North Sea sensitivity to atmospheric forcing

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Abstract

The sensitivity of North Sea physics and phytoplankton production to atmospheric forcing have been studied by performing permutations of the atmospheric forcing fields through a number of model simulations. The perturbations are kept in the range of expected climate change, to give a first indication of the climate change impacts on regional systems. The model simulations suggests that an increase in air temparature and short wave radiation will increase sea surface temperature, while an increase in wind will decrease it. Increased wind will incease the transports into the North Sea, while the other atmospheric forcings only have a small impact on that. Combining the perturbations indicate a smaller stratified area and a deeper mixed layer. Primary production is expected to increase, with an increase in wind speed having the largest impact.

Keywords: sensitivity study, ecological model, North Sea, climate change

1. Introduction

Carbon dioxide (CO_2) concentrations in the atmosphere increased during the last century due to a combination of industrialization, urbanization and deforestation and are continuing their rapid rise during the present century. The global response of atmospheric variables such as temperature, winds, precipitation, water vapour and atmospheric pressure to the increasing CO_2, can be examined using coupled ocean/atmosphere/sea-ice/land models. These Global Circulation Models (GCMs) suggest that the present observed warming can only be explained by such

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anthropogenic forcing and project further warming world-wide throughout the present century due to the high levels of greenhouse gases (IPCC, 2007).

The horizontal spatial resolution of GCMs has generally been too coarse (typically grid sizes of 200-400 km), to adequately resolve local or regional topography and ocean dynamics. For impact studies, therefore, the approach has been to develop higher resolution (typically grid sizes of 1-20 km) regional climate models, using the results from the GCMs as boundary conditions (termed downscaling). A number of such studies have been performed for the Baltic and North Sea (Meier et al., 2004, 2006; Ådlandsvik and Bentsen, 2007; Ådlandsvik, 2008). The regional downscaling focusing on the North Sea by Ådlandsvik (2008) clearly identifies the limitations and major problems for regional downscaling. He found a major drawback in the global climate model selected for his projection (Bergen Climate Model). In this model, the westerly winds were displaced too far south. Hence, the climate of the present day reference simulation had little to no connection to the observed climate over the North Sea. Meier et al. (2004, 2006) utilized different regional and global climate models (RCM/GCM) for the Baltic scenarios, and was able to provide a minimum uncertainty range based on the model spread. A consistent positive SST trend was modelled in all scenarios, with an ensemble averaged SST increase of $2.9\,^{\circ}C$. In contrast, projected salinity changes were inconsistent with large differences depending upon the global model used to force the RCMs. For example, a significant decrease in salinity (outside the present day climate variability) was found only for the runs forced directly by the ECHAM4 and ECHAM5 GCM models. This clearly points to deviations in regional dynamics in the global models as being one of the most significant factors for regional projections (BACC, 2008). These results also clearly highlight that an impact study based only on a single global model projection could be strongly biased and can be seen only as demonstrating downscaling methodology (Ådlandsvik and Bentsen, 2007).

Without an assessment of the regional performance of a GCM for the present day conditions together with an estimation of the range of uncertainties based at least on a number of global model projections (Overland and Wang, 2007; Jacob et al., 2007), a regional projection cannot provide an adequate base for assessment of the future climate change of a regional system since it does not allow for even the simplest uncertainty measures. Through the ENSEMBLES project (http://ensembles-eu.metoffice.com) a number of RCMs were weighted based on their performance given a set of metrics. However, it is concluded (ENSEMBLES, 2009) that even these weights are not sufficient to separate good models from bad models, and it was recommended to use the whole set of RCMs when applying them. Also, to provide atmospheric forcing for impact studies using only a sub-set of available RCMs, it was recommended to use results based on two or more RCMs that again are forced by at least two GCMs (ENSEMBLES, 2009).

Another more process-oriented approach which isolates different contributions from climate variables and test their regional impacts under climate change, is to perform a traditional sensitivity study using a typical projected climate change range for a number of parameters. Such sensitivity simulations are a simple way to test the sensitivity of regional systems to changes in atmospheric forcing. If the perturbations of atmospheric forcing are in the range of expected climate change as identified by IPCC assessments (IPCC, 2007), they give a first indication of the range of climate change impacts on regional systems. For these sensitivity simulations and model exercises, impacts of wind, radiation and temperature changes can be separated and linear combinations and nonlinear interactions can be identified providing useful insight into climate change effects and improve understanding and identification of relevant climate controls.

We have used this approach to assess the sensitivity of the North Sea physical oceanography to atmospheric forcings, and identify some possible ranges of potential change. The sensitivity simulations are constructed by simply perturbing one or more climate forcing variable by an arbitrary amount (e.g., by increasing wind by 30%) and seeing what their effect is on the ocean (e.g. SST, heat content, salinity, etc.). Generally the forcing factor was varied one at a time and the response of each of the ocean variables was determined. However, we also changed three forcing variables simultaneously, i.e., an increase in temperature coupled with an increase in wind and shortwave radiation, and observed the corresponding responses. It is virtually impossible to describe a realistic set of changes for all atmospheric forcing variables which are physically plausible and consistent, and the prescribed changes tend to be arbitrary and may not conform to the uncertainty range of global changes. Therefore, the simulations presented serve as sensitivity studies to possible future changes rather than to predict a realistic future ocean state.

2. Material and methods

2.1. The NORWECOM model

The NORWegian ECOlogical Model system (NORWECOM) is a coupled physical, chemical, biological model system (Aksnes et al., 1995; Skogen et al., 1995; Skogen and Søiland, 1998) applied to study primary production, nutrient budgets and dispersion of particles such as fish larvae and pollution. The model has been validated by comparison with field data in the North Sea/Skagerrak, e.g. Svendsen et al. (1996); Skogen et al. (1997); Søiland and Skogen (2000); Skogen et al. (2004); Hjøllo et al. (2009).

