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European COastal-shelf sea OPerational Observing and forecasting system
Integrated Project

D10.1.3.1: Quantify the potential effects on shelf seas-coastal climate and ecosystem from global climate change predictions.

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1. Publishable Executive Summary

Knowledge of how hydrography, circulation and production on the lower trophic levels will change due to climate change, is crucial for our understanding and management of the ecosystem in the future. Three different models have been used to predict the effect of climate change in the North Sea and Baltic (one model in both areas, and the two others in one area each)

Despite different set-up and focus and two very different approaches for the predictions, the models agree on the level of change in ocean temperature. The IMR model also shows that North Sea transports and primary production is most sensitive to changes in wind forcing.

2. Introduction

The horizontal spatial resolution of GCMs has generally been too coarse to adequately resolve local or regional topography and ocean dynamics. For regional and local impact studies, therefore, the approach has been to develop higher resolution regional climate models, using the results from the GCMs as boundary conditions. A number of such *dynamical downscaling* studies have been performed for the Baltic and North Sea (Meier *et al*., 2004, 2006; Ådlandsvik and Bentsen, 2007; Ådlandsvik, 2008). However, the downscaling focusing on the North Sea by Ådlandsvik (2008) identifies the limitations of the approach. He found a drawback in the global climate model selected for his projection (Bergen Climate Model). In this model, the westerly winds were displaced too far south in both the present day 20th century simulation and in the future projection. Hence, the climate of the present day reference simulation has little to no connection to the observed climate over the North Sea. Meier *et al*. (2004, 2006) utilized different regional and global models for the Baltic scenarios, and was able to provide a minimum uncertainty range based on the model spread. This study projected large differences depending upon the global model used to force the regional models. This points to deviations in regional dynamics in the global models as being one of the most significant factors for regional projections. The results also highlight that an impact study based on a single global model projection could be strongly biased and can be seen only as demonstrating downscaling methodology. One downscaling study, made by DMI, is presented here. Opposed to earlier simulations, the DMI regional ocean model includes both the North Sea and the Baltic Sea, and resolves the transition zone. It does not have the problems described for Ådlandsvik (2008), but is based on only one GCM scenario due to limited computational resources.

An alternative approach is so called *sensitivity* scenarios involving a range of different model approaches to address the impacts of potential climate changes. Such scenarios 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. IMR has used this approach to assess the potential sensitivity of the North Sea to climate change and identify some possible ranges of potential change.

The main advantage of using the dynamical downscaling approach over the sensitivity approach is that the model system calculates a full climate change scenario from a few fundamental data. For the current simulations input to the GCM was the observed atmospheric greenhouse gas and aerosol contents and a scenario for the future changes in these (an IPCC SRES scenario), as well as the observed ocean sea surface temperature and sea ice extent. From this, the model system generates a complete climate change scenario, where all processes and feedback mechanisms included in the model are taken into account. However, the model system is not perfect, and the model output will contain errors. The errors can be assessed by validating the model results of the control run against observations. In a time slice experiment, it is also common to focus on the changes between the control- and scenario runs, with the expectation that model errors cancel out.

On the other hand, the sensitivity study approach has the advantage of more realistic forcing of the ocean model. The dynamical downscaling method is not made to reproduce the full observed variability of the past except in a statistical sense, whereas the assimilated observations in the reanalysis largely secure this. Also, in the downscaling experiment, the model is so complex that it can be difficult to determine cause and effect relations in the climate change signal; this may be easier in a sensitivity study.

Thus, the best choice of approach depends on the application, and the two approaches taken by DMI and IMR should thus be seen as complimenting each other.

3. PARTNER CONTRIBUTIONS

3.1. Univ-GDA

3.1.1. Introduction

The main goal of this work was creating a three-dimensional, biological model for simulation of the biological and chemical processes of the plankton system that are the most important on quantify of the annual primary production for the Baltic Sea (Figure 1). The biological model was embedded in existing hydrodynamical model of the Baltic Sea. Described in WP 10.1.1 sea – ice model (POPCICE) has been use to implement biological equations for plankton system.
The aim of the study is to quantify the annual biological production under circulation and solar radiation forcing conditions. The time scales of the atmosphere are governed by ERA 40 (ECMWF). The most prominent feature of the Baltic Sea dynamics for annual productivity studies is the seasonal stratification in deeper parts and for regions of low tidal currents. The basis for any ecological simulation is a three-dimensional, time-dependent hydrodynamical model, POPCICE for the Baltic Sea (see ECOOP WP 10.1.1), that provides the velocities, diffusion coefficients and the temperature on a temporal and spatial scale that resolves the atmospherically induced variability mentioned above.

3.1.2. The model

This three-dimensional model is the first step towards a Polish ecosystem model of the Baltic Sea that is being developed at the Institute of Oceanology PAS, called Coupled Ecosystem Model of Baltic Sea, Version 1 (CEMBS1). The three-dimensional model is implemented for an extended Baltic Sea area (Figure 1), discretized on a 9 km $\times$ 9 km grid. A maximum of 21 vertical layers is used with 5 m resolution from the surface to ~300 m depth and with progressively increasing grid steps to span a maximum depth of 459 m for the Jama Landsort. The mean water depth in the Baltic Sea is 55 m. Model domain and bathymetry is presented in the Figure 1 (see ECOOP WP 10.1.1).

