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Comparing reconstructed past variations and future projections of the Baltic Sea ecosystem—first results from multi-model ensemble simulations

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Abstract

Multi-model ensemble simulations for the marine biogeochemistry and food web of the Baltic Sea were performed for the period 1850–2098, and projected changes in the future climate were compared with the past climate environment. For the past period 1850–2006, atmospheric, hydrological and nutrient forcings were reconstructed, based on historical measurements. For the future period 1961–2098, scenario simulations were driven by regionalized global general circulation model (GCM) data and forced by various future greenhouse gas emission and air- and riverborne nutrient load scenarios (ranging from a pessimistic ‘business-as-usual’ to the most optimistic case). To estimate uncertainties, different models for the various parts of the Earth system were applied. Assuming the IPCC greenhouse gas emission scenarios A1B or A2, we found that water temperatures at the end of this century may be higher and salinities and oxygen concentrations may be lower than ever measured since 1850. There is also a tendency of increased eutrophication in the future, depending on the nutrient load scenario. Although cod biomass is mainly controlled by fishing mortality, climate change together with eutrophication may result in a biomass decline during the latter part of this century, even when combined with lower fishing pressure. Despite considerable shortcomings of state-of-the-art models, this study suggests that the future Baltic Sea ecosystem may unprecedentedly change compared to the past 150 yr. As stakeholders today pay only little attention to adaptation and mitigation strategies, more information is needed to raise public awareness of the possible impacts of climate change on marine ecosystems.

Keywords: Baltic Sea, numerical modeling, climate change, eutrophication, scenarios, ensemble modeling, marine biogeochemical cycles, marine food web, Baltic Sea Action Plan, decision support system

1. Introduction

The Baltic Sea is a semi-enclosed sea with a positive freshwater balance due to runoff from a catchment area which is four times the sea surface area (e.g., Leppäranta and Myrberg 2009). As the mean water depth is only 54 m, temporal variations in stratification and currents are large compared to other seas, making the Baltic Sea vulnerable to global change.

About 85 million people live in the catchment basin, and the intensive agriculture, especially in the southern part, is mainly responsible for the release of nutrients into the watershed and subsequent transport towards the sea. As a consequence, the Baltic Sea today suffers from severe environmental problems due to eutrophication, e.g., extensive cyanobacteria blooms and an expansion of dead bottoms (e.g., Elmgren 2001, Conley *et al* 2009, Savchuk 2010). To overcome these problems, a reduction of nutrient loads from the atmosphere, point sources and rivers is of vital importance. This is envisaged to be achieved with the help of international policies, e.g., the Helsinki Commission’s (HELCOM’s) Baltic Sea Action Plan (BSAP), which is a unique collaboration of all Baltic Sea riparian states, aiming for a healthy Baltic Sea with good water quality (HELCOM 2007).

To understand the potential consequences of different management measures on the marine ecosystem, we developed a multi-model system tool to support decision making (figure 1). The model system produces scenario simulations of the whole marine ecosystem, which are suited to support management strategies in order to ensure water quality standards, biodiversity and viable fish stocks.

As the response time scale of the Baltic Sea system to changing nutrient loads from land amounts to several decades (e.g., Conley *et al* 2009, Savchuk 2010), long scenario simulations are needed, taking into account the combined effects of changing climate and nutrient loads (e.g., Meier *et al* 2011). To estimate uncertainties caused by model biases, we used a model ensemble approach (cf figure 1). Future projections are compared with variations during the past 150 yr.

To evaluate the models’ sensitivity to changing drivers on long time scales, we reconstructed atmospheric surface fields, runoff and nutrient loads from land and atmospheric deposition for the period 1850–2006. These reconstructions gave clues about eutrophication, warming trends related to anthropogenic influences, and decadal variations (such as stagnation periods) in the past, helping to understand expected future changes. For coupled climate–environmental modeling, the ensemble approach is novel and, to our knowledge, a comprehensive downscaling approach as in this study[14] has never been applied before.