The physical model is based on the three-dimensional, primitive equation, time-dependent, wind and density-driven Princeton Ocean Model (POM). The model is fully described in Blumberg and Mellor (1987). In the present study the model is used with a horizontal resolution of 10 km (Figure 1). In the vertical, 20 bottom following sigma layers are used.

The chemical-biological model is coupled to the physical model through the subsurface light, the hydrography and the horizontal and the vertical movement of the water masses. The prognostic variables are dissolved inorganic nitrogen (DIN), phosphorus (DIP) and silicate (SI), two different types of phytoplankton (diatoms and flagellates), two detritus (dead organic matter) pools (N and P), diatom skeletals (biogenic silica) and oxygen. The processes included are primary production, respiration, alga death, remineralisation of inorganic nutrients from dead organic matter, self-shading, turbidity, sedimentation, resuspension, sedimental burial and denitrification. Phytoplankton mortality is given as a constant fraction, and is assumed to account also for zoo plankton grazing, which in this context is included as a forcing function. The material produced by mortality is partly regenerated through the detritus pool, but 10% is instantly regenerated as dissolved inorganic nitrogen (in nature as ammonium) and 25% as phosphorus available for uptake by phytoplankton (Bode et al., 2004; Garber, 1984).

Particulate matter has a sinking speed relative to the water and may accumulate on the bottom if the bottom stress is below a certain threshold value and resuspension takes place if the bottom stress is above a limit. Remineralization takes place both in the water column and in the bottom sediments. The bottom stress is due to both currents (including tides) and surface

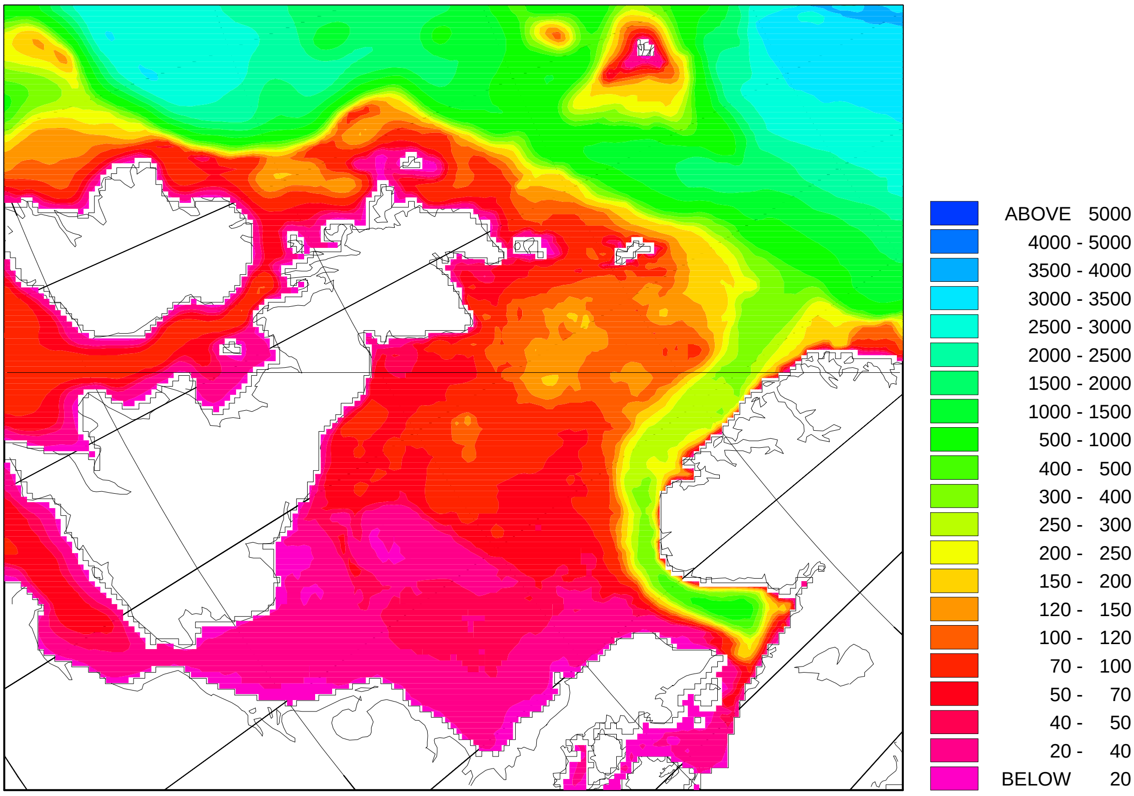

Figure 1: Model bathymetry (depth in meters)

waves. To calculate the wave component of the bottom stress, data from DNMI's operational wave model, WINCH (SWAMP-Group, 1985; Reistad et al., 1988), are used. Parameterization of the biochemical processes is taken from literature based on experiments in laboratories and mesocosms, or deduced from field measurements (Aksnes et al., 1995; Pohlmann and Puls, 1994; Mayer, 1995; Gehlen et al., 1995; Lohse et al., 1995, 1996).

2.2. Model set-up, forcing and strategy

Seven different simulations were carried out, one reference run using the present day forcing, and six sensitivity experiments with atmospheric perturbations considered in the range of the future climate change (IPCC, 2007). The reference run was part of a long-term simulation (1985-2007) (Hjøllo et al., 2009). For the present study the period 2002-2004 has been selected, which implies almost 20 years of model integration before the period to be analyzed. The sensitivity experiments have been initialised from the reference run using mean fields for December 2001, and then the perturbations were made to the 2002-2004 atmospheric forcing. The forcing variables are six-hourly hindcast atmospheric pressure fields and wind stress from the European Center for Medium-Range Weather Forecasts (ECMWF), four tidal constituents at the lateral boundaries, and freshwater runoff. Surface heat fluxes (short and long-wave radiation, sensible and latent heat fluxes), are calculated using data available from the ECMWF archive applying standard bulk formulae.

