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Climate Change Impacts on Marine Biodiversity and Habitats in the Baltic Sea– and Possible Human Adaptations

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Abstract

Climate change is expected to induce substantial changes in the Baltic Sea ecosystem. The Baltic Sea is generally recognized as a fragile ecosystem characterized by a low number of species that virtually all find their distribution range within the area. This article demonstrates, in a number of case studies, how first of all climate stressors, like increasing temperature, changing precipitation patterns and increasing sea level, are expected to severely affect ecosystem stressors like eutrophication and oxygen depletion. Secondly, the article focuses on how one or several climate or climate driven ecosystem pressures are expected to affect the Baltic Sea ecosystem using examples of expected changes in primary production, biodiversity and key habitats. The findings are based on existing reports as well as new analyses carried out as a part of the Baltadapt project. Finally, possible adaptation measures to secure a healthy Baltic Sea ecosystem in the future climate situation are discussed as well as management implications to existing policies.

1 Introduction and aim

The Baltic Sea is one of the world´s largest brackish inland seas with nine countries bordering its coast, which has a length of around 8,000 km. An additional five countries are included in the Baltic Sea Drainage Basin. Approximately 16 million people live within a distance of 10 km from the coast (Hannerz & Destouni 2006).

The Baltic Sea is still influenced and shaped by on-going postglacial uplift in the northern part whereas the area in the south-western part is slightly sinking. The Baltic Sea has a limited water exchange with the North Sea and is characterized by strong horizontal salinity gradients. As a consequence, the Baltic Sea also exhibits strong horizontal gradients in ecosystem variables, with dominance of marine and warm-water species at lower latitudes and freshwater and cold-water species at higher latitudes.

The Baltic Sea is distinguished by a low number of species inhabiting the sea. This is due to the brackish living conditions and that the Baltic Sea in an evolutionary sense is a young sea with short time for species to invade and adapt to the special living conditions. The fact that most species are living on the very edge of their physiological ability somewhere along the gradients of structuring factors in the Baltic combined with the relatively few number of species, justify the assumptions that the ecosystem in this area is particularly vulnerable for even minor changes in the overall living conditions.

Assessments of climate change impacts on the Baltic ecosystem are available in a number of reports and papers (e.g. the BACC report 2008). The aim of this report, however, is to focus on possible adaptive measures that can be taken either directly to counteract climate change effects on the ecosystem or measures that can be taken in general with regard to management and planning of the future Baltic Sea.

The report will focus on selected case studies including key habitats, species communities and important key species. Potential changes in different climate factors and their impact on the bio-logical diversity in the Baltic Sea will be discussed as well as management implications and adaptive measures.

Some work presented in this report is based on existing knowledge. However, some analyses have been carried out as a part of the Baltadapt project (effects of temperature on distribution of selected macrophytes in Danish waters) or represent an updated analysis of previous studies presented in this report for the first time (temperature effects on nutrient concentrations in Danish Fjords and effects of temperature on oxygen depletion). Projections of future species distributions based on changing salinities have also been carried out as part of the Baltadapt work and the results are presented in this report.

2 Expected and recent climate change in the physical-chemical living condition for the Baltic Sea species

The Baltic Sea water is characterized by large variations in the salinity, both horizontally and vertically. The surface salinity is very low in the Gulf of Bothnia and the Gulf of Finland, due to large river run-off, and increases gradually towards the south and the entrance region. The Kattegat and the Belt Sea area is a transition zone between the brackish Baltic Proper and the more oceanic Skagerrak. The Baltic Sea water is strongly stratified with a permanent halocline (layer where the salinity changes rapidly with depth). In the central part of the Baltic Proper the halocline is usually found at a depth of 60–70 m.

As a consequence of the strong stratification, the water becomes stagnant in the deeper parts of the Baltic Proper and depleted of oxygen. Eutrophication will aggravate the situation in the bottom waters where oxygen is consumed. Irregular Inflows through the Danish straits and the Sound of more saline and oxygen-rich water temporarily improve the conditions.

The Baltic Sea surface temperature shows large seasonal variations, from more than 20°C in summer to freezing conditions in winter. In spring the surface water warms up and a shallow thermo-cline (layer where the temperature changes rapidly with depth) is created. Winter turnover of the water mass will break down the thermocline and in areas with depths less than 60 m, or with weak salinity stratification, the turnover may reach down to the bottom and renew the bottom water.

The Gulf of Bothnia and the Gulf of Finland are normally ice covered during the winter season. The ice cover records show large inter-annual variations in the maximum ice extent.

Large inputs of nutrients from its vast catchment area enter the Baltic Sea mainly through riverine transport and atmospheric deposition. Internal fluxes of nutrients from the sediments can also be significant. Due to the small volume of water and the limited exchange with the North Sea, the Baltic Sea is very sensitive to excessive nutrient loads. Most parts of the Baltic Sea are affected by eutrophication today (HELCOM 2010).

2.1 Model simulation of future physical-chemical conditions

Climate change will in many ways affect the future conditions in the Baltic Sea. Model simulations indicate a strong increase in air temperature in the Baltic region, especially in winter and most so in the north-eastern part, influencing the sea ice conditions in the area. Cold winter extremes are expected to be unusual while hot summer extremes will become more frequent.

The climate simulations also show an increase in precipitation and, again, the winter will be more affected. The amount of extreme events will also increase according to the scenarios. Although many models indicate an increase in wind speed over the Baltic Sea region, the uncertainty is very great. Consequently, projected sea surface currents, which are wind driven to a large degree, and wind waves will be uncertain as well.

Changes in sea surface level are determined by changes in the global mean sea level, the uplift and future changes in the local wind and pressure patterns. In the IPPC Report (2007) the future global sea level rise was estimated to 18–59 cm. However, ice transport from Greenland and Antarctica was not included and later reports suggest that the rise may be twice as high. Although the size of the global mean level change is under debate, the total effect is anticipated to be larger in the southern and south-eastern part of the Baltic Sea while the northern part will be less affected due to the on-going uplift.

The ocean climate simulations yield a general increase in sea surface temperature, with the largest change found in the Bothnian Bay in summer. In winter a substantial increase is found in the Gulf of Finland. The projected volume averaged temperature will also be higher than today (Meier et al. 2012a).

Although the modelled future averaged river discharge shows an increase in most areas, the largest change is found in the seasonal variations. Hence, it is anticipated that the discharge will in-crease by a large amount in winter but decrease in summer.

Scenario simulations show a future decrease in both surface and bottom salinity (e.g. Meier et al., 2012a, Neumann 2010, Neumann et al. 2012, Friedland et al. 2012). The decrease is mainly due to the expected increase in river run-off and a deepening of the permanent halocline.

A reduction in bottom oxygen concentrations in the deeper parts of the Bothnian Sea and the Baltic Proper may be expected due to climate change (Meier et al. 2011a, Meier et al. 2012b, Neumann 2012), see Figure 1. The decrease is explained by higher temperatures causing lower solubility in the inflowing water and an increased decomposition/oxidation rate of organic matter (Meier et al. 2011b). The total nutrient load from rivers may also increase, due to an increase in river run-off, there-by enhancing the oxygen consumption.

A study of the impact of warming of water masses in the Kattegat and Belt Sea area clearly demonstrates a large effect on oxygen content and duration of hypoxic conditions in bottom waters (Bendtsen & Hansen 2013). The distribution of oxygen has been successfully modelled for three consecutive years 2001–2003 with marked differences with respect to hypoxia. Then the sensitivity to a climate change scenario was simulated by forcing the circulation model with a 3°C increase in air temperature and surrounding water masses but otherwise applying the same climatic conditions in terms of solar radiation, precipitation, wind and humidity as observed in 2001–2003. The outcome of this scenario was oxygen depletion in much larger areas in the Kattegat and the Danish straits and low-oxygen conditions (hypoxia) lasted for a longer period during late summer and autumn and the oxygen deficiency were more severe (Figure 2 and Appendix 2 for further details). An overall reduced export of oxygen in water masses to the central Baltic Sea is then expected.

In the surface layer nutrients and phytoplankton concentrations may increase and the water transparency in the Baltic Proper may be reduced (e.g. Meier et al. 2011a, Meyer et al. 2012b, Friedland et al. 2012). If the Baltic Sea Action Plan (BSAP) is implemented, bottom oxygen concentrations may in-crease along the slopes of the Gotland Sea and in the Gulf of Finland.

However, in a warmer climate the effect of BSAP on the water quality may not be as large as it would in today's climate (e.g. Meier et al. 2011a, Friedland et al. 2012).

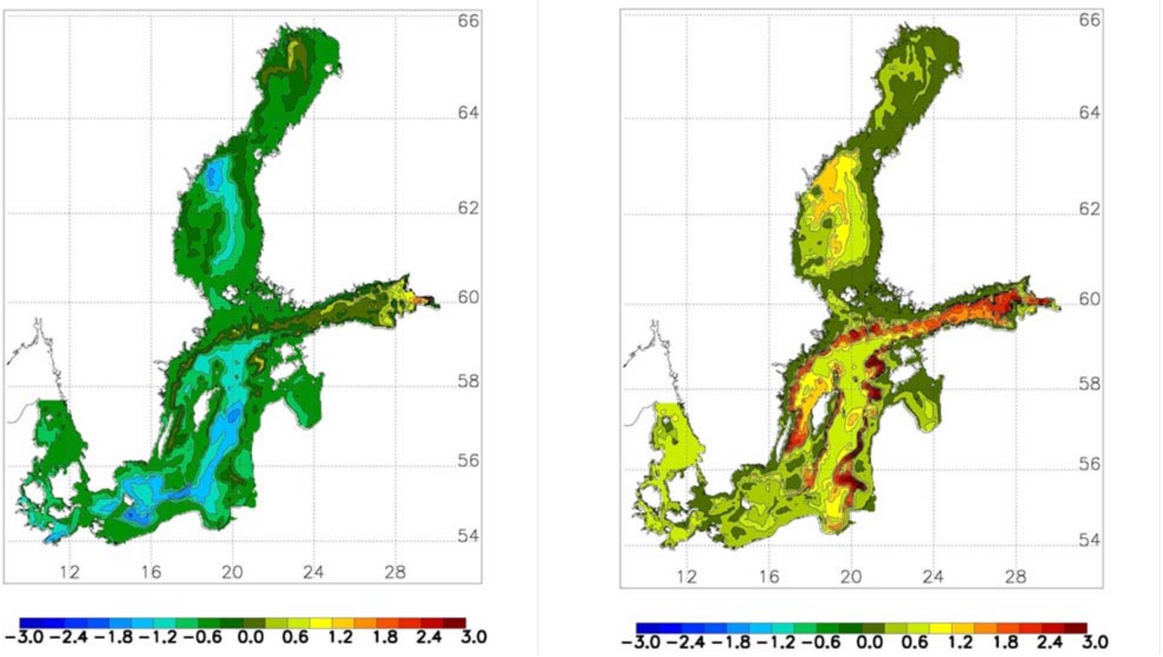

Figure 1: Left panel: The mean change in the annual bottom oxygen concentrations (ml/l) between 2070–2099 and 1969–1998 based on four simulations. The nutrient load scenario is based on current loads from rivers and atmospheric deposition.
Right panel: The range of the changes. (From Meier et al. 2011a).

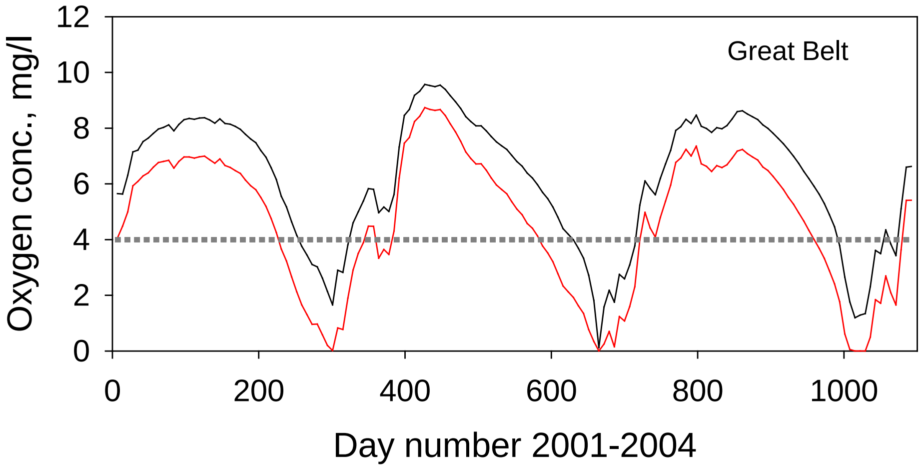

Figure 2: Black line: Temporal distribution of bottom water oxygen during 2001–2003 in the Great Belt. Red line shows the distribution of oxygen in a 3 °C warmer climate change scenario. Dotted line indicates the conventional limit for hypoxia in the area (see Appendix 2 for the situation in central and northern Kattegat as well as for further details).

