario simulations, earlier projections for salinity and biogeochemical cycles differ substantially because of different experimental setups and different bioavailable nutrient input scenarios.

During the time in which this paper was prepared, shortly before submission, 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 the climate modeling of the Baltic Sea, North Sea and North Atlantic regions.

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1 Introduction

The Baltic Sea is a shallow, semi-enclosed sea with a mean depth of 54 m located in northern Europe (Fig. 1). Due to the strongly varying bottom topography, the Baltic Sea can be divided into a number of sub-basins with limited transports between sub-basins (Sjöberg, 1992). In particular, the water exchange with the North Sea is hampered because of two shallow sills located in narrow channels connecting the Baltic Sea with the North Sea. Large saltwater inflows occur only sporadically, on average once per year mainly during the winter season but never during summer (Mohrholz, 2018). Furthermore, the Baltic Sea is embedded into a catchment area that is about four times larger than the Baltic Sea surface with a large annual freshwater input relative to the volume of the Baltic Sea (Bergström and Carlsson, 1994) causing large horizontal and vertical salinity gradients (Fonselius and Valderrama, 2003).

Due to its location and physical characteristics such as the long residence time, the Baltic Sea is vulnerable to external pressures such as eutrophication, pollution, or 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 $m^3 s^{-1}$ (Meier and Kauker, 2003) is about 40 years. Using ocean circulation modeling, 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, were living in the catchment area, representing a considerable anthropogenic pressure for the marine ecosystem (HELCOM, 2018). Insufficiently treated wastewater, emissions of pollutants, overfishing, habitat degradation, and intensive marine traffic such as oil transports put a heavy burden on the ecosystem of the Baltic Sea (Reckermann et al., 2021). One example is the oxygen depletion of the Baltic Sea deep water, with the consequence of dead sea bottoms 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 size of the Republic of Ireland, with an area of about 73,000 km^2, which is about one sixth of the sea surface of the Baltic Sea. Bottom oxygen of the deeper parts of the Baltic is depleted because of the limited ventilation of the deep water and because of the accelerated oxygen consumption due to the remineralization of organic matter (Meier et al., 2018b). Hence, nutrient input abatement strategies, the so-called Baltic Sea Action Plan (BSAP) were discussed (HELCOM, 2007) and projections are requested by stakeholders such as the Helsinki Commission (HELCOM) or national environmental protection agencies[1].

Projections for the Baltic Sea 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., 2001). The dynamical downscaling approach utilizes regional climate models (RCMs) to refine the global climate change to regional and local scales of the Baltic Sea (e.g., Rummukainen et al., 2004; Döscher et al., 2002). However, these first projections were based on a single global climate model (GCM) and a single greenhouse gas (GHG) concentration scenario (150% increase in equivalent CO_2 concentration in the atmosphere in future climate

[1]https://helcom.fi/helcom-at-work/events/events-2021/ccfs-launch/

https://doi.org/10.5194/esd-2021-68
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compared to historical climate) and only covered 10-year time slices. After these very first attempts, more advanced scenario simulations using mini-ensembles (e.g., Döscher 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., 2011b) (Table 1). However, the latter studies considered only monthly mean changes of the future climate compared to present climate, applying the so-called delta approach, neglecting possible changes in inter-annual variability. From these oceanographic studies it was concluded that "mean annual sea surface temperatures (SSTs) could increase by some 2 to 4˚C by the end of the 21st century. Ice extent in the sea would then decrease by some 50 to 80%. The average salinity of the Baltic Sea could range between present day values and decreases of as much as 45%. However, it should be noted that these oceanographic findings, with the exception of salinity, are based upon only four regional scenario simulations using two emissions scenarios and two global models" (BACC Author Team, 2008).

For the second assessment of climate change in the Baltic Sea region (BACC II Author Team, 2015), continuously integrated transient simulations from present to future climates became available, even including marine biogeochemical modules (e.g., Eilola et al., 2013; Friedland et al., 2012; Gräwe and Burchard, 2012; Gräwe et al., 2013; Gröger et al., 2019; Gröger et al., 2021b; Holt et al., 2016; Kuznetsov and Neumann, 2013; Meier et al., 2011a; Meier et al., 2011b; Meier et al., 2012a; Meier et al., 2012c; Meier et al., 2012d; Neumann, 2010; Neumann et al., 2012; Omstedt et al., 2012; Pushpadas et al., 2015; Ryabchenko et al., 2016; Skogen et al., 2014) and higher tropic 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". Detailed key messages were 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 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 regional 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).

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There is a notable difference in salinity projections between the first two assessments (BACC Author Team, 2008; BACC II Author Team, 2015) and recent scenario simulations (Meier et al., 2021). While the first Baltic Sea scenario simulations driven by nine RCMs and five GCMs showed a pronounced negative ensemble mean change in salinity because two of the involved GCMs showed a significant increase in the mean west wind component (Meier et al., 2006), such pronounced changes in the large-scale atmospheric circulation were not observed in later studies anymore (Saraiva et al., 2019a). The large spread in river discharge did not decrease between the various studies ranging between -8 and +26% (Meier et al., 2006; 2021). As global sea level rise projections were corrected in more recent assessments towards higher rates (e.g., IPCC, 2019a; Bamber et al., 2019), recent scenario simulations for the Baltic Sea also considered 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 are only small (Table 2).

The aim of this study is to provide an overview over 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 physics and biogeochemistry. Variables such as temperature, salinity, oxygen, phosphate, nitrate, phytoplankton concentration, primary production, nitrogen fixation, hypoxic area and Secchi depth (measuring water transparency) are analyzed. An accompanied study by Christensen et al. (2021) investigated atmospheric projections in the Baltic Sea region. For an overview on the development of RCSMs and their applications the reader is referred to Gröger et al. (2021a). For the comparison between the various studies of scenario simulations, we analyze only published data (Table 1). We focus 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), that we compare 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 the impact of climate change on the Baltic Sea primary production without utilizing a regional climate model (Holt et al., 2016; Pushpadas et al., 2015) are not addressed in this study. Also nutrient input reduction scenarios under present climate, e.g. described by Friedland et al. (2021), are not considered. To our knowledge, further coordinated experiments of projections for the coupled physical-biogeochemical system of the Baltic Sea after 2013 were not 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, for historical and future climates results of the three sets of scenario simulations, ECOSUPPORT, BalticAPP and CLIMSEA, are compared. Knowledge gaps and a summary finalize the study.

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2 Methods

2.1 Regionalization of changing climate

Dieterich et al. (2019) produced an ensemble of scenario simulation with a coupled RCSM, called RCA4-NEMO. RCA4-NEMO was introduced by Wang et al. (2015). Gröger et al. (2019; 2021b), and Dieterich et al. (2019) have validated and analyzed different aspects of the RCA4-NEMO ensemble discussed here. The atmospheric component RCA4 was run at a resolution of 0.22 degrees and 40 levels in the EURO-CORDEX domain (Jacob et al., 2014). Coupled to it is the North Sea-Baltic Sea model NEMO at a resolution of two nautical miles (3.7 km) and 56 levels. The two components of the RCSM are coupled by sending sea level pressure, energy, mass and momentum fluxes every three hours from the atmosphere to the ocean. Vice versa, the atmosphere receives at the same frequency sea and ice surface temperatures and the sea-ice fraction and albedo.

This RCSM has been applied to downscale eight different Earth System Models (ESMs) driven by three Representative Concentration Pathways (RCPs) each. For the Baltic Sea projections, four ESMs (MPI-ESM-LR, EC-Earth, IPSL-CM5A-MR, HadGEM2-ES; see Gröger et al. (2019) with 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 by 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 the 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, the 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 had 41 levels with varying layer thicknesses 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 model

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 (Meier et al., 2012c) were applied to calculate river runoff and nutrient inputs under changing climate but without considering land surface changes. While the statistical model calculates river runoff from precipitation minus evaporation over the catchment area, riverborne nutrient inputs were estimated from 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) were used (Fig. 3). In BalticAPP, nutrient input scenarios followed BSAP, REF and worst (WORST) scenarios (Saraiva et al., 2019a; b; Pihlainen et al., 2020). Finally in ECOSUPPORT, instead of WORST a business-as-usual (BAU) scenario was applied (Gustafsson et al., 2011; Meier et al., 2011a). In the BSAP scenario in CLIMSEA and BalticAPP, nutrient inputs linearly decrease from 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, the nutrient inputs remain constant until the end of the century. A similar temporal evolution was defined in ECOSUPPORT but with a reference period 1997-2003 (Gustafsson et al., 2011; their Fig. 3.1). In the REF scenario, in CLIMSEA and BalticAPP, the nutrient inputs were calculated by E-HYPE that considered the impact of changing river flow on nutrient inputs but that neglected any changes in land use or socioeconomic development. These inputs correspond approximately to the observed inputs during the period 2010-2012. The two additional, above-mentioned scenarios on future projections, BAU and WORST, cannot be 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 for the sake of completeness.

2.3 Baltic Sea model

The coupled physical-biogeochemical ocean model (RCO-SCOBI) was driven by the atmospheric surface field data calculated by RCA4-NEMO and by the river runoff and nutrient input scenarios derived from E-HYPE projections and atmospheric deposition (Fig. 2). Atmospheric depositions were assumed to be constant at the observed levels during 2010-2012 or reduced as in the BSAP. RCO is a Bryan-Cox-Semtner-type ocean circulation model with horizontal and vertical grid resolutions of 3.6 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, phytoplankton concentrations of three algal types (diatoms, flagellates and others, cyanobacteria) and detritus (Eilola 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 (Eilola et al., 2011; Placke et al., 2018; Meier et al., 2018a).

2.4 Scenario simulations

In CLIMSEA, we have analysed an ensemble of 48 RCO-SCOBI scenario simulations for the period 1976-2098 (Table 3) that was produced following the dynamical downscaling approach described in the Sections 2.1 to 2.3 (Fig. 2) and presented by Meier et al. (2021). Contrary to previous studies (Meier et al., 2011a; Saraiva et al., 2019a), the CLIMSEA scenario simulations also consider various scenarios of global sea level rise (SLR). 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 are: (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 low- (1.26 m, here combined with RCP4.5) and high-case (2.34 m, here combined with RCP8.5) scenarios following Bamber et al. (2019) (Table 3). By deepening the water depth at all grid points every 10 years the relative sea level linearly increased. 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. (2011a; 2012c) and Neumann et al. (2012), 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 as used for 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 the mean sea level relative to the seabed will not change. 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), an optimistic scenario for the future would be an unchanged relative water level above the sills (Meier et al., 2021). In CLIMSEA, mean and high-case scenarios follow the median values of RCP4.5 and RCP8.5 ensembles by (Oppenheimer et al., 2019) and the 95th percentiles of low- and high-case scenarios by Bamber et al. (2019) (Table 3).

2.5 Analysis

Evaluation of the historical period

To evaluate model results of the BalticAPP and CLIMSEA scenario simulations during the historical period, annual and seasonal mean biases during the historical period between RCO-SCOBI simulations and reanalysis data (Liu et al., 2017) were calculated. As the reanalysis data are available for the period 1971-1999, we limit the calculation of biases to 1976-1999. Model data of historical periods of BalticAPP and ECOSUPPORT scenario simulations were evaluated by Saraiva et al. (2019a, b) and Meier et al. (2011a; 2012c, d), respectively.

Mixed layer depth

The mixed layer depth (MLD) was calculated following de Boyer Montégut et al. (2004).

Secchi depth

Secchi depth (Sd) is a measure of water transparency and is calculated from Sd = 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 (ERGOM) of the ECOSUPPORT ensemble as a proxy of the spatio-temporal dynamics of yellow substances.

Trends

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First, the monthly average of SST was computed from model output every 48 hours. Then the linear trend was calculated with the Theil-Sen estimator (Theil, 1950; Sen, 1968). The trend computed with this method is the median of the slopes determined by all pairs of sample points. The advantage of this expensive method is that it is much less sensitive to outliers. The significance of 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 is removed before computing the linear trend.

Following Kniebusch et al. (2019), a ranking analysis was performed to determine, which atmospheric drivers others than air temperature are most important for the monthly variability of SST in each ESM forcing of the CLIMSEA data set and in both RCP scenarios, RCP4.5 and RCP8.5. The SST trend is dominated by the trend in air temperature, thus to partly cancel the air temperature effect on SST, the residuals from a linear model fitting the SST to the surface atmosphere temperature (SAT) was subtracted from the SST. Then a cross-correlation analysis was applied 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 decades, the Baltic Sea region warmed up faster than the global mean warming (Rutgersson et al., 2015; Kniebusch et al., 2019) and any other coastal sea (Belkin, 2009) making this region prone to marine heat waves (MHWs). 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. 90th, 95th, 98th percentile temperature) or by exceeding absolute temperature thresholds to be defined with respect to end user applications (Hobday et al., 2018). In most cases, MHWs are defined by the number of periods, the intensity, and duration and for specific purposes (Hobday et al., 2018). We here only focus on the general impact of climate change since an appropriate definition of metrics for MHWs suitable for the Baltic is lacking. In the following, MHWs are defined as periods with an SST >= 20°C lasting for at least 10 days to better reflect the sensitivity of ecosystem dynamics.

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 to 1999, the annual mean SST amounts to about 7.8°C (Fig. 4). The mean seasonal cycle of the SST is pronounced and the northern Baltic Sea is sea-ice covered every winter (not shown). Due to the large latitudinal extension, the Baltic Sea is characterized during all seasons by a distinct SST difference between 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

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circulation that advects warmer and more saline southern waters along the eastern coast and colder less saline waters of northern origin at the western side (see Gröger et al., 2019, their Suppl. Mat. S1; Fig. 4).