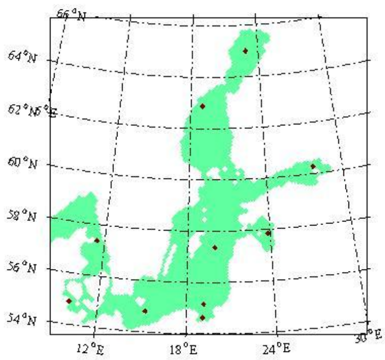
Conceptual basis
The intention was to simulate water column production by using simple biological dynamics within a three-dimensional physical environment which is as realistic as possible. The starting-point was the 1D biological model of Dzierzbicka-Glowacka (2005). In this 3D model, phytoplankton is represented by one state variable and the model formulations are based on a simple total inorganic nitrogen (NO_3+NO_2+NH_4) cycle. Nutrient serves initially as a means to trigger the bloom of phytoplankton and later to limit the phytoplankton production. The model is conceptualized for a shelf sea including the shallow sea characteristic for the replenishment of the mixed layer with nutrients from the bottom. The water column dynamics are implemented in a three-dimensional frame, where phytoplankton and nutrient (nitrogen) are transported by advection and diffusion.

Forcing
The intention was to simulate production within a physical environment which is as realistic as possible. The actual oceanographic forcing is required for reliable simulations of the phytoplankton dynamics. The external forcing depend on meteorological data (as air density, wind stresses and wind speed, surface 2 meters air temperature and dew point, short and long waves radiation) and all atmospheric forces are provided by the ECMWF (ERA 40 reanalysis).The simple biological model is setuped on the same grid as the hydrodynamical model POPCICE for Baltic Sea (ECOOP WP 10.1.1) and uses the daily forcing values to advect and diffuse phytoplankton and phosphate. The biological reaction terms are not implemented within the circulation model. The primary production model is an independent transport model that uses the circulation model output, since no major effects from the biology back to the physics are expected, and this makes simulations much easier to implement. Another important forcing for primary production simulations is solar radiation with its daily cycle. The total irradiance at the surface is calculated using the model by Rozwadowska and Isemer (1999) and Isemer and Rozwadowska (1999).

This method was tested by Isemer and Rozwadowska (1999). The local weather conditions were made on board Voluntary Observing Ships and those data has been used to estimate climatological characteristics of the solar radiation flux at the surface of the Baltic Sea. The monthly loads are interpolated to give daily values. The nutrient contributions by the rivers are not included in this model, but the initial values for nutrients are based on SCOBI 3D-model. Phytoplankton production is limited in the model by light and total inorganic nitrogen. The phytoplankton biomass is limited by zooplankton grazing due to mezozooplanktonu. The zooplankton biomass is prescribed as forcing using the abundance data from the Mańkowski (1978), Ciszewski (1983) and Mudrak (2004) for the southern Baltic Sea. Using these observed biomass values and the abundances, the annual cycles of abundances were transformed to carbon biomass cycles. Trigonometric polynomial has been used to assign values at any model time and for all of the grid points.

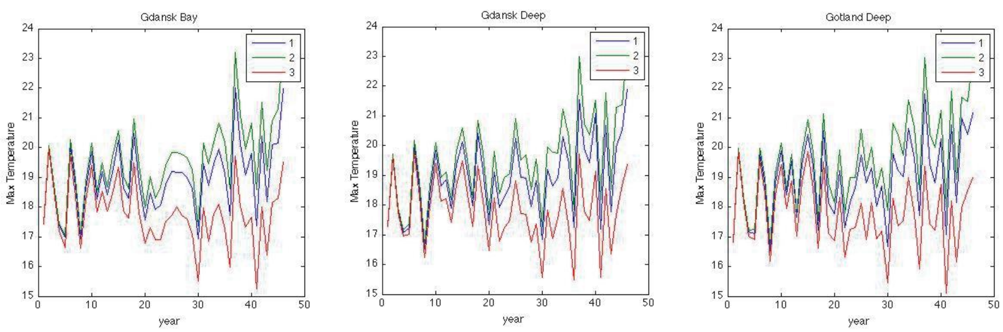
Initial and boundary values
Phytoplankton values for January and December are sparse, therefore a constant value of 0.1 mg C m^{-3} was prescribed. The model is not sensitive to the initial phytoplankton concentration due to the start in January with a long simulation time preceding the spring bloom development. Finally, data for the detritus content at the bottom were not available, and the instantaneous sinking of detritus is a more arbitrary model assumption. The initial detritus content at the bottom was prescribed as 200 mg C m^{-2} for the whole Baltic Sea. The initial values for total inorganic nitrogen are taken from SCOBI 3D-model for January.