The projected climate change is linked to uncertainties of various degrees. Results that are based on a large set of simulations are more robust than those based on just a few scenario runs. In general, statements about future conditions in the ocean are based on a more limited set of simulations.

The most robust results are those concerned with the future atmospheric temperature. Since the ocean is heated by the atmosphere, the projected ocean temperatures are also relatively certain.

The future regional precipitation is more uncertain and, consequently, the projected river run-off and salinity. The largest uncertainties concern changes in wind speed which means that statements on future currents and waves, and possibly also mixing, are highly uncertain as well.

The simulated changes generally get stronger with time. However, the high degree of natural variability in the region implies that changes temporarily may be stronger or weaker than what would be expected from a continuous change. Such variability can amplify or weaken the signal on time scales of years to decades.

The emission scenarios that form the basis of the simulations are coupled to different “story lines”, describing the future developments on Earth. These developments may be faster or slower, or take another course, than those anticipated.

2.2 Measurements of recent climate change in the Baltic Region

Several studies indicate an increase in the mean sea surface temperature in the Baltic Sea, especially in summer (e.g. Siegel 2006, Belkin 2009).

For the last 40 years, a 1.5°C temperature rise has been observed in the inner Danish surface water and bottom water (Carstensen 2011). However, most of this increase has occurred during the past 25 years and particularly during the late summer where the temperature has increased about 2°C. The seasonal bias in the temperature changes is particularly important for the oxygen conditions during the hypoxic season in late summer. In general, the changes in temperature have occurred concomitantly with the major changes in the eutrophication levels with possible coupled effects on the marine ecosystem.

2.3 Eutrophication – a human effect sensitive to climate change

Nutrients are essential for organisms but can also threaten the ecosystem when excessively available. Eutrophication occurs when high nutrient concentrations stimulate growth of primary production (‘algae blooms’) leading to alterations in flora and fauna communities and imbalanced functioning of the ecosystem (HELCOM 2009 and HELCOM 2012). Increasing sedimentation of organic material enhances decomposition and oxygen consumption from the water column. This leads to low oxygen conditions (hypoxia) especially in areas where water mixing is restricted, such as in deeper waters below the halocline or in shallower waters affected by thermal stratification during summer (HELCOM 2012). In the worst case, death of benthic organisms and fish is the consequence. Anoxic conditions cause phosphorus release from the sediments (‘internal loading’). High phosphorus and low nitrogen concentrations favour cyanobacteria which are able to fix atmospheric nitrogen and thus are not dependent on nitrogen availability in the water. These processes add even more nutrients into the water column.

Due to anthropogenic emissions, nutrient loads from the catchment to the Baltic Sea have in-creased severely during the last century: dissolved inorganic nitrogen (DIN) loads more than doubled and dissolved inorganic phosphorus (DIP) loads nearly tripled (Savchuk et al. 2008, Schernewski and Neumann 2005). The DIP pool more than doubled mainly due to the increased river loads but also due to the internal phosphorus release from the hypoxic sediments in the last 100 years (Gustafsson 2012). However the DIN pool decreased by 50%, due to the increased denitrification in the Baltic Proper in the last 50 years (Gustafsson 2012). The nutrient concentration changes lead to a change of the nutrient composition which is of high importance for phytoplankton communities and primary production.

Following increasing nutrient concentrations, chlorophyll-a concentrations (indicator for primary production) increased and water transparency decreased in the Baltic Sea up to the 1980s. Recent developments vary strongly among regions and include as well improvements, stagnant conditions as deteriorations (HELCOM 2009). According to a HELCOM assessment (2010), only the Bothnian Bay and the Swedish parts of the north-eastern Kattegat are not affected by eutrophication today.

The open waters of all other basins and also most coastal waters are still classified as areas affected by eutrophication. Oxygen depletion and hypoxia are still a major problem in many parts of the Baltic Sea. The relative importance of sources for anthropogenic nutrient emissions have been changing over time, but at present the main pollution source for both nitrogen and phosphorus in the Baltic Sea catchment is the diffuse input with agriculture being the main emitter (60–90% of the diffuse loads). The second largest nutrient emitters are the point sources of municipalities (HELCOM 2011).

Future changes in precipitation will have large effects on discharge and thereby on the nutrient flux between land and the Baltic Sea. Yet different hydrological conditions between years cause varying nutrient loads to the Baltic Sea. The overall projected increase of precipitation and discharge in the Baltic Sea region in the future might lead to increased nutrient loads from the catchments to the Baltic Sea and accelerated eutrophication (HELCOM 2009). The yearly river discharge will mainly increase in the forested northern catchment areas whereas it will decrease in the agriculturally dominated southern and continental areas of the Baltic Sea catchment (HELCOM 2007b). However, a seasonal change in the intensively cultivated south-western area with more precipitation in winter and dryer summer combined with warmer climate is expected to increase the overall nutrient turnover and run-off as nutrient loss from agricultural soils is primarily associated with vegetation free seasons (Jeppesen et al. 2011). Despite the overall trend of precipitation changes, regional projections for discharge are still lacking for most areas of the Baltic Sea region or are very uncertain. Climate change might also influence nutrient inputs to the Baltic Sea by changes in the timing of spring run-off, autumn low flow, ice and snow cover, and by changes in the frequency and severity of extreme events such as floods/erosion and droughts (HELCOM 2007b).

Counteractive pressures and processes complicate the projections of effects on nutrient loads to the Baltic Sea and “there is currently no overall scientific consensus on the influence of climate change on nutrient inputs to the Baltic Sea” (HELCOM 2007b).

Studies conducted on 22 years’ monitoring data from Danish fjords connected to Kattegat and the Belt Sea area as part of the Baltadapt project (for further details see Appendix 1) demonstrate counteracting influences of different climate change effects on the eutrophication. Increased temperature stimulates removal of total nitrogen but increase phosphorous concentrations in the fjords. The removal of nitrogen might level out load expected from the changing precipitation while it adds to the expected run-off of phosphorous (Table 1).

Not only precipitation itself but also the conditions influencing evaporation (e.g. kind of land use) do have an impact on discharge rates. Climate-driven choice of land use and crops, but also irrigation habits, has an impact on discharge (evaporation) and nutrient emissions. Recently, political decisions such as the promotion of renewable energies had serious and very rapid impacts. For example, the German renewable energy act has caused an immense increase in the cultivation of maize which has now become one of the most common crops in the German Baltic catchment area. Maize cultivation can lead to very high nutrient emissions. From such past experiences, it can be expected that political and economic developments and decisions will have a strong impact on nutrient emissions in the future which can be even stronger than climate change impacts.

Table 1: Schematic summary of the predicted change in nutrient loadings in Danish estuaries and rivers due to climate change in the most extreme scenario (SRES A2). A less extreme scenario is expected to give changes in the low end of the predictions. Climate scenario is mainly from the Danish Meteorological Institute (DMI) and riverine changes are derived from literature (Jeppesen et al. 2009, Jeppesen et al. 2011) while estuaries changes are predictions based on own data, empirical modelling and other studies. Some of the same effects are expected for northern and western part of the Baltic region but can deviate locally depending on local climate and land use.

<table>
<tr><th>Scenario</th><th colspan="2">Impact</th><th>Effect</th></tr>
<tr><td rowspan="4">SRES A2</td><td colspan="2">Temperature</td><td>Increase (3-5°C)</td></tr>
<tr><td colspan="2">Winter precipitation</td><td>Increase (>40%)</td></tr>
<tr><td colspan="2">Summer precipitation</td><td>Decrease (3-15%)</td></tr>
<tr><td colspan="2">Sea level</td><td>Increase (0.5-1.5 m)</td></tr>
<tr><th colspan="4">Rivers</th></tr>
<tr><th>Climate change</th><th>Impact</th><th>Effect</th><th>Main cause</th></tr>
<tr><td rowspan="2">Increased run-off</td><td>Nitrogen concentration</td><td>Increase (7-35%)</td><td>Subsurface and surface run-off</td></tr>
<tr><td>Phosphorous concentration</td><td>Increase (3-17%)</td><td>Surface run-off</td></tr>
<tr><th colspan="4">Estuaries</th></tr>
<tr><th>Climate change</th><th>Impact</th><th>Effect</th><th>Main cause</th></tr>
<tr><td rowspan="3">Increased temperature</td><td>Nitrogen concentration</td><td>Decrease (3-20%)</td><td>Increased denitrification</td></tr>
<tr><td rowspan="2">Phosphorous concentration</td><td rowspan="2">Increase (5-50%)</td><td>Decreasing redoxpotential in sediment</td></tr>
<tr><td>Increased mineralization</td></tr>
</table>

3 Climate change impacts on habitats and biodiversity

3.1 Scenarios on future biogeographic distribution of selected Baltic Sea species

In addition to effects from hypoxia and anoxia, the present distributions of flora and fauna in the Baltic Sea are strongly regulated by salinity. The salinity gradient from fully marine (salinity of 33) in the Kattegat to almost freshwater in the Bothnian Bay and eastern parts of the Gulf of Finland restricts the distribution of marine species resulting in a decrease in numbers of species with marine origin towards less saline living conditions. No species with marine origin that can cope with salinities below 3. At the same time there is an increase in the number of freshwater species able to cope with salinities from 0 to 5 (Remane 1934). Species richness is lowest in the northern Baltic where salinity is less than 5, where only some freshwater and highly euryhaline species occur. Overall this results in the lowest species richness in the coastal regions of the northern Baltic. The effects of the salinity gradient have been documented in several studies (e.g. Remane 1934, Nielsen et al 1995, Bonsdorff & Pearson 1999, Bonsdorff 2006, Zettler et al. 2007, Glockzin & Zettler 2008, Josefson 2009, Ojaveer et al. 2010, Bleich et al. 2011, Villnäs & Norkko 2011).

Global warming will likely be accompanied by increased precipitation and consequently in-creased freshwater run-off to the Baltic Sea. Thus, a likely result of warming will be a lowering of the salinity, and also increased risk of hypoxia formation in the bottom water (e.g. Meier et al. 2011a). A temperature increase will also increase the duration of the ice-free period particularly in the northern parts. It is therefore likely to expect dramatic changes in species distributions in the Baltic Sea as a consequence of global warming.

3.1.1 Species distribution in a future more brackish Baltic Sea

Approximate present geographical distributions in the Baltic for some selected species are depicted in Bonsdorff (2006) and shown in Figure 3A and C. This include the fish species Cod (*Gadus morrhua*) and flounder *Platichthys flesus*, and mussel species like blue mussel (*Mytilus edulis/trossulus*), Baltic tellin (*Macoma balthica*) and Sand gaper (*Mya arenaria*), as well as some crustaceans and polychaetes.

Given one of the possible future scenarios for changing the salinity condition in the Baltic presented by Meier et al. 2011a, we predict possible geographic distributions of the same species in approximately 100 years from now (Figure 3B).

At the same time we expect these species to be replaced by species with freshwater orrigin like cyprinid fishes and pike-perch (*Sander lucioperca*). Among invertebrates midges (chironomids) are likely to increase. However, due to higher temperatures some cold water species like the white fish *Coregonus lavaretus* may decrease their distribution ranges (Figure 3D).

The effects of decreased salinity can influence marine species in several ways. The maintenance of turgor pressure is one of the key processes in marine macrophytes at low salinity. When salinity is reduced further, the amount of energy used for turgor pressure maintenance may increase to a level intolerable for an individual and it will die. The examples discussed here include two large brown macroalgal species bladder wrack (*Fucus vesiculosus*) and serrated wrack (*Fucus serratus*) and the red algae *Furcellaria lumbricalis*. Bladder wrack and serrated wrack form important underwater habitats on hard substrates in shallow littoral areas. One of the factors influencing the distribution of macroalgae at low salinities is their reproductive success. Low salinity is e.g. known to reduce spore survival and germination success in bladder wrack.

The red macroalga *Furcellaria lumbricalis* is the most important red algal species in the Northern Baltic Sea forming a red algal belt on rocky shores below the *Fucus* belt. The species is known for its wide tolerance range for salinity and can be found at salinities above 3. However, the sexual reproduction is prohibited below 7 and at this salinity, the population regeneration occurs via asexual reproduction by spores or detached thallus pieces. The genetic effects of asexual population regeneration may reduce the genetic diversity within algal populations and therefore sudden environmental changes can destroy populations existing at the low salinity as the algae cannot acclimate to sudden changes.

