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Uncertainty assessment of projected ecological quality indicators in future climate

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Front:
Baltic Sea view from Ölands Södra Udde (Source: Silke Malz, 2009).

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Summary

Uncertainties of projected physical key parameters and ecological quality indicators of the Baltic Sea environment, like water temperature, salinity, oxygen, nutrients and water transparency in future climate are assessed. We analyzed an ensemble of 38 scenario simulations for 1961-2099. Three state-of-the-art coupled physical-biogeochemical models are forced with four regionalized climate projections assuming either the A1B or A2 greenhouse gas emission scenario and with four nutrient load scenarios covering the entire range from a pessimistic to a optimistic assumption of the future socioeconomic development in the Baltic Sea region. We found considerable discrepancies of projected ecological quality indicators because the sensitivities of the ecosystem response to nutrient load and temperature changes differ among the models. However, despite these uncertainties all three models agree qualitatively well in their overall response. In particular, the impact of warmer water counteracts in all models the impact of nutrient load reductions.

Sammanfattning

Osäkerheter i framtidsprojektioner av fysikaliska nyckelparametrar, som vattentemperatur och salthalt, och indikatorer för ekologisk kvalitet i Östersjön, som syrehalt, näringsämnen och vattnets genomskinlighet utvärderades. Vi analyserade en ensemble av 38 scenario simuleringar för perioden 1961-2099. Tre aktuella kopplade fysikaliska-biogeokemiska modeller drevs av fyra regionaliserade projektioner av framtida klimat, baserade på scenario A1B eller A2 för globala utsläpp av växthusgaser, samt fyra scenarier för tillförsel av näringsämnen till Östersjön som täcker en skala från en pessimistisk till en optimistisk socioekonomisk utveckling i Östersjöregionen. Vi fann betydande skillnader i framtids scenarier för indikatorerna av ekologisk kvalitet på grund av modellernas olika känslighet för ändringar i temperaturer och närsaltstillförsel. Men trots dessa osäkerheter stämmer de övergripande resultaten kvalitativt överrens mellan modellerna. Speciellt motverkas effekterna av reducerad näringstillförsel i samtliga modeller av effekter orsakade av ett varmare vatten.

1. Introduction

Today the Baltic Sea suffers from severe environmental problems due to eutrophication, e.g. large cyanobacteria blooms and dead sea beds [*Elmgren*, 2001]. To overcome these problems it is of vital importance to reduce nutrient loads from the atmosphere, point sources and rivers with the help of international policies, e.g. HELCOMs Baltic Sea Action Plan (BSAP) [*HELCOM*, 2007]. The BSAP includes the load reductions necessary to obtain good water quality as well as nutrient load abatement strategies based upon a country-wise allocation scheme.

As the response of the Baltic Sea system to changing nutrient loads from land is slow [*Savchuk*, 2010], long scenario simulations are needed that take also the effects of changing climate into account. Hence, a new modelling approach was developed to calculate the combined effects of changing climate and changing nutrient loads on the Baltic Sea ecosystem [*Meier et al.*, 2011c, b].

As models have biases due to our limited knowledge of climate and ecosystem processes, uncertainties need to be quantified [*Eilola et al.*, 2011]. In this study we focus on uncertainties in the response of three state-of-the-art physical-biogeochemical models to changing nutrient loads from land and atmosphere in future climate. We are using a multi-model ensemble approach to take uncertainties of climate projections into account. In particular, we are interested in the question how large are the discrepancies in the models' response to nutrient load abatement strategies like BSAP. The quantification of uncertainties is an important information for marine management and for the revision of BSAP.

2. Methods

In this study we used a model hierarchy of two global General Circulation Models (GCMs), one regional climate model (RCM), one hydrological model and three coupled physical-biogeochemical models for the Baltic Sea to calculate projections for the Baltic Sea. The approach follows the study by *Meier et al.* [2011b]. Below the downscaling approach and the applied models are briefly introduced.

2.1. Dynamical downscaling approach

A RCM with high horizontal resolution is used to resolve small-scale processes explicitely and to represent surface conditions like the regional orography and land-sea mask satisfactorily. In the dynamical downscaling approach of this study the RCM is driven at the lateral boundaries of its model domain by GCM data. Thus, the large-scale circulation is controlled by the GCM dynamics whereas the RCM adds regional details. As atmospheric surface fields of the RCM are more realistic than GCM results, they are used to force three coupled physical-biogeochemical models for the Baltic Sea.

2.2. Global Climate Models

In this study, lateral boundary data from two GCMs are used: HadCM3 from the Hadley Centre in the U.K. [*Gordon et al.*, 2000] and ECHAM5/MPI-OM from the Max Planck Institute for Meteorology in Germany [*Roeckner et al.*, 2006; *Jungclaus et al.*, 2006], henceforth short ECHAM5. HadCM3 is forced with the A1B greenhouse gas emission scenario [*Nakićenović et al.*, 2000] whereas ECHAM5 is driven both with A1B and A2. As in both ECHAM5 scenario simulations the projected increases of global mean surface temperature (and also of the Baltic Sea region mean temperature) are relatively close to each other, they are considered together within one ensemble. In addition, two realizations of ECHAM5 forced with A1B with differing initial conditions have been studied (denoted with r1 and r3). Hence, in total four GCM datasets, HadCM3-A1B, ECHAM5-r3-A1B, ECHAM5-r1-A1B, and ECHAM5-r1-A2, are used. The simulations are transient runs for the period 1961-2099.

