Oceanographic regional climate projections for the Baltic Sea until 2100

H. E. Markus Meier[1,2], Christian Dieterich[2,┼], Matthias Gröger[1], Cyril Dutheil[1], Florian Börgel[1], Kseniia Safonova[1], Ole B. Christensen[3] and Erik Kjellström[2]

[1]Department of Physical Oceanography and Instrumentation, Leibniz Institute for Baltic Sea Research Warnemünde, Rostock, 18119, Germany
[2]Research and Development Department, Swedish Meteorological and Hydrological Institute, Norrköping, 601 76, Sweden
[3]Danish Climate Center, Danish Meteorological Institute, Copenhagen, Denmark
┼Deceased

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

Abstract. ~~Recently performed scenario simulations for the Baltic Sea including marine biogeochemistry were analyzed and compared with earlier published projections.~~ The Baltic Sea, located in northern Europe, is a semi-enclosed, shallow and tide-less sea with seasonal sea~~-~~ice cover in its northern sub-basins. ~~and a~~Its long water residence time ~~causing~~ contributes to oxygen depletion in the bottom water of ~~the~~ its southern sub-basins. ~~With the help of~~In this study, recently performed scenario simulations for the Baltic Sea including marine biogeochemistry were analy~~z~~sed and compared with earlier published projections. Specifically, dynamical downscaling using a regionally coupled atmosphere-ocean climate model was used to regionalise ~~,~~ four global Earth System Models ~~were regionalized~~. ~~As~~ However, as the regional climate model does not include components ~~for the~~representing terrestrial and marine biogeochemistry, an additional catchment and a coupled physical-biogeochemical model for the Baltic Sea were ~~use~~included~~d~~. ~~In addition to~~ Previous scenario simulations~~,~~ and scenarios taking into account the impact of various water levels were ~~scenarios was~~ examined ~~as well~~. According to the projections, compared to the present climate, ~~suggest~~ higher water temperatures, a shallower mixed layer with a sharper thermocline during summer, ~~reduced~~ less sea~~-~~ice cover and ~~intensified~~ greater mixing in the northern Baltic Sea during winter can be expected ~~compared to present climate~~. Both the frequency and the duration of marine heat waves ~~would~~ will increase significantly~~,~~ in particular in the coastal zone of the southern Baltic Sea (except in regions with frequent upwellings). Nonetheless, due to the uncertainties in the projections ~~of~~ regarding ~~the~~ regional winds, the water cycle and the global sea ~~-~~level rise, robust and statistically significant salinity changes ~~cannot~~ could not be identified. The impact of a changing climate on biogeochemical cycling is predicted to be considerable but ~~in any case~~still smaller than ~~the impact of~~that of plausible nutrient input changes. Implementing the proposed Baltic Sea Action Plan, a nutrient input abatement plan for the entire catchment area, would result in a significantly improved ecological status of the Baltic Sea, including reductions in the ~~and reduced~~ size of the hypoxic area also in a future climate, ~~strengthening~~ which in turn would increase the resilience of the Baltic Sea against anticipated ~~future~~ climate change. While our findings ~~about~~ regarding changes in ~~in variables of the~~ heat~~-~~cycle variables mainly confirm earlier scenario simulations, ~~earlier projections for salinity and biogeochemical cycles~~ they differ substantially from earlier projections of salinity and biogeochemical cycles, ~~because of different~~due to differences in experimental setups and ~~different~~ in ~~bioavailable nutrient~~ input scenarios for bioavailable nutrients.

During the time in whichpreparation of this paper was prepared, shortly before its 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 modelling of for the Baltic Sea, North Sea and North Atlantic regions.

1 Introduction

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

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

Formatiert: Englisch (Großbritannien), Ausgeblendet

In the early 21st century, about Some 85 million people, in 14 countries, currently were livinglive in the catchment area of the Baltic Sea, representing a considerableand anthropogenic pressure for on the marine ecosystem is accordingly high (HELCOM, 2018). Insufficiently treated wastewater, emissions of pollutant emissionss, overfishing, habitat degradation, and intensive marine traffic, including such as oil transport,s put place a heavy burden on the ecosystem of the Baltic Sea ecosystem (Reckermann et al., 2021). One example consequence is the oxygen depletion of the Baltic Sea's deep waters, with the consequence of dead seasuch that bottom areass lacking lack higher forms of life forms (e.g., Carstensen et al., 2014; Meier et al., 2018b). In 2018, the area of the dead bottoms was equal to the sizethat of the Republic of Ireland, with an area of about ~73,000 km^2, which is about one sixth of the sea surface area of the Baltic Sea. Bottom oxygen ofOxygen depletion in the deeper parts of the Baltic Sea is depleted because ofarise from the the limited ventilation of those waters of the deep water and because of the accelerated oxygen consumption due tothat accompanies the remineralizsation of organic matter (Meier et al., 2018b). Hence, nutrient input abatement strategies, ~~the so-called~~such as the Baltic Sea Action Plan (BSAP), ~~were~~ have been ~~discussed~~ proposed (HELCOM, 2007), ~~and~~ with projections of their impact ~~are~~ requested by stakeholders such as the Helsinki Commission (HELCOM) or national environmental protection agencies[1].

Projections ~~for~~ of the Baltic Sea's climate at the end of the 21st century were among the first to be made for coastal seas worldwide (Meier and Saraiva, 2020). Already at the beginning of the 2000s, the first scenario simulations, ~~based upon dynamical downscaling (Fig. 2)~~ were carried out for selected time slices in present and future climates (e.g.~~,~~ Haapala et al., 2001; Meier, 2002a, b; Omstedt et al., 2000~~; Rummukainen et al., 2001~~). ~~The~~ In the dynamical downscaling approach used for those simulations, ~~utilizes~~ regional climate models (RCMs) were employed to refine ~~the~~ predictions of global climate change to regional and local scales, in this case for ~~of~~ the Baltic Sea (e.g.~~,~~ Rummukainen et al., 2004; Döscher et al., 2002). However, ~~these~~ those first projections were based on scenarios consisting of~~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 the future ~~climate compared to~~vs. the historical climate) and only covered 10-year time slices. ~~After~~ These ~~very first~~initial attempts~~,~~ were therefore followed by 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~~2011c; Table 1). However, the latter studies considered only monthly mean changes ~~of~~ in the future ~~climate compared to~~vs. the present climate, applying ~~the~~ a so-called delta approach,~~;~~ while 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~~,~~ and even ~~including~~ included 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~~2011b; Meier et al., ~~2011b~~2011c; 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 trophic levels (e.g.~~,~~ Bauer et al., 2019; Ehrnsten et al., 2020; Gogina et al., 2020; Holopainen et al., 2016; MacKenzie et al., 2012; Niiranen et al., 2013; Vuorinen et al., 2015; Weigel et al., 2015). The BACC II Author Team (2015) concluded that "recent studies confirm the findings of the first assessment of climate change in the Baltic Sea basin". A ~~Detailed~~ key ~~messages were~~finding of ~~that~~ their report was that "No clear tendencies in saltwater transport were found. However, the uncertainty in salinity projections is likely to be large due to biases in atmospheric and hydrological models. Although wind speed is projected to increase over sea, especially over areas with diminishing ice cover, no significant trend was found in potential energy …" (a measure of energy to homogenize the water column). "In accordance with earlier results, it was found that sea-level rise has greater

Formatiert: Deutsch (Deutschland)

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

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

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

There is a notable difference in the salinity projections between the first two assessments (BACC Author Team, 2008; BACC II Author Team, 2015) and recent scenario simulations (Meier et al., 2021). ~~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~~ included a significant increase in the mean west wind component (Meier et al., 2006). These~~, such~~ pronounced changes in the large-scale atmospheric circulation were not ~~observed in~~a feature of later studies ~~anymore~~ (Saraiva et al., 2019a). However, ~~note that~~as the natural variability ~~is~~was poorly sampled, ~~and these~~this finding ~~differences might be just by chance~~may be coincidental.

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

~~The aim of this study is to~~In the following, we provide an overview ~~over~~ of the projections performed since 2013, i.e. after the last assessment of climate change for the Baltic Sea basin, and ~~to~~ compare ~~-~~recent results with previous findings by the BACC II Author Team (2015). We focus on projections for the marine environment, ~~both~~ from both physical~~s~~ and biogeochemical perspectives. ~~stry. Variables such as~~Among the analysed variables are temperature, salinity, oxygen, phosphate, nitrate, phytoplankton~~ concentration~~, primary production, nitrogen fixation, hypoxic area and Secchi depth (measuring water transparency)~~ are analyzed~~. An ~~accompanied~~ accompanying study by Christensen et al. (2021) investigated atmospheric projections in the Baltic Sea region. For an overview ~~on~~ of the development of RCSMs and their applications, the reader is referred to Gröger et al. (2021a). ~~For the~~In our comparisons ~~between~~ of the various ~~studies of~~ scenario simulations, we ~~analyze~~ analyse only published data (Table 1), with a~~.~~ ~~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). These are~~,~~ ~~that we~~ compared with the previous~~, henceforth called~~ ECOSUPPORT scenario simulations (Meier et

Formatiert: Englisch (Großbritannien)

Formatiert: Englisch (Großbritannien)

Formatiert: Englisch (Großbritannien)

Formatiert: Englisch (Großbritannien)

al., 2014)~~, which were~~ assessed by the BACC II Author Team (2015). ~~Efforts of investigating~~Investigations of the impact of climate change on ~~the Baltic Sea~~ primary production in the Baltic Sea ~~without utilizing a regional climate model~~that did not utilise a RCM (Holt et al., 2016; Pushpadas et al., 2015) are not addressed ~~in this study~~herein~~.~~, nor are ~~Also~~ nutrient input reduction scenarios under present climate, e.g. as described by Friedland et al. (2021)~~,~~ ~~are not considered~~. To our knowledge, further coordinated experiments ~~of~~ aimed at projections for the coupled physical-biogeochemical system of the Baltic Sea after 2013 ~~were~~ have not been published. Uncoordinated scenario simulations performed prior to 2013 (including Ryabchenko et al., 2016) and their uncertainties were previously discussed by Meier et al. (2018a; 2019b).

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

2 Methods

2.1 ~~Regionalization~~ Regionalisation of a changing climate

Dieterich et al. (2019) produced an ensemble of scenario simulations with a coupled RCSM, called RCA4-NEMO~~.~~ ~~RCA4-NEMO~~, which was introduced by Wang et al. (2015). Gröger et al. (2019; 2021b)~~,~~ and Dieterich et al. (2019) ~~have~~ validated and ~~analyzed~~ analysed the different aspects of the RCA4-NEMO ensemble discussed herein. The atmospheric component, RCA4 (Rossby Centre Atmosphere model Version 4), was run at a resolution of 0.22° ~~degrees~~ and 40 vertical levels in the EURO-CORDEX domain (Jacob et al., 2014), and the~~.~~ ~~Coupled to it is the~~coupled North Sea-Baltic Sea model NEMO (Nucleus for European Modelling of the Ocean) at a resolution of two nautical miles (3.7 km) and 56 levels. The two components of the RCSM are coupled by sending sea surface data of sea level pressure, energy, mass and momentum fluxes every ~~three hours~~3 h from the atmosphere to the ocean model. ~~Vice versa~~Conversely, the atmosphere model receives data of ~~at the same frequency~~ sea and ice surface temperatures and the sea-ice fraction and albedo at the same frequency.

This RCSM ~~has been~~was applied to downscale eight different Earth System Models (ESMs), each one 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~~ and references for the ESMs therein) and the GHG concentration scenarios RCP4.5 and RCP8.5 were selected (Table 3). The four ESMs were part of the Fifth Coupled Model Intercomparison Project (CMIP5; Taylor et al., 2012) and their results were assessed ~~by~~ in the Fifth IPCC Assessment Report (AR5; IPCC, 2013).

Surface variables of the atmospheric component were saved at hourly to 6-hourly ~~frequency~~ frequencies to allow for an analysis of means and extremes in present and future climates. As RCA4-NEMO does not contain model

Formatiert: Schriftart: Nicht Fett

Formatiert: Schriftart: Nicht Fett

Formatiert: Schriftart: Nicht Fett

Formatiert: Schriftart: Nicht Fett

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~~ has 41 levels with ~~varying~~ layer thicknesses ranging between 3 m close to the surface and 12 m at 250 m depth. The latter was the maximum depth in the model.

2.2 Catchment models

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

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

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

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

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

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

2.3 Baltic Sea models

~~In this~~This study~~,~~ used ~~the~~ data from three different Baltic Sea models ~~were used~~. The Swedish Coastal and Ocean Biogeochemical model coupled to the Rossby Centre Ocean model ~~coupled physical-biogeochemical ocean model~~ (RCO-SCOBI) ~~was~~ is driven by the atmospheric surface field data calculated by either RCAO or RCA4-NEMO and by the river runoff and nutrient input scenarios derived from either STAT or E-HYPE projections and atmospheric deposition (Fig. 2). Atmospheric depositions ~~were~~ are assumed to be constant ~~at the observed levels during 2010-2012~~ or reduced as in the BSAP (Fig. 3). RCO is a Bryan-Cox-Semtner-type ocean circulation model with horizontal and vertical grid resolutions of 3.7~~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~~; it considers state variables such as phosphate, nitrate, ammonium, oxygen concentration, the 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~~ has been 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).

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

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

Formatiert: Englisch (Großbritannien)
Formatiert: Englisch (Großbritannien)
Formatiert: Englisch (Großbritannien)
Formatiert: Englisch (Großbritannien)
Formatiert: Englisch (Großbritannien)
Formatiert: Englisch (Großbritannien)
Formatiert: Englisch (Großbritannien)
Formatiert: Englisch (Großbritannien)
Formatiert: Englisch (Großbritannien)
Formatiert: Englisch (Großbritannien)
Formatiert: Englisch (Großbritannien)
Formatiert: Englisch (Großbritannien)
Formatiert: Englisch (Großbritannien)
Formatiert: Englisch (Großbritannien)
Formatiert: Englisch (Großbritannien)
Formatiert: Englisch (Großbritannien)
Formatiert: Englisch (Großbritannien)
Formatiert: Englisch (Großbritannien)
Formatiert: Schriftart: (Standard) Times New Roman, Englisch (Großbritannien)
Formatiert: Englisch (Großbritannien)

2.4 Scenario simulations

In CLIMSEA, we have analysed an the ensemble of 48 RCO-SCOBI scenario simulations for the period 1976-–2098 (Table 3) that was produced following the dynamical downscaling approach described in the Sections 2.1–to 2.3 (Fig. 2) and presented by in Meier et al. (2021). Contrary toUnlike in previous studies (Meier et al., 2011a2011b; Saraiva et al., 2019a), the CLIMSEA scenario simulations also consider various scenarios of global sea- level rise (SLR). In the three SLR scenarios starting from the year 2005 that were applied by Meier et al. (2021) applied three SLR scenarios starting from the year 2005. In these scenarios, by the year 2100 the projected the mean sea level changes relative to the seabed projected by the year 2100 areare: (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-lowest case (1.26 m, here combined with RCP4.5) and high-casehighest case (2.34 m, here combined with RCP8.5) scenarios following Bamber et al. (2019; Table 3). By A deepening of the water depth at all grid points every 10 years -increases 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 are compared with earlier ensemble scenario simulations by Meier et al. (2011a2011b; 2012c) and Neumann et al. (2012) using, called (ECOSUPPORT), and by Saraiva et al. (2019a, b) and Meier et al. (2019a) using, called (BalticAPP). Both sets of scenario simulations, ECOSUPPORT and BalticAPP, applied rely on a similar downscaling approach similar to that as used for in the CLIMSEA projections (Fig. 2). However, the scenario simulations of ECOSUPPORT were are 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 is enlarged by three SLR scenarios (Table 3) whereas previous projections assumed that no change in the mean sea level relative to the seabed will not change. The need for includinginclusion of SLR scenarios is based uponfollowed the finding that the relative sea level above the sills in the entrance area limits the transport and controls salinity in the entire Baltic Sea (Meier et al., 2017). As the relative SLR during the period 1915–2014 was estimated to be 0–1 mm year^{-1}, resulting from the net effect of past eustatic SLR and land uplift (Madsen et al., 2019), a lowest-casen optimistic scenario for the future would be an unchanged relative a water level above the sills that is relatively unchanged (Meier et al., 2021). In CLIMSEA, mean and highest-case scenarios follow the median values of the RCP4.5 and RCP8.5 ensembles reported by (Oppenheimer et al. (, 2019) and the 95th percentiles of the lowest- and highest-case scenarios by of Bamber et al. (2019; Table 3).

2.5 Analysis

Evaluation of the historical period

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

Mixed~~-~~ layer depth

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

Secchi depth

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

Trends

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

Following Kniebusch et al. (2019), ~~a~~ we performed a ranking analysis ~~was performed~~ to ~~determine,~~identify the ~~which~~ atmospheric drivers others than air temperature that are most important for the monthly variability of SST in each ESM forcing of the CLIMSEA data set and in ~~both~~ the RCP scenarios~~,~~ RCP4.5 and RCP8.5. The SST trend is dominated by the trend in air temperature.~~,~~ ~~t~~Thus, to ~~partly~~ eliminate~~cancel~~ the air temperature effect on SST, the difference~~s~~ between~~residuals~~ the SSTs and~~from~~ a linear regression~~model fitting~~ between~~the~~ the SSTs and~~to the~~ surface air~~atmosphere~~ temperatures (SATs) ~~were~~was calculated~~was subtracted from the SST~~. ~~Then~~ This was followed by applying a cross-correlation analysis of the residual SSTs ~~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~~recent decades, the Baltic Sea region has warmed ~~up~~ faster than either the global mean warming (Rutgersson et al., 2015; Kniebusch et al., 2019) ~~and~~ or any other coastal sea (Belkin, 2009), making ~~this region~~it prone to marine heat waves (MHWs). Indeed, short periods of abnormally high water temperatures have ~~recently~~ been documented for the Baltic Sea (Suursaar, 2020). MHWs can be defined with reference to the mean climatology (e.g. the 90th, 95th, 98th percentile temperature) or by temperatures exceeding absolute temperature thresholds, ~~to be~~ defined with respect to the end-~~-~~user application~~s~~ (Hobday et al., 2018). In most cases, MHWs are defined by the number of periods, ~~the~~ their intensity,~~,~~ ~~and~~ their duration and ~~for~~ the specific purpose~~s~~ (Hobday et al., 2018). In this study, ~~w~~~~We here only~~the focus was on the general impact of climate change ~~addressing~~and the sensitivity of ecosystem dynamics. Hence, ~~since an appropriate definition of metrics for MHWs suitable for the Baltic is lacking. In the following,~~ MHWs ~~are~~ are defined herein as periods of ~~consecutive days with an~~ SST ≥ ~~>=~~ 20°C lasting for at least 10 consecutive days ~~to better reflect the sensitivity of ecosystem dynamics~~. For comparison, we showed also MHWs defined as periods of SST exceeding the 95th percentile of the SST distribution also lasting for at least 10 consecutive days.

3 Results

3.1 Historical period

3.1.1 Water temperature

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

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

In the ECOSUPPORT scenario simulations, there is also a systematic warm bias of the RCAO driven by GCMs at the lateral boundaries, ~~particularly resulting in too warm~~such that winter water temperatures are too warm and

~~too low~~ sea-ice cover is too low (Meier et al., ~~2011c~~2011d, d; 2012c, d). While these biases ~~are~~ occur~~found~~ in all three applied Baltic Sea models (Table 3) forced with ~~the~~ RCSM atmospheric surface fields, in the simulations driven ~~with~~ by ~~regionalized~~ regionalised reanalysis data (ERA-40) ~~showed smaller~~ the mean biases are smaller (Eilola et al., 2011).