Along the open boundaries interpolation between monthly climatologies (Martinsen et al., 1992) are used, except at the inflow from the Baltic where the volume fluxes have been calculated from the modelled water elevation in Kattegat and the climatological monthly mean freshwater runoff to the Baltic (Stigebrandt, 1980). To absorb inconsistencies between the forced boundary conditions and the model results, a 7 grid-cell ”Flow Relaxation Scheme” (FRS) zone (Martinsen and Engedahl, 1987) is used around the open boundaries in all simulations.

Irradiation and light in the water column is modelled using a formulation based on Skartveit and Olseth (1986, 1987), using surface solar radiation data from the European Centre for Medium-Range Weather Forecasts (ECMWF, www.ecmwf.int) as input data. Nutrients (inorganic nitrogen, phosphorus and silicate) are added to the system from the rivers and from the atmosphere (only inorganic nitrogen). Monthly mean river data (freshwater and nutrient loads) are derived from data that originates from Rijkswaterstaat (Belgium and the Netherlands), Arbeitsgemeinschaft für die Reinhaltung der Elbe and Niedersächsisches Landesamt für Ökologie (Germany), National Environmental Research Institute (Denmark), the Swedish Meteorological and Hydrological Institute and Swedish University of Agriculture (Sweden), the Norwegian Water Resources and Energy Directorate and the Norwegian State Pollution Control Authority (Norway), while data from the U.K. are from raw data provided by the Environment Agency (S. Painting, CEFAS, pers. comm). In addition some extra freshwater is added along the Norwegian and Swedish coast to fulfill requirements of the estimated total freshwater runoff from these coastlines (Egenberg, 1993).

The model assumes saturated oxygen conditions at the surface boundary. The initial nutrient fields are derived and extrapolated/ interpolated (Ottersen, 1991) from data (obtained from ICES) together with some small initial amounts of algae. Nutrient data (monthly means) measured in the Baltic (ICES) are used for the water flowing into Kattegat.

Atmospheric surface temperature is expected to increase, according to IPCC (2007) assessments, as a consequence of anthropogenic greenhouse gas emissions and a change of $3\,^{\circ}\mathrm{C}$ is within the range of projections. For wind speed, there is no clear coherent signal projected by the global climate models (BACC, 2008; IPCC, 2007, e.g.). The dynamic causes for the inconsistencies are still largely uninvestigated, however, an increase of 30% in wind speed is well in the range of the climatic variability and is used here. Additionally, a change in solar radiation is considered. This is not to mimic the direct changes due to greenhouse gases, which would act on the long-wave rather than on the short-wave radiation, but to test the sensitivity of the regional systems to changes in solar forcing. The tested range of about a 20% increase and decrease was chosen to be consistent with observed decadal trends in solar radiation over sea (Pinker et al., 2005). The current trend was estimated to be 0.24 Wm^{-2} year^{-1}, while the approximate average short-wave radiation at the sea surface in the North Sea is about 110 Wm^{-2} (Loewe, 2009). Under the assumption that this long-term trend is ongoing for 100 yrs, this could amount to an increase close to 20% in solar radiation in mid-latitudes. Since the future short-wave radiation trends over the ocean are currently not consistently projected by the different GCMs (specifically not at regional scales like the North Sea) as both increased as well as decreased cloudiness are projected, we decided as well to test the case of a decreasing trend in solar radiation of the same order of magnitude. Finally we used the combination of increased air temperatures, wind speeds and short-wave radiation (SWR). The various model experiments are listed in Table 1.

3. Results

3.1. Effects on heat and transports

The effect on North Sea SST and heat content for the different sensitivity simulations are shown in Figure 2. The change in SST varies between $1.4\,^{\circ}\mathrm{C}$ for Sc6 (combined) to $-1.3\,^{\circ}\mathrm{C}$ for Sc5 (20% decrease in SWR). The largest mean increase and decrease is 1.1 and -0.7 degrees (Sc6

Scenario	Model experiment
Ref	Reference 2002-2004
Sc1	Increased air temperature $3\,℃$
Sc2	30% intensification of wind speed
Sc3	30% intensification of westerly wind component
Sc4	20% increase of short wave radiation
Sc5	20% decrease of short wave radiation
Sc6	combined 1+2+4

Table 1: Specifications of model sensitivity experiments

and Sc5 respectively). Using the annual means from Hjøllo et al. (2009), the standard deviation in annual mean SST is found to be 0.29 degrees, which is equal to the change in the sensitivity with the smallest effetc (Sc3). All sensitivity simulations show a pronounced seasonality with the largest changes in spring or summer, but the maximum in Sc1 and Sc6 is seen 1-3 months earlier than that in the other sensitivity simulations. Wind speed changes result in a decrease in SST from the unperturbed state of the same order as the temperature increase in Sc1. The response in SST due to the changes in SWR are symmetric, i.e. approximately the same magnitude but of the opposite sign and are stronger than the response due to changes in temperature and wind. The combined simulation (Sc6) gives an almost linear response to the three different changes performed and also the strongest response of all simulations.

