Third assessment of climate change for the Baltic Sea region (BACC III)

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Kommentiert [m1]: In blue auxiliary text from EN CLIME fact sheets.

Kommentiert [m2]: Not confirmed yet

Kommentiert [m3]: Not confirmed yet

Kommentiert [m4]: Not confirmed yet

Kommentiert [m5]: Not confirmed yet

Kommentiert [m6]: Not confirmed yet

Kommentiert [m7]: Not confirmed yet

Kommentiert [m8]: Not confirmed yet

Abstract. Please use only the styles of this template (MS title, Authors, Affiliations, Correspondence, Normal for your text, and Headings 1–3). Figure 1 uses the style Caption and Fig. 1 is placed at the end of the manuscript. The same is applied to tables (Aman et al., 2014; Aman and Bman, 2015)

1 Introduction

1.1 Overview

General introduction, changing climate and knowledge needs for society, policymakers and stakeholders, IPCC and needs for regional information
Focus: Atmosphere, hydrosphere, cryosphere, lithosphere and biosphere
Not anthroposphere

1.2 Baltic Sea Region characteristics

Kommentiert [m9]: Introduction into the region and differences between the Baltic Sea and other coastal seas

Atmosphere:

The climate of the Baltic Sea region is strongly influenced by the large-scale atmospheric circulation (e.g. Andersson, 2002; Tinz, 1996; Meier and Kauker, 2003; Omstedt and Chen, 2001; Zorita and Laine, 2000; Lehmann et al., 2002), in particular the North Atlantic Oscillation (NAO) and blocking and on longer time scales the Atlantic Multidecadal Oscillation (AMO).
The NAO is the dominant mode of near-surface pressure variability over the North Atlantic and its impact is strongest during winter (Hurrel et al., 2003), when it accounts for almost one-third of the sea level pressure (SLP) variance. During the positive (negative) phase of the NAO the Icelandic Low and Azores High pressure systems are enhanced (reduced), leading to a stronger (weaker) than normal westerly flow (Hurrell, 1995). For the Baltic Sea region the positive phase of the NAO is related to mild and wet winters and increased storminess (Hurrell et al., 2003).
Atmospheric blocking occurs when persistent high pressure systems interrupt the normally westerly flow over the middle and high latitudes, like e.g. the North Atlantic. This is also frequently observed in the Baltic Sea region. Due to the persistence of blocking events they are often responsible for extreme weather events (Rex, 1950a; Rex, 1950b).
The AMO describes fluctuations in North Atlantic sea surface temperature (SST) with a period of 60-90 years (Knight et al., 2006). Thus in the 150-year instrumental record only a few distinct phases have been observed. However, a recent model study suggests that variations in the AMO may have an impact on the precipitation over the Baltic Sea region (Börgel et al., 2018).

Precipitation is water falling to the ground. It can take various forms including melted (e.g. rainfall and drizzle) or frozen (e.g. snowfall and hail) or in mixed forms involving both snow and rain (e.g. sleet). Precipitation is measured in mm of melted water over a certain time interval that could include one or several precipitation events.

Precipitation is strongly linked to other parameters describing the water cycle. The amount of water in the air is one of the most important factors implying that the history of an air mass including previous evaporation and precipitation events is important. As the amount of water that can be held in air depends on temperatures, precipitation has some temperature dependency (generally more precipitation in summer than in winter in large parts of the Baltic Sea region). Precipitation is also strongly modified by orographic features implying that the large-scale circulation of the atmosphere including wind direction and vertical stability are important factors.

Precipitation is a key feature in determining soil moisture conditions, runoff and discharge. The impact on soil moisture can represent a strong feedback mechanism as dry conditions lead to less evaporation and thereby less precipitation etc.

Precipitation is one of the key parameters in the water cycle, it can be stratiform, convective and orographic and is depending on atmospheric circulation patterns, convection and accessibility to water.

Land:

The magnitude of water flow in a river is the result of various complex hydrological processes including *precipitation*, *evapotranspiration*, *infiltration* and *storage* (e.g. in the form of snow, soil moisture, and sub-surface and groundwater storage). Therefore, explaining changes in streamflow requires an understanding of these parameters of which precipitation is often the pivotal one in the cool climate of the Baltic Sea region.

River runoff and net precipitation (precipitation minus evaporation) over the sea surface are dominant drivers of Baltic Sea salinity explaining together with the limited water exchange with the North Sea the large gradient in sea surface salinity between about 20 g kg^{-1} in Kattegat and 2 g kg^{-1} in the Bothnian Bay (REF). Net precipitation amounts to about 10% of the total river runoff (e.g., REF, Meier and Döscher, 2002).

Ocean:

Salinity:

Due to freshwater supply from the Baltic Sea catchment area and due to the limited water exchange with the world ocean, surface salinity varies from > 20 g kg^{-1} in Kattegat to < 2 g kg^{-1} in the Bothnian Bay. The dynamics of the Baltic Sea is characterized by a two layer system because of a pronounced, perennial vertical gradient in salinity.
Meteorologically driven large saltwater inflows (so-called Major Baltic Inflows, MBIs) sporadically renew the deeper parts of the Baltic Sea with saline, oxygen rich water. Hence, MBIs are the only process that effectively ventilate the deep water. However, MBIs are estimated to contribute to the total salt important by only 20%.

Stratification:

Stratification denotes the vertical layering of water bodies according to different water densities mainly determined by layer specific water temperature and salt concentrations. Stratification controls vertical transports in the water column, e.g. the downward flow of dissolved oxygen from the sea surface into the deep layers. A number of parameters exist to characterize stratification. Pycnocline commonly denotes the strongest density gradient in the vertical water column. Corresponding definitions exist for the temperature gradient (thermocline) and salinity gradient (halocline) which highlight the governing parameters for the density layering.

The forces of the winds (i.e. wind stress working at the air water interface) can potentially homogenize the water column fully (some shallow water regions) or partly (deep water regions) and thus influence stratification.

In the Baltic Sea a pronounced halocline persists over the year between 60-80 meters in most regions. During the warm season a thermocline develops at much shallower depths (10-20 meter).

Theoretical considerations imply that increased freshwater supply (precipitation minus evaporation, snow melt) over the Baltic Sea drainage basin accompanied by the supply of deep salt rich waters from the North Sea as well as warming of the surface layer would favor stronger stratification.

Sea level:

Sea level is traditionally measured with a scale on the harbor wall. The earliest scales from the 18th century were marks on large, prominent boulders along the shoreline of the Baltic Sea (Ekman, 2009). Sea level changes when water is added to the global ocean, when it expands by warming or when the land is rising to which the scale is attached. These are the three most important contributions to long-term changes in sea level in the Baltic Sea (BACC I, Hünicke et al., 2015). Changes in oceanic and atmospheric circulation cause variations of sea levels in the Baltic Sea on seasonal to decadal time scales (Chen and Omstedt, 2005). Winter sea level in the Baltic Sea is usually higher than summer sea level (Samuelsson and Stigebrandt, 1996). And mild winters with stronger than average winds show higher sea levels than severe winters (Andersson, 2002, Karabil et al., 2018). During the cold seasons from fall to spring the risk is higher for storms to produce storm surges along the coasts of the Baltic Sea (Lehmann et al., 2011). Storm surges are water masses pushed against the coasts by the wind of atmospheric low pressure systems. The lower atmospheric pressure in a storm can add to the amplitude of the storm surge. Storms also excite oscillations in the Baltic Sea that are highest at the ends of the different basins and lowest in the Baltic Proper (Weisse and Weidemann, 2017). Waves that are generated during storms can add to extreme sea levels measured along the coast (Eelsalu et al., 2014). The amplitude of tides is relatively small in the Baltic Sea and adds to extreme sea levels only in the Kattegat and Skagerrak.

The mean sea level of the global ocean is closely related to the volume of the ocean. The volume is changing due to geologic activity and to the addition of water that was previously frozen on land like the Antarctic and Greenland ice sheets and mountain glaciers. Melting rates of glaciers are sensitive to changes in air temperature, snow cover and the resulting brightness. Ice sheets in polar regions are affected additionally by contact with ocean water melting the ice from below, which can cause instabilities in the integrity and the flow of the ice sheets. Ocean temperatures affect the mean sea level because warmer water is lighter and takes up more volume than colder water. The continuous redistribution of heat from the tropics to the polar regions establishes the ocean circulation systems that form a sea surface relief along which the ocean currents are flowing. This sea surface relief modulates the global mean sea level by up to half a meter (e.g. Yin et al., 2009). The mean sea level in the Baltic Sea depends on the strength of the ocean circulation in the Atlantic (Yin et al., 2009, 2010, Yin, 2012, Balmaseda et al., 2013b). Temperature and freshwater distribution in the ocean leave their imprint on height of the sea surface and cause it to vary on decadal time scales (Balmaseda et al., 2013a). Atmospheric winds are another important driver of sea level variability on time scales from decades down to a couple of hours during a storm surge.

Sedimentation:

Sediment transport is triggered mainly by currents in marine environment, by waves in the nearshore and by wind in subaerial coastal environment. Its direct consequence is a gradual change of the earth surface landform, leading to erosion or accretion.

Short-term and small-scale sediment transport is strongly hinged on a variety of local state variables including wind velocity and direction, water level, waves as well as the antecedent state of the system, while long-term and large-scale sediment transport and coastal erosion are primarily controlled by sediment supply modulated by large-scale processes, notably mean sea level, storms, the regional wind and wave pattern, and engineering structures.

Due to a combined effect of isostatic adjustment and eustatic sea level change, the coastline change of the Baltic Sea is characterized by a North-South gradient from an uplift of max. 9 mm/yr in the North to a subsidence of min. -2 mm/yr in the south since the onset of the Holocene. The subsiding southern Baltic Sea coast is characterized by a series of barrier islands and sandy dunes connected with soft moraine cliffs. The composition of soft, mobile sediments makes the southern Baltic Sea coast extremely vulnerable to wind-wave induced transport and erosion.

Most coastline erosion along the southern Baltic Sea is caused either by storms or human-induced depletion of sediment supply (e.g. side effect of engineering structures).

Oxygen concentration and hypoxia:

Dissolved oxygen concentration in the water column is controlled by physical transport supply (advection and diffusion) and biological oxygen demand for oxidation of organic matter. Due to limited ventilation largely incapable to meet the oxygen demand by elevated concentrations of organic matter in the water column and sediments (eutrophication), the Baltic Sea deeps suffer from deoxygenation and hypoxia. Hypoxic area is defined as the extent of bottom water with oxygen concentrations below a threshold such as 2 mL O2 L^{-1}. Hypoxia is characterized by the lack of higher forms of live.

1.3 Global climate change

1.4 The BACC process

What is new in BACC III? BACC III is an update of BACC II, assessment of knowledge from literature published after BACC II (focus period 2013-2019), ESD peer-reviewed journal, independent editors, independent scientific reviewers, part of BEAR (9 review articles), common figures of atmospheric, hydrological and oceanographic projections based on published climate simulations, common uncertainty analysis

1.5 Summary of BACC I and II key messages

1.5.1 Past climate change

Long-term changes on paleoclimate timescales

1.5.2 Recent climate change

Climate change observed during the instrumental period

1.5.3 Future climate change

Projections based upon IPCC (2007)

2 Methods

2.1 Assessment of literature

Assessment of scientific peer-reviewed literature and reports, statistics of references

2.2 Climate model data

Published model data based upon IPCC (2013),

uncoupled simulations with several RCMs and GCMs (Ole, Erik) and coupled simulations with one RCSM and 8 GCMs (Matthias, Christian, Markus), RCP 2.6, 4.5 and 8.5

An additional ensemble is available that has been produced with a coupled RCM. The RCM RCA4-NEMO has been introduced by Wang et al., 2015. Gröger et al., 2015, 2019 and Dieterich et al. 2019 have validated different aspects of the ensemble discussed here. The atmosphere component RCA4 is run at a resolution of 0.22 [degrees] and 40 levels in the EURO-CORDEX domain. Coupled to it is the North Sea-Baltic Sea model NEMO-Nordic at a resolution of 2 nautical miles and 56 levels. The two components of the RCM are coupled by sending sea level pressure, energy, mass and momentum fluxes every 3 hours from the atmosphere to the ocean. Vice versa, the atmosphere receives at the same frequency sea and ice surface temperatures and the sea ice fraction and albedo.

Table 2: Ensemble members of three RCP scenarios with the coupled RCM.

	RCP8.5	RCP4.5	RCP2.6
EC-EARTH	1961 - 2099	1961 - 2099	1961 - 2099
MPI-ESM-LR	1961 - 2099	1961 - 2099	1961 - 2099
HadGEM2-ES	1961 - 2099	1961 - 2099	1961 - 2099
GFDL-ESM2M	1961 - 2099	1961 - 2099	1961 - 2099
IPSL-CM5A-MR	1961 - 2099	1961 - 2099	1961 - 2099
CanESM2	1961 - 2099	1961 - 2099	1961 - 2099
NorESM1-M	1961 - 2099	1961 - 2099	1961 - 2099
MIROC5	1961 - 2099	1961 - 2099	1961 - 2099

This RCM has been used to downscale eight different GCMs with three RCPs each (Table 2). Surface variables of the atmosphere component are saved at hourly to 6-hourly frequency to allow for an analysis of means and extremes in present and future climates.

2.3 Uncertainty estimates

IPCC terminology, methods applied in this study

3 Current state of knowledge

3.1 Past climate change

Knowledge gained from proxy data and paleoclimate modeling

3.2 Present climate change

The past 200 years (instrumental records, model based reconstructions and reanalyses), changes in mean and extremes, trends and decadal/multi-decadal variability

3.2.1 Atmosphere

Large-scale circulation (teleconnection patterns), surface pressure, wind, surface atmosphere temperature, precipitation, cloudiness and solar radiation

3.2.1.1 Large-scale circulation

NAO:

While the NAO exhibited a positive trend from the 1960s to the 1990s it has returned to lower values in the early 2000s with exceptionally low anomalies in the winters of 2009/2010 and 2010/2011, which considerably weakened the positive trend.

Kommentiert [m10]: But there is no long-term trend since 1850.

Blocking:

While some studies find an eastward shift of blocking events over the North Atlantic (Davini et al., 2012; Croci-Maspoli et al., 2007) and increase in blocking duration over the Northern Hemisphere since about 1990 (Mokhov et al., 2013), there is low confidence in these changes due to methodological differences between studies (IPCC, 2013).

AMO:

The AMO has been warming from the late 1970s to the 2000s as part of its natural variability and has since remained in a warm state. Natural fluctuations in the AMO over the coming few decades will likely influence regional climates, like e.g. the Baltic Sea region, at least as strongly as human-induced changes (IPCC, 2013).

increasing linear trend of the number of deep cyclones for the period 1950-2010 (Lehmann et al., 2016)

3.2.1.2 Air temperature

Air temperature introduction: Air temperature shows the clearest response to the increased green-house effect. Changes in temperature extremes may influence human activity much more than changes in average temperature.

Air temperature: A significant surface air temperature increase in the Baltic Sea region during the last century was detected (BACC Author Team 2008; 2014; Rutgersson et al., 2014). The temperature increase is not monotonous but accompanied by large (multi-) decadal variations dividing the 20th century into 3 main phases: (1) warming in the beginning of the century until the 1930s; (2) cooling until 1960s; and (3) another distinct warming during the last decades of the time series. Linear trends of the annual mean temperature anomalies during 1871−2013 were 0.10 K decade−1 north of 60°N and 0.08 K decade−1 south of 60°N in the Baltic Sea region. This is larger than the global mean temperature trend. There are large variations, in particularly during winter, but the warming is seen for all seasons (being largest during spring). These changes are also resulting in seasonality changes: the length of the growing season has increased, whereas the length of the cold season has decreased. The number of days by which autumn and winter are delayed differs from south to north and east to west, but as an example in Tartu, Estonia, the number of deep winter days (with snow cover) has decreased by 29 d over the past century while the growing season has increased by 13 d in this period (Kull et al. 2008).

Air temperature extremes: The duration of extremely mild periods has increased significantly in winter, while the number of heat waves has increased in summer as well as during the year as a whole. A general increase has been observed for the annual numbers of days with daily maximum temperature above both 25 and 30 °C, and a decrease in the length of the frost season and in the annual number of frost days.

3.2.1.3 Solar radiation

Solar radiation introduction:

Total cloudiness consists of clouds on all levels (low, medium and high) and is related to the general circulation as well as the water cycle. Solar radiation is to a large extent depending on the cloudiness (amount and type of clouds), but also to atmospheric aerosols. Atmospheric aerosols affect solar radiation under clear skies directly and through interaction with clouds indirectly.

Solar radiation: Multidecadal variations, known as “dimming” and “brightening” have been observed both in Europe and many other parts of the world, e.g. Wild et al. 2005, Wild et al. 2012, Wild et al. 2017 (especially on the northern hemisphere). No long-term measurements over oceans. However, (aerosol-induced) multidecadal variations in surface solar radiation could be expected also over oceans (Wild et al. 2016).

Satellite data records of trends in cloudiness since the 1980s disagree over many areas but there is some consistency about a decline in cloudiness over the Baltic area (Karlsson and Devasthale, 2018 (fig 4)).

3.2.1.4 Precipitation

Anna:

Precipitation is highly variable, and the amount has varied between regions and seasons, with both increasing and decreasing precipitation and no general trend for the entire region, however areas have experienced both increasing and decreasing trends.

Kommentiert [m11]: Disensus?

Erik:

On average, annual mean precipitation has generally increased over most of the Baltic Sea region over the 20th Century. Differences between different parts of the region and between seasons are prominent.

Kommentiert [m12]: Disensus?

Precipitation extremes:

Anna:

An increase in extreme precipitation and duration of the lengths of wet periods. Also the length of dry periods have been seen in some areas.

Decreased summer precipitation and increased length of dry periods is closely linked to increased risks of forest fires and limitations in accessibility to drinking water. It would also cause problems for agriculture. More intense precipitation increases the risks of flooding, if drainage systems are not adapted.

Erik:

Precipitation increase in northern Europe is generally associated with an increase in the frequency and intensity of extreme precipitation events. Observed changes include increasing intensity and/or frequency of intense precipitation events, changes in duration of wet and dry spells.

3.2.1.5 Wind

Wind

Wind extremes

3.2.1.6 Atmospheric chemistry

3.2.2 Land

River runoff, nutrient and carbon loads, river ice, lakes, lake ice, snow, permafrost, terrestrial and freshwater ecosystems

3.2.2.1 River discharge

Run-off to the Baltic Sea appears to be strongly linked to temperature, wind and rotational circulation components in the northern region and Gulf of Finland. In contrast, run-off in the southern region is more associated with the strength and torque of the cyclonic or anticyclonic pressure systems. (Hansson et al. 2011)

Although decadal and regional variability is large, no *statistically significant* long-term change has been detected in the reconstructed total river runoff to the Baltic Sea over the past 500 years.

As a whole, over the past 500 years, the total river runoff to the Baltic Sea has decreased slightly in response to the rise in temperature; at a rate of 3%, or 450 m^{-3} s^{-1}, per 1°C (Hansson et al. 2011).

Kommentiert [m13]: This number is rather uncertain. The reconstructed runoff by Hansson et al. 2010 underestimates interannual variability considerably. Multidecadal variability is almost missing

The observed temperature increase has clearly affected stream flow in the Nordic countries. These changes correspond well to the projected consequences of a continued rise in global temperature, whereas the impacts of both the observed and projected changes in precipitation on stream flow are unclear (Hisdal et al. 2010).

In the Baltic States (Lithuania, Latvia and Estonia) in general, changes in stream flow over the 20th century show a redistribution of runoff throughout the year: with a significant increase in winter river discharge and a tendency for decreasing spring floods (Reihan et al. 2007).

Kommentiert [m14]: Not only in the Baltic States. Isn't the winter mean trend of the total river flow statistically significant as well? Check!
Check!

river flow to the Bothnian Bay show a statistically significant positive trend during 1921-2004 (Kniebusch et al., 2019)

Stahl et al. (2010)

Kniebusch et al. (2019b)

No statistically significant linear trends in annual river discharge to the sea has been detected. Winter flows have increased due to temperature while spring flows have decreased (BACC II)

For the period 1850-2008, the total river runoff from the Baltic Sea catchment area reconstructed from observations (Hansson et al., 2011a; Cyberski and Wroblewski, 2000; Mikulski, 1986; Bergström and Carlsson, 1994) and hydrological model results (Graham, 1999) shows no statistically significant trend but a pronounced multi-decadal variability with a period of about 30 years (Meier et al., 2018b).

3.2.2.2 Lakes

3.2.2.3 Terrestrial biogeochemistry

Nutrient loads

In the reference scenario, nutrient loads represent the average loads of the period 2010-2012. The high or worst case scenario assumes changes caused by a ‘fossil-fuelled development’ scenario coupled to increasing river runoff. Changes in nitrogen and phosphorus loads were calculated from the regional assumptions, e.g., on population growth, changes in agricultural practices such as land and fertilizer use and expansion of sewage water treatment plants.

PLC reports statistically significant reductions in riverine nutrient loads to the sea relative to the 1997 to 2003 reference period (PLC6).
These reductions are not attributed to climate.

DOC inputs to the sea have increased over the past century but the cause is not known (BACC II).

3.2.2.4 Terrestrial ecosystems and biodiversity

Land cover
Agriculture and forest
Birds

3.2.3 Cryosphere

3.2.3.1 Snow

3.2.3.2 Glaciers

3.2.3.3 Permafrost

3.2.3.4 Sea ice

Looking back a little bit more than 100 years, the ice winters have become milder, the maximum ice extent has decreased and the ice season is shorter. Also indexes based on the total ice volume of the winter show a decreasing trend. Severe ice winters can still happen nowadays, but the possibility therefore has decreased.
The maximum ice extent in the Baltic Sea is changing between 50 and 400 km^2 from year to year. During mild winters just the Bothnian Bay is ice covered while in severe winter the whole Baltic Sea can be ice covered like in the ice winter 1986.

Kommentiert [m15]: More information is available

3.2.3.5 Cryospheric ecosystems and biodiversity

3.2.4 Ocean and sediment

Water temperature, salinity, stratification, currents, water exchange, sea ice, sea level, wind waves, sediment transports, marine ecosystems (including coastal ecosystems, biogeochemistry), acidification,

3.2.4.1 Water temperature

The temperature rises fastest at the surface. With time the heat spreads downward through different processes and eventually the whole water column warms up. This has consequences for the stratification (EN-CLIME stratification), eutrophication (EN-CLIME nutrient cycle) and sea level rise (EN-CLIME sea level).

The marginal seas around the globe have warmed more than the average over the global ocean (Belkin, 2009). The Baltic Sea has warmed during the second half of the past century, although the interannual variability is high (Kniebusch et al., 2019a). During the period 1982 to 2006 the SST increased by 1.35 C in the Baltic Sea. No other sea has warmed up that much. Fonselius and Valderrama (2003). The accelerated warming is partly explained by the phase of the AMO (Kniebusch et al., 2019a).

3.2.4.2 Salinity and saltwater inflows

New research results contributed to the understanding of the role of natural variability and climate change for salinity changes in the Baltic Sea (e.g., Börgel et al., 2018; Kniebusch et al., 2019b; Lehmann and Post, 2015; Lehmann et al., 2016; Mohrholz, 2018; Schimanke and Meier, 2016). A new reconstruction of saltwater inflows for the period 1887–2017 showed that the apparent decline in frequency and intensity of MBIs in the reconstructed record by Fischer and Matthäus (1996) since 1976 was based on inhomogeneous data (Mohrholz, 2018). Hence, we can conclude that there are no statistically significant trends in salinity (Fonselius and Valderrama, 2013; Meier et al., 2018b; Kniebusch et al., 2019b), stratification (Meier and Kauker, 2003), river flow (Meier and Kauker, 2003a; REF), large volume changes (LVC) (Lehmann and Post, 2015) and MBIs (Mohrholz, 2018) on centennial time scales since about 1900. However, salinity, river flow and MBIs showed a pronounced multi-decadal variability with a period of about 30 years (Winsor et al., 2001; 2003; Gailiušis et al., 2011; Mohrholz, 2018). Part of this variability is, for instance, the stagnation period during 1983-1992 without MBI and with decreasing salinity (Nehring and Matthäus, 1991).

According to model results, multi-decadal variations in runoff explained about 50% of the long-term variability of volume averaged salinity of the Baltic Sea (Meier and Kauker, 2003a). Radtke et al. (2019) found that the direct dilution effect was responsible for about one fourth of the multidecadal variability only and that the impact of vertical turbulent mixing is small. Salt water inflows contribute to the multidecadal variability in salinity as well, in particular of the bottom layer salinity. Further, model results suggest that decreasing salinity over ten years appear approximately once per century on average and belongs to the natural variability of the system (Schimanke and Meier, 2016). On longer time scales, Baltic Sea salinity is under the influence of the Atlantic Multidecadal Oscillation with a period of about 60-90 years (Börgel et al., 2018). Probably part of this long-term natural variability, since about the 1980s observed surface and bottom salinities decreased and increased, respectively (Vuorinen et al., 2015; Liblik and Lips, 2019).