3.1.2 Mixed-layer depth

Figure 5 shows the seasonal MLD cycle calculated after de Boyer Montégut et al. (2004). A deeper MLD with pronounced west-east gradients ~~is seen over the~~characterises the open ocean~~, with pronounced west - east gradients~~. This is related to the predominant south-westerly wind regime, with the larger wind fetches and higher significant wave heights in the eastern Gotland Basin causing wave-induced vertical mixing. Furthermore, a positive sea-atmosphere temperature contrast ~~favors~~ favours higher wind speeds (‘positive winter thermal feedback loop’; Gröger et al., 2015; 2021b). In spring, a weakening wind regime, which ~~lowering~~ reduces heat exchange (~~thereby turning from~~with a shift from heat loss to heat gain), ~~and~~ together with the increased solar irradiance leads to a thinner MLD in the southern Baltic Sea while ~~in the northern part~~ melting sea ice and subsequent thermal convection and wind-induced mixing ~~still~~ maintain a MLD~~s~~ > 50 m in the sea’s northern part. During summer, ~~the~~ when atmosphere-ocean dynamics ~~is~~ are weakest, ~~leading to~~ a pronounced thermocline develops and ~~shallowest~~ MLDs are shallowest (the ~~so-called~~ ‘summer thermal short circuit’; Gröger et al., 2021b). During autumn, the atmosphere cools faster than the E~~e~~arth’s surface, and land masses ~~cool~~ faster than ~~the~~ open sea areas. ~~Because of the~~These increased thermal ~~contrasts~~differences result in a stronger~~,~~ ~~the~~ large-scale wind regime ~~strengthens~~ with a positive feedback on the MLD.

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

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

3.1.3 Marine heat waves

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

The first ~~index for~~ MHW indexs uses a fixed threshold ~~focusing more on~~that emphasises the environmental impact of the heat waves. In particular, diazoetrophic 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 periodsMHWs are mostly absent in the open sea of the Baltic proper and further north in the Gulf of Bothnia. MHWs, but they are most highly abundant in shallow marginal bays like such as the Gulf of Finland and Gulf of Riga as well as along the coasts. The RCO ensemble mean produces The MHWs produced by the RCO ensemble mean are generally more frequent MHWs and MHWsand of longer duration than those of the reanalysis data set. Furthermore, the coastal signature of high abundance extents moreextends further offshore (Fig. 6a). In case ofFor 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 defined as that of 1976-–1999. The number of MHWs (Fig. 6c) correlates is negatively correlated towith their average duration (Fig. 6d). This is somewhat more pronounced in the reanalysis data set. In general, the patterns obtained with the reanalysis data and the RCO show are similar patterns but the amplitude of spatial variance is higher in the reanalysis dataformer (Fig. 6c), which assimilatedas it includes small-scale regional observations. The duration of MHWs In the RCO (Fig. 6d), MHWs is highest in the open sea are of the longest duration, where withwind events are probably the main process interrupting heat waves their interruption likely due to the vertical mixing induced by wind events by induced vertical mixing.

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

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

3.1.4 Salinity

The annual mean sea surface salinity (SSS) distribution shows a large north–south gradient mirroring both the input of freshwater from rivers, mostly located in the northern catchment area, and saltwater inflows from the North Sea (Fig. 7). The SSS drops from about 20 g kg^{-1} in the Kattegat to < 2 g kg^{-1} in the northern Bothnian Bay and eastern Gulf of Finland. For the period 1970– to 1999, the annual mean SSS of the Baltic Sea including the Kattegat amounts to aboutwas ~7.3 g kg^{-1}. Occasionally big Large inflows of heavy saltwater from the Kattegat occasionally ventilate the bottom water of the Baltic Sea, filling its deeper regions (Fig. 7). Due to almost absentAs tides are almost absent, mixing is limited and such that the water column is characterized characterised by a pronounced vertical gradient in salinity, and consequently also in density, between the sea surface and the bottom.

Probably due to differences in the data of the- hydrological model (E-HYPE) data compared to observations, in the CLIMSEA climate models SSS in the coastal zone and in the Kattegat is on average lower in the CLIMSEA climate models compared tothan in the reanalysis data byof Liu et al. (2017) (Fig. 7). The spatially averaged, annual mean bias ~~amounts to~~is −~~-~~0.4 g kg^{-1}. ~~In the climate models,~~ Bottom salinities in the Belt Sea, Great Belt area and the Gotland Basin (~~most pronounced~~especially in the northwestern part) are considerably higher and in the Bornholm Basin considerably lower in the climate models than in the reanalysis data (Fig. 7). The spatially averaged, annual mean bias ~~amounts to~~is +0.3 g kg^{-1}. Hence, ~~the~~ vertical stratification in the Belt Sea, Great Belt area and the Gotland Basin is also larger in the climate models than in the reanalysis data, because the difference between surface and bottom ~~salinity~~salinities is a good proxy for ~~the~~ vertical stratification.

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

3.1.5 Sea level

Due to the seasonal cycle in wind speed, with wind directions predominantly from the southwest, the sea level in the Baltic Sea varies considerably throughout the year, ~~with~~with the highest ~~sea~~ levels ~~of about~~ (~40 cm), measured relative to the Kattegat, occurring during winter~~,~~ at the northern coasts ~~in~~ of the Bothnian Bay and at the eastern coasts ~~in~~ of the Gulf of Finland (Fig. 7). For the period 1976–~~ to~~ 1999, the annual mean sea level in the Nordic height system 1960 (NH60) as determined by Ekman and Mäkinen (1996) ~~amounts to~~was ~~about~~ ~16 cm, with a horizontal north–south difference of ~~about~~ ~35 cm (not shown). This sea level slope ~~is~~ was explained by the lighter brackish water in the northeastern Baltic Sea ~~compared to~~than in the Kattegat and by ~~the mean~~ wind coming from the southwesterly direction,~~s~~ which pushes the water to the north and ~~to the~~ east (Meier et al., 2004a).

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

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

3.1.6 Oxygen concentration and hypoxic area

Since the 19~~5~~40s, nutrient inputs into the Baltic Sea have increased due to population growth and intensified ~~fertilizer~~ fertiliser use in agriculture (Gustafsson et al., 2012; Fig. 3). Nutrient inputs reached their peak in the 1980s ~~and~~ but have steadily declined ~~thereafter until the early 21st century as a consequence of~~following the implementation of nutrient input abatement strategies. Nonetheless, since the 1960s, the bottom water of the Baltic Sea below the permanent halocline ~~is~~ has been ~~characterized~~ characterised by oxygen depletion and large-scale hypoxia (Fig~~s~~. 9 ~~and 22~~).

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

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

3.1.7 Nutrient concentrations

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

~~During~~ For the historical period of 1976–1999, winter surface phosphate concentrations ~~in~~ according to the climate simulations are relatively close to those of the reanalysis data (Fig. 9). The ~~Considerably dDifferent~~ concentrations ~~are only~~differ substantially ~~found~~ only in those coastal regions influenced by large rivers ~~probably due to differing inputs. Such regions are, for instance,~~, such as ~~the coastal zones~~those affected by ~~the~~ discharges of the Odra, Vistula and Pärnu rivers. Spatially averaged biases are largest during summer and autumn, with an average bias ~~and~~ in summer ~~amounted to~~of +0.2 mmol P m^{-3} ~~in summer~~.

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

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

(Meier et al., 2012d). According to hindcast simulations, the biases in the coupled physical-biogeochemical models ~~for~~ of the Baltic Sea ~~showed larger biases~~ relative to the standard deviations of observations are larger ~~in~~ for the northern Baltic Sea than ~~in~~ for the Baltic proper (Eilola et al., 2011).

3.1.8 Phytoplankton concentrations

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

~~Following~~ Due to nutrient concentration biases, the ~~simulated~~ annual mean surface phytoplankton concentrations of the simulations are close to those of the reanalysis data ~~by~~of Liu et al. (2017) but they deviate~~d~~ in coastal regions (Fig. 10). Spatially averaged biases during winter, spring, summer, and autumn and in the annual mean are relatively~~rather~~ small: ~~and amount to~~ +0.02, −~~-~~0.1, −~~-~~0.009, +0.06 and −~~-~~0.008 mg chlorophyll (Chl) m^{-3}~~,~~ respectively. Note that ~~in~~ the reanalysis ~~by~~data of Liu et al. (2017) assimilate~~incorporate~~ nutrient and oxygen concentrations ~~were assimilated~~ but not chlorophyll data.

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

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

In the ECOSUPPORT scenario simulations, Secchi depth ~~has not been~~~~is~~was not ~~analyzed relative to~~compared with observations.

3.1.9 Biogeochemical fluxes

An evaluation of biogeochemical fluxes, such as primary production and nitrogen fixation, is difficult because ~~of lacking~~ observations are lacking. An exception is the study by Hieronymus et al.~~,~~ (2021), ~~who compared~~in which historical simulations ~~were compared~~ with RCO-SCOBI were compared with in situ observations of nitrogen fixation. The RCO-SCOBI model~~latter~~ includes ~~including~~ a cyanobacteria life cycle (CLC) model (Hense and

Beckmann, 2006; 2010) driven by reconstructed atmospheric and hydrological data and combined with in in situ observations of nitrogen fixation. Hieronymus et al. (2021)The authors found a satisfactory agreement, with the results mainly within the uncertainty range of the observations. However, simulated monthly mean nitrogen fixation during 1999-–2008 showed a prolonged peak period in July and August while whereas according to the observations showed athe peak was more mostly confined to July. However, Iit should be noted that the RCO-SCOBI version that has been used forused in the scenario simulations discussed here (e.g., Saraiva et al., 2019a) doesdid not contain a CLC model.

3.2 Future period

3.2.1 Water temperature

Annual and seasonal mean changes

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

In the CLIMSEA/BalticAPP RCSM projections, the annual mean SST changes in the Baltic Sea driven by four ESMs, i.e. MPI-ESM-LR, EC-EARTH, IPSL-CM5A-MR, HadGEM2-ES, under the RCP8.5 scenario amount toare +2.327, +3.70, +3.52 and +4.67°C respectively (Gröger et al., 2019). Thus, the ensemble mean change is +3.54°C. The corresponding ensemble mean change in the RCO-SCOBI scenario simulations is smaller, and amount to +2.92°C. Different MLDs, vertical stratification and sea-ice cover in the two ocean models, RCO-SCOBI and NEMO, may explain the different responses. Indeed, the a comparison of the MLD between the two models reveals a systematic shallower MLD in the RCSM compared tothan in RCO-SCOBI (not shown), which would argues for a higher sensitivity of the RCSM to climate warming.

While the spatial patterns of the SST changes in the scenario simulations of ECOSUPPORT (e.g., Meier et al., 2012c) and CLIMSEA (e.g., Saraiva et al., 2019b) scenario simulations are similar. However, the uncertainties due to the applied global (Meier et al., 2011d2011a) or regional (Meier et al., 2012b) model might beare in some cases considerable. In particular,Of note is the summer ensemble range caused byof the various GCMs is

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

notablesignificant (Meier et al., 2011d2011a). The differences in the magnitude of the warming are explained by the various GHG concentration scenarios (shown in Fig. 12).

Trends

Since SLR and nutrient input scenarios have a negligible impact on SST changes, only a comparison betweenthe RCP4.5 and RCP8.5 scenarios in CLIMSEA/BalticAPP has been doneare compared. The multi-model mean of the annual mean SST trends averaged over the Baltic Sea is about ~0.18 °CK decade^{-1} and ~0.35 °CK decade^{-1} in the RCP4.5 and RCP8.5 scenarios, respectively (Fig. 13a, f). At the Baltic Sea scale, seasonal SST trends from based on annual values vary only slightly (±0.01 °CK decade^{-1} in both scenarios). However at the sub-basin scale, seasonal variations are much stronger, reaching ±0.05 °CK decade^{-1} in the northern Baltic Sea, with a maximum in summer (Fig. 13). This summer maximum in the northern Baltic Sea can likely be explained by the projected decline ining sea-ice cover in in this seasonsummer, as occurred during the period 1850––2008 period (Kniebusch et al., 2019).

As seen in Figure 14, the relative SST trends indicate that faster warming of the northern Baltic Sea will warm faster than the southern Baltic Sea (0.02 °CK decade^{-1} and 0.04 °CK 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 °CK decade^{-1} and ~0.45 °CK 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 over a period of about 30 years. For exampleHowever, in the RCP8.5 scenario, SST trends gradually increase over the first 50 years of the period, reaching a maximum of 0.5 °CK decade^{-1} decade^{-1} over the periodbetween 2046- and 2075, before declining slightly from 2060 onwards., As in the RCP4.5 scenario, this is a result of the pronounced natural variability in this scenario as well. Despite the robustness of the spatial pattern of the SST trends spatial pattern (p-value < 0.05 everywhere), the an analysis of SST trends for the four ESM forcings reveals an important dependency of SST those trends to on atmospheric forcings, with a spread of ±0.06 °CK decade^{-1} decade^{-1} from the multi-model mean in of both scenarios (not shown).

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

To analyze theThe processes responsible for the SST trends were analysed using, a rank analysis from of 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 in the SST differs according to the location and ESM. Nevertheless, in all ESMs and in both RCP scenarios, zonal and meridional wind components are the variables most correlatedthat best correlate with SST along most of the coastal areas, probably because of upwelling. In the open sea of the Baltic proper and in the Bothnian Bay, the second most important variable is cloudiness. This is also the case in the Bothnian Sea under the RCP4.5 scenario. However,

Formatiert: Hochgestellt

Formatiert: Hochgestellt

Formatiert: Hochgestellt

Formatiert: Hochgestellt

Formatiert: Hochgestellt

in the RCP8.5 the second most important variable is at this location is the latent heat flux. The difference might be explained byis perhaps due to the absencecomplete melting of the sea ice under RCP8.5, amplifying and therefore the amplified air-sea exchange, under RCP8.5.

In the vertical, temperature trends are largest larger in the surface layer compared tothan in the Baltic Sea winter water of the Baltic Sea above the halocline, thus causing a more intense seasonal thermocline (see Section 3.2.2) with in which the largest trends are largest in spring and summer (not shown). Elevated trends are also found in thealso characterise deep water, due to the influence of saltwater inflows that will be warmer in a future climate because the inflowsthey originate from the shallow entrance area and occur 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, the deep water below the halocline will warm more than the overlaying intermediate layer water.

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

3.2.2 Mixed--layer depth

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

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

It wasWhile (Hordoir et al. (, 2018; 2019). speculated that these changes in thermocline depth during summer might have anwill 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 rather a northward expansion of the main overturning cell (Gröger et al., 2019). Indeed, the effect is expected to be small (Placke et al., 2021).

3.2.3 Marine heat waves

Figure 18 shows The number of MHWs within climatological 30-year time slices is shown in Figure 18. Under conditions of the historical climate conditions, MHWs are virtually absent in open ocean areas. They are most frequent in shallow regions and more abundant along the eastern (Baltic States) compared tothan the western (Swedish) coasts, which may reflect that the greater frequency of coastal upwelling events occur more frequent along the western compared tothan the eastern Baltic Sea coasts of the Baltic Sea. Even Already under the RCP4.5 scenario, wide areas of the Baltic proper are affected by MHWs ~ roughly once a year. The strongest response is projected for the high- emission RCP8.5 scenario, and specifically in marginal basins like such as the Gulf of Riga or and the Gulf of Finland, where in the future MHWs would will occur 2-3two or three times per year in future. Not only the frequency but also the average duration of the MHWs will increase with climate warming. Under RCP8.5, even in the open Gulf of Bothnia MHWs of ~20 days duration would will occur in even in the open Gulf of Bothnia future (Fig. 18). The This 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 calculatecan also be analysed by calculating them with respect to the 95th percentile temperature of the historical reference climate (Fig. 19). For the historical climate, the average duration of such periodsMHWs isare in most regions less thanis < 20-–30 days, although in . In the southern Baltic Sea, especially west of the Baltic proper, they MHWs are more frequent. The However, the climate change signal is characterized characterised by more frequent MHWs that are both more frequent and of longer duration. Already In RCP4.5, MHWs in the Baltic Sea occur at least every year. The strongest increase in frequency is near the coasts, whereas but their the average duration increases increases less compared tothan in 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 in the coastal zone compared tothan in the open sea. In addition, with their lower heat storage capacity, shallow areas are, due to their lower heat storage, more sensitive to cold weather events and the associated oceanic heat loss.

3.2.4 Salinity

In the CLIMSEA ensemble, salinity changes are not robust, i.e. the ensemble spread is larger than the signal (Meier et al., 2021). Under both RCP4.5 and RCP8.5, tThe ensemble mean salinity changesignal is small compared to the ensemble spread because the impact on salinity of the projected increase in total river runoff from the entire catchment (Fig. 3) on salinity is approximately compensated by the impact of larger saltwater inflows due to the projected SLR (Table 8not 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. (2011a2011b; ECOSUPPORT) and Saraiva et al. (2019a; BalticAPP; Fig. 12), the ensemble mean salinity changes in CLIMSEA are much smaller (Table 8not shown), and it is impossible to judge whether these changes will be positive or negative. In idealizsed sensitivity experiments performed with the RCO-SCOBI model for the period 1850-–2008 (Meier et al., 2017; 2019d), suggested that the change in the average Baltic Sea salinity (1988-–2007) linearly increasesd linearly with sea-level riseSLR withand at a rate of about ~1.4 g kg^{-1} m^{-1} (Table 9).

Formatiert: Hochgestellt

Formatiert: Englisch (Großbritannien), Hochgestellt

Formatiert: Englisch (Großbritannien), Hochgestellt

3.2.5 Sea level

Following global sea level changes, SLR in the Baltic Sea will accelerate ~~in future~~ (Hünicke et al., 2015; Church et al., 2013; Bamber et al., 2019; Oppenheimer et al., 2019; Weisse and Hünicke, 2019), albeit at a somewhat slower rate than the global mean because of the remote impact of the melting Antarctic ice sheet (Grinsted, 2015). Changes in SLR in the North Atlantic (and the Baltic Sea) ~~would~~will be larger ~~resulting from~~in response to the melting of the Antarctic ice sheet ~~compared to~~than to the melting of Greenland, due to gravitational effects. For a mid-range scenario, ~~Baltic~~ SLR in the Baltic Sea is projected to be ~87% of the global mean (Pellikka et al., 2020). ~~Further,~~ Land uplift will partly compensate~~s~~ 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~~than during the period 1986–2005 (Oppenheimer et al., 2019). For these two scenarios, likely ranges ~~amount to~~are 29–59 cm and 61–110 cm~~,~~ respectively. ~~Assessing the ice sheet dynamics in more detail,~~ Bamber et al. (2019) assessed ice sheet dynamics in detail and subsequently estimated ~~for low- and high- case scenarios~~ global-median SLRs in 2100 of 69 cm and 111 cm for low- and high-case scenarios~~in 2100,~~ respectively. ~~They found~~ Likely ranges according to the authors ~~of~~ were 49–98 cm and 79–174 cm and very likely ranges ~~of~~ 36–126 cm and 62–238 cm.

In BalticAPP and CLIMSEA scenario simulations, sea level changes are small (Fig. 12, Table 8)~~. On the other hand, sea level changes~~whereas in ECOSUPPORT scenario simulations they are larger, particularly in spring, because one member of the multi-model ensemble consider~~ed~~s Archimedes' principle (not shown). Note that ~~in Figure 12~~ the sea level changes shown in Figure 12 consider only changing river runoff, changing wind, and melting sea ice ~~-~~as affecting the sea level ~~via~~ according to Archimedes' principle (only in the ECOSUPPORT ensemble); as ~~whereas~~ neither the global mean SLR ~~and~~ nor land uplift ~~are not~~is included, ~~and~~they have to be added (e.g.~~,~~ Meier, 2006; Meier et al., 2004a).

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

~~Due~~ In response to the global mean SLR, the sea level extremes in the Baltic Sea that are rare today will become more common in the future (e.g.~~,~~ Hieronymus and Kalén, 2020). However, changes in sea level extremes relative to the mean sea level ~~are statistically~~ will not be statistically significant because wind velocities are projected to remain unchanged (Christensen et al., 2021). ~~Exceptions are areas with sea ice decline because the planetary boundary will get less stable and wind speeds will increase (Meier et al., 2011b).~~The

~~E~~exceptions are areas with sea~~-~~-ice decline since they are linked to a decrease~~d~~ in atmospheric stability accompanied by increased wind velocities, ~~which follows from~~the result of increase~~d~~s in temperature and ~~increased~~ turbulent fluxes (Meier et al., 2011~~b~~c). These increases will mostly ~~relate to~~translate as changes from calm to light

Formatiert: Englisch (Großbritannien)
Formatiert: Englisch (Großbritannien)
Formatiert: Englisch (Großbritannien)
Formatiert: Englisch (Großbritannien)
Formatiert: Englisch (Großbritannien)
Formatiert: Englisch (Großbritannien)

wind conditions ~~when~~as the stable atmospheric boundary layer ~~gets~~becomes less stable. For stronger wind conditions related to high sea ~~-~~level extremes, the impact of stratification effects on mixing is small. In addition, open water areas after sea-ice loss have a smaller surface roughness ~~compared to~~than ice-covered areas, ~~also~~with the reduced surface friction leading to an increase in wind velocities ~~because of reduced surface friction~~.