On average, during the historical period 1976-2005 CLIMSEA climate simulations are warmer compared 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, autumn and the annual mean amount 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 RCSM. Driven by the reanalysis data ERA40 (Uppala et al., 2005), RCA4-NEMO systematically overestimates water temperatures and underestimates sea-ice cover in the Baltic Sea during the historical period (Gröger et al., 2019; their Suppl. Mat. S1).

In ECOSUPPORT scenario simulations, there is also a systematic warm bias of RCAO driven by GCMs at the lateral boundaries, particularly resulting in too warm winter water temperatures and too low sea-ice cover (Meier et al., 2011c, d; 2012c, d). While these biases are found in all three applied Baltic Sea models (Table 3) forced with the RCSM atmospheric surface fields, simulations driven with regionalized reanalysis data (ERA40) showed smaller mean biases (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 is seen over the open ocean with pronounced west - east gradients. This is related to the predominant south-westerly wind regime with larger wind fetches and higher significant wave heights in the eastern Gotland Basin causing wave-induced vertical mixing. Furthermore, a positive sea - atmosphere temperature contrast favors higher wind speeds ("positive winter thermal feedback loop"; Gröger et al., 2015; 2021b). In spring, a weakening wind regime, lowering heat exchange (thereby turning from heat loss to heat gain) and increased solar irradiance lead 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. During summer, the atmosphere-ocean dynamics is weakest leading to a pronounced thermocline and shallowest MLDs (the so-called "summer thermal short circuit"; Gröger et al., 2021b). During autumn, the atmosphere cools faster than the earth surface and landmasses cool faster than the open sea areas. Because of the increased thermal contrasts, the large-scale wind regime strengthens with positive feedback on MLD.

The ensemble model mean in CLIMSEA reproduces this dynamics and the spatial pattern relatively well. During the cold season, however, MLD is somewhat smaller than in the reanalysis data by Liu et al. (2017). This may be the result of the air-sea coupling. Gröger et al. (2015, 2021b) have demonstrated that standalone ocean models do not very well 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, causes of the underestimated winter MLD are unknown.

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

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3.1.3 Marine heat waves

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

The first index uses a fixed threshold focusing more on the environmental impact of heat waves. In particular, diazetrophic 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 are mostly absent in the open sea of the Baltic proper and further north in the Gulf of Bothnia. MHWs are most abundant in shallow marginal bays like the Gulf of Finland and Gulf of Riga as well as along the coasts. The RCO ensemble mean produces generally more frequent MHWs and MHWs of longer duration than the reanalysis data set. Furthermore, the coastal signature of high abundance extents more offshore (Fig. 6a). In case of 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 here as 1976-1999. The number of MHWs (Fig. 6c) is negatively correlated to their average duration (Fig. 6d). This is somewhat more pronounced in the reanalysis data set. In general, reanalysis data and RCO show similar patterns but the amplitude of spatial variance is higher in the reanalysis data (Fig. 6c) which assimilated small-scale regional observations. The duration of MHWs in RCO (Fig. 6d) is highest in the open sea where wind events are probably the main process interrupting heat waves 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 the dynamics of MHWs and processes favoring vertical mixing can be considered a benchmark in the models ability to simulate MHW. Taking into account that mixing is highly parameterized in current ocean models, RCO reproduces the spatial pattern of MHW reasonably well.

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

3.1.4 Salinity

The annual mean sea surface salinity (SSS) distribution shows a large north–south gradient mirroring 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 Kattegat to < 2 g kg^{-1} in the northern Bothnian Bay and eastern Gulf of Finland. For the period 1970 to 1999, the annual mean SSS of the Baltic Sea including Kattegat amounts to about 7.3 g kg^{-1}. Occasionally big inflows of heavy saltwater from Kattegat ventilate the bottom water of the Baltic Sea, filling its deeper regions (Fig. 7). Due to almost absent tides, mixing is limited and the water column is characterized 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 hydrological model (E-HYPE) data compared to observations, in the CLIMSEA climate models SSS in the coastal zone and in Kattegat is on average lower compared to the

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reanalysis data (Fig. 7). The spatially averaged, annual mean bias amounts to -0.4 g kg^{-1}. In the climate models, bottom salinities in the Belt Sea, Great Belt area and the Gotland Basin (most pronounced 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 amounts to +0.3 g kg^{-1}. Hence, the vertical stratification in the Belt Sea, Great Belt area and the Gotland Basin is larger in climate models than in the reanalysis data.

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

3.1.5 Sea level

Due to the seasonal cycle in wind speed, with wind directions predominantly from southwest, the sea level in the Baltic Sea varies considerably throughout the year, with highest sea levels of about 40 cm relative to Kattegat during winter, at the northern coasts in the Bothnian Bay and at the eastern coasts in the Gulf of Finland (Fig. 7). For the period 1976 to 1999, the annual mean sea level amounts to about 16 cm, with a horizontal north–south difference of about 35 cm (not shown). This sea level slope is explained by the lighter brackish water in the northeastern Baltic Sea compared to the Kattegat and by the mean wind from southwesterly directions which pushes the water to the north and to the east (Meier et al., 2004a).

Differences in mean sea level between CLIMSEA climate models and reanalysis data are small (Fig. 7) and the spatially averaged, winter mean bias amounts to +0.6 cm only. Sea levels in some parts of the coastal zone such as the western Bothnian Sea are higher in climate models compared to 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, with overestimated sea level in early spring and underestimated sea level in summer at all investigated tide gauge locations compared to both observations and a hindcast simulation driven by regionalized ERA40 data (Fig. 8).

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

3.1.6 Oxygen concentration and hypoxic area

Since the 1940s, nutrient inputs into the Baltic Sea have increased due to population growth and intensified fertilizer use in agriculture (Gustafsson et al., 2012; Fig. 3). Nutrient inputs reached their peak in the 1980s and declined thereafter until the early 21st century as a consequence of the implementation of nutrient input abatement strategies. Since the 1960s, the bottom water of the Baltic Sea below the permanent halocline is characterized by oxygen depletion and large-scale hypoxia (Figs. 9 and 22).

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Following stratification biases in the deeper sub-basins of the Baltic Sea, summer bottom oxygen concentrations in the Bornholm and Gotland basins in CLIMSEA/BalticAPP climate simulations are higher and lower, respectively, compared to the reanalysis data (Fig. 9). Hence, stronger vertical stratification 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, autumn and the annual mean are small but systematic and amount to -0.6, -0.7, -0.7, -0.5 and -0.6 mL L^{-1}.

In ECOSUPPORT scenarios, 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 significantly lower compared to observations, respectively (Meier et al., 2011a; 2012d).

3.1.7 Nutrient concentrations

Nutrients (i.e., phosphorus and nitrogen) in the surface layer during winter are a good indicator for the intensity of the following spring bloom. Highest sea surface concentrations of winter mean phosphate and nitrate are found 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 the historical period 1976-1999, winter surface phosphate concentrations in climate simulations are relatively close to reanalysis data (Fig. 9). Different concentrations are only found in coastal regions influenced by large rivers probably due to differing inputs. Such regions are, for instance, the coastal zones affected by the discharges of the Odra, Vistula and Pärnu rivers. Spatially averaged biases are largest during summer and autumn and amounted to +0.2 mmol P m^{-3} in summer.

Similarly, simulated winter surface nitrate concentrations are close to reanalysis data but differed in coastal regions due to different inputs from large rivers (Fig. 9). In particular, larger differences are found in the Gulf of Riga and in the eastern Gulf of Finland influenced by the Neva River. Spatially averaged biases during winter, spring, summer, autumn and the annual mean are rather small but systematic and amount to -1.1, -1.3, -0.5, -0.7 and -0.9 mmol N m^{-3}.

In ECOSUPPORT scenario simulations, simulated profiles of phosphate, nitrate and ammonium were within the range of observations during 1978-2007, except for phosphate in the Gulf of Finland (Meier et al., 2012d). According to hindcast simulations coupled physical-biogeochemical models for the Baltic Sea showed larger biases relative to the standard deviations of observations in the northern Baltic Sea than in the Baltic proper (Eilola et al., 2011).

3.1.8 Phytoplankton concentrations

During the period 1976 to 1999, high concentrations of phytoplankton blooms were confined to the coastal zone, the area with the highest nutrient concentrations (Fig. 10). Water transparency, measured by Secchi depth, is low in the Baltic Sea compared to the open ocean (Fleming-Lehtinen and Laamanen, 2012). For the period 1970 to 1999, the annual mean Secchi depth averaged for the entire Baltic Sea, including Kattegat, amounts to about 6.6

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m only. In the coastal zone, the Secchi depth is much smaller than in the open Baltic Sea (Fig. 10). Also in the northern Baltic Sea, Secchi depth is smaller than in the Gotland Basin due to yellow substances originating from land (Fleming-Lehtinen and Laamanen, 2012).

Following nutrient concentration biases, simulated annual mean surface phytoplankton concentrations are close to reanalysis data but deviated in coastal regions (Fig. 10). Spatially averaged biases during winter, spring, summer, autumn and the annual mean are rather small and amount to +0.02, -0.1, -0.009, +0.06 and -0.008 mg Chl m^{-3}.

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

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

In ECOSUPPORT scenario simulations, Secchi depth has not been analyzed relative to observations.

3.1.9 Biogeochemical fluxes

An evaluation of biogeochemical fluxes such as primary production and nitrogen fixation is difficult because of lacking observations. An exception is the study by Hieronymus et al., (2021) who compared historical simulations with RCO-SCOBI including a cyanobacteria life cycle (CLC) model (Hense and Beckmann, 2006; 2010) driven by reconstructed atmospheric and hydrological data with in in situ observations of nitrogen fixation. Hieronymus et al. (2021) found a satisfactory agreement, 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 while the observations showed a peak more confined to July. However, it should be noted that the RCO-SCOBI version that has been used for 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 Figs. 11 and 12, annual and seasonal mean SST changes between 1976-2005 and 2069-2098 in RCO-SCOBI are depicted. The maximum seasonal warming signal propagates between winter and summer from the Gulf of Finland via the Bohnian Sea into the Bothnian Bay (Fig. 11). Maximum warming occurs during summer in the Bothnian Sea and Bothnian Bay. Comparing RCP4.5 and RCP8.5, seasonal patterns are similar although the

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warming is greater in RCP8.5 compared to RCP4.5. The SLR has almost no impact on SST changes. Hence, BalticAPP and CLIMSEA scenario simulation results are similar (not shown). The warming in ECOSUPPORT is in between the CLIMSEA/BalticAPP RCP4.5 and RCP8.5 results because the GHG emissions of the A1B scenario, which forces the ECOSUPPORT ensemble[2], are in between the RCP4.5 and RCP8.5 scenarios.

In the CLIMSEA/BalticAPP RCSM projections, annual mean SST changes in the Baltic Sea driven by four ESMs, i.e. MPI-ESM-LR, EC-EARTH, IPSL-CMA-MR, HadGEM2-ES, under the RCP8.5 scenario amount to +2.27, +3.70, +3.52 and +4.67°C (Gröger et al., 2019). Thus, the ensemble mean change is 3.54°C. The corresponding ensemble mean change in 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.

Spatial patterns of SST changes in ECOSUPPORT (e.g., Meier et al., 2012c) and CLIMSEA (e.g., Saraiva et al., 2019b) scenario simulations are similar. However, uncertainties due to the applied global (Meier et al., 2011d) or regional (Meier et al., 2012b) model might be considerable. In particular, the summer ensemble range caused by various GCMs is significant (Meier et al., 2011d). The differences in magnitude of the warming are explained by the various GHG concentration scenarios (Fig. 12).

Trends

Since SLR and nutrient input scenarios have a negligible impact on SST changes, only a comparison between RCP4.5 and RCP8.5 scenarios in CLIMSEA/BalticAPP has been done. The multi-model mean of annual SST trends is about 0.18 K decade^{-1} and 0.35 K decade^{-1} in the RCP4.5 and RCP8.5 scenarios, respectively (Fig. 13a, f). At the Baltic Sea scale, seasonal SST trends from annual values vary only slightly (±0.01 K decade^{-1} in both scenarios). However at the sub-basin scale, seasonal variations are much stronger, reaching ±0.05 K 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 declining sea-ice cover in this season, as during the 1850-2008 period (Kniebusch et al., 2019).

As seen in Figure 14, relative SST trends indicate that the northern Baltic Sea will warm faster than the southern Baltic Sea (0.02 K decade^{-1} and 0.04 K 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 K decade^{-1} and ~0.45 K 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. However, in the RCP8.5 scenario, SST trends gradually increase over the first 50 years of the period reaching a maximum of 0.5 K decade^{-1} over the period 2046-2075, before declining

[2]One of the scenario simulations of ECOSUPPORT was driven by the generally warmer A2 scenario due to higher GHG emissions compared to A1B. However, this simulation of the ECHAM5 – MPIOM GCM is exceptional and at the end of the 21st century not much warmer than the corresponding run with the same model under the A1B scenario.

slightly from 2060 onwards, as in the RCP4.5 scenario, a result of the pronounced natural variability in this scenario as well. Despite the robustness of the SST trends spatial pattern (p-value <0.05 everywhere), the analysis of SST trends for the four ESM forcings reveals an important dependency of SST trends to atmospheric forcings with a spread of ±0.06 K decade^{-1} from the multi-model mean in both scenarios (not shown).