Since about the 1970s, the mean seasonal cycle of the total river flow has changed with increasing and decreasing runoff during winter and summer, respectively (REF; Meier and Kauker, 2003a). These changes might be explained by river regulation of large rivers in the North (Matthäus and Schinke, 1999) and systematic changes in precipitation patterns due to warming in the Baltic Sea region (REF). However, as the change in seasonality does not affect the total discharge trend and as there is no statistically significant trend in saltwater inflows on centennial time scale (Mohrholz, 2018), changes in salinity are regional only. In Baltic Sea reconstructions and local observations, Kniebusch et al. (2019b) found a statistically significant positive trend in the North-South gradient of sea surface salinity for 1900-2008. This change is mainly attributed to increased river runoff from the northernmost catchment indicating a footprint of the anthropogenic impact on salinity.

3.2.4.3 Stratification

Direct consequences of increasing stratification is that mixing between well ventilated surface waters and deep waters weakens. This makes the Baltic Sea more vulnerable against deoxygenation of bottom waters (haline stratification). An increase in seasonal thermal stratification can additionally lower the vertical nutrient transport from deeper layers to the euphotic zone thereby limiting nutrient supply and potentially facilitate cyanobacteria blooms in the Baltic Sea.

3.2.4.4 Overturning circulation

3.2.4.5 Sea level

Global mean sea level rise is measured at 1.5 mm/year during the 20st century. It is estimated at a rate of 2.8 mm/year during the period since satellites are measuring (1993 to 2010). The rate of global mean sea level rise is increasing [high confidence]. During the second half of the past century thermal expansion of sea water and the addition of melt water from the Antarctic and Greenland ice sheets and from glaciers have contributed about equally to the process [high confidence] (Church et al., 2013). Sea level rise (relative to the ellipsoid) in the Baltic Sea in the past 50 years is estimated between 1 and 3 mm/year (Milne et al., 2001, Hill et al., 2010, Richter et al., 2011, BACC I, BACC II). For the period 1886-2017, Swedish Baltic Sea records showed an increase of about 24 cm corresponding to 1.8 mm/year (Source: SMHI).

Kommentiert [m16]: Uncertainty range from the literature. What are the latest numbers? Is there an acceleration since 1980?

Sea level extremes:

Return levels with corresponding return periods is a concept to assess the amplitude and the probability of extreme events. A storm surge with a 100-year return period will occur on average once in 100 years. The amplitude of the event depends on the location in the Baltic Sea. Storm surges at the end of the basins furthest away from the Baltic Proper are higher than those in the center of the Baltic Sea [high confidence] (Meier et al., 2004, Wolski et al., 2014, Dieterich et al., 2019). No long-term trend has been found so far that points to an increase of extreme sea levels in the Baltic Sea (EN-CLIME wind, BACC II). There are however studies (e.g. Suursaar and Sooäär, 2007) that confirm extreme sea level e.g. in the Gulf of Finland to be very sensitive to the position of the storm tracks.

Kommentiert [m17]: Subtracting the mean sea level rise?

Kommentiert [m18]: What does this mean? Will the projected northward shift of the storm track have an impact on extremes? You should also add the results by Lang and Mikolajewicz (2019).

No changes during different climate conditions (Lang and Mikolajewicz, 2019)

3.2.4.6 Waves

3.2.4.7 Sedimentation

Mean erosional rate along Latvia and Lithuania for the sandy coasts and soft cliffs are 1–2 m/yr and 0.5-0.6 m/yr in the latter half of the twentieth century, respectively. Since 1980s erosional rates of certain sections have been enhanced to 1.5–4 m/yr;

Mean erosional rate along Lithuania and Russia (Kaliningrad) for the sandy coast and cliff are 0.5-0.8 m/yr and 1-1.5 m/yr, respectively, and rates have increased over the past decade.

The Polish coast is mainly formed of soft sandy sediments, with an average rate of retreat of 0.5–1.5 m year^{-1}. Coastal towns which experienced erosion of 0.3–0.7 m/yr now have a nourished beach.

Mean erosion rate along the German sandy coast is 0.4 m/yr.

In southern Sweden, the soft moraine cliffs have retreated 1–1.5 m year^{-1} over the past 150 years.

Erosion rates along the dune coasts in the Kattegat are within 2 m year^{-1}.

Coastal erosion has the following direct consequences:
1. loss of coastal lands;
2. loss of coastal resilience;
3. loss of valuable natural habitats;
4. loss of economic value and private property;
5. increasing cost to society in terms of coastal protection.

Coastal erosion extremes:

Many sandy beaches along the Gulf of Finland have recently been severely damaged by frequent storm surges, despite extensive protective measures.

Soft cliffs in Latvia are eroded 3–6 m/yr after each storm, with a maximum of up to 20–30 m/yr at local sites.

Extreme erosional rate along Lithuania and Russia (Kaliningrad) for cliff are 10 m/yr.

Poland: recent erosion after each storm surge reaches 3–6 m/yr;

Germany: erosion by storms has reached 3 m/yr at some local coastal sections

Maximum erosion rates along the dune coasts in the Kattegat are ~2 m/yr.

3.2.4.8 Marine carbonate and biogeochemistry

Air-sea exchange of CO_2:

There is clear seasonal pattern in the partial pressure of CO_2 (pCO_2) in the surface Baltic Sea. It is controlled by the biologically driven processes (organic matter production and remineralization) as well as changes in the mixed layer depth.

In winter the surface Baltic Sea is oversaturated with CO_2, while in the productive periods pCO_2 goes down below the atmospheric level with 2 clear minima: during spring bloom and N_2-fixing cyanobacteria bloom.

The difference between seawater pCO_2 and atmospheric pCO_2 during the productive periods has increased due to the eutrophication and development of cyanobacteria blooms.
During spring bloom it changed from about 50 µatm (Buch, 1945) to ca. 250 µatm (BACC II), while during summer from about 40 µatm (Buch, 1945) to 300 µatm (BACC II).

The pCO_2 seasonal cycle in the surface water controls the annual CO_2 exchange through the air/sea interface.

A_T is increasing in the Baltic Sea. The highest A_T trend was found in the Gulf of Bothnia (7.0 µmol kg^{-1} yr^{-1}), followed by 3.4 µmol kg^{-1} yr^{-1} in the central Baltic whereas no trend could be detected in the Kattegat (Müller et al., 2016).

The mean CO_2 concertation is increasing in the surface Baltic Sea due to the increase of CO_2 in the atmosphere. (Schneider et al., 2015, BACC II).

Acidification:

According to the thermodynamics of the CO_2 system the increase of 2.0 ppm yr^{-1} in the atmospheric pCO_2 should result in the pH decrease of about 0.02 per decade if the total alkalinity would be constant.

However, the pH trend expected based on the pCO_2 increase could not be definitively identified in the Baltic Sea.
Ocean acidification (pH decrease) is to large extent mitigated in the Baltic Sea by the total alkalinity (A_T) increase (Müller et al., 2016).

The highest A_T increase was found in the Gulf of Bothnia (7.0 µmol kg^{-1} yr^{-1}), followed by 3.4 µmol kg^{-1} yr^{-1} in the central Baltic whereas no trend could be detected in the Kattegat.

Other drivers:
Enhanced organic matter production (euthrophication) and remineralization causes high amplitude of the seasonal pH changes in the Baltic Sea

Oxygen concentration and hypoxia:

Despite the decrease of nutrient loads from land after the 1980s, recently observed oxygen consumption rates are higher than ever observed, limiting the impact of natural ventilation by oxygen-enriched saltwater intrusions in the open Baltic Sea. Improving oxygen conditions have been observed in some coastal systems, where inputs of nutrients and organic matter have been abated. However, hypoxia remains a large problem for many coastal systems, displaying unaltered or even worsening conditions.
In the Baltic Sea hypoxia has expanded considerably since the first oxygen measurements became available in 1898. In 2016 the annual maximum extent of hypoxia covered an area of about 70,000 km^2, comparable with the size of Ireland, whereas 150 years ago hypoxia was presumably not existent or at least very small. Hypoxia was mainly caused by accumulation of increasing riverborne nutrient loads and atmospheric deposition. The impacts of other drivers like observed warming and eustatic sea level rise were comparatively smaller but still important.

Despite the decrease of riverborne nutrient loads after the 1980s, recently observed oxygen consumption rates are higher than ever observed, limiting the impact of natural ventilation by oxygen-enriched saltwater intrusions in the open Baltic Sea (Meier et al., 2018a).

In the Baltic Sea, hypoxia has expanded considerably since the first oxygen measurements became available in 1898. In 2016, the annual maximum extent of hypoxia covered an area of about 70,000 km^2, comparable with the size of Ireland, whereas 150 years ago hypoxia was presumably not existent or at least very small (Carstensen et al., 2011; Meier et al., 2018b). Hypoxia was mainly caused by accumulation of increasing riverborne nutrient loads and atmospheric deposition (Savchuk, 2010; 2018). The impacts of other drivers like observed warming and eustatic sea level rise were comparatively smaller but still important (Carstensen et al., 2011; Meier et al., 2018b). Hence, also halocline variations had an impact on hypoxia (Väli et al., 2013). Although in some coastal regions, as a consequence of implemented abatements, improved oxygen conditions have been observed, persistent and seasonal hypoxia remains a large problem for many coastal systems (Conley et al., 2011).

Future changes:

Projected warming and global mean sea level rise may reinforce eutrophication and oxygen depletion in the Baltic Sea by reducing air-sea fluxes and vertical transports of oxygen in the water column, intensifying internal nutrient cycling, and increasing river-borne nutrient loads due to increased river runoff (Meier et al., 2011; 2012a; 2012b). However, the response of deep-water oxygen conditions to changing climate will mainly depend on the nutrient load scenario (Saraiva et al., 2019a; 2019b). In the case of high (low) nutrient loads, the impact of the changing climate would be considerable (negligible). Scenario simulations suggest that the complete implementation of the Baltic Sea Action Plan (BSAP) resulting in required load reductions will lead to a significantly improved ecosystem state of the Baltic Sea irrespective of the driving global climate model (Saraiva et al., 2019b) and regional coupled climate-environmental model (Meier et al., 2018c).

For the end of the century (2069-2098), hypoxic area is projected to change only slightly in the ensemble mean under reference (-14 … -5%) and high (-2 … +5%) nutrient load scenarios compared to the period 1976-2005 (Saraiva et al., 2019b). In the reference scenario, nutrient loads represent the average loads of the period 2010-2012. The high or worst case scenario assumes changes caused by a ‘fossil-fuelled development’ scenario coupled to increasing river runoff (Saraiva et al., 2019a). Changes in nitrogen and phosphorus loads were calculated from the regional assumptions, e.g., on population growth, changes in agricultural practices such as land and fertilizer use and expansion of sewage water treatment plants (Zandersen et al., 2019). Under the BSAP scenario, hypoxic area will at the end of the century be reduced by 50 to 60% in the ensemble mean compared to 1976-2005 (Saraiva et al., 2019a).

For the first time, recently uncertainties in projections of the Baltic Sea ecosystem have systematically been assessed (Meier et al., 2018c; 2019). One of the identified larger sources of uncertainty are caused by biases of global and regional climate models, in particular, with respect to GMSL rise and regional water cycling (Meier et al., 2019). The mechanism behind the correlation between large-scale meteorological conditions in the different climate periods and O_2 conditions in the Baltic Sea is not well understood and subject to ongoing research.

Kommentiert [m19]: From Lehmann et al.

Secchi depth:

3.2.4.9 Marine ecosystems and biodiversity

Pelagic habitats (incl. phytoplankton and zooplankton community structure, spring blooms, functional traits etc.)

Spring bloom phenology (timing and length): Observed for a time series 2000-2014 from the Baltic Proper and the Gulf of Finland; consequence is potential mismatch with timing of zooplankton (Groetsch et al., 2016), other drivers: warming and prevalent high pressures

Changes in plankton communities: Observed on the northern Baltic Sea between 1979 and 2011 (Suikkanen et al., 2013), a complex set of drivers including warming, eutrophication and trophic cascades

Summer biomass of cyanobacteria: Observed on the northern Baltic Sea between 1979 and 2011 (Suikkanen et al., 2013), other drivers: warming, decreasing salinity and changes in nutrient ratios

Spring bloom dinoflagellate biomass increase: Observed in some basins (Klais et al., 2013; BACC II, 2015), other drivers: ice free winters favor dinoflagellates

Wasmund (2017), Wasmund et al. (2017)

Benthic habitats (incl. benthic organisms and community structure, functional traits)

Fish

Water birds

Marine mammals

Non indigenous species

Ecotoxology

Ecosystem function

3.3 Future climate change

3.3.1 Atmosphere

Large-scale circulation (teleconnection patterns), surface pressure, wind, surface atmosphere temperature, precipitation, cloudiness and solar radiation,

Figures of ensemble mean changes in mean and extreme variables in uncoupled (Ole, Erik) and coupled simulations (Matthias, Christian)

3.3.1.1 Large-scale circulation

NAO:
In the future, the NAO is very likely to continue to exhibit large natural variations similar to those observed in the past. It is likely to become on average slightly more positive due to an increase in greenhouse gases (GHG) (IPCC, 2013).
Blocking:
There is medium confidence that the frequency of blocking will not increase. However, trends in the intensity and persistence of blocking remain uncertain and therefore also the implications of blocking related changes in the Baltic Sea region (IPCC, 2013).
AMO:
Based on paleoclimate reconstructions and long model simulations it is unlikely that the AMO will change its behaviour in the future under a changing mean climate (IPCC, 2013).

consistently across the ensemble a northward shift in the mean summer position of the westerlies at the end of the
twenty-irst century compared to the twentieth century (Gröger et al., 2019). century. Associated with this is an anomalous precipitation pattern marked by increased rainfall over northern Europe and dryer conditions over the continental central part. In response to these large-scale atmospheric changes, a strong freshening mainly resulting from a higher net precipitation over the year combined with higher annual mean runof is registered for the Baltic Sea and adjacent seas.

3.3.1.2 Air temperature

Air temperatures in the Baltic Sea area are projected to increase with time, with the increase generally greater than the corresponding increase in global mean temperature. This is usually the case for land areas, which warm more quickly than sea areas but is also the case for the Baltic Sea region, largely due to the strong winter increase. This winter increase is the result of a positive feedback mechanism involving declining snow and sea-ice cover, leading to even higher temperatures—reduced snow and ice cover will enhance the absorption of sunlight, and so enable greater amounts of heat to be stored in the soil and water (BACCII, 2015).

The increase in winter temperatures are projected to reach 8 degrees C in northern Scandinavia depending on the representative concentration pathway (RCP). The RCP2.6 scenario leads to a temperature rise of 3 degrees C. Less warming (2 C to 4 C) is projected for the southern Baltic Sea region. There is uncertainty in these projections from different sources (e.g. greenhouse gas emission scenarios, global and regional climate model uncertainties, natural variability). The largest uncertainty is due to the unknown future emissions (RCPs) (Kjellström et al. 2011, Strandberg et al., 2014).

Uncertainties:

Trends in surface temperature can be expected to follow the change in air temperature due to air sea heat exchange. Here global models highly agree at least qualitatively. Under the assumption of moderate greenhouse gas emissions high resolution model simulations project a warming of surface air temperature by up to 8 °C degree in winter and up to X °C during summer for the Baltic Sea region (Lind and Kjellström, 2008) at the end of the 20th century.

Kommentiert [m20]: Individual scenarios? I suggest to refer to information from IPCC 2013

Kommentiert [JH21]: Missing number

Air temperature extremes:

The strong increase in winter daily mean temperature is most pronounced for the coldest episodes (Kjellström 2004). This is also the case for the most extreme daily maximum and minimum temperatures (Kjellström et al. 2007; Nikulin et al. 2011) with a significant decrease in probabilities of cold temperatures (Benestad 2011). In summer, warm extremes are projected to become more pronounced. For example, Nikulin et al. (2011) showed that warm extremes in today's climate (1961–1990) with a 20-year return value (defined as the temperature that will be exceeded once every 20 years as a statistical average) will occur around once every 5 years in Scandinavia by 2071–2100 according to an ensemble of six RCM simulations, all downscaling GCMs under the SRES A1B scenario.

Kommentiert [m22]: Reference?

3.3.1.3 Solar radiation

Mean change is uncertain. Global climate models indicate an increase which is highest over southern Europe and decreases towards north, but still showing a slight increase over the Baltic. However, regional climate model runs could instead show a decrease in surface solar radiation (SSR) over the Baltic area, i.e. there is a large discrepancy in modelled SSR between global and regional models (Bartók et al., 2017). Unknown future aerosol emissions add to the uncertainty.

3.3.1.4 Precipitation

Anna:

Based on fundamentals of the climate system, a warming is expected to result in an intensification of the hydrological cycle i.e. higher precipitation in already wet regions and less precipitation in already dry regions. This is also reproduced by models and scenarios indicate an increase in the entire area during winter and mainly in the northern parts during summer. For some areas a decrease in summer precipitation is expected.

Erik:

A warmer climate leads to an amplification of the hydrological cycle. For areas with large amounts of precipitation this implies even more precipitation while for dry areas there is a risk of further drying. In the Baltic Sea region this implies increasing precipitation, most notably in the winter half of the year and in the north in summer. There is a large uncertainty as whether precipitation will increase or decrease in summer in the southern part of the Baltic Sea region that is closer to the dry regime of southern Europe.

A warmer future climate will lead to a shortening of the snow season. In winter, climate models project more precipitation and higher temperatures. In many areas this will likely be manifested as more rain and less snow but in some areas that are still cold increasing amounts of snow may be seen.

The degree of change depends on the change in forcing conditions and the regional response of the climate system. Both of these are associated with large uncertainties. In addition, internal natural variability of the climate system adds another level of uncertainty when addressing precipitation changes for a certain time period.

Precipitation extremes:

Anna:

More intense precipitation is expected on time scales ranging from single rain showers to long-lasting synoptic-scale precipitation. Where particularly the shorter duration extremes is expected to increase (for example is the return period for 20-year rainfall events on a 1-hour basis decreased to 4 years in model simulations).

Erik:

A warmer atmosphere that can hold more water vapor increases the potential for precipitation extremes. Both droughts and heavy rainfall events can become more intense.

Recent climate model simulations performed for other regions in Europe and North America indicate that high-intensity rainfall events associated with summertime convection may generally increase with up to 10-15% per degree of temperature increase.

3.3.1.5 Wind

Wind:

Wind extremes:

3.3.1.6 Atmospheric chemistry

3.3.2 Land

River runoff, nutrient and carbon loads, river ice, lakes, lake ice, snow, permafrost, terrestrial and freshwater ecosystem, Figures of ensemble mean changes in mean and extreme variables in uncoupled (Ole, Erik) and coupled simulations (Matthias, Christian, Markus)

3.3.2.1 River discharge

Climate change is likely to have a clear influence on the seasonal flow regime as a direct response to changes in the form of the precipitation, as well as by altering the temperature-evapotranspiration regime. (BACC II)
For areas in the northern Baltic Sea region presently characterized by spring floods due to snow melt, the floods are likely to occur earlier in the year and their magnitude is likely to decrease owing to less snowfall, shorter snow accumulation period, and repeated melting during winter. As a consequence, sediment transport and the risk of inundation are likely to decrease.

In the southern part of the Baltic Sea area, increasing winter precipitation is projected to result in increased river discharge during winter. In addition, groundwater recharge is projected to increase in areas where infiltration capacity is not exceeded currently, resulting in higher groundwater levels. Decreasing precipitation combined with rising temperature and evapotranspiration during summer is projected to result in a drying of the root zone, which would drive increasing irrigation demands in the southern part of the Baltic Sea area. Projections with a process-oriented hydrological model suggest that under RCP 4.5 and RCP 8.5 scenarios the total river flow will increase between 1 and 21% and between 6 and 20%, respectively, illustrating the large uncertainty in hydrological projections (Saraiva et al., 2019). Thereby, the future period 2069-2098 is compared to the reference period 1976-2005 and 4 (3) GCMs are regionalized.
The decrease in snow melt induced spring floods in the southern Baltic rivers contrasts with the situation in the Nordic countries, where changes in winter snowmelt are not yet apparent in the river runoff data, although they are expected in the future (Veijalainen et al. 2010).

3.3.2.2 Lakes

3.3.2.3 Terrestrial biogeochemistry

Nutrient loads:
GCMs suggest the north be wetter and the south will be drier (BACC II).

Models suggest land-based nutrient management will have greater effect on loads than uncertainties caused by greenhouse gas emission scenarios
(Saraiva et al. 2019)

DOC inputs will increase in areas affected by permafrost thaw (BACC II)
Existing scenario simulations of the Baltic Sea were carried out with nutrient load scenarios that span the range of plausible future socio-economic conditions from the most optimistic (BSAP) to the worst scenario (Saraiva et al., 2019; Meier et al., 2019).

In the reference scenario, nutrient loads represent the average loads of the period 2010-2012. The high or worst case scenario assumes changes caused by a ‘fossil-fuelled development’ scenario coupled to increasing river runoff. Changes in nitrogen and phosphorus loads were calculated from regional assumptions, e.g., on population growth, changes in agricultural practices such as land and fertilizer use and expansion of sewage water treatment plants (Zandersen et al., 2019).

3.3.2.4 Terrestrial ecosystems and biodiversity

3.3.3 Cryosphere

3.3.3.1 Snow

3.3.3.2 Glaciers

3.3.3.3 Permafrost

3.3.3.4 Sea ice

In the future it is likely, that the inter-annual variability continues to be very large, although the probability of very strong winters will very likely be lower than in the past. But in climatological sense it is very likely that the maximum sea ice extent of a winter season will decrease. The level ice thickness will also very likely decrease in the future, but there are still larger uncertainties in the thickness of ridged ice. It is likely that the length of the ice season will decrease, but with larger regional differences.
There is some indication (low confidence) in climate scenarios that the snow cover on the sea ice will decrease. This will reduce the reflectivity of the surface and more heat can be absorbed and thereby amplifying the ice reduction (Höglund et al., 2017).

3.3.3.5 Cryospheric ecosystems and biodiversity

3.3.4 Ocean and sediment

Water temperature, salinity, stratification, currents, water exchange, sea ice, sea level, wind waves, sediment transports, marine ecosystem (including coastal ecosystems, biogeochemistry), acidification,

Figures of ensemble mean changes in mean and extreme variables in uncoupled (Ole, Erik) and coupled simulations (Matthias, Christian, Markus)

3.3.4.1 Water temperature

Water temperature introduction:

The response time of water temperature is short compared to the time scale of climate warming on centennial time scales. In quasi-steady state, the warming at the surface is larger than in the deep water.

With time the heat spreads downward through different processes and eventually the whole water column warms up. This has consequences for the stratification, eutrophication and sea level rise.

Water temperature: The temperature of the oceans are rising [high confidence] (e.g. Balmaseda et al., 2013a, 2013b) and will continue to rise [medium confidence]. Regional scenarios for the Baltic Sea project an increase of SST of 1 C (RCP2.6) to 4 C (RCP8.5) in 2100 relative to the period 1970 to 1999. The projections include a possible range of 1.5 C (RCP2.6) and 2.5 C (RCP8.5). The SST changes in the RCP8.5 scenarios are significantly above the natural variability (Source SMHI).

Water temperature extremes: In the RCP4.5 and RCP8.5 scenarios an increase in the occurrence of tropical nights over the Baltic Sea has been observed. Tropical nights are an indicator for heat waves. This has consequences for the water temperature which will reach record breaking values from year to year much more often under projected climate change in RCP8.5 (Meier et al., 2019).

RCP 8.5: the sea surface temperature response in the Baltic Sea varies between + 2.5 and + 4.7 K depending on the applied global model scenario (Gröger et al., 2019)

3.3.4.2 Salinity and saltwater inflows

Future changes in salinity are difficult to project as they depend on the large-sale atmospheric moisture transport to the Baltic Sea drainage basin (Schinke and Matthäus, 1998), local wind fields (Lass and Matthäus, 1996) and global mean sea level

(GMSL) rise (Hordoir et al., 2017; Meier et al., 2017). However, to robustly estimate future moisture transport and runoff to the Baltic Sea and regional wind fields requires high resolution atmosphere models to resolve local orography along continental water sheds. Furthermore, even on a global scale projections of the water cycle and sea level rise suffer from uncertainties (IPCC, 2013). This makes projections for the future development of salinity highly uncertain (BACC II Author team, 2015).