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

3.2.6 Oxygen concentration and hypoxic area

Bottom oxygen concentration

Projected changes in bottom oxygen concentrations ~~changes~~ differ considerably between ECOSUPPORT and BalticAPP/CLIMSEA scenario simulations, as illustrated for summer (Fig. 21, Table 10),~~;~~ whereas the differences between ~~the~~ BalticAPP (SLR = 0 cm) and CLIMSEA (SLR > 0 cm) scenarios are ~~relatively~~ smaller (Meier et al., 2021). The differences between the ECOSUPPORT and BalticAPP ensembles mainly reflect the different experimental setups of the simulations and the different nutrient input scenarios (Meier et al., 2018a). While in ~~the~~ shallow regions without a pronounced halocline future bottom oxygen concentrations decrease in all scenario simulations, due to the ~~the reduced~~lower oxygen saturation concentrations, in ~~the~~ deeper offshore regions with a halocline, changes in bottom oxygen concentration depend largely on the ~~applied~~ nutrient input scenario (Fig. 21). In ECOSUPPORT scenario simulations, the future bottom oxygen concentration decreases significantly in all scenarios ~~significantly~~ except ~~under~~ the BSAP, where ~~the bottom oxygen concentrations~~ in ~~the~~ deeper regions ~~-~~it changes only slightly ~~change~~ on average (~~cf.~~see Meier et al., ~~2011a~~2011b). By contrast, in the BalticAPP projections, ~~bottom oxygen concentrations~~ under the BSAP bottom oxygen concentrations ~~increase~~ in ~~the~~ deeper regions increase considerably, ~~considerably~~ regardless of the degree of warming (~~cf.~~see Saraiva et al., 2019a; Meier et al., ~~2011a~~2011b). Under RCP4.5, bottom oxygen concentrations increase even under the nutrient inputs of REF and WORST ~~nutrient inputs~~ whereas ~~under~~ RCP8.5~~-~~ predicts 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~~ were ~~also~~ calculated for the CLIMSEA ensemble (~~cf.~~ Meier et al., 2021).

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

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

Hypoxic area

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

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

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

3.2.7 Nutrient concentrations

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

3.2.8 Phytoplankton concentrations

Annual mean changes in surface phytoplankton concentration (expressed as chlorophyll concentration) follow the changes in nutrient concentrations and are confined to the productive zone along the coasts (Fig. 23). In ECOSUPPORT projections, annual mean Secchi depths ~~are decreasing~~decrease in all scenario simulations (see Fig. 24 and Table 11~~7~~). ~~On the other hand, in~~In the BalticAPP projections, the area~~-~~–averaged Secchi depths generally increase, except in the ~~combination of~~combined RCP8.5 and BAU scenario~~s~~ (Table 11~~7~~), indicating a general~~n~~ improvement of the water quality in future compared to the present climate. The most striking changes occur in the BSAP scenario, ~~showing~~ in which the Secchi depth increases ~~of~~ by up to 2 m in the coastal zone of the eastern Baltic proper. Changes in stratification (illustrated by the differences between BalticAPP and CLIMSEA ensembles and between the CLIMSEA ensemble mean and high SLR scenarios) have only a minor impact on ~~the~~ water transparency ~~response~~ (Table 11~~7~~). The overwhelming driver of ~~Secchi depth~~ the changes in the Secchi depth are nutrient input scenarios (illustrated by the differences between ECOSUPPORT and BalticAPP/CLIMSEA ensembles and highlighted by, in some cases, ~~even~~ contradictory signs in the changes).

3.2.9 Biogeochemical fluxes

In CLIMSEA under the BSAP, primary production and nitrogen fixation ~~were~~ are projected to considerably decrease in a future climate (Fig. 22). ~~Under~~ According to this scenario, the interannual variability ~~would~~ declines. 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~~ in response to increased nutrient inputs ~~increase~~ and warming. At the end of the century, ~~both~~ primary production and nitrogen fixation ~~would~~ will be at the same level as under current conditions. The impact of warming is larger under high than~~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~~its influence is not stationary but depends on other modes of variability, such as the Atlantic Multidecadal Oscillation (AMO; Börgel et al., 2020). During the past climate, the relationship between the NAO index and regional climate variables in the Baltic Sea region, such as SST, changed over time (Vihma and Haapala, 2009; Omstedt and Chen, 2001; Hünicke and Zorita, 2006; Chen and Hellström, 1999; Meier and Kauker, 2002; Beranová and Huth, 2008).

Figure 25 shows the calculated ensemble mean winter (December~~–through~~ February) NAO index for the period 2006~~–~~2100. For the RCP4.5 emission scenario, ~~it is found that~~ the NAO shows high interannual variability. ~~By applying~~Following a wavelet analysis, ~~it is found that~~ the calculated NAO index ~~contains~~ exhibits ~~some~~ decadal variability, which differs for every model (not shown). ~~By~~ A comparison of ~~comparing~~ RCP4.5 ~~and~~ with the high-emission scenario RCP8.5~~, it can be seen~~ shows that the spread of the ensemble increases with ~~enlarged~~ increasing ~~greenhouse gas~~GHG concentrations. ~~Furthermore,~~ Figure 25 also ~~shows~~ depicts the running correlation between the NAO index and the area-~~-~~averaged SST. ~~Indeed, the~~The correlation remains positive but it is not constant in time. ~~By comparing~~Also evident from a comparison of RCP4.5 and RCP8.5 ~~it is found~~is that there are no systematic changes ~~between~~ in ~~both~~ the two emission scenarios~~. However,~~, although for RCP8.5 ~~a~~ the ensemble spread is slightly larger ~~ensemble spread is found~~.

4 Knowledge gaps

~~As~~ In the largest set of scenario simulations of this study, the CLIMSEA ensemble, only four ESMs were ~~regionalized~~ regionalised using only one RCSM; consequently,~~,~~ this~~the CLIMSEA~~ ensemble is still too small to estimate the uncertainties caused by ESM and RCSM differences. ~~It should be noted that~~While ~~recently even~~ nine ESMs with the same RCSM were recently ~~regionalized~~regionalised, ~~but without~~they did not include running modules for ~~the~~ terrestrial and marine biogeochemistry ~~(~~Gröger et al., 2021b), such that these simulations were~~.~~ ~~therefore, we have~~ not considered ~~these simulations~~ in our assessment.

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

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

~~We have not analyzed~~ Changes in sea-ice cover were not analysed in this study 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. (2011c2011d; 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 completely unknown future bioavailable nutrient inputs from land and atmosphere were classified as one of the biggest uncertainties (Meier et al., 2019b).

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

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

5 Summary

As shown in Section 3, t~~T~~he 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 RCP~~GHG concentration~~ scenarios, the ensemble mean annual ~~SST~~ changes in SST between 1978~~-~~–2007 and 2069~~-~~–2098 ~~amount to~~are 2°C and 3°C~~,~~ respectively. Warming would enhance the stability across the seasonal thermocline and cause a shallower ~~mixed layer depth~~MLD during summer ~~would be shallower~~. During winter, however, the mixed layer in the northern Baltic Sea would be deeper, probably because of the declining sea~~-~~ ice cover and the associated intensification of wind speed, waves and vertical mixing. Both the frequency and the duration of ~~marine heat waves~~MHWs would increase significantly, in particular south of 60ºN and ~~in particular~~ in the coastal zone (except in regions with frequent upwellings).

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

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

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

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

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

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

In the present climate, the climate variability of the Baltic Sea region during winter is dominated by the impact of the NAO. However, ~~during~~ in the past ~~climate~~ the correlation between the NAO and regional variables such as water temperature or sea ice varied in time. ~~These low-frequency changes in correlation were projected to continue and systematic changes in the influence of the large-scale atmospheric circulation on regional climate and in the NAO itself could not be detected, although a northward shift in the mean summer position of the westerlies at the end of the twenty-first century compared to the twentieth century was reported earlier (Gröger et al., 2019).~~ ~~These~~The low-frequency changes in this correlation ~~were~~are projected to continue. Furthermore, systematic changes in the influence of the large-scale atmospheric circulation on regional climate and on the NAO itself could not be detected. ~~However,~~While a northward shift in the mean summer position of the westerlies at the end of the ~~twenty-first~~21st century compared to the ~~twentieth~~20th century was reported ~~earlier~~ (Gröger et al., 2019),~~.~~ ~~This conclusion was drawn~~it was based upon a limited set of simulations with a few ESMs.

Acknowledgements

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

This study belongs to the series of Baltic Earth Assessment Reports (BEARs) of the Baltic Earth Program (Earth System Science for the Baltic Sea Region). The work was financed by the Copernicus Marine Environment Monitoring Service through the CLIMSEA project (Regionally downscaled climate projections for the Baltic and

Formatiert: Englisch (Großbritannien)

Formatiert: Englisch (Großbritannien)

Formatiert: Englisch (Großbritannien)

Formatiert: Englisch (Großbritannien)

Formatiert: Englisch (Großbritannien)

Formatiert: Englisch (Großbritannien)

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~~were conducted on the Linux clusters Krypton, Bi, Triolith and Tetralith, all operated by the National Supercomputer Centre in Sweden (NSC, http://www.nsc.liu.se/). Resources on Triolith and Tetralith were funded by the Swedish National Infrastructure for Computing (SNIC) (grants SNIC 002/12-25, SNIC 2018/3-280 and SNIC 2019/3-356). Furthermore, we thank Berit Recklebe (Leibniz Institute for Baltic Sea Research Warnemünde, IOW) for technical support and Dr. Boris Chubarenko and Dr. Vladimir Ryabchenko for very good comments that helped to improve an earlier version of the manuscript.

Figures

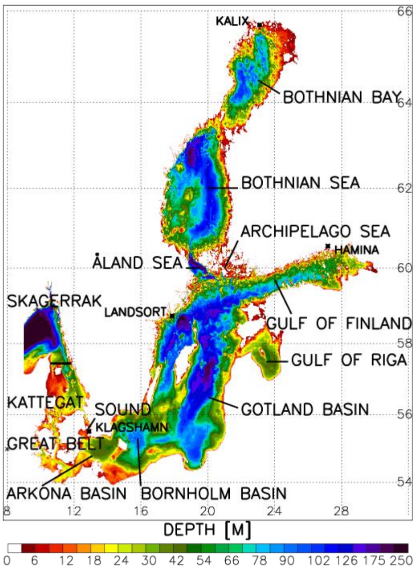


Figure 1: Bottom topography of the Baltic Sea (depth in m). The Baltic proper comprises the Arkona Basin, Bornholm Basin and Gotland Basin. The border of the ~~analyzed~~analysed domain of the Baltic Sea models is shown as a black line in the northern Kattegat. ~~In addition, the~~The tide gauges Klagshamn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

Formatiert: Deutsch (Deutschland)

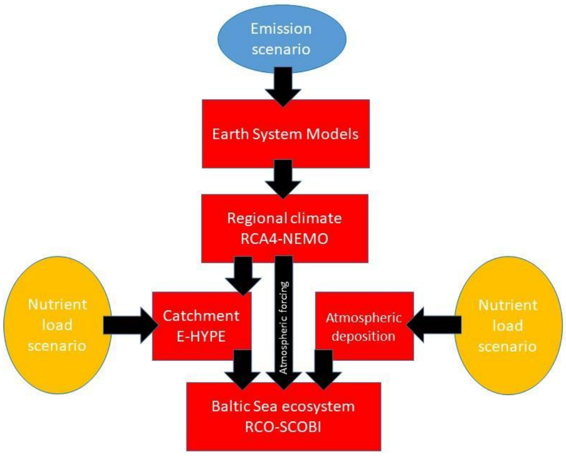


Figure 2. Dynamical downscaling approach for the Baltic Sea region. ~~In Section 2, the~~ The models for the various components of the Earth System are explained in Section 2. (Source: Meier et al., 2021)

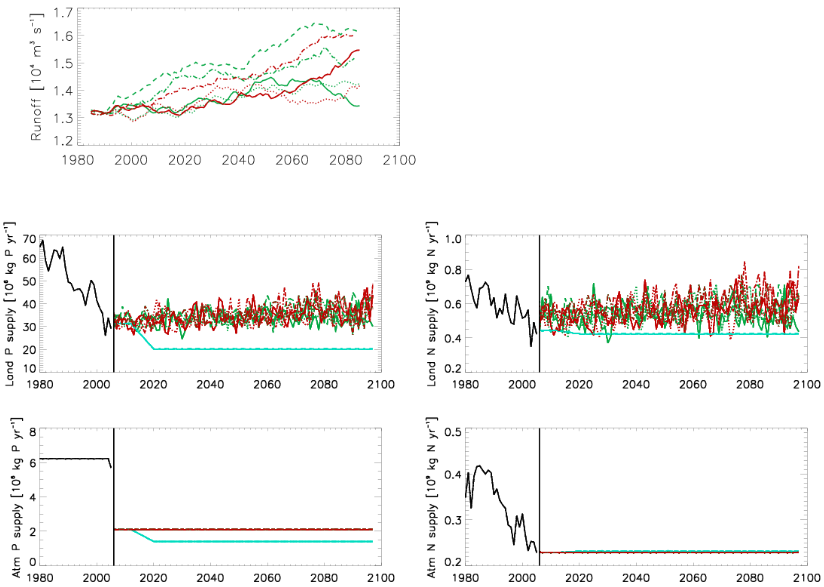


Figure 3. Projections of river discharge and nutrient inputs from land and atmosphere into the entire Baltic Sea ~~in~~ according to the BalticAPP and CLIMSEA scenario simulations. Upper panel: Low-pass filtered runoff data (in $m^3 s^{-1}$) using a cut-off period of 30 years ~~of~~ in four ~~regionalized~~ regionalised Earth System models (ESMs ~~(;~~ illustrated by different line types) under RCP4.5 (green) and RCP8.5 (red) scenarios. Lower panels: Bioavailable phosphorus (in 10^6 kg P year^{-1}, left panels) and nitrogen inputs (in 10^9 kg N year^{-1}, ~~yr^{-1},~~ right panels) from land (upper panels) and the atmosphere (lower panels) under RCP4.5, BSAP (blue), RCP4.5, REF (green), RCP8.5, BSAP (orange) and RCP8.5, REF (red) scenarios. Nutrient inputs during the historical period are depicted in black. The nutrient input scenario WORST of the BalticAPP scenario simulations (Saraiva et al., 2019a; their Fig. 4) is not displayed, ~~and~~ neither are the ECOSUPPORT nutrient input scenarios (Gustafsson et al., 2011; their Fig. 3.1) ~~are not displayed here~~. (Source: Meier et al., 2021)

Formatiert: Schriftart: Nicht Kursiv
Formatiert: Schriftart: Nicht Kursiv, Hochgestellt
Formatiert: Schriftart: Nicht Kursiv
Formatiert: Schriftart: Nicht Kursiv
Formatiert: Schriftart: Nicht Kursiv
Formatiert: Schriftart: Nicht Kursiv, Hochgestellt
Formatiert: Schriftart: Nicht Kursiv
Formatiert: Schriftart: Nicht Kursiv

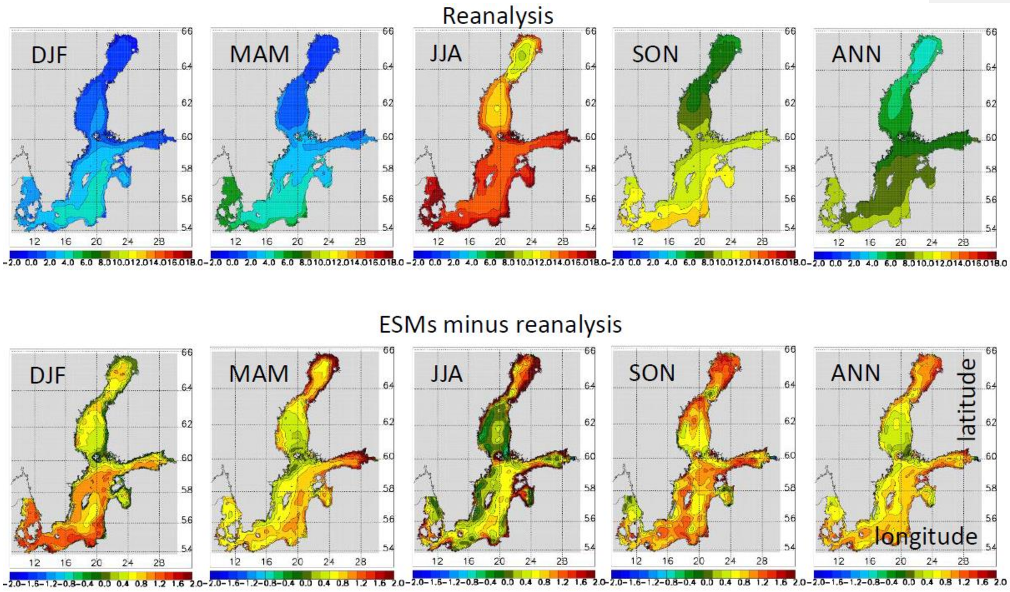


Figure 4: Upper panels: Annual and seasonal mean sea surface temperature (SST) (, in °C) in a reanalysis of data during from 1970- to 1999 (Liu et al., 2017). Lower panels: Difference between the climatologies of the ensemble mean of the regionalized regionalised ESMs used in BalticAPP (Saraiva et al., 2019a) and CLIMSEA (Meier et al., 2021) during the historical period (1976-2005) and those of the reanalysis data. From the left to the right panels: winter (December–February, DJF), spring (March–May, MAM), summer (June–August, JJA), autumn (September–November, SON) and annual (ANN) mean SSTs or SST differences are shown.

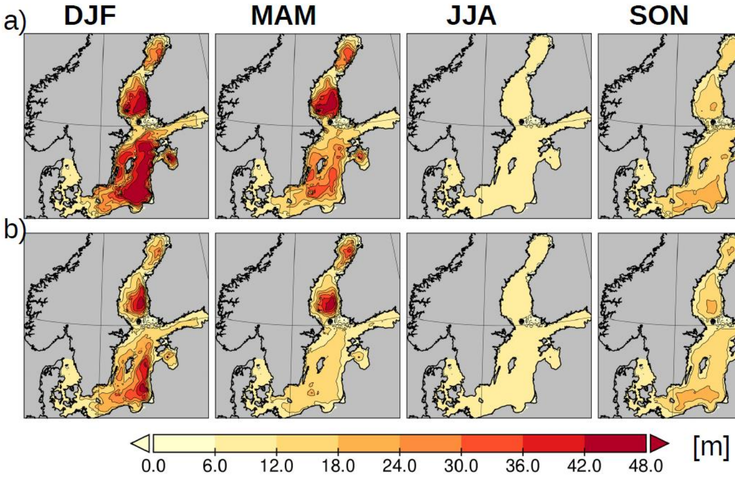


Figure 5: Mixed- layer thickness calculated according to the 0.03 kg m^{-3} criterion following (de Boyer Montégut et al., (2004). a) Reanalysis data (Liu et al., 2017). b) Ensemble mean over the four models (Saraiva et al., 2019a). Shown are the averages over during 1976- 1999.