2.3. Regional Climate Model

The results of the four global scenario simulations are downscaled using the coupled atmosphere-ice-ocean model RCAO (Rossby Centre Atmosphere Ocean model [*Döscher et al.*, 2002, 2010]) with a horizontal resolution of 25 km [*Meier et al.*, 2011d]. Six-hourly atmospheric surface fields of RCAO like 2m air temperature, 2m specific humidity, sea level pressure, 10 m wind speed, precipitation and total cloudiness are used to force three Baltic Sea models and a hydrological model (see below). For the control period 1978-2007 the quality of the RCAO atmospheric surface fields was assessed by *Meier et al.* [2011d]. ECHAM5 and HadCM3 were selected for the downscaling experiments because their biases over the Baltic Sea region are relatively small compared to the biases of other GCMs [*Kjellström et al.*, 2011; *Meier et al.*, 2011d]. In the Baltic Sea region the four investigated projections suggest that the annual mean air temperature and precipitation will increase between 2.7 and 3.8°C and between 12 and 18%, respectively [*Meier et al.*, 2011a].

2.4. Hydrological model

Runoff is calculated from the difference of precipitation and evaporation over land in RCAO using a statistical model which resolves the Baltic catchment in five sub-basins, that is, Bothnian Bay, Bothnian Sea, Gulf of Finland, Baltic proper, and Kattegat [*Meier et al.*, 2011a]. The simulated discharge is used to force the Baltic models.

2.5. 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; *Neumann and Schernewski*, 2008], and the Swedish Coastal and Ocean Biogeochemical model coupled to the Rossby Centre Ocean circulation model (RCO-SCOBI) [*Meier et al.*, 2003; *Eilola et al.*, 2009]. 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 above). The time steps of RCO-SCOBI, ERGOM and BALTSEM amount to 150 s, 600 s and three hours, respectively. Hence, relevant time scales of physical and biogeochemical processes are resolved.

A thorough comparison of hindcast simulation results of the three biogeochemical models driven with regionalized ERA40 re-analysis data [*Samuelsson et al.*, 2011] during 1970-2005 was performed by *Eilola et al.* [2011]. *Eilola et al.* [2011] found that the models capture much of the observed variability and that during 1970-2005 the response of the biogeochemical cycles to changing physical conditions is simulated realistically.

2.6. Nutrient load scenarios

Nutrient loads from rivers are calculated from the products of riverine nutrient concentrations and water discharges following, for instance, *Stålnacke et al.* [1999]. In this study four scenarios are considered:

- REFerence (REF): current riverine nutrient concentrations and current atmospheric deposition,
- Current LEGislation (CLEG): riverine nutrient concentrations according to the legislation on sewage water treatment (EU wastewater directive) and 25% reduction of atmospheric nitrogen,
- Baltic Sea Action Plan (BSAP): reduced riverine nutrient concentrations following *HELCOM* [2007] and 50% reduced atmospheric deposition,
- Business-As-Usual (BAU): business-as-usual for 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 in rivers, loads from point sources and atmospheric deposition change linearly from present to future values. After 2020 nutrient concentrations are assumed to be constant. For a detailed description of the nutrient load scenarios the reader is referred to *Gustafsson et al.* [2011].

2.7. Boundary conditions in Kattegat or Skagerrak

All three models have an open boundary in the northern Kattegat (BALTSEM, RCO-SCOBI) or in the Skagerrak (ERGOM). At the boundaries vertical profiles of temperature, salinity and nutrients (inorganic and organic) are relaxed to climatologically mean observations of the control period in a model specific manner. In the scenario simulations these boundary conditions do not change with time. Sea levels at the open boundaries are calculated with the help of statistical models from the meridional atmospheric pressure difference across the North Sea following *Gustafsson and Andersson* [2001]. In case of RCO-SCOBI and BALTSEM a statistical method is applied to correct underestimated sea level extremes [*Meier et al.*, 2011b].

2.8. Initial conditions

The Baltic Sea models are started from initial conditions representing the beginning of the 1960s following *Eilola et al.* [2011]. Due to model specific spin-up periods these initial conditions differ among the models. However, in all scenario simulations the same initial conditions for each model are used.

2.9. Analysis strategy

We focus the analysis on nine selected physical and biogeochemical variables, that is, summer (July to August) sea surface temperature (SST), annual mean sea surface salinity (SSS), annual mean bottom salinity, winter (December to January) mean sea surface height (SSH), summer mean bottom oxygen concentration, winter mean surface phosphate and nitrate concentration, annual mean phytoplankton concentration, and annual mean Secchi depth. Changes between two time slices representing present (1978-2007) and future (2069-2098) climates are calculated. Surface concentrations of biogeochemical variables are vertically averaged over the upper 10 m.

Secchi depth (Sd) is calculated from Sd=1.7/k(PAR), where k(PAR) is the coefficient of underwater attenuation of the photosynthetically available radiation [*Kratzer et al.*, 2003]. Factors controlling k(PAR) in all three models are the concentrations of phytoplankton and detritus. In addition, salinity is used in BALTSEM as a proxy of the spatio-temporal dynamics of yellow substances (Savchuk et al., manuscript in preparation).

