Hypoxia in future climates: A model ensemble study for the Baltic Sea

H. E. M. Meier,1 H. C. Andersson,1 K. Eilola,1 B. G. Gustafsson,2 I. Kuznetsov,1 B. Müller-Karulis,2 T. Neumann,3 and O. P. Savchuk2

Received 9 October 2011; revised 16 November 2011; accepted 22 November 2011. Published 29 December 2011.

1 Using an ensemble of coupled physical-biogeochemical models driven with regionalized data from global climate simulations we are able to quantify the influence of changing climate upon oxygen conditions in one of the numerous coastal seas (the Baltic Sea) that suffers worldwide from eutrophication and from expanding hypoxic zones. Applying various nutrient load scenarios we show that under the impact of warming climate hypoxic and anoxic areas will very likely increase or at best only slightly decrease (in case of optimistic nutrient load reductions) compared to present conditions, regardless of the used global model and climate scenario. The projected decreased oxygen concentrations are caused by (1) enlarged nutrient loads due to increased runoff, (2) reduced oxygen flux from the atmosphere to the ocean due to increased temperature, and (3) intensified internal nutrient cycling. In future climate a similar expansion of hypoxia as projected for the Baltic Sea can be expected also for other coastal oceans worldwide. Citation: Meier, H. E. M., H. C. Andersson, K. Eilola, B. G. Gustafsson, I. Kuznetsov, B. Müller-Karulis, T. Neumann, and O. P. Savchuk (2011), Hypoxia in future climates: A model ensemble study for the Baltic Sea, Geophys. Res. Lett., 38, L24608, doi:10.1029/2011GL049929.

1. Introduction

Zones in the coastal oceans with missing higher forms of life at the sea bottom, so-called hypoxic areas or dead zones, have spread exponentially since the 1960s [Diaz and Rosenberg, 2008]. Hypoxia occurs when the biogeochemical oxygen consumption exceeds ventilation by water transports and the dissolved oxygen concentration at the bottom falls approximately below 2 ml O2 l\(^{-1}\) [Conley et al., 2009]. The spreading of hypoxia, caused by eutrophication driven by anthropogenic nutrient loads from land and atmospheric deposition, has large consequences for the ecosystem functioning and is today perhaps one of the most serious environmental problems of the coastal oceans worldwide. Further spreading of hypoxia will depend both on future human activities on land (e.g., fertilizer use, burning of fossil fuels) and on climate change with increasing water temperature and (eventually) changing stratification.

2. Methods

2.1. Baltic Sea Models

Transient simulations for 1961–2099 with three state-of-the-art coupled physical-biogeochemical models have been carried out. These are 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) [Meier et al., 2011a]. The models are structurally different in that ERGOM and RCO-SCOBI are three-dimensional circulation models with uniformly high horizontal resolution of 5.6 and 3.7 km, respectively, while BALTSEM resolves the Baltic Sea spatially in 13 dynamically interconnected and horizontally integrated sub-basins with high vertical resolution. All models are forced with the same six-hourly atmospheric and monthly river runoff data from four climate projections (see

---

1Department of Research and Development, Swedish Meteorological and Hydrological Institute, Norrköping, Sweden.
2Stockholm Resilience Centre, Baltic Nest Institute, Stockholm University, Stockholm, Sweden.
3Leibniz-Institute for Baltic Sea Research Warnemünde, Rostock, Germany.

Copyright 2011 by the American Geophysical Union. 0094-8276/11/2011GL049929
Figure 1
2.2. Regional Climate Data Sets

[6] The atmospheric forcing is calculated applying a dynamical downscaling approach using one regional climate model [Döscher et al., 2002] with lateral boundary data from two General Circulation Models (GCMs; HadCM3 and ECHAM5/MPI-OM, for references see Meier et al. [2011b]). Further, two emission scenarios (A1B and A2 [Nakićenović et al., 2000]) and two realizations of ECHAM5/MPI-OM with differing initial conditions were used [Meier et al., 2011b]. Summarizing, the four climate scenarios of this study are driven by HadCM3 A1B, two realizations of ECHAM5/MPI-OM A1B, and ECHAM5/MPI-OM A2. The two GCMs used in this study were selected because the quality of their downscaled atmospheric surface fields is satisfactory to force ocean and hydrological models for the Baltic Sea region [Meier et al., 2011b].

[7] The hydrological forcing is calculated from the difference of precipitation and evapotranspiration in the Baltic catchment area using a statistical model.

2.3. Nutrient Load Scenarios

[10] For three scenarios riverine nutrient loads are calculated from the product of nutrient concentrations and volume flows [Stålnecke et al., 1999]. (1) REFerence (REF): current nutrient concentrations in the rivers, atmospheric deposition and point sources; (2) Baltic Sea Action Plan (BSAP): reduced nutrient concentrations in rivers following HELCOM [2007] and 50% reduced atmospheric deposition; (3) Business-As-Usual (BAU): increased nutrient concentrations in rivers assuming an exponential growth of agriculture in all Baltic Sea countries as projected by HELCOM [2007] and current atmospheric deposition.