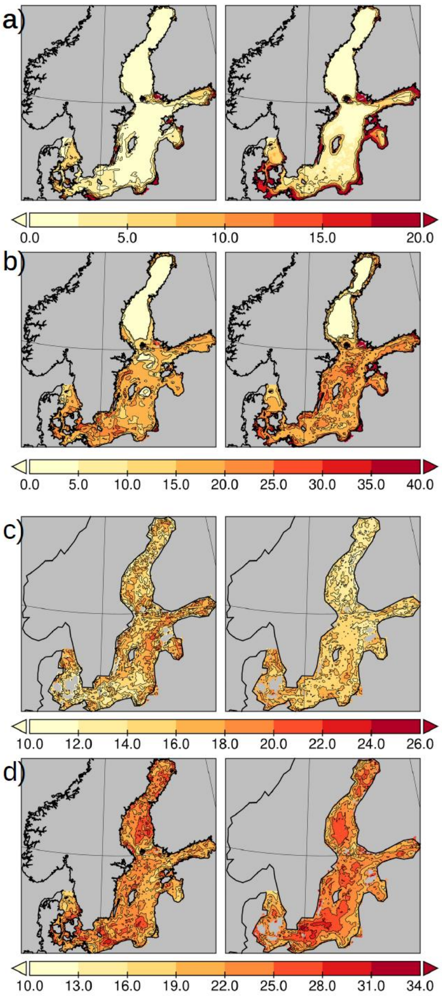


Figure 6: a) Number of >10-day periods ~~where~~ in which the ~~sea surface temperature (~~SST~~)~~ ~~is >~~exceeds 20°C. b) Average duration of the periods displayed in a). c) Number of 10-day periods ~~where~~ in which the SST ~~is >~~exceeds the 95th percentile. d) Average duration of the periods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

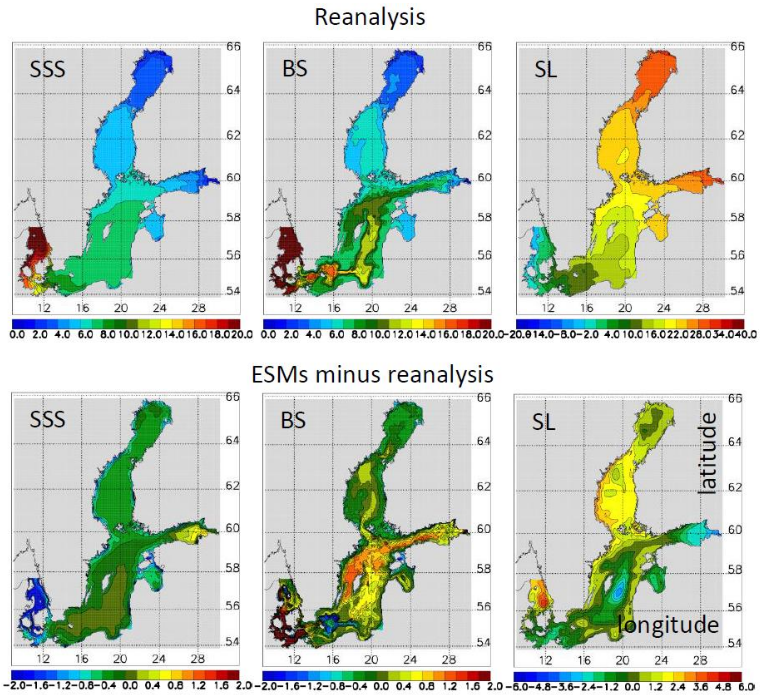
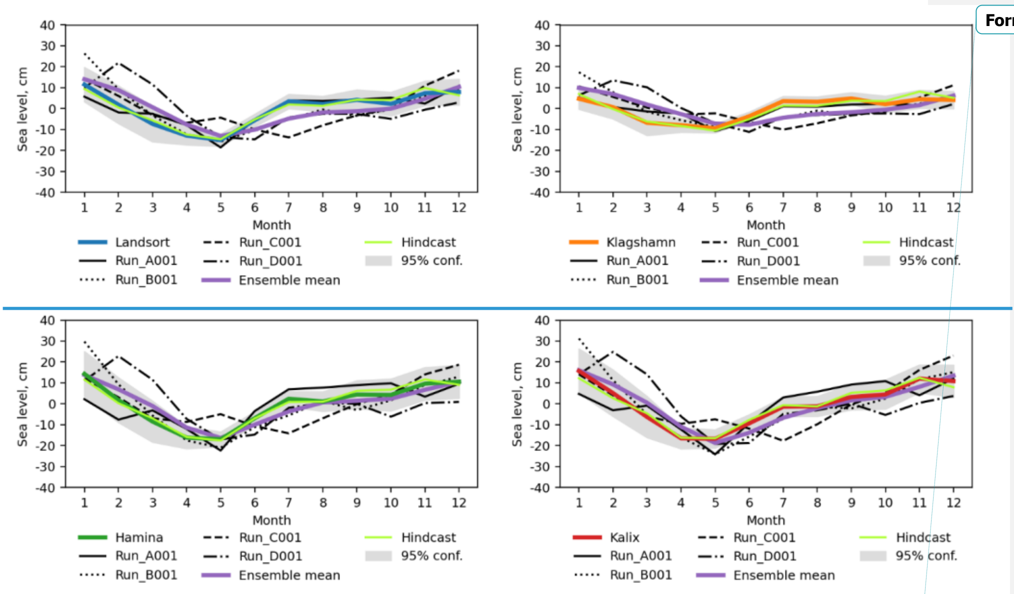


Figure 7: Upper panels: Annual mean sea surface salinity (SSS) and bottom salinity (BS) (in g kg^{-1}) and the winter (December–February) mean sea level (SL; in cm) in the reanalysis data during of 1971-–1999 (Liu et al., 2017; from left to right). Note that the model results of thefor sea level are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

Formatiert: Hochgestellt

Formatiert: Schriftart: Fett



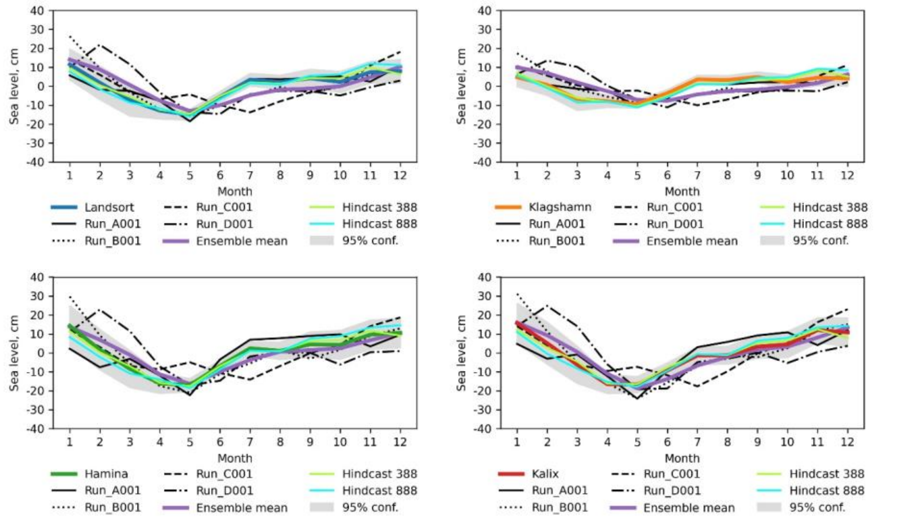


Figure 8: Monthly mean sea level ~~of~~ according to a ~~one~~ hindcast (driven by a ~~regionalized~~ regionalised reanalysis of atmospheric surface fields, i.e. RCA4 driven by ERA-40; Hindcast 388), reanalysis with the data assimilation ~~by~~of Liu et al. (2017) (Hindcast 888) and four climate simulations following ~~(~~Saraiva et al. ~~(,~~ 2019a) (Run_A001, …, Run_D001), the ensemble mean and observations for the historical period 1976~~-~~–2005 at the sea level stations Klagshamn, Landsort, Hamina and Kalix (for the locations, see Figure 1). The 95% confidence interval of the observations is shown as a grey shaded area.

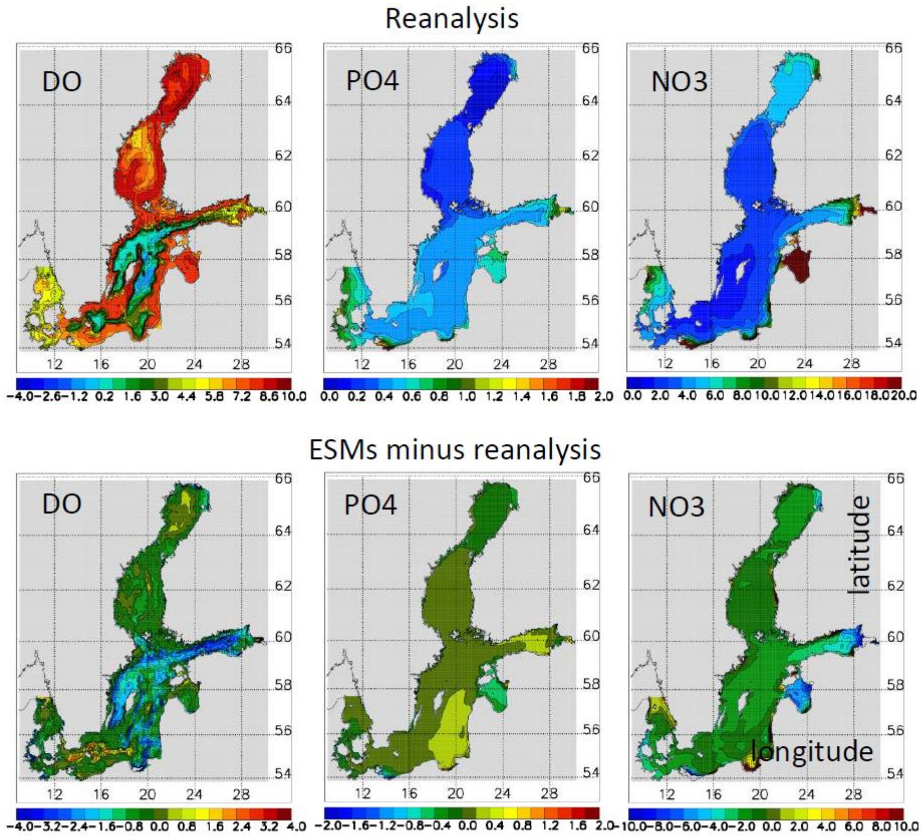


Figure 9: Upper panels: Summer (June–August) mean bottom dissolved oxygen (DO) concentrations (in mL L^{-1}), winter (December–February) mean surface phosphate (PO4) concentrations (in mmol P m^{-3}) and winter (December–February) mean surface nitrate (NO3) concentrations (in mmol N m^{-3}) in the reanalysis data during of 1976–1999 (Liu et al., 2017). Negative oxygen concentration equivalents denote hydrogen sulfidesulphide concentrations, with 1 mL H_2S L^{-1} = –2 mL O_2 L^{-1}. Nutrient concentrations are vertically averaged for the upper 10 m. Lower panels: Difference between the climatologies of the ensemble mean of the ESMs (Saraiva et al., 2019a) and those of the reanalysis data during of the historical period (1976–2005).

Formatiert: Hochgestellt

Formatiert: Hochgestellt

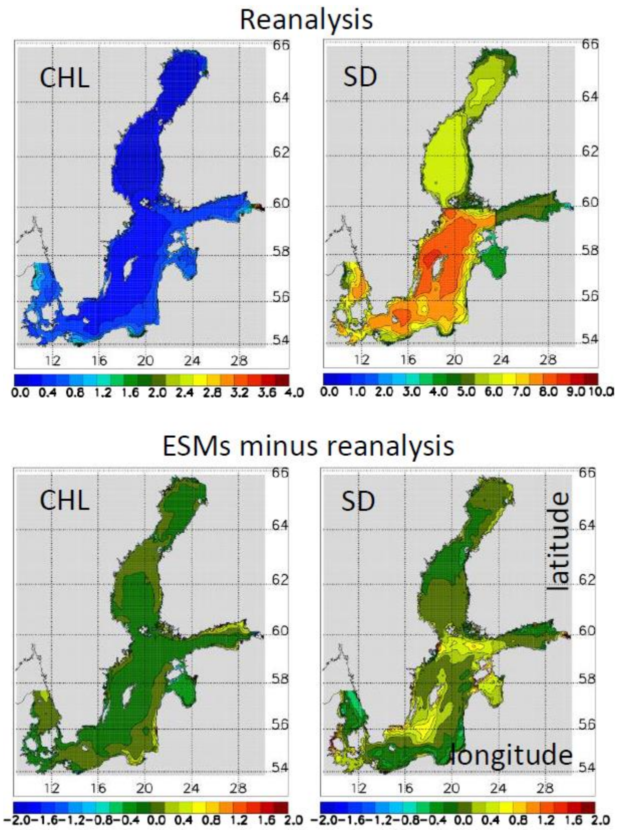


Figure 10: Upper panels: Annual mean phytoplankton concentrations (CHL; in mg Chl m^{-3}) and annual mean Secchi depth (SD; in cm) ~~in~~ of the reanalysis data ~~during~~ for 1976–1999 (Liu et al., 2017). Phytoplankton concentrations are vertically averaged for the upper 10 m. ~~As~~ Since ~~for~~ in the calculation of the Secchi depth as background only one value for the concentration of yellow substances per sub-basin is available, artificial borders between sub-basins become visible. Lower panels: Difference between the climatologies of the ensemble mean of the ESMs (Saraiva et al., 2019a) and those of the reanalysis data ~~during~~ for the historical period (1976–2005).

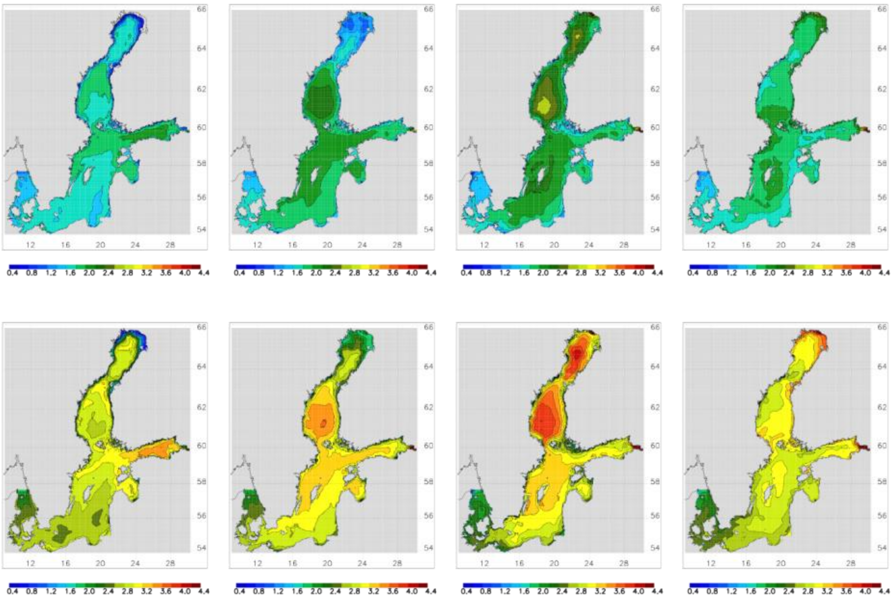


Figure 11. Changes in seasonal mean ~~sea surface temperatures~~SST as simulated by the CLIMSEA ensemble (Meier et al., 2021). From left to right, mean SST changes (in °C) in winter (December, January and February; DJF), spring (March, April and May; MAM), summer (June, July and August; JJA) and autumn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

Formatiert: Schriftart: Nicht Fett

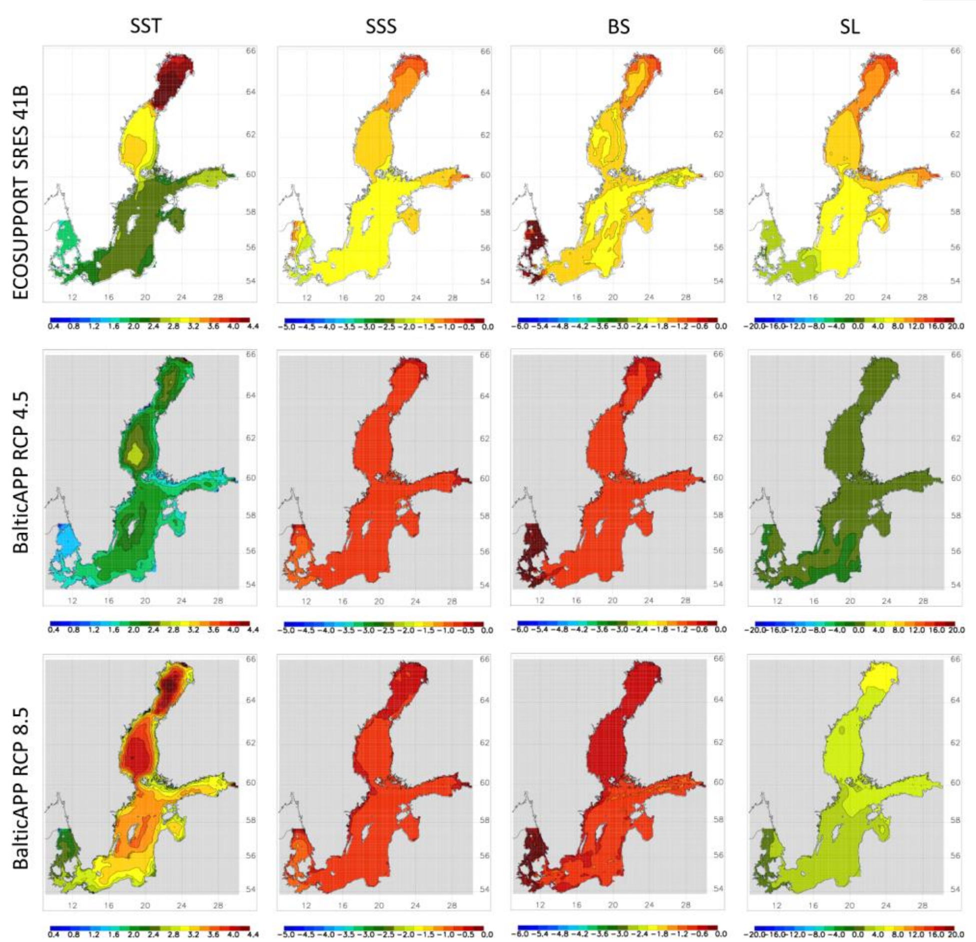


Figure 12: From left to right, changes ~~of~~ in the mean SST (°C) in summer (June–August), the ~~mean sea surface temperature (SST; °C),~~ annual mean sea surface salinity (SSS; g kg^{-1}), annual mean bottom salinity (BS; g kg^{-1} ~~kg^{-1}~~), and winter (December–February) mean sea level (SL; cm)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

Formatiert: Hochgestellt

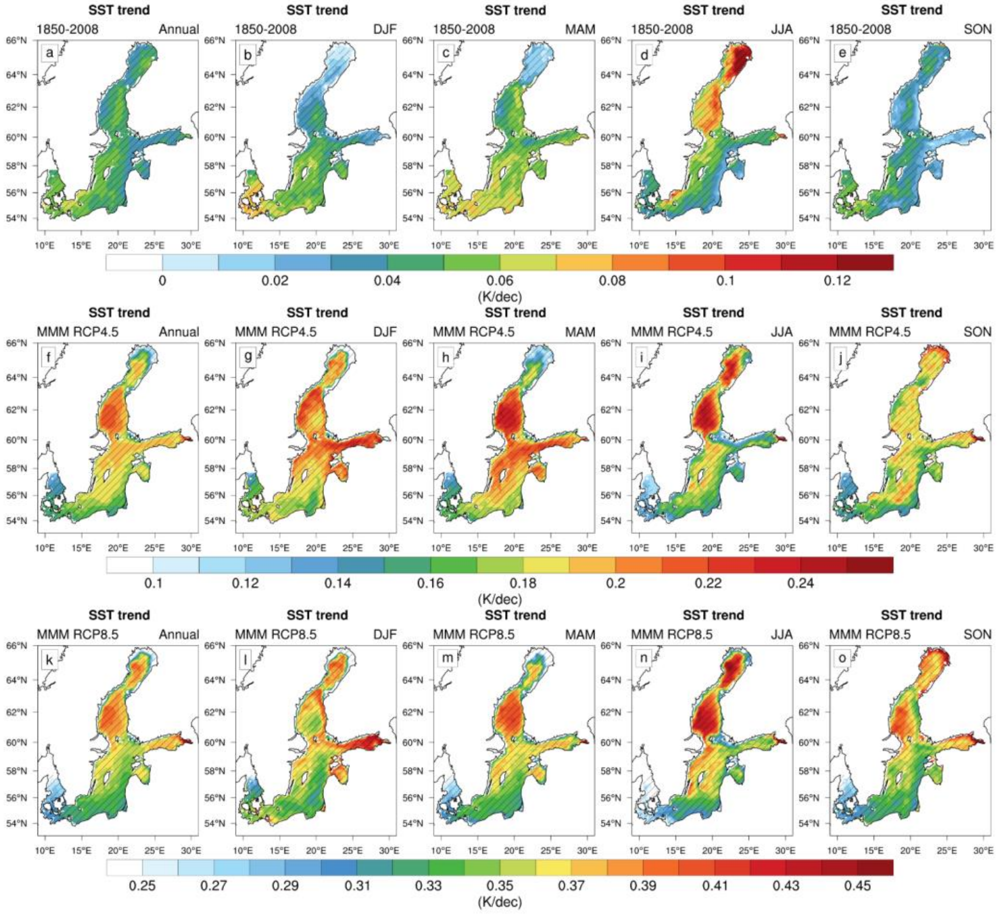


Figure 13: Multi-model mean (MMM) of annual (panels a, and f, k) and seasonal (panels b–e, and g–j, l–o) surface temperature (SST) trends (in °CK decade^{-1-1}) computed for the period 1850–2008 (top), 2006–2099 in RCP4.5 (middle) and RCP8.5 (bottom) scenario. Hatched areas represent the regions where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