3.1.3. Examples of results for three scenarios



Fifty years of model variables for all of selected parts of the Baltic Sea

Figures 1-4 present variability of the investigated variables for next 50 years at selected stations.



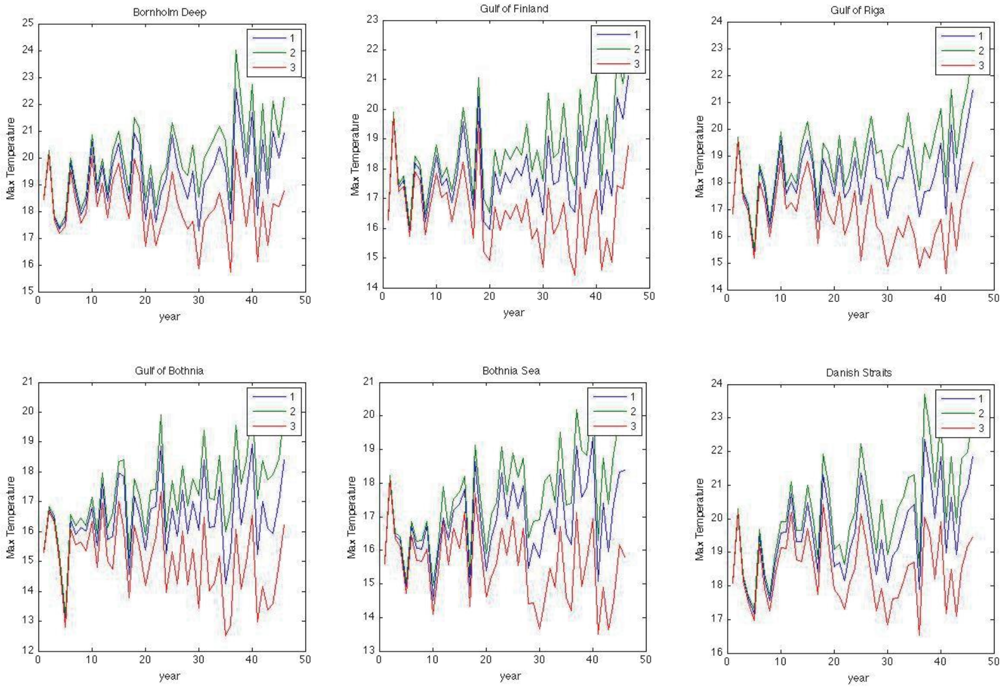
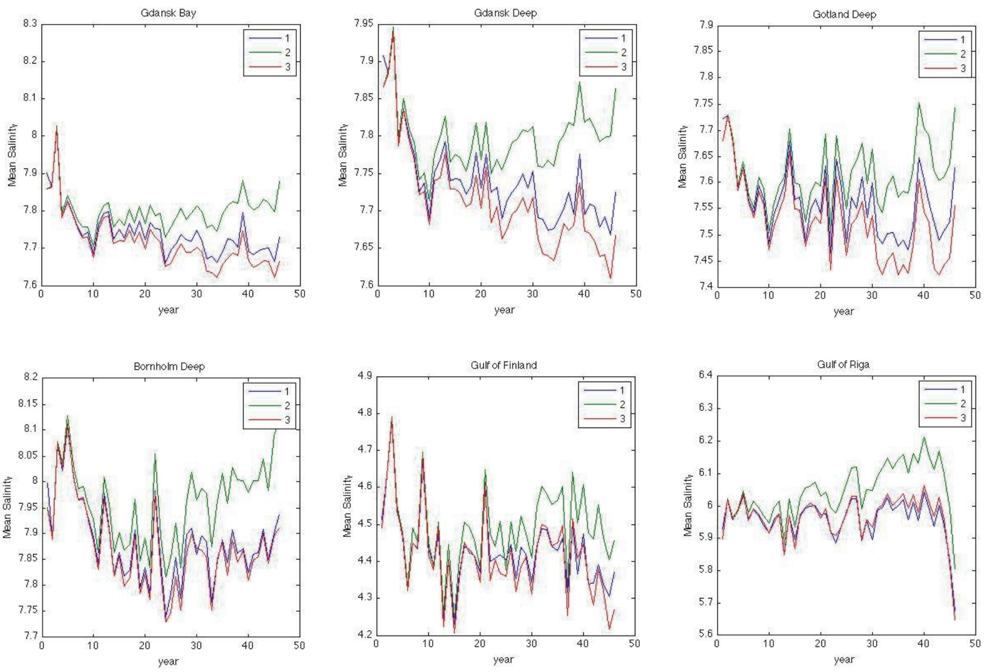


Figure 1. One year maximum sea surface temperature (SST) (^{o}C) at selected stations.