2. Methods

2.1. Future climate forcing

Following Meier *et al* (2011), four climate scenario simulations using regionalized data from two general circulation models (GCMs) and two greenhouse gas emission scenarios (A2, A1B) were used to force three state-of-the-art coupled physical–biogeochemical models in the period 1961–2098. For the dynamical downscaling, a regional, high-resolution coupled atmosphere–ice–ocean–land surface model (the Rossby Centre Atmosphere Ocean model, RCAO; Döscher *et al* 2002) with lateral boundary data from GCMs was applied. Runoff is calculated using a statistical model (Meier *et al* 2012). In the investigated four scenario simulations, annual mean air temperature in the Baltic Sea

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[14] The present study summarizes selected research highlights of the BONUS project ECOSUPPORT (advanced modeling tool for scenarios of the Baltic Sea ECOsystem to SUPPORT decision making, see www.baltex-research.eu/ecosupport). During 2009–11, 11 institutes from seven Baltic Sea countries contributed to research on the effects different mitigation measures may have on the marine ecosystem. More detailed results of the ECOSUPPORT project will be published elsewhere.

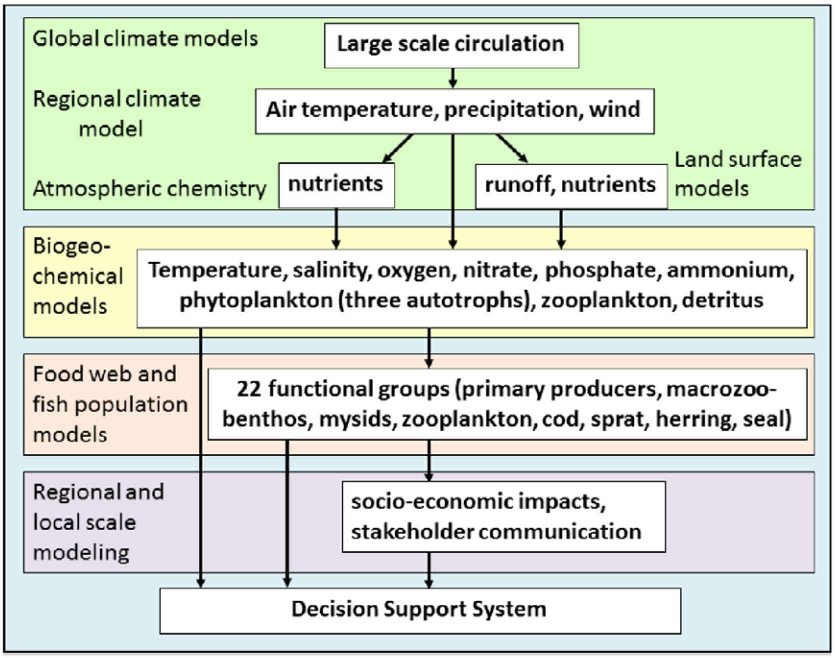

Figure 1. The ECOSUPPORT decision support system is based on scenario simulations from a Regional Climate Model, forced with lateral boundary data from Global Climate Models (GCMs), hydrological models to calculate river flow and nutrient loadings, atmospheric deposition data, marine physical–biogeochemical models of differing complexity, food web and statistical fish population models, regional case studies and socio-economic impact studies.

Region (BSR) is projected to be 2.7–3.8 K higher in 2070–99 relative to 1969–98 (Meier *et al* 2012). Due to an increase of net precipitation over the Baltic Sea catchment area, river runoff is projected to increase between 15 and 22%. Over the Baltic proper (comprising the Arkona, Bornholm and Gotland sub-basins) small, but statistically significant wind speed changes are only found in two out of four scenario simulations.

Three nutrient load scenarios, ranging from a pessimistic 'business-as-usual' to a more optimistic case, were used in the models: a reference case with a continuation of present loads (REF), the implementation of abatements according to the BSAP (BSAP), and a 'business-as-usual' case (BAU) with increasing loads due to increased use of fertilizers in transitional Baltic Sea countries (Gustafsson *et al* 2011). Atmospheric deposition changes vary between a 50% reduction in BSAP and no change in BAU, compared to present conditions. In addition, the food web simulations presented here employ two cod fishery scenarios ('business-as-usual' and 'cod recovery plan' with a fishing mortality $F_{\mathrm{cod}} = 0.3$ following EC (2007)). Note that cod is the main predatory fish in the Baltic Sea and has a high value for fisheries.