At annual timescale, it is well-known that the variability of air temperature, through the sensible heat fluxes, is the main driver of Baltic Sea SST (Kniebusch et al., 2019), as illustrated here by the high variance explained between 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 SST trends, a rank analysis from atmospheric variables (i.e. latent heat fluxes, cloud cover, and u-v wind components) was performed following Kniebusch et al. (2019; Fig. 16). The second parameter (after SAT) explaining the variability of 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 Bothnian Bay, the second most important variable is cloudiness. This is also the case in the Bothian Sea under the RCP4.5 scenario. However, in the RCP8.5 the second most important variable is at this location the latent heat flux. The difference might be explained by the complete melting of the sea ice under RCP8.5, amplifying air-sea exchange.

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

In the literature, trends in ECOSUPPORT scenario simulations were not analyzed.

3.2.2 Mixed layer depth

In Figure 17, changes in MLD are shown. During winter reduced sea ice cover favors a widespread deepening of the MLD in the Bothnian Sea and Bothnian Bay likely caused by wind-induced mixing. In spring, the most pronounced feature is a strong shallowing of MLD in the Bothnian Sea 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 (Fig. 4) so warming between 1.6 and 2.4 °C (Fig. 11) may hamper thermal convective mixing in future.

Changes during summer are less pronounced. Contrary to winter, an overall shallowing is found. This is in agreement with a shallower and more intense thermocline in warming scenarios as suggested by Gröger et al.

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(2019) and a common feature among projections because 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 historical period.

It was speculated that these changes in thermocline depth during summer might have an 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 MHW within climatological 30-year time slices. 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 compared to the western coasts, which may reflect that coastal upwelling events occur more frequent along the western compared to the eastern Baltic Sea coasts. Already under the RCP4.5 scenario, wide areas of the Baltic proper are affected by MHWs ~ once a year. The strongest response is projected for the high emission RCP8.5 scenario in marginal basins like the Gulf of Riga or the Gulf of Finland where MHWs would occur 2-3 times per year in future. Not only the frequency but also the average duration of MHW increase with climate warming. Under RCP8.5 even in the open Gulf of Bothnia MHWs of ~20 day duration would occur in 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 analyze MHWs is to calculate them with respect to the 95th percentile temperature of the historical reference climate (Fig. 19). For the historical climate, such periods are in most regions less than 20-30 days. In the southern Baltic Sea, especially west of the Baltic proper they are more frequent. The climate change signal is characterized by more frequent MHWs of longer duration. Already in RCP4.5 MHWs occur at least every year. The strongest increase in frequency is near the coasts whereas their 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 larger variability of the coastal zone compared to the open sea. In addition, 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). The ensemble mean signal is small compared to the ensemble spread because the impact of the projected increase in total river runoff from the entire catchment (Fig. 3) on salinity is compensated by the impact of larger saltwater inflows due to the projected SLR (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. (2011a) (ECOSUPPORT) and Saraiva et al. (2019a) (BalticAPP) (Fig. 12), salinity changes in CLIMSEA are much smaller (not shown) and it is impossible to judge whether these changes will be positive or negative.

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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 somewhat slower than the global mean because of the remote impact of the melting Antarctic ice sheet (Grinsted, 2015). For a mid-range scenario, Baltic SLR is projected to be ~87% of the global mean (Pellikka et al., 2020). Further, land uplift partly compensates 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 the period 1986–2005 (Oppenheimer et al., 2019). For these two scenarios, likely ranges amount to 29–59 cm and 61–110 cm, respectively. Assessing the ice sheet dynamics in more detail, Bamber et al. (2019) estimated for low- and high case scenarios global-median SLRs of 69 and 111 cm in 2100, respectively. They found likely ranges of 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). On the other hand, sea level changes in ECOSUPPORT scenario simulations are larger, particularly in spring, because one member of the multi-model ensemble considered Archimedes' principle (not shown). Note that in Figure 12 sea level changes consider only changing river runoff, changing wind, and melting sea ice affecting the sea level via Archimedes' principle (only in the ECOSUPPORT ensemble) whereas the global mean SLR and land uplift are not included and have to be added (e.g., Meier, 2006; Meier et al., 2004a).

In CLIMSEA, pronounced seasonal changes relative to the SLR do not exist (Fig. 20). In both GHG concentration scenarios, largest changes of only about ±5 cm were found. These results confirm that systematic changes in the regional wind field are small (Christensen et al., 2021). Nonlinear effects are small as well, i.e. mean sea level changes do not significantly differ between various SLR scenarios (not shown).

Due to the global mean SLR, 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 not 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).

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

3.2.6 Oxygen concentration and hypoxic area

Bottom oxygen concentration

Projected bottom oxygen concentration changes differ considerably between ECOSUPPORT and BalticAPP/CLIMSEA scenario simulations as illustrated for summer (Fig. 21) whereas the differences between the BalticAPP (SLR = 0 cm) and CLIMSEA (SLR > 0 cm) scenarios are relatively smaller (Meier et al., 2021).

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

Hypoxic area

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

In CLIMSEA under REF, hypoxic area is projected to slightly decrease until about 2050 as a delayed response to nutrient input reductions and then to increase again towards the end of the century likely a response to nutrient input increase and warming (Fig. 22). Larger hypoxic areas are calculated under RCP8.5 than under RCP4.5. Under BSAP, hypoxic area is projected to considerably decrease. At the end of the century, the size of hypoxic area is between 78 and 22% smaller compared to the average size of the period 1976–2005. The given range denotes the results of the various ensemble members.

3.2.7 Nutrient concentrations

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

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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 7). On the other hand, in BalticAPP projections, area averaged Secchi depths generally increase, except in the combination of RCP8.5 and BAU scenarios (Table 7), indicating an improvement of the water quality in future compared to present climate. The most striking changes occur in the BSAP scenario, showing Secchi depth increases of 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 CLIMSEA ensemble mean and high SLR scenarios) have only a minor impact on the water transparency response (Table 7). The overwhelming driver of Secchi depth changes are nutrient input scenarios (illustrated by the differences between ECOSUPPORT and BalticAPP/CLIMSEA ensembles highlighted by even contradictory signs in the changes).

3.2.9 Biogeochemical fluxes

In CLIMSEA under the BSAP, primary production and nitrogen fixation were projected to considerably decrease in future climate (Fig. 22). Under 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 again towards the end of the century likely a response to nutrient input increase and warming. At the end of the century, both primary production and nitrogen fixation would be at the same level as under current conditions. The impact of warming is larger under high as under low nutrient conditions (cf. Saraiva et al., 2019b).

3.2.10 Relation to the large-scale atmospheric circulation

The most 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; Börgel et al., 2020). During 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; Hünicke and Zorita, 2006; Chen and Hellström, 1999; Meier and Kauker, 2002; Beranová and Huth, 2008).

Figure 25 shows the calculated ensemble mean 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 comparing RCP4.5 and the high emission scenario RCP8.5, it can be seen that the spread of the ensemble increases with enlarged greenhouse gas concentrations. Furthermore, Figure 25 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 RCP4.5 and RCP8.5 it is found that there are no systematic changes between both emission scenarios. However, for RCP8.5 a slightly larger ensemble spread is found.

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4 Knowledge gaps

As in this study only four ESMs were regionalized using one RCSM, the CLIMSEA ensemble is still too small to estimate uncertainties caused by ESM and RCSM differences. It should be noted that recently even nine ESMs with the same RCSM were regionalized but without running modules for the terrestrial and marine biogeochemistry (Gröger et al., 2021b). 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, 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. Further, the AMO may influence also the centers of action of the NAO (Börgel et al., 2020). The lateral tilting of the positions of Icelandic Low and Azores High explains the correlation changes between 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.

We have not analyzed changes in sea-ice cover because in the recent scenario simulations of the CLIMSEA ensemble sea-ice cover is systematically underestimated. However, we found that 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 Höglund et al. (2017) confirmed earlier results by Meier (2002b) and Meier et al. (2011c; 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., 2011; Meier et al., 2011a). 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 BalticAPP and CLIMSEA ensembles would give a more realistic model response compared to the ECOSUPPORT scenario simulations. However, not exactly known current and

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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 scenario simulations have in common that plausible nutrient input changes have a bigger impact on changes in biogeochemical variables such as nutrients, phytoplankton and oxygen concentrations than projected changes in climate such as warming or changes in vertical stratification. The latter would be caused by freshwater increase, 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 present-day hypoxic area, model results suggested that the main reason for hypoxia in the Baltic Sea were 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 the medieval climate anomaly (Zillén and Conley, 2010). However, paleoclimate modeling could not explain such conditions without substantial increases in nutrient inputs (Schimanke et al., 2012). Thus, the sensitivity of state-of-the-art physical-biogeochemical to various drivers might be questioned and models do not reproduce all important processes correctly.

For a more detailed discussion of uncertainties in Baltic Sea projections, the reader is referred to Meier et al. (2018a; 2019b; 2021).

5 Summary

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, 2008; 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 GHG concentration scenarios, ensemble mean annual SST changes between 1978-2007 and 2069-2098 amount to 2 and 3°C, respectively. Warming would enhance the stability across the seasonal thermocline and mixed layer depth 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 frequency and duration of marine heat waves would increase significantly, in particular south of 60ºN and in particular in the coastal zone (except in regions with frequent upwelling).

Projected spatial patterns of seasonal SST trends during 2006-2099 are similar compared to those in historical reconstructions during 1850-2008 although in most regions the magnitude of trends are larger. Largest trends were found in summer in the northern Baltic Sea (Bothnian Sea and Bothnian Bay) in regions where on average under a warmer climate sea ice would melt earlier or would even have disappeared completely. With increasing warming, SST trends in the northern Baltic Sea would get larger relative to SST trends in the southern Baltic Sea indicating a weaker north-south SST gradient in future. The latter might be caused by the ice-albedo feedback.

Contrary to previous scenario simulations, recent scenario simulations considered the impact of global mean SLR on Baltic Sea salinity causing a more or less complete compensation for the projected increasing river runoff. However, as future changes in all three drivers of salinity, i.e. wind, runoff and SLR, are very uncertain, the spread in 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 increased wind speed or changed wind direction.

In agreement with earlier studies, nutrient inputs changes of the BSAP or REF scenarios would have a larger impact on biogeochemical cycling in the Baltic Sea than changing climate driven by RCP4.5 or RCP8.5 scenarios. Further, the impact of climate change would be more pronounced under higher than under lower nutrient conditions. However, the response in recent studies differ from the results of previous studies considerably because of more plausible assumptions on historical and future nutrient inputs resulting, for instance, in sometimes opposite signs in the response of bottom oxygen concentrations. The new scenarios suggest that 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 identified. Depending on the combination of SLR and RCP scenario, a significant impact on bottom oxygen concentration was found. Higher mean sea level relative to the seabed at the sills would cause increased saltwater inflows, stronger vertical stratification in the Baltic Sea and larger hypoxic area. The relationship between vertical stratification and 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 changes in hypoxic area, phytoplankton concentration, water transparency (expressed by Secchi depth), primary production and nitrogen fixation than projected changes in climate.

The available ensembles of scenario simulations are now larger than in previous studies. It was shown that the uncertainty caused by ESM differences became now also larger. However, the ensemble size might still be too small and the model uncertainty is very likely underestimated. Further, natural variability might be a more important source of uncertainty than previously estimated.

In present climate, the climate variability of the Baltic Sea region during winter is dominated by the impact of the NAO. However, during past climate the correlation between 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).

Acknowledgements

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

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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). Further, we thank Berit Recklebe (Leibniz Institute for Baltic Sea Research Warnemünde, IOW) for technical support.

Figures

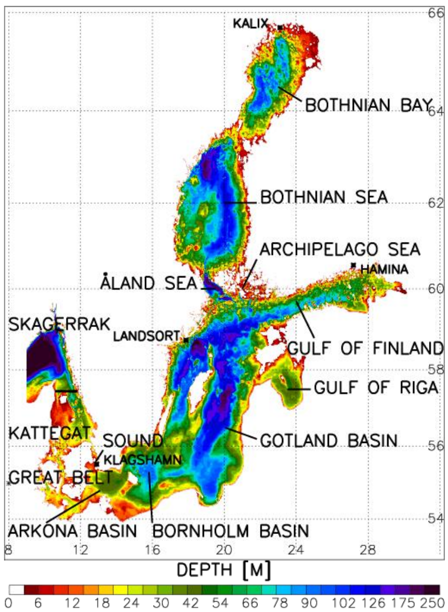

Figure 1: Bottom topography of the Baltic Sea (depth in m). The Baltic proper comprises the Arkona Basin, Bornholm Basin and Gotland Basin. The border of the analyzed domain of the Baltic Sea models is shown as black line in the northern Kattegat. In addition, the tide gauges Klagshamn (55.522ºN, 12.894ºE), Landsort (58.742ºN, 17.865ºE), Hamina (60.563ºN, 27.179ºE), and Kalix (65.697ºN, 23.096ºE) are shown.

