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Hypoxia in future climates - a model ensemble study for the Baltic Sea

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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.

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 O_2 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.

To study the impacts of these two dominating drivers we have focussed on the shallow Baltic Sea (Fig. 1), a well-described brackish water body with limited water exchange with the world ocean and pronounced vertical stratification (e.g. *BACC author team* [2008], Annex A1). Although hypoxia has been intermittently present since its formation ca. 8000 cal. yr BP [*Zillén et al.*, 2008], the Baltic Sea has changed during the past 100 years from an oligotrophic to an eutrophic system (e.g. *Elmgren* [2001]) due to increasing population and intensified agriculture in its catchment area. As a consequence hypoxic areas increased and permanent anoxia developed both in the deep offshore waters (e.g. *Conley et al.* [2009]) and coastal zones [*Conley et al.*, 2011].

Climate projections for the 21st century suggest that in the Baltic Sea water temperature may increase and (eventually) salinity may decrease [*BACC author team*, 2008]. Both runoff and wind speed changes will cause vertical stratification changes [*Meier et al.*, 2011a] that together with increasing temperatures may affect hypoxia.

Single projections of marine biogeochemical cycles are of limited use because of the uncertainties caused by biases of the Baltic Sea models [*Eilola et al.*, 2011], by biases of the driving global models [*Meier et al.*, 2011b] and by uncertain nutrient inputs [*Meier et al.*, 2011a]. Hence, ensemble simulations are necessary to quantifiy uncertainties of projections (e.g. *Christensen and Christensen* [2007]). In this study, the combined effects of changing climate and nutrient loads on hypoxia in the Baltic Sea are investigated using a model ensemble approach and uncertainties of the projections are identified.

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 below). Hence, the models resolve physical and biogeochemical cycles at least seasonally.

The results of the three models at standard monitoring stations forced with regionalized re-analysis data for 1970-2005 are close to observations although some fluxes and variables that can not be observed, like integrated sediment pools, differ considerably between the models [*Eilola et al.*, 2011]. It was also found that ensemble average results are better than or as good as the results of any of the individual models [*Eilola et al.*, 2011].

2.2. Regional climate data sets

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].

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

For three scenarios riverine nutrient loads are calculated from the product of nutrient concentrations and volume flows [*Stålnacke 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 in *HELCOM* [2007] and current atmospheric deposition.

Between 2007 and 2020 simulated nutrient concentrations from rivers, point sources and the atmosphere change linearily 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

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 (Fig. 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.

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) km^2, 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

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.

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 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 (Fig. 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 $1.7\,\mathrm{g\,kg^{-1}}$ as a response to the increased runoff (Fig. 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 (Figs. 1 and 2).

As the solubility of atmospheric oxygen decreases in warmer water, in the projections the oxygen concentrations of the surface layers (Fig. 2) and consequently also of the bottom waters in weakly stratified coastal areas (Fig. 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 (Figs. 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 Figs. 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 (Fig. 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 (Fig. 1).

Hypoxic and anoxic areas are eutrophication indicators that both increase in REF and BAU (Fig. 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 (Fig. 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 (Fig. 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 (Fig. 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.