As the salinity declines, a larger part of the shallow benthic primary production on hard bottom will be taken over by species tolerating low salinities, such as green algal species like gut weed *(Enteromorpha intestinalis)* and *Cladophora spp.* All of these species can efficiently utilize the increased amount of nutrients in the seawater and also grow epiphytic on other macrophyte species. Thus the competition for light and space on suitable substrate may facilitate the disappearance of perennial, large algae and increase the amount of annual species. The effects of such a changing structure of the macrophytes community are hard to predict in the littoral zone. Increasing amount of filamentous algae may also influence deep sea bottoms as a large part of the biomass often get detached and accumulate at deeper waters where their degradation might cause oxygen deficiency.

It is important to keep in mind that this is just a rough estimate of changes in the spatial distribution of a number of selected species. Combined effects with other possible changes in the physical environment caused by changing climate conditions are likely to interfere with salinity changes. Changed oxygen conditions in bottom waters are predicted (Meier et al. 2011a, Meier et al. 2011b) but the range of change in oxygen is likely depending on the success of implementing the Baltic Sea Action Plan. The future distribution of Baltic cod is an example of a species that might suffer in several ways in a future climate. It can be found in small numbers in the salinity interval between 7 and 11 but prefers higher salinities (Tomkiewicz et al 1998) and its recruitment is already today under pressure because of low oxygen conditions in the former major breeding areas at Bornholm Deep, Gotland Deep and Gdansk Deep (Köster et al. 2005).

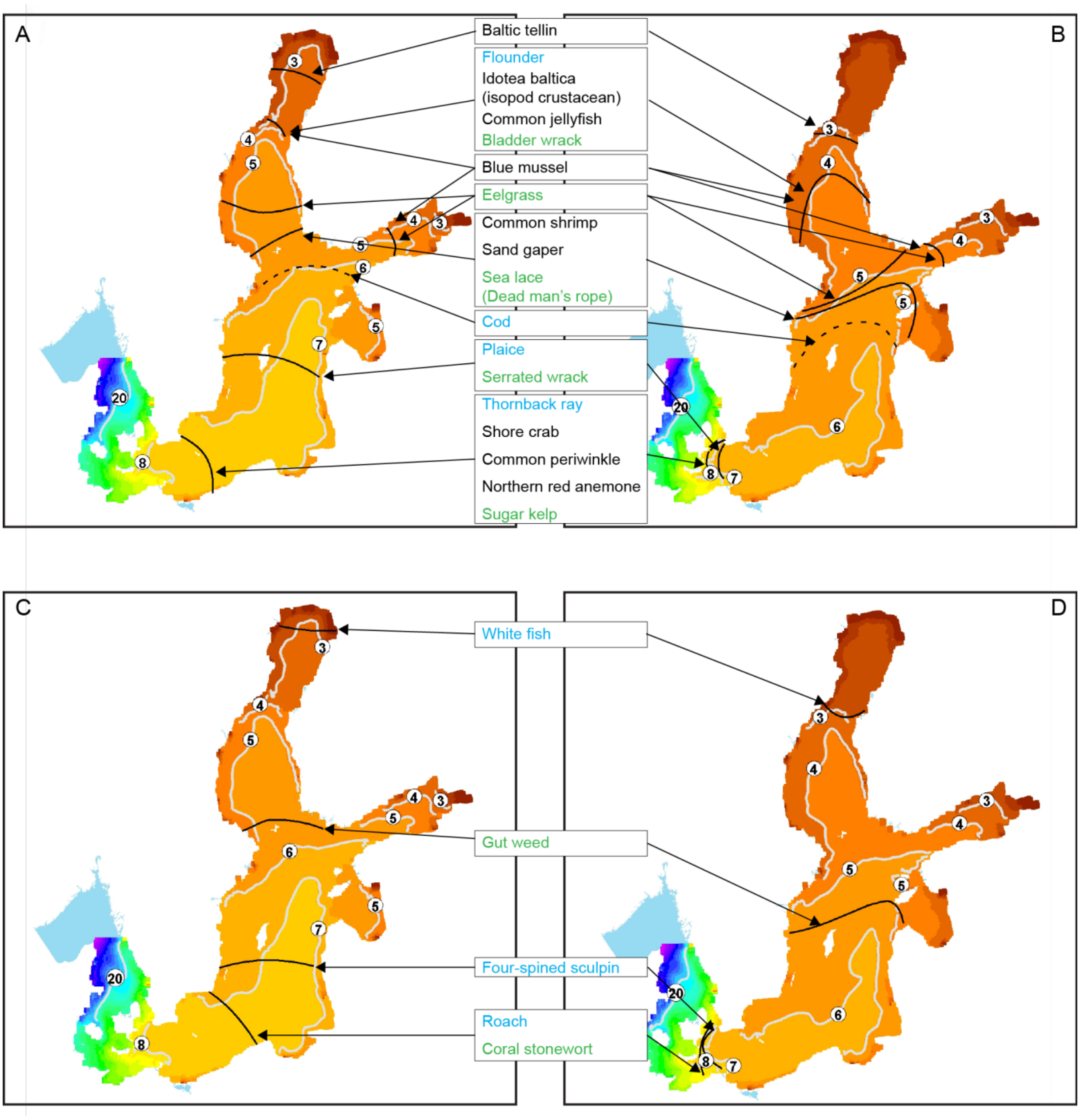

Figure 3: Distribution of selected macrophytes, fish and benthic invertebrate species today (A and C) and predicted based on future climate scenarios (B and D). Surface salinities (top 3 m) in the Baltic Sea modelled by Meier et al. 2011a and the present distribution of species with marine origin in A and with freshwater origin in C are taken from Bonsdorff. 2006. The predicted changes are solely based on simulated salinity changes and not changes in ice cover and oxygen deficiency.

Another example is a scenario predicting that salinity conditions prevailing today in the Gulf of Finland and in the northern Kvark (transition between Bothnian Sea and Bothnian Bay) or the inner Gulf of Finland will dominate in the Archipelago Sea (Åland to Finnish mainland, i.e. the most “marine" part of Finland today) in 100 years from now. However, warmer water and longer ice-free periods may increase the frequency of algal blooms (including harmful algal blooms). This new scenario opens the doors for invasive, non-native species and the bristle worms (Figure 4) of the genus *Marenzelleria* (see below) is no doubt an outstanding recent example (e.g. Maximov 2011). Altogether, non-native species with broad physiological tolerance are likely to increase.

3.1.2 Tolerance against low oxygen – a competitive advantage in hypoxic environments

One plausible/possible consequence of global warming in the Baltic Sea is lowering of oxygen levels in the waters below the haloclines (Meier et al. 2011a). Tolerance towards low oxygen differs between species, and the invasive bristle worms (*Marenzelleria spp.*) are more tolerant (Schiedek 1997) than for instance the native crustacean amphipods *Monoporeia* and *Pontoporeia*. Increased hypoxic conditions in the Baltic Sea will likely promote dominance of the bristle worm *Marenzelleria* in the future, a shift that has already occurred in the Gulf of Finland (Maximov 2011).

Figure 4: A possible future winner in the Baltic Sea system – the invasive bristle worm *Marenzelleria spp.* Photo: Jan-Erik Bruun

3.1.3 Low oxygen conditions and bristle worm feedback mechanism

Invasive species sometimes have a negative impact on the native ecosystem, but this is not always the case as indicated by recent studies of two invasive bristle worm species (*Marenzelleria spp.*). Being recent invaders in the northern and eastern parts of the Baltic Sea, *Marenzelleria neglecta* and *Marenzelleria arctia* apparently have the potential to provide important ecosystem services in the form of mitigating hypoxia in bottom areas earlier populated by native fauna. In a modelling study Norkko et al. (2012) found that bristle worm had the potential, through irrigation of burrows, to bind substantial amounts of phosphorous in the surface sediments. This phosphorous binding is important as it otherwise could have leaked to the water masses, fuelling phytoplankton production and later increased problems with reduced oxygen content in bottom waters. A concomitant correlative field study Josefson et al. (2012) indicated active burial of labile carbon materials by this bristle worm, which eventually also could mitigating hypoxia. By transporting labile organic matter from the oxygenated surface sediment environment down to sediment layers with less oxygen, degradation will likely slow down and consequently oxygen consumption of the near bottom water is decreased. This is because often oxic degradation is faster than anoxic degradation.

While the first mentioned mitigation effect will be effective when phosphorous is the limiting nutrient for primary production, the latter mitigating effect will be effective irrespective of limiting nutrient. Provided that the two mitigation processes do not interfere negatively with each other, we may expect the greatest mitigating effect of bristle worms in areas where phosphorous is limiting, i.e. coastal areas, the Bothnian Bay and the inner parts of the Gulf of Finland.

The effects on carbon cycling and oxygen dynamics by bristle worms are different from effects by several previous residents in soft sediments like the mussel Baltic tellin and the native amphipods *Monoporeia/Pontoporeia*. These species increase degradation rates of organic matter through intensive bioturbation, and thereby likely contribute to increased oxygen consumption in the bottom waters. The phosphorous binding and burial functions exhibited by bristle worms are new to the Baltic Sea system and implies that increased dominance of the worms will have significant effects on carbon cycling and oxygen dynamics in the Baltic Sea (Norkko et al. 2012, Josefson et al. 2012). A likely implication of such a species shift is a build-up of the organic pool in sub-surface sediments and, although microbial activities like sulphate reduction and methanogenesis will increase, overall mineralization rates are likely to decrease and thus mitigate hypoxia in the bottom waters.

3.2 Plankton communities

3.2.1 Impacts of past and present climate change

In the last decades, several profound changes of plankton ecosystem in the Baltic Sea were regarded as long-term trends relevant to climate change. Next to changes of nutrient loads and concentrations (see Chapter 2), a case study for inflowing rivers in the Gulf of Riga confirms an increase in dissolved organic matter (characterised as total or dissolved organic carbon—TOC or DOC) during the last few decades (Kokorite et al. 2011, Klavins et al. 2012).

The oxygen condition has been deteriorating since the 1950s due to increased external nutrient inputs. The oxygen decrease due to increased temperature is also observed in riverine ecosystems flowing into the Baltic Sea (Springe et al. 2012). The total phytoplankton biomass has roughly doubled during the last century (Wasmund et al. 2008). The nutrient concentration changes lead to the change of the nutrient composition, which is responsible for the nutrient limitation to phytoplankton growth. For example, the Gulf of Finland and the Gulf of Riga might show silicate limitation in the future (Danielsson et al. 2008). The likely nutrient limitation change due to N/P ratio change was suggested by Wan et al. (2011 and 2012). Nutrient composition change can lead to the phytoplankton species change. For example, newly appearing bloom-forming species are mostly potentially toxic (*Dictyocha speculum*, *Prorocentrum minimum*, *Pseudo-nitzschia spp.*). Climate change impact on rivers has also caused enlarged phytoplankton biomass, changes in the structure of cyanobacteria communities, increased overgrowth by macrophytes as well as changes of fish communities' structure (Springe et al. 2012).

3.2.2 Some predicted future effects of climate change

Each of the predicted physical changes of climate change would have a different consequence for the ecosystem. However, little is known about the consequences of their interactions or of combined changes. Uncertainties are large in the projection of the Baltic Sea ecosystem.

Temperature has only little direct effect on algal growth because it depends more on the availability of nutrient and light. Global warming will likely lead to increased vertical stratification and water column stability in the Kattegat and the Danish straits. The lacking convective mixing in late winter will prevent resuspension of diatom spores or floating of the vegetative cells. In contrast to diatoms, dinoflagellates prefer stable water columns and are expected to profit from the increase in stratification (Wasmund et al. 1998). The spring bloom in the Baltic Sea is dominated by diatoms and dinoflagellates. Hence, warming may inhibit mostly spring-bloom diatoms and influence phytoplankton composition. Higher temperatures during winter can result in increased metabolic rates for bacteria and a shift in species composition from cold to warm water species. Higher temperatures in summer may enhance blooms of cyanobacteria (BACC 2008) (Figure 5).

The season favouring cyanobacteria blooms can be prolonged, with the spring bloom in the northern Baltic Sea beginning earlier in the season due to the declining sea-ice cover (Neumann 2010).