16 scenario simulations for 1961-2098 have been performed both with RCO-SCOBI and BALTSEM. With ERGOM only six transient experiments have been carried out. Because ERGOM results as well as climate projections based upon HadCM3 are underrepresented in our ensemble compared to the other two Baltic Sea models and compared to ECHAM5 driven simulations, the ensemble members have been weighted to take underrepresented models better into account.

Ensemble means are calculated for each individual Baltic Sea model and for each nutrient load scenario by averaging the results of available climate scenario simulations. Finally, these ensemble means for individual models and nutrient load scenarios are compared with the overall ensemble mean.

3. Results

3.1. Sea surface temperature

In all three Baltic Sea models the summer mean SST will increase between about 2 and 4°C in the southern and northern Baltic Sea, respectively (Fig. 1). Consequently, spatial patterns in the changes simulated with the three Baltic Sea models and in the ensemble mean are similar although BALTSEM is warming slightly more than ERGOM and RCO-SCOBI. The north-south gradient of the SST changes is caused by the ice-albedo feedback which increases the SST sensitivity in the northern Baltic [*Meier et al.*, 2011d].

3.2. Sea surface salinity

Ensemble mean SSS changes are small in the northern and eastern Baltic (smallest in the Bothnian Sea) and largest in the Danish Straits region, especially in the Belt Sea (Fig. 1). The SSS changes are similar in all three models although in RCO-SCOBI changes are slightly larger than in the other two models.

3.3. Bottom salinity

Largest bottom salinity changes are found in BALTSEM in the depth range of the halocline, in particular in the Gulf of Finland, and in RCO-SCOBI in the deeper areas of the Baltic proper (Fig. 1). In ERGOM bottom salinity changes are generally smaller than in BALTSEM and RCO-SCOBI. However, in all three models bottom salinities are considerably reduced by about 1-2.5 g kg^{-1} in the Baltic proper. By definition, bottom salinity in Kattegat does not change.

3.4. Sea surface height

Winter SSH changes are largest in ERGOM with more than 20 cm in the northern Bothnian Bay and eastern Gulf of Finland (Fig. 1). In BALTSEM and RCO-SCOBI SSH changes are considerably smaller than in ERGOM and amount to about 4 and 8 cm in maximum, respectively. Although the ensemble mean changes in ERGOM are calculated from only two climate scenario simulations whereas the ensemble in both BALTSEM and RCO-SCOBI consists of four members, an explanation for the different SSH changes is difficult because the two scenario simulations that have been used to force ERGOM show only small changes in wind speed over sea. Wind speed changes are larger in the two other climate projections that have not been used in ERGOM simulations. Either differences in the treatment of the sea ice dynamics or different bottom drag coefficients may explain the variety of SSH changes in the models. Further investigations are neccessary to illuminate possible causes.

3.5. Bottom oxygen concentration

Depending on the nutrient load scenario and area of interest significant discrepancies in simulated changes of bottom oxygen concentrations between the three Baltic Sea models are found (Fig. 2). In scenarios with increased nutrient loads, like in REF and BAU, bottom oxygen concentration reductions are largest in BALTSEM and smallest in ERGOM. In BAU bottom oxygen concentrations simulated with BALTSEM will decrease by more than 3 ml l^{-1} (these changes are larger than the range of the color bar shown in Fig. 2). Note that in the models hydrogen sulfide concentrations are represented as negative oxygen equivalents (1 mol H_2S = -2 mol O_2).

In BSAP bottom oxygen concentration changes in the Baltic proper are relatively small in all three models. Depending on the model and region negative and positive changes are found. In the Gulf of Finland bottom oxygen concentrations in all three models forced by the BSAP scenario are projected to increase (largest in BALTSEM) because the stratification will decrease due to the larger runoff. In BALTSEM improved bottom oxygen conditions in the Gulf of Finland are visible in all four nutrient load scenarios (even in BAU). In ERGOM we found improved bottom oxygen conditions in the Bothnian Bay, independently of the applied nutrient load scenario.

3.6. Surface phosphate concentration

As in all three models the phosphorus retention capacity of the sediment depends on the bottom oxygen concentration, changes of the latter may affect phosphate concentrations of the deep water and even at the surface [*Eilola et al.*, 2009]. Areas of decreased bottom oxygen concentrations coincide with areas of increased surface phosphate concentrations (Fig. 3). In the Baltic proper largest changes of winter surface phosphate concentrations are found in scenarios with largest changes of bottom oxygen concentrations, that is in BALTSEM and RCO-SCOBI in BAU. Changes in projections calculated with BALTSEM and RCO-SCOBI are qualitatively similar perhaps because the sediment modules of the biogeochemical models contain similar process descriptions. In all scenarios of ERGOM largest increases of surface phosphate concentrations are located in the Bothnian Sea and also in the Gulf of Riga (in BAU).

3.7. Surface nitrate concentration

In the Baltic proper largest surface nitrate concentration changes are found in BAU in RCO-SCOBI (Fig. 4). In the other models nitrate concentration changes are smaller except in BALTSEM in the Gulf of Riga. In ERGOM river estuaries are implemented where most of the externally supplied nitrate is sedimented or denitrified. Depite the discrepancies in magnitude winter surface nitrate concentrations increase in all scenarios with increasing nitrogen loads (REF and BAU). In particular, nitrate concentrations in the Gulf of Riga, eastern Gulf of Finland and along the eastern coasts of the Baltic proper increase. Small reductions are found only in BSAP in RCO-SCOBI along the eastern coasts of the Baltic proper close to the river mouths of the largest rivers.