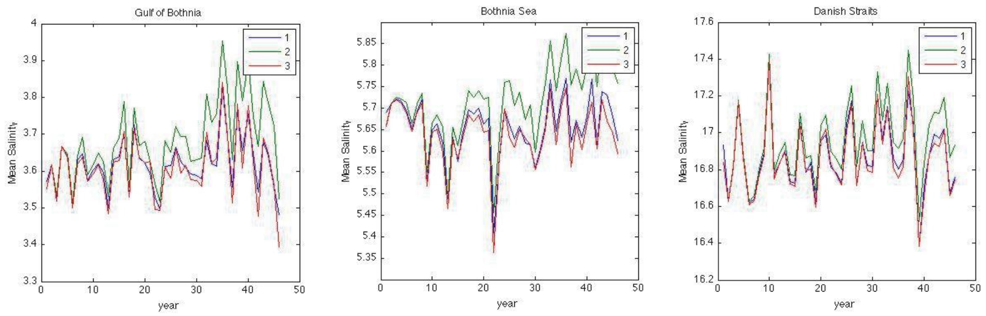


Figure 2. One year averaged of salinity for surface layer at selected stations

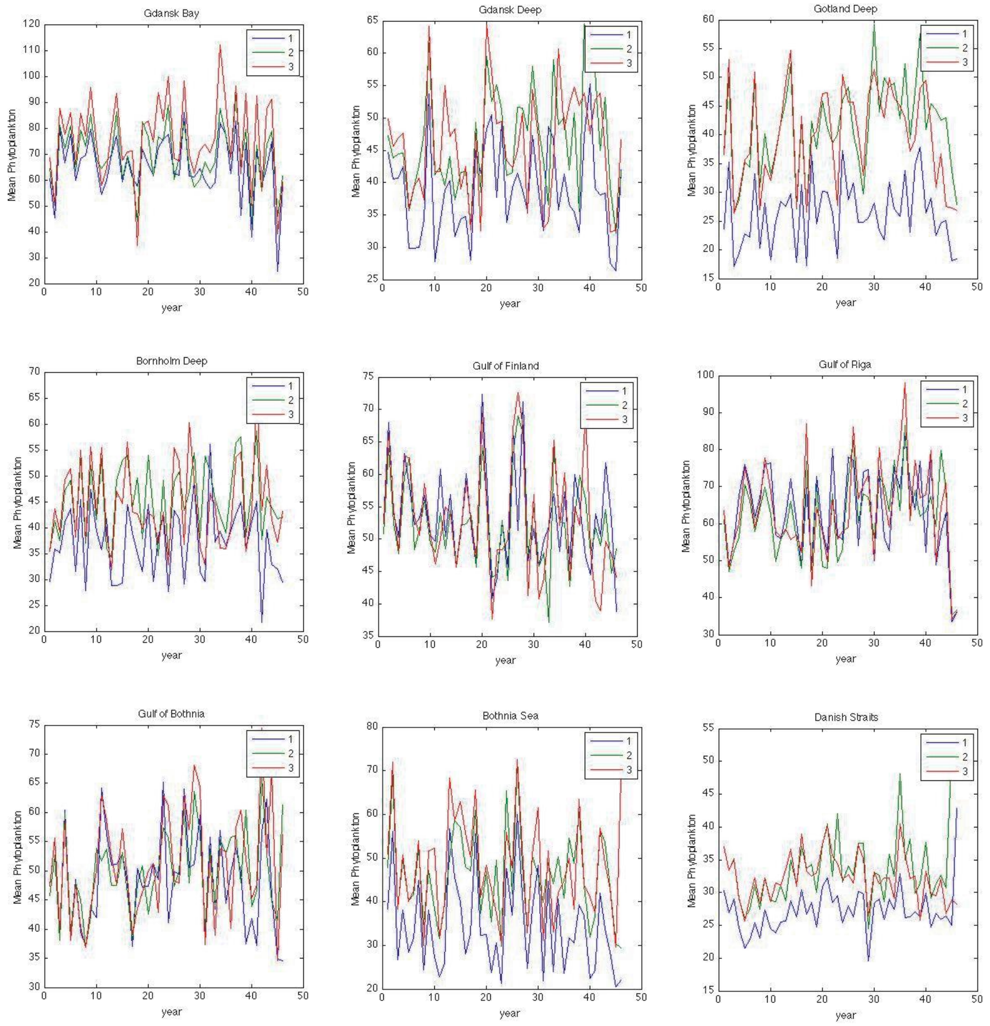


Figure 3a. One year averaged of phytoplankton biomass (mgC m^{-3}) for surface layer at selected stations.