2.2. *Past climate forcing*

For 1850–2006, multivariate high-resolution atmospheric forcing fields were reconstructed (Schenk and Zorita 2012). The daily fields are homogeneous and physically consistent by making use of both long European historical station data since 1850, and simulated atmospheric fields from RCAO over Northern Europe in the period 1958–2006, driven by re-analysis data at the lateral boundaries (Samuelsson *et al* 2011). The reconstruction of monthly nutrient loads from rivers and point sources and of atmospheric nitrogen deposition for 1850–2006 is based on available historical data (Savchuk *et al* 2012).

2.3. *Biogeochemical and food web models*

Three coupled physical–biogeochemical models are used to calculate either historical climate variations in the period 1850–2006 (driven by reconstructed data), or changing climate in the period 1961–2098 (driven by regionalized GCM data): the BAltic sea Long-Term large-Scale Eutrophication Model (BALTSEM) (Gustafsson 2003, Savchuk 2002), the Ecological ReGional Ocean Model (ERGOM) (Neumann *et al* 2002), and the Swedish Coastal and Ocean BIogeochemical model coupled to the Rossby Centre Ocean circulation model (RCO-SCOBI) (Eilola *et al* 2009, Meier *et al* 2012). To calculate appropriate initial conditions, customized spin-up strategies for each of the models were developed.

A new Baltic proper Ecopath with Ecosim food web model (BaltProWeb) is used to analyze climate induced changes in marine food webs and the implications on ecosystem services (Tomczak *et al* 2012). The model contains 22 functional groups, from primary producers to seals and fishery, and was calibrated with data across trophic levels. BaltProWeb is forced by model outputs (primary production, temperature, salinity, hypoxic area and cod reproductive volume) from the three biogeochemical models. In addition,