Due to the projected increased freshwater supply from the catchment area by about 1 to 21% at the end of the century depending on the climate model, surface and bottom salinity is projected to decrease by about 0.6 g kg^{-1} in the ensemble mean with a large spread among the ensemble members (Saraiva et al., 2019). However, ensemble studies taking rising global mean sea level and changes in wind fields and river flows into account do not exist (Meier et al., 2018b).

Hordoir et al. (2017) investigated the influence of rising GMSL on saltwater inflows into the Baltic Sea. They performed idealized model sensitivity experiments using a regional ocean general circulation model covering the North Sea and the Baltic Sea. Hordoir et al. (2017) found a non-linear increase in saltwater inflow intensity and frequency with rising GMSL. However, their explanation of reduced mixing in the Danish straits was shown to be wrong (Arneborg, 2016). Instead, Arneborg (2016) proposed an alternative theory. Due to the smaller depth, the volume flux through the Sound is more sensitive to GMSL rise than that through the Belt Sea. Under present conditions, the amount of dense water passing the Drogden sill in the Sound is determined by a baroclinic control in the narrow northern end of the Sound (Nielsen, 2001). With rising GMSL this control is degraded and relatively more saltwater is transported into the Baltic Sea compared to the expected increase when the transport change is proportional to the area of the limiting cross section.

Assuming a negligible impact of GMSL rise, the intensity and frequency of MBIs were projected to remain unchanged, with a potential tendency of a slight increase (Schimanke et al., 2014). However, in future high-end global mean sea level projections, reinforced saltwater inflows result in higher salinity and increased vertical stratification compared to present conditions (Meier et al., 2017; Saraiva et al., 2019b).

3.3.4.3 Stratification

Theoretical considerations imply that increased freshwater supply (rain, snow melt) over the Baltic Sea drainage basin accompanied by the supply of deep salt rich waters from the North Sea as well as warming of the surface layer would favor stronger stratification. Thus the future development of stratification mainly depends on how the Baltic Sea surface will warm up compared to deeper layers and how the freshwater supply will change (which in turn is linked to atmospheric moisture transport to the region).

The complex interplay between temperature change, wind change and changing precipitation makes it difficult to predict future climate effects on stratification. Furthermore, stratification is subject to complex processes like winter convection which are likely to change with future climate change.

Most model studies project increasing sea surface temperatures for the end of the 21st century for the Baltic Sea (BACC II). Future climate projections for the Baltic Sea based on previous assumptions on greenhouse emission scenarios imply an SST increase between 2-4 °C (Meier 2015). More recent scenarios with revised emission pathway imply an increase of 2-3 °C (Saraiva et al., 2018).

Kommentiert [m23]: Meier and Saraiva (2019). Would be good to specify the underlying scenarios? A1B, A2 or RCP 4.5 and 8.5. 2-3°C corresponds to ensemble mean changes under RCP 4.5 and 8.5 averaged for the entire Baltic Sea.

Kommentiert [JH24]: What time of year? Annual mean? Link to sea ice cover? Which region doe this refer to (in the Baltic)?

Kommentiert [JH25]: Why do we present an older projection if we have a newer more specific one?

Most studies suggest rather moderate changes or slightly lowered surface salinities in the Baltic Sea (Meier, 2015). In certain weaker stratified regions like the Gulf of Finland or Bothnian Bay changes in deep salinity could lead to decreased stratification (Meier 2015)

Little is known about future trends in salt inflows to the Baltic Sea which mainly impact on deep water salinity (with positive effect on stratification). Favorable atmospheric preconditions i.e. the prevalent wind regime for salt inflows have been reported to occur slightly more frequent in future (Schimanke et al., 2014).

Few available studies suggest a tendency towards only slightly modified mean and extreme wind speed over the Baltic Sea at the end of the century (e.g. Kjellström et al., 2011).

Kommentiert [m26]: Merge with the other variables

The above described changes in governing parameters would favor stratification to increase. In fact few studies report that stratification is likely to increase in future climate (Gröger et al., 2019).

The entire ensemble consistently indicates a basin-wide intensification of the pycnocline (9–35%) for the Baltic Sea and a shallowing of the pycnocline depth in most regions as well (Gröger et al., 2019).

3.3.4.4 Overturning circulation

All ensemble members indicate a strengthening of the zonal, wind driven near surface overturning circulation in the southwestern Baltic Sea towards the end of the twenty-first century whereas the more thermohaline driven overturning at depth is reduced by ~ 25% (Gröger et al. 2019). In the Baltic proper, the meridional overturning shows no clear climate change signal. However, three out of five ensemble members indicate at least a northward expansion of the main overturning cell. In the Bothnian Sea, all ensemble members show a significant weakening of the meridional overturning.

3.3.4.5 Sea level

Since the ice has melted that covered Scandinavia during the last ice age the earth crust is rebounding. The highest rates of land uplift of 10 mm/year are found at Höga Kusten in the Bothnian Bay. The land uplift diminishes away from this center and is very small along the German and Polish coasts of the Baltic Sea. This process is expected to continue for thousands of years [high confidence]. Along most of the Baltic Sea coasts the land uplift causes sea level to fall. On top of this change, global mean sea level rise will continue to raise sea levels in the Baltic Sea at an increasing rate [high confidence] (Church et al., 2013). When the rate of sea level rise becomes larger than the land uplift, sea level will start to rise relative to land. First in the southern Baltic Sea and with accelerating rates of global mean sea level rise the line of rising sea level will move northward.

Kommentiert [m27]: But not with the same rising rate? Replace with hundred years

During this century melting ice sheets in Antarctica and Greenland will contribute more to the total than in the past [medium confidence] (Church et al., 2013). The sea level rise due to melting ice is not distributed uniformly around the global ocean. Sea level rise from melting ice sheets in Antarctica is more pronounced in the northern hemisphere because the missing ice mass has a smaller gravitational pull on the surrounding water. As in Scandinavia, the missing ice causes the earth crust to rebound which makes the sea level rise slower where the ice is melting [medium confidence]. Based on these processes the mean sea level rise in the Baltic Sea is projected to amount to 80% of the global mean sea level rise (Grinsted, 2015). Recent efforts since the latest IPCC report that focused on the contribution of Antarctic ice sheets to global mean sea level rise have shown that the interaction of warming ocean water, melting the ice sheets from below can lead to instabilities in the ice sheet dynamics. The ice sheets flowing from land into the ocean are in contact with the ocean floor out to the grounding line. From there on outward the ocean is melting the ice from below and the ice sheets become thinner and lighter. If the weight of the ice sheet becomes less than the weight of the ocean water it replaces, it floats up and away. The grounding line retreats inland where the ice sheet is thicker and the ice flow larger and reinforces the ice loss (Mercer, 1978). This and related feedback loops could lead to an extra meter of sea level rise until the end of the century [low confidence] (e.g. Sweet et al., 2017). The most recent estimates (Bamber et al., June 2019) for global mean sea level rise in 2100 relative to 2000, including these potential contributions (including land water storage) are 69 cm and 111 cm for low and high sea level scenarios, respectively. For the high sea level scenario the likely range (5% to 95%) is between 62 cm and 238 cm.

Kommentiert [JH28]: Are there studies for the Baltic Sea that tried to combine all the effects? Meier et al. 2004

Kommentiert [m29]: Baltic Sea numbers?

Sea level extremes:

In the Baltic Sea, return levels show a low to moderate increase for increasing return periods (HazardSupport, 2018)(true everywhere?). The 100-year return level for Stockholm for example is estimated at 102 cm, while the 200-year return level is 107 cm. Both estimates have a large uncertainty of 25 cm and 30 cm, respectively (SMHI report regeringsuppdraget). Even under moderate increase of mean sea level in the Baltic Sea, extreme events that are rare today will be much more common towards the end of the century. In the above example a sea level rise of 20 cm in 2100 will turn the 100-year storm surge in Stockholm into an event that occurs every 10 years on average [medium confidence]. Thus, the main driver of changes in Baltic Sea storm surges is the global mean sea level rise [medium confidence].

3.3.4.6 Waves

3.3.4.7 Sedimentation

If the relative sea level rise in the southern Baltic Sea follows the mean value of RCP2.6 projection, which is ~0.24 m until 2065, the rate of sea level rise in this region (~1.2 mm/yr for the past few decades) would be accelerated. As a natural consequence coastal erosion would be regionally enhanced to fill the increased underwater accommodation space. The extent of enhancement in erosion depends on not only the sea level but also storms.

Due to the impact of the prevailing westerly winds, the dominant sediment transport will remain eastwards along a major part of the southern Baltic coast, but with a high variability along some local coast sections which have small incidence angle of incoming wind-waves.

Development of the foredunes will continue in prograding coasts.

A critical threshold, which distinguishes a linear and a non-linear (following a quadratic or a higher power law) relationship between foredune height and rate of relative sea level rise, seems to exist in the southern Baltic Sea coast. If a rise by 0.3 m in the relative sea level (RCP8.5) would occur by 2065 in this region, such critical threshold would probably be reached before 2050, causing drastic change on the foredune characteristics and much stronger erosion on cliffs and old coastal dunes.

3.3.4.8 Marine carbonate and biogeochemistry chemistry

Carbonate chemistry (incl. air-sea exchange of CO2) and acidification

The atmospheric CO_2 concentration will increase in the future and influence the marine CO_2 system.

Kuznetsov et al. (2013)
Omstedt et al. (2012)

Marine biogeochemistry

Oxygen concentration and hypoxia

Projected warming and global mean sea level rise may reinforce eutrophication and oxygen depletion in the Baltic Sea by reducing air-sea and vertical transports of oxygen -, intensifying internal nutrient cycling, and increasing river-borne nutrient loads. However, the response of deep-water oxygen conditions to changing climate will mainly depend on the nutrient load scenario. In the case of high (low) nutrient loads, the impact of the changing climate would be considerable (negligible). Scenario simulations suggest that the complete implementation of the Baltic Sea Action Plan (BSAP) resulting in required load reductions will lead to a significantly improved ecosystem state of the Baltic Sea irrespective of the driving global climate model. The latter was shown for the ecosystem indicators water clarity and summer mean oxygen deficit due to biogeochemical oxygen consumption compared to saturated oxygen conditions.

For the end of the century (2069-2098), hypoxic area is projected to change only slightly in the ensemble mean under reference/present-day (-14 … -5%) and high (-2 … +5%) nutrient load scenarios compared to the period 1976-2005.

Under the BSAP scenario, hypoxic area will be reduced by 50 to 60% in the ensemble mean at the end of the century compared to 1976-2005.

3.3.4.9 Marine ecosystems and biodiversity

Pelagic habitats (incl. phytoplankton and zooplankton community structure, spring blooms, functional traits etc.)

Spring blooms start earlier and are longer

Both phyto- and zooplankton communities are composed of smaller species

Increasing cyanobacteria blooms (why?)

Shifting diatom/dinoflagellate ratios

Benthic habitats (incl. benthic organisms and community structure, functional traits)

Fish

Bauer et al. (2018, 2019)

Water birds

Marine mammals

Non indigenous species

Ecotoxology

Ecosystem function

4 Interactions with other drivers

Summary of the BEAR paper by Reckermann et al.:

Marine (shipping), terrestrial and airborne traffic

Tourism

Built structures (incl. offshore renewable energy constructions and maintenance)

Fisheries
Aquaculture
Eutrophication
Pollution and hazardous substances
Coastal defence and erosion
Marine Protected Areas (MPAs)
Forestry
Urbanisation and population changes
Aerosols
Land cover changes
Etc.

5 Comparison with other coastal sea regions

6 Knowledge gaps

Large-scale circulation:

NAO:

While CMIP5 climate models are able to simulate the main features of the NAO, its future changes might be sensitive to boundary processes, which are not yet well represented in many climate models (IPCC, 2013).

Blocking:

Most CMIP5 models still underestimate the frequency of blocking over the Euro-Atlantic sector (IPCC, 2013).

AMO:

Since the observational record is relatively short, our understanding of the AMO and its possible changes largely depend on models, whose assumptions are difficult to verify (Knight, 2009).

However, while possible changes in these climate phenomena contribute to the uncertainty in near-term climate projections, they are not the main driver of the projected warming over Europe by the end of the century (Cattiaux et al., 2013; IPCC, 2013).

Air temperature:

There are limitations in the knowledge concerning the link to changes in large-scale circulation patterns.

Kommentiert [m30]: More specific

Kommentiert [m31]: More specific

Surface solar radiation:

Multidecadal variations in SSR are generally not well captured by current climate model simulations (Allen et al. 2013, Storelvmo et al. 2018). The extent to which the observed SSR variations are caused by natural variation in cloudiness induced by atmospheric dynamic variability (Stanhill etal. 2014, Parding et al. 2016), or anthropogenic aerosol emissions (Ruckstuhl et al. 2008, Philipona et al 2009, Wild 2012, Storelvmo et al. 2018), or perhaps additional causes, is not well quantified.

Precipitation:

Focus on different aspects of precipitation characteristics, different methods and different data sets used in various national studies in the Baltic Sea region implies that the picture of the precipitation climate including its past changes is not fully coherent.

Even if climate scenarios are becoming more frequent and there is now a growing ensemble of relatively high-resolution regional climate scenarios for Europe the scenarios still only samples a subset of the global climate model projections assessed by the IPCC. This means that the uncertainties of future climate change in the Baltic Sea region is not fully captured at adequate horizontal resolution for pursuing detailed studies of climate change impacts in the region.

New, very high-resolution so called convective-permitting climate models operating at grid spacing of 1-3 km are lacking for the Baltic Sea region. In other regions such models have shown better agreement with observations in representing precipitation extremes and sometimes also a larger climate change signal compared to the more traditional “high-resolution” models operating at c. 10 km grid spacing.

In addition: Analysis of changes in extreme precipitation is uncertain due to the problem with statistical significance of changes in extreme events.

Runoff:

The impact of how climate model results are transferred to the hydrological model are still inadequately understood. More research is needed to quantify the accuracy and uncertainty associated with various bias correction methods.

Several uncertainties are associated with impact modelling, including parameter uncertainty and model structure uncertainty. The values of the parameters of a hydrological model are normally found through calibration against historical data and are always associated with uncertainty. This uncertainty will translate into uncertainty in the projected changes.

Nutrient loads:

How fertilization practices, crops grown, and land use will change in response to climate change.

Salinity:

Due to uncertain changes in regional water cycles (precipitation) and global sea levels, the confidence in future salinity projections is low (BACC II Author Team, 2015; Meier et al., 2019). Ensemble studies taking rising global mean sea level and changes in wind fields and river flows into account do not exist but would be needed (Meier et al., 2018).

Sea level:

There is potential for mean sea level rise in the Baltic Sea that is caused by the freshening of the Baltic Sea. Under a warming climate precipitation patterns over the Baltic Sea drainage basin change (EN-CLIME precipitation) and the river discharge is expected to increase (EN-CLIME discharge). Fresher water in the Baltic Sea will take up more volume and sea levels in the Baltic Sea will rise. There has been no comprehensive study so far to assess the impact of halosteric contributions to the Baltic Sea level. Also the impact of changing land water storage for the Baltic Sea region on Baltic Sea levels needs to be assessed (Haasnoot et al., 2015 for the Netherlands).

On the global scale it has been shown (Bingham and Hughes, 2012) that sea level will raise proportionally more on the shallow shelf regions around the continents than in the deeper, open ocean. For the Baltic Sea no such study exists that could answer whether mean sea level rise applies to coastal regions in the same way as for the open Baltic Sea.

Storm surges and other hazards can turn into disaster if they occur concurrently. There have been some examples and studies (e.g. Zscheischler et al., 2018) that have shown that the impact of multiple hazards can be much worse than a single extreme event. Not much is known today about the interaction of extreme events with a focus on storm surges.

The coverage in time and space of sea level measurements in the Baltic Sea is among the best in the world. Many records date back to late 19th century. Nevertheless, the observational record tends to underestimate the natural variability that is inherent in storm floods (Lang and Mikolajewicz, 2019) in the Baltic Sea. One example is the Backafloden 1872. It is not clear which return period should be attributed to this event (Fredriksson, 2016, 2017). With today's observational time series it cannot be categorized. Two conclusions can be drawn here. First, more research is needed to investigate the influence of natural variability on storm surges in the Baltic Sea. Second, long measurement records are of vital importance to assess natural variability in coastal flooding around the Baltic Sea.

Sea level rise for coastal cities around the Baltic Sea is more sensitive to the thermosteric expansion of the global ocean compared to coastal cities around the coasts of the Atlantic or Pacific Ocean (Larour et al., 2017). Also, ice sheet melt in Antarctica has a disproportional high impact in the Baltic Sea while ice sheet melt in Greenland has no effect. Sea level research focused on the Baltic Sea may take this into account.

Kommentiert [m32]: Why? And why is there a policy gap related to this fact?

Kommentiert [m33]: Missing reference

Sedimentation:

We lack a comprehensive understanding of alongshore sediment transport and associated spatial and temporal variability along the Baltic coast. In general, an eastward transport dominates along a major part of the southern Baltic coast due to the impact of the prevailing westerly winds. However, the intensity of secondary transport induced by easterly and northerly winds is much less understood. Its combination with storm surges further complicated the understanding because in such circumstance the sandy dunes and cliffs are exposed to highest erosional impact.

Another knowledge gap in understanding coastal erosion in response to future climate change is on the impact of water levels and the submergence of the beach.

Anthropogenic influence imposes one of the largest uncertainty in sediment transport and coastal erosion.

An engineering structure (e.g. pier, seawall) influences coastline change at a much larger spatial scale than the dimension of the structure itself.

Changes in carbonate chemistry (incl. air-sea exchange of CO2) and acidification:

Due to the high spatial and temporal variability of the seawater pCO_2 it is not known whether the Baltic Sea as a whole is a net sink or net source of CO_2.

It is unclear what is the source of total alkalinity increase in the Baltic Sea, and whether it will continue in the future with the same magnitude.

Oxygen concentrations:

A recent assessment suggests that the biggest uncertainties in projections of biogeochemical cycles are caused by (1) poorly known current and future bioavailable nutrient loads from land and atmosphere, (2) the setup of numerical scenario experiments (including the spin up strategy), (3) differences between the projections of global and regional climate models, in particular, with respect to the global mean sea level rise and regional water cycle, (4) differing model-specific responses of the simulated biogeochemical cycles to long-term changes in external nutrient loads and climate of the Baltic Sea region, and (5) unknown future greenhouse gas emissions.

Pelagic habitats:

Long-term development, effect on species composition and carbon transfer (including settling)

Evaluation on the importance of the climate change component

Evaluation on the importance of the climate change component

The connection still not clear, the effect may depend on other factors

6.1 Knowledge gaps - consensus

6.2 Knowledge gaps - dissensus

6.3 Research needs [this is what we need to know]

7 Key messages

Confirmed and new knowledge of BACC III

Author contributions

Chapter	Title	Authors	Pages[1]
1	**Introduction**	All	8
1.1	Overview	H.E.M. Meier and all	0.5
1.2	Baltic Sea Region characteristics	H.E.M. Meier, E. Kjellström, J. Käyhko and all	2
1.3	Global climate change	E. Kjellström and M. Gröger	2
1.4	The BACC process	M. Reckermann	0.5
1.5	Summary of BACC I and BACC II key messages	H.E.M. Meier and all	3
1.5.1	Past climate change	H.E.M. Meier and all	1
1.5.2	Recent climate change	H.E.M. Meier and all	1
1.5.3	Future climate change	H.E.M. Meier and all	1

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[1] Without references, figures and tables (just approximations)

2	**Methods**	H.E.M. Meier, C. Dieterich, O. Bøssing-Christensen, E. Kjellström	1.5
2.1	Assessment of literature	H.E.M. Meier and M. Reckermann	0.5
2.2	Climate model data	C. Dieterich, E. Kjellström and O. Bøssing-Christensen	0.5
2.3	Uncertainty estimates	E. Kjellström and H.E.M. Meier	0.5
3	**Current state of knowledge**	All	45
3.1	**Past climate change**	E. Zorita	5
3.2	**Present climate change**	All	20
3.2.1	Present climate change - Atmosphere	A. Rutgersson, M. Stendel, C. Frauen, M. Quante	6
3.2.1.1	Large-scale circulation	C. Frauen	
3.2.1.2	Air temperature	A. Rutgersson	
3.2.1.3	Solar radiation	A. Rutgersson	
3.2.1.4	Precipitation	M. Stendel	
3.2.1.5	Wind	M. Stendel	
3.2.1.6	Atmospheric chemistry	M. Quante	
3.2.2	Present climate change - Land	J. Käyhko	4
3.2.2.1	River discharge	J. Käyhko	
3.2.2.2	Lakes	J. Käyhko	
3.2.2.3	Terrestrial biogeochemistry	C. Humborg	
3.2.2.4	Terrestrial ecosystems and biodiversity	P. Miller	
3.2.3	Present climate change - Cryosphere	J.J. Haapala	4
3.2.3.1	Snow	S. Rasmus	
3.2.3.2	Glaciers	S. Rasmus	
3.2.3.3	Permafrost	S. Rasmus	
3.2.3.4	Sea ice	J.J. Haapala	
3.2.3.5	Cryospheric ecosystems and biodiversity		
3.2.4	Present climate change – Ocean and sediment	H.E.M. Meier, M. Kniebusch, B. Hünicke, E. Zorita, M. Viitasalu, K. Kulinski, W. Zhang	6

3.2.4.1	Water temperature	M. Kniebusch, H.E.M. Meier	
3.2.4.2	Salinity and saltwater inflows	M. Kniebusch, H.E.M. Meier	
3.2.4.3	Stratification	M. Kniebusch, H.E.M. Meier	
3.2.4.4	Overturning circulation	H.E.M. Meier	
3.2.4.5	Sea level	B. Hünicke, E. Zorita, C. Dieterich	
3.2.4.6	Waves	B. Hünicke	
3.2.4.7	Sedimentation	W. Zhang	
3.2.6.8	Marine carbonate and biogeochemistry	K. Kulinski and H.E.M. Meier	
3.2.6.9	Marine ecosystems and biodiversity	M. Viitasalu	
3.3	**Future climate change**	All	20
3.3.1	Future climate change - Atmosphere	O. Bøssing-Christensen, E. Kjellström, M. Quante	6
3.3.1.1	Large-scale circulation	O. Bøssing-Christensen, E. Kjellström	
3.3.1.2	Air temperature	O. Bøssing-Christensen, E. Kjellström	
3.3.1.3	Solar radiation	O. Bøssing-Christensen, E. Kjellström	
3.3.1.4	Precipitation	O. Bøssing-Christensen, E. Kjellström	
3.3.1.5	Wind	O. Bøssing-Christensen, E. Kjellström	
3.3.1.6	Atmospheric chemistry	M. Quante	
3.3.2	Future climate change - Land	???, J. Käyhko, O. Bøssing-Christensen, E. Kjellström, C. Dieterich	4
3.3.2.1	River discharge	J. Käyhko	
3.3.2.2	Lakes	J. Käyhko	
3.3.2.3	Terrestrial biogeochemistry	C. Humborg	
3.3.2.4	Terrestrial ecosystems and biodiversity	P. Miller	
3.3.3	Future climate change - Cryosphere	J.J. Haapala	4
3.3.3.1	Snow	O. Bøssing-Christensen, E. Kjellström	
3.3.3.2	Glaciers	O. Bøssing-Christensen, E. Kjellström	
3.3.3.3	Permafrost	O. Bøssing-Christensen, E. Kjellström	
3.3.3.4	Sea ice	J.J. Haapala	

3.3.3.5	Cryospheric ecosystems and biodiversity		
3.3.4	Future climate change – Ocean and sediment	H.E.M. Meier, B. Hünicke, E. Zorita, M. Viitasalu, K. Kulinski, W. Zhang, C. Dieterich, M. Gröger	6
3.3.4.1	Water temperature	H.E.M. Meier, C. Dieterich, M. Gröger	
3.3.4.2	Salinity and saltwater inflows	H.E.M. Meier, C. Dieterich, M. Gröger	
3.3.4.3	Stratification	M. Gröger, C. Dieterich, H.E.M. Meier	
3.3.4.4	Overturning circulation	M. Gröger, C. Dieterich, H.E.M. Meier	
3.3.4.5	Sea level	C. Dieterich, B. Hünicke, E. Zorita	
3.3.4.6	Waves	C. Dieterich, B. Hünicke,	
3.3.4.7	Sedimentation	W. Zhang	
3.3.4.8	Marine carbonate and biogeochemistry	K. Kulinski, H.E.M. Meier	
3.3.4.9	Marine ecosystems and biodiversity	M. Viitasalu	
4	**Interaction with other drivers**	M. Reckermann	1
5	**Comparison with other coastal sea regions**	M. Quante, M. Reckermann, H.E.M. Meier, E. Kjellström, J. Käyhko	2
6	**Knowledge gaps**	All	2
7	**Key messages**	All	2
Figures and Tables	Analysis of observed time series	M. Kniebusch	
Figures and Tables	Analysis of scenario simulations	O. Bøssing-Christensen, E. Kjellström, H.E.M. Meier, F. Börgel, C. Dieterich, M. Gröger, G. Väli	

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References

Kommentiert [m34]: In red relevant references after BACC II

Aman, A. A. and Bman, B. B.: The test article, J. Sci. Res., 12, 135–147, doi:10.1234/56789, 2015.