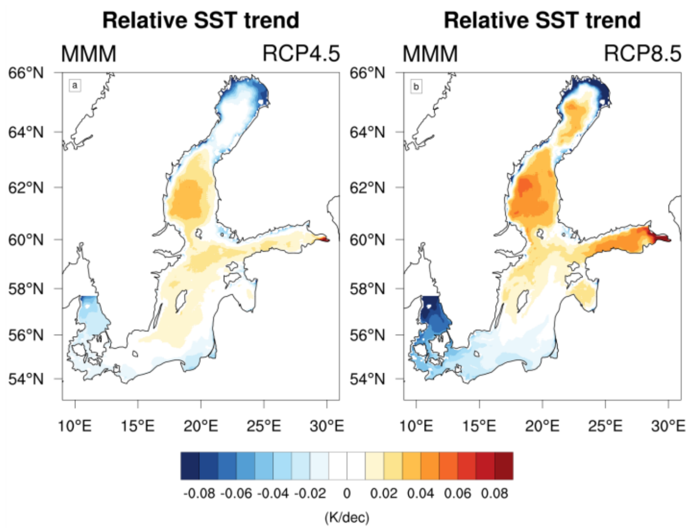


Figure 14: Multi-model mean (MMM) of the annual ~~sea surface temperature (~~SST~~)~~ trends relative to the spatial average (in °C~~K~~ decade^{-1}) for a) RCP4.5 and b) RCP8.5 scenario simulations. (Data source: Saraiva et al., 2019a)

Formatiert: Hochgestellt

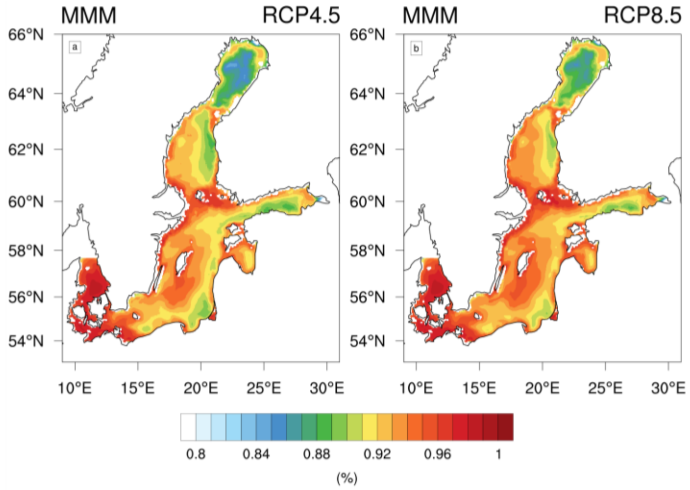


Figure 15: Multi-model mean (MMM) explained variance (in percent) between the monthly mean ~~sea surface temperature~~SST and the forcing air temperature over the period 2006~~-~~–2099 ~~period~~ in the a) RCP4.5 and b) RCP8.5 scenario simulations. (Data source: Saraiva et al., 2019a)

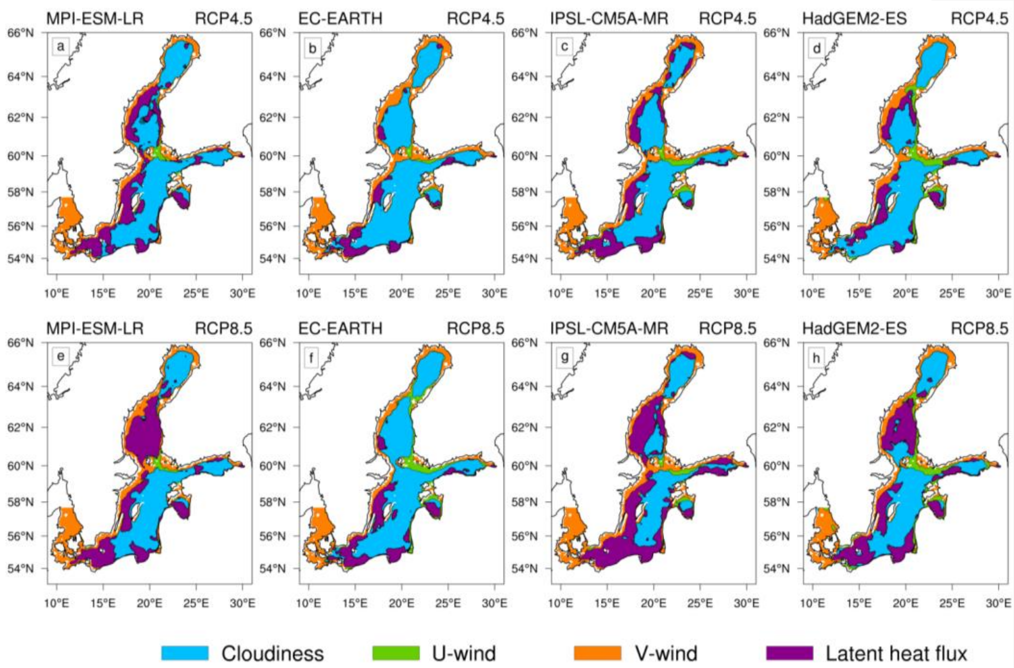


Figure 16: Results of the cross-correlation analysis of the detrended ~~sea surface temperature~~SST (monthly mean ~~is used~~) with the wind components, latent heat flux~~,~~ and cloudiness. Maps of the atmospheric drivers with the highest cross~~-~~correlations in the RCP4.5 (top) and RCP8.5 (bottom) scenarios for various GCM~~s~~ forcings (Saraiva et al., 2019a). From left to right: MPI-ESM-LR, EC-EARTH, IPSL-CM5A-MR, HadGEM2-ES.

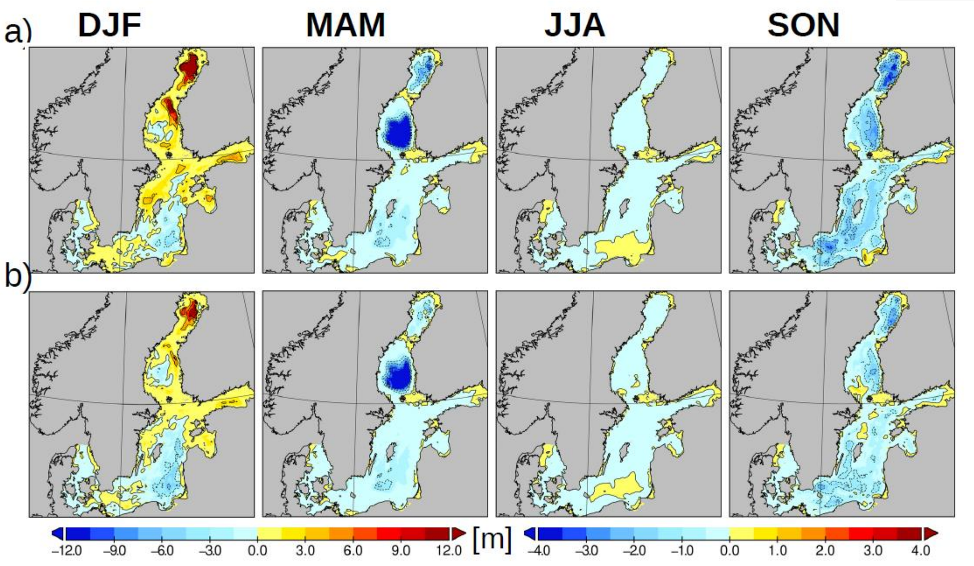


Figure 17. Mixed-layer depth calculated ~~after~~ according to the ~~0.03 kg m~~$^{-3}$ criterion ~~after~~ of de Boyer Montégut et al. (2004). Shown are the ensemble average changes of four different ESMs between 1976–2005 and 2069–2098 with the mean sea-level rises a) 0.90 m (RCP8.5) and b) 0.54 m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

Formatiert: Hochgestellt

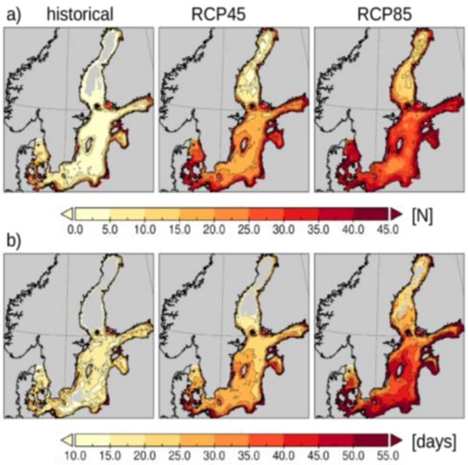


Figure 18. a) Number of h~~H~~eat waves (defined as the number of periods ≥ ~~of >=~~10 days ~~with~~ in which the~~a~~ water temperature ~~of >=~~is ≥ 20°C) for historical (1976~~-~~–2005), and future (2069~~-~~–2098) climates. b) Average duration of the heat waves. Note that no temperature bias adjustment was done prior to the analysis. Shown are the ensemble averages of four different ESMs with the mean sea~~-~~ level rises a) 0.54 m (RCP4.5) and b) 0.90 m (RCP8.5). (Data source: Meier et al., 2021)

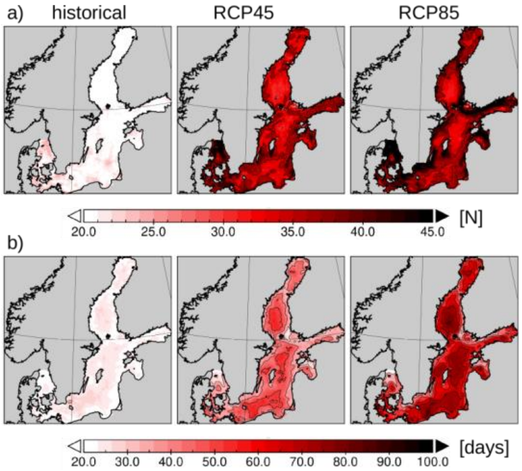


Figure 19. As Same as in Fig. ure 18 but for heat waves defined as periods of ≥>=10 days with in which thea water temperature of >=exceeded the 95th percentile of the historical reference temperature. (Data source: Meier et al., 2021)

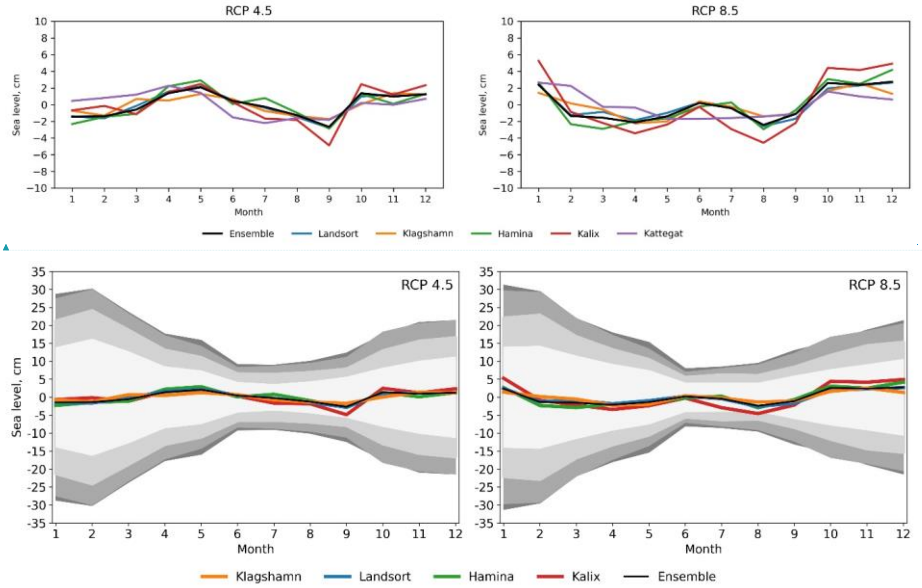
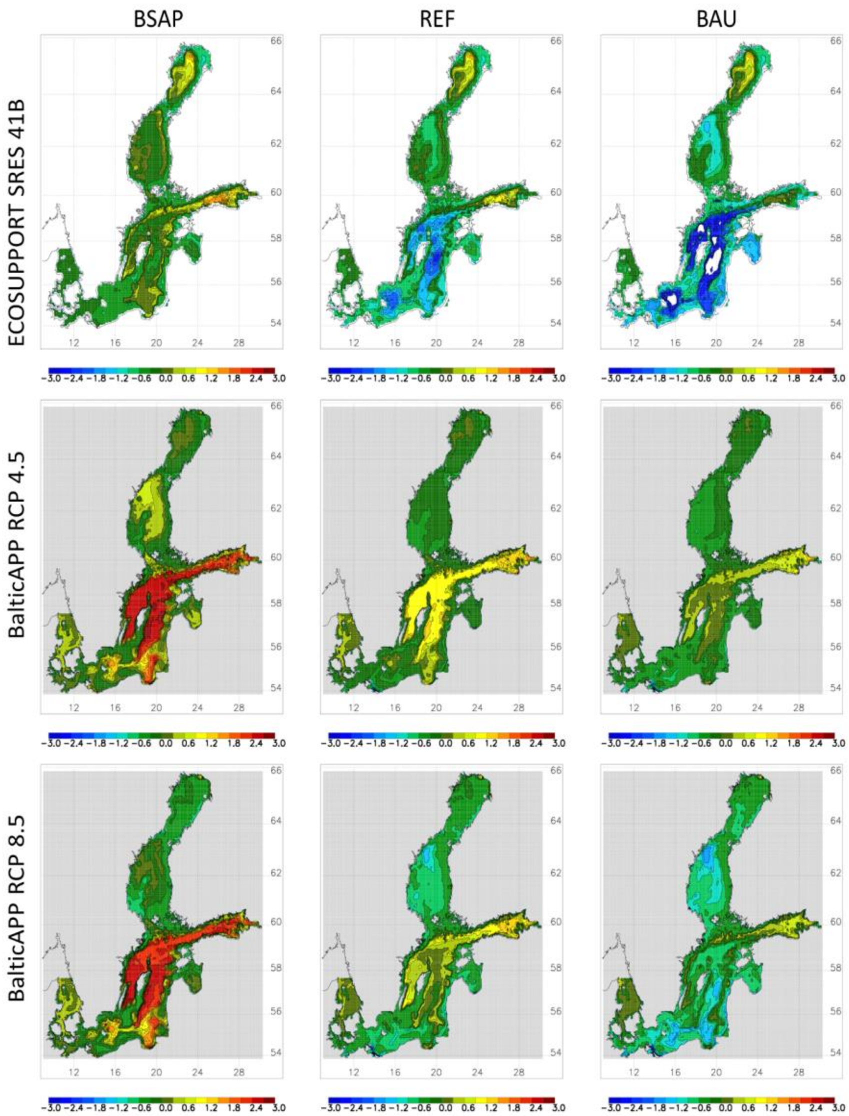


Figure 20: Monthly mean sea level changes between 1976-_2005 and 2069-_2098 at Klagshamn, Landsort, Hamina and , Kalix and Kattegat (for the locations, see Figure 1) for RCP4.5 (left panel) and RCP8.5 (right panel). Shown are the changes relative to the mean sea - level rise a) 0.54 m (RCP4.5) and b) 0.90 m (RCP8.5). Shaded areas in white to dark grey denote +/- two standard deviations at Klagshamn to Kalix respectively. The chosen model approach does not indicate any non-linear effects for scenarios with a larger sea- level rise in sea level scenarios. (Data source: Meier et al., 2021)

Formatiert: Schriftart: Fett

(a)


BSAP
REF
BAU
ECOSUPPORT SRES 41B
BalticAPP RCP 4.5
BalticAPP RCP 8.5
−3.0 −2.4 −1.8 −1.2 −0.6 0.0 0.6 1.2 1.8 2.4 3.0

(b)

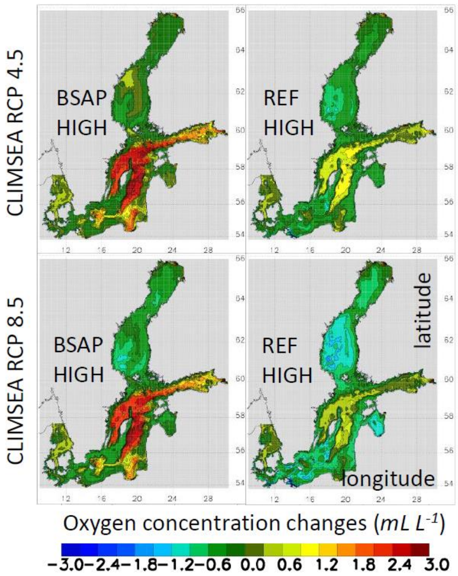


Figure 21: a) Ensemble mean changes in the ~~summer (June – August)~~ bottom dissolved oxygen concentration ~~changes~~ (mL L^{-1}) in summer (June–August) between 1978~~-~~–2007 and 2069~~-~~–2098. From left to right, the results of the nutrient~~-~~ input scenarios of the Baltic Sea Action Plan (BSAP),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

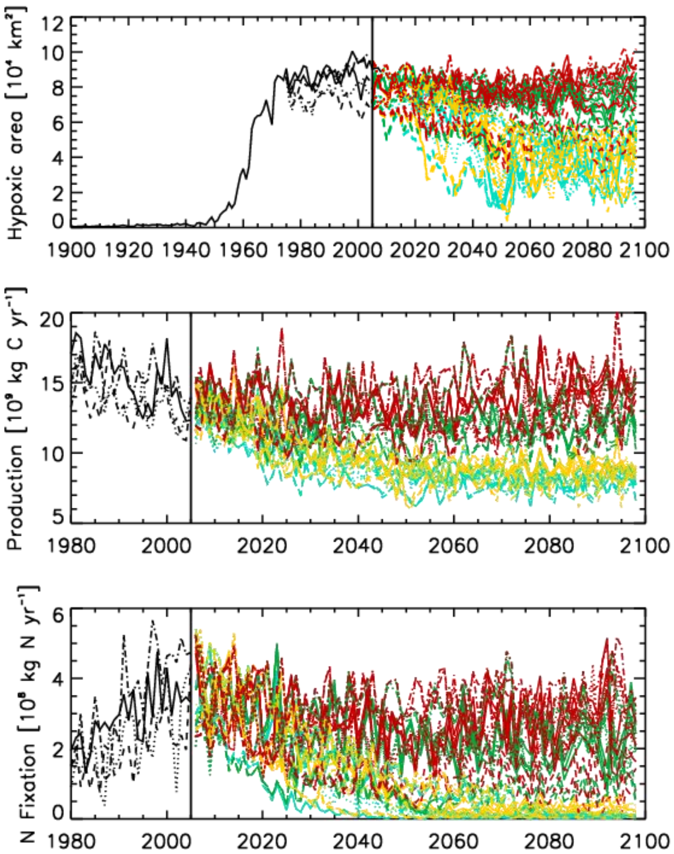


Figure 22: From top to bottom: hypoxic area (in km^2), volume-averaged primary production (in kg C year^{-1}) and volume-averaged nitrogen fixation (in kg N year^{-1}) for the entire Baltic Sea, including the Kattegat (see Fig~~.~~ure 1) in the historical ~~(≤~~ (until 2005, black lines) and scenario ~~simulations~~ (after~~>~~ 2005, coloured lines) simulations driven by four regionalised ESMs (illustrated by different line types) under RCP4.5, BSAP (blue), RCP4.5, REF (green), RCP8.5, BSAP (orange) and RCP8.5, REF (red) scenarios. A spin-up simulation since 1850 was performed, as illustrated by the evolution of hypoxia. (Source: Meier et al., 2021)