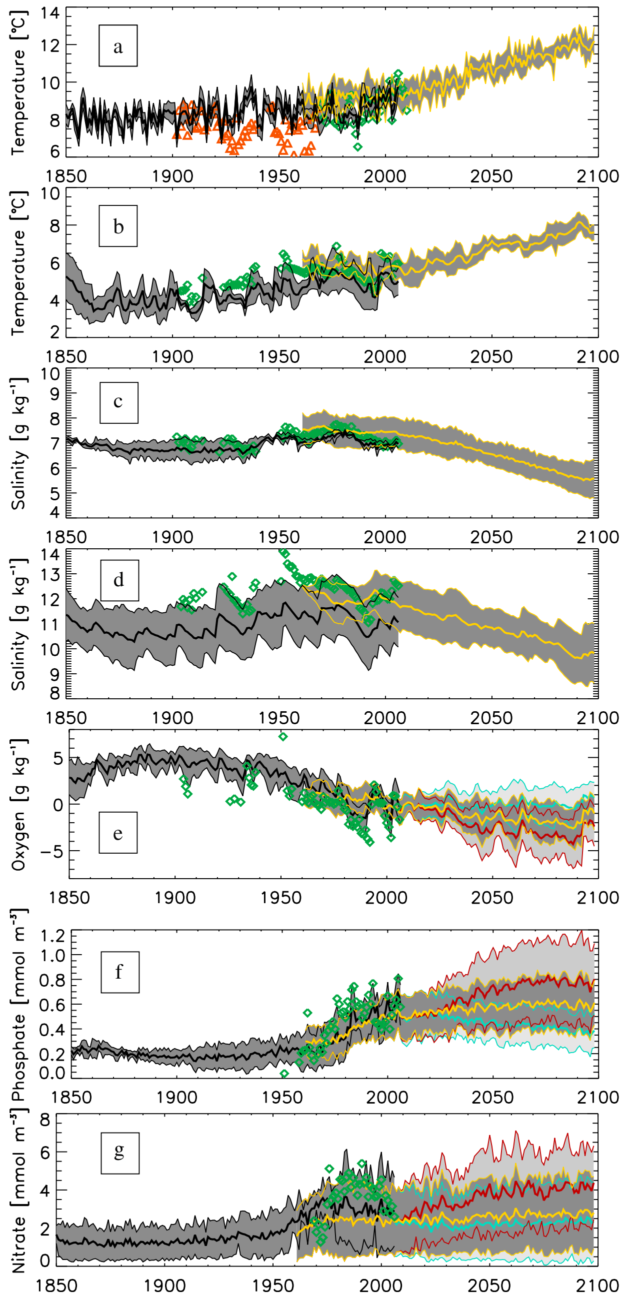

Figure 2. Simulated ensemble averages and observed annual mean water temperatures ((a), (b)) and salinities ((c), (d)) at Gotland Deep at 1.5 and 200 m depth, annual mean oxygen concentrations at 200 m depth (e), and winter (January–March) mean surface phosphate (f) and nitrate (g) concentrations. Shaded areas denote the ranges of plus/minus one standard deviation around the ensemble averages. The various nutrient load scenarios (1961–2098) are shown by colored lines (REF—yellow, BSAP—blue, BAU—red) and the reconstruction (1850–2006) by the black line. For comparison, observations from monitoring cruises at Gotland Deep (green diamonds, in panel (a) since 1970 only) and from the light ship Svenska Björn, operated during 1902–1968 (orange triangles in panel (a)), were used.

statistical single- and multi-species models are used to link climatic forcing and lower trophic level processes to fish dynamics. Furthermore, an assessment of plausible impacts of ocean acidification on key functional groups using available food web data is carried out to better understand the response of Baltic Sea organisms.

2.4. Socio-economic impact assessment

Assessments of the impact of climate change on regional and local developments and a cross-country analysis of stakeholder perceptions in eight Baltic Sea countries are performed. As the awareness of stakeholders will ultimately affect their actions, the results of the questionnaires are important for the implementation of climate change adaptation strategies in long-term coastal management.

3. Results

3.1. Evaluation 1850–2006

Simulated water temperature, salinity, oxygen and nutrients are evaluated using long observational records at Gotland Deep, a monitoring station which characterizes typical hydrographic properties of the Baltic proper (figure 2). Although during the period 1961–90 sea surface temperatures (SSTs) in GCM driven simulations are usually warmer compared to SSTs in the reconstructions, SSTs in the 1990s and 2000s are relatively close in both datasets (figure 2(a)). Note that annual mean, observed SSTs might be biased because the seasonal cycle during some years is not well resolved. For instance, the lightships did not operate during winter.

Observations of water temperature at 200 m depth at Gotland Deep suggest that reconstructions and GCM driven simulations have cold and warm biases, respectively (figure 2(b)). Nevertheless, temperature variations in reconstructions and observations are similar.

Reconstructed sea surface salinities (SSSs) show realistic long-term variations but are slightly underestimated compared to observations, in particular prior to 1930. In the GCM driven simulations mean SSS values, averaged for the period 1961–2006, are slightly overestimated compared to observations (figure 2(c)).

Although many of the saltwater inflows are reproduced using the reconstructed atmospheric forcing, salinities at 200 m depth are considerably underestimated in two out of three models, whereas mean deep water salinities in the GCM driven simulations are close to observations (figure 2(d)). However, the chronologies of natural variations differ among the climate realizations due to the chaotic behavior of the Earth system. Hence, the temporal evolution of the ensemble mean of the GCM driven simulations does not include observed decadal variations, like the stagnation period 1983–92.

Although oxygen concentrations at 200 m depth are overestimated in the reconstructions compared to observations, in particular prior to 1930, the negative trend since the 1950s caused by eutrophication is well captured (figure 2(e)). The too high deep water oxygen concentrations during the early period might be caused partly by a too weak vertical stratification (due to the too low salinities in the deep water) and partly by shortcomings in simulated oxygen consumption in oligotrophic ecosystems. Note that