Aman, A. A., Cman, C., and Bman, B. B.: More test articles, J. Adv. Res., 35, 13–28, doi:10.2345/67890, 2014.

Kommentiert [m35]: Reference format of ESD

Ahlgren, J., Grimvall, A., Omstedt, A., Rolff, C., and Wikner, J. (2017). Temperature, DOC level and basin interactions explain the declining oxygen concentrations in the Bothnian Sea. Journal of Marine Systems 170, 22-30. https://doi.org/10.1016/j.jmarsys.2016.12.010.

Andersson, H. C. (2002). Influence of long-term regional and large-scale atmospheric circulation on the Baltic sea level. Tellus A: Dynamic Meteorology and Oceanography 54(1), 76-88. https://doi.org/10.3402/tellusa.v54i1.12125.

Andersson, A., Meier, H. E. M., Ripzsam, M., Rowe, O., Wikner, J., Haglund, P., Eilola, K., Legrand, C., Figueroa, D., Paczkowska, J., Lindehoff, E., Tyskland, M., and Elmgren, R. (2015). Future climate change scenarios for the Baltic Sea ecosystem and impacts for management. Ambio 44(Suppl. 3), S345S356. https://doi.org/10.1007/s13280-015-0654-8.

Arheimer, B., & Lindström, G. (2015). Climate impact on floods: changes in high flows in Sweden in the past and the future (1911-2100). Hydrology and Earth System Sciences, 19(2), 771-784.

Arheimer, B., Dahné, J., and Donnelly, C. (2012). Climate change impact on riverine nutrient load and land-based remedial measures of the Baltic Sea Action Plan. Ambio 41(6), 600-612. https://doi.org/10.1007/s13280-012-0323-0.

Arneborg, L. (2016). Comment on "Influence of sea level rise on the dynamics of salt inflows in the Baltic Sea" by R. Hordoir, L. Axell, U. Löptien, H. Dietze, and I. Kuznetsov. Journal of Geophysical Research: Oceans 121(3), 2035-2040. https://doi.org/10.1002/2015JC011451.

Asmala, E., Carstensen, J., Conley, D. J., Slomp, C. P., Stadmark, J., and Voss, M. (2017). Efficiency of the coastal filter: Nitrogen and phosphorus removal in the Baltic Sea. Limnology and Oceanography 62(S1). https://doi.org/10.1002/lno.10644.

BACC Author Team (2008). Assessment of climate change for the Baltic Sea basin. Regional Climate Studies. Berlin, Heidelberg: Springer-Verlag. https://doi.org/10.1007/978-3-540-72786-6.

BACC II Author Team (2015). Second assessment of climate change for the Baltic Sea Basin. Regional Climate Studies. Cham: Springer. https://doi.org/10.1007/978-3-319-16006-1.

Balmaseda, M. A., Mogensen, K., and Weaver, A. T. (2013a). Evaluation of the ECMWF ocean reanalysis system ORAS4, Q J Roy Meteor Soc, 139, 1132–1161, https://doi.org/doi:10.1002/qj.2063

Balmaseda, M. A., Trenberth, K. E., and Källén, E. (2013b). Distinctive climate signals in reanalysis of global ocean heat content, Geophys Res Lett, 40, 1754–1759, https://doi.org/10.1002/grl.50382

Bamber, J. L., Oppenheimer, M., Kopp, R. E., Aspinall, W. P., and Cooke, R. M. (2019). Ice sheet contributions to future sea-level rise from structured expert judgment, Proceedings of the National Academy of Sciences, 116, 11195–11200, https://doi.org/10.1073/pnas.1817205116

Bartolino V., H. Tian, U. Bergström, P. Jounela, E. Aro, C. Dieterich, H. E. M. Meier, M. Cardinale, B. Bland, and M. Casini (2017). Spatiotemporal dynamics of a fish predator: density-dependent and hydrographic effects on Baltic Sea cod population.

PLOS ONE, http://dx.doi.org/10.1371/journal.pone.0172004

Bauer, B., Gustafsson, B. G., Hyytiäinen, K., Meier, H. E. M., Müller-Karulis, B., Saraiva, S., et al. (2019). Food web and fisheries in the future Baltic Sea. AMBIO, https://doi.org/10.1007/s13280-019-01229-3 (published online 26 July 2019)

Bauer, B., Meier, H. E. M., Casini, M., Hoff, A., Margoński, P., Orio, A., et al. (2018). Reducing eutrophication increases spatial extent of communities supporting commercial fisheries: a model case study. ICES Journal of Marine Sciences 75(4), 1306–1317. https://doi.org/10.1093/icesjms/fsy023.

Bendtsen, J., and Hansen, J. L. (2013). Effects of global warming on hypoxia in the Baltic Sea–North Sea transition zone. Ecological Modelling 264, 17-26. https://doi.org/10.1016/j.ecolmodel.2012.06.018.

Bengtsson, L. (2010). The global atmospheric water cycle. Environmental Research Letters 5(2), 025202. https://doi.org/10.1088/1748-9326/5/2/025202.

Binczewska, A., Moros, M., Polovodova Asteman, I., Sławińska, J., & Bąk, M. (2018). Changes in the inflow of saline water into the Bornholm Basin (SW Baltic Sea) during the past 7100 years–evidence from benthic foraminifera record. *Boreas*, *47*(1), 297-310.

Bingham, R. J. and Hughes, C. W. (2012). Local diagnostics to estimate density-induced sea level variations over topogra- phy and along coastlines, Journal of Geophysical Research: Oceans, 117, https://doi.org/10.1029/2011JC007276

Börgel, F., Frauen, C., Neumann, T., Schimanke, S., and Meier, H. E. M. (2018). Impact of the Atlantic Multidecadal Oscillation on Baltic Sea Variability. Geophysical Research Letters, 45(18), 9880-9888. https://doi.org/10.1029/2018GL078943.

Bülow, K., Dieterich C., Elizalde A., Gröger M., Heinrich H., Hüttl-Kabus S., et al. (2014). Comparison of three regional coupled ocean atmosphere models for the North Sea under today's and future climate conditions. KLIWAS Zeitschriftenreihe 27/2014. Koblenz: Bundesanstalt für Gewässerkunde. https://doi.org/10.5675/Kliwas 27/2014.

Burson, A., Stomp, M., Akil, L., Brussaard, C. P., and Huisman, J. (2016). Unbalanced reduction of nutrient loads has created an offshore gradient from phosphorus to nitrogen limitation in the North Sea. Limnology and Oceanography 61(13), 869-888. https://aslopubs.onlinelibrary.wiley.com/doi/full/10.1002/lno.10257.

Carstensen, J., Andersen, J. H., Gustafsson, B. G., and Conley, D. J. (2014). Deoxygenation of the Baltic Sea during the last century. Proceedings of the National Academy of Sciences 111(15), 5628-5633. https://doi.org/10.1073/pnas.1323156111.

Cattiaux, J., H. Douville, and Y. Peings (2013): European temperatures in CMIP5: Origins of present-day biases and future uncertainties. Clim. Dyn., 41, 2889-2907.

Chen, D., and Omstedt, A. (2005). Climate-induced variability of sea level in Stockholm: influence of air temperature and atmospheric circulation. Advances in Atmospheric Sciences 22(5), 655-664. https://doi.org/10.1007/BF02918709.

Christensen, J. H., and Christensen, O. B (2007). A summary of the PRUDENCE model projections of changes in European climate by the end of this century. Climatic Change 81(1), 7-30. https://doi.org/10.1007/s10584-006-9210-7.

Christensen, J. H., Kjellström, E., Giorgi, F., Lenderink, G., and Rummukainen, M. (2010). Weight assignment in regional climate models. Climate Research 44(2-3), 179-194. https://doi.org/10.3354/cr00916.

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. (2013a). Sea Level Change, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I 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., chap. 13, pp. 1137–1216, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., et al. (2013). ”Long-term climate change: projections, commitments and irreversibility.” in Climate Change 2013: The Physical Science Basis. IPCC Working Group I Contribution to IPCC AR5, ed. T.F. Stocker et al. (Cambridge, UK and New York, USA: Cambridge University Press), 1029-1136.

Croci-Maspoli, M., C. Schwierz, and H. C. Davies (2007): A multifaceted climatology of atmospheric blocking and its recent linear trend. J. Clim., 20, 633–649.

Daewel, U., and Schrum, C. (2013). Simulating long-term dynamics of the coupled North Sea and Baltic Sea ecosystem with ECOSMO II: model description and validation, Journal of Marine Systems 119-120, 30–49. https://doi.org/10.1016/j.jmarsys.2013.03.008.

Daniel J. Conley, Svante Björck, Erik Bonsdorff, Jacob Carstensen, Georgia Destouni, Bo G. Gustafsson, Susanna Hietanen, Marloes Kortekaas, Harri Kuosa, H. E. Markus Meier, Baerbel Müller-Karulis, Kjell Nordberg, Alf Norkko, Gertrud Nürnberg, Heikki Pitkänen, Nancy N. Rabalais, Rutger Rosenberg, Oleg P. Savchuk, Caroline P. Slomp, Maren Voss, Fredrik Wulff, and Lovisa Zillén (2009). Hypoxia-Related Processes in the Baltic Sea. Environmental Science & Technology 43 (10), 3412-3420, DOI: 10.1021/es802762a

Daniel J Conley, Hans W Paerl, Robert W Howarth, Donald F Boesch, Sybil P Seitzinger, Karl E Havens, Christiane Lancelot, Gene E Liken (2009). Controlling eutrophication: nitrogen and phosphorus. Science, 323.

Davini, P., C. Cagnazzo, S. Gualdi, and A. Navarra (2012): Bidimensional diagnostics, variability, and trends of Northern Hemisphere blocking. J. Clim., 25, 6496–6509.

Deng, J., J. Harff, S. Schimanke, and H. E. M. Meier, 2015: A method for estimating coastline recession due to sea level rise by assuming stationary wind-wave climate. Journal of Oceanological and Hydrobiological Studies, 44(3), 362-380.

Déqué, M., Rowell, D., Lüthi, D., Giorgi, F., Christensen, J., Rockel, B., et al. (2007). An intercomparison of regional climate simulations for Europe: assessing uncertainties in model projections. Climatic Change 81(1), 53-70. https://doi.org/10.1007/s10584-006-9228-x.

Déqué, M., Somot, S., Sanchez-Gomez, E., Goodess, C., Jacob, D., Lenderink, G. et al. (2012). The spread amongst ENSEMBLES regional scenarios: regional climate models, driving general circulation models and interannual variability. Climate Dynamics 38(5-6), 951-964. https://doi.org/10.1007/s00382-011-1053-x.

Deser, C., Phillips, A. S., Alexander, M. A., and Smoliak, B. V. (2014). Projecting North American climate over the next 50 years: Uncertainty due to internal variability. Journal of Climate 27(6), 2271-2296. https://doi.org/10.1175/JCLI-D-13-00451.1.

Dieterich, C., Schimanke, S., Wang, S., Väli, G., Liu, Y., Hordoir, R., Axell, L., Höglund, A., and Meier, H. E. M. (2013).

Evaluation of the SMHI coupled atmosphere-ice-ocean model RCA4-NEMO, vol. 47 of Report Oceanography, SMHI, Norrköping, Sweden.

Dieterich, C., Gröger, M., Arneborg, L., and Andersson, H. C. (2019a). Extreme Sea Levels in the Baltic Sea under Climate Change Scenarios. Part 1: Model Validation and Sensitivity, Ocean Sci Discuss.

Dieterich, Christian, Wang, Shiyu, Schimanke, Semjon, Gröger, Matthias, Klein, Birgit, Hordoir, Robinson, Samuelsson, Patrick, Liu, Ye, Axell, Lars, Höglund, Anders, Meier, H. E. Markus (2019b). Surface Heat Budget over the North Sea in Climate Change Simulations, Atmosphere, 10, 10.3390/atmos10050272

Donnelly, C., Arheimer, B., Capell, R., Dahné, J., and Strömqvist, J. (2013). Regional overview of nutrient load in Europe – challenges when using a large-scale model approach, E-HYPE. Proceedings of H04, IAHS-IAPSO-IASPEI Assembly, Gothenburg, Sweden, IHS Publ. 361, 49-58.

Donnelly, C., Greuell, W., Andersson, J., Gerten, D., Pisacane, G., Roudier, P. et al. (2017). Impacts of climate change on European hydrology at 1.5, 2 and 3 degrees mean global warming above preindustrial level. Climatic Change 143(1-2), 13-26. https://doi.org/10.1007/s10584-017-1971-7.

Donnelly, C., Yang, W., and Dahné, J. (2014). River discharge to the Baltic Sea in a future climate. Climatic Change 122(1-2), 157-170. https://doi.org/10.1007/s10584-013-0941-y.

Döscher, R., and Meier, H. E. M. (2004). Simulated sea surface temperature and heat fluxes in different climates of the Baltic Sea. Ambio 33(4), 242-248. https://doi.org/10.1579/0044-7447-33.4.242.

Döscher, R., Willén, U., Jones, C., Rutgersson, A., Meier, H. E. M., Hansson, U. et al. (2002). The development of the regional coupled ocean-atmosphere model RCAO. Boreal Environment Research 7(3), 183-192.

Dudzinska-Nowak, P. (2017): Morphodynamic processes of the Swina Gate coastal zone development (Southern Baltic Sea). In: Harff J, Furmanczyk K, von Storch H (eds) Coastline changes of the Baltic Sea from south to east – past and future projection. Coastal research library, vol 19. Springer, Cham, Switzerland.

Edman, M. K., and Anderson, L. G. (2014). Effect on pCO2 by phytoplankton uptake of dissolved organic nutrients in the Central and Northern Baltic Sea, a model study. Journal of Marine Systems 139, 166-182. https://doi.org/10.1016/j.jmarsys.2014.06.004.

Edman, M., and Omstedt, A. (2013). Modeling the dissolved CO2 system in the redox environment of the Baltic Sea. Limnology and Oceanography 58(1), 74-92. https://doi.org/10.4319/lo.2013.58.1.0074.

Edman, M., Eilola, K., Almroth-Rosell, E., Meier, H. E. M., Wåhlström, I., and Arneborg, L. (2018). Nutrient retention along the Swedish coastline. Frontiers in Marine Science 5:415. https://doi.org/10.3389/fmars.2018.00415.

Eelsalu, M., Soomere, T., Pindsoo, K., and Lagemaa, P. (2014). Ensemble approach for projections of return periods of extreme water levels in Estonian waters. Cont Shelf Res, 91, 201–210, https://doi.org/ https://doi.org/10.1016/j.csr.2014.09.012, 2014

Eggert, A., and Schneider, B. (2015). A nitrogen source in spring in the surface mixed-layer of the Baltic Sea: evidence from total nitrogen and total phosphorus data. Journal of Marine Systems 148, 39-47. https://doi.org/10.1016/j.jmarsys.2015.01.005.

Eilola, K., Almroth-Rosell, E., Dieterich, C., Fransner, F., Höglund, A., and Meier, H. E. M. (2012). Modeling nutrient transports and exchanges of nutrients between shallow regions and the open Baltic Sea in present and future climate. Ambio 41(6), 586-599. https://doi.org/10.1007/s13280-012-0317-y.

Eilola, K., E. Almroth-Rosell, and H. E. M. Meier, 2014: Impact of saltwater inflows on phosphorus cycling and eutrophication in the Baltic Sea. A 3D model study. Tellus A, 66, 23985.

Eilola, K., Gustafsson, B.G., Kuznetsov, I., Meier, H.E.M., Neumann, T., and Savchuk, O.P. (2011). Evaluation of biogeochemical cycles in an ensemble of three state-of-the-art numerical models of the Baltic Sea. Journal of Marine Systems 88(2), 267-284. https://doi.org/10.1016/j.jmarsys.2011.05.004.

Eilola, K., Mårtensson, S., and Meier, H.E.M. (2013). Modeling the impact of reduced sea ice cover in future climate on the Baltic Sea biogeochemistry. Geophysical Research Letters 40(1), 149-154. https://doi.org/10.1029/2012GL054375.

Eilola, K., Meier, H. E. M., and Almroth, E. (2009). On the dynamics of oxygen, phosphorus and cyanobacteria in the Baltic Sea; A model study. Journal of Marine Systems 75(1-2), 163-184. https://doi.org/10.1016/j.jmarsys.2008.08.009.

Elken J., Lehmann A., Myrberg K. (2015) Recent Change—Marine Circulation and Stratification. In: The BACC II Author Team (eds) Second Assessment of Climate Change for the Baltic Sea Basin. Regional Climate Studies. Springer, Cham

Ekman, M. (2009). The Changing Level of the Baltic Sea during 300 Years: A Clue to Understanding the Earth, Summer Institute for Historical Geophysics, Åland Islands.

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J. et al. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. Geoscientific Model Development 9(5), 1937-1958. https://doi.org/10.5194/gmd-9-1937-2016.

Feser, F., Rockel, B., von Storch, H., Winterfeldt, J., and Zahn, M. (2011). Regional climate models add value to global model data: a review and selected examples. Bulletin of the American Meteorological Society 92(9), 1181-1192. https://doi.org/10.1175/2011BAMS3061.1.

Finni, T., Kononen, K., Olsonen, R., and Wallström, K. (2001). The history of cyanobacterial blooms in the Baltic Sea. Ambio 30 (4), 172-178. https://doi.org/10.1579/0044-7447-30.4.172.

Fonselius, S., & Valderrama, J. (2003). One hundred years of hydrographic measurements in the Baltic Sea. *Journal of Sea Research*, *49*(4), 229-241.

Fransner, F., Gustafsson, E., Tedesco, L., Vichi, M., Hordoir, R., Roquet, F. et al. (2018). Non-Redfieldian dynamics explain seasonal pCO_2 drawdown in the Gulf of Bothnia. Journal of Geophysical Research - Oceans 123(1), 166-188. https://doi.org/10.1002/2017JC013019.

Fredriksson, C., Feldmann Eellend, B., Larson, M., and Martinez, G. (2017). Historiska stormhändelser som underlag vid riskanalys – Studie avöversvämningarna 1872 och 1904 längs Skånes syd- och ostkust, Vatten, Journal of Water Management and Research, 73, 93–108

Fredriksson, C., Tajvidi, N., Hanson, H., and Larson, M. (2016). Statistical Analysis of Extreme Sea Water Levels at the Falsterbo Peninsula, South Sweden, Vatten, Journal of Water Management and Research, 72, 129–142

Frederikse, T., Jevrejeva, S., Riva, R. E., & Dangendorf, S. (2018). A consistent sea-level reconstruction and its budget on basin and global scales over 1958–2014. *Journal of Climate*, *31*(3), 1267-1280.

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

Gailiušis, B., Kriaučiūnienė, J., Jakimavičius D.,Šarauskienė, D., 2011. The variability of long–term runoff series in the Baltic Sea drainage basin**.** *Baltica, 24(1),* 45–54**.** Vilnius. ISSN 0067-3064.

Graham LP, Olsson J, Kjellström E, Rosberg J, Hellström S-S, Berndtsson R (2009) Simulating river flow to the Baltic Sea from climate simulations over the past millennium. Boreal Environ Res 14:173-182

Giorgi, F., and Gao, X.-J. (2018). Regional earth system modeling: review and future directions. Atmospheric and Oceanic Science Letters 11(2). 189-197. https://doi.org/10.1080/16742834.2018.1452520.

Gordon, C., Cooper, C., Senior, C. A., Banks, H., Gregory, J. M., Johns, T. C. et al. (2000). The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. Climate Dynamics 16(2-3), 147–168. https://doi.org/10.1007/s003820050010.

Gorokhova, E., Lehtiniemi, M., Postel, L., Rubene, G., Amid, C., Lesutiene, J., ... & Demereckiene, N. (2016). Indicator properties of Baltic Zooplankton for classification of environmental status within Marine Strategy Framework Directive. PloS one, 11(7), e0158326.

Graham, P. (1999). Modeling runoff to the Baltic Sea. Ambio 28(4), 328-334.

Gräwe, U., Friedland, R., and Burchard, H. (2013). The future of the western Baltic Sea: two possible scenarios. Ocean Dynamics 63(8), 901-921. https://doi.org/10.1007/s10236-013-0634-0.

Gräwe, U., Klingbeil, K., Kelln, J., & Dangendorf, S. (2019). Decomposing mean sea level rise in a semi-enclosed basin, the Baltic Sea. *Journal of Climate*, *32*(11), 3089-3108.

Grinsted, A. (2015). Projected Change—Sea Level, pp. 253–263, Springer International Publishing, Cham, https://doi.org/10.1007/978-3- 319-16006-1 14

Groetsch PMM, Simis SGH, Eleveld MA and Peters SWM (2016). Spring blooms in the Baltic Sea have weakened but lengthened from 2000 to 2014. Biogeosciences 13: 4959–4973

Gröger, M., Dieterich, C., Meier, H. E. M., and Schimanke, S. (2015). Thermal air–sea coupling in hindcast simulations for the North Sea and Baltic Sea on the NW European shelf. Tellus A: Dynamic Meteorology and Oceanography 67(1), 26911. https://doi.org/10.3402/tellusa.v67.26911.

Gröger, M., Maier-Reimer, E., Mikolajewicz, U., Moll, A., and Sein, D. (2013). NW European shelf under climate warming: implications for open ocean-shelf exchange, primary production, and carbon absorption. Biogeosciences 10(6), 3767-3792. https://doi.org/10.5194/bg-10-3767-2013.

Gröger, M., L. Arneborg, C. Dieterich, A. Höglund, and H. E. M. Meier, 2019: Hydrographic changes in the North Sea and Baltic Sea projected in an ensemble of climate scenarios downscaled with a coupled regional ocean-sea ice-atmosphere model. Climate Dynamics, accepted.

Gustafsson, B. G. (2003). A time-dependent coupled-basin model for the Baltic Sea. Report C47, Göteborg: Earth Sciences Centre, Göteborg University.

Gustafsson, B. G. (2004). Sensitivity of Baltic Sea salinity to large perturbations in climate. Climate Research 27(3), 237-251. https://doi.org/10.3354/cr027237.

Gustafsson, B. G., and Mörth, C. M. (2014). Revision of the Maximum Allowable Inputs and Country Allocation Scheme of the Baltic Sea Action Plan.

Gustafsson, B. G., Schenk, F., Blenckner, T., Eilola, K., Meier, H. E. M., Müller-Karulis, B. et al. (2012). Reconstructing the development of Baltic Sea eutrophication 1850–2006. Ambio 41(6), 534-548. https://doi.org/10.1007/s13280-012-0318-x.

Gustafsson, E., Deutsch, B., Gustafsson, B. G., Humborg, C., and Mörth, C.-M. (2014a). Carbon cycling in the Baltic Sea - The fate of allochthonous organic carbon and its impact on air-sea CO2 exchange. Journal of Marine Systems 129, 289-302. https://doi.org/10.1016/j.jmarsys.2013.07.005.

Gustafsson, E., Omstedt, A., and Gustafsson, B. G. (2015). The air-water CO2 exchange of a coastal sea - A sensitivity study on factors that influence the absorption and outgassing of CO2 in the Baltic Sea. Journal of Geophysical Research: Oceans 120(8), 5342-5357. https://doi.org/10.1002/2015JC010832.

Gustafsson, E., Wällstedt, T., Humborg, C., Mörth, C.-M., and Gustafsson, B. G. (2014b). External total alkalinity loads versus internal generation: The influence of nonriverine alkalinity sources in the Baltic Sea. Global Biogeochemical Cycles 28(11), 1358-1370. https://doi.org/10.1002/2014GB004888.

Gustafsson, N., Nyberg, L., and Omstedt, A. (1998). Coupling of a high-resolution atmospheric model and an ocean model for the Baltic Sea. Monthly Weather Review 126(11), 2822-2846. https://doi.org/10.1175/1520-0493(1998)126<2822:COAHRA>2.0.CO;2.

Haapala, J., Meier, H.E.M., and Rinne, J. (2001). Numerical investigations of future ice conditions in the Baltic Sea. Ambio 30(4), 237-244. https://doi.org/10.1579/0044-7447-30.4.237.