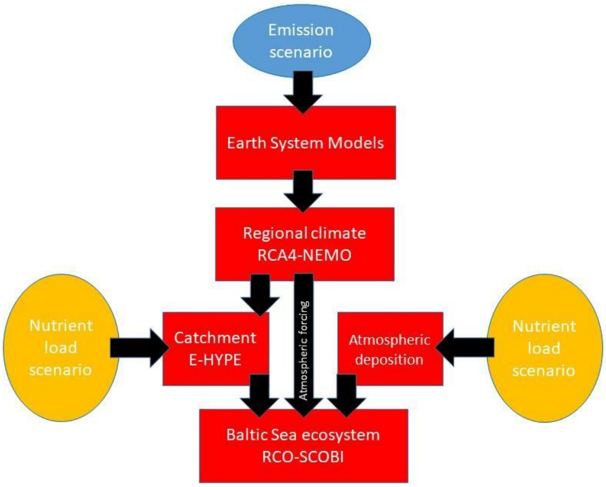

Figure 2. Dynamical downscaling approach for the Baltic Sea region. In Section 2, the models for the various components of the Earth System are explained. (Source: Meier et al., 2021)

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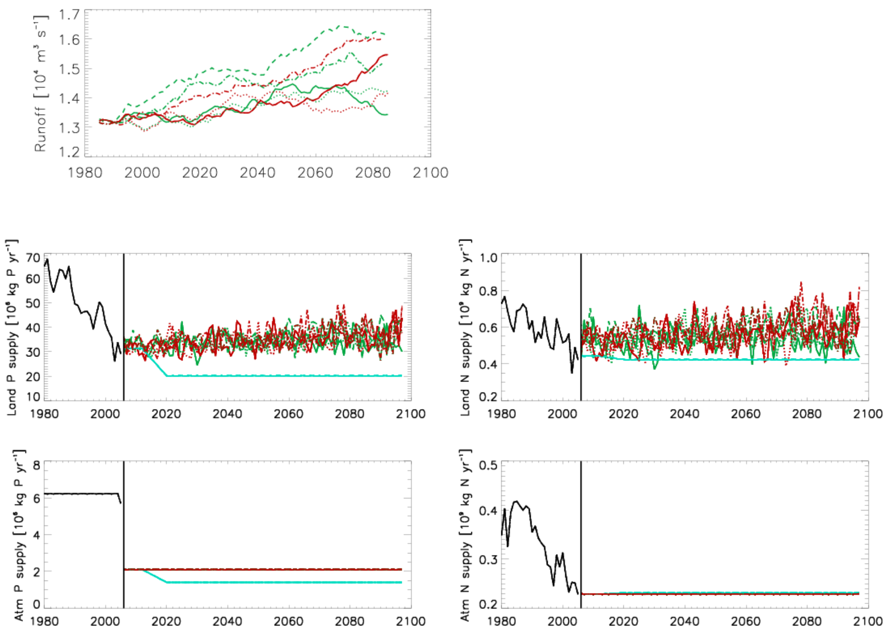

Figure 3. Projections of river discharge and nutrient inputs from land and atmosphere into the entire Baltic Sea in BalticAPP and CLIMSEA scenario simulations. Upper panel: Low-pass filtered runoff data (in m^3 s^{-1}) using a cut-off period of 30 years of four regionalized ESMs (illustrated by different line types) under RCP4.5 (green) and RCP8.5 (red) scenarios. Lower panels: Bioavailable phosphorus (in 10^6 *kg P* yr^{-1}, left panels) and nitrogen inputs (in 10^9 *kg N* yr^{-1}, right panels) from land (upper panels) and 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) and the ECOSUPPORT nutrient input scenarios (Gustafsson et al., 2011; their Fig. 3.1) are not displayed here. (Source: Meier et al., 2021)

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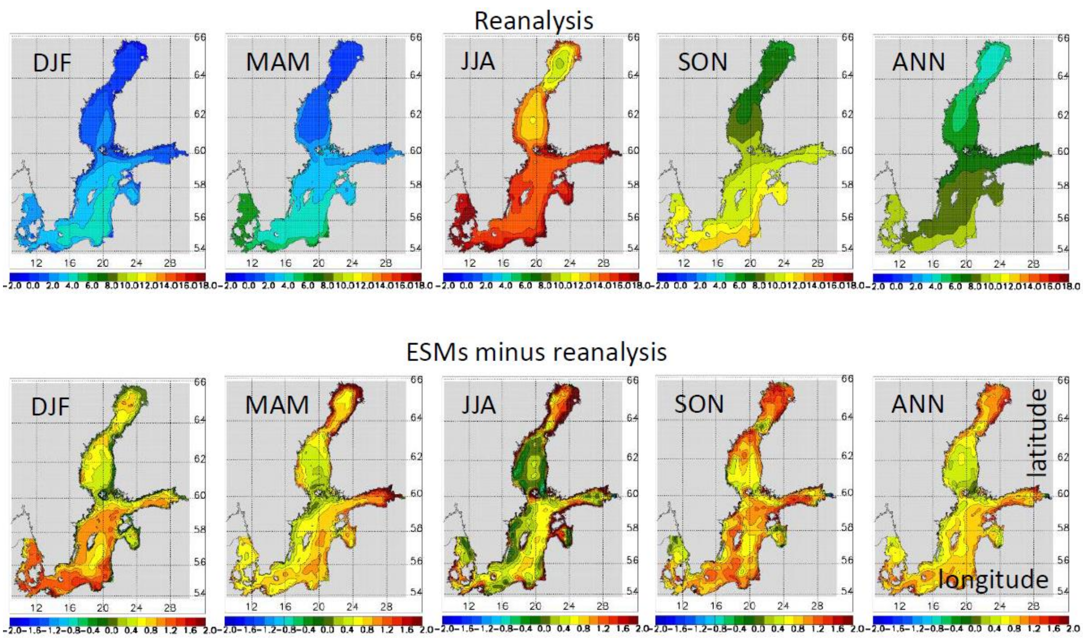

Figure 4: Upper panels: Annual and seasonal mean sea surface temperature (SST) (in °C) in reanalysis data during 1970-1999 (Liu et al., 2017). Lower panels: Difference between climatologies of the ensemble mean of the regionalized ESMs used in BalticAPP (Saraiva et al., 2019a) and CLIMSEA (Meier et al., 2021) during the historical period (1976-2005) and 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 are shown.

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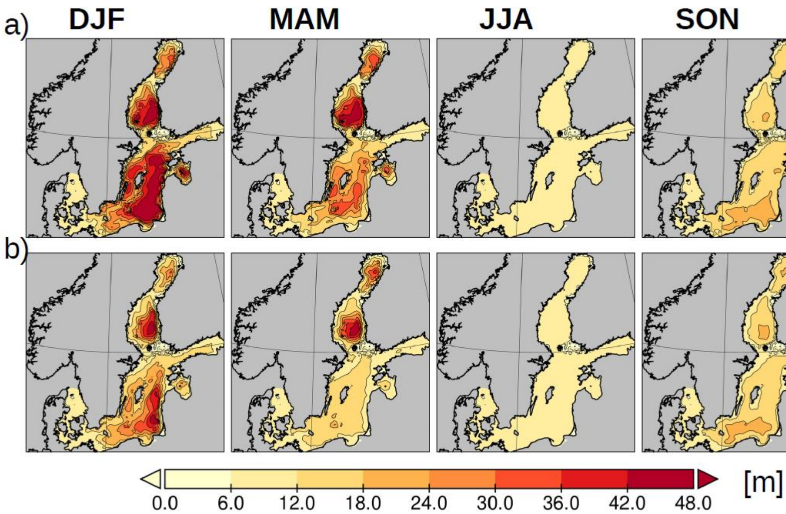

Figure 5: Mixed layer thickness calculated according to the 0.03 kg m^{-3} criterion following (de Boyer Montégut et al., 2004). a) Reanalysis data (Liu et al., 2017). b) Ensemble mean over the four models (Saraiva et al., 2019a). Shown are averages over 1976-1999.

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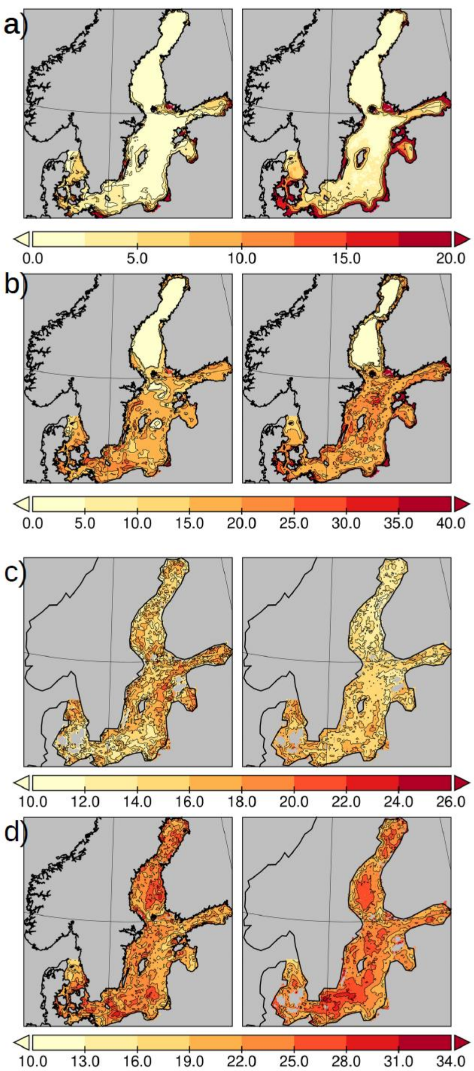

Figure 6: a) Number of >10-day periods where SST is > 20°C. b) Average duration of periods displayed in a). c) Number of 10-day periods where the SST is >95th percentile. d) Average duration periods displayed in c). Left column: reanalysis data (Liu et al., 2017). Right column: ensemble mean of the scenario simulations driven by four ESMs (Saraiva et al., 2019a). The analysis period is 1976-1999. Note the different color scales used in c) and d).

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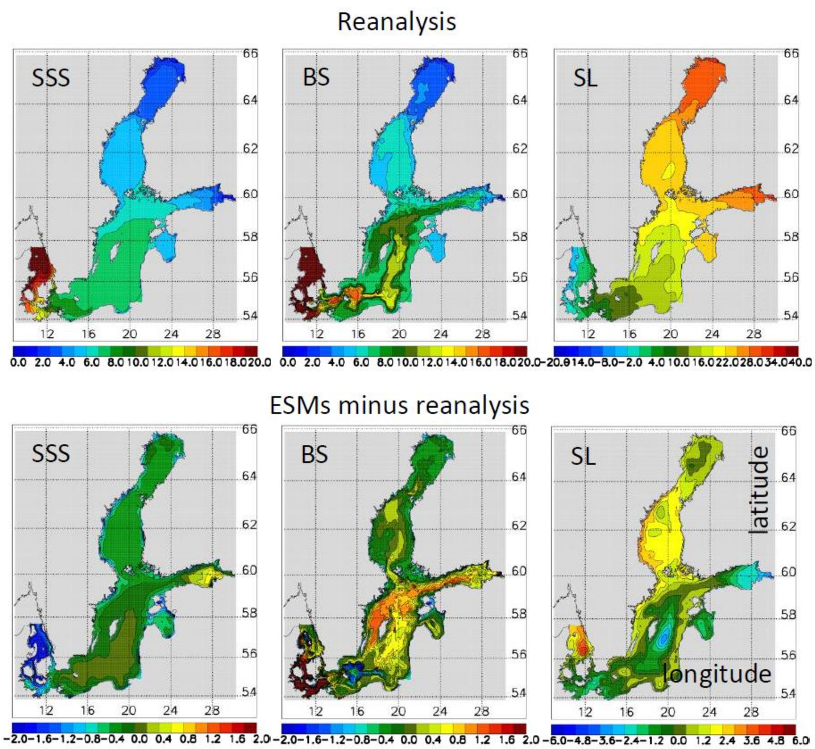

Figure 7: Upper panels: Annual mean sea surface salinity (SSS) and bottom salinity (BS) (in g kg^{-1}) and winter (December–February) mean sea level (SL) (in cm) in reanalysis data during 1971-1999 (Liu et al., 2017) (from left to right). Note that the model results of the sea level are given in the Nordic height system 1960 (NH60) by Ekman and Mäkinen (1996). Lower panels: Difference between climatologies of the ensemble mean of the regionalized ESMs used in BalticAPP (Saraiva et al., 2019a) during the historical period (1976-2005) and of the reanalysis data.

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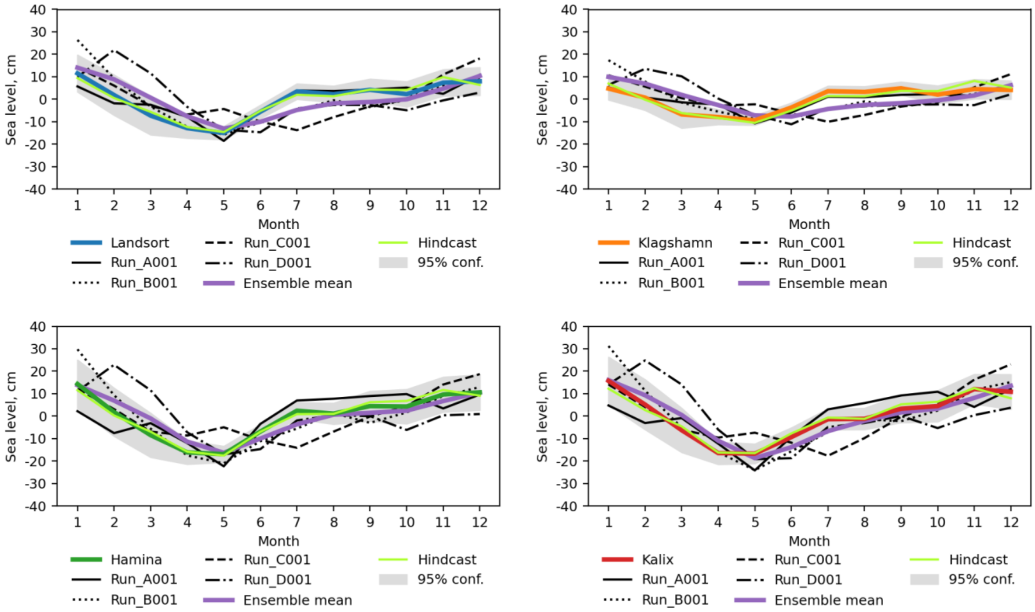

Figure 8: Monthly mean sea level of one hindcast (driven by regionalized reanalysis atmospheric surface fields) and four climate simulations (Saraiva et al., 2019a), the ensemble mean and observations for the historical period 1976-2005 at the sea level stations Klagshamn, Landsort, Hamina and Kalix (for the locations see Figure 1).