Formatiert: Schriftart: Nicht Kursiv

Formatiert: Schriftart: Nicht Kursiv

Formatiert: Schriftart: Nicht Kursiv, Hochgestellt

Formatiert: Schriftart: Nicht Kursiv

Formatiert: Schriftart: Nicht Kursiv

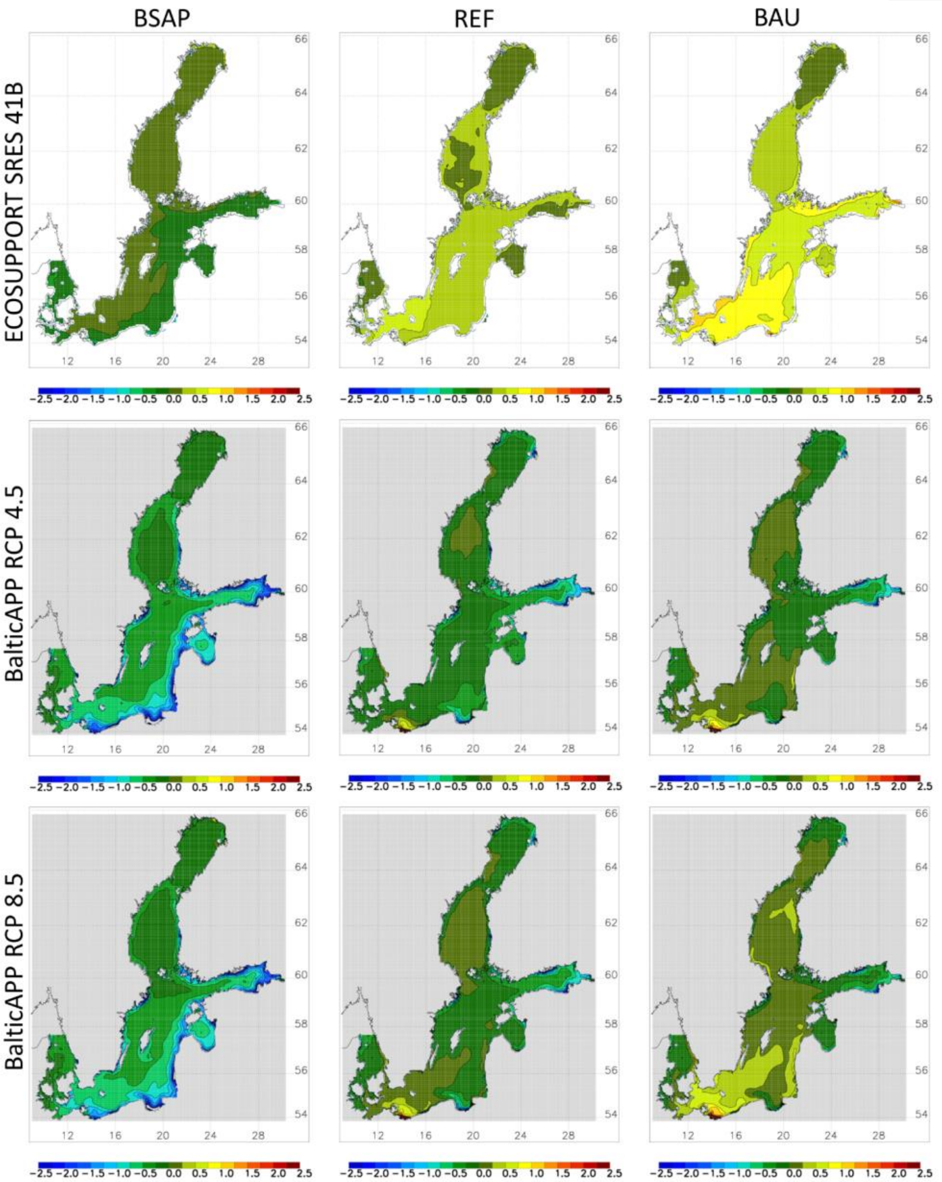


Figure 23: As in Fig.ure 21a but for annual mean surface phytoplankton concentration changes (mg Chl m−$^{-3}$). Concentrations are vertically averaged for the upper 10 m. (Source: Meier et al., 2011a2011b; Saraiva et al., 2019a)

Formatiert: Hochgestellt

Formatiert: Schriftart: Nicht Kursiv

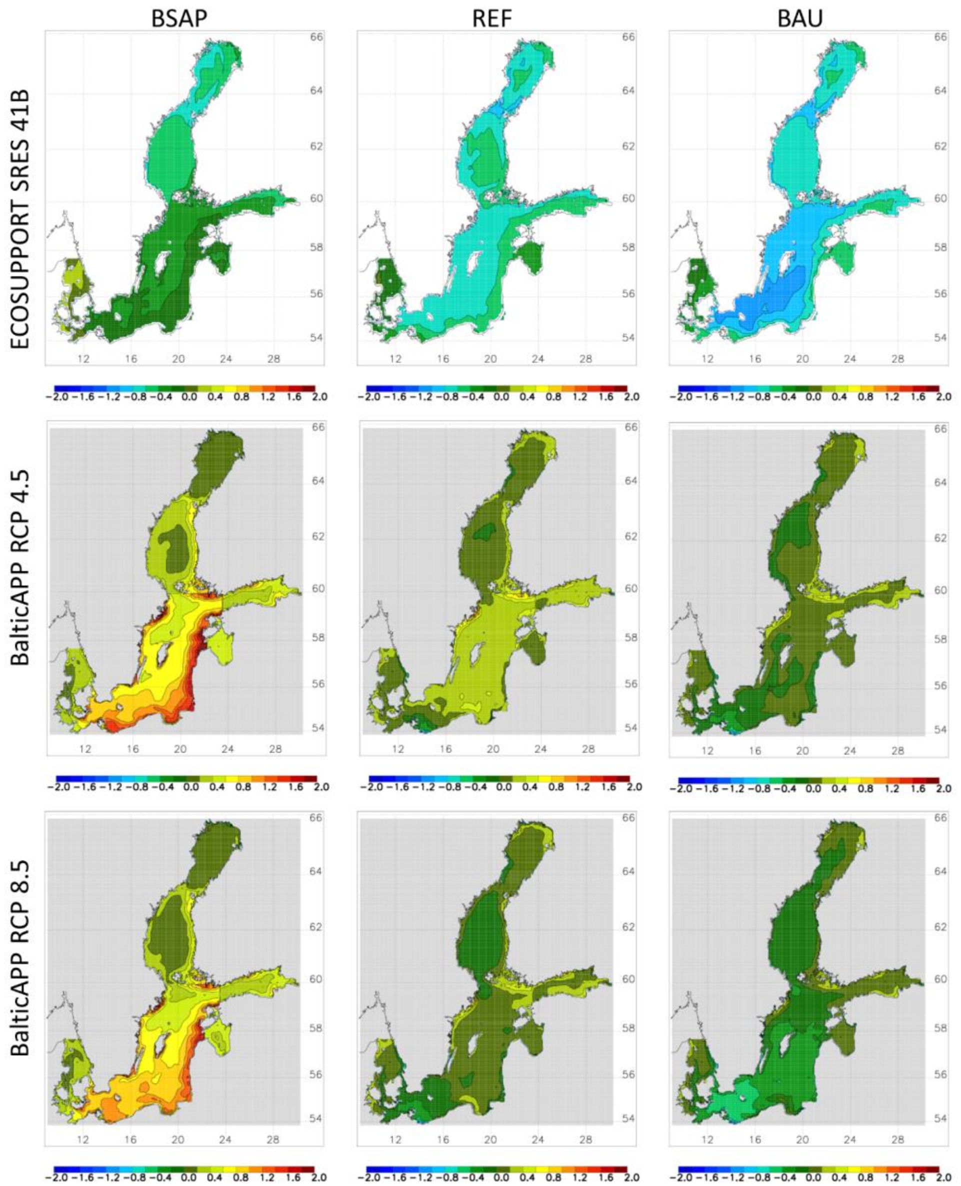
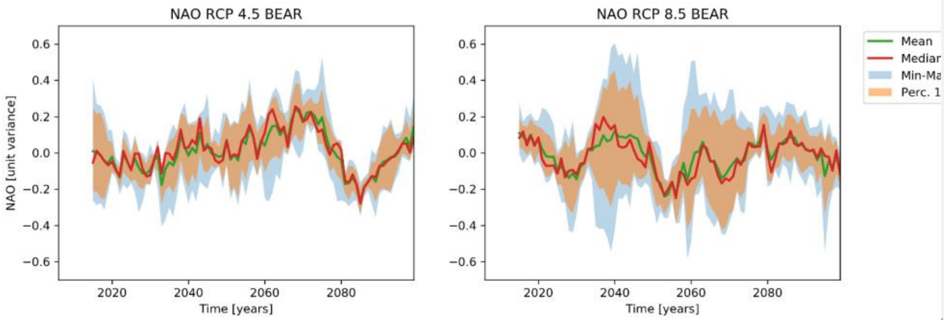
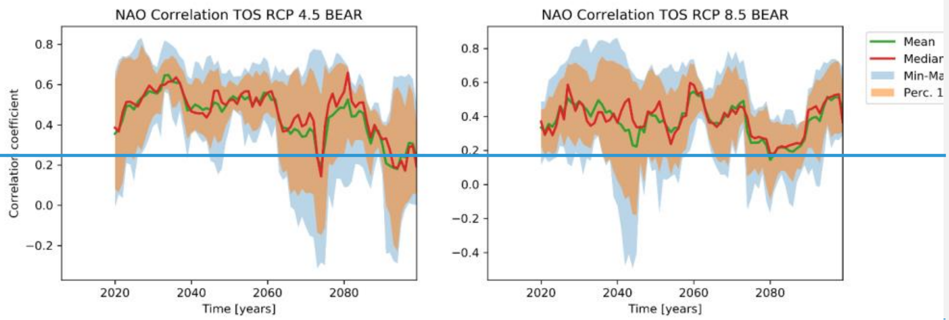


Figure 24. As in Fig.~~.~~ure 21a but for changes in the annual mean Secchi depth ~~changes~~ (m). (Source: Meier et al., ~~2011a~~2011b; Saraiva et al., 2019a)





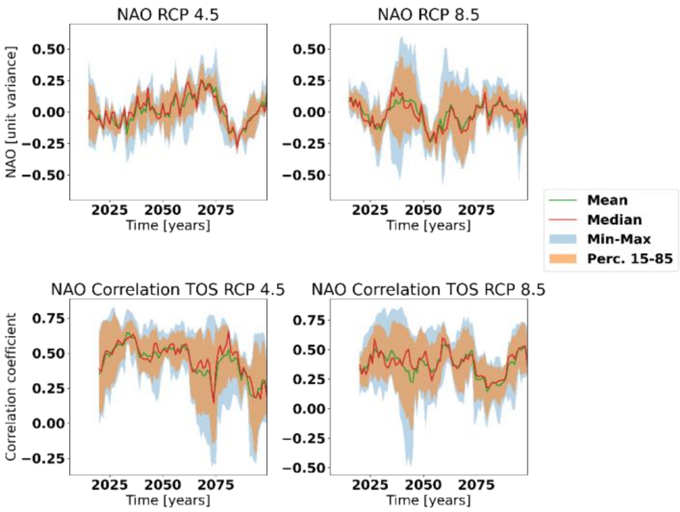


Figure 25. Ensemble 10-year running mean North Atlantic Oscillation (NAO) index (upper panels) and 10-year running correlation between the NAO and area averaged ~~sea surface temperature (~~SST~~)~~ in the Baltic Sea (lower panels) under RCP4.5 (left panels) and RCP8.5 (right panels) scenarios. Depicted are winter (December~~–through~~ February) mean, median, minimum, maximum and 15~~th~~ and 85~~th~~ percentiles. (Data source: Meier et al., 2021)

Tables

Table 1. Selected ensembles of the 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~~Modelling Program	Advanced ~~modeling~~modelling 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	Meier~~Dieterich~~ et al., 202~~1~~1~~9~~
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~~2011b; 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

Formatiert: Deutsch (Deutschland)
Formatiert: Schwedisch (Schweden)
Formatiert: Deutsch (Deutschland)
Formatiert: Englisch (Großbritannien)
Formatiert: Englisch (Großbritannien)

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

	West wind	River discharge (%)	~~Sea-level rise~~SLR	Salinity
BACC (2008)	Large increase	-8 to +26~~%~~	0	0 to −3.7 g kg^{-1} ~~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

Formatiert: Hochgestellt

Table 3. List of scenario simulations of three ensembles. From left to right, the columns show the Earth System Model (ESM), the Regional Climate System Model (RCSM), the Baltic Sea Ecosystem Model, the greenhouse gas (GHG) emission or concentration scenario, the nutrient input scenario, the sea-level rise (SLR) scenario and the simulation period, including historical and scenario periods. The four nutrient input scenarios were used: Baltic Sea Action Plan (BSAP), Reference (REF), Business-As-Usual (BAU) and Worst Case (WORST) scenarios. 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., 2011a2011b)						
ESM	RCSM	Baltic Sea Model	GHG scenario	Nutrient input scenario	SLR scenario	Period
HadCM3	RCAO	BALTSEM	A1B	BSAP/REF/BAU	0	1961–2099
ECHAM5/MPI-OM-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	MOM-ERGOM	A1B	BSAP/REF	0	1961–2099
ECHAM5/MPI-OM-r1	RCAO	MOM-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
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

Table 4: Summary of the characteristics of the ECOSUPPORT, BalticAPP and CLIMSEA scenario simulations discussed in this study. For further details, the reader is referred to Tables 1 and 3. Acronyms are ~~explained~~defined in Table 5.

Acronym	Atmospheric forcing	GHG emission or concentration scenario	Hydrological forcing	Nutrient input scenario	Special features
ECOSUPPORT	Regionali~~z~~sed CMIP3 data, two GCMs	SRES A1B, A2	STAT	BSAP, REF, BAU	Three Baltic Sea models
BalticAPP	Regionali~~z~~sed CMIP5 data, four ESMs	RCP4.5, 8.5	E-HYPE	Revised scenarios BSAP, REF, WORST	Four ESMs
CLIMSEA	Regionali~~z~~sed CMIP5 data, four ESMs	RCP4.5, 8.5	E-HYPE	Revised scenarios BSAP, REF	SLR is considered

Formatiert: Schriftart: Nicht Fett, Englisch (Großbritannien)

Formatiert: Schriftart: Nicht Fett, Englisch (Großbritannien)

Formatierte Tabelle

Table 5. List of acronyms (in alphabetical order), their ~~explanation~~definitions and references~~ in alphabetical order.~~

Acronym	~~Explanation~~Definition	Comment	Reference
AMO	Atlantic Multidecadal Oscillation	Mode of climate variability	Knight et al. (2005)
BACC	Assessment of climate change for the Baltic Sea basin	Regional climate change assessment	BACC Author Team (2008), BACC II Author Team (2015)
BalticAPP	Well-being from the Baltic Sea~~–~~: applications combining natural science and economics	Climate modelling project for the Baltic Sea	Saraiva et al. (2019a)
BEAR	Baltic Earth assessment reports	Regional climate change assessment	https://baltic.earth
BSAP	Baltic Sea Action Plan	Nutrient load abatement strategy for the Baltic Sea	HELCOM (2013b)
BSAP, REF, BAU, WORST	Baltic Sea Action Plan, Reference, Business-As-Usual and WORST	Nutrient load scenarios	Meier et al. (2012a), Saraiva et al. (2019b)
CLC	Cyanobacteria Life Cycle Model	Advanced biogeochemical model including a cyanobacteria life cycle	Hense and Beckmann (2006, 2010)
CLIMSEA	Regionally downscaled climate projections for the Baltic and North Seas	Climate modelling project for the Baltic Sea	Meier et al. (2021)
CMIP	Coupled Model Intercomparison Project of the World Climate Research Programme~~ (WRCP)~~	In this study, GCM/ESM results from CMIP3 and CMIP5 were assessed	https://www.wcrp-climate.org/wgcm-cmip
EC-EARTH	European Countries Earth System Model	ESM, CMIP5	https://www.knmi.nl/home
ECHAM5-MPI-OM	Max Planck Institute Global Climate Model	GCM, CMIP3	Roeckner et al. (2006), Jungclaus et al. (2006)
ECOSUPPORT	Advanced ~~modeling~~modelling tool for scenarios of the Baltic Sea ECOsystem to SUPPORT decision making	Climate modelling project for the Baltic Sea	Meier et al. (2014)
E-HYPE	Hydrological Predictions For The Environment applied for Europe	Process-based multi-basin model for the land surface	https://hypeweb.smhi.se/~~http://hypeweb.smhi.se~~, Arheimer et al. (2012), Hundecha et al. (2016), Donnelly et al. (2013), Donnelly et al. (2017)

Formatiert: Englisch (Großbritannien)
Formatiert: Englisch (Großbritannien)
Formatiert: Englisch (Großbritannien)
Formatiert: Englisch (Großbritannien)
Formatiert: Schwedisch (Schweden)
Formatiert: Schwedisch (Schweden)
Formatiert: Schwedisch (Schweden)
Feldfunktion geändert
Formatiert: Schwedisch (Schweden)

ERA-40	40-year reanalysis of the European Centre for Medium Range Weather Forecast	Reanalysis data used, e.g. ~~for instance~~ as atmospheric forcing for ocean models	Uppala et al. (2005)
ESM	Earth System Model	Model applied for global climate simulations including the carbon cycle	Heavens et al. (2013)
EURO-CORDEX	Coordinated Downscaling Experiment: ~~–~~ European Domain	High-resolution climate change projections for European impact research	Jacob et al. (2014), https://euro-cordex.net/
GCM	General Circulation Model	Model applied for global climate simulations	Meehl et al. (2004)
GHG	Greenhouse gas	Emission or concentration scenarios	Nakićenović et al. (2000), Moss ~~-~~et al. (2010), ~~V~~van Vuuren et al. (2011)
HadCM3	Hadley Centre Global Climate Model	GCM, CMIP3	Gordon et al. (2000)
HadGEM2-ES	Hadley Centre Global Environment Model version 2: ~~–~~Earth System	ESM, CMIP5	http://www.metoffice.gov.uk
HELCOM	Helsinki Commission	Consists of the Baltic Sea countries and the European Union	https://helcom.fi
IOW	Leibniz Institute for Baltic Sea Research Warnem~~u~~ünde	German research institute	http://io-warnemuende.de
IPCC	Intergovernmental Panel of Climate Change	~~Performed~~Generated assessment reports (AR) of past and future changes in 1990, 1995, 2001, 2008, 2013 *inter alia* based upon CMIP results	http://www.ipcc.ch
IPSL-CM5A-MR	Institut Pierre Simon Laplace Climate Model: ~~–~~Medium Resolution	ESM, CMIP5	http://~~i~~cmc.ipsl.fr/
MPI-ESM-LR	Max Planck Institute Earth System Model: ~~–~~Low Resolution	ESM, CMIP5	https://www.mpimet.mpg.de
NAO	North Atlantic Oscillation	Mode of climate variability	Hurrel (1995)
NOSCCA	North Sea Region Climate Change Assessment ~~Report~~	Regional climate change assessment	Quante and Colijn (2016)
RCA3	Rossby Centre Atmosphere Model version 3	Regional climate model	Samuelsson et al. (2011)

Formatiert: Schriftart: Nicht Fett, Englisch (Großbritannien)

Formatiert: Schriftart: Nicht Fett, Englisch (Großbritannien)

Formatiert: Schwedisch (Schweden)

RCA4-NEMO	Rossby ~~Center~~Centre Atmosphere model Version 4: ~~–~~Nucleus for European Modelling of the Ocean	Coupled atmosphere-ocean model applied ~~for~~to the Baltic Sea and North Sea	Dieterich et al. (2013), Wang et al. (2015), Kupiainen et al. (2014), Madec (2016)
RCAO	Rossby Centre Atmosphere Ocean Model	Regional climate model	Döscher et al. (2002)
RCM	Regional Climate Model	Regional atmosphere or coupled atmosphere-ocean model applied ~~for~~to the dynamical downscaling of a changing climate	Giorgi (1990), Rummukainen (2010, 2016a), Rummukainen et al. (2015), Feser et al. (2011), Rockel (2015), Schrum (2017)
RCO-SCOBI, BALTSEM, MOM-ERGOM	Model abbreviations	Coupled physical-biogeochemical models for the Baltic Sea	Meier et al. (2018a), their Tables 1 and 2 and references therein
RCP	Representative Concentration Pathway	Greenhouse gas concentration scenario	Moss et al. (2010), ~~V~~van Vuuren et al. (2011)
RCSM	Regional Climate System Model	Regional coupled atmosphere–sea ice–ocean–wave–land surface–atmospheric chemistry–marine ecosystem model	Giorgi and Gao (2018)
SRES	Special Report on Emission Scenarios	Described greenhouse gas emission scenarios, e.g. A1B, A2	Nakićenović et al. (2000)
STAT	Hydrological model	Statistical model for river runoff calculated from precipitation and evaporation over land	Meier et al. (2012a)