3.8. Surface phytoplankton concentration

Increased external nutrient supply causes increased surface nutrient concentrations during winter and consequently increased surface phytoplankton concentrations during spring and summer (Fig. 5). This is the case especially for RCO-SCOBI in BAU. On the other hand, in BSAP phytoplankton concentrations do not change significantly. The latter result is found in all three models.

3.9. Secchi depth

In general, Secchi depths, that indicate water transparency, are decreasing in all scenario simulations (Fig. 6). In particular, in RCO-SCOBI in BAU Secchi depth is reduced by almost 2 m. Only in BSAP and only in RCO-SCOBI slight increases in the Baltic proper are found. Whereas in BALTSEM and RCO-SCOBI largest changes in Secchi depth are calculated for the Baltic proper, the largest changes in ERGOM are found in the Bothnian Bay indicating that in this model nutrient cycles between the water column, sediment and external supply work different compared to those in the two other models.

4. Conclusions

In this study uncertainties of future projections simulated with three different physical-biogeochemical models for the Baltic Sea are investigated. Calculated changes depend not only on the physical-biogeochemical model but also on future climate and nutrient load scenarios. However, in this study we do not focus on uncertainties caused by either global or regional climate models or greenhouse gas emission scenarios. For each of the three Baltic Sea models and each of the four nutrient load scenarios that are investigated in this study ensemble mean changes forced by the A1B or A2 greenhouse gas emission scenarios are calculated.

We found in all three models similar changes in SST, SSS and bottom salinity. However, discrepancies in changes of biogeochemical variables are larger compared with discrepancies in changes of physical parameters. Overall the sensitivities of the ecosystem response to nutrient load changes differ considerably among the models. For instance, in BAU bottom oxygen and surface phosphate concentration changes in the Baltic proper are largest in BALTSEM and smallest in ERGOM. However, largest changes in surface nitrate and phytoplankton concentrations and in Secchi depth are found in RCO-SCOBI. In ERGOM the largest changes in bottom oxygen and surface phosphate concentrations are found in the Bothnian Bay and Bothnian Sea, respectively, whereas in BALTSEM and RCO-SCOBI the largest changes are in the Baltic proper located.

Despite these uncertainties indicating different sensitivities all three models agree astonishing well in their overall response of the ecosystem to changes in the external nutrient supply. Water qualities in BAU or BSAP are either strongly reduced or at the best only slightly improved. In all projections the impact of warmer water counteracts the impact of nutrient load reductions.

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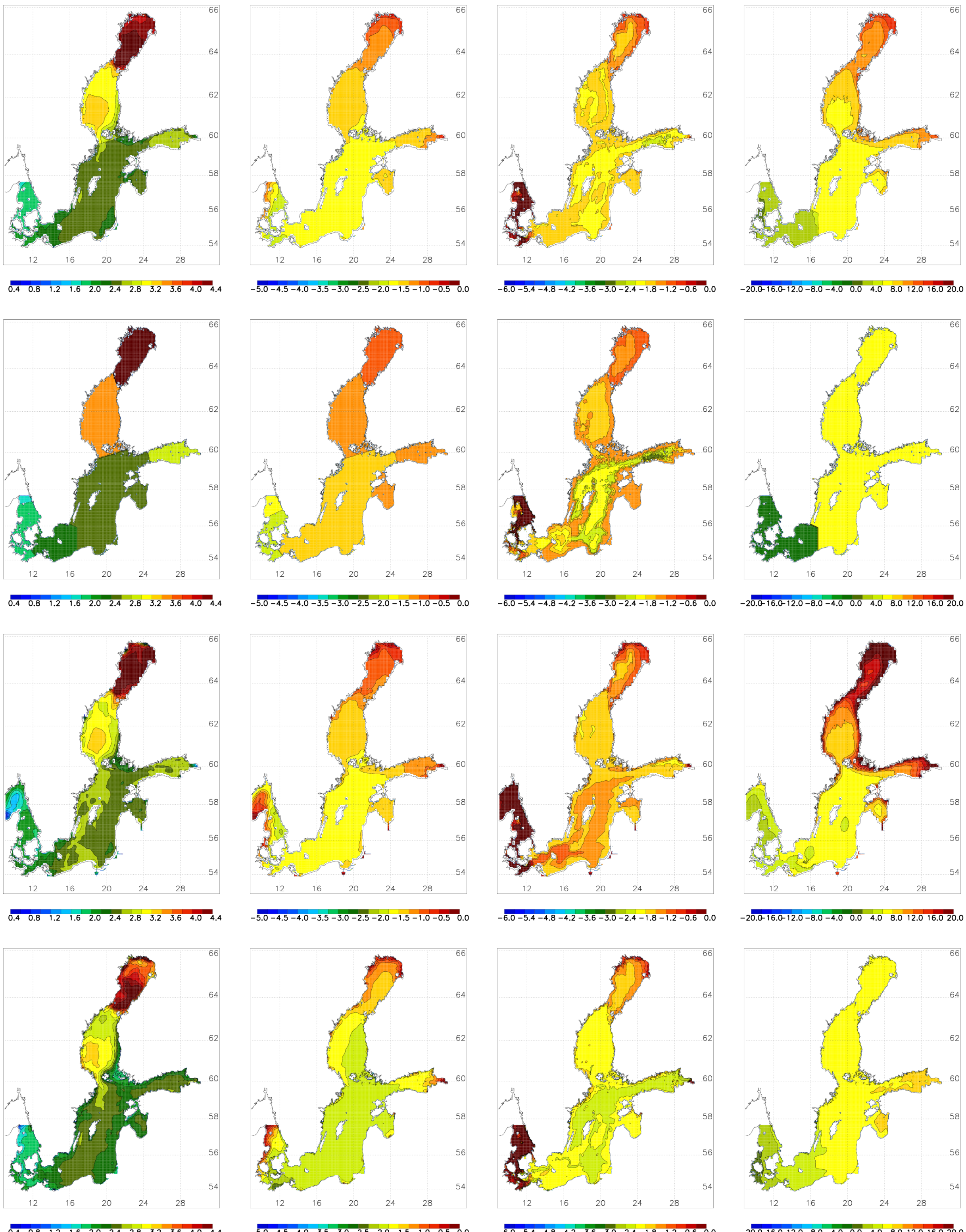