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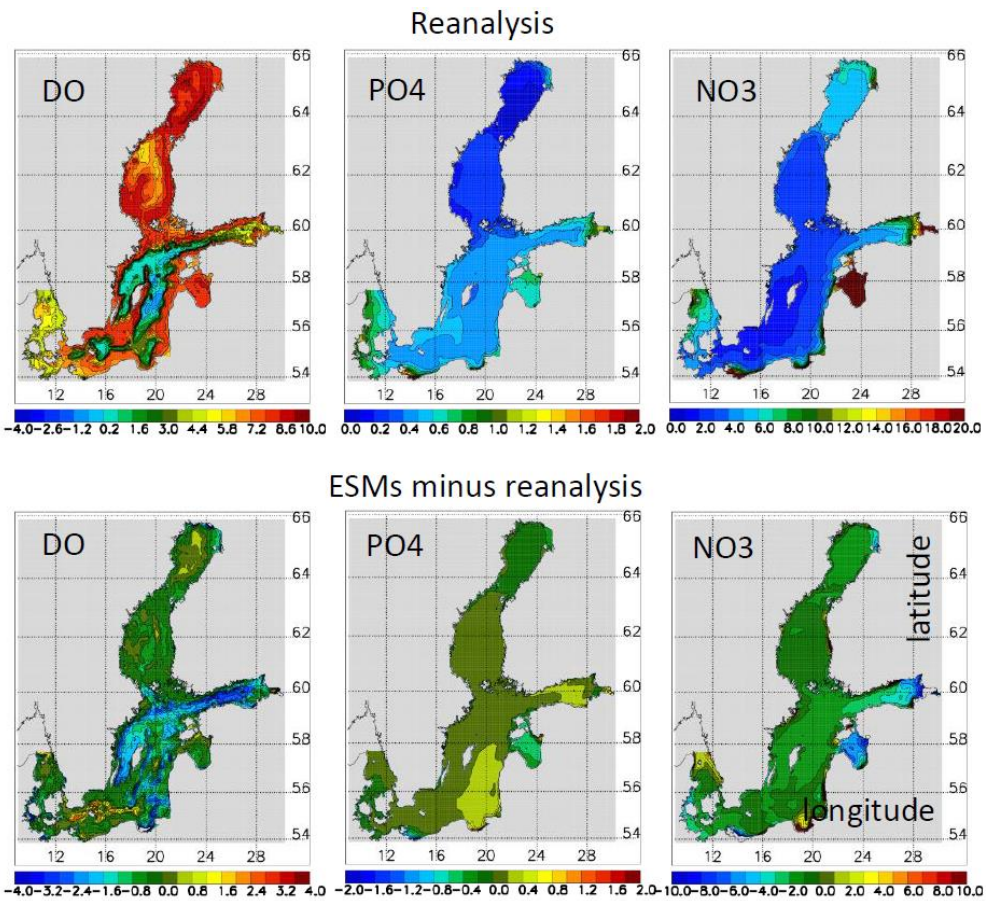

Figure 9: Upper panels: Summer (June–August) mean bottom dissolved oxygen (DO) concentrations (in mL L^{-1}), winter (December–February) mean surface phosphate (PO4) concentrations (in mmol P m^{-3}) and winter (December–February) mean surface nitrate (NO3) concentrations (in mmol N m^{-3}) in reanalysis data during 1976-1999 (Liu et al., 2017). Nutrient concentrations are vertically averaged for the upper 10 m. Lower panels: Difference between climatologies of the ensemble mean of the ESMs (Saraiva et al., 2019a) and the reanalysis data during the historical period (1976-2005).

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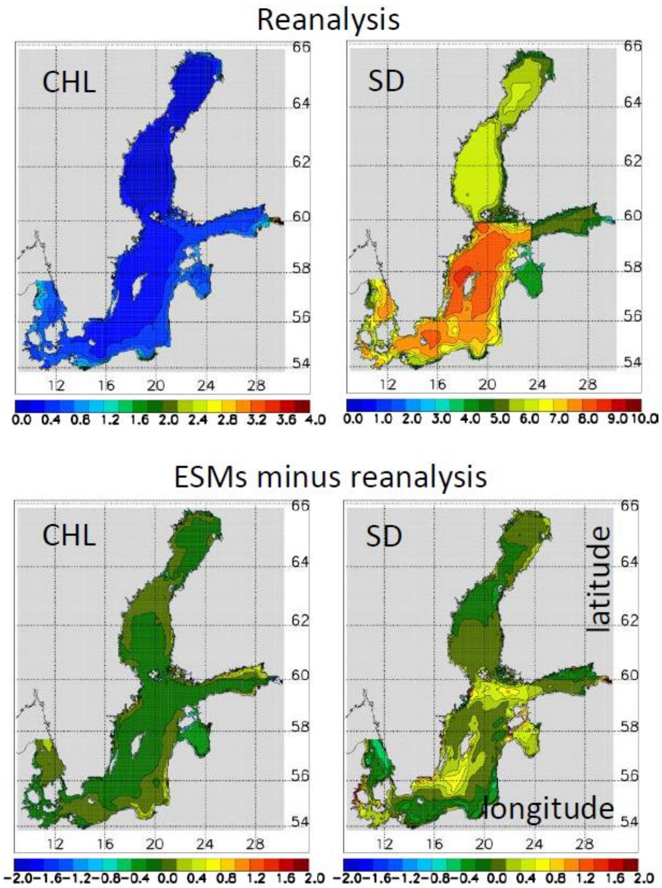

Figure 10: Upper panels: Annual mean phytoplankton concentrations (CHL) (in mg Chl m^{-3}) and annual mean Secchi depth (SD) (in cm) in reanalysis data during 1976-1999 (Liu et al., 2017). Phytoplankton concentrations are vertically averaged for the upper 10 m. As for the calculation of Secchi depth 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 climatologies of the ensemble mean of the ESMs (Saraiva et al., 2019a) and the reanalysis data during the historical period (1976-2005).

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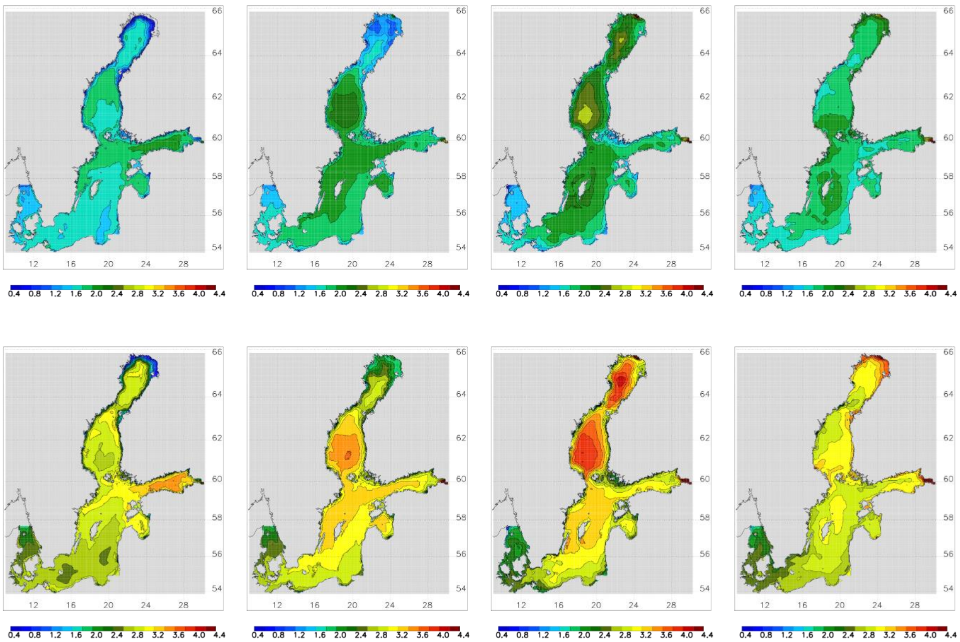

Figure 11. Changes in seasonal mean sea surface temperatures simulated by the CLIMSEA ensemble (Meier et al., 2021). From left to right, winter (December, January and February; DJF), spring (March, April and May; MAM), summer (June, July and August; JJA) and autumn (September, October and November; SON) 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.

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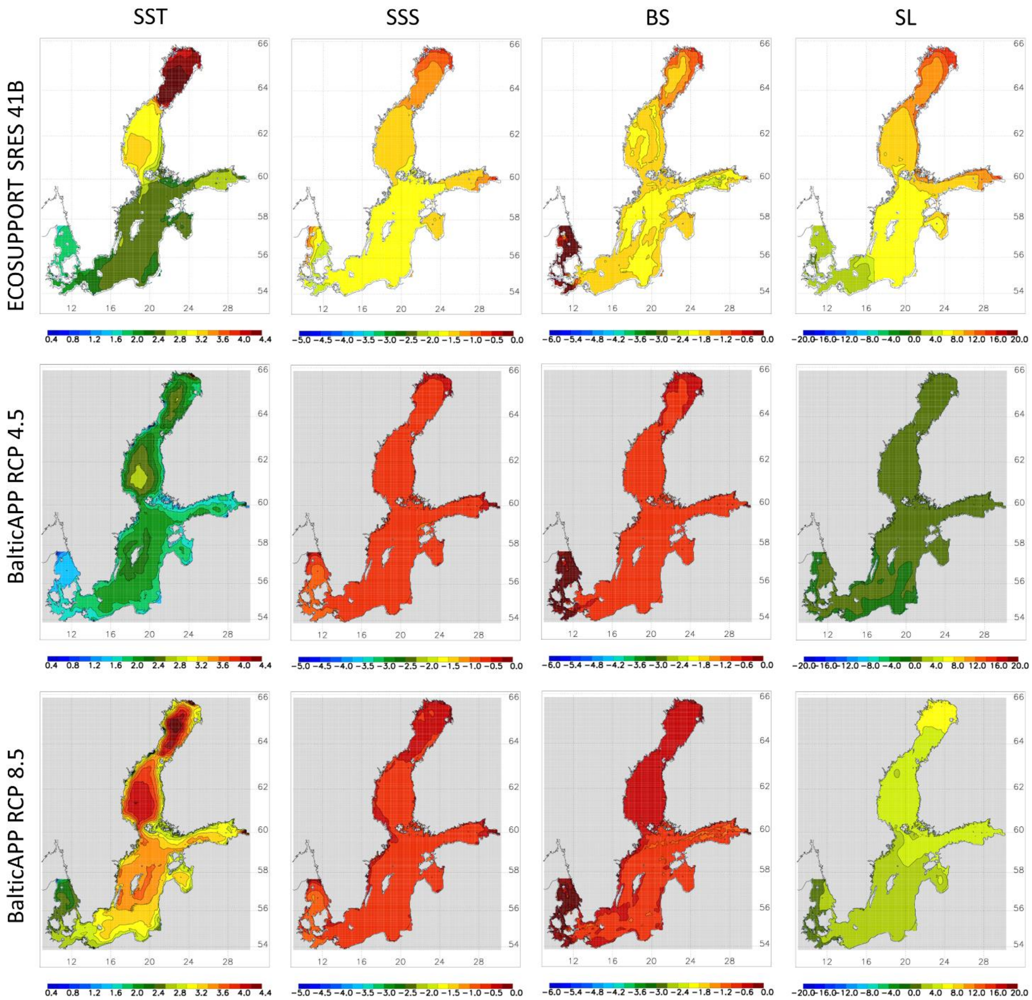

Figure 12: From left to right changes of summer (June – August) mean sea surface temperature (SST) (°C), annual mean sea surface salinity (SSS) (g kg^{-1}), annual mean bottom salinity (BS) (g kg^{-1}), and winter (December – February) mean sea level (SL) (cm) between 1978-2007 and 2069-2098 are shown. From top to bottom results of the ensembles ECOSUPPORT (white background, Meier et al., 2011a), BalticAPP RCP4.5 (grey background, Saraiva et al., 2019a) and BalticAPP RCP8.5 (grey background, Saraiva et al., 2019a) are depicted.