A warmer hydrographical environment seems to affect the timing of zooplankton blooms (Calewaert et al. 2011). In general, for zooplankton that has their maximum abundance in spring/summer, the pattern is 'earlier when warmer', while species that peak in late summer and autumn the pattern is 'later when warmer'. However, diatom blooms in spring and autumn are free of temperature control and have remained relatively static. This will cause a mismatching of the energy flow from primary to herbivorous secondary producers and appear to be of crucial importance to the dynamics of the whole ecosystem (Edwards & Richardson 2004). Furthermore, warmer water is anticipated to decline the relative importance of *Pseudocalanus sp.* in the Baltic Sea because of an increase in instantaneous mortality rates and a decline of the net growth efficiency with temperatures (Isla et al. 2008). This will have consequences for the food web and ultimately the fish stocks.

Figure 5: Left picture: A rare example of the cyanobacteria bloom observed in Kattegat august 2006 (photo: Karsten Dahl). The bloom dominated by the species Nodularia spumigena covered huge areas in the western Baltic Sea and penetrated into the Danish straits and up into the Kattegat with an outflowing low saline surface water mass.
Right picture (photo: Michael Bo Rasmussen) during a dive in a patch: nearly no light penetrated through the patches just beneath the surface. Blooms of cyanobacteria might be more frequent in the Kattegat in the future.

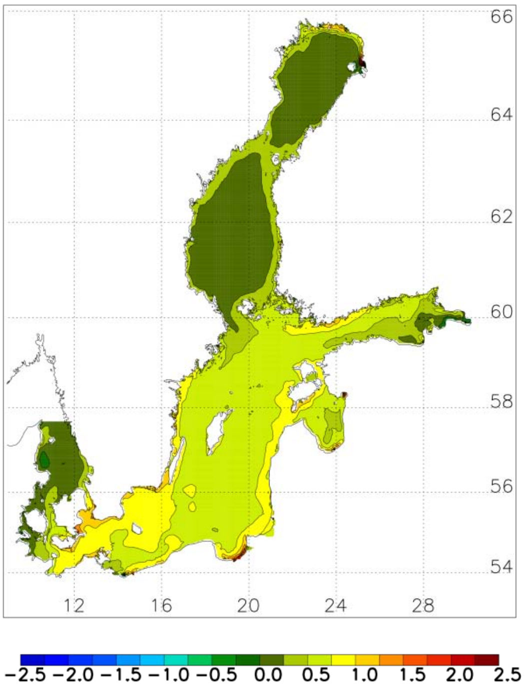

Figure 6: The simulated annual mean phytoplankton production change comparing a 30-year period between 2070-2099 and 1969-1998 for the scenario without implementation of the Baltic Sea Action Plan's nutrient reduction (HELCOM 2007a) (From Meier et al. 2011a).

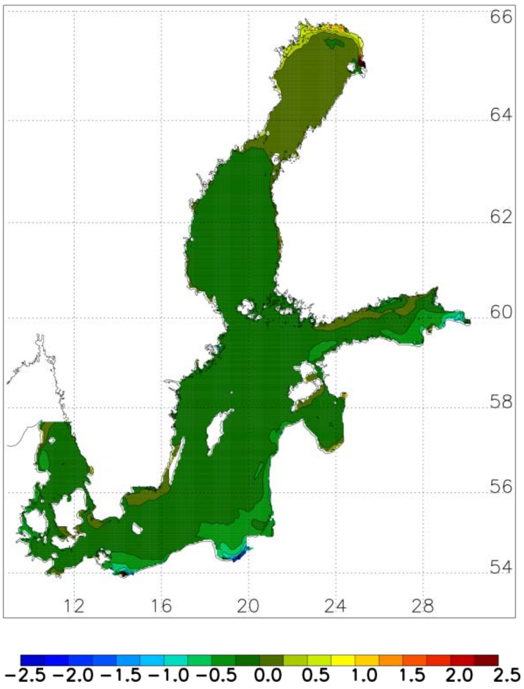

Figure 7: The simulated annual mean phytoplankton production change comparing a 30-year period between 2070-2099 and 1969-1998 for the scenario with the Baltic Sea Action Plan nutrient reduction fully implemented. (From Meier et al. 2011a).

Salinity generally controls the biodiversity of the Baltic Sea. Lower salinities can cause osmotic stress for phyto- and zooplankton and result in a shift in species composition from marine to limnic species. The expected decrease in salinity of the Baltic Sea would result in distribution changes. Freshwater species are expected to enlarge their significance, and invaders from warmer seas are expected to enlarge their distribution area. The lower limit of approximate salinity tolerance for certain species is critical. Decreases in species number due to changes in species distribution areas are expected along the complete range of the Baltic Sea surface salinity (Calewaert et al. 2011).

The climate change impact on phytoplankton in the Baltic Sea has been modelled assuming a change in nutrient loads, increased water temperature and winter wind mixing and a reduction in ice cover. These physical changes tend to increase the nutrient availability for phytoplankton production.

The nutrient loads may have different scenarios depending on the implementation of policy of reducing nutrient loads and land usage. However, a future increase in plankton production can be expected for the scenario without nutrient reduction plan (Figure 6) and the scenario with the Baltic Sea Action Plan (Figure 7).

3.3 Seaweed communities – sensitive for future increasing temperature?

Climate change scenarios indicate that we will face an increasing water temperature in coastal water within the next 100 years. This is expected to influence the geographic distributions of species living in an environment close to their tolerance to warm water temperature.

In the north-western Europe scientific concern has been raised about a possible present effect of global warming on the large sugar kelp, *Saccharina latissima* (Figure 8). This species is also present in the Baltic Sea as far east as Bornholm where it can be found at water depths down to 20 m.

Sugar kelp has a lifecycle with a large stage called sporophyte which forms a leave that can be more than 1 m long and very small male and female plants called gametophytes.

© Peter Bondo Christensen

Figure 8: Sugar kelp on a gravel dominated seabed covering part of the Natura 2000 area Hatter Barn. The species is highly productive, has a lifetime of 3–5 years and favour less exposed sites.
Photo: Peter Bondo Christensen.

The growths of sporophytes are generally inhibited at 17 to 20°C. For the gametophytes and young sporophytes of *S. latissima*, the upper temperature tolerance is 22–23°C (Lee & Brinkhuis 1988). The sporophyte plants exist for 3–5 years.

A study by Moy et al. (2008) concluded that high surface water temperature in coastal waters in the south-western part of Norway in 1997 was one of the reasons for a regime shift in the seaweed forests along the cost. This regime shift resulted in a major reduction in sugar kelp which was substituted by filamentous algal species. High seawater temperature for *S. Latissima* of more than 19°C was observed over a longer time in the summers of 1997, 2002 and 2006 in the Skagerrak and part of the North Sea coasts. Field studies indicated a reduction in *S. Latissima* after 1997 and 2006 in the same area.

As part of the Baltadapt project we have studied possible temperature sensitivity on sugar kelp and four other algal species: Dulse (*Palmaria palmata*), Sea oak (*Halidrys siliquosa*), Sea beech *(Delesseria sanguinea*) and Carrageen (*Chondrus crispus*). All species are common in the Kattegat and the Danish straits and they play an important role as key species in some seaweed communities or as important primary producers on hard bottom structures in general.

The selection was based on indications from literature studies that they could be potential casualties of global warming in this region.

We have analysed the distribution of the species over a period of 20 years from 1990 to 2010 and their responses to fluctuating water temperatures during the period. The hypothesis was that species close to their physiological heat tolerance would respond to high water temperatures with a reduced distribution in the following year. Algal data were collected as part of the Danish national monitoring programme and they were coupled to the nearest water chemistry station where temperature data were also available. The statistical analyses were done on two data sets, one dealing with algal sampling stations in fjords and the other dealing with algal sampling stations in open waters.

It was not possible to find any effect of temperature on the distribution of the selected species. On the other hand, observations of sugar kelp declined dramatically in Danish fjords in 1993 and 1994. The decline happened just before high temperature observations were observed. In Flensburg Fjord, the *Saccharina* was dramatically reduced in 1993 and the stock collapsed on the monitoring stations between 1995 and 1996 following two very hot summers with measured water temperatures above 22°C (Figure 9). Signs of recovery of sugar kelp were not seen in the fjord until 2010.

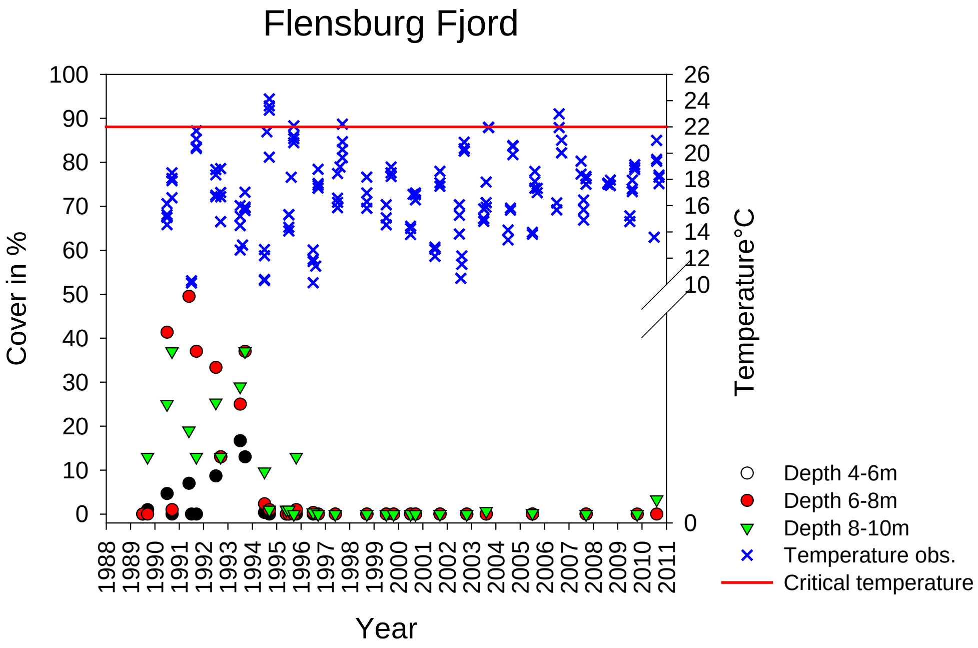

Figure 9: *Saccharina latissima* cover on hard substrate from three depth intervals in Flensburg Fjord and water temperature from the water chemistry station in the fjord. Data from the Danish MADS database.

The question is then what caused the effect on sugar kelp? Observations done by divers reported in the yearly national assessment of the marine environment in 1994 pointed out that massive settlement of blue mussels and observation of intensive snail grassing on kelp combined with exceptionally bad water quality were responsible for a major reduction in the benthic vegetation this year (Dahl et al. 1995). Sugar kelp is known as a species with a relatively quick recolonization response in experiments with harvesting (Kain 1979), however, the observed very high temperatures in 1994 after the vegetation monitoring in June in 1995, 2003 and 2006 may have prevented the recolonization in a 15-year period. No effects on sugar kelp were observed on reefs in the open part of the Kattegat.

In the last 40 years a 1.5° C temperature rise has been observed in the inner Danish surface and bottom water (Carstensen 2011). If this trend continues as expected, the pressure on species like sugar kelp might be too high to sustain populations in the fjord system. Even though there might be years with conditions below temperature tolerance values, the re-colonization might be hampered by lack of a standing stock within the range of distribution spores.

In these days there are huge interests in cultivating sugar kelp. Several research projects are investigating the potential use of this highly productive species as a measure to mitigate nutrient loss from e.g. aquaculture and the species is highly interesting as a future resource for production of biofuel and feed for livestock.

3.4 Seaweed forests on hard bottom – sensitive to eutrophication and sea level rise

The seaweed forests on reef areas are very important and productive habitats hosting a large number of algal and bottom fauna species. They are also an important habitat for a large number of fish species. The macroalgal species depend first of all on available hard substrate where they can settle but also on sufficient light penetrating to the bottom.

As light disappears with increasing depth, hard bottom fauna species will gradually dominate the surface of the hard substrate (Figure 10). Eutrophication does also play an important role for the distribution of seaweed forests. Nutrients stimulate phytoplankton growth and biomasses in the water column and by that decrease the level of light reaching the seabed.

Figure 10: *Fucus* community on shallow water (left) and fauna community at 20 m depth in the central Kattegat (right). Photos Karsten Dahl.

Along the southern Baltic coastline and in Danish waters, the seabed in more shallow waters is made up by glacial deposits and hard substrate is in general rare and made up by boulders “washed out” of glacial deposits. In those parts of the Baltic Sea and the transitional waters, algal forests are “hot spots” for biodiversity.