[11] Between 2007 and 2020 simulated nutrient concentrations from rivers, point sources and the atmosphere change linearly from present to future values. After 2020 nutrient concentrations are assumed to be constant. The three nutrient load scenarios are combined with the four climate scenarios (Section 2.2).

3. Results

3.1. Evaluation of the Control Period

[12] In general, during the control period (1978–2007) simulated mean vertical profiles of physical and chemical variables, like temperature, salinity, oxygen, phosphate and nitrate, differ from the observed ensemble mean (henceforth mean) profiles by less than one standard deviation of the observations. As an example, the oxygen profile in the central Baltic proper is shown, which mirrors the two-layer vertical structure of the highly stratified estuary (Figure 2). The simulated mean profile reproduces the observed oxygen profile rather well. However, in the deep water the simulated hydrogen sulfide concentrations might be systematically too low although it has to be remembered that the investigated period contained an exceptionally long stagnation period not present in the scenario simulations.

[13] During 1961–2010 hypoxic and anoxic areas are simulated realistically. Mean simulated and observed hypoxic (anoxic) areas amount to 48,600 (15,900) and 56,500 (16,800) km², respectively. Hence, mean simulated hypoxic and anoxic areas are underestimated compared to observations by 14 and 5%, respectively.

3.2. Changes of the External Forcing

[14] Depending on the climate scenario, the 2 m air temperature and precipitation over the Baltic Sea region will increase at the end of the century by 2.7–3.8°C and 12–18%, respectively. In general, changes of the mean 10 m wind speed are small. In the Baltic proper only in two out of four projections significantly increased wind speeds of about 1 m s⁻¹ during winter are found.

[15] Between 1978–2007 and 2069–2098 the annual mean runoff into the Baltic Sea is projected to increase between 15 and 22%. The changes are larger in the northern than in the southern part of the catchment area. As the runoff changes into the Baltic proper (the sub-basin with the largest nutrient

Figure 1. (a–c) Ensemble average changes between 2069–2098 and 1978–2007 of summer (June to August) bottom oxygen concentration (in ml O₂ l⁻¹) and (d–f) the signal-to-noise ratio, i.e., the absolute value of the ratio between the ensemble average change and the standard deviation of the individual changes. From top to bottom, the results of the nutrient load scenarios BSAP, REF and BAU are depicted. Signal-to-noise ratios larger than four are depicted in brown. The location of the monitoring station at Gotland Deep (BY15) is denoted by a black square (in Figure 1a).

Figure 2. (left) Ensemble average vertical profiles and (right) changes in oxygen concentration (in ml O₂ l⁻¹) at the monitoring station BY15 (for the location see Figure 1): observations (green), control period 1978–2007 (black), changes between 2069–2098 and 1978–2007 in BSAP (blue), REF (black) and BAU (red). Negative oxygen values represent hydrogen sulfide. The range of variability is indicated by the ±1 standard deviation band around the ensemble average of model results (dotted lines) or observations from the Baltic Environmental Database (BED, see http://nest.su.se/bed) (grey shaded area).
loads in present climate consisting of the Arkona, Bornholm and Gotland basins) are positive, the total nutrient loads from rivers will increase in all climate scenarios consistently if the nutrient concentrations remain constant as in REF. However, due to varying runoff changes in the climate scenarios and due to differing assumptions for the bioavailable nutrient fractions in the three biogeochemical models, the differences between nutrient loads for a given nutrient load scenario are considerable (Figure 3).

3.3. Changes in Oxygen Conditions

Towards the end of the 21st century the volume averaged water temperature rises by about 2.5°C due to increased air temperature, while the salinity decreases by about 1.7 g kg\(^{-1}\) as a response to the increased runoff (Figure 4). In contrast to earlier scenario simulations by Meier et al. [2011a], this study indicates that wind speed changes are of minor importance for changes in salinity. However, increased runoff and even small increases of the wind speed may cause a deepening of the halocline. Consequently, we found largest bottom salinity changes along the slopes of the Baltic proper and Gulf of Finland in depths where the halocline shifts. Due to the decreased stratification, reductions of the bottom oxygen concentration in this depth range are smaller (or concentrations even increase as in BSAP) than in the deep water (Figures 1 and 2).

As the solubility of atmospheric oxygen decreases in warmer water, in the projections the oxygen concentrations of the surface layers (Figure 2) and consequently also of the bottom waters in weakly stratified coastal areas (Figure 1) are reduced. The counteracting effect of reduced salinity on the solubility of oxygen in water is smaller.