Formatiert: Deutsch (Deutschland)

Formatiert: Schwedisch (Schweden)

Formatiert: Deutsch (Deutschland)

Formatiert: Deutsch (Deutschland)

Formatiert: Schwedisch (Schweden)

Table 6. Projected ensemble mean changes in total (land and atmosphere) bioavailable annual phosphorus (ΔP) and nitrogen (ΔN) inputs (in ktons) into the Baltic Sea between historical (1980–2005) and future (2072–2097) climates under the scenarios REF and BSAP. (Source: Meier et al., 2018a; their Fig. 3)

Nutrient input scenario	REF		BSAP	
Nutrient input changes	ΔP	ΔN	ΔP	ΔN
ECOSUPPORT BALTSEM	+2	−17	−15	−208
ECOSUPPORT MOM-ERGOM	+1	−15	−8	−180
ECOSUPPORT RCO-SCOBI	+4	+72	−11	−230
BalticAPP/CLIMSEA RCO-SCOBI (RCP4.5)	−18	−129	−34	−269

Table 74. Ensemble mean changes in sea surface temperature (SST; in °C) in the ECOSUPPORT, BalticAPP RCP4.5, BalticAPP RCP8.5, CLIMSEA RCP4.5 and CLIMSEA RCP8.5 scenario simulations averaged for the Baltic Sea including the Kattegat (data sources: Meier et al., 2011a2011b; 2021; Saraiva et al., 2019a). (DJF = December, January, February, MAM = March, April, May, JJA = June, July, August, SON = September, October, November)

Δ SST	Winter (DJF)	Spring (MAM)	Summer (JJA)	Autumn (SON)	Annual mean
ECOSPPORT SRES A1B	+2.5	+2.8	+2.8	+2.5	+2.6
BalticAPP RCP4.5	+1.7	+1.9	+2.0	+1.8	+1.8
BalticAPP RCP8.5	+2.9	+3.2	+3.3	+3.0	+3.1
CLIMSEA RCP4.5	+1.7	+1.9	+2.0	+1.9	+1.9
CLIMSEA RCP8.5	+2.8	+3.0	+3.0	+2.9	+2.9

Formatiert: Schriftart: Fett, Englisch (Großbritannien)

Table 8~~5~~. Ensemble mean changes in annual mean sea surface salinity (SSS; in g kg~~–~~$^{-1}$), annual mean bottom salinity (BS; in g kg^{-1}~~kg-1~~) and winter mean sea level (SL) relative to the global mean ~~sea level~~SL (in cm) in ECOSUPPORT, BalticAPP RCP4.5, BalticAPP RCP8.5, CLIMSEA RCP4.5 and CLIMSEA RCP8.5 scenario simulations averaged for the Baltic Sea including the Kattegat. For CLIMSEA, both the ensemble mean and the high ~~sea level~~SL scenarios are listed. In ECOSUPPORT and BalticAPP/CLIMSEA, the changes between 1978~~-~~–2007 and 2069~~-~~–2098 and between 1976~~-~~–2005 and 2069~~-~~–2098 were calculated~~,~~ respectively. (Data sources: Meier et al., ~~2011a~~2011b; 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

Formatiert: Hochgestellt

Table 9. Salinity changes averaged for the Baltic Sea in 1988–2007 relative to 1850 as a function of sea-level rise (SLR). In the reference simulation, the mean salinity is 7.42 g kg^{-1}. In method 1, the increase in the water level was added to the first vertical grid box of the RCO-SCOBI model, while in method 2 the increase in the water level was evenly divided between the first and second grid boxes.

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

Table 10. As in Table 8, but showing the ensemble mean changes in the summer mean bottom oxygen concentration (in mL L^{-1}) in ECOSUPPORT, BalticAPP RCP4.5, BalticAPP RCP8.5, CLIMSEA RCP4.5 and CLIMSEA RCP8.5 scenario simulations averaged for the Baltic Sea including the Kattegat. The projected changes depend on the nutrient input scenario: Baltic Sea Action Plan (BSAP), Reference (REF), Business-As-Usual (BAU) or Worst Case (WORST). (Data sources: Meier et al., 2011ab; 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	−1.1	-	-	-	-	-	-
WORST	-	−0.1	−0.5	-	-	-	-

Formatiert: Schriftart: Fett, Englisch (Großbritannien)

Formatiert: Englisch (Großbritannien), Hochgestellt

Formatiert: Englisch (Großbritannien), Hochgestellt

Formatiert: Englisch (Großbritannien), Hochgestellt

Formatiert: Schriftart: Nicht Fett

Table 11~~7~~. As in Table 8~~5~~, but showing the ensemble mean changes in the annual Secchi depth (in m) in the ECOSUPPORT, BalticAPP RCP4.5, BalticAPP RCP8.5, CLIMSEA RCP4.5 and CLIMSEA RCP8.5 scenario simulations averaged for the Baltic Sea including the Kattegat. The projected changes depend on the nutrient -input scenario: ~~Baltic Sea Action Plan (~~BSAP~~)~~, ~~Reference (~~REF~~)~~, ~~and Business-As-Usual (~~BAU~~)~~ or ~~Worst Case (~~WORST~~)~~. (Data sources: Meier et al., ~~2011a~~2011b; 2021; Saraiva et al., 2019a)

Annual changes	ECOSUPPORT A1B/A2	BalticAPP RCP4.5	BalticAPP RCP8.5	CLIMSEA RCP4.5 mean	CLIMSEA RCP4.5 high	CLIMSEA RCP8.5 mean	CLIMSEA RCP8.5 high
BSAP	~~-~~–0.3~~1~~	+0.6	+0.6~~5~~	+0.6	+0.6	+0.6	+0.6
REF	~~-~~–0.6	+0.2~~1~~	~~-~~0.1~~2~~	+0.2	+0.2	+0.1	+0.1
BAU~~/WORST~~	~~-~~–0~~1~~.8~~1~~	~~-0.1~~	~~-0.5~~	-	-	-	-
WORST	-	0.1	~~-~~–0.1	-	-	-	-

References

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

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

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

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

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

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

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

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

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

Beranová, R., and Huth, R.: Time variations of the effects of circulation variability modes on European temperature and precipitation in winter, Int. J. Climatol., 28, 139-158, https://doi.org/10.1002/joc.1516, 2008.

Bergström, S., and Carlsson, B.: River runoff to the Baltic Sea - 1950-1990, Ambio, 23, 280-287, 1994.

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Formatiert: Schwedisch (Schweden)

Börgel, F., Frauen, C., Neumann, T., Schimanke, S., and Meier, H. E. M.: Impact of the Atlantic Multidecadal Oscillation on Baltic Sea Variability, Geophys. Res. Lett., 45, 9880-9888, https://doi.org/10.1029/2018GL078943, 2018.

Börgel, F., Frauen, C., Neumann, T., and Meier, H. E. M.: The Atlantic Multidecadal Oscillation controls the impact of the North Atlantic Oscillation on North European climate, Environ. Res. Lett., https://doi.org/10.1088/1748-9326/aba925, 2020.

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

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

Chen, D., and Hellström, C.: The influence of the North Atlantic Oscillation on the regional temperature variability in Sweden: spatial and temporal variations, Tellus A, 51, 505-516, https://doi.org/10.1034/j.1600-0870.1999.t01-4-00004.x, 1999.

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

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

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

Dieterich, C., Schimanke, S., Wang, S., Väli, G., Liu, Y., Hordoir, R., Höglund, A., and Meier, H. E. M.: Evaluation of the SMHI coupled atmosphere-ice-ocean model RCA4-NEMO, SMHI, Norrköping, Sweden, 80, 2013.

Dieterich, C., Wang, S., Schimanke, S., Gröger, M., Klein, B., Hordoir, R., Samuelsson, P., Liu, Y., Axell, L., and Höglund, A.: Surface heat budget over the North Sea in climate change simulations, Atmosphere, 10, 272, https://doi.org/10.3390/atmos10050272, 2019.

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

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

Döscher, R., Willén, U., Jones, C., Rutgersson, A., Meier, H. E. M., Hansson, U., and Graham, L. P.: The development of the regional coupled ocean-atmosphere model RCAO, Boreal Environ. Res., 7, 183-192, 2002.

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

Ehrnsten, E., Norkko, A., Müller-Karulis, B., Gustafsson, E., and Gustafsson, B. G.: The meagre future of benthic fauna in a coastal sea—Benthic responses to recovery from eutrophication in a changing climate, Global Change Biol., 26, 2235-2250, https://doi.org/10.1111/gcb.15014, 2020.

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Eilola, K., Meier, H. E. M., and Almroth, E.: On the dynamics of oxygen, phosphorus and cyanobacteria in the Baltic Sea; A model study, J. Mar. Syst., 75, 163-184, https://doi.org/10.1016/j.jmarsys.2008.08.009, 2009.

Eilola, K., Gustafsson, B. G., Kuznetsov, I., Meier, H. E. M., Neumann, T., and Savchuk, O. P.: Evaluation of biogeochemical cycles in an ensemble of three state-of-the-art numerical models of the Baltic Sea, J. Mar. Syst., 88, 267-284, https://doi.org/10.1016/j.jmarsys.2011.05.004, 2011.

Eilola, K., Mårtensson, S., and Meier, H. E. M.: Modeling the impact of reduced sea ice cover in future climate on the Baltic Sea biogeochemistry, Geophys. Res. Lett., 40, 149-154, https://doi.org/10.1029/2012GL054375, 2013.

Ekman, M., and Mäkinen, J.: Mean sea surface topography in the Baltic Sea and its transition area to the North Sea: A geodetic solution and comparisons with oceanographic models, J. Geophys. Res-Oceans, 101, 11993-11999, https://doi.org/10.1029/96JC00318, 1996.

EURO-CORDEX – Coordinated Downscaling Experiment – European Domain: https://euro-cordex.net/, access: 13-10-2021

Feser, F., Rockel, B., von Storch, H., Winterfeldt, J., and Zahn, M.: Regional Climate Models Add Value to Global Model Data: A Review and Selected Examples, Bull. Amer. Meteor. Soc., 92, 1181-1192, https://doi.org/10.1175/2011BAMS3061.1, 2011.

Fleming-Lehtinen, V., and Laamanen, M.: Long-term changes in Secchi depth and the role of phytoplankton in explaining light attenuation in the Baltic Sea, Estuar. Coast. Shelf Sci., 102-103, 1-10, https://doi.org/10.1016/j.ecss.2012.02.015, 2012.

Fonselius, S., and Valderrama, J.: One hundred years of hydrographic measurements in the Baltic Sea, J. Sea Res., 49, 229-241, https://doi.org/10.1016/S1385-1101(03)00035-2, 2003.

Friedland, R., Neumann, T., and Schernewski, G.: Climate change and the Baltic Sea action plan: model simulations on the future of the western Baltic Sea, J. Mar. Syst., 105-108, 175-186, https://doi.org/10.1016/j.jmarsys.2012.08.002, 2012.

Friedland, R., Macias, D., Cossarini, G., Daewel, U., Estournel, C., Garcia-Gorriz, E., Grizzetti, B., Grégoire, M., Gustafson, B., Kalaroni, S., Kerimoglu, O., Lazzari, P., Lenhart, H., Lessin, G., Maljutenko, I., Miladinova, S., Müller-Karulis, B., Neumann, T., Pärn, O., Pätsch, J., Piroddi, C., Raudsepp, U., Schrum, C., Stegert, C., Stips, A., Tsiaras, K., Ulses, C., and Vandenbulcke, L.: Effects of nutrient management scenarios on marine eutrophication indicators: a Pan-European, multi-model assessment in support of the Marine Strategy Framework Directive, Front. Mar. Sci., 8, 596126, https://doi.org/10.3389/fmars.2021.596126, 2021.

Giorgi, F.: Simulation of Regional Climate Using a Limited Area Model Nested in a General Circulation Model, J. Climate, 3, 941-963, https://doi.org/10.1175/1520-0442(1990)003<0941:Sorcua>2.0.Co;2, 1990.

Giorgi, F., and Gao, X.-J.: Regional earth system modeling: review and future directions, AOSL, 11, 189-197, https://doi.org/10.1080/16742834.2018.1452520, 2018.

Gogina, M., Zettler, M. L., Wåhlström, I., Andersson, H., Radtke, H., Kuznetsov, I., and MacKenzie, B. R.: A combination of species distribution and ocean-biogeochemical models suggests that climate change overrides eutrophication as the driver of future distributions of a key benthic crustacean in the estuarine ecosystem of the Baltic Sea, ICES J. Mar. Sci., 77, 2089-2105, https://doi.org/10.1093/icesjms/fsaa107, 2020.

Gordon, C., Cooper, C., Senior, C. A., Banks, H., Gregory, J. M., Johns, T. C., Mitchell, J. F. B., and Wood, R. A.: The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments, Clim. Dyn., 16, 147-168, https://doi.org/10.1007/s003820050010, 2000.

Gräwe, U., and Burchard, H.: Storm surges in the Western Baltic Sea: the present and a possible future, Clim. Dyn., 39, 165-183, https://doi.org/10.1007/s00382-011-1185-z, 2012.

Gräwe, U., Friedland, R., and Burchard, H.: The future of the western Baltic Sea: two possible scenarios, Ocean Dynam., 63, 901-921, https://doi.org/10.1007/s10236-013-0634-0, 2013.

Griffies, S. M.: Fundamentals of ocean climate models, Princeton University Press, 2004.

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Formatiert: Englisch (Großbritannien)

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Formatiert: Standard, Leerraum zwischen asiatischem und westlichem Text nicht anpassen, Leerraum zwischen asiatischem Text und Zahlen nicht anpassen

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Formatiert: Schriftart: Englisch (Großbritannien)

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Grinsted, A.: Projected Change - Sea Level, in: Second Assessment of Climate Change for the Baltic Sea Basin, edited by: BACC II Author Team, *Regional Climate Studies*, Springer International Publishing, Cham, 253-263, https://doi.org/10.1007/978-3-319-16006-1_14, 2015.

Gröger, M., Dieterich, C., Meier, H. E. M., and Schimanke, S.: Thermal air-sea coupling in hindcast simulations for the North Sea and Baltic Sea on the NW European shelf, Tellus A, 67, 26911, https://doi.org/10.3402/tellusa.v67.26911, 2015.

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

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

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

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

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

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

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

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

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

HELCOM: HELCOM Copenhagen Ministerial Declaration - Taking Further Action to Implement the Baltic Sea Action Plan - Reaching Good Environmental Statusfor a healthyBaltic Sea, Copenhagen, Denmark, HELCOM Ministrial Meeting, 2013b.

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

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

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

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

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

Hieronymus, M., and Kalén, O.: Sea-level rise projections for Sweden based on the new IPCC special report: The ocean and cryosphere in a changing climate, Ambio, https://doi.org/10.1007/s13280-019-01313-8, 2020.

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Formatiert: Englisch (Großbritannien)

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Hill, E. M., Davis, J. L., Tamisiea, M. E., and Lidberg, M.: Combination of geodetic observations and models for glacial isostatic adjustment fields in Fennoscandia, J. Geophys. Res.-Sol. Ea., 115, https://doi.org/10.1029/2009jb006967, 2010.

Hobday, A. J., Oliver, E. C. J., Gupta, A. S., Benthuysen, J. A., Burrows, M. T., Donat, M. G., Holbrook, N. J., Moore, P. J., Thomsen, M. S., Wernberg, T., and Smale, D. A.: Categorizing and Naming MARINE HEATWAVES, Oceanography, 31, 162-173, 2018.

Höglund, A., Pemberton, P., Hordoir, R., and Schimanke, S.: Ice conditions for maritime traffic in the Baltic Sea in future climate, Boreal Environ. Res., 22, 245-265, 2017.

Holopainen, R., Lehtiniemi, M., Meier, H. E. M., Albertsson, J., Gorokhova, E., Kotta, J., and Viitasalo, M.: Impacts of changing climate on the non-indigenous invertebrates in the northern Baltic Sea by end of the twenty-first century, Biol. Invasions, 18, 3015-3032, https://doi.org/10.1007/s10530-016-1197-z, 2016.

Holt, J., Schrum, C., Cannaby, H., Daewel, U., Allen, I., Artioli, Y., Bopp, L., Butenschon, M., Fach, B. A., Harle, J., Pushpadas, D., Salihoglu, B., and Wakelin, S.: Potential impacts of climate change on the primary production of regional seas: A comparative analysis of five European seas, Prog. Oceanogr., 140, 91-115, https://doi.org/10.1016/j.pocean.2015.11.004, 2016.

Hordoir, R., and Meier, H. E. M.: Effect of climate change on the thermal stratification of the baltic sea: a sensitivity experiment, Clim. Dyn., 38, 1703-1713, https://doi.org/10.1007/s00382-011-1036-y, 2012.

Hordoir, R., Höglund, A., Pemberton, P., and Schimanke, S.: Sensitivity of the overturning circulation of the Baltic Sea to climate change, a numerical experiment, Clim. Dyn., 50, 1425-1437, https://doi.org/10.1007/s00382-017-3695-9, 2018.

Hordoir, R., Axell, L., Höglund, A., Dieterich, C., Fransner, F., Gröger, M., Liu, Y., Pemberton, P., Schimanke, S., Andersson, H., Ljungemyr, P., Nygren, P., Falahat, S., Nord, A., Jönsson, A., Lake, I., Döös, K., Hieronymus, M., Dietze, H., Löptien, U., Kuznetsov, I., Westerlund, A., Tuomi, L., and Haapala, J.: Nemo-Nordic 1.0: a NEMO-based ocean model for the Baltic and North seas – research and operational applications, Geosci. Model Dev., 12, 363-386, https://doi.org/10.5194/gmd-12-363-2019, 2019.

Hundecha, Y., Arheimer, B., Donnelly, C., and Pechlivanidis, I.: A regional parameter estimation scheme for a pan-European multi-basin model, J. Hydrol-Reg. Stud., 6, 90-111, https://doi.org/10.1016/j.ejrh.2016.04.002, 2016.

Hünicke, B., and Zorita, E.: Influence of temperature and precipitation on decadal Baltic Sea level variations in the 20th century, Tellus A, 58, 141-153, https://doi.org/10.1111/j.1600-0870.2006.00157.x, 2006.

Hünicke, B., Zorita, E., Soomere, T., Madsen, K. S., Johansson, M., and Suursaar, Ü.: Recent Change—Sea Level and Wind Waves, in: Second Assessment of Climate Change for the Baltic Sea Basin, edited by: BACC II Author Team, Springer International Publishing, Cham, 155-185, 10.1007/978-3-319-16006-1_9, 2015.

Hurrell, J. W.: Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation, Science-AAAS-Weekly Paper Edition, 269, 676-679, https://doi.org/10.1126/science.269.5224.676 1995.

IPCC: Climate Change 2013 – The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, https://doi.org/10.1017/CBO9781107415324, 2013.

IPCC: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, edited by: Pörtner, H.-O., Roberts, D. C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B., and Weyer, N. M., 2019a.

IPCC: Summary for Policymakers, in: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, edited by: Pörtner, H.-O., Roberts, D. C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B., and Weyer, N. M., 2019b.

IPCC: The Intergovernmental Panel on Climate Change: https://www.ipcc.ch/, access: 13-10-2021.

IPSL - Climate Modelling Centre: https://cmc.ipsl.fr/, access: 13-10-2021.

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O. B., Bouwer, L. M., Braun, A., Colette, A., Déqué, M., Georgievski, G., and others: EURO-CORDEX: new high-resolution climate change projections for European impact research, Reg. Environ. Change, 14, 563-578, https://doi.org/10.1007/s10113-013-0499-2, 2014.

Jungclaus, J. H., Keenlyside, N., Botzet, M., Haak, H., Luo, J.-J., Latif, M., Marotzke, J., Mikolajewicz, U., and Roeckner, E.: Ocean circulation and tropical variability in the coupled model ECHAM5/MPI-OM, J. Climate, 19, 3952-3972, https://doi.org/10.1175/JCLI3827.1, 2006.