Figure 1. From left to right changes of summer (JJA) mean sea surface temperature (SST) (°C), annual mean sea surface salinity (SSS) (g kg^{-1}), annual mean bottom salinity (g kg^{-1}), and winter (DJF) mean sea surface height (SSH) (cm) between 2069-2098 and 1978-2007 are shown. From top to bottom results of the ensemble mean, BALTSEM, ERGOM and RCO-SCOBI are depicted.

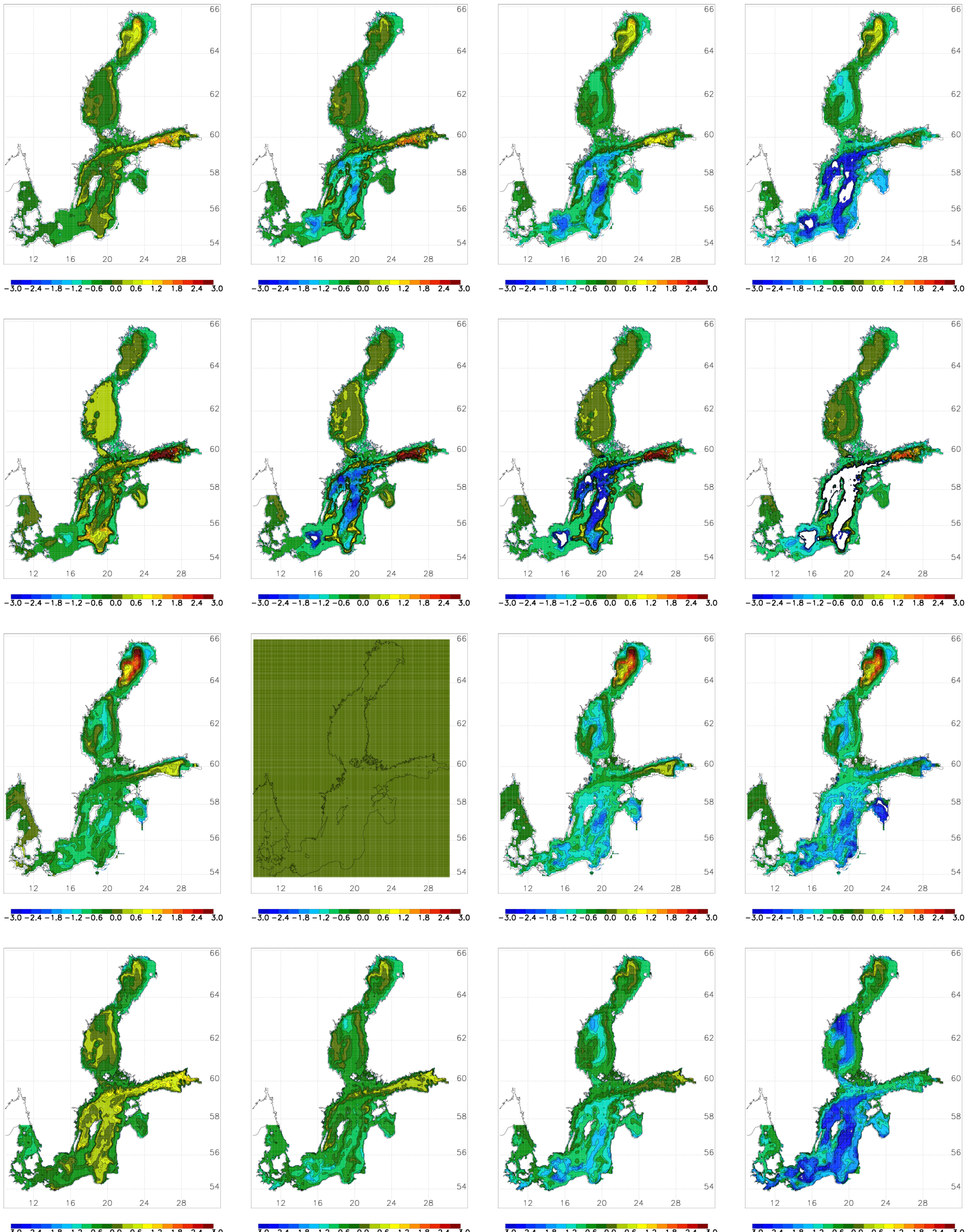

Figure 2. Ensemble mean summer (JJA) bottom oxygen concentration changes (ml l^{-1}) between 2069-2098 and 1978-2007. From left to right results of the nutrient load scenarios BSAP, CLEG, REF and BAU are shown. From top to bottom results of the ensemble mean, BALTSEM, ERGOM and RCO-SCOBI are depicted.