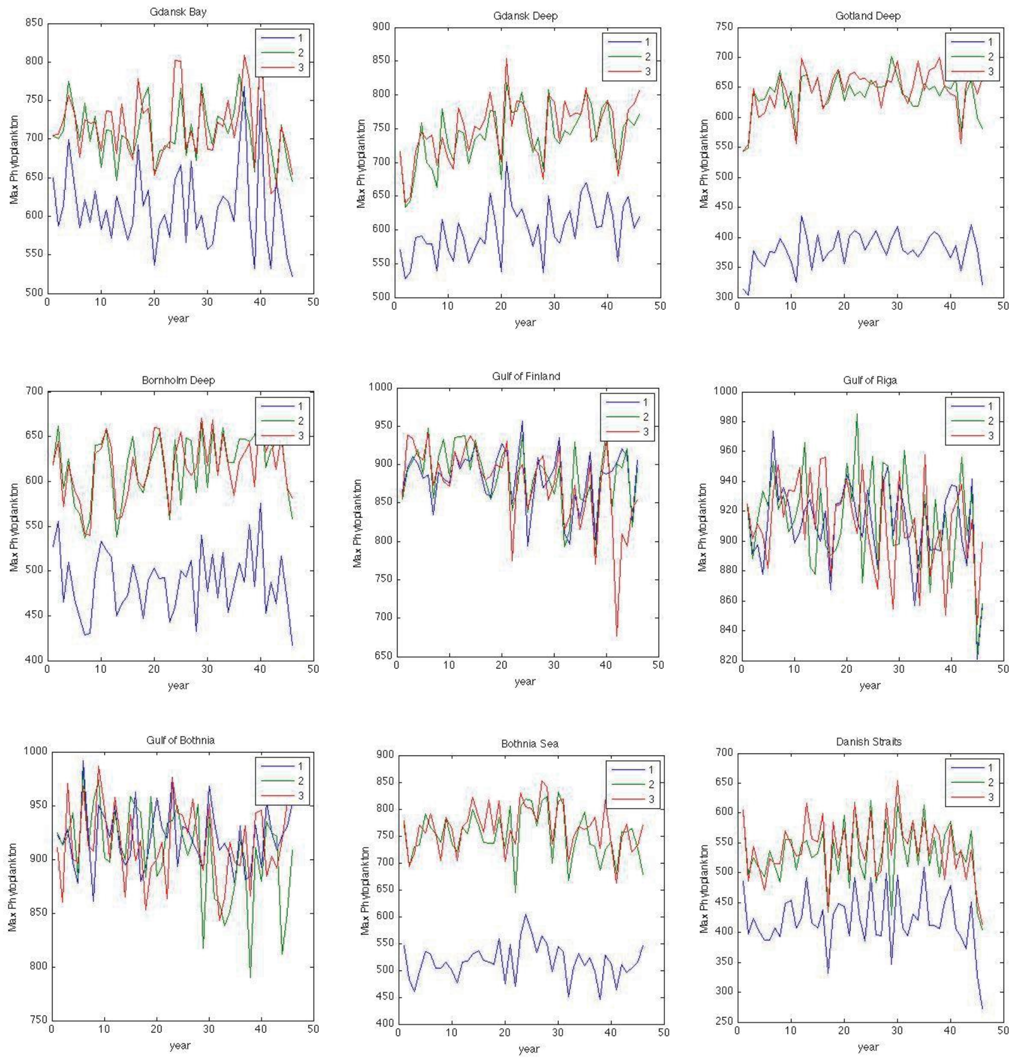
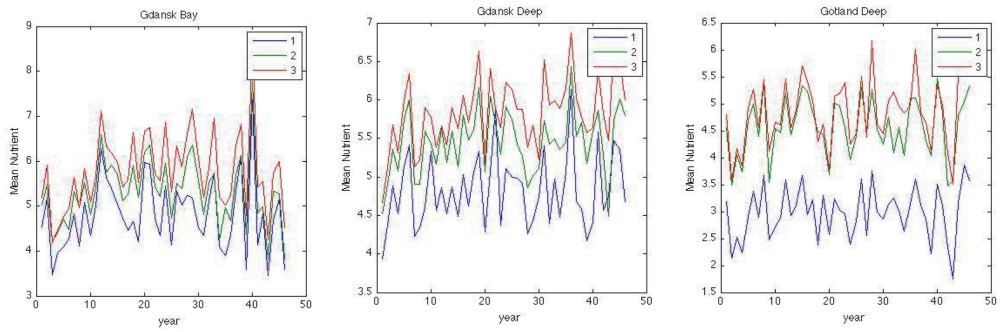


Figure 3b. One year maximum of phytoplankton biomass (mgC m^{-3}) for surface layer at selected stations.