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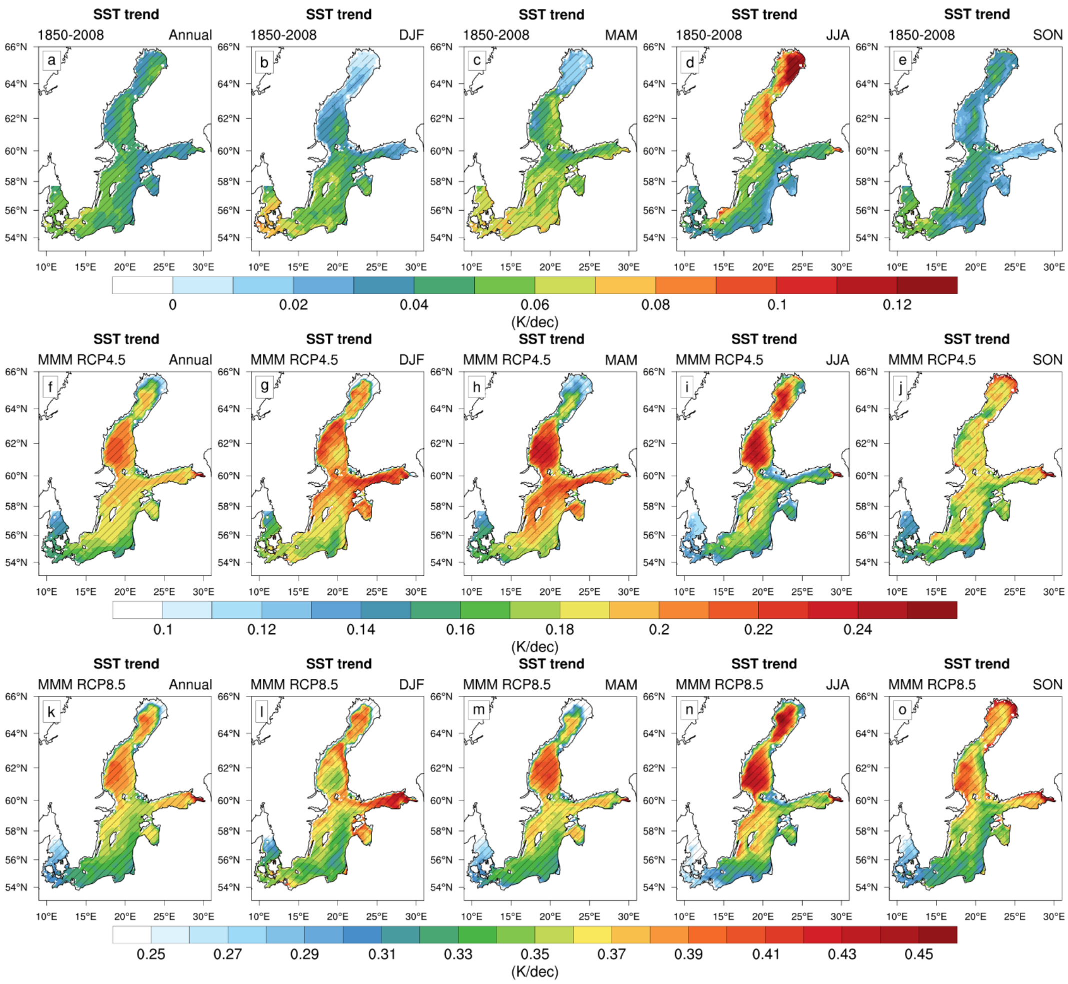

Figure 13: Multi-model mean (MMM) of annual (panels a and f) and seasonal (panels b-e and g-j) SST trends (in K decade^{-1}) computed for the period 1850-2008 (top), 2006-2099 in RCP4.5 (middle) and RCP8.5 (bottom) scenario. Hatched areas represent the regions where the trend is statistically significant (p-value<0.05, Mann-Kendall test). Data sources for historical reconstructions and projections are Meier et al. (2019d) and Saraiva et al. (2019a), respectively.

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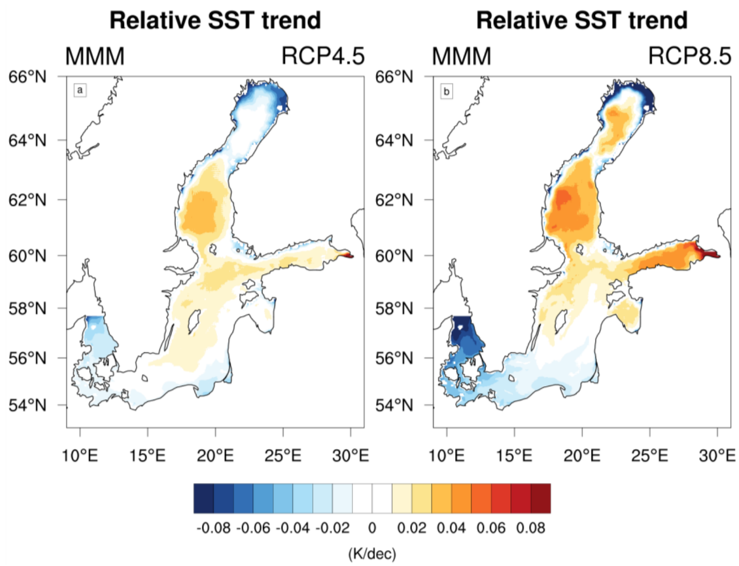

Figure 14: Multi-model mean of annual SST trends relative to spatial average (in K decade^{-1}) for a) RCP4.5 and b) RCP8.5 scenario simulations. (Data source: Saraiva et al., 2019a)

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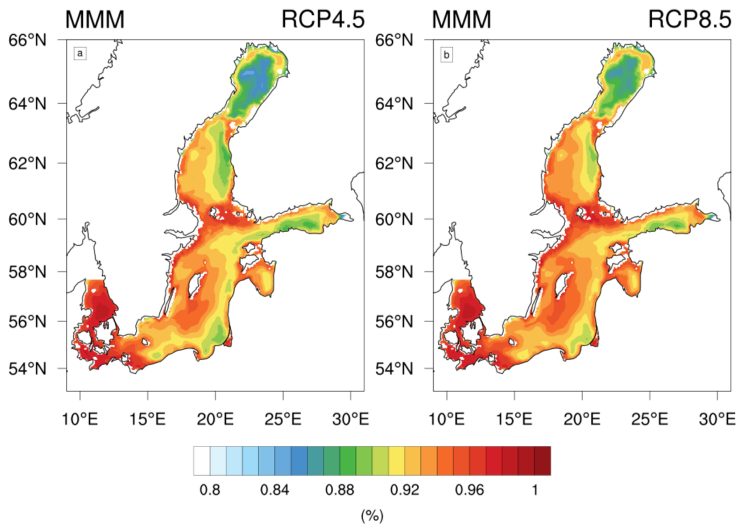

956
957 **Figure 15:** Multi-model mean explained variance (in percent) between the monthly mean sea surface
958 temperature and the forcing air temperature over 2006-2099 period in a) RCP4.5 and b) RCP8.5 scenario. (Data
959 source: Saraiva et al., 2019a)
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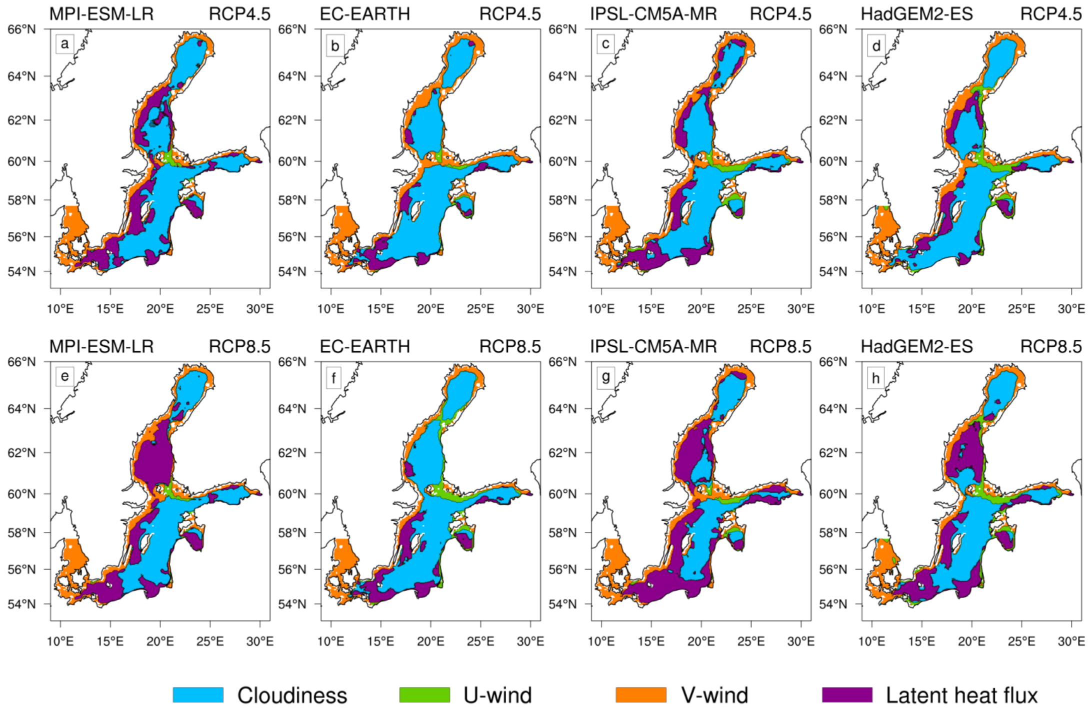

Figure 16: Results of the cross-correlation analysis of the detrended sea surface temperature (monthly mean is used) with the wind components, latent heat flux, and cloudiness. Maps of atmospheric drivers with the highest cross correlations in RCP4.5 (top) and RCP8.5 (bottom) scenarios for various GCMs forcings (Saraiva et al., 2019a). From left to right: MPI-ESM-LR, EC-EARTH, IPSL-CMA-MR, HadGEM2-ES.

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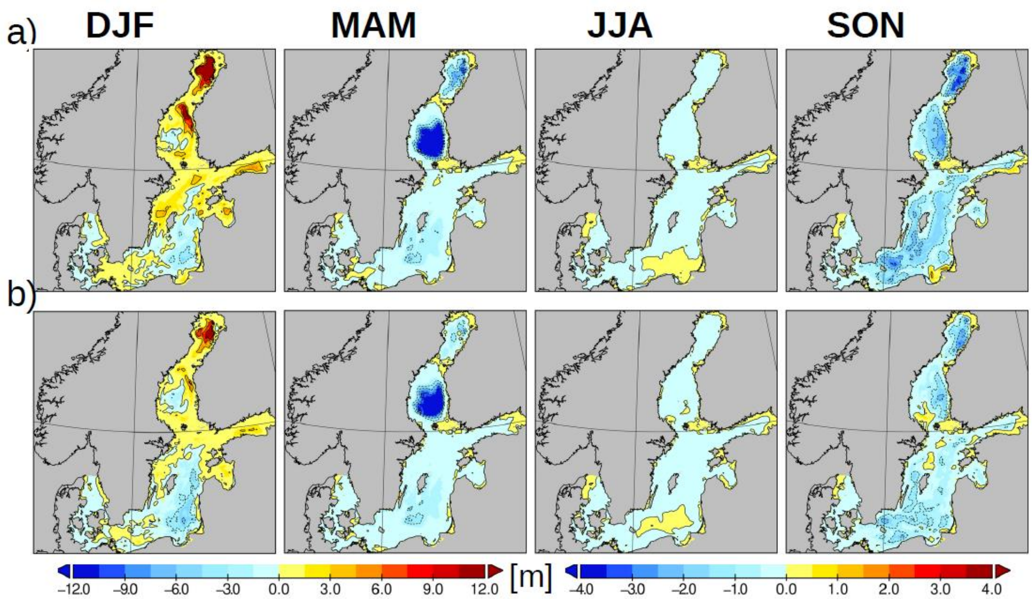

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970 **Figure 17.** Mixed layer depth calculated after the 0.03 kg m^{-3} criterion after de Boyer Montégut et al. (2004).
971 Shown are ensemble average changes of four different ESMs between 1976-2005 and 2069-2098 with the mean
972 sea level rises (a) 0.90 m (RCP8.5) and (b) 0.54 m (RCP4.5). (Data source: Meier et al., 2021)

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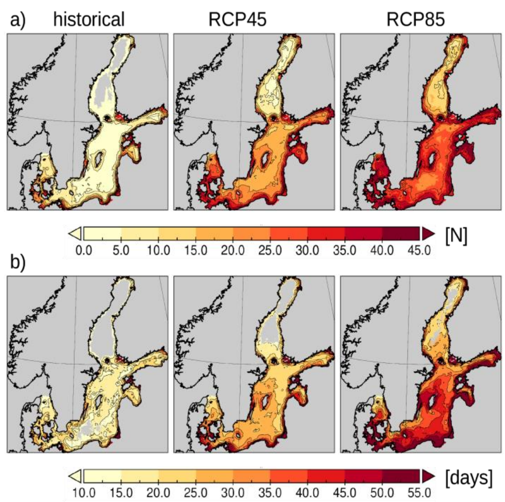

Figure 18. a) Heat waves (defined as periods of >=10 days with a water temperature of >= 20°C) for historical (1976-2005), and future (2069-2098) climates. b) Average duration of heat waves Note that no temperature bias adjustment was done prior to the analysis. Shown are ensemble averages of four different 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)

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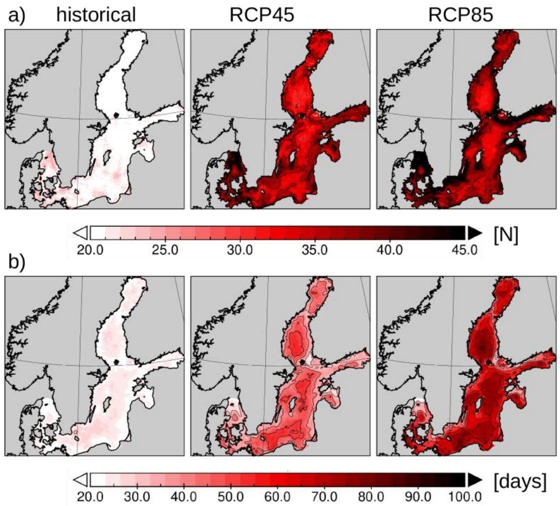

Figure 19. As Fig. 18 but for heat waves defined as periods of >=10 days with a water temperature of >= 95th percentile of the historical reference temperature. (Data source: Meier et al., 2021)