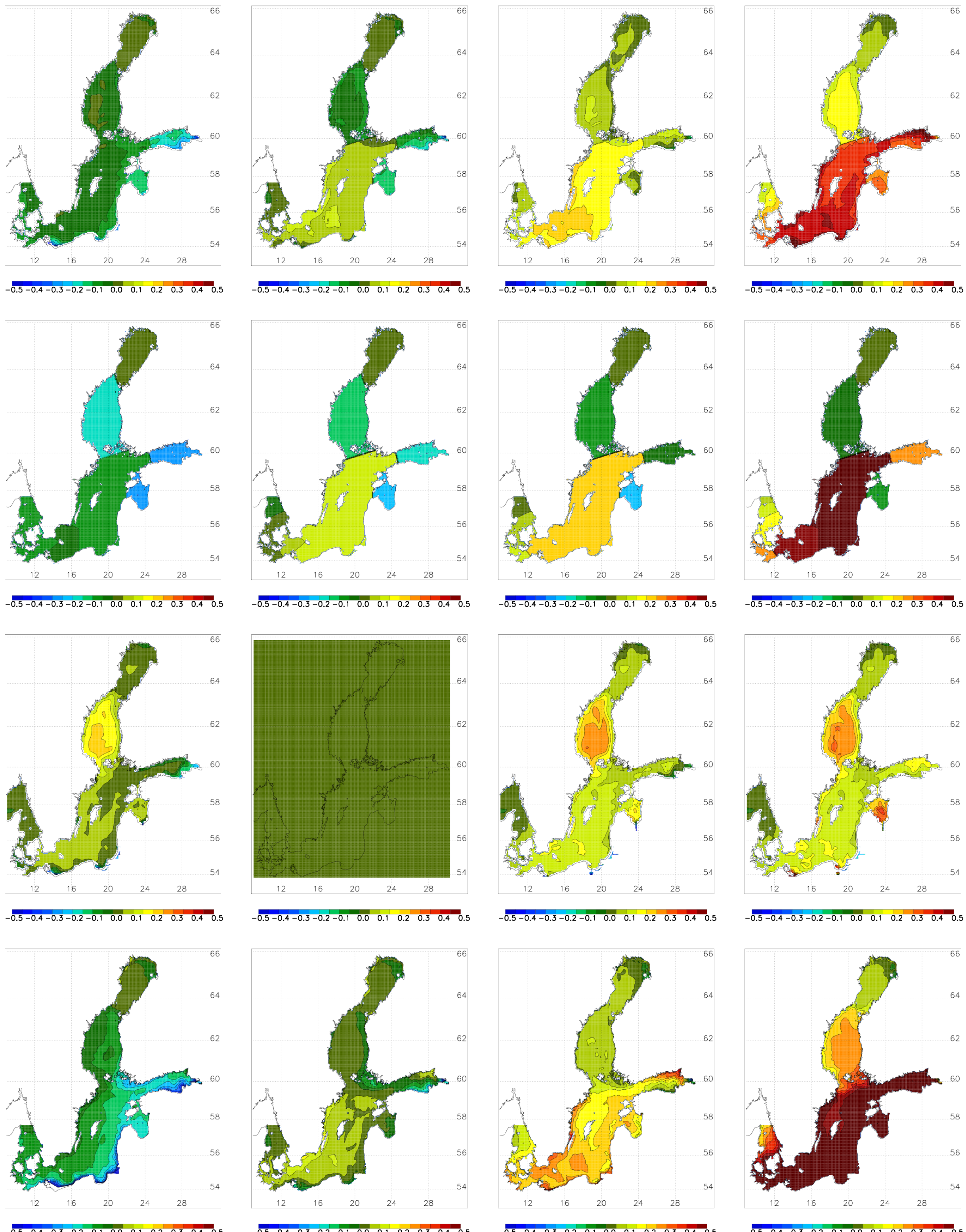

Figure 3. As Fig. 2 but for winter (DJF) mean phosphate concentration changes (mmolP m^{-3}).