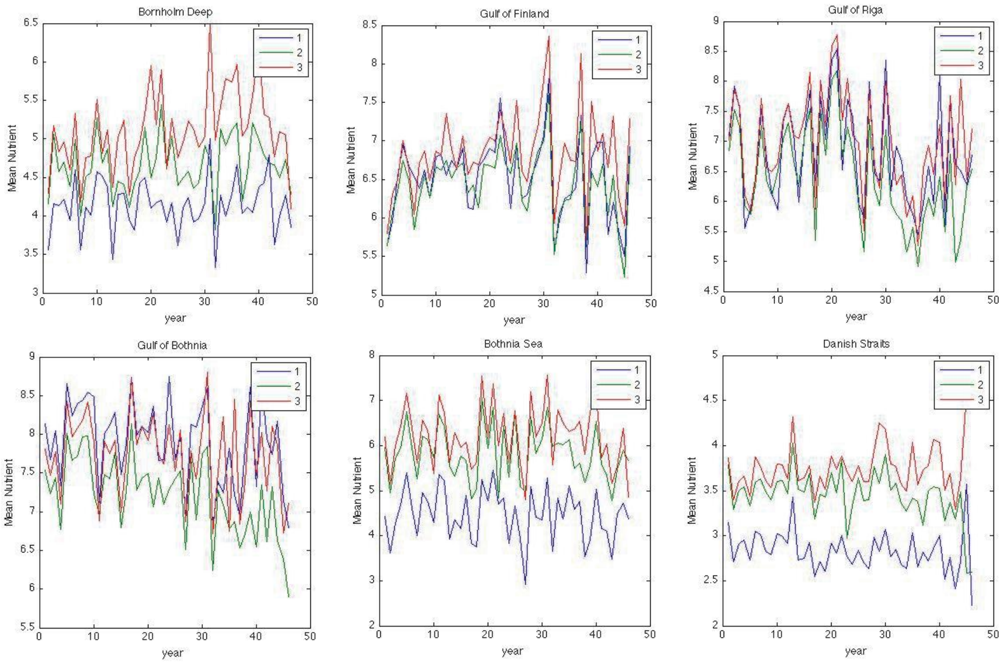


Figure 4. One year averaged of total inorganic nitrogen concentration (mmolN m^{-3}) for surface layer at selected stations.

Extreme values of some investigated variables for the Baltic Sea after three scenarios.

Year (scenario)	T[^{o}C] min max	S [PSU] min max	Phyt [mgC m^{-3}] min max	Nutr [mmol m^{-3}] min max	Current [cm s^{-1}] min max
2004	-1.96 22.08	1.5 35.1	0 982	0 ~14	0 ~20
2050 (1)	-1.19 22.86	1.4 34.9	0 976	0 ~16	0 ~50
2050 (2)	-1.11 24.12	0.0 35.2	0 972	0 ~16	0 ~100
2050 (3)	-1.59 19.91	0.0 35.1	0 965	0 ~16	0 ~100

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3.2. DMI

The DMI contribution was reported and illustrated together with the control run result in ECOOP D10.1.1.1. A summary is given here. Further details can be found in Madsen (2009).

3.2.1. Model set-up

The DMI-BSHcmod model (cmod) is a 3D primitive equation physical ocean model developed for regional ocean modeling, especially in the North Sea–Baltic Sea area (Kleine, 1994; Dick et al., 2001, further development at DMI). The cmod model is characterized by its 2-way nesting system, which allows integrated simulations of the whole North Sea–Baltic Sea system and high resolution in the North Sea–Baltic Sea transition zone than in the rest of the model area. The grid domain and resolution is:
Fine grid: 9.35E–14.85E, 53.59N–57.59N, 1 nm, 52 z-layers
Coarse grid: 4.08W–30.25E, 48.45N–65.85N (59.25N in the North Sea), 6 nm, 50 z-layers
NOAmod grid: 21.08W–13.25E, 48.2N–66.3N, 6 nm, 1 layer (used for sea level boundary forcing)

The atmospheric forcing was obtained from a 12 km version of DMI HIRHAM, which again was forced by the HadAM3H GCM (Christensen et al., 1996, Jones et al., 2001). Two time slices have been simulated, year 1960–1990 (control run) and 2070–2100 (scenario run). For the future scenario, the GCM was forced by the IPCC SRES A2 scenario. The GCM forcing gives rise to a change in Baltic Sea precipitation which is larger than the one seen in other scenarios. Therefore the future scenario has been run both with and without the changes in precipitation included.

Other model forcing includes monthly climatological river runoff, tides, and temperature and salinity fields at the open boundary. The open boundary temperature and salinity forcing was calculated from 10 year averaged ICES observations, and for the future scenario the temperature change as calculated by Ådlandsvik (2008) were added. No changes were made to the open boundary salinity forcing.

3.2.2. Effects on heat, salinity, and transports

The cmod scenario run showed a volume mean warming of the North Sea of 1.5°C, with no large changes in the features of the interannual variations or the seasonal cycle. The difference in the heat content between the scenarios with and without changed precipitation is insignificant. The Baltic Sea showed a mean warming of 2.7°C. The warming is larger in the summertime (2.9°C in September) than in the winter (2.5°C in March), which, according to Kjellström et al. (2005), is a feature of the spurious changes in the atmospheric forcing.

The salinity results depend on the scenario. In the North Sea, the magnitude of the changes is comparable to the interannual variability, and if the changes in precipitation were ignored a small increase in volume averaged salinity was seen, whereas the scenario including precipitation changes showed a small decrease in salinity. The future scenario salinity of the Baltic Sea is highly dependent on whether the change in precipitation is included in the simulation. In the simulation where changes in precipitation were ignored, salinity remained much like in the control run, with a 0.3 psu increase towards the end of the simulation. When changes in precipitation were included, the salinity fell with a rate comparable to the observed in stagnation periods (e.g. Feistel et al., 2008). However, since the characteristic time scale of the Baltic Sea salinity is comparable to the length of the model simulations, and the scenario initial conditions are by nature unknown, the time slice simulations cannot be used to put an absolute value on the Baltic Sea salinity, only to indicate that the cmod model supports a stabile or decreasing future Baltic Sea salinity, in agreement with BACC (2008) and references therein.