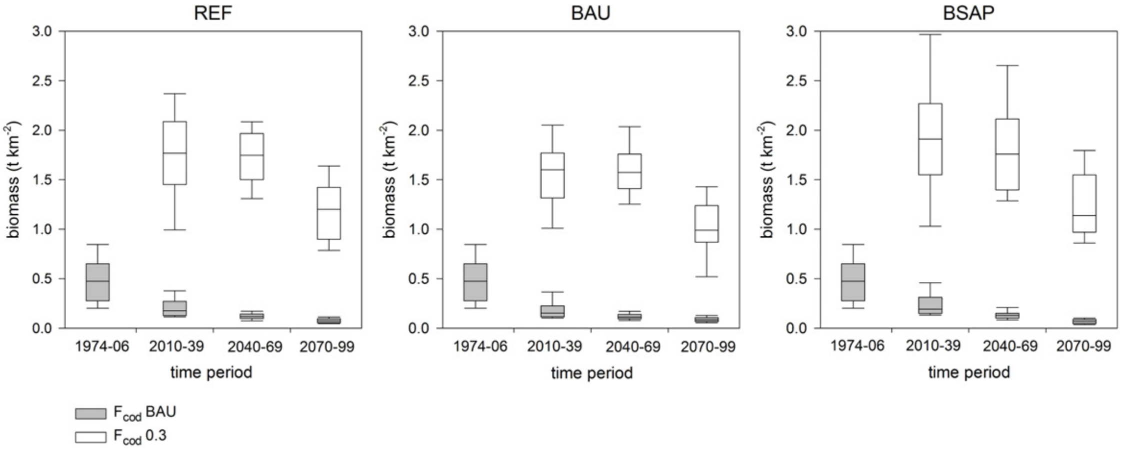

Figure 3. BaltProWeb model projections of adult cod biomass under REF, BAU and BSAP nutrient load conditions in combination to an intensive (F_{cod} BAU) and a more precautionary (F_{cod} 0.3) cod fishing scenario. Box and whisker plots, with 50% (median), 25% and 75% quartiles, are calculated as ensemble mean from four climate projections and three oceanographic-biogeochemical models.

the temperature offset plays a minor role only. Also, mean oxygen concentrations in GCM driven simulations are slightly overestimated compared to observations.

Furthermore, surface phosphate concentrations in the reconstructions reflect the history of eutrophication since the 1950s satisfactorily (figure 2(f)). However, in the GCM driven simulations, the positive trend in the ensemble mean surface phosphate concentration is somewhat too small. This might be explained by the fact that at least in one out of three models, external nutrient loads do not represent the observed temporal evolution correctly. In this case, riverine nutrient concentrations are assumed to be constant during 1961–2006.

For surface nitrate concentrations, the discrepancies among the models during 1961–2006 are even larger than for surface phosphate concentrations (figure 2(g)). During the 1980s and 1990s ensemble average, surface nitrate concentrations are in both, the reconstructions and GCM driven simulations, too small compared to observations.

3.2. *Changing climate and marine biogeochemistry 2007–98*

Figure 2 also shows results from scenario simulations of future climate in the central Gotland Basin. As a consequence of increased air temperature and freshwater supply, water temperatures are projected to increase and salinities to decrease (figures 2(a)–(d)), in accordance with results by Meier *et al* (2011). At the end of the 21st century, both surface and deep water temperature and salinity changes in the A1B/A2 scenarios are larger than all decadal variations ever observed or reconstructed since 1850.

Warmer water changes the oxygen saturation concentrations and turnover rates of biogeochemical processes, enhancing eutrophication (Meier *et al* 2011). Hence, depending on the nutrient load scenario, oxygen concentrations in the Baltic deep water are projected to decrease, compared to the 2000s (figure 2(e)). Only in the BSAP nutrient load scenario, oxygen concentrations during the 21st century remain more or less the same. However, compared to the observed, exceptionally low oxygen concentrations during the beginning of the 1990s and 2000s, projected oxygen concentrations reach only lower values by 2100 in the lower range of the BAU and REF scenarios (ensemble mean minus one standard deviation). Both the reconstructions and scenario simulations suggest that the oxygen concentrations during the beginning of the 1990s and 2000s are unusually low. These extremes are explained by the coincidence of a 10 yr long stagnation period and the impact of eutrophication caused by the excessive nutrient loads from land that reached a maximum during the beginning of the 1980s (Savchuk *et al* 2012).

Future surface phosphate concentrations are projected to continue to increase in the REF and BAU nutrient load scenarios but decrease in BSAP, compared to the 2000s (figure 2(f)). Also, surface nitrate concentrations increase in BAU and (slightly) in REF, but remain approximately unchanged in BSAP (figure 2(g)). In none of the nutrient load scenarios could the environmental status of the 1950s be restored.