Haapala, J. J., Ronkainen, I., Schmelzer, N., & Sztobryn, M. (2015). Recent change—Sea ice. In *Second Assessment of Climate Change for the Baltic Sea Basin* (pp. 145-153). Springer, Cham.

Haasnoot, M., Schellekens, J., Beersma, J. J., Middelkoop, H., and Kwadijk, J. C. J. (2015). Transient scenarios for robust climate change adaptation illustrated for water management in The Netherlands, Environ. Res. Lett., 10, 105 008, https://doi.org/10.1088/1748-9326/10/10/105008

Hammarklint T (2009) Swedish Sea Level Series – A Climate Indicator. Swedish Meteorological and Hydrological Institute

Hansen, J., Ruedy, R., Sato, M., and Lo, K. (2010). Global surface temperature change. Reviews of Geophysics, 48(4). https://doi.org/10.1029/2010RG000345.

Hansson, D., and Gustafsson, E. (2011). Salinity and hypoxia in the Baltic Sea since A.D. 1500. Journal of Geophysical Research: Oceans 116(C3). https://doi.org/10.1029/2010JC006676.

Hansson, D., and Omstedt, A. (2008). Modelling the Baltic Sea ocean climate on centennial time scale: temperature and sea ice. Climate Dynamics 30(7-8), 763-778. https://doi.org/10.1007/s00382-007-0321-2.

Kommentiert [m36]: Teil von BACC II

Hansson D, Eriksson C, Omstedt A, Chen D (2011) Reconstruction of river runoff to the Baltic Sea, AD 1500–1995. *Int J Climatology* 31:696-703.

Harff, J., Lemke, W., Lampe, R., Lüth, F., Lübke, H., Meyer, M., Tauber, F., Schmoelcke, U. (2007): The Baltic Sea coast – a model of interrelations among geosphere, climate, and anthroposphere. In: Harff J, Hay WW, Tetzlaff DM (eds) Coastline changes: interrelation of climate and geological processes. Geol Soc Am Spec Paper 426:133–142

Harff, J., J. Deng, J. Durzinska-Nowak, P. Fröhle, A. Groh, B. Hünicke, T. Soomere, and Zhang, W. (2017): Chapter 2: What determines the change of coastlines in the Baltic Sea? In: Harff J, Furmanczyk K, von Storch H (eds) Coastline changes of the Baltic Sea from south to east – past and future projection. Coastal research library, vol 19. Springer, Cham, Switzerland. DOI:10.1007/978-3-319-49894-2

Harff, J., Furmańczyk, K., and von Storch, H. (2017). Coastline Changes of the Baltic Sea from South to East: Past and Future Projection. Cham: Springer International Publishing AG. https://doi.org/10.1007/978-3-319-49894-2.

Harff, J., Lemke, W., Lampe, R., Lüth, F., Lübke, H., Meyer, M., Tauber, F., Schmoelcke, U. (2007): The Baltic Sea coast – a model of interrelations among geosphere, climate, and anthroposphere. In: Harff J, Hay WW, Tetzlaff DM (eds) Coastline changes: interrelation of climate and geological processes. Geol Soc Am Spec Paper 426:133–142

Hari, P., Aakala, T., Hilasvuori, E., Häkkinen, R., Korhola, A., Korpela, M., ... & Seppä, H. (2017). Reliability of temperature signal in various climate indicators from northern Europe. *PloS one*, *12*(6), e0180042.

Havenhand, J. N. (2012). How will ocean acidification affect Baltic Sea ecosystems? An assessment of plausible impacts on key functional groups. *Ambio*, *41*(6), 637-644.

Kommentiert [m37]: Impact of acidification. Included in BACC II?

Hawkins, E., and Sutton, R. (2009). The Potential to Narrow Uncertainty in Regional Climate Predictions. Bulletin of the American Meteorological Society 90(8), 1095-1108. https://doi.org/10.1175/2009BAMS2607.1.

Heavens, N. G., Ward, D. S., and Natalie, M. M. (2013). Studying and projecting climate change with earth system models. Nature education knowledge, 4(5):4.

HELCOM (2007a). Baltic Sea Action Plan, HELCOM Ministerial Meeting 2007, Krakow, Poland.

HELCOM (2007b). Towards a Baltic Sea unaffected by eutrophication. Helcom Overview 2007, Background document for the HELCOM Ministerial Meeting.

HELCOM (2013a). Approaches and methods for eutrophication target setting in the Baltic Sea region. Baltic Sea Environment Proceedings 133.

HELCOM (2013b). Copenhagen Ministerial Declaration, HELCOM Ministerial Meeting, Copenhagen, Denmark.

HELCOM (2013c). Summary report on the development of revised Maximum Allowable Inputs (MAI) and updated Country Allocated Reduction Targets (CART) of the Baltic Sea Action Plan. Background Document for the 2013 HELCOM Ministerial Meeting.

HELCOM (2015). Updated Fifth Baltic Sea pollution load compilation (PLC-5.5). Baltic Sea Environment Proceedings No. 145.

HELCOM (2018a). Sources and pathways of nutrients to the Baltic Sea. Baltic Sea Environment Proceedings No. 153, 48pp

HELCOM (2018b) Inputs of nutrients to the subbasins. HELCOM core indicator report. available at: http://www.helcom.fi/baltic-sea-trends/indicators/inputs-of-nutrients-to-the-subbasins (accessed December 5, 2018)

HELCOM (2018c): State of the Baltic Sea – Second HELCOM holistic assessment 2011-2016. Baltic Sea Environment Proceedings 155, ISSN 0357-2994. Available at: www.helcom.fi/baltic-sea-trends/holistic-assessments/state-of-the-baltic-sea-2018/reports-and-materials/

Hense, I., H. E. M. Meier, and S. Sonntag, 2013: Projected climate change impact on Baltic Sea cyanobacteria. Climatic Change, 119, 391-406, doi:10.1007/s10584-013-0702-y

Hieronymus, J., Eilola, K., Hieronymus, M., Meier, H. E. M., Saraiva, S., and Karlson, B. (2018). Causes of simulated long-term changes in phytoplankton biomass in the Baltic proper: a wavelet analysis. Biogeosciences, 15(16), 5113–5129. https://doi.org/10.5194/bg-15-5113-2018

Hill, E. M., Davis, J. L., Tamisiea, M. E., and Lidberg, M. (2010). Combination of geodetic observations and models for glacial isostatic adjustment fields in Fennoscandia, Journal of Geophysical Research: Solid Earth, 115, https://doi.org/10.1029/2009JB006967

Hisdal H, Holmqvist E, Jónsdóttir JF, Jónsson P, Kuusisto E, Lindström G, Roald LA (2010) Has streamflow changed in the Nordic countries? *Norwegian Water Resources and Energy Directorate*, No 1.

Höglund, A., Meier, H. E. M., Broman, B., and Kriezi, E. (2009). Validation and correction of regionalised ERA-40 wind fields over the Baltic Sea using the Rossby Centre Atmosphere model RCA3.0, Rapport Oceanografi 97, Norrköping: SMHI, Sweden.

Höglund, A., Pemberton, P., Hordoir, R. and Schimanke, S. (2017): Ice conditions for maritime traffic in the Baltic Sea in future climate. Boreal Environment Research 22: 245–265

Ho-Hagemann, H. T. M., Gröger M., Rockel, B., Geyer, B., Zahn, M., and Meier, H. E. M. (2017). Effects of air-sea coupling over the North Sea and the Baltic Sea on simulated summer precipitation over Central Europe. Climate Dynamics, 49(11), 3851-3876. https://doi.org/10.1007/s00382-017-3546-8.

Holopainen, R., Lehtiniemi, M., Meier, H. E. M., Albertsson, J., Gorokhova, E., Kotta, J. et al. (2016). Impacts of changing climate on the non-indigenous invertebrates in the northern Baltic Sea by end of the 21st century. Biological Invasions 18(10), 3015-3032. https://doi.org/10.1007/s10530-016-1197-z.

Holt, J., Butenschoen, M., Wakelin, S. L., Artioli, Y., and Allen, J. I. (2012). Oceanic controls on the primary production of the northwest European continental shelf: model experiments under recent past conditions and a potential future scenario. Biogeosciences 9, 97-117. https://doi.org/10.5194/bg-9-97-2012.

Holt, J., Schrum, C., Cannaby, H., Daewel, U., Allen, I., Artioli, Y., et al. (2016). Potential impacts of climate change on the primary production of regional seas: a comparative analysis of five European seas. Progress in Oceanography 140, 91-115. https://doi.org/10.1016/j.pocean.2015.11.004.

Hong, B., Swaney, D. P., Mörth, C.-M., Smedberg, E., Hägg, H. E., Humborg, C., et al. (2012). Evaluating regional variation of net anthropogenic nitrogen and phosphorus inputs (NANI/NAPI), major drivers, nutrient retention pattern and management implications in the multinational areas of Baltic Sea basin. Ecological Modelling 227, 117–135. https://doi.org/10.1016/j.ecolmodel.2011.12.002.

Hordoir, R., C. Dieterich, C. Basu, H. Dietze, and H. E. M. Meier, 2013: Freshwater outflow of the Baltic Sea and transport in the Norwegian current: A statistical correlation analysis based on a numerical experiment. Continental Shelf Research, 64, 1-9

Kommentiert [m38]: Relevant?

Hordoir, R., Axell, L., Löptien, U., Dietze, H., and Kuznetsov, I. (2015). Influence of sea level rise on the dynamics of salt inflows in the Baltic Sea. Journal of Geophysical Research - Oceans 120(10), 6653-6668. https://doi.org/10.1002/2014JC010642.

Hordoir, R., Höglund, A., Pemberton, P., and Schimanke, S. (2017). Sensitivity of the overturning circulation of the Baltic Sea to climate change, a numerical experiment. Climate Dynamics 50(3-4), 1425-1437. https://doi.org/10.1007/s00382-017-3695-9.

Kommentiert [m39]: Relevant?

Hourdin, F., Mauritsen, T., Gettelman, A., Golaz, J.-C., Balaji, V., Duan, Q. et al. (2017). The art and science of climate model tuning. Bulletin of the American Meteorological Society 98(3), 589-602. https://doi.org/10.1175/BAMS-D-15-00135.1.

Humborg, C., Mörth, C.-M., Sundbom, M., and Wulff, F. (2007). Riverine transport of biogenic elements to the Baltic Sea – past and possible future perspectives. Hydrol. Earth Syst. Sci. 11, 1593-1607. https://doi.org/10.5194/hess-11-1593-2007.

Hundecha, Y., Arheimer, B., Donnelly, C., and Pechlivanidis, I. (2016). A regional parameter estimation scheme for a pan-European multi-basin model. Journal of Hydrology: Regional Studies 6, 90-111. https://doi.org/10.1016/j.ejrh.2016.04.002.

Hünicke, B., Zorita, E., Soomere, T., Madsen, K. S., Johansson, M., and Suursaar, Ü. (2015). Recent Change—Sea Level and Wind Waves, pp. 155–185, Springer International Publishing, Cham, https://doi.org/10.1007/978-3- 319-16006-1 9

Kommentiert [m40]: BACC II

Hünicke, B., Zorita, E., & von Storch, H. (2017). The challenge of Baltic Sea level change. In *Coastline Changes of the Baltic Sea from South to East* (pp. 37-54). Springer International Publishing.

Hurrell, J. W. (1995): Decadal trends in the North Atlantic Oscillation and relationships to regional temperature and precipitation. Science, 269:676-679.

Hurrell, J. W., Y. Kushnir, G. Ottersen, and M. Visbeck (2003): An overview of the North Atlantic Oscillation. The North Atlantic Oscillation: climatic significance and environmental impact. Geophys Monogr, 134:1-36.

Hjalmarsson, S., Wesslander, K., Anderson, L. G., Omstedt, A., Perttila, M., and Mintrop, L. (2008). Distribution, long-term development and mass balance calculation of total alkalinity in the Baltic Sea. Continental Shelf Research 28(4-5), 593-601. https://doi.org/10.1016/j.csr.2007.11.010.

IPCC (2013): Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

Irannezhad, M., Chen, D., & Kløve, B. (2015). Interannual variations and trends in surface air temperature in Finland in relation to atmospheric circulation patterns, 1961–2011. International Journal of Climatology, 35(10), 3078-3092.

Isaev, A.V., Eremina, T.R., Ryabchenko, V.A., and Savchuk, O.P., (2017). Model estimates of the impact of bioirrigation activity of *Marenzelleria* spp. on the Gulf of Finland ecosystem in a changing climate, Journal of Marine Systems 171, 81-88. http://dx.doi.org/10.1016/j.jmarsys.2016.08.005.

Jacob, D. (2001). A note to the simulation of the annual and inter-annual variability of the water budget over the Baltic Sea drainage basin. Meteorology and Atmospheric Physics 77(1-4), 61-73. https://doi.org/10.1007/s007030170017.

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O. B, Bouwer, L. M. et al. (2014). EURO-CORDEX: new high-resolution climate change projections for European impact research. Regional Environmental Change 14(2), 563-578. https://doi.org/10.1007/s10113-013-0499-2.

Jevrejeva, S., Moore, J. C., Grinsted, A., Matthews, A. P., & Spada, G. (2014). Trends and acceleration in global and regional sea levels since 1807. Global and Planetary Change, 113, 11-22.

Johansson, M. M., & Kahma, K. K. (2016). On the statistical relationship between the geostrophic wind and sea level variations in the Baltic Sea.

Kommentiert [m41]: Referenz?

Johansson, M. M., Pellikka, H., Kahma, K. K., and Ruosteenoja, K. (2014). Global sea level rise scenarios adapted to the Finnish coast. Journal of Marine Systems 129, 35-46. https://doi.org/10.1016/j.jmarsys.2012.08.007.

Johns, T.C., Carnell, R.E., Crossley, J.F., Gregory, J.M., Mitchell, J.F.B., Senior, C.A. et al. (1997). The second Hadley Centre coupled ocean-atmosphere GCM: model description, spinup and validation. Climate Dynamics 13(2), 103–134. https://doi.org/10.1007/s003820050155,

Jungclaus, J. H., Botzet, M., Haak, H., Keenlyside, N., Luo, J.-J., Latif, M. et al. (2006). Ocean circulation and tropical variability in the coupled ECHAM5/MPI-OM. Journal of Climate 19(16), 3952–3972. https://doi.org/10.1175/JCLI3827.1.

Jutterström, S., Andersson, H., Omstedt, A., and Malmaeus, J. (2014). Multiple stressors threatening the future of the Baltic Sea - Kattegat marine ecosystem: Implications for policy and management actions. Marine pollution bulletin 86(1-2), 468-480. https://doi.org/10.1016/j.marpolbul.2014.06.027.

Kabel, K., Moros, M., Porsche, C., Neumann, T., Adolphi, F., Andersen, T. J., ... & Damsté, J. S. S. (2012). Impact of climate change on the Baltic Sea ecosystem over the past 1,000 years. *Nature Climate Change*, *2*(12), 871.

Kahru, M., Elmgren, R., and Savchuk, O. P. (2016). Changing seasonality of the Baltic Sea. Biogeosciences 13, 1009–1018. https://doi.org/10.5194/bg-13-1009-2016.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., et al. (1996). The NCEP/NCAR 40-Year Reanalysis Project. Bulletin of the American Meteorological Society 77(3), 437–471. https://doi.org/10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2.

Karabil, S. (2017). Influence of Atmospheric Circulation on the Baltic Sea Level Rise under the RCP8. 5 Scenario over the 21st Century. *Climate*, *5*(3), 71.

Karabil, S., Zorita, E., and Baehr, J. (2017a). Mechanisms of variability in decadal sea-level trends in the Baltic Sea over the 20th century. Earth System Dynamics 8(4), 1031-1046. https://doi.org/10.5194/esd-8-1031-2017.

Karabil, S., Zorita, E., and Baehr, J. (2017b) Mechanisms of sea level variability in the Baltic Sea region for the period 1850-2100. [Doctoral dissertation]. [Hamburg]: Universität Hamburg.

Karabil, S., Zorita, E., and Hünicke, B. (2018). Contribution of atmospheric circulation to recent off-shore sea-level variations in the Baltic Sea and the North Sea. Earth System Dynamics 9(1), 69-90. https://doi.org/10.5194/esd-9-69-2018.

Karpechko, A. Y., Peterson, K. A., Scaife, A. A., Vainio, J., & Gregow, H. (2015). Skilful seasonal predictions of Baltic Sea ice cover. *Environmental Research Letters*, *10*(4), 044007

Kauker, F., and Meier, H. E. M. (2003). Modeling decadal variability of the Baltic Sea: 1. Reconstructingatmospheric surface data for the period 1902-1998. Journal of Geophysical Research - Oceans 108(C8). https://doi.org/10.1029/2003JC001797.

Kjellström, E., Nikulin, G., Hansson, U. L. F., Strandberg, G., and Ullerstig, A. (2011). 21st century changes in the European climate: uncertainties derived from an ensemble of regional climate model simulations. Tellus A: Dynamic Meteorology and Oceanography 63(1), 24-40. https://doi.org/10.1111/j.1600-0870.2010.00475.x.

Klais R, Tamminen T, Kremp A, Spilling K, Woong An B, Hajdu S, Olli K (2013). Spring phytoplankton communities shaped by interannual weather variability and dispersal limitation: Mechanisms of climate change effects on key coastal primary producers. Limnol Oceanogr 58: 753-762

Kniebusch, M., H. E. M. Meier, and T. Neumann, 2019a: Temperature variability of the Baltic Sea since 1850 in model simulations and observations and attribution to atmospheric forcing. Journal of Geophysical Research – Oceans, 124.

Kniebusch, M., H. E. M. Meier, and H. Radtke, 2019b: Changing salinity gradients in the Baltic Sea as a consequence of altered freshwater budgets. Geophysical Research Letters, in press.

Knight, J. (2009): The Atlantic Multidecadal Oscillation inferred from the forced climate response in coupled general ciculation models. J. Clim., 22, 1610–1625.

Knight, J. R., Allan, R. J., Folland, C. K., Vellinga, M., and Mann, M. E. (2005). A signature of persistent natural thermohaline circulation cycles in observed climate. Geophysical Research Letters, *32*(20). https://doi.org/10.1029/2005GL024233.

Knight, J. R., C. K. Folland, and A. A. Scaife (2006): Climate impacts of the Atlantic Multidecadal Oscillation. Geophysical Research Letters, 33, L17706.

Knutti, R., and Sedláček, J. (2013). Robustness and uncertainties in the new CMIP5 climate model projections. Nature Climate Change 3(4), 369. https://doi.org/10.1038/nclimate1716.

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

Kreus, M., Schartau, M., Engel, A., Nausch, M., and Voss, M. (2015). Variations in the elemental ratio of organic matter in the central Baltic Sea: Part I-Linking primary production to remineralization. Continental Shelf Research 100, 25-45. https://doi.org/10.1016/j.csr.2014.06.015.

Kristiansen, T., and Aas, E. (2015). Water type quantification in the Skagerrak, the Kattegat and off the Jutland west coast. Oceanologia 57(2), 177-195. https://doi.org/10.1016/j.oceano.2014.11.002.

Kuliński, K., Schneider, B., Hammer, K., Machulik, U., and Schulz-Bull, D. (2014). The influence of dissolved organic matter on the acid--base system of the Baltic Sea. Journal of Marine Systems 132, 106-115. https://doi.org/10.1016/j.jmarsys.2014.01.011.

Kupiainen, M., Jansson, C., Samuelsson, P., Jones, C.,Willén, U. et al. (2014). Rossby Centre regional atmospheric model, RCA4, Rossby Center News Letter. SMHI, Norrköping, Sweden. online at: http://www.smhi.se/en/Research/Research-departments/climate-research-rossby-centre2-552/1.16562. (14.08.2018)

Kuznetsov, I., Eilola, K., Dieterich, C., Hordoir, R., Axell, L., Höglund, A. et al. (2016). Model study on the variability of ecosystem parameters in the Skagerrak-Kattegat area, effect of load reduction in the North Sea and possible effect of BSAP on Skagerrak-Kattegat area. Rapport Oceanografi 119, Norrköping: SMHI, Sweden.

Kuznetsov, I., and Neumann, T. (2013). Simulation of carbon dynamics in the Baltic Sea with a 3D model. Journal of Marine Systems 111, 167-174. https://doi.org/10.1016/j.jmarsys.2012.10.011

Laane, R., Brockmann, U., van Liere, L., and Bovelander, R. (2005). Immission targets for nutrients (N and P) in catchments and coastal zones: a North Sea assessment. Estuarine Coastal Shelf Science 62(3), 495-505. https://doi.org/10.1016/j.ecss.2004.09.013.

Łabuz, T. A. (2015): Environmental impacts – coastal erosion and coastline changes. Chapter 20. In: BACC II Team (eds.), Second assessment of climate change for the Baltic Sea basin. Springer (515p.): 381–396.

Lang, A., & Mikolajewicz, U. (2019). The long-term variability of extreme sea levels in the German Bight. Ocean Science, 15, 651-668.

Lass, H. U., & Matthäus, W. (1996). On temporal wind variations forcing salt water inflows into the Baltic Sea. *Tellus A*, *48*(5), 663-671.

Lehmann, A., & Post, P. (2015). Variability of atmospheric circulation patterns associated with large volume changes of the Baltic Sea. *Advances in Science and Research*, *12*, 219-225.

Lehmann, A., Krauß, W., & Hinrichsen, H. H. (2002). Effects of remote and local atmospheric forcing on circulation and upwelling in the Baltic Sea. *Tellus A: Dynamic Meteorology and Oceanography*, *54*(3), 299-316.

Lehmann, A., Getzlaff, K., & Harlaß, J. (2011). Detailed assessment of climate variability in the Baltic Sea area for the period 1958 to 2009. *Climate Research*, *46*(2), 185-196.

Lehmann, Andreas, Höflich, Katharina, Post, Piia, Myrberg, Kai (2016). Pathways of deep cyclones associated with large volume changes (LVCs) and major Baltic inflows (MBIs), *Journal of Marine Systems* (2016), doi:10.1016/j.jmarsys.2016.10.014

Lenhart, H.-J., Mills, D. K., Baretta-Bekker, H., van Leeuwen, S. M., van der Molen, J., Baretta, J. W., et al. (2010). Predicting the consequences of nutrient reduction on the eutrophication status of the North Sea. Journal of Marine Systems 81(1-2), 148-170. https://doi.org/10.1016/j.jmarsys.2009.12.014.

Lessin, G., Raudsepp, U., Maljutenko, I., Laanemets, J., Passenko, J., and Jaanus, A. (2014). Model study on present and future eutrophication and nitrogen fixation in the Gulf of Finland, Baltic Sea. Journal of Marine Systems 129, 76-85. https://doi.org/10.1016/j.jmarsys.2013.08.006.

Liblik, T. and Lips, U. 2019. Stratification Has Strengthened in the Baltic Sea – An Analysis of 35 Years of Observational Data. Frontiers in Earth Science, 7. doi:10.3389/feart.2019.00174

Lind, P., and Kjellström, E. (2009). Water budget in the Baltic Sea drainage basin: Evaluation of simulated fluxes in a regional climate model. Boreal Environment Research 14, 56-67.

Liu, Y., H. E. M. Meier, and L. Axell, 2013: Reanalyzing temperature and salinity on decadal time scales using the Ensemble Optimal Interpolation data assimilation method and a 3D ocean circulation model of the Baltic Sea. J. Geophys. Res., 118, 5536-5554, doi:10.1002/jgrc.20384

Liu, Y., H. E. M. Meier, and K. Eilola, 2014: Improving the multi-annual, high-resolution modelling of biogeochemical cycles in the Baltic Sea by using data assimilation. Tellus A, 66, 24908, http://dx.doi.org/10.3402/tellusa.v66.24908.

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

Liu, W., Xie, S.-P., Liu, Z., and Zhu, J. (2017). Overlooked possibility of a collapsed Atlantic Meridional Overturning Circulation in warming climate. Science Advances 3(1), e1601666. https://doi.org/10.1126/sciadv.1601666.

Löptien, U., Mårtensson, S., Meier, H. E. M., and Höglund, A. (2013). Long-term characteristics of simulated ice deformation in the Baltic Sea (1962-2007). Journal of Geophysical Research: Oceans 118(2), 801-815. https://doi.org/10.1002/jgrc.20089.

Luomaranta, A., Ruosteenoja, K., Jylhä, K., Gregow, H., Haapala, J., and Laaksonen, A. (2014). Multimodel estimates of the changes in the Baltic Sea ice cover during the present century. Tellus A: Dynamic Meteorology and Oceanography 66(1), 22617. https://doi.org/10.3402/tellusa.v66.22617.