Oxygen concentrations in the deep water of the Baltic proper decrease due to the lower solubility in the inflowing water as well as increased decomposition/oxidation rates of organic matter due to higher temperature. Oxygen consumption also increases due to an enhanced supply of organic matter from primary production in surface layers, depending on the implemented nutrient load scenario (Figures 1 and 2). In addition, increased phosphorus release from the sediments due to lowered oxygen concentrations may intensify the internal nutrient cycling and may cause a positive feedback to the productivity of the Baltic Sea [Jilbert et al., 2011].

In BAU a considerable decrease of the bottom oxygen concentration in the deep water of the Baltic proper (up to 4 ml O\(_2\) l\(^{-1}\) at BY15, see Figures 1 and 2) is found. Also in REF the bottom oxygen concentrations decrease in almost all regions of the Baltic proper. On the other hand, in BSAP bottom oxygen conditions improve along the slopes of the Baltic proper but still decrease in other regions (Figure 1). However, the changes in BSAP are smaller than the standard deviations of the ensemble because the signs of the individual changes calculated with the three biogeochemical models differ.
Projected climate changes will not in all regions of the Baltic Sea reinforce oxygen depletion. The depth range of the halocline in the BSAP simulations was mentioned already. Also in the deeper parts of the Gulf of Finland, which is less stratified than the Baltic proper, the overwhelming impact of a reduced stratification due to increased runoff causes an increase of bottom oxygen concentrations in all three investigated nutrient load scenarios (Figure 1).

Hypoxic and anoxic areas are eutrophication indicators that both increase in REF and BAU (Figure 4). Only in BSAP they will slightly decrease compared to the level in 2007. The sensitivity of hypoxic area to changes in nutrient supply is smaller than the sensitivity of anoxic area because already in present climate hypoxic area extends close to its upper limit given by the bottom area below the halocline. However, the different nutrient load scenarios are well reflected in changes in anoxic areas.

According to our model ensemble, significant changes of volume averaged temperature and salinity will become detectable during the 2020s (Figure 4). In BSAP hypoxic and anoxic areas will, compared to REF, significantly be improved after the 2040s and 2030s, respectively.

4. Discussion of Uncertainties

Any projection for the marine environment in any coastal area of the world is limited by large uncertainties of unknown socio-economic developments affecting nutrient loads and of the partly unknown sensitivity of some biogeochemical key processes to changing climate [e.g., Meier et al., 2011a]. In addition, biases of the GCMs limit the quality of regional projections.

For a given nutrient load scenario the discrepancies of bottom oxygen concentration changes are largest in regions that are affected by the varying position of the halocline due to runoff and wind speed changes that differ among the climate projections (Figure 1). In these regions along the slopes of the Baltic proper and Gulf of Finland the signal-to-noise ratio is smaller than one indicating that changes are smaller than the discrepancy between projections. In addition, changes of the halocline depth in the Baltic proper are much larger in the horizontally integrated BALTSEM model than in the 3D models (not shown). Also the sensitivity to changes of the nutrient loads is considerably larger in BALTSEM than in the 3D models (not shown). Otherwise the sensitivity of physical parameters in the three Baltic Sea models to changing climate is comparable.

In the northern Baltic Sea the signal-to-noise ratio is also smaller than one (Figure 1). Although the standard deviations of sea surface temperature changes within the ensemble are largest in the northern Baltic Sea during summer due to biases of the GCMs affecting the ice-albedo feedback [Meier et al., 2011b], the uncertainties due to biases of the biogeochemical models are even larger (not shown), perhaps because processes important for the nutrient cycling in the northern Baltic Sea are not adequately described in the models [Eilola et al., 2011].

5. Summary

Increased loads and temperature-augmented rates of biogeochemical processes will result in an overall intensification of internal nutrient cycling, including substantial increases in both primary production of organic matter and oxygen consumption for its mineralization. With respect to the targets of the BSAP we conclude that in future climate BSAP is very likely not as efficient as in present climate and it is unclear whether the environmental situation is improved at all compared to present conditions. However, without drastic nutrient load abatements hypoxic and anoxic areas will continue to increase until a limit set by the bottom area below the halocline.

Uncertainties of the projections are dominated by unknown nutrient loads, biases of the GCMs and biases of the biogeochemical models. Uncertainties caused by the GCMs and by the biogeochemical models are of comparable magnitude and depend on the region and variable of interest. We found largely differing sensitivities of the models to changing nutrient loads.

The impacts of the BSAP (assumed to be fully implemented in 2020) on the mean hypoxic and anoxic areas will statistically not be significant compared to REF before the 2040s and 2030s, respectively. Time scales of the transient response to changing climate and changing nutrient loads are of the same magnitude.