The mean North Sea heat content (not shown) for the reference simulation is 1.15×10^{21}J, in agreement with other estimates (Hjøllo et al., 2009). The North Sea heat content increases with increased air temperature (Sc1) and SWR (Sc4) and decreases with a reduction in SWR. The largest increase is again Sc6 (0.18×10^{21}J), while the decrease for Sc5 is 0.04×10^{21}J, which is the same as the standard deviation in annual mean heat content from Hjøllo et al. (2009). The effect on SSTs from the perturbations in SWR is symmetric, i.e. of the same amplitude but different sign for increases and decreases in SWR. The changes in wind conditions result in both an increase and a decrease in heat content, with a negative impact in winter (January-April) and a

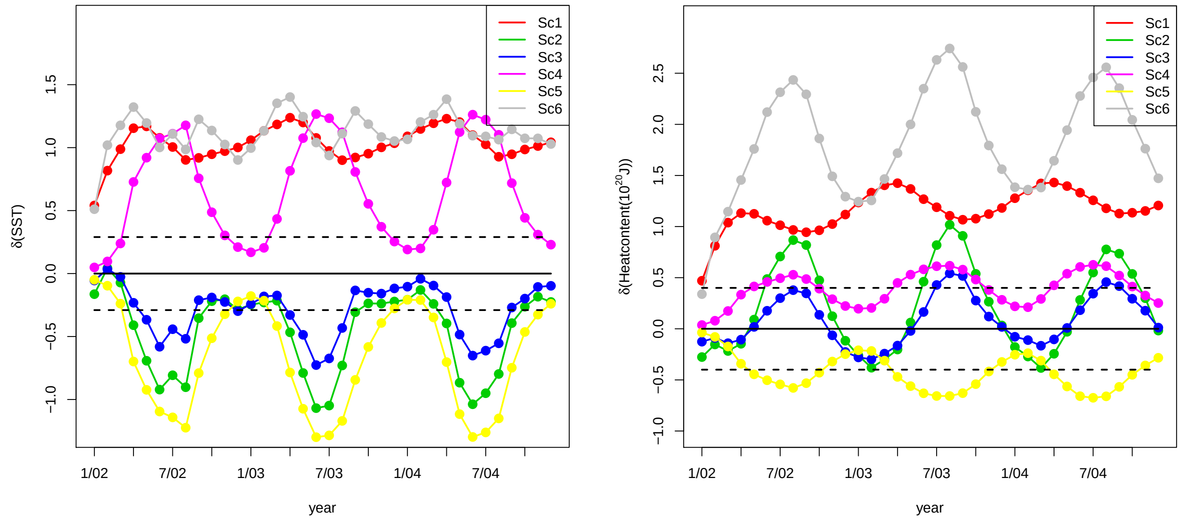

Figure 2: Monthly mean difference in North Sea sea surface temperature (left) and heat content (10^{20} J) (right) between sensitivity simulations and reference run. Dotted black line is one standard deviation of the annual mean SST and heat content

positive one for the rest of the year. Again the combined simulation (Sc6) gives an almost linear response. The seasonality of the heat content is slightly different from that for the SST, with the largest difference to the unperturbed state 1-2 months later (August). The exception to this is the influence from the change in air temperature (Sc1) which is strongest during the spring season before the onset of stratification and lower during summer when the warming is mainly restricted to the surface mixed layer.

The effect of the perturbations to the North Sea inflow through the English Channel and through a section from Orkney to Utsira (Norway) along $59.17\,^oN$ have been examined. The mean modelled inflow in the reference run through the English Channel is 0.126 Sv. (1 Sv.= 10^6 m^3/s). The largest difference between the reference and the sensitivity simulations is to Sc2, with an increase of 0.021 Sv, while a change in SWR has the smallest effect (0.002 Sv). The largest decrease in English Channel inflow is seen in Sc1, where the new transport is estimated to 0.119 Sv. Using the annual mean transports from Hjøllo et al. (2009), the standard deviation in this inflow is estimated to 0.019 Sv, thus the perturbations implies a maximum effect of the same

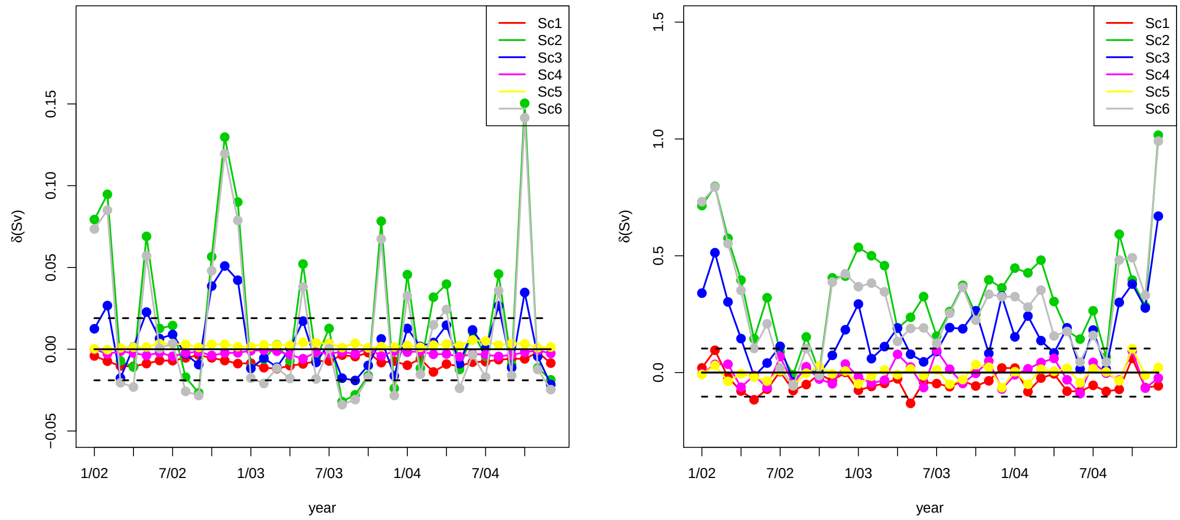

Figure 3: Monthly mean difference in English Channel (left) and Orkney-Utsira (right) North Sea inflow in Sverdrup between sensitivity simulations and reference run. Dotted black line is one standard deviation of the annual mean transports

order. The mean modelled inflow in the reference run through the Orkeny-Utsira section is 1.21 Sv. Again the largest difference is seen with Sc2 (mean transport of 1.56 Sv), while the lowest transport is found in Sc1 (1.17 Sv). A change in SWR has the smallest effect (changes 0.01 Sv). Using the annual means, the standard deviation of the transport is estimated to 0.10 Sv, thus the increase in wind results in an increase in the mean transport of almost three standard deviations. Focusing on the monthly transports (Figure 3) the change from the reference simulation are much larger in periods. For both sections, the effect of a 30% intensification of the wind speed is almost of the same order as the reference flow. At the northern section the changing wind always strengthens the inflow, while through the English Channel, some periods of weakening are also seen.