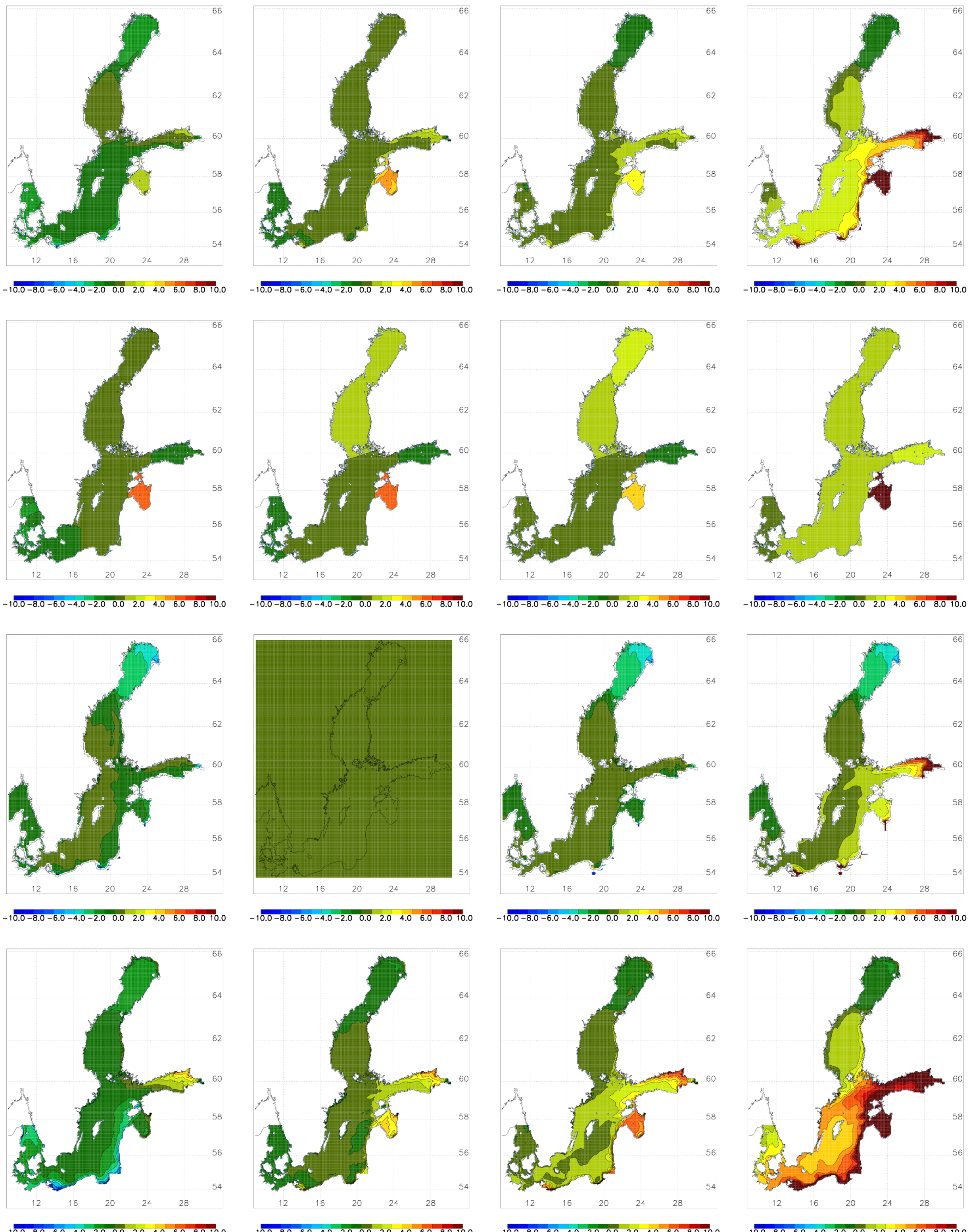

Figure 4. As Fig. 2 but for winter (DJF) mean nitrate concentration changes (mmolN m^{-3}).