Acknowledgments. The research presented in this study is part of the project ECOSUPPORT (Advanced modeling tool for scenarios of the Baltic Sea ECOSystem to SUPPORT decision making) and has received funding from the European Community’s Seventh Framework Program (FTP/2007-2013) under grant agreement 217246 made with BONUS, the joint Baltic Sea research and development program, from the Swedish Environmental Protection Agency (08F381) and from the German Federal Ministry of Education and Research (03F0492A). Additional support came from the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (FORMAS) within the project “Regime Shifts in the Baltic Sea Ecosystem - Modelling Complex Adaptive Ecosystems and Governance Implications”. We would like to acknowledge Eduardo Zorita for helpful comments on the paper.

The Editor wishes to thank two anonymous reviewers for their assistance evaluating this paper.

References

BACC Author Team (2008), Assessment of Climate Change for the Baltic Sea Basin, Reg. Clim. Stud., Springer, Berlin.

Christensen, J. H., and O. B. Christensen (2007), A summary of the PRUDENCE model projections of changes in European climate by the mid of the century, Clim. Change, 81, 7–30.

Conley, D. J., et al. (2009), Critical review: Hypoxia in the Baltic Sea, Environ. Sci. Technol., 43, 3412–3420.

Conley, D. J., et al. (2011), Hypoxia is increasing in the coastal zone of the Baltic Sea, Environ. Sci. Technol., 45, 6777–6783.

Diaz, R. J., and R. Rosenberg (2008), Spreading dead zones and consequences for marine ecosystems, Science, 321, 926–929.

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

Eilola, K., B. G. Gustafsson, H. E. M. Meier, T. Neumann, and O. P. Savevuk (2011), Evaluation of biogeochemical cycles in an ensemble of three state-of-the-art numerical models of the Baltic Sea, J. Mar. Syst., 88, 267–284.

Elmgren, R. (2001), Understanding human impact on the Baltic Sea ecosystem: Changing views in recent decades, Ambio, 30, 222–231.

Gustafsson, B. G. (2003), A time-dependent coupled-basin model for the Baltic Sea, Rep. C47, 61 pp., Earth Sci. Cent., Univ. of Gothenburg, Gothenburg, Sweden.

HELCOM (2007), Toward a Baltic Sea unaffected by eutrophication. Background document to HELCOM Ministerial Meeting, Krakow, Poland, technical report, Helsinki Comm., Helsinki.

Gilbert, T., C. P. Slomp, B. G. Gustafsson, and W. Boer (2011), Beyond the Fe-P-redox connection: Preferential regeneration of phosphorus from organic matter as a key control on Baltic Sea nutrient cycles, Biogeosciences, 8, 1699–1720.

Meier, H. E. M., K. Eilola, and E. Almroth (2011a), Climate-related changes in marine ecosystems simulated with a three-dimensional
coupled biogeochemical-physical model of the Baltic Sea, *Clim. Res.*, 48, 31–55.
Meier, H. E. M., A. Höglund, R. Döscher, H. Andersson, U. Löptien, and E. Kjellström (2011b), Quality assessment of atmospheric surface fields over the Baltic Sea of an ensemble of regional climate model simulations with respect to ocean dynamics, *Oceanologica*, 53, 193–227.
Nakićenović, N., et al. (2000), *Emission Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*, 599 pp., Cambridge Univ. Press, Cambridge, U. K.
Neumann, T., W. Fennel, and C. Kremp (2002), Experimental simulations with an ecosystem model of the Baltic Sea: A nutrient load reduction experiment, *Global Biogeochem. Cycles*, 16(3), 1033, doi:10.1029/2001GB001450.
Savchuk, O. P. (2002), Nutrient biogeochemical cycles in the Gulf of Riga: Scaling up field studies with a mathematical model, *J. Mar. Syst.*, 32, 235–280.
Stålnacke, P., A. Grimvall, K. Sundblad, and A. Tonderski (1999), Estimation of riverine loads of nitrogen and phosphorus to the Baltic Sea 1970–1993, *Environ. Monit. Assess.*, 58, 173–200.
Zillén, L., D. J. Conley, T. Andrén, E. Andréén, and S. Björk (2008), Past occurrences of hypoxia in the Baltic Sea and the role of climate variability, environmental change and human impact, *Earth Sci. Rev.*, 91, 77–92.

H. C. Andersson, K. Eilola, I. Kuznetsov, and H. E. M. Meier, Department of Research and Development, Swedish Meteorological and Hydrological Institute, SE-60176 Norrköping, Sweden. (markus.meier@smhi.se)
B. G. Gustafsson, B. Müller-Karulis, and O. P. Savchuk, Stockholm Resilience Centre, Baltic Nest Institute, Stockholm University, SE-10691 Stockholm, Sweden.
T. Neumann, Leibniz-Institute for Baltic Sea Research Warnemünde, D-18119 Rostock, Germany.