3.2. Stratification

Stratification can be defined in various ways, but in this study we define *stratified* to be equal to the existence of a mixed layer. Mixed-layer depth (MLD) is found by applying a finite difference criterion on density profiles: $\sigma_t - \sigma_t(0) = (\Delta\ \sigma_t)_c$, where σ_t is density anomaly, $\sigma_t(0)$

density anomaly value at surface and $(\Delta\ \sigma_t)_c$ is a specified difference criterion.

We have used a constant difference criterion $(\Delta\ \sigma_t)_c = 0.1$, which corresponds to a temperature difference of $0.5\,℃$ for water with salinity of S = 34.8 and temperature in the range $10 - 12\,℃$ which is characteristic for the North Sea (Levitus, 1982). The response to the changes in the atmospheric forcing to the North Sea stratified area and MLD are shown in Figure 4. In the reference run the North Sea stratified area varies between 0% in winter to about 85% in summer, and the MLD between 50 and 8 meters. Increased air temperature (Sc1) and SWR (Sc4) give a larger stratified area and a shallower mixed layer, while increased wind speed (Sc2, Sc3) and a decrease in SWR (Sc5) results in a smaller stratified area and deeper mixed layer. Increased wind speed has the largest negative impact (-4.9% and 3.8 meters), while an increase in SWR gives an increase in stratified area of 2% and shallowing of MLD of 1.0 meter. The standard deviation computed from Hjøllo et al. (2009) is 1.6% and 0.8 meters respectively. An increase in air temperature (Sc1) only changes the stratification and MLD to a small extent. Perturbations in SRW are not symmetric as the sensitivity to a 20% decrease is larger than that for a 20% increase, while there is still a strong linearity for the combined run (Sc6).

3.3. Effects on lower trophic levels

In Figure 5 (left panel) the modelled annual depth-integrated (gC m^{-2}) primary production for the reference run in 2003 is shown. The mean modelled production is 108 gC m^{-2}. In the North Sea the highest production is seen close to the large river outlets along the southern North Sea continental coast with an annual production of more than 200 gC m^{-2}. This is more than 3 times the values in the central and northern North Sea. In the Skagerrak (except for the Danish coast), the model gives annual production estimates between 100 and 150 gC m^{-2}, while the production along the Norwegian west coast is around 100 gC m^{-2}. These numbers are in general agreement with other model estimates (e.g. Moll and Radach (2003)). The annual mean modelled North Sea production for the period 1985-2008 is shown in the right panel of Figure 5. The production in 2002 is just below the long term average, 2003 is above, while 2004 has the lowest modelled primary production in the period.

The effects of the different sensitivity runs on the mean annual primary production for the

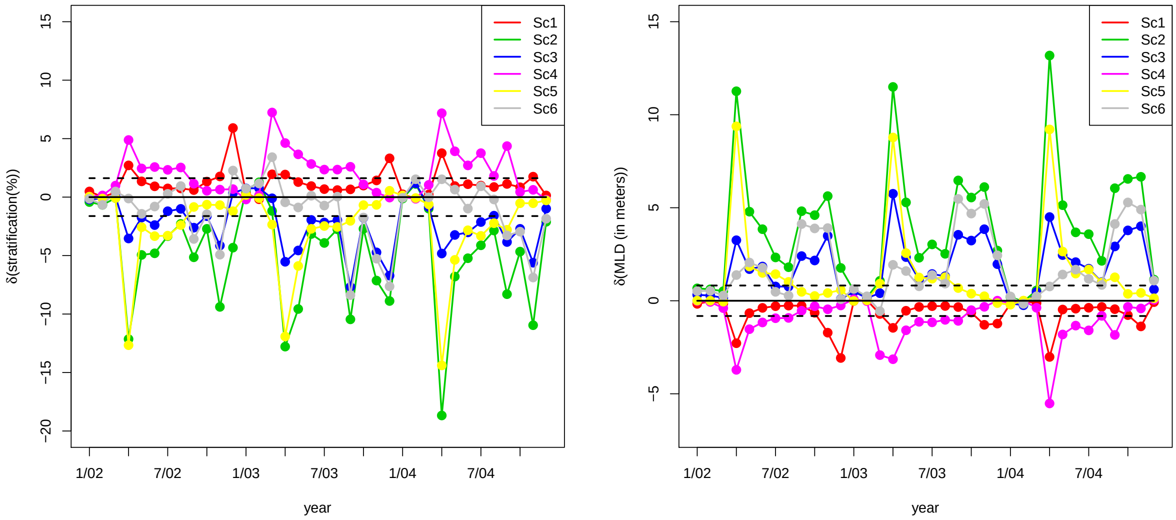

Figure 4: Monthly mean difference in North Sea stratification in percentage (left) and mixed-layer depth in m (right) between sensitivity simulations and reference run. Positive values indicate larger stratified area or deeper mixed layer. Dotted black line is one standard deviation of the annual mean stratified area and MLD

three model years (2002-2004) are seen in Figure 6 (left panel). The largest increase in primary production is seen from Sc6 (combined, i.e. increased air temperature, wind speed, and SWR), with a production about 20% above the reference, while the largest decrease is seen in Sc5 (decrease of SWR) with almost 10% below the reference. The single most important factor for an increase in primary production is the wind speed, while the temperature increase has almost no effect on the level of production. The decreased production due to the decrease in SWR is larger than the increased production due to an increase in SWR, due to the non-linear response of production to light intensity.