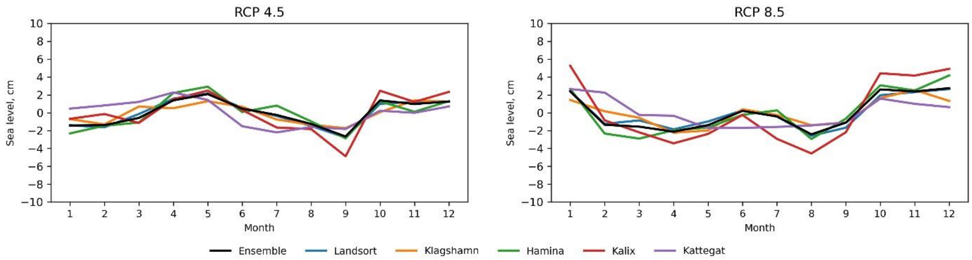

Figure 20: Monthly mean sea level changes between 1976-2005 and 2069-2098 at Klagshamn, Landsort, Hamina, Kalix and Kattegat (for the locations see Figure 1) for RCP4.5 (left panel) and RCP8.5 (right panel). Shown are the changes relative to the mean sea level rise (a) 0.54 m (RCP4.5) and (b) 0.90 m (RCP8.5). The chosen model approach does not indicate any non-linear effects for larger sea level rise scenarios. (Data source: Meier et al., 2021)

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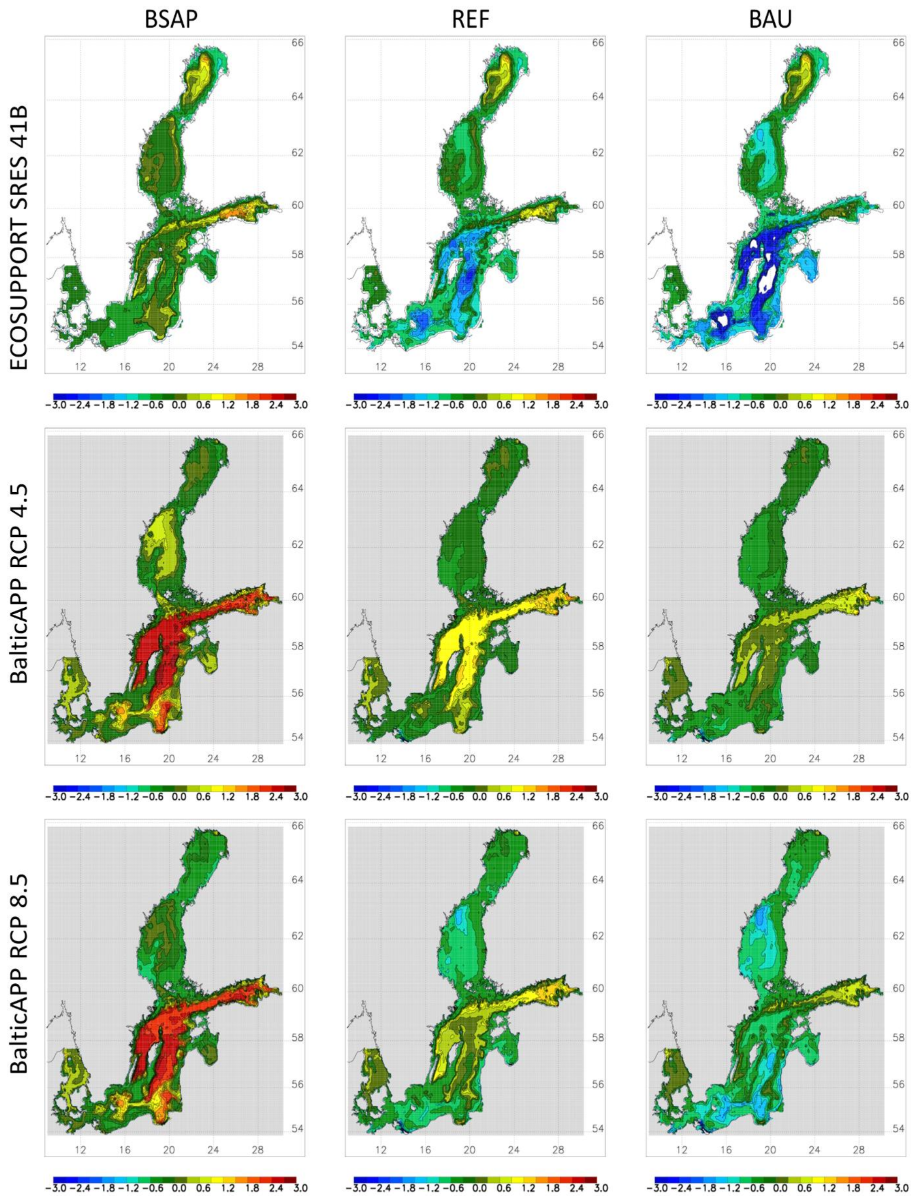
(a)



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(b)

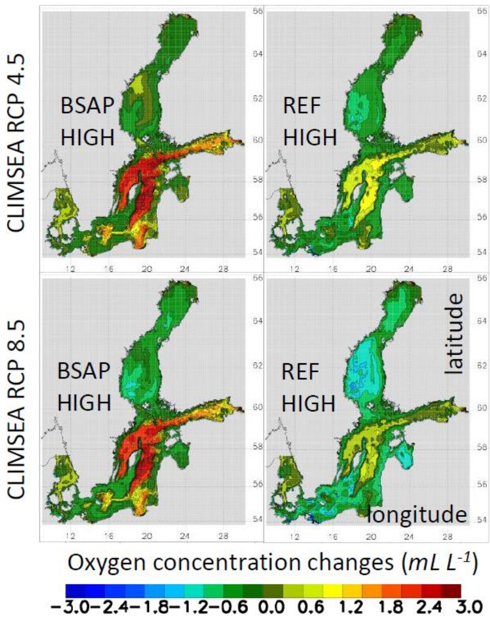

Figure 21: (a) Ensemble mean summer (June – August) bottom dissolved oxygen concentration changes (mL L^{-1}) between 1978-2007 and 2069-2098. From left to right results of the nutrient input scenarios Baltic Sea Action Plan (BSAP), Reference (REF) and Business-As-Usual (BAU) are shown. From top to bottom results of the ensembles ECOSUPPORT (white background, (Meier et al., 2011a)), BalticAPP RCP4.5 (grey background, (Saraiva et al., 2019a)) and BalticAPP RCP8.5 (grey background, (Saraiva et al., 2019a)) are depicted. (b) As panel (a) but for CLIMSEA RCP4.5 (upper panels) and CLIMSEA RCP8.5 (lower panels) under the high SLR scenario, i.e. 1.26 m (RCP4.5) and 2.34 m (RCP8.5). Left and right columns show BSAP and REF scenarios, respectively. (Source: Meier et al., 2021)

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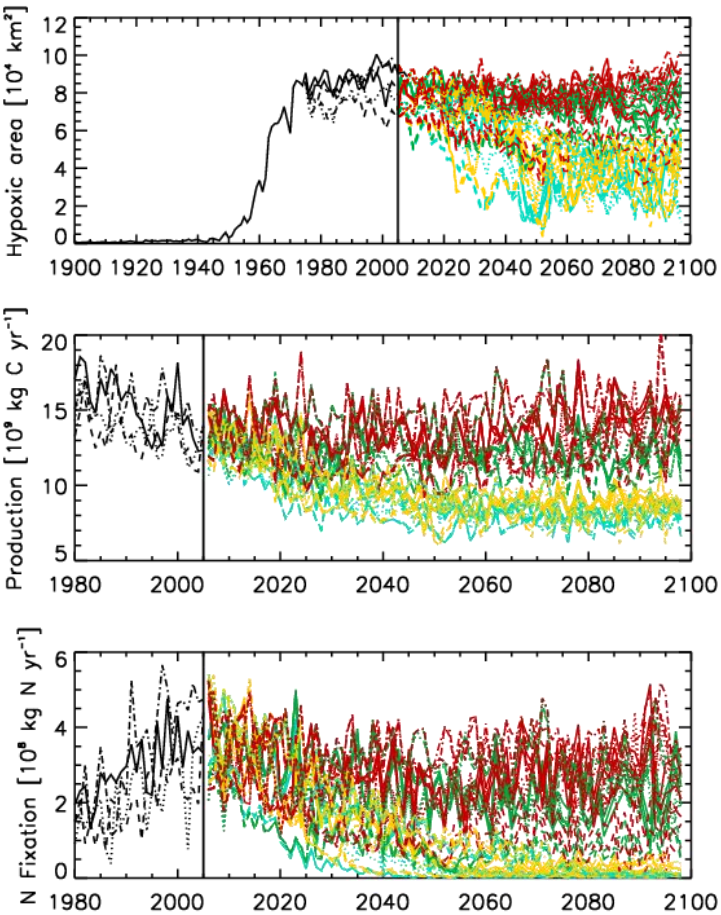
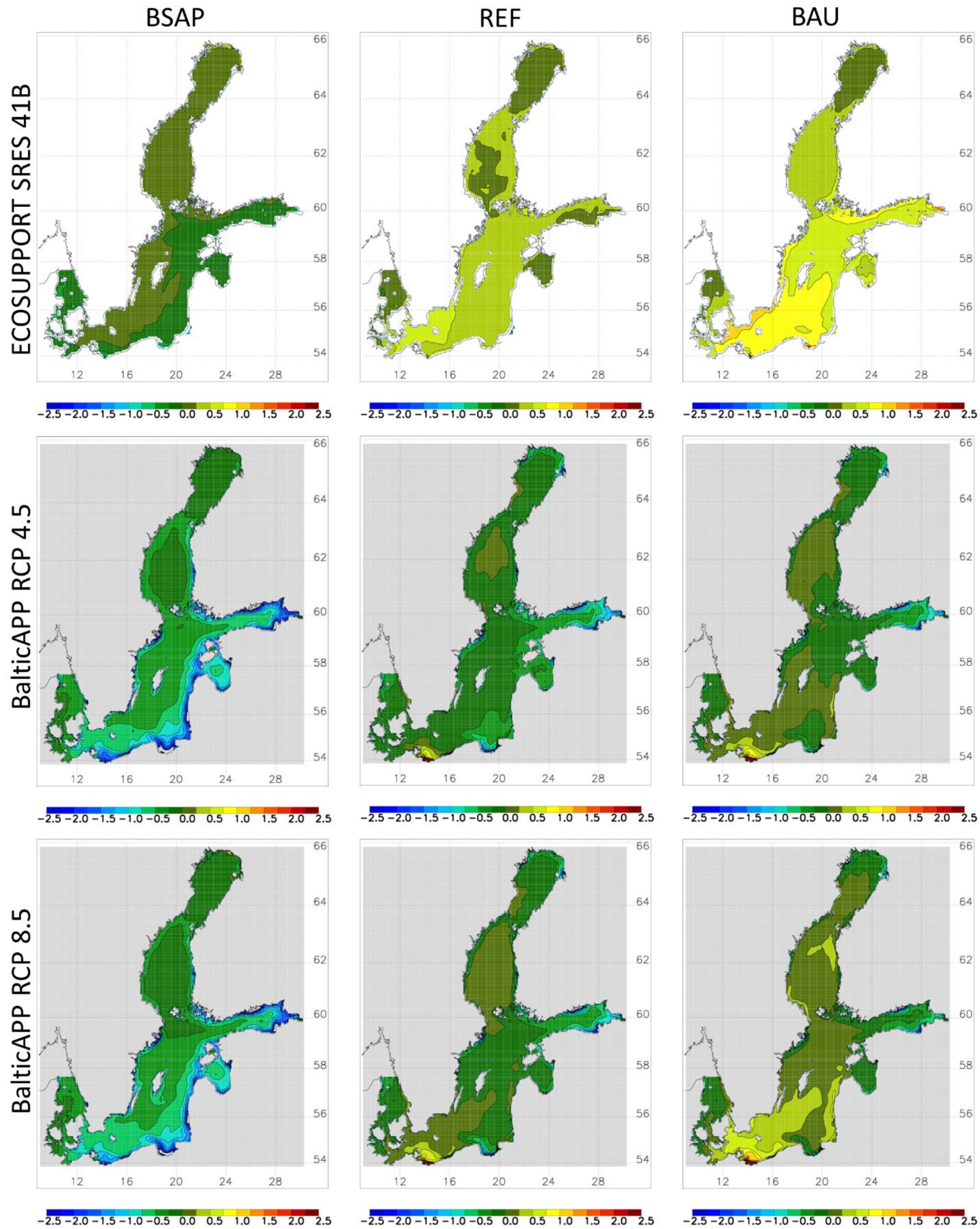


Figure 22: From top to bottom: hypoxic area (in km^2), volume-averaged primary production (in $kg\ C\ yr^{-1}$) and volume-averaged nitrogen fixation (in $kg\ N\ yr^{-1}$) for the entire Baltic Sea, including the Kattegat (see Fig. 1) in historical (≤ 2005, black lines) and scenario simulations (> 2005, coloured lines) 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)



1020

1021 **Figure 23:** As Fig. 21a but for annual mean surface phytoplankton concentration changes (mg Chl m^{-3}).
1022 Concentrations are vertically averaged for the upper 10 *m*. (Source: Meier et al., 2011a; Saraiva et al., 2019a)