In summary, climate induced changes, together with present external nutrient loads (REF) will very likely affect the marine environment, inter alia, with enhanced eutrophication (figures 2(f) and (g)), increased oxygen depletion (figure 2(e)), and reduced water transparency (due to increased organic material in the sea, not shown). In addition, decreased salinity (figures 2(c) and (d)) may contribute to reduced biodiversity and increased atmospheric CO_2 concentrations may lead to increased risk of acidification.

Note that for biogeochemical variables, especially in BAU, the spread among ensemble members increases with time because the sensitivities of the models to nutrient load changes differ. Despite these uncertainties, the scenario simulations suggest that climate induced changes are considerable and may not easily be counteracted by reductions of future nutrient loads.

3.3. *Changing food webs 2007–98*

Although fish population/food web models have very different parameterizations, assumptions and sensitivities to environmental forcing, all applied models under currently defined sustainable fishing conditions indicate that the sprat spawning biomass will likely increase in the Baltic Sea during the 21st century.

BaltProWeb was used for an extensive combination of climate, nutrient loading and fishery scenarios, using outputs from all three biogeochemical models (figure 3). These simulations demonstrate the dominant impact of fishing on cod. However, a worsening of reproduction conditions, due to climate change in combination with high nutrient loading (the cod reproductive habitat based on oxygen concentration and salinity is projected to decrease), seems to limit the cod stock even at low fishing levels. Previously, it has been described that a decreased cod biomass and a consequent increase in sprat abundance may, via top-down trophic cascades, lead to a decreased zooplankton biomass and consequent increases in phytoplankton biomass (e.g., Casini *et al* 2008). Some top-down cascades to the zooplankton level are observed in BaltProWeb, but they do not reach the level of phytoplankton. Overall, the projections of lower trophic level groups are mainly affected by climate and nutrient loads rather than by fishing on cod (not shown). Other food web models show that a recovery of the population of gray seals (which prey on cod) is also likely to have a smaller impact on the development of cod biomass in the Baltic Sea during the 21st century than exploitation and climate change (MacKenzie *et al* 2011).

Climate scenario simulations show a continuous acidification of the Baltic Sea, which is mainly controlled by the increasing atmospheric pCO_2. Changes in pH due to other factors such as increasing temperature and primary production are less important and differ between the regions. Future acidification may also affect Baltic Sea biota. Although available data suggest that many species and ecologically important groups in the Baltic Sea food web (zooplankton, macrozoobenthos, cod and sprat) will be robust to the expected changes in pH, a general conclusion cannot be drawn because most studies to date have only investigated the effects of single factors on single species, not multiple factors on multi-level ecosystems. A preliminary sensitivity analysis of the consequences of ocean acidification on the Baltic Sea ecosystem assuming 'worst case' impacts, suggests that ocean acidification may cause substantial (>50%) declines in some key fish populations of the Baltic Sea (herring, cod) and in biomass of other taxa (zooplankton, benthic filter feeders) because of increased mortality of target species.

3.4. Socio-economic impacts and stakeholder perceptions

BSR countries have different economic and social conditions, but these differences are not reflected in the attitudes towards climate change. When these attitudes were assessed by survey questions, the answers indicate in general that the effect of climate change is considered to be negative on many sectors of human activity. The respondents acknowledge that climate change may become increasingly pressing, but perceive these pressures to be distant in space and time. Because of the costs incurred by the actions necessary to mitigate the effects of climate change, the most prevailing view is that it is best to 'wait and see' and to take less costly soft actions, mainly related to education. The stakeholders declare to have knowledge about adaptation and mitigation but they do not consider them of primary importance. The respondents believe that climate change will not affect them personally. Their understanding of its consequences remains vague and abstract. Hence, our results suggest that there is a need for providing more information and knowledge about the importance of adequate adaptation and mitigation actions.

4. Discussion

A diverse set of climate-oceanographic-biogeochemical, population and food web models was linked to simulate impacts of various combinations of drivers (fishing, climate change, nutrient loading, marine mammal predation) on ecosystem dynamics. The assembled framework is intended to facilitate future studies on the applicability of potential ecosystem and fishery management decisions, and is expected to be a valuable tool for both marine scientists and policymakers. For instance, we showed that in the case of cod, dynamical downscaling from GCMs to food web models is a feasible approach. However, there are considerable uncertainties due to model biases, unknown initial conditions, and unknown greenhouse gas emission and nutrient load scenarios.