Focusing on the spatial patterns of the annual primary production, the main patterns are similar to the reference run (left panel Figure 5), but locally some differences are seen (Figure 7). With an increase in wind (Sc2), the highest increase in primary production is seen in the Atlantic inflow area in the north, off south eastern England, and in the inflow area towards the Skagerrak. With a reduction in the incoming light (Sc5) there is a decrease in the southern North Sea, while the rest of the area is almost unchanged (less than 10%). In the combined simulation

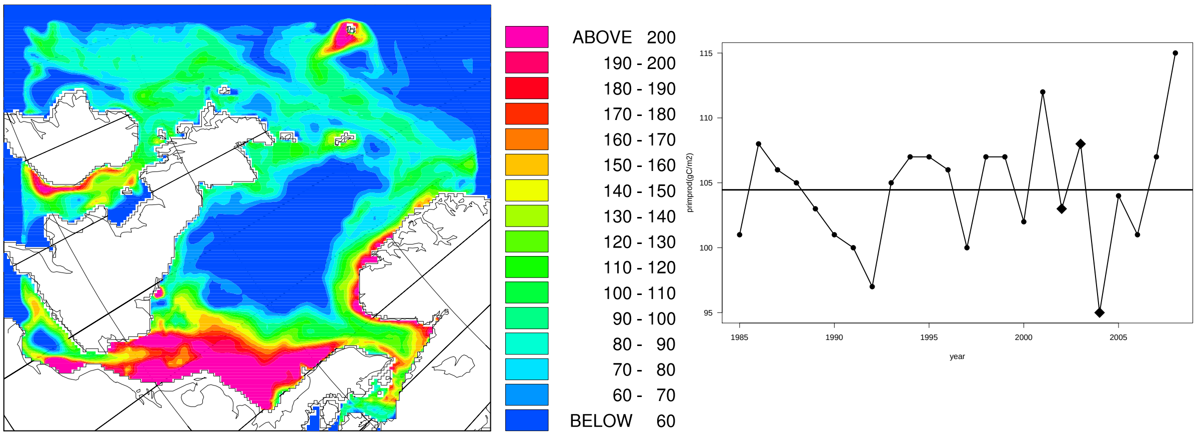

Figure 5: Annual depth-integrated North Sea primary production (gC m^{-2}, left) and its time series (gC m^{-2}, right). Solid line are mean annual production, diamonds indicate the reference period 2002-2004

the largest increase is seen in the south west and in the north, while a decrease is seen in the German Bight (Figure 7).

The changes in the monthly North Sea primary production is examined in the right panel of Figure 6. For all sensitivity simulations the peak 2003 production is seen in May, varying from about 22 (Sc5) to 35 (Sc6) gC m^{-2}. The main effect from the increased wind is an extended spring bloom into June. This is not seen when only the westerly wind component is increased. A decrease in the SWR also results in a low but prolonged bloom into June, when the primary production is higher than the primary production in all sensitivity simulations except for Sc2. This is further investigated in Figure 8 where the monthly differences between the reference run and the different sensitivity simulations are shown. The maximum amplitude change of Sc2 and Sc6 are similar but occur in June and May, respectively, while Sc5, due to the delayed bloom, have periods when it is lower and higher than the reference. Such a change in sign is also the case with Sc1 (increased air temperature) and Sc4 (increased SWR). The start of the spring bloom (not shown) is delayed by almost 10 days in Sc5, while the bloom starts about 10 days earlier in Sc4. For the other perturbations, the difference is only a few days. Except for Sc5 there is a shift in the phytoplankton biomass towards a decrease in the diatoms:flagellate ratio.

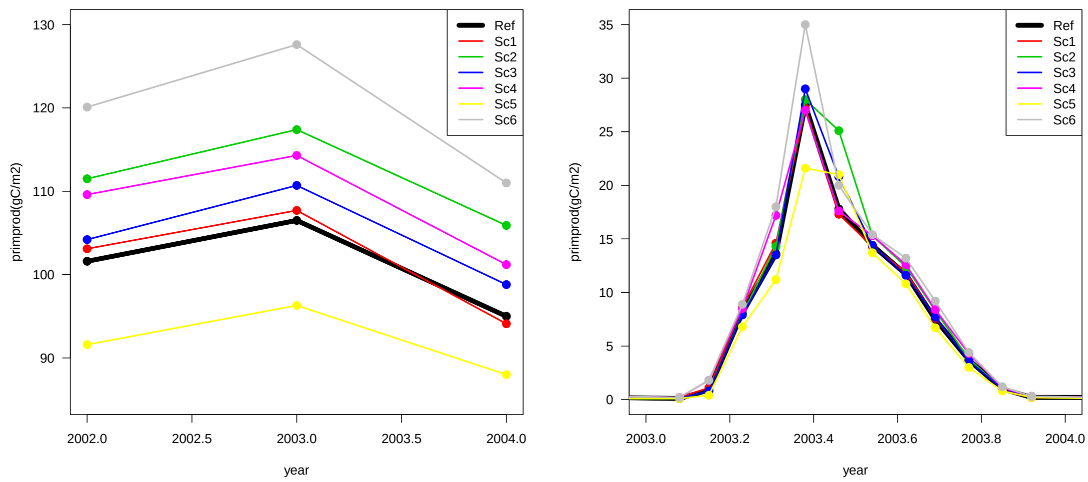

Figure 6: Annual mean depth integrated North Sea primary production (gC m^{-2}, left) and time series of monthly (2003) mean modelled North Sea primary production (gC m^{-2}, right)