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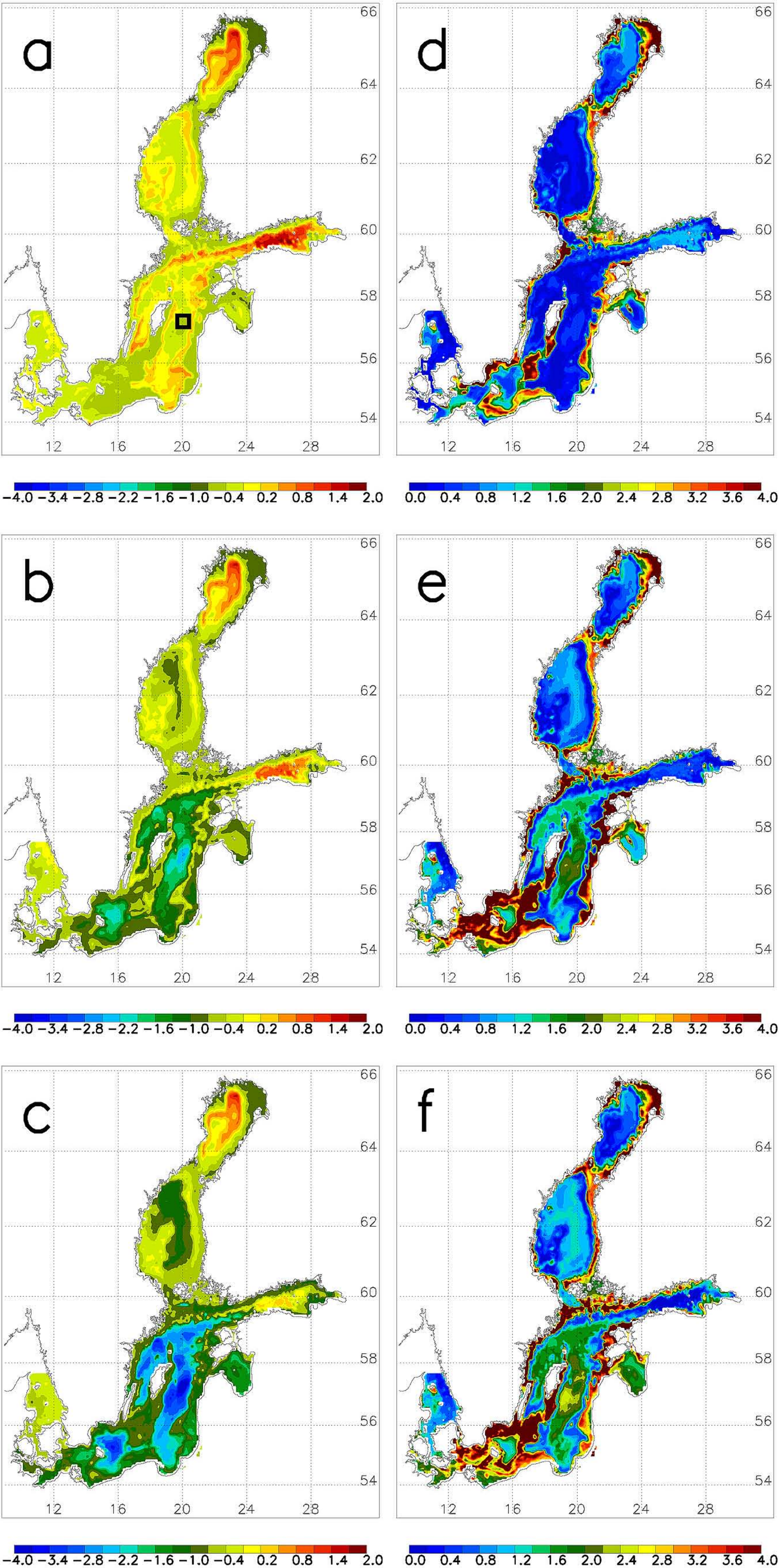
Figure 1. Ensemble average changes between 2069-2098 and 1978-2007 of summer (June to August) bottom oxygen concentration (in ml O_2 l^{-1}, a-c) and the signal-to-noise ratio, i.e. the absolute value of the ratio between the ensemble average change and the standard deviation of the individual changes (d-f). 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 a).

Figure 2. Ensemble average vertical profiles (left) and changes (right) in oxygen concentration (in ml O_2 l^{-1}) at the monitoring station BY15 (for the location see Fig. 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).

Figure 3. Ensemble average changes of the annual mean biologically available total phosphorus and nitrogen loads (in %) from rivers, point sources and atmospheric deposition. Here, the load changes into the total Baltic Sea (including Kattegat) are calculated between 1971-2000 and 2070-2099. In addition, the ±1 standard deviation bands around the ensemble average changes are shown.