The depth distribution and development of algal vegetation are also used as an important element assessing the quality of the Baltic Sea in accordance with criteria set up by the three EU Directives; Habitats Directive, Water Framework Directive and Marine Strategy Framework Directive.

3.4.1 Effects of nutrients and salinity

Effects of nutrient load on the development of macro algal vegetation have been investigated and statistical well-founded empirical models have been developed for NATURA 2000 reef sites in the open part of Kattegat. The models describe the overall vegetation cover (total vegetation cover) and the cover of all added species specific covers (cumulative vegetation cover) as a function of locality, solar radiation, depth, grassing pressure of sea urchins and total load of nitrogen to Kattegat from Denmark and Sweden (Dahl & Carstensen 2008). Both algal indicators responded clearly on observed year to year changes in nitrogen load from January-June prior to the algal monitoring in the late summer.

In the context of the Baltadapt project, a climate scenario was run using the same model setup as described in Dahl & Carstensen 2008. Total nitrogen load in the baseline was set to approx. 78,000 tonnes equal to the average of the investigated 20-year period. A regional model for Danish areas (Jeppesen et al. 2011) estimated a possible increase in nitrogen load to marine areas of 19% in the first 6 months of the year based on the A2 climate projection over a 100-year period. A potential future load of nitrogen of approx. 92,000 tonnes was used as the other input to the model. The difference between the two scenarios in terms of changing total macroalgal vegetation cover is shown for the reef Kim’s Top in the central Kattegat (Figure 11). This reef shows the clearest response to changes in nutrient load.

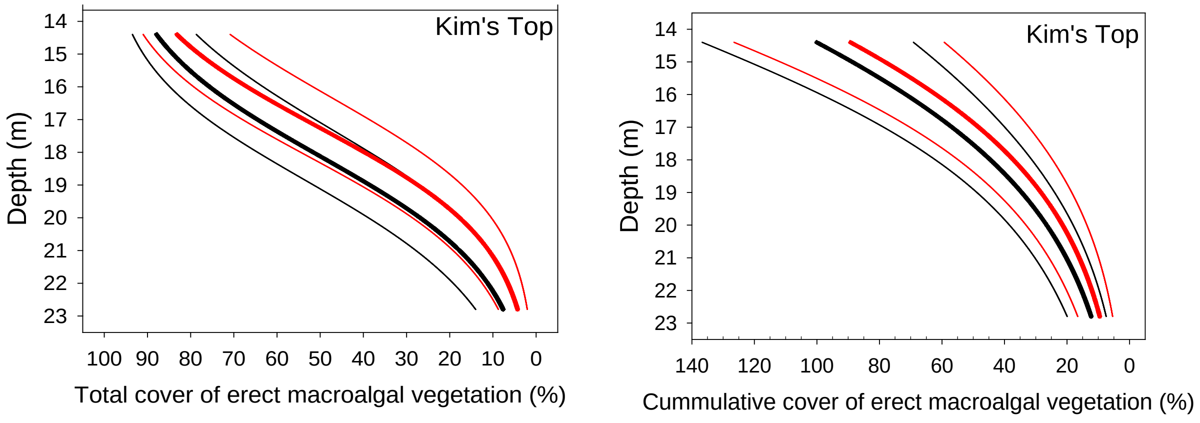

Figure 11: Total cover (left) and cumulative cover (right) of erect macroalgal vegetation at different depths and at different nutrient load scenarios at the reef Kim’s Top in the central part of Kattegat. The thick black lines describe the average load scenario with approx. 78,000 tonnes from rivers and point sources in January-June from the past 20 years. The thick red line describes an average load scenario equal to 91,000 tonnes in the same 6 months based on a regional A2 climate projection (Jeppesen 2009). The thinner red and black lines describe the upper and lower 95% confidence intervals on the estimated covers.

Empirical modelling of algal data sets collected on hard, stable substrate in fjords and shallow coastal areas of Denmark has also been done recently (Carstensen et al. 2008). More or less all data sets collected as part of the Danish national monitoring programme in 2001, 2003 and 2005 have been included in the work. Six different algal indicators were tested and important structuring factors identified and quantified. All macro algal variables were found to respond statistically significantly to a combination of changes in total nitrogen and salinity. Increase in nitrogen concentration in the coastal water resulted in a reduced vegetation cover and the vegetation cover was more developed at high salinities compared to more brackish waters.

The strongest responses to changes in nitrogen concentration and the least variability were found for the indicators ‘total algal cover’, ‘number of late-successional species’ and ‘fraction of opportunists’ in less saline waters.

3.4.2 Impact of sea level rise

The productivity and biodiversity on hard bottom habitats originating from glacial and post glacial processes will be directly impacted by increasing sea level rise. An increase in sea level will affect the level of light available for the seaweed forests on the seabed. Unlike the rocky shores characteristic along the Swedish and Finnish coastline, the algal vegetation will only in some coastal areas be able to adapt by upward movement of the vegetation belt due to lack of substrate. In very shallow water the light level might exceed the need for optimal macrophyte production but in most areas available light is the limiting factor for algal production given a suitable hard substrate.

The average Secchi depth (a simple way to measure the light penetration in surface waters) in the open part of the Kattegat and the Danish straits is approx. 7 m. In Danish coastal and fjord areas the light penetration is reduced to 4.1 m due to higher phytoplankton production and more frequent re-suspension of particulate matter (Figure 12).

An increase in the water level by 1 m in the coming 100 years, as suggested by some studies, will result in an average loss of light for the seaweed forests of approx. 20% in coastal areas and 13% in open inner waters.

The effect on macroalgal vegetation cover of reduced light on the seabed was also tested in the context of the Baltadapt project. In this case the Secchi depth was set to describe year to year changes in vegetation cover and then subtract 1 m as a possible climate change scenario for sea level rise. In this case the vegetation was reduced by 1.5–9% at 18 m depth for reefs in Kattegat and Danish straits. However, the estimated cover was subjected to a relatively high variation in all scenarios.

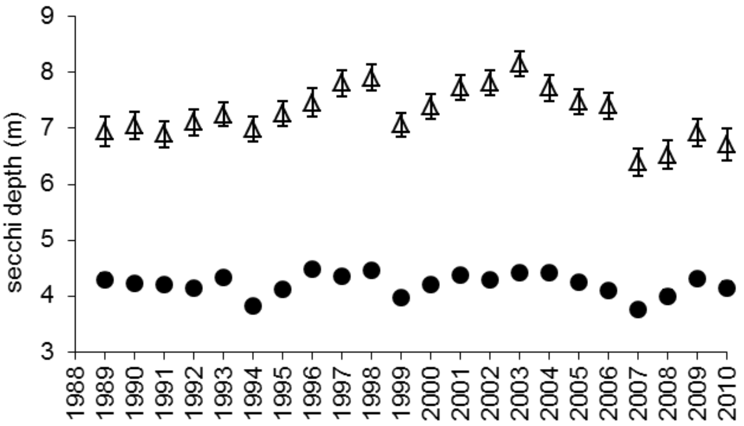

Figure 12: Development in the yearly average values and ± 95 % confidence intervals of Secchi depths in open parts of the Kattegat and the Danish straits (△) and in fjords/coastal waters (●).
From Henriksen et al. 2011.

3.4.3 Overall potential climate effects on seaweed habitats

The outcome of vegetation models indicated that there will be a reduction in algal cover if nutrient load in the spring increases or if sea level rise occurs in the future. The models describe changes in the cover of algal vegetation on hard substrate which is a measure given in two dimensions. In terms of biomasses the differences are considerably larger as the vegetation grows higher both in terms of individual plants but also in terms of number of vegetation layers when the vegetation cover increases.

Impact of water clarity and nutrients on the vegetation cover is also proven on a larger data set covering a large part of the Baltic (Skov et al. 2012).

3.5 Eelgrass meadows in a future Baltic Sea

Eelgrass (*Zostera marina*) forms biologically diverse underwater meadows in the Baltic Sea. Its current distribution ranges from the Kattegat in the south to the Archipelago Sea and the mid part of the Gulf of Finland in the north (Figure 13). Eelgrass grows on sandy seabeds in relatively sheltered areas with a depth distribution of 0.7 to 8 m in the Kattegat and the Danish straits and 1 to 7 m in the rest of the Baltic Sea.

Eelgrass meadows host biologically diverse communities of flora and fauna and act as nursery grounds for several commercially important fish species. The eelgrass beds also recycle nutrients and protect the seabed against erosion.

Figure 13: Eelgrass meadow in the Finnish archipelago. Snails (such as river nerites, *Theodoxus fluviatilis*) sitting on the leaves are common in-habitants of the eelgrass communities in the northern Baltic Sea. Photo: Metsähallitus NHS Finland.

Eelgrass can tolerate salinities down to approx. 5. The temperature optimum of the species is wide, varying from 5 to 30°C, and the species can tolerate near-freezing temperatures and survive under ice-cover for four months. On the other hand, reproduction is limited to much higher temperatures, and since the species also suffers from eutrophication, eelgrass is in its northern distribution area classified as “near threatened”.

A sea level rise of 100 cm as presently discussed in the south-western part of the Baltic will most likely be counteracted by intensive diking in areas where it is needed and feasible. Diking also causes increased water turbidity, and it is probable that eelgrass meadows will not be able to adapt to the lowered light conditions. Therefore eelgrass meadows today present on deep waters will probably disappear in the future if the water quality is not improved to counteract the loss of light.

The low persistence of the northern eelgrass populations against environmental changes has been attributed to their low genotypic and genetic diversity (Montalvo et al. 1997). In the northern Baltic Sea, flowering or fruit production of eelgrass is very rare (Boström 1995) and most of the genetic variability is due to clonal competition over long time (Eriksson 1993). In the northern Baltic Sea most of the population consists of the same genotype, which has been estimated to be 800-1600 years old (Reusch et al. 1999). Clonal growth and low genetic diversity may reduce the acclimation capacity and survival of the species in rapidly changing environmental conditions.

Persisting eutrophication and lowering of salinity will probably diminish the areal coverage of the eelgrass beds in the northern Baltic Sea. What happens to the associated ecosystem after disappearance of the eelgrass is not known. Sandy seabeds are also preferred habitats for other marine vascular plants and Charophytes, which tolerate lower salinities than eelgrass, so sandy areas may be taken over by these taxa. Some of the invertebrates and fish associated with eelgrasses may find refuge from vascular plants and Charophytes, too, but only if they survive lower salinities. In case the functional groups inhabiting eelgrass meadows will be replaced by freshwater species, the functions of the ecosystem may change, and living conditions for many species, including commercially important fish, will also change. Knowledge of such ecosystem processes will be necessary for designing adaptation measures for coastal fisheries.

4 Adaptive measures to secure the Baltic Sea ecosystem services in a future climate

The four major potential climate stressors in a future global change scenario are a general warming of water masses, a reduction in the Baltic Sea salinity, increasing sea level rise and an increasing precipitation especially in winter season.

The influence of climate change on the fate of hazardous substances might also be of importance because several factors like rise in temperature, decrease in oxygen, flooding and increased run-off can alter and modify the distribution, partitioning and degradation of such pollutants in the aquatic environments. In addition, also other indirect effects on the fate of hazardous substances can be linked to climate change, e.g. increased use of agricultural pesticides due to more plant diseases, erosion of coastal areas and altered growth conditions and prey-predator interactions in the food webs. All these factors have the potential to enhance the bioavailability of pollutants and with an increasing risk of transfer of bio-accumulative toxic pollutants in the food web. However, there is still a major knowledge gab on how such changes in the fate and bioavailability of toxic pollutants can result in actual effects on species, population and community levels.

Climate change can have various effects on the nutrient status and eutrophication processes in the Baltic Sea as outlined in Figure 14. Although first studies and model simulations exist, research needs to continue and more precise regional projections are necessary. Besides, numerous interaction feedback mechanisms and complex cause effect chains make it difficult to draw simple conclusions and large uncertainties exist.

Agreed strategies to obtain a good ecological status of the Baltic Sea and its coastal waters, as obligated through the EC Water Framework Directive (WFD) and the Marine Strategy Framework Directive (MSFD), the Baltic Sea Action Plan by HELCOM (BSAP) and national action plans such as the Danish Action Plan for the Aquatic Environment III, have to be implemented. In the implementation process, climate change effects such as changes in precipitation and run-off patterns should be considered, respecting the time scales of climate change and political actions. Although climate change is not explicitly included in the text of the WFD, a guidance document for river basin management in a changing climate has been published (EC 2009). It states that the step-wise and cycling approach of the river basin management planning process makes it well suitable to adaptively manage climate change impacts. This approach means that plans can be revisited to scale up or down the response to climate change in accordance with monitored data. The document highlights the importance that long-term climate projections are built in to the design of measures that have a long design life and high costs. The guidance also includes suggestions for handling available knowledge and uncertainties about climate change, which are important issues that all adaptation actions have to deal with.