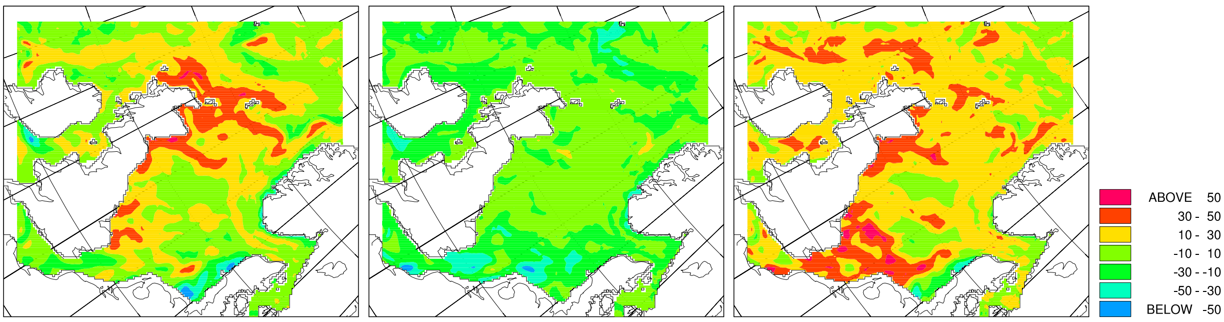

Figure 7: Change (gC/m^2/year) in annual depth integrated North Sea primary production in 2003 for Sc2 (left), Sc5 (center) and Sc6 (right)

4. Discussion

A number of model sensitivity simulations were run by performing permutations of the atmospheric forcing fields. This modeling exercise has shown how the atmospheric changes can impact the North Sea system with anticipated affects on the water properties (heat, stratification and transport) and productivity (phytoplankton). A warmer atmosphere (Sc1) and an increase in SWR (Sc4) will increase SST, while stronger winds will decrease it. The combined effect of all (Sc6) suggests an increase in SST all through the year. The effect on the stratification is more uncertain, but the combined simulation (Sc6) indicate a smaller stratified area (except for winter

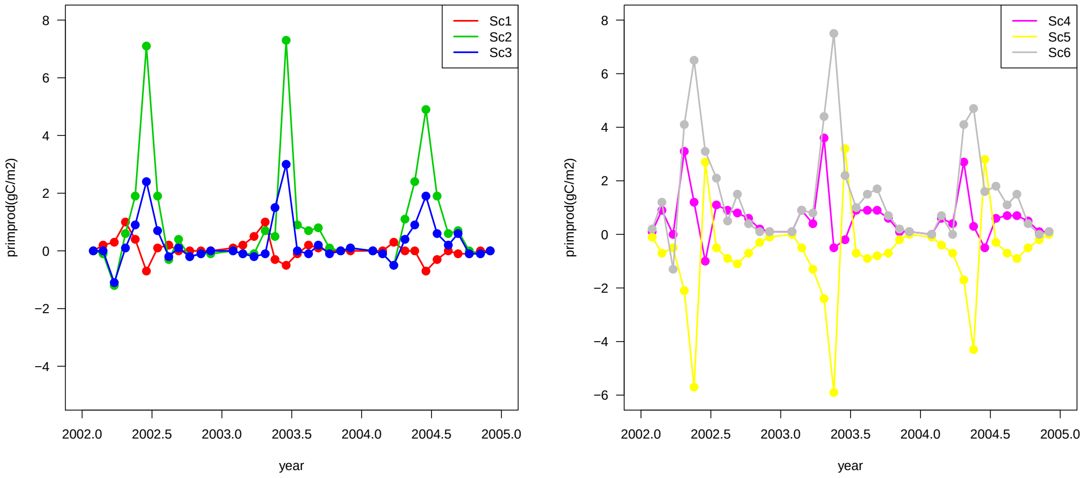

Figure 8: Monthly mean North Sea depth integrated primary production difference (gC m^{-2}) between the reference run and the sensitivity simulations for year 2003

and early spring), and a deeper mixed layer especially during fall.

Assuming to represent parts of a future climate state, the combined simulation (Sc6) has been compared to a climate study. Ådlandsvik (2008) downscaled the SRES A1B scenario from the Bergen Climate Model for the period 2072-2097 in the North Sea, and compared it to a 20C3M run for the period 1972-1997. The results showed a warming of the North Sea with a volume average of $1.4\,^{\circ}C$ and a mean SST change of $1.7\,^{\circ}C$. The mean temperature increase was strongest in May with a minimum in November, while the SST peak warming was found in June. Comparing this to the present results (Figure 2), the mean SST increase in Sc6 was $1.1\,^{\circ}C$ with a maximum in April, while the volume averaged increase for Sc6 was $1.4\,^{\circ}C$ with a maximum in August and a minimum in February. This indicates a somewhat stronger and strengthened stratification in Ådlandsvik (2008) compared to the present study where Sc6 gives a somewhat weaker stratification than the reference run (Figure 4). The main reason for this is probably that the mean wind stress over the North Sea is rather weak in the downscaled study with the westerly winds displaced too far south. Ådlandsvik (2008) also report on changes in the North Sea inflow. Using a slightly different section (Orkney-Feie) the mean inflow is increased from 1.4 to 1.5 Sv from the control to the future scenario with a maximum (0.3) in May and a minimum (-0.2) is

October. Comparing this to the results reported in Figure 3 the mean inflow is 1.2 Sv with an increase in Sc6 is 0.3 Sv, but without any clear seasonal signal.

Oceanic inflow to the North Sea is the major source of new nutrients to the system (e.g. Brockmann et al. (1990)), and other studies (Skogen and Moll, 2000), concluded that the interannual variability in the North Sea primary production to a large extent is determined by the Atlantic inflow. As the increase in wind speed also resulted in an increased inflow of Atlantic water (see Figure 3) and thereby also of the available nutrients, this explains why the most important factor determining primary production was found to be the wind speed. Earlier studies (Skogen and Moll, 2000) suggest that the interannual variability in the mean North Sea primary production is around 15%, and it should be noticed that even with the increased wind (Sc2 and Sc3), the production is almost within the limits of natural variability (see Figure 5).