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

Kniebusch, M., Meier, H. E. M., Neumann, T., and Börgel, F.: Temperature Variability of the Baltic Sea Since 1850 and Attribution to Atmospheric Forcing Variables, J. Geophys. Res-Oceans, 124, 4168-4187, https://doi.org/10.1029/2018jc013948, 2019.

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

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

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

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

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

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

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

Lehmann, A., Getzlaff, K., and Harlaß, J.: Detailed assessment of climate variability in the Baltic Sea area for the period 1958 to 2009, Clim. Res., 46, 185-196, https://doi.org/10.3354/cr00876, 2011.

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

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

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

Madec, G., and the NEMO team: NEMO ocean engine, version 3.6 stable, Note du Pôle de modélisation de l'Institut Pierre-Simon Laplace (IPSL) No 27, France, 396pp, https://www.nemo-ocean.eu/wp-content/uploads/NEMO_book.pdf, 2016.

Madsen, K. S., Høyer, J. L., Suursaar, Ü., She, J., and Knudsen, P.: Sea Level Trends and Variability of the Baltic Sea From 2D Statistical Reconstruction and Altimetry, Front. Earth Sci., 7, https://doi.org/10.3389/feart.2019.00243, 2019.

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Schwedisch (Schweden)

Formatiert: Schwedisch (Schweden)

Feldfunktion geändert

Formatiert: Schwedisch (Schweden)

Formatiert: Schwedisch (Schweden)

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Formatiert: Deutsch (Deutschland)

Feldfunktion geändert

Formatiert: Deutsch (Deutschland)

Formatiert: Deutsch (Deutschland)

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Max-Planck-Institut für Meteorologie: https://www.mpimet.mpg.de, access: 13-10-2021.

Meehl, G. A., Washington, W. M., Ammann, C. M., Arblaster, J. M., Wigley, T. M. L., and Tebaldi, C.: Combinations of Natural and Anthropogenic Forcings in Twentieth-Century Climate, J. Climate, 17, 3721-3727, https://doi.org/10.1175/1520-0442(2004)017<3721:conaaf>2.0.co;2, 2004.

Meier, H. E. M., Doescher, R., Coward, A. C., Nycander, J., and Döös, K.: RCO – Rossby Centre regional Ocean climate model: model description (version 1.0) and first results from the hindcast period 1992/93, SMHI, Norrköping, Sweden, 102pp, 1999.

Meier, H. E. M.: On the parameterization of mixing in three-dimensional Baltic Sea models, J. Geophys. Res-Oceans, 106, 30997-31016, https://doi.org/10.1029/2000JC000631, 2001.

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

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

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

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

Meier, H. E. M., and Kauker, F.: Modeling decadal variability of the Baltic Sea: 2. Role of freshwater inflow and large-scale atmospheric circulation for salinity, J. Geophys. Res-Oceans, 108, https://doi.org/10.1029/2003JC001799, 2003.

Meier, H. E. M., Broman, B., and Kjellström, E.: Simulated sea level in past and future climates of the Baltic Sea, Clim. Res., 27, 59-75, https://doi.org/10.3354/cr027059, 2004a.

Meier, H. E. M., Döscher, R., and Halkka, A.: Simulated distributions of Baltic Sea-ice in warming climate and consequences for the winter habitat of the Baltic ringed seal, Ambio, 33, 249-256, https://doi.org/10.1579/0044-7447-33.4.249, 2004b.

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

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

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

Meier, H. E. M., Andersson, H., Dieterich, C., Eilola, K., Gustafsson, B., Höglund, A., and Schimanke, S.: Transient scenario simulations for the Baltic Sea Region during the 21st century, SMHI, Norrköping, Sweden, 81pp, 2011~~d~~a.

Meier, H. E. M., Andersson, H. C., Eilola, K., Gustafsson, B. G., Kuznetsov, I., Müller-Karulis, B., Neumann, T., and Savchuk, O. P.: Hypoxia in future climates: A model ensemble study for the Baltic Sea, Geophys. Res. Lett., 38, L24608, https://doi.org/10.1029/2011GL049929, ~~2011a~~2011b.

Meier, H. E. M., Eilola, K., and Almroth, E.: Climate-related changes in marine ecosystems simulated with a 3-dimensional coupled physical-biogeochemical model of the Baltic Sea, Clim. Res., 48, 31-55, https://doi.org/10.3354/cr00968 ~~2011b~~2011c.

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Meier, H. E. M., Höglund, A., Döscher, R., Andersson, H., Löptien, U., and Kjellström, E.: Quality assessment of atmospheric surface fields over the Baltic Sea from an ensemble of regional climate model simulations with respect to ocean dynamics, Oceanologia, 53, 193-227, https://doi.org/10.5697/oc.53-1-TI.193, ~~2011c~~2011d.

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

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

Meier, H. E. M., Hordoir, R., Andersson, H. C., Dieterich, C., Eilola, K., Gustafsson, B. G., Höglund, A., and Schimanke, S.: Modeling the combined impact of changing climate and changing nutrient loads on the Baltic Sea environment in an ensemble of transient simulations for 1961–2099, Clim. Dyn., 39, 2421-2441, https://doi.org/10.1007/s00382-012-1339-7, 2012c.

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

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

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

Meier, H. E. M., Edman, M. K., Eilola, K. J., Placke, M., Neumann, T., Andersson, H. C., Brunnabend, S.-E., Dieterich, C., Frauen, C., Friedland, R., Gröger, M., Gustafsson, B. G., Gustafsson, E., Isaev, A., Kniebusch, M., Kuznetsov, I., Müller-Karulis, B., Omstedt, A., Ryabchenko, V., Saraiva, S., and Savchuk, O. P.: Assessment of Eutrophication Abatement Scenarios for the Baltic Sea by Multi-Model Ensemble Simulations, Front. Mar. Sci., 5, https://doi.org/10.3389/fmars.2018.00440, 2018a.

Meier, H. E. M., Väli, G., Naumann, M., Eilola, K., and Frauen, C.: Recently accelerated oxygen consumption rates amplify deoxygenation in the Baltic Sea, J. Geophys. Res-Oceans, 123, 3227-3240, https://doi.org/10.1029/2017JC013686, 2018b.

Meier, H. E. M., Dieterich, C., Eilola, K., Gröger, M., Höglund, A., Radtke, H., Saraiva, S., and Wåhlström, I.: Future projections of record-breaking sea surface temperature and cyanobacteria bloom events in the Baltic Sea, Ambio, 48, 1362-1376, https://doi.org/10.1007/s13280-019-01235-5, 2019a.

Meier, H. E. M., Edman, M., Eilola, K., Placke, M., Neumann, T., Andersson, H. C., Brunnabend, S.-E., Dieterich, C., Frauen, C., Friedland, R., Gröger, M., Gustafsson, B. G., Gustafsson, E., Isaev, A., Kniebusch, M., Kuznetsov, I., Müller-Karulis, B., Naumann, M., Omstedt, A., Ryabchenko, V., Saraiva, S., and Savchuk, O. P.: Assessment of Uncertainties in Scenario Simulations of Biogeochemical Cycles in the Baltic Sea, Front. Mar. Sci., 6, https://doi.org/10.3389/fmars.2019.00046, 2019b.

Meier, H. E. M., Eilola, K., Almroth-Rosell, E., Schimanke, S., Kniebusch, M., Höglund, A., Pemberton, P., Liu, Y., Väli, G., and Saraiva, S.: Correction to: Disentangling the impact of nutrient load and climate changes on Baltic Sea hypoxia and eutrophication since 1850, Clim. Dyn., 53, 1167-1169, https://doi.org/10.1007/s00382-018-4483-x, 2019c.

Meier, H. E. M., Eilola, K., Almroth-Rosell, E., Schimanke, S., Kniebusch, M., Höglund, A., Pemberton, P., Liu, Y., Väli, G., and Saraiva, S.: Disentangling the impact of nutrient load and climate changes on Baltic Sea hypoxia and eutrophication since 1850, Clim. Dyn., 53, 1145-1166, https://doi.org/10.1007/s00382-018-4296-y, 2019d.

Meier, H. E. M., and Saraiva, S.: Projected Oceanographical Changes in the Baltic Sea until 2100, Oxford Research Encyclopedia of Climate Science, https://doi.org/10.1093/acrefore/9780190228620.013.699, 2020.

Meier, H. E. M., Dieterich, C., and Gröger, M.: Natural variability is a large source of uncertainty in future projections of hypoxia in the Baltic Sea, Commun. Earth Environ., 2, 50, https://doi.org/10.1038/s43247-021-00115-9, 2021.

~~Meier, H. E. M., Andersson, H., Dieterich, C., Eilola, K., Gustafsson, B., Höglund, A., and Schimanke, S.: Transient scenario simulations for the Baltic Sea Region during the 21st century, SMHI, Norrköping, Sweden, 81pp, 2011d.~~

Met Office: http://www.metoffice.gov.uk, access: 13-10-2021.

Mohrholz, V.: Major Baltic Inflow Statistics – Revised, Front. Mar. Sci., 5, https://doi.org/10.3389/fmars.2018.00384, 2018.

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., Van Vuuren, D. P., Carter, T. R., Emori, S., Kainuma, M., Kram, T., and others: The next generation of scenarios for climate change research and assessment, Nature, 463, 747-756, https://doi.org/10.1038/nature08823, 2010.

Nakicenovic, N., Alcamo, J., Grubler, A., Riahi, K., Roehrl, R. A., Rogner, H.-H., and Victor, N.: Special report on emissions scenarios (SRES), a special report of Working Group III of the intergovernmental panel on climate change, IPCC Special Report, 2000.

Neumann, T.: Climate-change effects on the Baltic Sea ecosystem: A model study, J. Mar. Syst., 81, 213-224, https://doi.org/10.1016/j.jmarsys.2009.12.001, 2010.

Neumann, T., Eilola, K., Gustafsson, B., Müller-Karulis, B., Kuznetsov, I., Meier, H. E. M., and Savchuk, O. P.: Extremes of temperature, oxygen and blooms in the Baltic Sea in a changing climate, Ambio, 41, 574-585, https://doi.org/10.1007/s13280-012-0321-2, 2012.

Niiranen, S., Yletyinen, J., Tomczak, M. T., Blenckner, T., Hjerne, O., MacKenzie, B. R., Müller-Karulis, B., Neumann, T., and Meier, H. E. M.: Combined effects of global climate change and regional ecosystem drivers on an exploited marine food web, Global Change Biol., 19, 3327-3342, https://doi.org/10.1111/gcb.12309, 2013.

Omstedt, A., Gustafsson, B., Rodhe, J., and Walin, G.: Use of Baltic Sea modelling to investigate the water cycle and the heat balance in GCM and regional climate models, Clim. Res., 15, 95-108, https://doi.org/10.3354/cr015095, 2000.

Omstedt, A., and Chen, D.: Influence of atmospheric circulation on the maximum ice extent in the Baltic Sea, J. Geophys. Res-Oceans, 106, 4493-4500, https://doi.org/10.1029/1999JC000173, 2001.

Omstedt, A., Edman, M., Claremar, B., Frodin, P., Gustafsson, E., Humborg, C., Hägg, H., Mörth, M., Rutgersson, A., Schurgers, G., and others: Future changes in the Baltic Sea acid--base (pH) and oxygen balances, Tellus B, 64, 19586, https://doi.org/10.3402/tellusb.v64i0.19586, 2012.

Omstedt, A., Humborg, C., Pempkowiak, J., Perttilä, M., Rutgersson, A., Schneider, B., and Smith, B.: Biogeochemical control of the coupled CO2--O2 system of the Baltic Sea: a review of the results of Baltic-C, Ambio, 43, 49-59, https://doi.org/10.1007/s13280-013-0485-4, 2014.

Oppenheimer, M., Glavovic, B. C., Hinkel, J., Wal, R. v. d., Magnan, A. K., Abd-Elgawad, A., Cai, R., Cifuentes-Jara, M., DeConto, R. M., Ghosh, T., Hay, J., Isla, F., Marzeion, B., Meyssignac, B., and Sebesvari, Z.: Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities, in: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, edited by: Pörtner, H.-O., Roberts, D. C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B., and Weyer, N. M., 2019.

Pellikka, H., Särkkä, J., Johansson, M., and Pettersson, H.: Probability distributions for mean sea level and storm contribution up to 2100 AD at Forsmark, Swedish Nuclear Fuel and Waste Management Company (SKB), 49pp, 2020.

Pihlainen, S., Zandersen, M., Hyytiäinen, K., Andersen, H. E., Bartosova, A., Gustafsson, B., Jabloun, M., McCrackin, M., Meier, H. E. M., Olesen, J. E., Saraiva, S., Swaney, D., and Thodsen, H.: Impacts of changing

Formatiert: Englisch (Großbritannien)

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

society and climate on nutrient loading to the Baltic Sea, Sci. Total Environ., 138935, https://doi.org/10.1016/j.scitotenv.2020.138935, 2020.

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

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

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

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

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

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

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

Roeckner, E., Brokopf, R., Esch, M., Giorgetta, M., Hagemann, S., Kornblueh, L., Manzini, E., Schlese, U., and Schulzweida, U.: Sensitivity of simulated climate to horizontal and vertical resolution in the ECHAM5 atmosphere model, J. Climate, 19, 3771-3791, https://doi.org/10.1175/JCLI3824.1, 2006.

~~Rummukainen, M., Räisänen, J., Bringfelt, B., Ullerstig, A., Omstedt, A., Willén, U., Hansson, U., and Jones, C.: A regional climate model for northern Europe: model description and results from the downscaling of two GCM control simulations, Clim. Dyn., 17, 339-359, https://doi.org/10.1007/s003820000109, 2001.~~

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

Rummukainen, M.: State-of-the-art with regional climate models, Wires. Clim. Change, 1, 82-96, https://doi.org/10.1002/wcc.8, 2010.

Rummukainen, M., Rockel, B., Bärring, L., Christensen, J. H., and Reckermann, M.: Twenty-first-century challenges in regional climate modeling, Bull. Amer. Meteor. Soc., 96, ES135-ES138, https://doi.org/10.1175/BAMS-D-14-00214.1, 2015.

Rummukainen, M.: Added value in regional climate modeling, Wires. Clim. Change, 7, 145-159, https://doi.org/10.1002/wcc.378, 2016.

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

Ryabchenko, V. A., Karlin, L. N., Isaev, A. V., Vankevich, R. E., Eremina, T. R., Molchanov, M. S., and Savchuk, O. P.: Model estimates of the eutrophication of the Baltic Sea in the contemporary and future climate, Oceanology+, 56, 36-45, https://doi.org/10.1134/S0001437016010161, 2016.

Samuelsson, P., Jones, C. G., Willén, U., Ullerstig, A., Gollvik, S., Hansson, U. L. F., Jansson, C., Kjellström, E., Nikulin, G., and Wyser, K.: The Rossby Centre Regional Climate model RCA3: model description and performance, Tellus A, 63, 4-23, https://doi.org/10.1111/j.1600-0870.2010.00478.x, 2011.

Saraiva, S., Meier, H. E. M., Andersson, H., Höglund, A., Dieterich, C., Gröger, M., Hordoir, R., and Eilola, K.: Uncertainties in Projections of the Baltic Sea Ecosystem Driven by an Ensemble of Global Climate Models, Front. Earth Sci., 6, https://doi.org/10.3389/feart.2018.00244, 2019a.

Saraiva, S., Meier, H. E. M., Andersson, H., Höglund, A., Dieterich, C., Gröger, M., Hordoir, R., and Eilola, K.: Baltic Sea ecosystem response to various nutrient load scenarios in present and future climates, Clim. Dyn., 52, 3369-3387, https://doi.org/10.1007/s00382-018-4330-0, 2019b.

Savchuk, O. P., Larsson, U., and Elmgren, L.: Secchi depth and nutrient concentration in the Baltic Sea: model regressions for MARE's Nest, Department of Systems Ecology, Stockholm University, Sweden, Technical Report, 12pp, 2006.

Schimanke, S., Meier, H. E. M., Kjellström, E., Strandberg, G., and Hordoir, R.: The climate in the Baltic Sea region during the last millennium simulated with a regional climate model, Clim. Past, 8, 1419, https://doi.org/10.5194/cp-8-1419-2012, 2012.

Schimanke, S., and Meier, H. E. M.: Decadal-to-Centennial Variability of Salinity in the Baltic Sea, J. Climate, 29, 7173-7188, https://doi.org/10.1175/JCLI-D-15-0443.1, 2016.

Schrum, C., Lowe, J., Meier, H. E. M., Grabemann, I., Holt, J., Mathis, M., Pohlmann, T., Skogen, M. D., Sterl, A., and Wakelin, S.: Projected Change - North Sea, in: North Sea Region Climate Change Assessment, edited by: Quante, M., and Colijn, F., SpringerOpen, Cham, 175-217, https://doi.org/10.1007/978-3-319-39745-0_6, 2016.

Schrum, C.: Regional Climate Modeling and Air-Sea Coupling, *Oxford Research Encyclopedia of Climate Science*, Oxford University Press, 2017.

Sen, P. K.: Estimates of the Regression Coefficient Based on Kendall's Tau, J. Am. Stat. Assoc., 63, 1379-1389, https://doi.org/10.1080/01621459.1968.10480934, 1968.

Sjöberg, B.: Sea and coast. National atlas of Sweden, 1992.

Skogen, M. D., Eilola, K., Hansen, J. L. S., Meier, H. E. M., Molchanov, M. S., and Ryabchenko, V. A.: Eutrophication status of the North Sea, Skagerrak, Kattegat and the Baltic Sea in present and future climates: A model study, J. Mar. Syst., 132, 174-184, https://doi.org/10.1016/j.jmarsys.2014.02.004, 2014.

SMHI Hypeweb: World-Wide Hydrological Predictions: https://hypeweb.smhi.se/, access: 13-10-2021

Suursaar, Ü., and Sooäär, J.: Decadal variations in mean and extreme sea level values along the Estonian coast of the Baltic Sea, Tellus A, 59, 249-260, https://doi.org/10.1111/j.1600-0870.2006.00220.x, 2007.

Suursaar, Ü.: Combined impact of summer heat waves and coastal upwelling in the Baltic Sea, Oceanologia, 62, 511-524, https://doi.org/10.1016/j.oceano.2020.08.003, 2020.

Taylor, K. E., Stouffer, R. J., and Meehl, G. A.: An Overview of CMIP5 and the Experiment Design, Bull. Amer. Meteor. Soc., 93, 485-498, https://doi.org/10.1175/BAMS-D-11-00094.1, 2012.

Theil, H.: A rank-invariant method of linear and polynomial regression analysis, 3, Indagat. Math., 1, 1397-1412, 1950.

Uppala, S. M., KÅllberg, P. W., Simmons, A. J., Andrae, U., Bechtold, V. D. C., Fiorino, M., Gibson, J. K., Haseler, J., Hernandez, A., Kelly, G. A., Li, X., Onogi, K., Saarinen, S., Sokka, N., Allan, R. P., Andersson, E., Arpe, K., Balmaseda, M. A., Beljaars, A. C. M., Berg, L. V. D., Bidlot, J., Bormann, N., Caires, S., Chevallier, F., Dethof, A., Dragosavac, M., Fisher, M., Fuentes, M., Hagemann, S., Hólm, E., Hoskins, B. J., Isaksen, L., Janssen, P. A. E. M., Jenne, R., Mcnally, A. P., Mahfouf, J.-F., Morcrette, J.-J., Rayner, N. A., Saunders, R. W., Simon, P., Sterl, A., Trenberth, K. E., Untch, A., Vasiljevic, D., Viterbo, P., and Woollen, J.: The ERA-40 re-analysis, Q. J. Roy. Meteor. Soc., 131, 2961-3012, https://doi.org/10.1256/qj.04.176, 2005.

Formatiert: Englisch (Großbritannien)

Formatiert: Englisch (Großbritannien)

Formatiert: Englisch (Großbritannien)

Formatiert: Englisch (Großbritannien)

Feldfunktion geändert

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Formatiert: Englisch (Großbritannien)

van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S. J., and Rose, S. K.: The representative concentration pathways: an overview, Clim. Change, 109, 5, https://doi.org/10.1007/s10584-011-0148-z, 2011.

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

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

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

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

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

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

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

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

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

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)

Formatiert: Schriftart: (Standard) Times New Roman, 10 Pt., Englisch (Großbritannien)