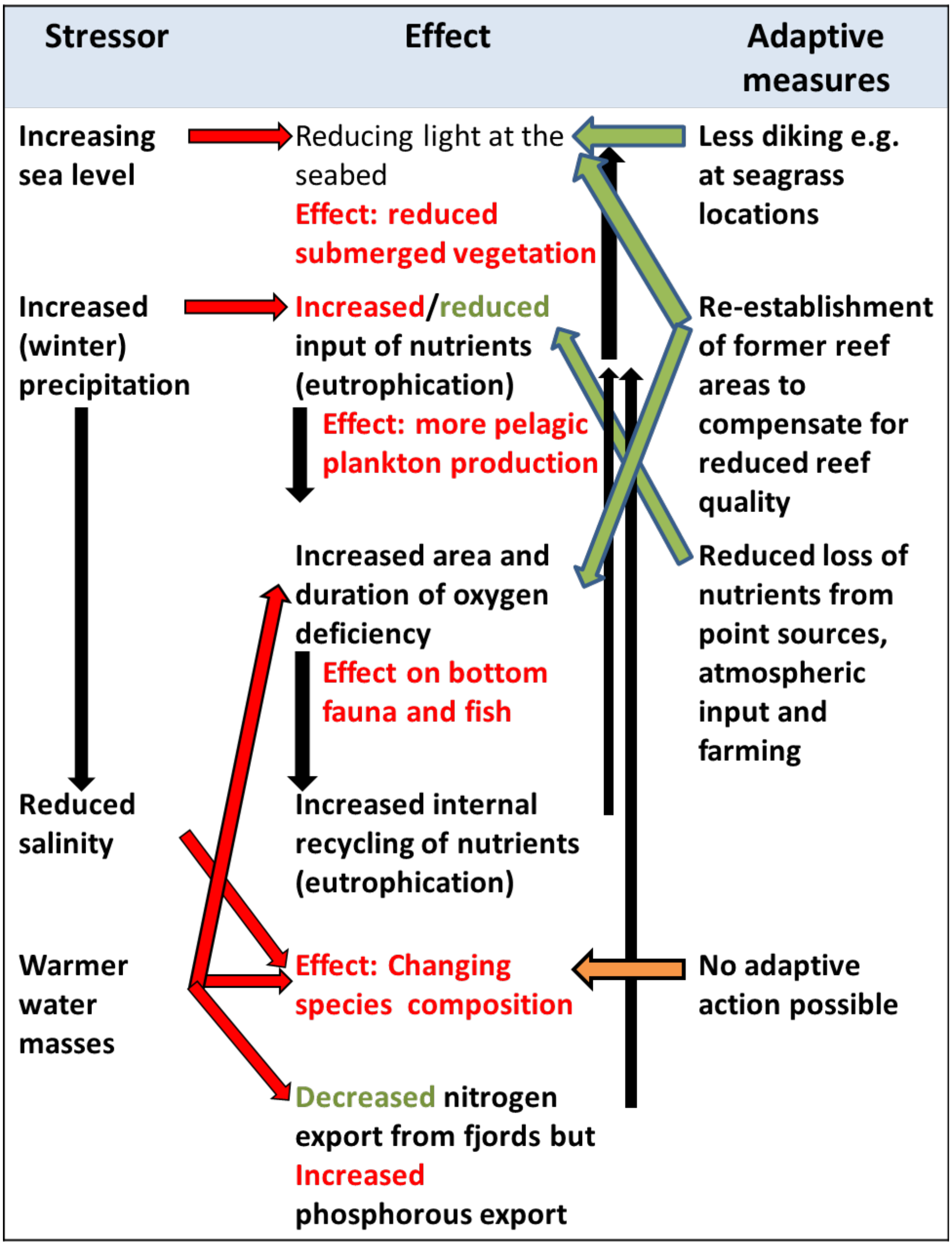

Figure 14: Projected climate change effects on the Baltic Sea ecosystem and possible adaptation to sustain the ecosystem services. Red arrows indicate negative effects on the ecosystem components induced by climate related stressors. Black arrows indicate feedback mechanisms. Green arrows indicate possible adaptation measures. With regard to changing species composition no adaptation seems possible (orange arrow).

Although different future developments are possible and many uncertainties exist, improvement of water quality will be important and for certain a "no-regret-measure" regarding climate change adaptation. Possible adaptation towards a good water quality of the Baltic Sea and its coastal waters in the future includes all kinds of nutrient reduction measures as e.g. suggested by the BSAP and WFD. These measures should be implemented both in the catchment as well as in the coastal waters and include e.g. improvement/construction of wetlands, buffer strips, filter systems in connection with drained agricultural areas, but also supporting (re-)establishment of reefs with macrophytes, mussel beds, etc. In accordance with other studies, we recommend to reduce intense cultivation in lowland areas and increase riparian buffer zones and especially for nitrogen increased retention time from both diffuse sources and point sources would be beneficial (Kronvang et al. 2005). We also suggest a strong focus on temperature effects on phosphorus including further investigations. In addition P and N loadings should be decreased simultaneously to prevent adverse effects on the ecological structure (Howarth & Marino 2006).

No adaption measures are possible to sustain ecosystem services provided by specific species that might be affected by changing temperature and reduced salinity. In case of changing distribution of commercially important fish stocks or e.g. macroalgal species used for mitigation purposes, the adaptation has to be socio-economic.

Figure 15: The result of the nature restoration project “Blue Reef” at the Danish reef Læsø Trindel in the northern Kattegat. A huge amount of Norwegian rocks was deployed on the reef area which was suffering from many years of boulder excavation for harbour protection. The quality of the reef is now restored with high biomasses and seaweed, increased biodiversity and lots of fish.
Photo: Karsten Dahl.

5 Overall evaluation of potential climate change effects on the Baltic Sea ecosystem

It is shown from the model work by e.g. Meier et al. (2012 b) and in the Danish case study that increasing temperature enlarges the area in the Baltic affected by oxygen depletion.

Increasing oxygen depletion will have a profound effect on the Baltic ecosystem. Macrobenthic communities will disappear in areas where permanent oxygen depletion will develop in the future. Changes in community structure towards species that are more tolerant to low oxygen concentrations can be expected in areas with low or frequent problems with oxygen. The ongoing spreading of the three tolerant *Marenzelleria* polychaete species replacing native species may be seen as an example of biological community adaptation to changing oxygen conditions. Increasing areas affected by low oxygen in the Baltic Proper will have a negative influence on the breeding success of the Baltic cod stock. The former important breeding areas Gotland Deep and Gdansk Deep are more or less lost today due to low oxygen concentrations in the water depth where eggs and larvae develop, and the last breeding area at Bornholm Deep is today under pressure as well, for the same reason.

The decline of cod stocks, which has partly been caused by climatic reasons, has 'cascading' effects on the lower trophic levels. Due to the disappearance of cod from the northern Baltic in the 1990s, the number of clupeids (sprat and herring) increased tremendously. This caused fierce resource competition between these plankton eating species, which induced a decline in growth of herring (Peltonen et al., pp. 35-54, this volume). Because climate change may worsen this process by increasing eutrophication and decreasing salinity in the Baltic, conditions for cod reproduction probably remain poor in a changing climate. This need to be taken into account when adapting the fisheries: the future cod stock probably does not tolerate heavy fishing in a less saline Baltic Sea – unless the status of the Baltic Sea will be markedly improved.

Previous studies by Hansen & Bendtsen (2009) and ongoing work during this project (Hansen & Bendtsen 2013) demonstrate the expected increase in oxygen deficiency in the Kattegat and the Danish straits can be counteracted by a further reduction in nutrient loads from Sweden, Denmark and German areas, given a temperature increase of 3°C over the coming 100 years.

The effect of the already observed 1.5 degree increase in the temperature may explain why the oxygen conditions have not yet improved in the Danish waters after two decades of decreasing nutrient concentrations (Hansen & Bendtsen 2009).

Increasing temperature will probably also effect the distribution of the large habitat forming algal species sugar kelp in fjords and other coastal shallow waters in the Kattegat, the Danish straits and western Baltic. The vulnerability of this species is particular interesting as there is presently a high focus on culturing sugar kelp for biofuel and feed production as well as using algal farming as a mitigating action to reduce nutrient loss from future expansion of fish farming. Such mitigating actions are now required by regulation in Denmark.

A likely climate scenario for the Baltic Sea catchment area is more precipitation in the winter and more events with heavy rainfall. Both of these climate effects will increase the risk of nutrient loss from agriculture areas, given the present crops and cultivation. If we for a moment do not consider the political actions taken to improve the water quality in the Baltic Sea region in the future, then increased nutrient loss will stimulate phytoplankton production (e.g. Meier et al. 2011c). This will result in development of oxygen depletion in new areas and promote release of nutrients otherwise buried in the seabed. Increased plankton production will also affect the development of the benthic macro vegetation consisting of e.g. eelgrass and Characean on soft bottoms and macroalgae vegetation on hard substrates. Higher phytoplankton biomasses will decrease the light reaching the seabed and the result will be a reduced depth penetration of e.g. eelgrass meadows and seaweed forests of macroalgae.

A rising sea level will result in significant loss of productivity on hard bottom areas in the southern and western part of the Baltic Sea. An increasing depth of 1 m suggested by some studies will result in a considerable loss of light available at the reef habitats. The loss will be highest in coastal areas where e.g. light reductions of 20% can be expected given the present status of eutrophication in Danish areas. In open waters the effect will be approx. half the size.

The ecological consequences of reduced light penetration to the seabed due to rising sea level and eutrophication will be reduced habitat quality for a large number of invertebrate and fish species using the reefs as breeding, nursery and feeding areas. In rocky coastal areas, adaptation in the seaweed belt is likely to take place as sea level increases.

Changes in species composition are also expected with regard to the forecasted changing salinities, especially in the central part of the Baltic and the changes will probably be accelerated by warmer waters, less ice-cover in the northern part and increasing problems with oxygen in large areas. Changes will include decreasing ratio of biomass between diatoms and dinoflagellates during spring blooms, earlier timing of plankton production and seasonal migration of zooplankton and fish in mild winters. These potential changes in plankton production, biodiversity and species distribution may further result in a mismatch between predators and preys through the marine food chain, ultimately placing additional stress on already declining fish stocks.

It is obvious that nutrient limitations are an adaptive measure to ensure important benthic fauna communities and habitats with submerged vegetation, given expected climate change with regard to warmer waters and increasing sea level rise. On the positive side, studies made as part of this project indicate that a warmer climate might reduce the nitrogen pool in shallow coastal areas primarily by increased denitrification but other processes such as shorter turn over time might also influence the burial rate of nutrients. Unfortunately the effect on phosphorus is contrary and more bioavailable phosphorous should be expected as a result of warming and hence increased risk of anoxic conditions and phosphorus release from the sediment as a consequence of this.

In reaction to the continuing problematic environmental status of the Baltic Sea, several political actions have been taken. The Baltic Sea Action Plan (BSAP, HELCOM 2007a) aims directly at improving the ecological status of the Baltic Sea whereas the EC Water Framework Directive (WFD) and the EC Marine Strategy Framework Directive (MSFD) aim at improving water quality in the European Union and thereby also in the Baltic Sea and its catchment. Efforts to reach the ambitious goals will most likely have profound effects on the Baltic Sea in the next decades. Simulation studies show that implementation of the BSAP will improve the conditions of the Baltic Sea, but in a warmer climate the effect of BSAP on the water quality may not be as large as it would in today's climate (Meier et al. 2011a, Neumann et al. 2012, Friedland et al. 2012).

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Appendix

Appendix 1: Temperature effect on nutrient concentrations in estuaries – less nitrogen and more phosphorous

Increased annual mean temperature seems to stimulate the removal of total nitrogen (TN) but increase total phosphorous (TP) concentrations.