Luyten, P.J., Jones, J.E., Proctor, R., Tabor, A., Tett, P., and Wild-Allen, K. (1999). COHERENS– a coupled hydrodynamical–ecological model for regional and shelf seas: user documentation. MUMM Report. Management Unit of the Mathematical Models of the North Sea. 914.

Madec, G., and the NEMO team (2016). NEMO ocean engine. version 3.6 stable. Note du Pôle de modélisation. Institut Pierre-Simon Laplace (IPSL)-LOCEAN. Paris, France. No 27. online at: https://www.nemo-ocean.eu/wp-content/uploads/NEMO_book.pdf (17.08.2018).

Madsen KS (2011) Recent and future climatic changes of the North Sea and the Baltic Sea – Temperature, salinity, and sea level. LAMBERT Academic Publishing, Germany

Madsen, K. S., Sørensen, C. S., Schmith, T., Nielsen, J. W., & Knudsen, P. (2017). Determining Storm Surge Return Periods: The Use of Evidence of Historic Events. In *International WCRP/IOC Conference 2017: Regional Sea Level Changes and Coastal Impacts*.

Kommentiert [m42]: Available? Relevant?

Marti, O., Braconnot, P., Bellier, J., Benshila, R., Bony, S., Brockmann, P. et al. (2006). The new IPSL climate system model: IPSL-CM4. Note du Pole de Modelisation 26. Institut Pierre-Simon Laplace (IPSL). France.

Mastrandrea, M. D., Field, C. B., Stocker, T. F., Edenhofer, O., Ebi, K. L., Frame, D. J., Held, H., Kriegler, E., Mach, K. J., Matschoss, P. R., Plattner, G.-K., Yohe, G. W., and Zwiers, F. W. (2010). Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties. Intergovernmental Panel on Climate Change (IPCC). Available at http://www.ipcc.ch.

Mathis, M., Mayer, B., and Pohlmann, T. (2013). An uncoupled dynamical downscaling for the North Sea: method and evaluation. Ocean Modelling 72, 153-166. https://doi.org/10.1016/j.ocemod.2013.09.004.

Mathis, M., Elizalde, A., and Mikolajewicz, U. (2018). Which complexity of regional climate system models is essential for downscaling anthropogenic climate change in the Northwest European Shelf? Climate Dynamics, 50(7-8), 2637-2659.

https://doi.org/10.1007/s00382-017-3761-3.

Mathis, M., Elizalde, A., and Mikolajewicz, U. (2019). The future regime of Atlantic nutrient supply to the Northwest European Shelf. Journal of Marine Systems 189, 98-115. https://doi.org/10.1016/j.jmarsys.2018.10.002

Matthäus, W., and Franck, H. (1992). Characteristics of major Baltic inflows - a statistical analysis. Continental Shelf Research 12(12), 1375-1400. https://doi.org/10.1016/0278-4343(92)90060-W.

Matthäus, W., & Schinke, H. (1999). The influence of river runoff on deep water conditions of the Baltic Sea. *Hydrobiologia* 393: 1-10.

Mauritsen, T., Stevens, B., Roeckner, E., Crueger, T., Esch, M., Giorgetta, M. et al. (2012). Tuning the climate of a global model. Journal of Advances in Modeling Earth Systems 4(3). https://doi.org/0.1029/2012MS000154.

Meehl, G. A., Goddard, L., Murphy, J., Stouffer, R. J., Boer, G., Danabasoglu, G. et al. (2009). Decadal prediction: Can it be skillful? Bulletin of the American Meteorological Society 90(10), 1467-1486. https://doi.org/10.1175/2009BAMS2778.1.

Meehl, G., Stocker, T., Collins, W., Friedlingstein, P., Gaye, A., Gregory, J. et al. (2007). "Global Climate Projections." In Climate Change 2007: the Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, ed. S. Solomon et al. (Cambridge, UK and New York, USA: Cambridge University Press), 747-845.

Meehl, G. A., Washington, W. M., Ammann, C. M., Arblaster, J. M., Wigley, T. M. L., and Tebaldi, C. (2004). Combinations of natural and anthropogenic forcings in twentieth-century climate. Journal of Climate 17(19), 3721-3727. https://doi.org/10.1175/1520-0442(2004)017<3721:CONAAF>2.0.CO;2.

Meier, H.E.M. (2002a). Regional ocean climate simulations with a 3D ice-ocean model for the Baltic Sea. Part 1: Model experiments and results for temperature and salinity. Climate Dynamics 19(3-4), 237-253. https://doi.org/10.1007/s00382-001-0224-6.

Meier, H.E.M. (2002b). Regional ocean climate simulations with a 3D ice-ocean model for the Baltic Sea. Part 2: Results for sea ice. Climate Dynamics 19(3-4), 255-266. https://doi.org/10.1007/s00382-001-0225-5.

Meier, H. E. M. (2006). Baltic Sea climate in the late twenty-first century: a dynamical downscaling approach using two global models and two emission scenarios. Climate Dynamics 27(1), 39-68. https://doi.org/10.1007/s00382-006-0124-x.

Meier, H. E. M. (2007). Modeling the pathways and ages of inflowing salt-and freshwater in the Baltic Sea. Estuarine, Coastal and Shelf Science 74(4), 610-627. https://doi.org/10.1016/j.ecss.2007.05.019.

Meier H.E.M. (2015) Projected Change—Marine Physics. In: The BACC II Author Team (eds) Second Assessment of Climate Change for the Baltic Sea Basin. Regional Climate Studies. Springer.

Meier, H.E.M., and F. Kauker (2002). Simulating Baltic Sea climate for the period 1902-1998 with the Rossby Centre coupled ice-ocean model. Reports Oceanography No.30, SMHI, Norrköping, Sweden, 111 pp.

Meier, H. E. M., and Kauker, F. (2003a). Modeling decadal variability of the Baltic Sea: 2. Role of freshwater inflow and large-scale atmospheric circulation for salinity. Journal of Geophysical Research - Oceans 108(C11), https://doi.org/10.1029/2003JC001799.

Meier, H. E. M., and Kauker, F. (2003b). Sensitivity of the Baltic Sea salinity to the freshwater supply. Climate Research 24(3), 231-242. https://doi.org/10.3354/cr024231.

Meier, H. E. M., Andersson, H. C., Eilola, K., Gustafsson, B. G., Kuznetsov, I., Müller-Karulis, B., et al. (2011b). Hypoxia in future climates: A model ensemble study for the Baltic Sea. Geophysical Research Letters 38(24), L24608. https://doi.org/10.1029/2011GL049929.

Meier, H. E. M., Andersson, H. C., Arheimer, B., Blenckner, T., Chubarenko, B., Donnelly, C., et al. (2012c). Comparing reconstructed past variations and future projections of the Baltic Sea ecosystem – first results from multi-model ensemble simulations. Environmental Research Letters 7(3), 034005. https://doi.org/10.1088/1748-9326/7/3/034005.

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

Meier, H. E. M., Broman, B., and Kjellström, E. (2004). Simulated sea level in past and future climates of the Baltic Sea, Clim Res, 27, 59–75, https://doi.org/10.3354/cr02705904

Meier, H. E. M., C. Dieterich, K. Eilola, M. Gröger, A. Höglund, H. Radtke, S. Saraiva, and I. Wåhlström, 2019d: Future projections of record-breaking sea surface temperature and cyanobacteria bloom events in the Baltic Sea. AMBIO, in press

Meier, H. E. M., Döscher, R., and Faxén, T. (2003). A multiprocessor coupled ice-ocean model for the Baltic Sea: Application to salt inflow. Journal of Geophysical Research - Oceans 108(C8). https://doi.org/10.1029/2000JC000521.

Meier, H. E. M., Edman, M., Eilola, K., Placke, M., Neumann, T., Andersson, H. et al. (2018a). Assessment of eutrophication abatement scenarios for the Baltic Sea by multi-model ensemble simulations. Frontiers in Marine Science, 5:440. https://doi.org/10.3389/fmars.2018.00440.

Meier, H. E. M., M. Edman, K. Eilola, M. Placke, T. Neumann, H. Andersson, S.-E. Brunnabend, C. Dieterich, C. Frauen, R. Friedland, M. Gröger, B. G. Gustafsson, E. Gustafsson, A. Isaev, M. Kniebusch, I. Kuznetsov, B. Müller-Karulis, M. Naumann, A. Omstedt, V. Ryabchenko, S. Saraiva, and O. P. Savchuk (2019c). Assessment of uncertainties in scenario simulations of biogeochemical cycles in the Baltic Sea. Frontiers in Marine Science, 6:46, https://doi.org/10.3389/fmars.2019.00046

Meier, H. E. M., Eilola, K., and Almroth, E. (2011a). Climate-related changes in marine ecosystems simulated with a three-dimensional coupled biogeochemical-physical model of the Baltic Sea. Climate Research 48(1), 31-55. https://doi.org/10.3354/cr00968.

Meier, H. E. M., Eilola, K., Almroth-Rosell, E., Schimanke, S., Kniebusch, M., Höglund, A. et al. (2019a). Disentangling the impact of nutrient load and climate changes on Baltic Sea hypoxia and eutrophication since 1850. Dynamics, 53:1145-1166, https://doi.org/10.1007/s00382-018-4296-y

Meier, H. E. M., Eilola, K., Almroth-Rosell, E., Schimanke, S., Kniebusch, M., Höglund, A. et al. (2019b). Correction to: Disentangling the impact of nutrient load and climate changes on Baltic Sea hypoxia and eutrophication since 1850. 53:1167-1169, https://doi.org/10.1007/s00382-018-4483-x

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

Meier, H. E. M., Höglund, A., Eilola, K., and Almroth-Rosell, E. (2017). Impact of accelerated future GMSL rise on hypoxia in the Baltic Sea. Climate Dynamics 49(1-2), 163-172. https://doi.org/10.1007/s00382-016-3333-y.

Meier, H. E. M., Hordoir, R., Andersson, H., Dieterich, C., Eilola, K., Gustafsson, B. G., et al. (2012a). 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. Climate Dynamics 39(9-10), 2421-2441. https://doi.org/10.1007/s00382-012-1339-7.

Meier, H. E. M., Kjellström, E., and Graham, L. P. (2006). Estimating uncertainties of projected Baltic Sea salinity in the late 21st century. Geophysical Research Letters. 33(15), L15705. https://doi.org/10.1029/2006GL026488.

Meier, H. E. M., Müller-Karulis, B., Andersson, H. C., Dieterich, C., Eilola, K., Gustafsson, B. G. et al. (2012b). Impact of climate change on ecological quality indicators and biogeochemical fluxes in the Baltic Sea: a multi-model ensemble study. Ambio 41(6), 558-573. https://doi.org/10.1007/s13280-012-0320-3.

Meier, H. E. M., Väli, G, Naumann, M., Eilola, K., and Frauen, C. (2018b). Recently accelerated oxygen consumption rates amplify deoxygenation in the Baltic Sea. Journal of Geophysical Research – Oceans 123(5), 3227-3240. https://doi.org/10.1029/2017JC013686.

Mercer, J. H. (1978). West Antarctic ice sheet and CO2 greenhouse effect: a threat of disaster, Nature, 271, 321–325

Merkouriadi, I., & Leppäranta, M. (2014). Long-term analysis of hydrography and sea-ice data in Tvärminne, Gulf of Finland, Baltic Sea. Climatic change, 124(4), 849-859.

Mitchell, J.F.B., and Johns, T.C. (1997). On modification of global warming by sulfate aerosols. Journal of Climate 10(2), 245–267. https://doi.org/10.1175/1520-0442(1997)010<0245:OMOGWB>2.0.CO;2.

Mohrholz V, Dutz J, Kraus G (2006) The impact of exceptionally warm summer inflow events on the environmental conditions in the Bornholm Basin. J Mar Sys 60:285-301

Mohrholz, V. (2018). Major Baltic Inflow Statistics – Revised. Frontiers in Marine Science 5, 384. https://doi.org/10.3389/fmars.2018.00384.

Mokhov, I. I., M. G. Akperov, M. A. Prokofyeva, A. V. Timazhev, A. R. Lupo, and H. Le Treut (2013): Blockings in the Northern Hemisphere and Euro-Atlantic region: Estimates of changes from reanalyses data and model simulations. Doklady, Earth Sci., 449, 430-433.

Mörth, C.-M., Humborg, C., Eriksson, E., Danielsson, A., Medina, R., Löfgren, S. et al. (2007). Modeling riverine nutrient transport of the Baltic Sea: a large-scale approach. Ambio 36(2-3), 124-133. https://doi.org/10.1579/0044-7447(2007)36[124:MRNTTT]2.0.CO;2.

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

Müller, J. D., Schneider, B., and Rehder, G. (2016). Long-term alkalinity trends in the Baltic Sea and their implications for CO2-induced acidification. Limnology and Oceanography 61(6), 1984-2002. https://doi.org/10.1002/lno.10349.

Murray Ciarán J., Müller-Karulis Bärbel, Carstensen Jacob, Conley Daniel J., Gustafsson Bo G., Andersen Jesper H. (2019). Past, Present and Future Eutrophication Status of the Baltic Sea. Frontiers in Marine Science. doi:10.3389/fmars.2019.00002

Musielak, S., Furmanczyk, K., Bugajny, N. (2017): Factors and processes forming the Polish southern Baltic Sea coast on various temporal and spatial scales. In: Harff J, Furmanczyk K, von Storch H (eds) Coastline changes of the Baltic Sea from south to east – past and future projection. Coastal research library, vol 19. Springer, Cham, pp 69–86.

Myhre, G., Highwood, E. J., Shine, K. P., and Stordal, F. (1998). New estimates of radiative forcing due to well mixed greenhouse gases. Geophysical Research Letters 25(14), 2715-2718. https://doi.org/10.1029/98GL01908.

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J. et al. (2013). “Anthropogenic and natural radiative forcing. Anthropogenic and natural radiative forcing.”, in Climate Change 2013: The Physical Science Basis. IPCC Working Group I Contribution to IPCC AR5, ed. T.F. Stocker et al. (Cambridge, UK and New York, USA: Cambridge University Press), 659-740, https://doi.org/10.1017/CBO9781107415324.018.

Myrberg, K., Ryabchenko, V., Isaev, A., Vankevich, R., Andrejev, O., Bendtsen, J. et al. (2010). Validation of three-dimensional hydrodynamic models of the Gulf of Finland. Boreal Environmental Research, 15, 453-479.

Nakićenović, N., Alcamo, J., Grubler, A., Riahi, K., Roehrl, R., Rogner, H.-H. et al. (2000). Special report on emissions scenarios (SRES), a special report of Working Group III of the intergovernmental panel on climate change. Cambridge University Press. 27.

Nehring, D., & Matthäus, W. (1991). Current trends in hydrographic and chemical parameters and eutrophication in the Baltic Sea. *Internationale Revue der gesamten Hydrobiologie und Hydrographie*, *76*(3), 297-316.

Neumann, T. (2010). Climate-change effects on the Baltic Sea ecosystem: A model study. Journal of Marine Systems 81(3), 213-224. https://doi.org/10.1016/j.jmarsys.2009.12.001.

Neumann T, Friedland R (2011) Climate change impacts on the Baltic Sea. In: Schernewski G, Hofstede J, Neumann T (eds), Global Change and Baltic Coastal Zones. Springer Science+Business Media (Coastal Research Library 1:23-32)

Neumann, T., Eilola, K., Gustafsson, B., Müller-Karulis, B., Kuznetsov, I., Meier, H. E. M., et al. (2012). Extremes of temperature, oxygen and blooms in the Baltic Sea in a changing climate. Ambio 41(6), 574-585. https://doi.org/10.1007/s13280-012-0321-2.

Neumann, T., Fennel, W., and Kremp, C. (2002). Experimental simulations with an ecosystem model of the Baltic Sea: a nutrient load reduction experiment. Global Biogeochemical Cycles, 16(3), 7-1-7-19. https://doi.org/10.1029/2001GB001450.

Neumann, T., Radtke, H., & Seifert, T. (2017). On the importance of M ajor B altic I nflows for oxygenation of the central B altic S ea. Journal of Geophysical Research: Oceans, 122(2), 1090-1101.

Nielsen JR, Thunberg E, Holland DS, et al. Integrated ecological–economic fisheries models—Evaluation, review and challenges for implementation. Fish and Fisheries. 2017;00:1–29. https://doi.org/10.1111/faf.12232.

Niiranen, S., Yletyinen, J., Tomczak, M. M., Blenckner, T., Hjerne, O., MacKenzie, B. et al. (2013). Combined effects of global climate change and regional ecosystem drivers on an exploited marine food web. Global Change Biology 19(11), 3327-3342. https://doi.org/10.1111/gcb.12309.

Nikulin, G., Kjellström, E., Hansson, U. L. F., Strandberg, G., and Ullerstig, A. (2011). Evaluation and future projections of temperature, precipitation and wind extremes over Europe in an ensemble of regional climate simulations. Tellus A: Dynamic Meteorology and Oceanography 63(1), 41-55. https://doi.org/10.1111/j.1600-0870.2010.00466.x.

Ning, W., Ghosh, A., Jilbert, T., Slomp, C. P., Khan, M., Nyberg, J., ... & Filipsson, H. L. (2016). Evolving coastal character of a Baltic Sea inlet during the Holocene shoreline regression: impact on coastal zone hypoxia. Journal of Paleolimnology, 55(4), 319-338

Norman, M., Rutgersson, A., and Sahlée, E. (2013). Impact of improved air-sea gas transfer velocity on fluxes and water chemistry in a Baltic Sea model. Journal of Marine Systems 111, 175-188. https://doi.org/10.1016/j.jmarsys.2012.10.013.

Oikkonen, A. (2017). *Evolution of sea ice cover: Result of interplay between dynamics and thermodynamics*. Finnish Meteorological Institute.

Omstedt, A. (2017). "The Development of Climate Science of the Baltic Sea Region.", in: Oxford Research Encyclopedia of Climate Science (Oxford University Press). https://doi.org/10.1093/acrefore/9780190228620.013.654.

Omstedt, A., and Chen, D. (2001). Influence of atmospheric circulation on the maximum ice extent in the Baltic Sea. Journal of Geophysical Research - Oceans 106(C3), 4493-4500. https://doi.org/10.1029/1999JC000173.

Omstedt, A., and Hansson, D. (2006a). The Baltic Sea ocean climate system memory and response to changes in the water and heat balance components. Continental Shelf Research 26(2), 236-251. https://doi.org/10.1016/j.csr.2005.11.003.

Omstedt, A., and Hansson, D. (2006b). Erratum to:"The Baltic Sea ocean climate system memory and response to changes in the water and heat balance components":[Continental Shelf Research 26 (2)(2006) 236--251]. Continental Shelf Research 26, 1685-1687. https://doi.org/10.1111/j.1600-0870.2004.00070.x.

Omstedt, A., and Nohr, C. (2004). Calculating the water and heat balances of the Baltic Sea using ocean modelling and available meteorological, hydrological and ocean data. Tellus A: Dynamic Meteorology and Oceanography 56(4), 400-414. https://doi.org/10.3402/tellusa.v56i4.14428.

Omstedt, A., Chen, Y., and Wesslander, K. (2005). A comparison between the ERA40 and the SMHI gridded meteorological databases as applied to Baltic Sea modelling. Hydrology Research 36(4-5), 369-380.

Omstedt, A., Edman, M., Claremar, B., Frodin, P., Gustafsson, E., Humborg, C., et al. (2012). Future changes in the Baltic Sea acid–base (pH) and oxygen balances. Tellus B: Chemical and Physical Meteorology 64(1), 19586. https://doi.org/10.3402/tellusb.v64i0.19586.

Omstedt, A., Edman, M., Claremar, B., and Rutgersson, A. (2015). Modelling the contributions to marine acidification from deposited SOx, NOx, and NHx in the Baltic Sea: Past and present situations. Continental Shelf Research 111, 234-249. https://doi.org/10.1016/j.csr.2015.08.024.

Omstedt, A., Elken, J., Lehmann, A., and Piechura, J. (2004). Knowledge of the Baltic Sea physics gained during the BALTEX and related programmes. Progress in Oceanography 63(1-2), 1-28. https://doi.org/10.1016/j.pocean.2004.09.001.

Omstedt, A., Gustafsson, B., Rodhe, J., and Walin, G. (2000). Use of Baltic Sea modelling to investigate the water cycle and the heat balance in GCM and regional climate models. Climate Research 15(2), 95-108. https://doi.org/10.3354/cr015095.

Omstedt, A., Gustafsson, E., and Wesslander, K. (2009). Modelling the uptake and release of carbon dioxide in the Baltic Sea surface water. Continental Shelf Research 29(7), 870-885. https://doi.org/10.1016/j.csr.2009.01.006.

Omstedt, A., Humborg, C., Pempkowiak, J., Perttilä, M., Rutgersson, A., Schneider, B. et al. (2014). Biogeochemical control of the coupled CO2–O2 system of the Baltic Sea: a review of the results of Baltic-C. Ambio 43(1), 49-59.

https://doi.org/10.1007/s13280-013-0485-4.

O’Neill, B. C., Kriegler, E., Riahi, K., Ebi, K. L., Hallegatte, S., Carter, T. R. et al. (2014). A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Climatic Change 122(3), 387-400. https://doi.org/10.1007/s10584-013-0905-2.

O'Neill, B. C., Tebaldi, C., van Vuuren, D.P., Eyring, V., Friedlingstein, P., Hurtt, G., et al. (2016). The scenario model intercomparison project (ScenarioMIP) for CMIP6. Geoscientific Model Development 9(9), 3461-3482. https://doi.org/10.5194/gmd-9-3461-2016.

Papadomanolaki, N. M., Dijkstra, N., Van Helmond, N. A., Hagens, M., Bauersachs, T., Kotthoff, U., ... & Slomp, C. P. (2018). Controls on the onset and termination of past hypoxia in the Baltic Sea. Palaeogeography, Palaeoclimatology, Palaeoecology, 490, 347-354.

Parker, W.S. (2013). Ensemble modeling, uncertainty and robust predictions. Wiley Interdisciplinary Reviews: Climate Change 4:213–223. https:/doi.org/10.1002/wcc.220.Pushpadas, D., Schrum, C., and Daewel, U. (2015). Projected climate change impacts on North Sea and Baltic Sea: CMIP3 and CMIP5 model based scenarios. Biogeosciences Discussions 12(15). https://doi.org/10.5194/bgd-12-12229-2015.

Pemberton, P., Löptien, U., Hordoir, R., Höglund, A., Schimanke, S., Axell, L., & Haapala, J. (2017). Sea-ice evaluation of NEMO-Nordic 1.0: a NEMO–LIM3. 6-based ocean–sea-ice model setup for the North Sea and Baltic Sea. *Geoscientific Model Development*, *10*(8), 3105.

Placke, M., H. E. M. Meier, U. Gräwe, T. Neumann, C. Frauen and Y. Liu, 2018: Long-term mean circulation of the Baltic Sea as represented by various ocean circulation models. Frontiers in Marine Science, 5:287. https://doi.org/10.3389/fmars.2018.00287

Radach, G., and Pätsch, J. (1997). Climatological annual cycles of nutrients and chlorophyll in the North Sea. Journal of Sea Research 38(3-4), 231-248. https://doi.org/10.1016/S1385-1101(97)00048-8.

Radtke, H., and Maar, M. (2016). Estimating the effective nitrogen import: An example for the North Sea-Baltic Sea boundary. Journal of Geophysical Research - Biogeosciences 121(10), 2562-2575. https://doi.org/10.1002/2016JG003516.

Räisänen, J. (2001). CO2-induced climate change in CMIP2 experiments: Quantification of agreement and role of internal variability. Journal of Climate 14(9), 2088-2104. https://doi.org/10.1175/1520-0442(2001)014<2088:CICCIC>2.0.CO;2.

Räisänen, J. (2017). “Future Climate Change in the Baltic Sea Region and Environmental Impacts.” in Oxford Research Encyclopedia of Climate Science (Oxford University Press), 37. https://doi.org/10.1093/acrefore/9780190228620.013.634.

Räisänen, J., Hansson U., Ullerstig A., Döscher R., Graham L.P., Jones C. et al. (2004). European climate in the late twenty-first century: regional simulations with two driving global models and two forcing scenarios. Climate Dynamics 22(13), 13-31. https://doi.org/10.1007/s00382-003-0365-x.

Räisänen, J., Rummukainen, M., and Ullerstig, A. (2001). Downscaling of greenhouse gas induced climate change in two GCMs with the Rossby Centre regional climate model for northern Europe. Tellus A: Dynamic Meteorology and Oceanography 53(2), 168–191. https://doi.org/10.1034/j.1600-0870.2001.00168.x.