The North Sea volume transport in the cmod future scenario showed the same general features as in the control run, but an increased seasonality, with a mean transport at the Hanstholm transect of 0.7 Sv in December and January.

3.2.3. References

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3.3. IMR

3.3.1. Model set-up

The NORWECOM model (Aksnes *et al*., 1995; Skogen *et al*., 1995; Skogen and Søiland, 1998) has been used in the simulations. The set-up equals that used in ECOOP D10.1.1.1 and D10.1.2.1. The focus has been on three years (2002-2004) and the reference case is equal to that reported in those deliverables. The sensitivities simulations are initialized from December 2001 using the long term simulations, and the following perturbations have been done to the forcing defining the following sensitivity simulations:

- Ref Reference 2002-2004
- Sc1: Increased air temperature 3 oC
- Sc2: 30% intensification of wind speed
- Sc3: 30% intensification of westerly wind component
- Sc4: Reduced river N and P with 50%
- Sc5-up: 20% increase of short wave radiation
- Sc5-down: 20% decrease of short wave radiation
- Sc6: combined 1+2+4

It should be noted that it is virtually impossible to describe a realistic set of changes for all climate 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 scenarios presented serve as sensitivity studies to possible future changes rather than to predict a realistic future ocean state.

3.3.2. Effects on heat and transport

The effect on North Sea heat content for the different scenarios is shown in Figure 3.3.1. The mean North Sea heat content for the reference simulation are 1.15×10^{21}J, and the modeled heat content are in agreement with other estimates (for details see Hjøllo *et al*., 2009). The heat content increases with increased air temperature (Sc1) and SWR (Sc5-up) and decreases with a reduction in SWR. The effect of the perturbations in SWR is symmetric. 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 positive one the rest of the year. The combined simulation (Sc6) gives an almost linear response. The seasonality of the heat content shows the largest difference to the unperturbed state in late summer (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 since the warming then is restricted to the surface mixed layer.

The effect of the forcing perturbations to the inflow through a section from Orkney to Utsira (Norway) along 59.17N is shown in the right panel of Figure 3.3.1. The effect of changing short wave radiation and temperature is generally low, while the perturbation of the wind forcing has a strong effect. The mean modeled inflow in the reference run is 1.21 Sverdrup, thus the effect of a 30% intensification of the wind speed is almost at the same order as the reference flow.

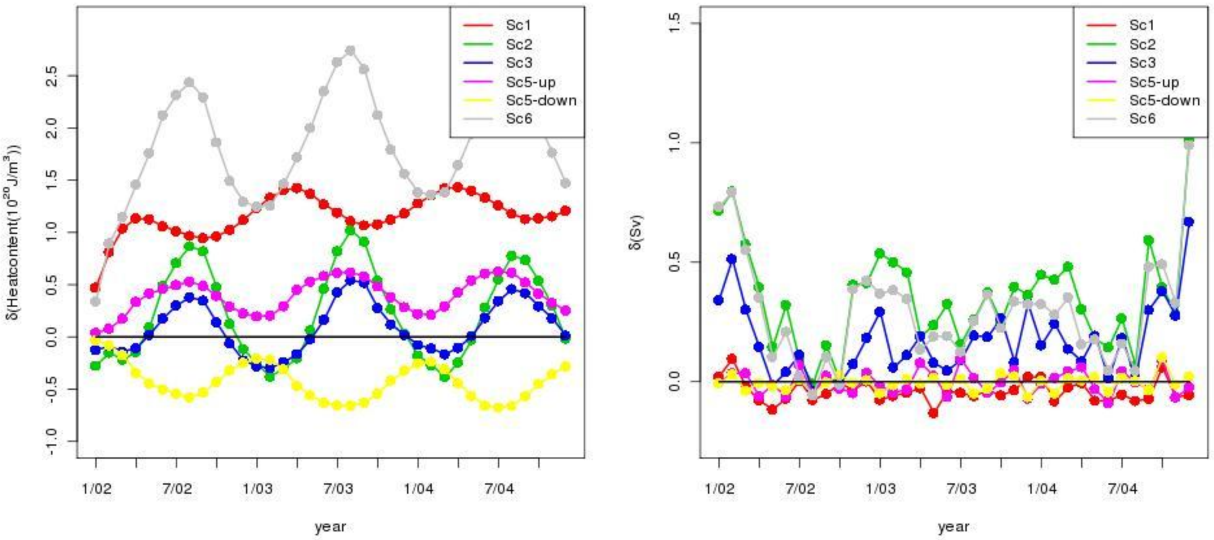

Figure 3.3.1. *Changes in North Sea heat content (left) and Orkney-Utsira inflow between the reference run and the sensitivity simulations.*