Based on 22 years of environmental monitoring in Danish seas and estuaries we made an analysis of the combined effect of climate parameters and the input of nutrients from rivers on the total nitrogen concentration in the estuaries. The analysis was made for five stations in inner and outer parts of three estuaries. All 5 data sets showed decreasing TN concentration with increasing annual mean temperature. Each of the individual correlations is not statistically significant but 5 negative correlations are a significant result ($p = 0.03$). The aforementioned correlations were robust against different statistical analysis methods. The results are consistent with a previous analysis in the estuary Limfjorden in northern Denmark where negative correlations between water temperature and TN-concentration were found for seven out of seven stations and in addition there are several other studies that support the findings (Nowicki et al. 1997). We therefore hypothesize that increased temperatures will reduce the level of nitrogen in temperate estuaries.

Our results predict a reduction of TN concentrations of 1-5% $°C^{-1}$ for three of the stations. At the two stations situated in Randers Fjord, correlations predicted reductions of 20-25% $°C^{-1}$. This is an order of magnitude higher than the other stations and significantly higher than what could be expected from denitrification alone according to literature values (Nielsen et al. 2001). Randers Fjord differs a lot from the two other estuaries, it is a long narrow estuary and receives most of its nutrients from its main tributary (Gudenåen river). In Gudenåen there has been a clear increase in macrophytes over the last decades. This has likely increased the N retention in the estuary since the N retention in Randers Fjord is mainly due to sedimentation and burial of organic material from the river. Since the macrophyte biomass in the river is not included in the analysis, the effect will be assigned to other co-varying parameters such as temperature. The retention time in Randers Fjord can be as low as three days, therefore the influence of sediment processes like denitrification is limited and highly dependent on variations in retention time.

Other studies have shown that the denitrification rate is temperature sensitive in an exponential relationship which results in an increased removal of 7% to 16% $°C^{-1}$ (Dawson & Murphy 1972, Nowicki 1994). Increasing temperatures have also been shown to speed up removal of N both in experiments and in field studies (Nowicki 1994, Nowicki et al. 1997). Other studies (Nielsen et al. 2001) have shown that denitrification removes from about 6% and up to 23% of the nitrogen input to estuaries depending on concentration and retention time. If this is combined with the coefficient for temperature, we would expect an increase in N removal of 1.2% to 3.7% $°C^{-1}$. This is in accordance with the increased N removal of 1-5% $°C^{-1}$ of TN that we report. If this trend is extrapolated to a predicted temperature increase of 3-5°C it will result in a decreased N concentration of approx. 3-20% in year 2070-2100 without any change in loading.

Cyanobacteria which can contribute significantly to the N input in aquatic system do not occur in substantial amount in the estuaries we have investigated. This is mainly due to high salinity. However, in estuaries or parts of the Baltic Sea with lower salinity, an increase in temperature and phosphorus concentration might stimulate the growth of cyanobacteria and their possible nitrogen fixation may act as a source for increased nitrogen input. There is evidence that N-fixing cyanobacteria blooms are enhanced by low N:P ratios and stable water column, especially in the Baltic Proper(Granéli et al. 1990, Stal et al. 1999, Kahru et al. 2000).

The analyses of total phosphorus concentration (TP) and temperature dependence showed generally a positive correlation between P and temperature. The correlations were not as robust as for N and they were very biased by the large reduction in the late 1980s, but there was still a general positive trend.

The observed increase ranged from approx. 5 to 15% $°C^{-1}$. If this trend is extrapolated to a predicted temperature increase of just 3 °C, it will result in an increased P concentration of approx. 15-50% in year 2070-2100 and for 5°C the concentration might at worst double, without any change in loading.

We suggest two mechanisms that can lead to a positive relationship between temperature and phosphorus concentration. The literature shows that increasing temperatures can lead to decreasing adsorption of soluble phosphorus to particles (Froelich 1988). However, the most important mechanism is probably that phosphorus is released during anoxic conditions in sediment and bottom waters. As anoxia and hypoxia are enhanced by elevated temperatures, it brings about an indirect effect of temperature rise.

Impacts

In many of the Danish estuaries, phosphorous concentration is limiting algae growth in the early season. Therefore even small increases in P levels can enhance algal growth and exacerbate Secchi depth especially during algal blooms in spring. An intense spring bloom may negatively influence water quality the rest of the season. A severe algal bloom can leave a large amount of organic material on the bottom which can enhance anoxic conditions later in the year. Normally spring blooms are dominated by diatoms but they tend to become silica limited where there is a major surplus of N and P; this may lead to blooms of toxic algae like *Chatonella spp.* subsequent to a diatom bloom. In-creased P run-off from increased precipitation has also been predicted (Jeppesen et al. 2009) which makes the demand for further reduction in P loading more current.

N is still thought to be the limiting nutrient in most of the growth season and it has also been shown to be the limiting nutrient in most parts of the Baltic Sea though large areas like the Bothnian Bay might be more controlled by phosphorous (Granéli et al.1990). Therefore, the focus should still be on reductions of both nutrients.

Depending on the exact temperature effect, the expected reductions in N might more or less cancel out the increased loading that is due to increased run-off from non-point sources and change in cropping patterns. In the Danish coastal catchment areas, the N run-off is predicted to increase annual loading by 5-7% in 2070-2100 compared with our prediction of a decreased N concentration of 3-20% for the SRES A2 scenario. The final development will be dependent on the specific estuary, hydraulic retention time and its catchment area but it is most likely that the combined changes due to climate change will be less important than the anthropogenic contribution and reduction in this. Our combined expectations are summarized in Figure 16.

In addition to the temperature effects on nutrients, other processes such as nitrification and degradation of organic material will increase with increasing ammonia and organic loading and the rates are also positively affected by temperature while warm water even contains less oxygen and hence increases the risk of hypoxia (see Chapter 4).

Uncertainties

The analytical methods are subject to some uncertainty while there are many co-varying parameters and relatively few observations. This increases the risk to conclude that there is a relationship where there is not. In our case we are very confident about the nutrient concentration and temperature relationships since they seem to be thorough and are supported by several other studies but because of co-variance, the complexity of the nutrient cycling and the relatively low variance in temperature the exact quantification of the effects are less confident. The residence time in each of the estuaries also has a high impact on the effect of e.g. denitrification and hence the effect of temperature variations.

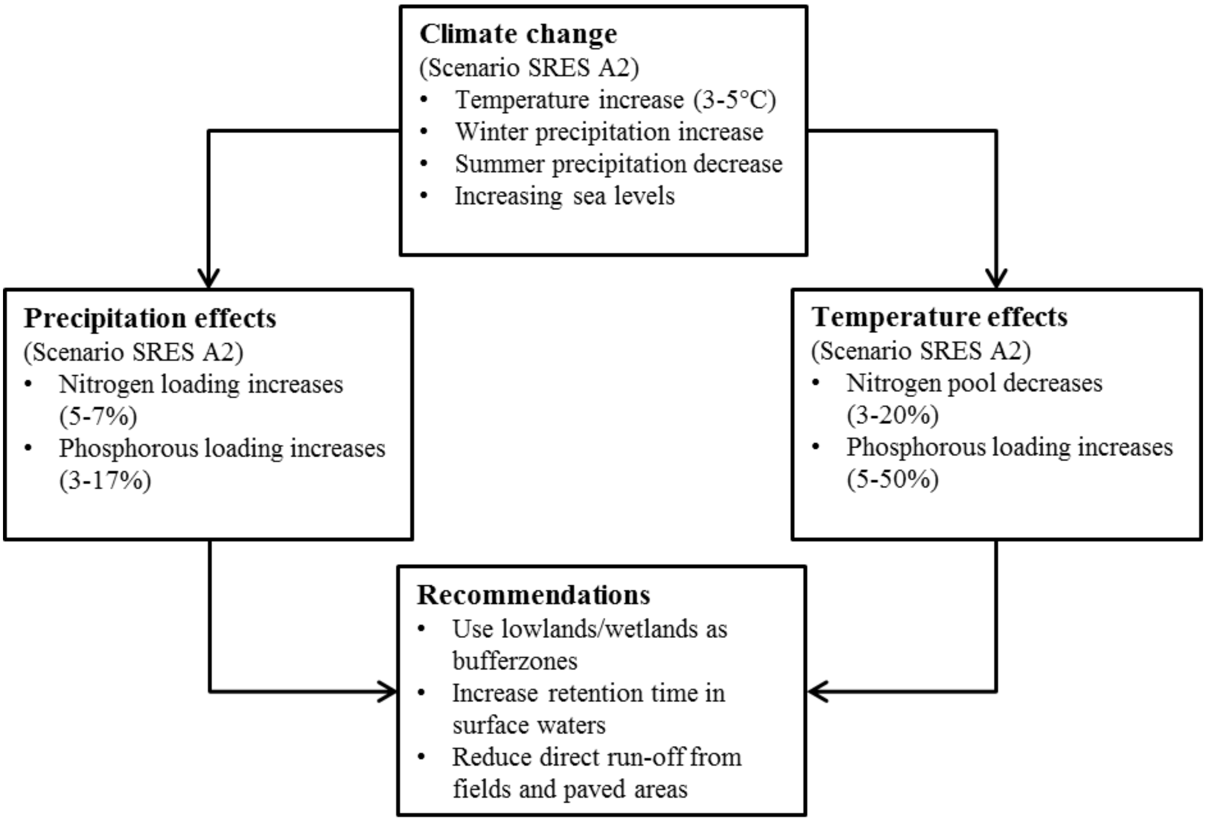

Figure 16: Schematic summary of the predicted change in nutrient loadings in Danish estuaries due to climate change and some recommendations. Some of the same effects are expected for northern and western part of the Baltic Region.

Appendix 2: Impact of a warmer climate on hypoxia in the North Sea – Baltic Sea transition zone

Oxygen conditions in the Baltic Sea have been deteriorating since the 1950s due to increased external nutrient inputs and eutrophication processes. Oxygen depletion is a reoccurring problem in the inner Danish coastal waters in the transition zone between the North Sea and the Baltic Sea (Figure 17). Every year in late summer hypoxic events occur but the extent of the affected areas varies considerably. However, almost every year the benthic fauna are damaged to some degree and in the worst cases, the fauna community becomes completely destroyed. The effect of hypoxia is evident when dead fish wash ashore. However, before the damages become so visible and spectacular, the benthic fauna has typically already been affected (Conley et al. 2007).The latest severe oxygen depletion event was in the years 2002 and 2003, when hypoxic water covered large areas of the sea bottom in the inner Danish waters for months. Oxygen depletion has become a growing problem in many coastal areas throughout the world due to eutrophication (Diaz & Rosenberg 2008) and has been considered as the greatest threat to benthic biodiversity (Gray 2002). Even though action plans have been implemented and the nutrient concentrations have been declining, there have been no significant improvements of the oxygen conditions in the inner Danish waters. However, the climate also plays a role for the oxygen dynamics in the area. In particular the wind determines the ventilation of the bottom water and the temperature determines the respiratory oxygen demand. In fact, the climate change that has been documented for the last decades may already have caused negative effects on the oxygen conditions.

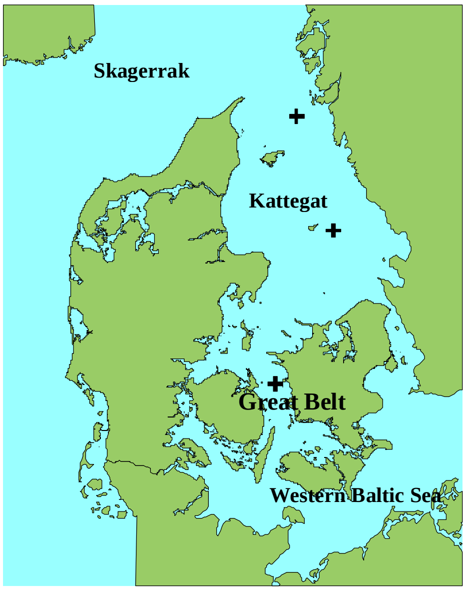

Figure 17: The inner Danish waters located in the transition zone between the North Sea/Skagerrak and the Baltic Sea. Crosses mark the position of monitoring stations used to calibrate the oxygen model OXYCON.