Rahmstorf, S., & Coumou, D. (2011). Increase of extreme events in a warming world. *Proceedings of the National Academy* *of Sciences of the United States of America*, *108*(44), 17905–17909. doi:10.1073/pnas.1101766108

Raschke, E., Meywerk, J., Warrach, K., Andrea, U., Bergström, S., Beyrich, F. et al. (2001). The Baltic Sea Experiment (BALTEX): a European contribution to the investigation of the energy and water cycle over a large drainage basin. Bulletin of the American Meteorological Society 82(11), 2389-2413. https://doi.org/10.1175/1520-0477(2001)082<2389:TBSEBA>2.3.CO;2.

Rechid, D., Meier, H. E. M., Schrum, C., Rummukainen, M., Moseley, C., Bülow, K., Elizalde, A., Su, J., and Pohlmann, T. (2016). Annex 2: Climate Model Simulations for the North Sea Region, in: Quante, M., and Colijn, F. (eds.), North Sea Region Climate Change Assessment, Regional Climate Studies. https://doi.org/10.1007/978-3-319-39745-0.

Reed, D. C., Gustafsson, B. G., and Slomp, C. P. (2016). Shelf-to-basin iron shuttling enhances vivianite formation in deep Baltic Sea sediments. Earth and Planetary Science Letters 434, 241-251. https://doi.org/10.1016/j.epsl.2015.11.033.

Reihan A, Koltsova T, Kriaučiūnienė J, Lizuma L, Meilutytė-Barauskienė D (2007) Changes in water discharges of the Baltic states rivers in the 20th century and its relation to climate change. *Nordic Hydrology* 38:401-412

Reissmann, J. H., Burchard, H., Feistel, R., Hagen, E., Lass, H. U., Mohrholz, V. et al. (2009). Vertical mixing in the Baltic Sea and consequences for eutrophication - A review. Progress in Oceanography 82(1), 47-80. https://doi.org/10.1016/j.pocean.2007.10.004.

Reusch, Thorsten B. H. and Dierking, Jan and Andersson, Helen C. and Bonsdorff, Erik and Carstensen, Jacob and Casini, Michele and Czajkowski, Mikolaj and Hasler, Berit and Hinsby, Klaus and Hyytiäinen, Kari and Johannesson, Kerstin and Jomaa, Seifeddine and Jormalainen, Veijo and Kuosa, Harri and Kurland, Sara and Laikre, Linda and MacKenzie, Brian R. and Margonski, Piotr and Melzner, Frank and Oesterwind, Daniel and Ojaveer, Henn and Refsgaard, Jens Christian and Sandström, Annica and Schwarz, Gerald and Tonderski, Karin and Winder, Monika and Zandersen, Marianne. 2018. The Baltic Sea as a time machine for the future coastal ocean. Science Advances, 4(5), https://doi.org/10.1126/sciadv.aar8195

Rex, D. F. (1950a): Blocking action in the middle troposphere and its effect upon regional climate. Part I: An aerological study of blocking action. Tellus, 2:196-211.

Rex, D. F. (1950b): Blocking action in the middle troposphere and its effect upon regional climate. Part II: The climatology of blocking action. Tellus, 2:275-301.

Ribeiro, A., Barbosa, S. M., Scotto, M. G., & Donner, R. V. (2014). Changes in extreme sea-levels in the Baltic Sea. Tellus A: Dynamic Meteorology and Oceanography, 66(1), 20921.

Richter, A., Groh, A., and Dietrich, R. (2012). Geodetic observation of sea-level change and crustal deformation in the Baltic Sea region. Physics and Chemistry of the Earth, Parts A/B/C, 53-54, 43–53, https://doi.org/ https://doi.org/10.1016/j.pce.2011.04.011

Riemann, B., Carstensen, J., Dahl, K. et al. (2016). Recovery of Danish Coastal Ecosystems After Reductions in Nutrient Loading: A Holistic Ecosystem Approach. Estuaries and Coasts 39: 82. https://doi.org/10.1007/s12237-015-9980-0

Rimkus, E., Kažys, J., Valiukas, D., & Stankūnavičius, G. (2014). The atmospheric circulation patterns during dry periods in Lithuania. Oceanologia, 56(2), 223-239.

Rockel, B. (2015). The regional downscaling approach: a brief history and recent advances. Current Climate Change Reports

1(1), 22-29. https://doi.org/10.1007/s40641-014-0001-3.

Roeckner, E., Bengtsson, L., Feicther, J., Lelieveld, J., and Rodhe, H. (1999). Transient climate change simulations with a coupled atmosphere-ocean GCM including the tropospheric sulfur cycle. Journal of climate 12(10), 3004–3032. https://doi.org/10.1175/1520-0442(1999)012<3004:TCCSWA>2.0.CO;2.

Roeckner, E., Brokopf, R., Esch, M., Giorgetta, M., Hagemann, S., and Kornblueh, S. (2006). Sensitivity of simulated climate to horizontal and vertical resolution in the ECHAM5 atmosphere model. Journal of climate 19(16), 3771–3791. https://doi.org/10.1175/JCLI3824.1.

Ronkainen, I. (2013). Long-term changes in Baltic Sea ice conditions. Master Thesis, University of Helsinki.

Rose, K. A., Allen, J. I., Artioli, Y., Barange, M., Blackford, J., Carlotti, F. et al. (2010). End-to-end models for the analysis of marine ecosystems: challenges, issues, and next steps. Marine and Coastal Fisheries 2(1), 115-130. https://doi.org/10.1577/C09-059.1.

Rukšėnienė, V., Dailidienė, I., Kelpšaitė-Rimkienė, L., & Soomere, T. (2017). Sea surface temperature variations in the south-eastern BalticSea in 1960-2015. *Baltica*, *30*(2).

Rummukainen, M. (2010). State-of-the-art with Regional Climate Models. Wiley Interdisciplinary Reviews: Climate Change 1(1), 82-96. https://doi.org/10.1002/wcc.8.

Rummukainen, M. (2016a). Added value in regional climate modeling. Wiley Interdisciplinary Reviews: Climate Change 7(1), 145–159. https://doi.org/10.1002/wcc.378.

Rummukainen, M. (2016b). “Annex 3: Uncertainties in Climate Change Projections”. in North Sea Region Climate Change Assessment, ed. M. Quante and F. Colijn (Switzerland: Springer), 505-513. https://doi.org/10.1007/978-3-319-39745-0.

Rummukainen M., Räisänen J., Bringfelt B., Ullerstig A., Omstedt A., Willén U. et al. (2001). A regional climate model for northern Europe - model description and results from the downscaling of two GCM control simulations. Climate Dynamics 17(5-6), 339–359. https://doi.org/10.1007/s003820000109.

Rummukainen, M., Rockel, B., Bärring, L., Christensen, J. H., and Reckermann, M. (2015). Twenty-first-century challenges in regional climate modeling. Bulletin of the American Meteorological Society 96(8), ES135-ES138. https://doi.org/10.1175/BAMS-D-14-00214.1.

Ruosteenoja, K., Jylhä, K., and Kämäräinen, M. (2016). Climate projections for Finland under the RCP forcing scenarios. Geophysica 51, 17 – 50.

Ryabchenko, V., Karlin, L., Isaev, A., Vankevich, R., Eremina, T., Molchanov, M. et al. (2016). Model estimates of the eutrophication of the Baltic Sea in the contemporary and future climate. Oceanology 56(1), 36-45. https://doi.org/10.1134/S0001437016010161.

Samuelsson, M. and Stigebrandt, A. (1996). Main characteristics of the long-term sea level variability in the Baltic sea, Tellus A, 48, 672–683, https://doi.org/10.1034/j.1600-0870.1996.t01- 4-00006.x

Samuelsson, P., Jones, C. G., Willén, U., Ullerstig, A., Gollvik, S., Hansson, U. et al. (2011). The Rossby Centre Regional Climate model RCA3: model description and performance. Tellus A: Dynamic Meteorology and Oceanography 63(1), 4-23. https://doi.org/10.1111/j.1600-0870.2010.00478.x.

Saraiva, S., Meier, H. E. M., Andersson, H., Höglund, A., Dieterich, C., Hordoir, R. et al. (2019a). Baltic Sea ecosystem response to various nutrient load scenarios in present and future climates. Climate Dynamics, 52:3369. https://doi.org/10.1007/s00382-018-4330-0.

Saraiva S., Meier, H. E. M., Andersson, H. C., Höglund, A., Dieterich, C., Gröger, M., Hordoir, R., and Eilola, K. (2019b). Uncertainties in projections of the Baltic Sea ecosystem driven by an ensemble of global climate models. Frontiers in Earth Science, Frontiers in Earth Science, 6:244, https://doi.org/10.3389/feart.2018.00244

Särkkä, J., Kahma, K. K., Kämäräinen, M., & Johansson, M. M. (2016). Simulating sea level variations in the Baltic Sea using regional climate scenarios. *Multiple drivers for Earth system changes in the Baltic Sea region*, 131.

Savchuk, O. P. (2002). Nutrient biogeochemical cycles in the Gulf of Riga: scaling up field studies with a mathematical model. Journal of Marine Systems 32(4), 253-280. https://doi.org/10.1016/S0924-7963(02)00039-8.

Savchuk, O. P. (2018). Large-Scale Nutrient Dynamics in the Baltic Sea, 1970–2016. Frontiers in Marine Science 5, 95. https://doi.org/10.3389/fmars.2018.00095.

Savchuk, O. P., Gustafsson, B. G., Medina, M.R., Sokolov, A., and Wulff, F. (2012b). External nutrient loads to the Baltic Sea, 1970-2006. Baltic Nest Institute Technical Report No. 5, 22.

Savchuk, O. P., Gustafsson, B. G., and Müller-Karulis, B. (2012a). BALTSEM: A marine model for decision support within the Baltic Sea Region. Baltic Nest Institute Technical Report No. 7, 55.

Savchuk, O., and Wulff, F. (1999). "Modelling regional and large-scale response of Baltic Sea ecosystems to nutrient load reductions." in Biological, Physical and Geochemical Features of Enclosed and Semi-enclosed Marine Systems, ed. E.M. Blomqvist (Dordrecht: Springer) 35-43. https://doi.org/10.1007/978-94-017-0912-5_5.

Schernewski, G., Friedland, R., Carstens, M., Hirt, U., Leujak, W., Nausch, G. et al. (2015). Implementation of European marine policy: New water quality targets for German Baltic waters. Marine Policy 51, 305-321. https://doi.org/10.1016/j.marpol.2014.09.002.

Schimanke, S., Dieterich, C., and Meier, H. E. M. (2014). An algorithm based on sea-level pressure fluctuations to identify major Baltic inflow events. Tellus A: Dynamic Meteorology and Oceanography 66(1), 23452. https://doi.org/10.3402/tellusa.v66.23452.

Schimanke, S., and Meier, H. E. M. (2016). Decadal-to-Centennial Variability of Salinity in the Baltic Sea. Journal of Climate 29(20), 7173-7188. https://doi.org/10.1175/JCLI-D-15-0443.1.

Schinke, H., & Matthäus, W. (1998). On the causes of major Baltic inflows—an analysis of long time series. *Continental Shelf Research*, *18*(1), 67-97.

Schmidt, G. A., Bader, D., Donner, L. J., Elsaesser, G. S., Golaz, J.-C., Hannay, C. et al. (2017). Practice and philosophy of climate model tuning across six US modeling centers. Geoscientific Model Development 10(9), 3207-3223. https://doi.org/10.5194/gmd-10-3207-2017.

Schrum, C. (1997). A coupled ice–ocean model for the North Sea and the Baltic Sea, in "Sensitivity of North Sea, Baltic Sea and Black Sea to Anthropogenic and Climatic Changes", in NATO ASI Series, ed. E. Özsoy, and A. Mikaelyan, A., (Dordrecht, Boston: Kluwer Academic Publishers), 311–325.

Kommentiert [m43]: Referenz?

Schrum, C. (2017). “Regional Climate Modeling and Air-Sea Coupling.” in Oxford Research Encyclopedia of Climate Science (Oxford University Press). https://doi.org/10.1093/acrefore/9780190228620.013.3.

Schrum, C., Lowe, J., Meier, H. E. M., Grabemann, I., Holt, J., Mathis M. et al. (2016). “Projected Change - North Sea.” in North Sea Region Climate Change Assessment, ed. M. Quante and F. Colijn (Switzerland: Springer), 175-217. https://doi.org/10.1007/978-3-319-39745-0.

Sein, D. V., Mikolajewicz, U., Gröger, M., Fast, I., Cabos, W., Pinto, J. G., et al. (2015). Regionally coupled atmosphere-ocean-sea ice-marine biogeochemistry model ROM: 1. Description and validation. Journal of Advances in Modeling Earth Systems 7(1), 268-304. https://doi.org/10.1002/2014MS000357.

Seitola, T., Ukkonen, P., Karpechko, A., Ruosteenoja, K., and Gregow, H. (2015). Co-variability of North Atlantic Oscillation and Maximum Sea Ice Extent in the Baltic Sea in CMIP5 Climate Models. OTC Arctic Technology Conference. https://doi.org/10.4043/25596-MS.

Sepp, M., Post, P., and Jaagus, J. (2005). Long-term changes in the frequency of cyclones and their trajectories in Central and Northern Europe. Hydrology Research 36(4-5), 297-309. https://doi.org/10.2166/nh.2005.002.

Sepp, M., Post, P., Mändla, K., and Aunap, R. (2018). On cyclones entering the Baltic Sea region. Boreal Environment Research, 23, 1-14.

Skogen, M. D., Søiland, H., and Svendsen, E. (2004). Effects of changing nutrient loads to the North Sea. Journal of Marine Systems 46(1-4), 23-38. https://doi.org/10.1016/j.jmarsys.2003.11.013.

Smith, D. M., Cusack, S., Colman, A. W., Folland, C. K., Harris, G. R., and Murphy, J. M. (2007). Improved surface temperature prediction for the coming decade from a global climate model. Science, 317(5839), 796-799, https://doi.org/10.1126/science.1139540.

Södling, J. and Nerheim, S. (2016). Statistisk metodik för beräkning av dimensionerande havsvattenstånd, Report, SMHI

Soomere, T., & Räämet, A. (2014). Decadal changes in the Baltic Sea wave heights. Journal of Marine Systems, 129, 86-95.

Soomere, T., Bishop, S. R., Viska, M., & Räämet, A. (2015). An abrupt change in winds that may radically affect the coasts and deep sections of the Baltic Sea. Climate Research, 62(2), 163-171.

Kommentiert [m44]: Relevant?

Stahl, K., H. Hisdal, J. Hannaford, L. Tallaksen, H. Van Lanen, E. Sauquet, S. Demuth, M. Fendekova, and J. Jordar (2010), Streamflow trends in Europe: evidence from a dataset of near-natural catchments, *Hydrology and Earth System Sciences*, *14*, p–2367.

Kommentiert [m45]: ????

Stålnacke, P., Grimvall, A., Sundblad, K., and Tonderski, A. (1999). Estimation of riverine loads of nitrogen and phosphorus to the Baltic Sea 1970–1993. Environmental Monitoring and Assessment 58(2), 73–200. https://doi.org/10.1023/A:1006073015871.

Stålnacke, P., Pengerud, A., Vassiljev, A., Smedberg, E., Mörth, C. M., Hägg, H. E., ... & Andersen, H. E. (2015). Nitrogen surface water retention in the Baltic Sea drainage basin. Hydrology and Earth System Sciences, 19(2), 981-996.

Kommentiert [m46]: Relevant?

Stocker, T., Qin, D., Plattner, G.-K., Alexander, L., Allen, S., Bindoff, N. et al. (2013). “Technical summary”, in Climate Change 2013: the Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the

Intergovernmental Panel on Climate Change, ed. T. Stocker, et al. (Cambridge: Cambridge University Press). 33-115. https://doi.org/10.1017/CBO9781107415324.

Stonevičius, E., Valiuškevičius, G., Rimkus, E., & Kažys, J. (2014). Climate induced changes of Lithuanian rivers runoff in 1960–2009. Water resources, 41(5), 592-603.

Stramska, M., & Białogrodzka, J. (2015). Spatial and temporal variability of sea surface temperature in the Baltic Sea based on 32-years (1982–2013) of satellite data. Oceanologia, 57(3), 223-235.

Strandberg, Gustav et al. (2014) CORDEX scenarios for Europe from the Rossby Centre regional climate model RCA4, report RMK 116

Suikkanen, S., Pulina, S., Engström-Öst, J., Lehtiniemi, M., and Lehtinen, S. (2013). Climate Change and Eutrophication Induced Shifts in Northern Summer Plankton Communities. PLoS ONE 8(6), e66475. https://doi.org/10.1371/journal.pone.0066475.

Surkova, G. V., Arkhipkin, V. S., & Kislov, A. V. (2015). Atmospheric circulation and storm events in the Baltic Sea. Open Geosciences, 7(1).

Suursaar, Ü., Alari, V., & Tõnisson, H. (2014). Multi-scale analysis of wave conditions and coastal changes in the north-eastern Baltic Sea. Journal of Coastal Research, 70(sp1), 223-228.

Suursaar, Ü., and Sooäär, J. (2007). 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

Sweet, W. V., Horton, R., Kopp, R. E., LeGrande, A. N., and Romanou, A. (2017). Sea level rise, in: Climate Science Special Report: Fourth National Climate Assessment, Volume I, edited by Wuebbles, D. J., Fahey, D. W., Hibbard, K. A., Dokken, D. J., Stewart, B. C., and Maycock, T. K., pp. 333–363, U.S. Global Change Research Program, Washington, DC, USA, https://doi.org/10.7930/J0VM49F2

Taws SL, Marsh R, Wells NC, Hirschi J (2011) Re-emerging ocean temperature anomalies in late-2010 associated with a repeat negative NAO. Geophys Res Lett 38:10.1029/2011GL048978

Taylor, K. E., Stouffer, R. J., and Meehl, G. A. (2012). An overview of CMIP5 and the experiment design. Bulletin of the American Meteorological Society 93(4), 485-498. https://doi.org/10.1175/BAMS-D-11-00094.1.

Tian, T., Boberg, F., Christensen, O.B., Christensen, J.H., She, J., and Vihma, T. (2013). Resolved complex coastlines and land--sea contrasts in a high-resolution regional climate model: a comparative study using prescribed and modelled SSTs. Tellus A: Dynamic Meteorology and Oceanography 65(1), 19951. https://doi.org/10.3402/tellusa.v65i0.19951.

Timmermann, K., Norkko, J., Janas, U., Norkko, A., Gustafsson, B.G. and Bonsdorff, E. (2012). Modelling macrofaunal biomass in relation to hypoxia and nutrient loading. Journal of Marine Systems 105, 60-69. https://doi.org/10.1016/j.jmarsys.2012.06.001

Tinker, J., Lowe, J., Holt, J., Pardaens, A., and Wiltshire, A. (2015). Validation of an ensemble modelling system for climate projections for the northwest European shelf seas. Progress in Oceanography 138, 211-237. https://doi.org/10.1016/j.pocean.2015.07.002.

Kommentiert [m47]: Relevant? Reference?

Tinker, J., Lowe, J., Pardaens, A., Holt, J., and Barciela, R. (2016). Uncertainty in climate projections for the 21st century northwest European shelf seas. Progress in Oceanography 148, 56-73. https://doi.org/10.1016/j.pocean.2016.09.003.

Tinz, B. (1996). On the relation between annual maximum extent of ice cover in the Baltic Sea and sea level pressure as well as air temperature field. Geophysica 32(3), 319-341.

Thomas, D. N., Kaartokallio, H., Tedesco, L., Majaneva, M., Piiparinen, J., Eronen-Rasimus, E., ... & Granskog, M. A. (2017). Life associated with Baltic Sea ice. In *Biological oceanography of the Baltic Sea* (pp. 333-357). Springer, Dordrecht.

Tomczyk, A. M., & Bednorz, E. (2014). Heat and cold waves on the southern coast of the Baltic Sea. Baltica: The International Journal on Geosciences, 27(1), 45-55.

Tonisson, H., Orviku, K., Lapinskis, J., Gulbinskas, S., Zaromskis, R. (2013): The Baltic states: Estonia, Latvia and Lithuania. In: Pranzini E, Williams A (eds) Coastal erosion and protection in Europe. Routledge, London/New York, pp 47–80

Topcu, D., Behrendt, H., Brockmann, U., and Claussen, U. (2011). Natural background concentrations of nutrients in the German Bight area (North Sea). Environmental monitoring and assessment 174(1-4), 361-388. https://doi.org/10.1007/s10661-010-1463-y.

Troost, T., De Kluijver, A., and Los, F. (2014). Evaluation of eutrophication variables and thresholds in the Dutch North Sea in a historical context—a model analysis. Journal of Marine Systems 134, 45-56. https://doi.org/10.1016/j.jmarsys.2014.01.015.

Tuomi, L. (2014). On modelling surface waves and vertical mixing in the Baltic Sea. Diss. FMI.

Kommentiert [m48]: Relevant?

Turco, M., Sanna, A., Herrera, S., Llasat, M.-C., and Gutiérrez, J. M. (2013). Large biases and inconsistent climate change signals in ENSEMBLES regional projections. Climatic Change 120(4), 859-869. https://doi.org/10.1007/s10584-013-0844-y.

Ulfsbo, A., Hulth, S., and Anderson, L. G. (2011). pH and biogeochemical processes in the Gotland Basin of the Baltic Sea. Marine Chemistry 127(1-4), 20-30. https://doi.org/10.1016/j.marchem.2011.07.004.

Ulfsbo, A., Kuliński, K., Anderson, L. G., and Turner, D. R. (2015). Modelling organic alkalinity in the Baltic Sea using a Humic-Pitzer approach. Marine Chemistry 168, 18-26. https://doi.org/10.1016/j.marchem.2014.10.013.

Uppala, S. M., Kållberg, P. W., Simmons, A. J., Andrae, U., Bechtold, V. d. C., Fiorino, M., et al. (2005). The ERA40 reanalysis, Quarterly Journal of the Royal Meteorological Society, 131(612), 2961–3012. https://doi.org/10.1256/qj.04.176.

Uotila, P., Vihma, T., & Haapala, J. (2015). Atmospheric and oceanic conditions and the extremely low Bothnian Bay sea ice extent in 2014/2015. *Geophysical Research Letters*, *42*(18), 7740-7749.

Vahtera, E., Conley, D. J., Gustafsson, B. G., Kuosa, H., Pitkänen, H., Savchuk, O. P. et al. (2007). Internal ecosystem feedbacks enhance nitrogen-fixing cyanobacteria blooms and complicate management in the Baltic Sea. Ambio 36(2), 186-194. https://doi.org/10.1579/0044-7447(2007)36[186:IEFENC]2.0.CO;2.

Vahtera, E., Laanemets, J., Pavelson, J., Huttunen, M., and Kononen, K. (2005). Effect of upwelling on the pelagic environment and bloom-forming cyanobacteria in the western Gulf of Finland, Baltic Sea. Journal of Marine Systems 58(1-2), 67-82. https://doi.org/10.1016/j.jmarsys.2005.07.001.

Väli, G., H. E. M. Meier, and J. Elken, 2013: Simulated halocline variability in the Baltic Sea and its impact on hypoxia during

1961-2007. *J. Geophys. Res.*, 118, 6982-7000, doi:10.1002/2013JC009192

Van der Linden, P., and Mitchell, JFB (2009). ENSEMBLES: Climate change and its impacts-Summary of research and results from the ENSEMBLES project. Online at: http://mfkp.org/INRMM/article/14257308 and download from: https://web.archive.org/web/20170116182610/http://ensembles-eu.metoffice.com/docs/Ensembles_final_report_Nov09.pdf (15.08.2018).

Van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K. et al. (2011). The representative concentration pathways: an overview. Climatic Change 109(1-2), 5. https://doi.org/10.1007/s10584-011-0148-z.

Veijalainen N, Lotsari E, Alho P, Vehviläinen B, Käyhkö J (2010). Changes in floods in Finland due to climate change: General assessment on national scale. *J Hydrology* 391:333-350.

Vihma, T., Cheng, B., Uotila, P., Lixin, W. E. I., & Ting, Q. I. N. (2014). Linkages between Arctic sea ice cover, large-scale atmospheric circulation, and weather and ice conditions in the Gulf of Bothnia, Baltic Sea. *极地研究*, *25*(4-English), 289-299.

Viitasalu, M. 2019 Impacts of Climate Change on the Ecosystem of the Baltic Sea. DOI: 10.1093/acrefore/9780190228620.013.692.

Vladimirova O. M., Eremina T. R., Isaev A. V., Ryabchenko V. A., and Savchuk O. P. (2018). Modelling dissolved organic nutrients in the Gulf of Finland. Fundamental and Applied Hydrophysics 11 (4), 90-101. https://doi.org/10.7868/S2073667318040111.