The only sensitivity experiment that gave a reduced primary production was the decrease in SWR (Sc5). This is due to the fact that the modelled production is limited by light, and a reduction in SWR will reduce the euphotic zone. This reduction in primary production can be seen in relation to the effect of river nutrients. The PARCOM Recommendation on reducing nutrients to the North Sea outlined that the inorganic nitrogen and phosphorus inputs to the coastal areas should be reduced by 50% of the 1985 concentrations (OSPAR, 1988) for those areas where nutrients cause, or are likely to cause, pollution, and the effect of such a reduction have been examined in a number of papers (see e.g. (Skogen and Mathisen, 2009; Lenhart et al., 2010)), The main conclusion from these studies are that when reducing the river DIN and DIP loads by 50% the largest effect could be detected in the coastal areas (1520% reduction in primary production) whereas the offshore areas had little or no response. Skogen and Moll (2000) estimated the total effect of river nutrient inputs on the whole North Sea primary production to be less than 10%, thus the impact of changing nutrients loads due to altering land use, sewage water treatment etc., is comparable to a 10% decrease in SWR. Sc4 is the only experiment that gives a shift in the phytoplankton biomass towards a decrease in the diatoms:flagellate ratio (not shown), the opposite to the effect from reduced N and P. The increase in temperature on the other hand (Sc1), had almost no effect on the level of production even if the production is temperature dependent. Increased temperature will give higher production rate, and an earlier spring bloom

(Figure 8). However, since neither the remineralization rate nor the phytoplankton mortality is temperature dependent in the model, the regenerated production will remain almost unchanged.

A similar sensitivity study using the coupled ecosystem model ECOSMO (Schrum et al., 2006) (which also includes zopoplankton) is reported in Drinkwater et al. (2009). The results from the ECOSMO model confirmed basically the here presented NORWECOM results for the first trophic level. The second trophic level response as calculated by ECOSMO was found to be in phase with the primary production, but its amplitude was relatively stronger in relation to the reference production (for the combined scenario (Sc6) 32.5 compared to 20.8%). Similarly to the results achieved by NORWECOM, radiation changes showed the largest impacts on North Sea lower trophic level productivity, followed by wind induced changes. A marginal decrease in annual primary and secondary production was estimated for the increase in air temperature. From this it is likely that an increase in primary productivity also would propagate to the second trophic level and thereby provide improved feeding conditions for larval fish and consequently for higher trophics (Drinkwater et al., 2009).

Potential changes in temperature, stratification, advection or productivity are also able to indicate some changes in ecosystem structure and functioning. With an increase in wind stress, the Atlantic inflow will be stronger (Figure 3), which will have a potential positive effect on the horse mackerel catches (Iversen et al., 2002). A potential increase in both Atlantic inflow to the North Sea and temperature could alter the drift patterns and growth and thereby the settlement location of spawning products, that again will have an effect on larvae survival and recruitment (Gallego et al., 1999; Stenseth et al., 2006; Daewel et al., 2008; Peck et al., 2009). An increase in temperature (Drinkwater, 2005) and in the westerly-component of the current velocity field (Daewel et al., 2010) is belived to be negatively related to North Sea cod recruitment, and it is also suggested that the abundance of North Sea plaice would decrease in a combination of higher winter temperatures and advection (Rijnsdorp, 2010). Higher temperatures, in combination with a shift in planktonic community, is also suggested to be the reason for the recruitment failure of the North Sea herring recent years Payne et al. (2009). Finally, in more stratified systems there is a tendency to favour a pelagic to demersal fish production (Frank et al., 1990).

5. Concluding remarks

The performed sensitivities are necessarily constrained by the unknown changes which would occur in a dynamically consistent atmospheric state under changed forcing, e.g. in a climate change situation, and hence the transferability of conclusions are restricted. This does not only apply to lacking large scale feedbacks and their regional impacts not incorporated here, but as well to lacking regional feedbacks impacting on the planetary boundary (roughly the lowest 1 to 2 km of the atmosphere).

Boundary layer feedbacks on the global scale as revealed from IPCC scenarios simulations with GCMs, result e.g. in a stable unchanged relative humidity in a changing climate. The IPCC report concludes that in the planetary boundary layer, humidity is controlled by strong coupling with the surface, and quasi unchanged relative humidity response is uncontroversial (IPCC 2007, Chapter 8, section 8.6.3). Consequently, dew point temperature could be considered to increase at the same rate as air temperature, since the relative humidity can in good approximation be assumed to linearly relate to the difference of air temperature and dew point temperature (Lawrence, 2005). The resulting evaporation rate can therefore be assumed to increase, but at a lower rate than in the here performed scenario runs for which we left the dew point temperature unchanged and the sensitivity simulations are likely to experience an unphysical cooling due to evaporation and hence might result in too low SSTs compared to consistent climate simulations.

Boundary layer processes comprise not only turbulent exchange processes acting in the surface boundary layer, but also radiative and water phase changes as well as cloud formation prominent at the upper levels of the planetary boundary layer. Regionally these changes might be very different and uncorrelated to the global climate change signals from GCMs. Regional feedback processes have previously been studied for the North Sea and Baltic Sea using a coupled 3-d ocean-atmosphere regional model (Schrum et al., 2003). Based on these results, both the radiation fluxes and the turbulent fluxes of heat and fresh water can be considered as being sensitive to regional air-sea feedback, with larger sensitivity of radiation fluxes to the local coupling mode than the turbulent fluxes. The deviations in short wave radiation caused by differences in cloud formation due to different regional coupling modes were reaching up to $20 W/m^2$ in monthly mean (about 10% of the monthly mean global radiation).

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