Concerning model biases, temperature and salinity dependences of some key biogeochemical and food web processes are not well understood. For instance, higher temperatures accelerate bacterial mineralization of phosphorus in the bottom sediments. Hence, the phosphorus accumulated and stored in the sediments during previous decades with higher external nutrient supply will be released faster. However, the overall rate is unknown.

Surface layer nutrient concentrations are highly sensitive to processes in the sediments (e.g., Eilola *et al* 2009). The reason for this may be explained by the fact that the depth of the very shallow sills in the Danish sounds at the entrance of the Baltic Sea is similar to the depth of the euphotic zone. This forces all nutrients that are not permanently removed inside the Baltic Sea to become eventually exported from the euphotic zone of the Baltic proper. If the sink in the Baltic Sea becomes less efficient in the deeper layers it will cause increased nutrient concentrations in the euphotic zone. Hence, changing sediment processes are very likely important for changing primary production.

Moreover, considerable uncertainty is introduced by the absence of elaborated nutrient load scenarios for the BSR. For instance, we studied a wide range of riverine and atmospheric nutrient load scenarios (REF, BAU, BSAP), which are based on simple general assumptions rather than on detailed assessments of future population growth, agricultural development, life style changes, etc.

Also, additional impacts of climate change on nutrient concentrations in rivers are not considered. For instance, according to process-oriented hydrological modeling, phosphorus will more intensively be flushed out from the soils due to the projected increase of heavy rainfall intensity, which will result in increased phosphorus concentrations in rivers.

Watershed simulations also suggest that nitrogen loads may decrease due to increased denitrification in warmer soils. Such impacts are not considered in this study. Still, one should keep in mind that the impact of climate change could be in the same order of magnitude as intentional man-made changes of nutrient concentration, e.g., as anticipated by BSAP.

In contrast to the nitrate and phosphate rich river flows in the southern Baltic Sea, higher runoff in the northern Baltic Sea will increase the supply of dissolved organic matter (DOM) and yellow substances. This may decrease the light penetration in the water and result in a shift towards a more bacterial based ecosystem feeding on the increased allochthonous organic carbon supply (e.g., Sandberg *et al* 2004). However, these processes are not directly included in the present setups of the biogeochemical models.

Finally, the existing simulations cannot fully represent the magnitude or the rates of ecological changes expected under a changing climate, eutrophication and human exploitation. Further investigations, monitoring and modeling of hydrographic, biogeochemical and ecological processes can potentially reduce these uncertainties.

5. Conclusions

- A unique, publicly available climate and environmental database of simulation results from a multi-model ensemble and observations is established, describing past and future climates of the Baltic Sea Region for 1850–2098. A decision support system based on 'Google Earth Maps' demonstrates a range of possible Baltic Sea environmental conditions under various nutrient load and climate change scenarios (see www.baltex-research.eu/ecosupport/DSS).
- State-of-the-art Baltic Sea models are capable of simulating past climate variations and eutrophication since 1850. In particular, variability of water temperature, salinity and oxygen concentrations are in good agreement with available observations, building confidence that the models are able to simulate future changes, provided that projected forcing from GCMs is realistic. However, some shortcomings of simulated nutrient dynamics are identified, emphasizing the need of further model development.
- Climate change may have considerable impacts on the Baltic Sea ecosystem. Assuming the greenhouse gas emission scenario A1B or A2, water temperature at the end of the 21st century will be higher and salinity and oxygen concentrations will be lower than any values since 1850. These changes will affect the marine food web. For instance, irrespective of the assumed nutrient load scenario, cod biomass will probably decline without lowered fishing mortality.
- These effects need to be taken into consideration in management plans. Our results give a state of the art, scientific basis for marine management and policy support. To reach HELCOM Baltic Sea Action Plan targets for a Baltic Sea unaffected by human impact, nutrient load reductions and a sustainable fishery are even more important in the future than in the present climate. Although our results will partly be considered for the revision of the Baltic Sea Action Plan, climate change is still perceived as distant in space and time by coastal stakeholders. Today only little attention is paid to adaptation and mitigation strategies.

Acknowledgments

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