Vollebregt, A. (2017). *Hypoxia in the Stockholm Archipelago during the last three millennia: natural factors versus human influence* (Master's thesis). Utrecht University.

Vuorinen, I., Hänninen, J., Rajasilta, M., Laine, P., Eklund, J., Montesino-Pouzols, F. et al. (2015). Scenario simulations of future salinity and ecological consequences in the Baltic Sea and adjacent North Sea areas - implications for environmental monitoring. Ecological Indicators 50, 196-205. https://doi.org/10.1016/j.ecolind.2014.10.019.

Wang, S., Dieterich, C., Döscher, R., Höglund, A., Hordoir, R., Meier, H. E. M., et al. (2015). Development and evaluation of a new regional coupled atmosphere–ocean model in the North Sea and Baltic Sea. Tellus A: Dynamic Meteorology and Oceanography 67(1), 24284. https://doi.org/10.3402/tellusa.v67.24284.

Wasmund, N. (2017). The Diatom/Dinoflagellate Index as an indicator of ecosystem changes in the Baltic Sea. 2. Historical data for use in determination of good environmental status. Frontiers in Marine Science, 4, 153.

Wasmund, N., Kownacka, J., Göbel, J., Jaanus, A., Johansen, M., Jurgensone, I., ... & Powilleit, M. (2017). The Diatom/Dinoflagellate Index as an indicator of ecosystem Changes in the Baltic Sea 1. Principle and handling instruction. Frontiers in Marine Science, 4, 22.

Weigel, A., Knutti, R., Liniger, M. A., and Appenzeller, C. (2010). Risks of model weighting in multimodel climate projections. Journal of Climate 23 (15), 4175-4197. https://doi.org/10.1175/2010JCLI3594.1.

Weigel, B., H. C. Andersson, H. E. M. Meier, T. Blenckner, M. Snickars and E. Bonsdorff, 2015: Long-term progression and drivers of coastal zoobenthos in a changing system. Marine Ecology Progress Series, 528, 141159, doi: 10.3354/meps11279.

Weisse, R., & Weidemann, H. (2017). Baltic Sea extreme sea levels 1948-2011: Contributions from atmospheric forcing.

Procedia IUTAM, *25*, 65-69.

Wikner, J., and Andersson, A. (2012). Increased freshwater discharge shifts the trophic balance in the coastal zone of the northern Baltic Sea. Global Change Biology 18(8), 2509-2519. https://doi.org/10.1111/j.1365-2486.2012.02718.x.

Wilcke, R. A. I., and Bärring, L. (2016). Selecting regional climate scenarios for impact modelling studies. Environmental Modelling and Software 78, 191-201. https://doi.org/10.1016/j.envsoft.2016.01.002.

Wolski, T., Wiśniewski, B., Giza, A., Kowalewska-Kalkowska, H., Boman, H., Grabbi-Kaiv, S., Hammarklint, T., Holfort, J., and Lydeikaite V. (2014). Extreme sea levels at selected stations on the Baltic Sea coast, Oceanologia, 56, 259–290, https://doi.org/http://dx.doi.org/10.5697/oc.56-2.259

Yin, J. (2012). Century to multi-century sea level rise projec- tions from CMIP5 models, Geophys Res Lett, 39, https://doi.org/ 10.1029/2012GL052947

Yin, J., Griffies, S. M., and Stouffer, R. J. (2010). Spatial Variability of Sea Level Rise in Twenty-First Century Projections, J Climate, 23, 4585–4607, https://doi.org/ 10.1175/2010JCLI3533.1

Yin, J., Schlesinger, M. E., and Stouffer, R. J. (2009). Model projections of rapid sea-level rise on the north- east coast of the United States, Nat Geosci, 2, 262–266, https://doi.org/ 10.1038/NGEO462

Zandersen, M., Hyytiainen, K., Meier, H. E. M., Tomzcak, M., Bauer, B., Haapasaari, P., et al. (2019). Extending shared socioeconomic pathways for the Baltic Sea region for use in studying regional environmental problems. Regional Environmental Change, https://doi.org/10.1007/s10113-018-1453-0.

Zscheischler, J., Westra, S., van den Hurk, B. J. J. M., Seneviratne, S. I., Ward, P. J., Pitman, A., AghaKouchak, A., Bresch, D. N., Leonard, M., Wahl, T., and Zhang, X. (2018). Future climate risk from compound events, Nat Clim Change, 8, 469–477, https://doi.org/10.1038/s41558-018-0156-3

Zhang, W., Harff. J and Schneider, R., (2011). Analysis of 50-year wind data of the southern Baltic Sea for modelling coastal morphological evolution - a case study from the Darss-Zingst Peninsula. Oceanologia, 53 (1-TI), 489-518. doi:10.5697/oc.53-1-TI.489

Zhang, W., Schneider, R., Harff, J., Hünicke, B., Froehle, P. (2017): Modeling of medium-term (decadal) coastal foredune morphodynamics – historical hindcast and future scenarios of the Swina Gate barrier coast (southern Baltic Sea). In: Harff J, Furmanczyk K, von Storch H (eds) Coastline changes of the Baltic Sea from south to east – past and future projection. Coastal research library, vol 19. Springer, Cham

Zorita, E., & Laine, A. (2000). Dependence of salinity and oxygen concentrations in the Baltic Sea on large-scale atmospheric circulation. *Climate Research*, *14*(1), 25-41.

Kommentiert [m49]: Referenz?

Tables (Ole, Erik, Madline, Florian, Germo, Christian, Matthias, Markus and all)

Table 1. Ensemble mean changes in sea surface temperature (SST) (in °C) in ECOSUPPORT, BalticAPP RCP 4.5 and BalticAPP RCP 8.5 scenario simulations averaged for the Baltic Sea including the Kattegat between 1978-2007 and 2069-2098. (DJF = December, January, February, MAM = March, April, May, JJA = June, July, August, SON = September, October, November)

Δ SST	DJF	MAM	JJA	SON	Annual mean
ECOSPPORT SRES A1B	2.5	2.8	2.8	2.5	2.6
BalticAPP RCP 4.5	1.7	1.9	2.0	1.8	1.8
BalticAPP RCP 8.5	2.9	3.2	3.3	3.0	3.1

Table 2. Ensemble mean changes in annual mean sea surface salinity (SSS) (in g kg^{-1}), annual mean bottom salinity (BS) (in g kg^{-1}) and winter mean sea level (SL) (in cm) in ECOSUPPORT, BalticAPP RCP 4.5 and BalticAPP RCP 8.5 scenario simulations averaged for the Baltic Sea including the Kattegat between 1978-2007 and 2069-2098.

Annual changes	ECOSUPPORT	BalticAPP RCP 4.5	BalticAPP RCP 8.5
Δ SSS	-1.5	-0.7	-0.6
Δ BS	-1.6	-0.6	-0.6
Δ SL	5.5	0.4	3.7

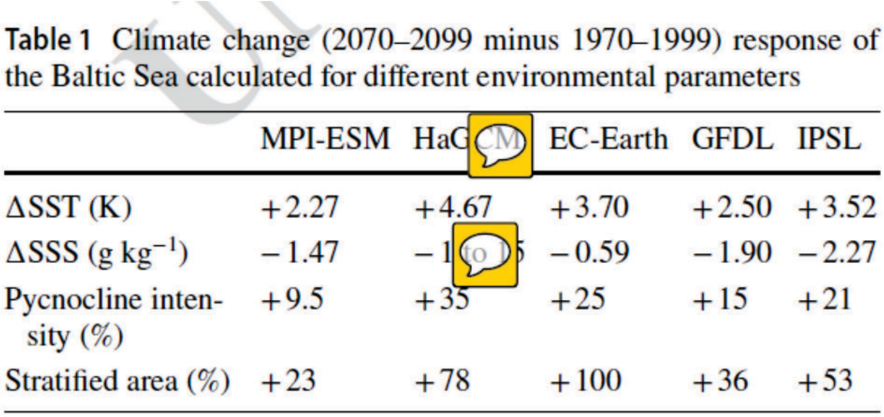

Table 1 Climate change (2070–2099 minus 1970–1999) response of the Baltic Sea calculated for different environmental parameters

	MPI-ESM	HaGCM	EC-Earth	GFDL	IPSL
ΔSST (K)	+2.27	+4.67	+3.70	+2.50	+3.52
ΔSSS (g kg^{-1})	−1.47	−1 to 15	−0.59	−1.90	−2.27
Pycnocline intensity (%)	+9.5	+35	+25	+15	+21
Stratified area (%)	+23	+78	+100	+36	+53

HadGCM delta SSS = -1 g/kg

Ensemble mean SSS changes (Gröger et al., 2019): -1.8 g kg^{-1}

Figures (Ole, Erik, Madline, Florian, Germo, Christian, Matthias, Markus and all)

Preliminary list of figures

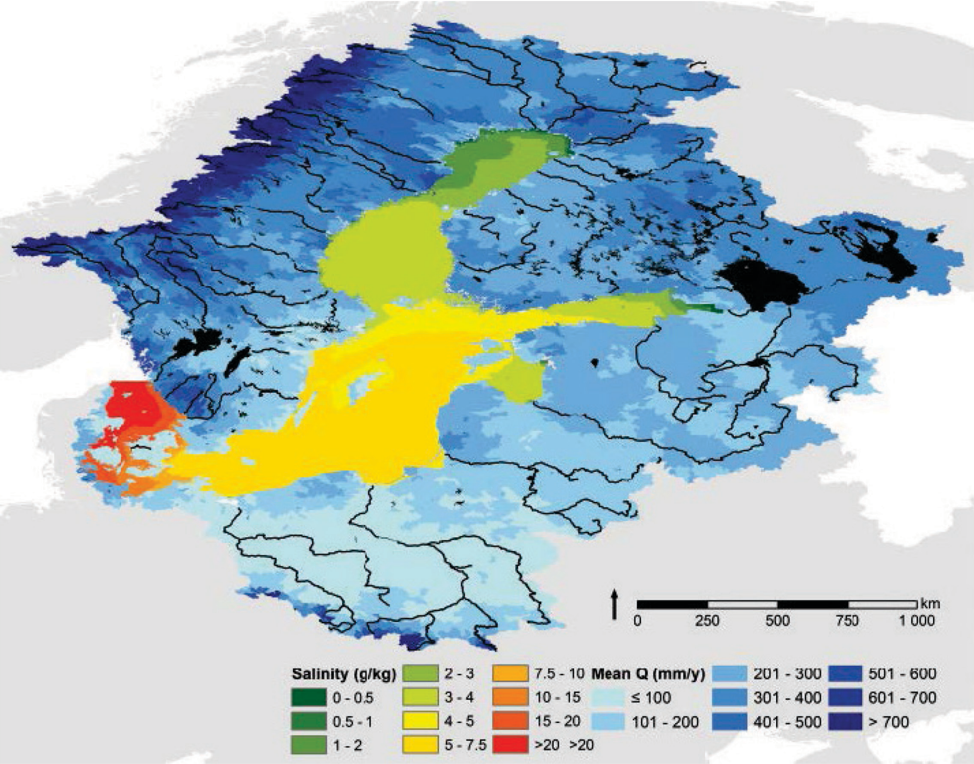

Figure 1: Baltic Sea and catchment area. (Source: Meier et al., 2014)

Past climate

….

Present climate

1. NAO
2. AMO
3. Blocking index/Scandinavia
4. Air temperature Stockholm 1756-2018
5. Annual and seasonal mean surface air temperature over the Baltic Sea calculated from CRU 1871-2018

6. Anomaly time series of annual and seasonal precipitation over Sweden, 1860–2004 (reference period 1961–1990) (somebody at SMHI who is updating the time series?) (BACC I Author Team, 2008)
7. Precipitation CRU ???
8. Runoff at single stations with homogeneous data ???
9. Runoff data for the entire Baltic Sea from SMHI (Göran Lindström), see BACC II Author Team (2015), Fig. 5.18 (I can ask him if he has time to update the figure)
10. Sea surface and bottom water temperature at selected stations (with sufficient data), summer and annual mean with data corrected for seasonal biases (following Hagen Radtke), since 1900
11. Sea surface and bottom salinity at selected stations (with sufficient data), summer and annual mean with data corrected for seasonal biases (following Hagen Radtke), since 1900
12. Temperature at MARNET station data Darss Sill, Arkona Basin, Hagen curve (Volker Mohrholz)
13. Salinity at MARNET station data Darss Sill, Arkona Basin
14. Maximum annual ice extent 1720/1721-2018/2019, 1900-2018 (see Table 8.1, Fig. 8.3, etc., BACC II)
15. Ice thickness at Kemi, Loviisa
16. Duration of the ice season
17. Ice breakup Tallinn ???
18. Swedish sea level climate indicator (Hammarklint T, 2009: Swedish Sea Level Series – A Climate Indicator. Swedish Meteorological and Hydrological Institute), already available for 2018
19. Sea level Stockholm 1774-2018

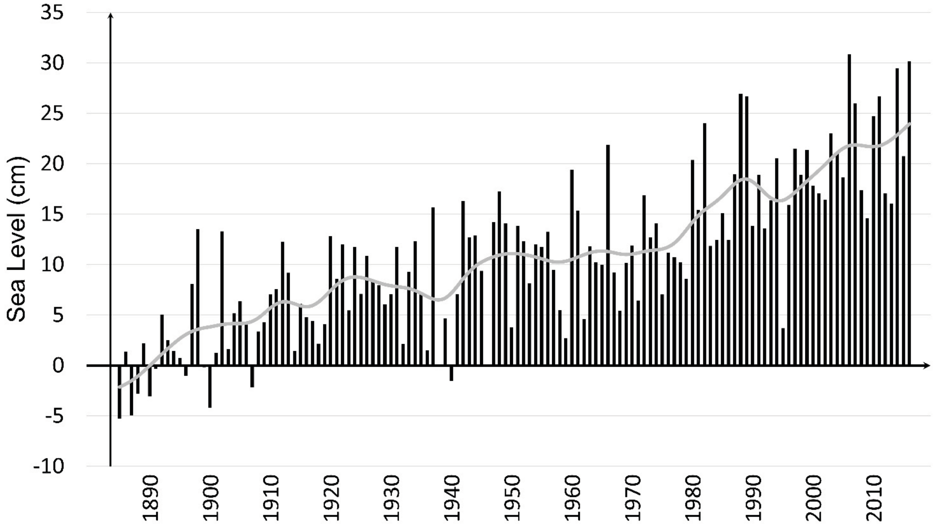

Figure 2: Annual mean sea level changes in centimeters for 14 Swedish mareographs since 1886. The data are corrected for land uplift. The grey line shows a smoothed curve. (Source: SMHI)

Future climate

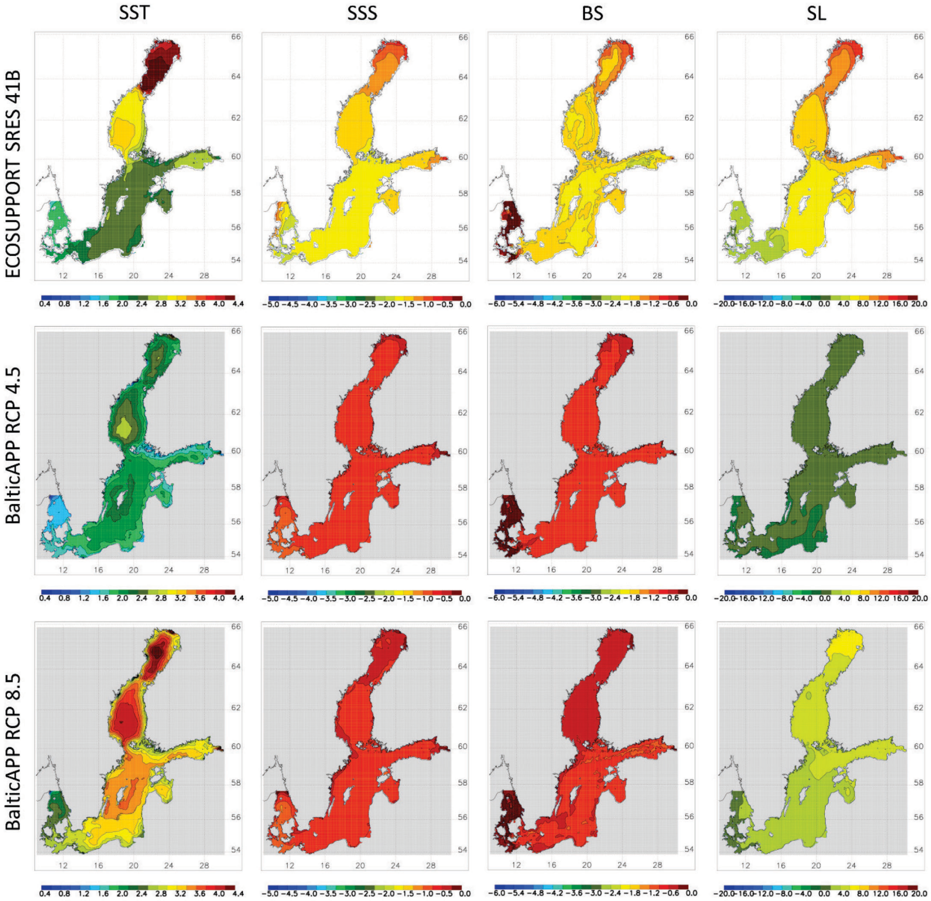

Figure 3: From left to right changes of summer (June – August) mean sea surface temperature (SST) (°C), annual mean sea surface salinity (SSS) (g kg^{-1}), annual mean bottom salinity (BS) (g kg^{-1}), and winter (December – February) mean sea level (SL) (cm) between 1978-2007 and 2069-2098 are shown. From top to bottom results of the ensembles ECOSUPPORT (white background), BalticAPP RCP 4.5 (grey background) and BalticAPP RCP 8.5 (grey background) are depicted.

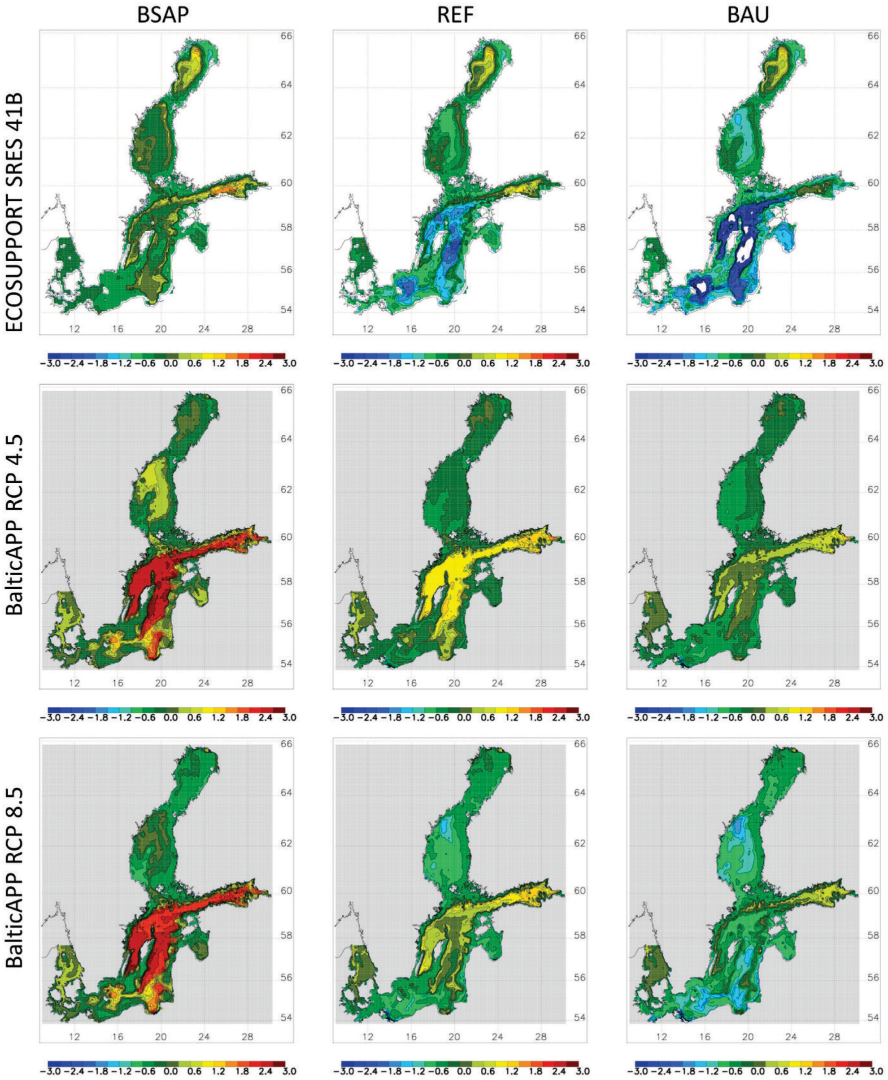
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Figure 4: Ensemble mean summer (June – August) bottom dissolved oxygen concentration changes (mL L^{-1}) between 1978-2007 and 2069-2098. From left to right results of the nutrient load scenarios Baltic Sea Action Plan (BSAP), Reference (REF) and Business-As-Usual (BAU) are shown. From top to bottom results of the ensembles ECOSUPPORT (white background), BalticAPP RCP 4.5 (grey background) and BalticAPP RCP 8.5 (grey background) are depicted.

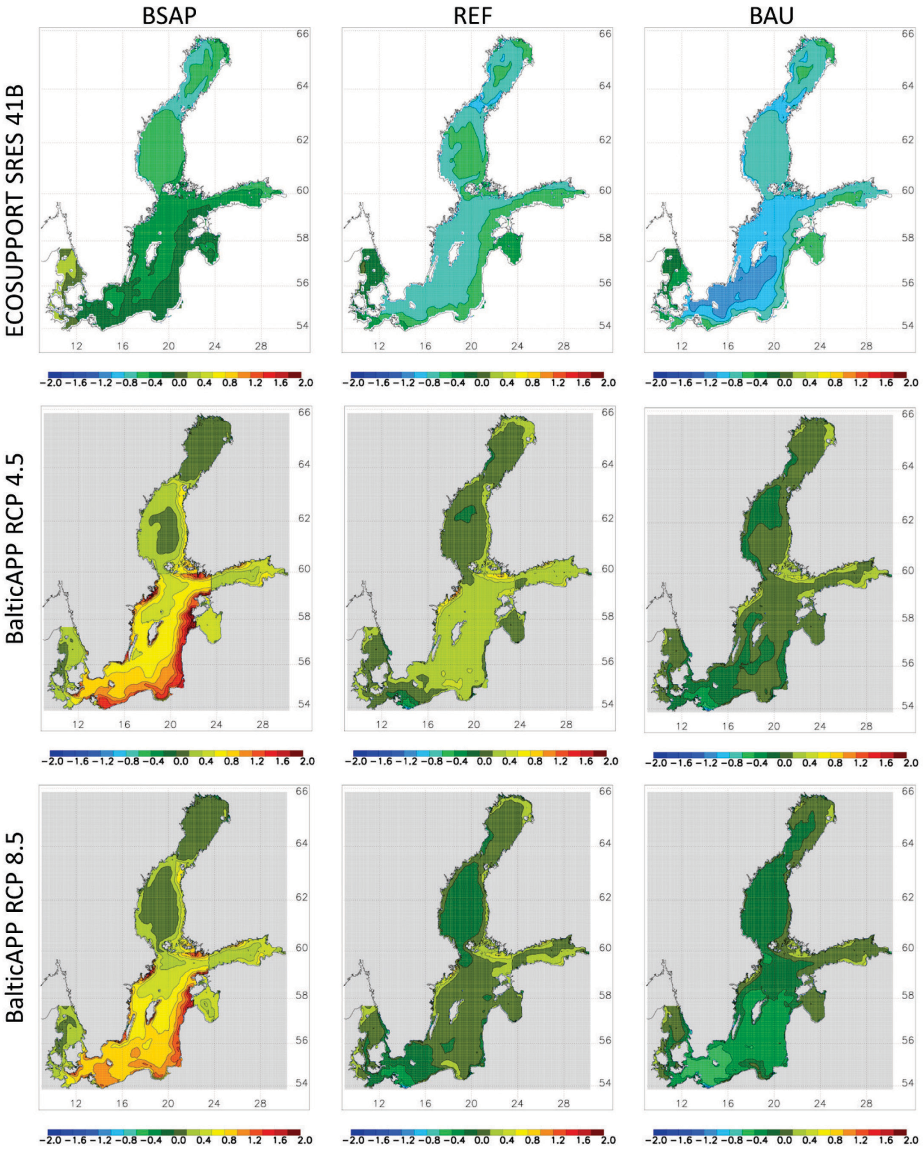
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Figure 5: As Fig. 4 but for annual mean Secchi depth changes (m).