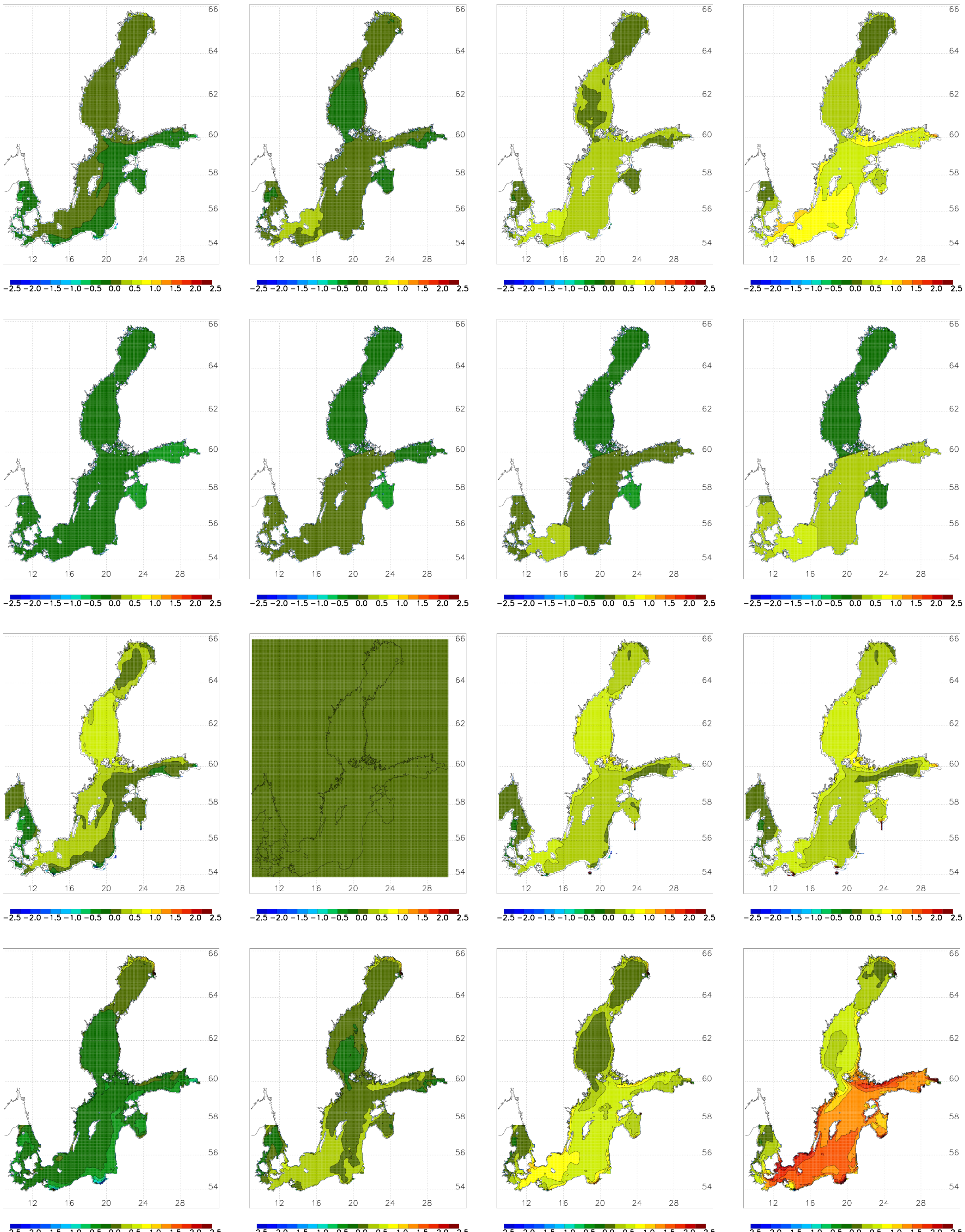

Figure 5. As Fig. 2 but for annual mean phytoplankton concentration changes (mgChl m^{-3}).

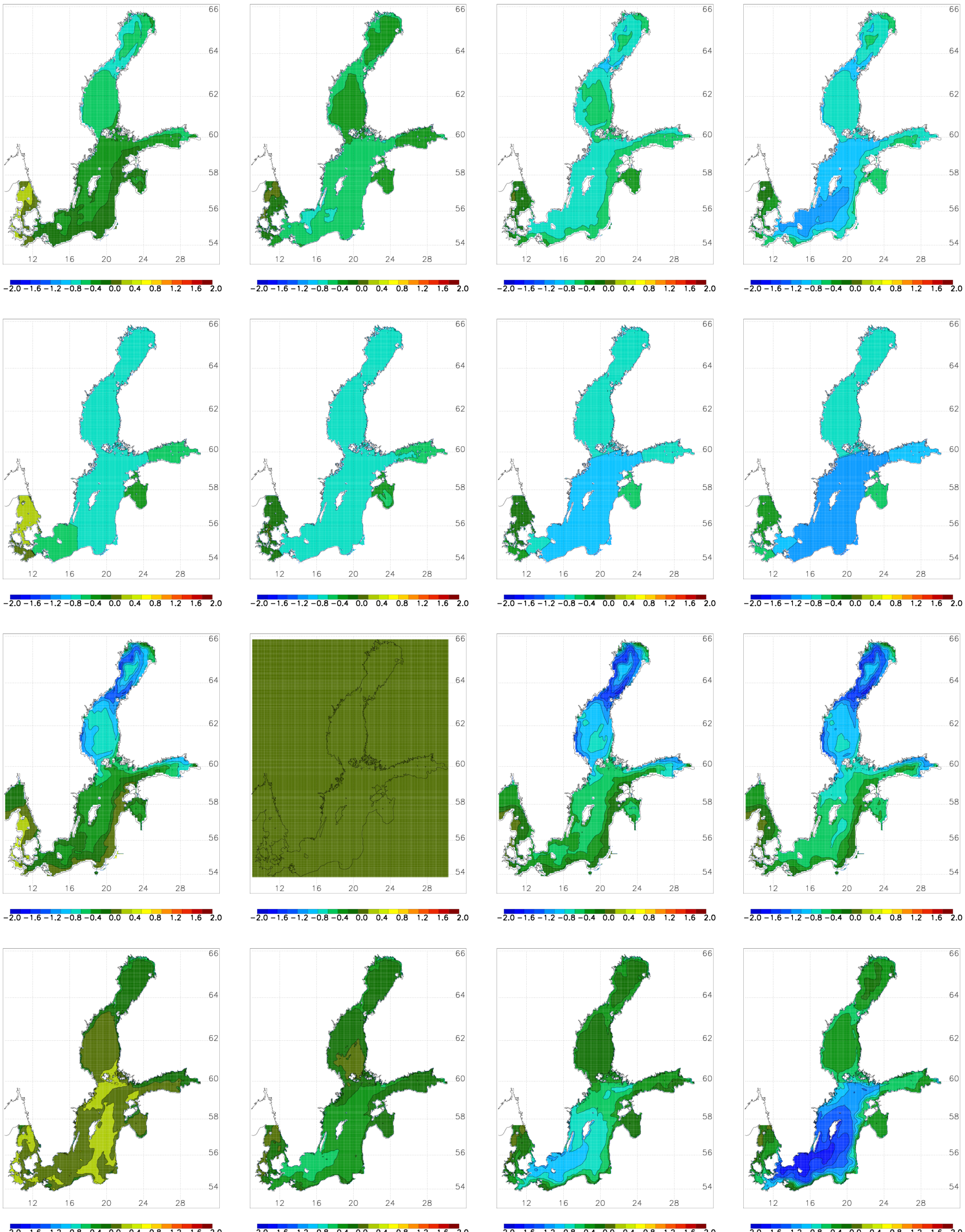

Figure 6. As Fig. 2 but for annual mean Secchi depth changes (m).

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