1023

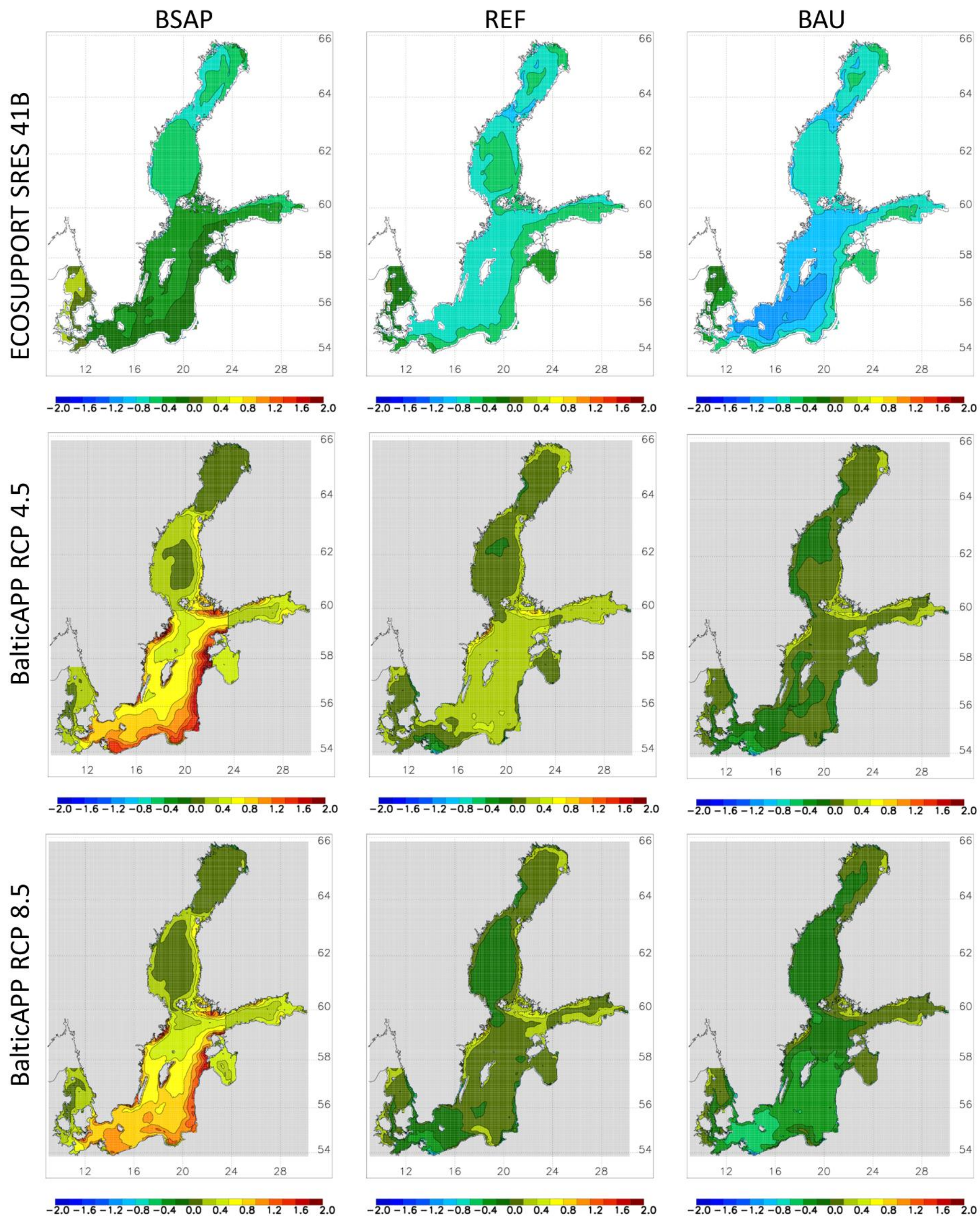


Figure 24. As Fig. 21a but for annual mean Secchi depth changes (m). (Source: Meier et al., 2011a; Saraiva et al., 2019a)

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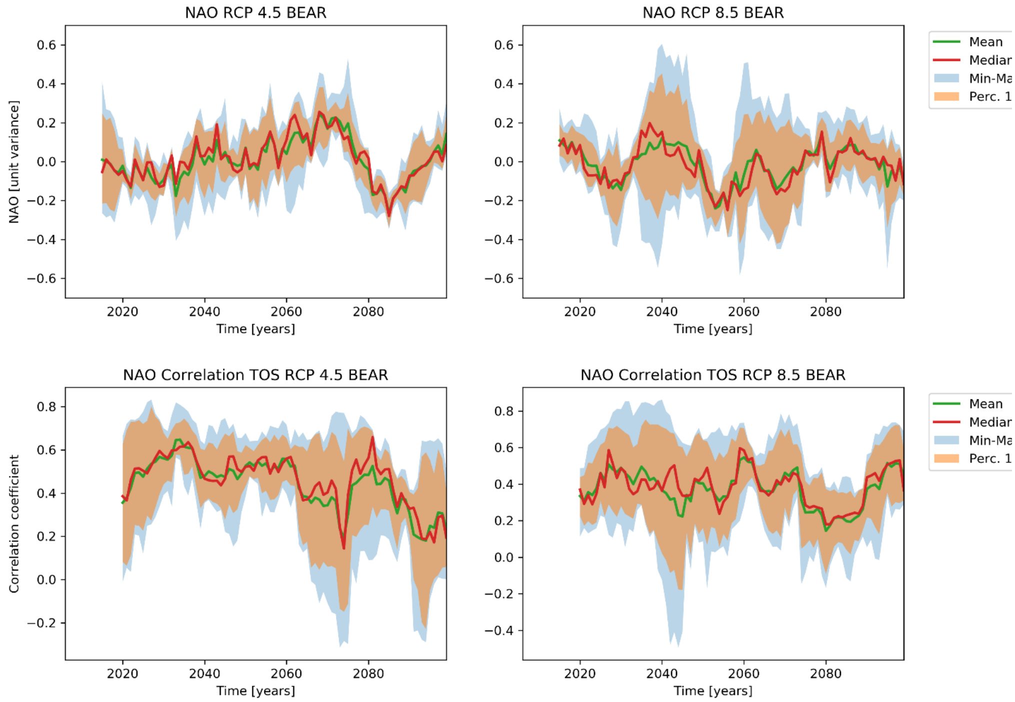

Figure 25. Ensemble mean North Atlantic Oscillation (NAO) index (upper panels) and 10-year running correlation between NAO and area averaged sea surface temperature (SST) in the Baltic Sea (lower panels) under RCP4.5 (left panels) and RCP8.5 (right panels) scenarios. (Data source: Meier et al., 2021)

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Tables

Table 1. Selected ensembles of scenario simulations for the Baltic Sea carried out in international projects (AR = IPCC Assessment Report, GCM = General Circulation Model, RCSM = Regional Climate System Model, RCAO = Rossby Centre Atmosphere Ocean model, RCA4 = Rossby Centre Atmosphere model Version 4, NEMO = Nucleus for European Modelling of the Ocean, REMO = Regional Model, MPIOM = Max Planck Institute Ocean Model, HAMSOM = Hamburg Shelf Ocean Model)

Project	Swedish Regional Climate Modeling Program	Advanced modeling tool for scenarios of the Baltic Sea ECOsystem to SUPPORT decision making	Holocene saline water inflow changes into the Baltic Sea, ecosystem responses and future scenarios	Building predictive capability regarding the Baltic Sea organic/inorganic carbon and oxygen systems	Wellbeing from the Baltic Sea - applications combining natural science and economics	Impacts of Climate Change on Waterways and Navigation	Regionally downscaled climate projections for the Baltic and North Seas
Acronym	SWECLIM	ECOSUPPORT	INFLOW	Baltic-C	BalticAPP	KLIWAS	CLIMSEA
Duration	1997-2003	2009-2011	2009-2011	2009-2011	2015-2017	2009-2013	2018-2020
Project summaries	Rummukainen et al., 2004	Meier et al., 2014	Kotilainen et al., 2014	Omstedt et al., 2014	Saraiva et al., 2019a	Bülow et al., 2014	Dieterich et al., 2019
GCMs	AR3	AR4	AR4	AR4	AR5	AR4/AR5	AR5
RCSM	RCAO	RCAO	RCAO	RCA	RCA4-NEMO	REMO-MPIOM, REMO-HAMSOM, RCA4-NEMO	RCA4-NEMO
Horizontal resolution atmosphere/ ocean	50 km/10.8 km	25 km/3.6 km	25 km/3.6 km and 50 km/3.6 km for paleoclimate	25 km /horizontally integrated	25 km /3.6 km	varying	25 km/3.6 km
Period(s)	1961–1990 and 2071–2100	1961-2099	1961-2099 and 950-1800 AD	1960-2100	1976-2100, improved initial conditions	1961-2099	1976-2100
Ocean model	One physical Baltic Sea model	Three physical-biogeochemical Baltic Sea models	See ECOSUPPORT	One physical-biogeochemical Baltic Sea model including the carbon cycle	One physical-biogeochemical Baltic Sea model	Two physical regional models with focus on the Baltic Sea and North Sea regions and one physical-biogeochemical ocean model	One physical-biogeochemical Baltic Sea model
References	Döscher and Meier, 2004; Meier et al., 2004a; Meier et al., 2004b	Meier et al., 2011a; Meier et al., 2012c; Neumann et al., 2012	See ECOSUPPORT, Schimanke and Meier, 2016	Omstedt et al., 2012	Saraiva et al., 2019a, b; Meier et al., 2019b	Bülow et al., 2014; Gröger et al., 2019; Dieterich et al., 2019	Gröger et al., 2021b; Meier et al., 2021

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Table 2. Salinity projections assessed by BACC Author Team (2008), BACC II Author Team (2015) and BEAR (this study). Salinity changes depend on changes in the wind field (in particular in the west wind component), river discharge and sea level rise (SLR).

	West wind	River discharge	Sea level rise	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 +22%	Medium SLR +0.54 to +0.90 m	No robust change with a considerable spread

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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 emission or concentration scenario, the nutrient input scenario, the sea level rise (SLR) scenario and the simulation period including historical and scenario periods. 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)						
HadCM3	RCAO	BALTSEM	A1B	BSAP/REF/BAU	0	1961-2099
ECHAM5/MPI-OM-r1	RCAO	BALTSEM	A1B	BSAP/REF/BAU	0	1961-2099
ECHAM5/MPI-OM-r3	RCAO	BALTSEM	A1B	BSAP/REF/BAU	0	1961-2099
ECHAM5/MPI-OM-r1	RCAO	BALTSEM	A2	BSAP/REF/BAU	0	1961-2099
HadCM3	RCAO	ERGOM	A1B	BSAP/REF	0	1961-2099
ECHAM5/MPI-OM-r1	RCAO	ERGOM	A1B	BSAP/REF	0	1961-2099
HadCM3	RCAO	RCO-SCOBI	A1B	BSAP/REF/BAU	0	1961-2099
ECHAM5/MPI-OM-r1	RCAO	RCO-SCOBI	A1B	BSAP/REF/BAU	0	1961-2099
ECHAM5/MPI-OM-r3	RCAO	RCO-SCOBI	A1B	BSAP/REF/BAU	0	1961-2099
ECHAM5/MPI-OM-r1	RCAO	RCO-SCOBI	A2	BSAP/REF/BAU	0	1961-2099
BalticAPP (21 scenario simulations, Saraiva et al., 2019a)						
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
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	1976-2098
HadGEM2-ES	RCA4-NEMO	RCO-SCOBI	RCP8.5	BSAP/REF/WORST	0	1976-2098
CLIMSEA (48 scenario simulations, Meier et al., 2021)						
MPI-ESM-LR	RCA4-NEMO	RCO-SCOBI	RCP4.5	BSAP/REF	0/0.54/1.26	1976-2099
MPI-ESM-LR	RCA4-NEMO	RCO-SCOBI	RCP8.5	BSAP/REF	0/0.90/2.34	1976-2099
EC-EARTH	RCA4-NEMO	RCO-SCOBI	RCP4.5	BSAP/REF	0/0.54/1.26	1976-2099
EC-EARTH	RCA4-NEMO	RCO-SCOBI	RCP8.5	BSAP/REF	0/0.90/2.34	1976-2099
IPSL-CM5A-MR	RCA4-NEMO	RCO-SCOBI	RCP4.5	BSAP/REF	0/0.54/1.26	1976-2099

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IPSL-CM5A-MR	RCA4-NEMO	RCO-SCOBI	RCP8.5	BSAP/REF	0/0.90/2.34	1976-2099
HadGEM2-ES	RCA4-NEMO	RCO-SCOBI	RCP4.5	BSAP/REF	0/0.54/1.26	1976-2098
HadGEM2-ES	RCA4-NEMO	RCO-SCOBI	RCP8.5	BSAP/REF	0/0.90/2.34	1976-2098

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Table 4. Ensemble mean changes in sea surface temperature (SST) (in °C) 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 (Data sources: Meier et al., 2011a; 2021; Saraiva et al., 2019a). (DJF = December, January, February, MAM = March, April, May, JJA = June, July, August, SON = September, October, November)

Δ SST	DJF	MAM	JJA	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

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Table 5. 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 (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 changes between 1978-2007 and 2069-2098 and between 1976-2005 and 2069-2098 were calculated, respectively. (Data sources: Meier et al., 2011a; 2021; Saraiva et al., 2019a)

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

https://doi.org/10.5194/esd-2021-68
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Table 6. As Table 5, but ensemble mean changes in 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 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; 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	-	-	-	-

https://doi.org/10.5194/esd-2021-68
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Table 7. As Table 5, but ensemble mean changes in annual Secchi depth (in m) 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 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; 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	-0.1	+0.6	+0.5	+0.6	+0.6	+0.6	+0.6
REF	-0.6	+0.1	-0.2	+0.2	+0.2	+0.1	+0.1
BAU/WORST	-1.1	-0.1	-0.5	-	-	-	-

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