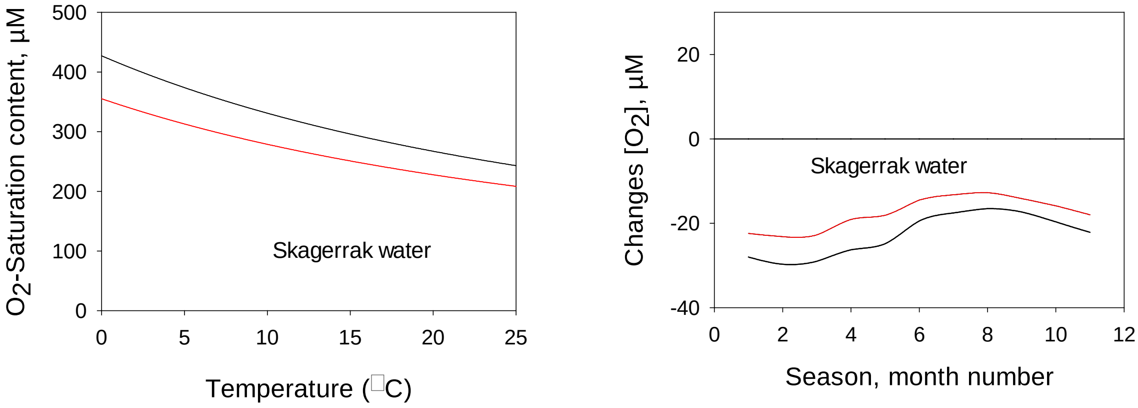

Figure 18: Left: Oxygen concentration at 100 % saturation in the two water masses that mix in the inner Danish waters: the water from the Baltic Sea (black Line) and the water from the North Sea and Skagerrak (red line) versus the water temperature. Right: The changes in the oxygen concentration during the seasons if the water column is warmed by 3°C all year round.

In contrast to life on land where oxygen is plentiful, the pool of oxygen available for respiration in aquatic environments is small due to its low solubility in water. Hypoxia describes the situation where biological respiration is limited by the amount of oxygen in the water and where the organisms begin to die depending on tolerance limits of the species. Logically, hypoxia starts to develop when oxygen consumption in a water body exceeds the input of oxygen due to production (photosynthesis) and due to ventilation of the water column by oxygen-rich surface water. The larger the initial pool of oxygen in the bottom water, the longer it takes for hypoxia to develop. In most cases hypoxia develops in periods where the bottom water is warm and stagnant due to calm weather conditions and thereby low ventilation efficiency.

The effect of global warming on hypoxia

The solubility of oxygen in water decreases with the temperature and this means that the pool of oxygen in the bottom water will be used up faster. This is particularly relevant for areas like the transition zone between the Baltic Sea and the North Sea where the water column is permanently stratified and where ventilation by mixing of the water column is limited. Advection of bottom water from the northern boundary of the area (the North Sea/Skagerrak) is the most important source of oxygen for the Kattegat area. Therefore increasing temperature will cause less oxygen in the bottom water advected into the Kattegat. The oxygen decrease due to increased temperature is also observed in riverine ecosystems flowing into the Baltic Sea (Springe et al. 2012). Increasing temperatures will also cause increasing respiratory oxygen consumption rates. Typically the respiration rate increases by a factor of 2-4 if the temperature rises by 10°C. Due to these two effects, hypoxia is tightly coupled to the temperature and almost exclusively occurs during the summer period. A model, OXYCON, has been developed to describe the influence of temperature on the oxygen dynamics in the North Sea-Baltic Sea transition zone (Hansen & Bendtsen 2013) and tested in Jonasson et al. (2012). The model considers the combined influence from biological processes and physical transports on oxygen concentration in the bottom water. Oxygen sinks due to the pelagic and benthic microbial respiration together with the benthic macrofaunal oxygen consumption are considered. Ventilation of bottom water due to mixing and advection (i.e. transport by currents) is described by applying a, so called, “ventilation age tracer” which has previously been shown to resolve the basic dynamics of bottom water ventilation in the area (Bendtsen et al. 2009).

Model simulations of the oxygen dynamics in the transition zone

The distribution of oxygen has been modelled for the three consecutive years 2001-2003 and the simulations correspond very well with observations from the area (Hansen & Bendtsen 2013, Jonasson et al. 2012). The years 2001-2003 differed markedly with respect to hypoxia. The oxygen conditions were relatively good in 2001, whereas 2002 experienced the worst conditions for decades due to calm weather conditions during the summer and in 2003 bad oxygen conditions were due to high temperatures (HELCOM 2003). Thereby the simulated period covers the range of seasonal hypoxia in the area. To describe the oxygen conditions in a future warmer climate, a scenario with the 2001-2003 climate conditions but with 3°C higher temperatures has been conducted (Figure 19). The temperature anomaly of 3°C is within the expected range of temperature increase by the end of this century (BACC 2008).

The results show that the oxygen concentration in the bottom water will be lowered significantly with 30-60 µM throughout the year with the most significant reductions during summer and in the southern part of the area. Hypoxia will occur in the northern area where there is presently no hypoxia. In the central Kattegat the hypoxic season will increase from a few weeks to about one month and in the Great Belt the duration will increase from about 1 month to about 3 months. The minimum oxygen concentration will also be lower and anoxia will occur in the Great Belt in some years in the future.

The total area affected by severe hypoxia (oxygen concentration < 2 mg O_2/l) under the present-day climate ranges from 3,000 km^2 to about 15,000 km^2. A climate change scenario where the temperature is 3°C higher than today but where the input of organic matter to the bottom water is at the same level as today will result in an increase in the hypoxic area by 50-100% (Figure 20, orange line). In the extreme case where the temperature is increased by 3°C and where the benthic communities respire 20% more organic material, the hypoxic area will increase by 100-400%.

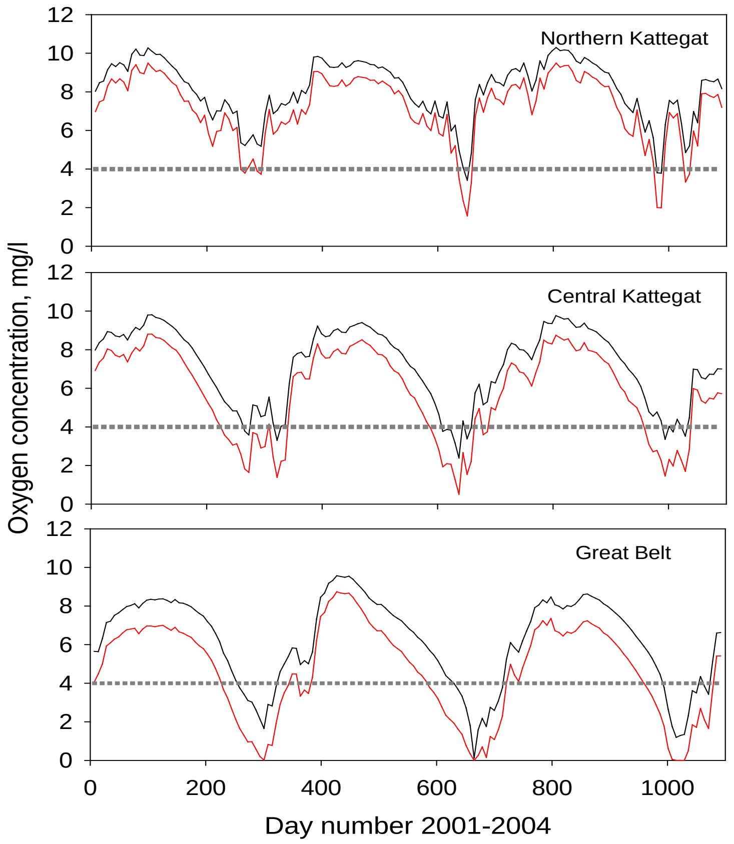

Figure 19: Black line: Temporal distribution of bottom water oxygen during 2001-2003 at three stations in the northern and central Kattegat and in the Great Belt. Red line shows the distribution of oxygen under similar meteorological conditions but with a 3°C higher air temperature and water temperature in the inflowing Skagerrak bottom water throughout the year. Dotted line indicates the conventional limit for hypoxia in the area.

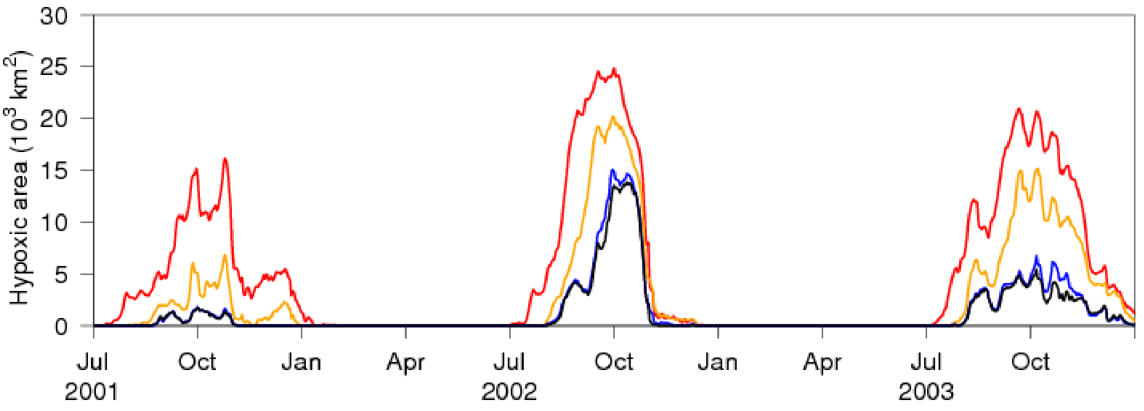

Figure 20: Total hypoxic area in the western Baltic Sea, the Belt Sea and in the Kattegat in km^2 during the season as simulated with OXYCON for different climate scenarios. All scenarios are based on the climate conditions obtained for the 2001-2003 period. Black lines show reference conditions (corresponding to the black line in Figure 18) and red lines show the hypoxic area under a 3°C warmer climate. Orange lines show a climate scenario with (+3°C) combined with a 45% reduction in the benthic respiration (the total carbon mineralization is maintained at the present-day level corresponding to the red line in figure 18) Blue lines show a climate scenario (+3°C) combined with a 30% reduction in the total primary productivity in the area.

In order to compensate for effects of increasing temperatures on the oxygen concentration, it is necessary to decrease the primary productivity. Model solutions show that a 30% reduction in the total primary export production combined with a 3°C temperature increase will result in the same oxygen conditions as observed during the present-day climate (Figure 20, blue line). In the Kattegat and the Belt Sea this means that inorganic nitrogen, which is the limiting nutrient for export production, should be decreased correspondingly. This is to some extent possible by reducing the riverine contribution from land.

The warmer the climate will be in the future, the stronger the negative effect on the oxygen conditions. Figure 21 shows the expected relationship between the number of hypoxic days in the central Kattegat and the temperature anomaly shows an almost linear relationship in the range of temperature changes between -2 and +5°C. This scenario corresponds to the most extreme scenario where the simulated oxygen concentration is not adjusted to the present-day primary productivity level.

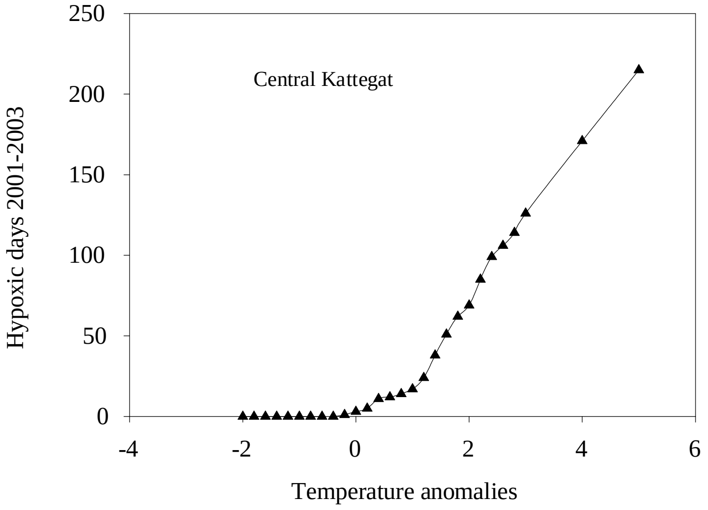

Figure 21: Number of hypoxic days in the central Kattegat versus the temperature anomalies as simulated with OXYCON.

For the Baltic Sea, different projections for climate change effects on oxygen contents exist. Projected increasing river discharge and precipitation might strengthen the stratification thereby reducing downward oxygen transport to deeper waters and worsen bottom oxygen condition in the deeper parts of the Bothnian Sea and the Baltic Proper. Other studies suggest a decreasing stability of vertical stratification e.g. in the Gotland Sea due to increased wind-induced mixing and slightly improved oxygen conditions in deep waters (Neumann 2010). Oxygen-rich inflows from the Northern Sea also play a major role for the oxygen conditions in the deeper parts of the Baltic Sea. Projected less oxygen-rich salt water inflows will have a negative effect on the oxygen content of bottom water (Meier et al. 2011a).