Figure 4. Volume averaged temperature (in °C) and salinity (in g kg^{-1}), as well as hypoxic ($<$ 2 ml O_2 l^{-1}) and anoxic ($<$ 0 ml O_2 l^{-1}) areas (in 10^3 km^2) for the entire Baltic Sea including Kattegat (solid lines). The ranges of the ±1 standard deviation band around the ensemble averages are depicted by dotted and dashed lines. Almost straight lines indicate the 95% confidence interval calculated with a t-test for statistically significant deviations from the ensemble mean temperature and salinity during 1978-2007. In the two lower panels simulated hypoxic and anoxic areas for the three nutrient load scenarios, BSAP (blue), REF (black) and BAU (red), are shown. Vertical lines mark the years 2029, 2023, 2048 and 2031 for temperature, salinity and hypoxic and anoxic areas, respectively, when during all subsequent years either the ensemble average temperature and salinity will become significantly different from the ensemble average during 1978-2007 or when the ensemble average hypoxic and anoxic areas in BSAP will significantly deviate from the corresponding ensemble averages in REF (at the 95 % confidence level).



a
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−4.0 −3.4 −2.8 −2.2 −1.6 −1.0 −0.4 0.2 0.8 1.4 2.0
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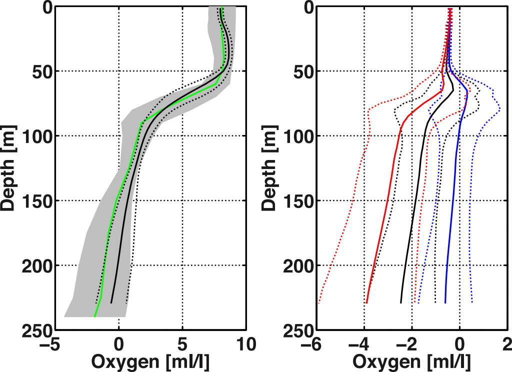
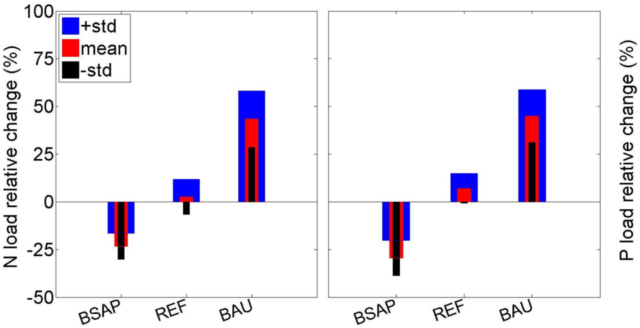
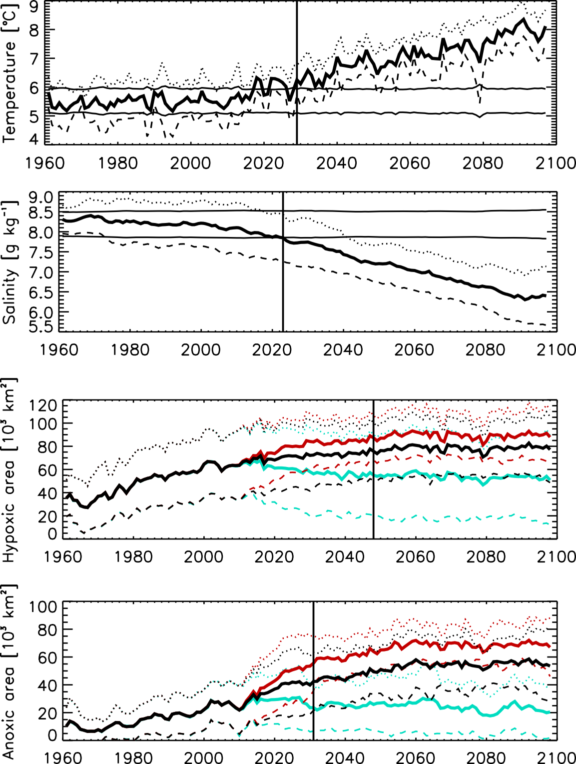


Depth [m]
Oxygen [ml/l]
0
50
100
150
200
250
−5
0
5
10
Depth [m]
Oxygen [ml/l]
0
50
100
150
200
250
−6
−4
−2
0
2



+std
mean
-std
N load relative change (%)
P load relative change (%)
100
75
50
25
0
-25
-50
BSAP
REF
BAU
BSAP
REF
BAU



Temperature [°C]
Salinity [g kg⁻¹]
Hypoxic area [10³ km²]
Anoxic area [10³ km²]
1960
1980
2000
2020
2040
2060
2080
2100