3.3.3. Effects on lower trophic levels

In Figure 3.3.2 the modelled annual depth integrated (gC/m^2/year) primary production for 2003 is shown for the NORWECOM model. The mean modelled production is 108 gC/m^2/year. 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/year. 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 production estimates between 100 and 150 gC/m^2/year, while the production outside the Norwegian west coast is around 100 gC/m^2/year. These numbers are in general agreement with other model estimates (e.g. Moll and Radach, 2003). Earlier studies (Skogen & Moll, 2000) suggest that the inter annual variability in the North Sea primary production is around 15%, but that the variability locally is much higher than this, thus an increase in one area is often compensated by a decrease somewhere else. This is illustrated in the right panel of Figure 3.3.2, where the mean North Sea production is given for the period 1985-2008. In this period the primary production varies between 95 and 115 gC/m^2/year . Oceanic inflow to the North Sea is the major source of new nutrients to the system, and more than 90% of the nutrients have oceanic origin (e.g. Brockmann *et al*., 1990). Therefore, even if the spatial differences are large, the impact of the river nutrient inputs is estimated to be less than 10% of the total production (Skogen & Moll, 2000).

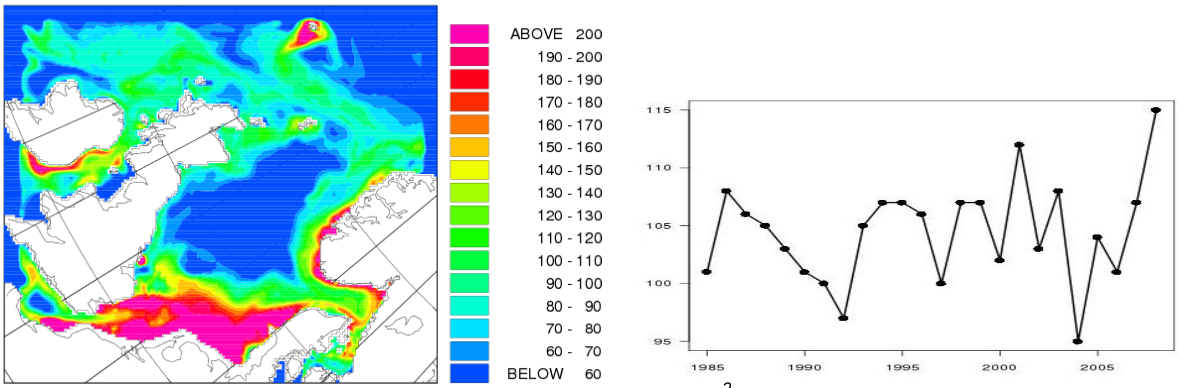

Figure 3.3.2. *Annual depth integrated primary production (gC/m^2/year) 2003 for NORWECOM, and time series of mean modelled North Sea primary production.*

The effect of the different what-if climate scenarios on the mean annual primary production for the three model years (2002-2004) is seen in Figure 3.3.3. The largest increase in primary production is seen from Scenario 6 (combined, i.e. increased air temperature, increased wind speed, and (increase in Short Wave Radiation (SWR)), with an increase of about 20%, while the largest decrease is seen in Scenario 5-down (decrease of SWR) with an almost 10% decrease, close to that for Scenario 4 (decrease in river nutrients). The single most factor of importance for an increased primary production is the wind speed. The large dependence of the wind speed is in accordance with previous studies (Skogen & Moll, 2000) that concluded that the inter annual variability in the NORWECOM production to a large extent is determined by the Atlantic inflow. Nevertheless, it should be noticed that even with the increased wind, the production is still within the limits of natural variability shown in Figure 3.3.2. The temperature increase on the other hand has almost no effect on the production. An interesting observation is that there is a larger effect of a decrease in SWR than in increase. The effect of reduced river nutrients gradually increasing and becomes larger than that of a decrease in SWR the last year. This gradually increase is in agreement with a long term modelling experiment concluding that the full effect of a change in river nutrients is seen after 2-3 years (Skogen & Mathisen, 2009).

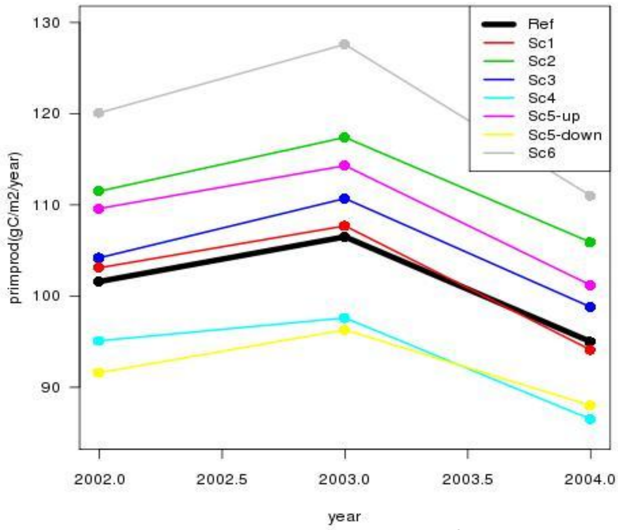

Figure 3.3.3. *Annual mean North Sea primary production (gC/m^2/year) for the reference and sensitivity simulations*

The depth integrated annual primary production (gC/m^2/year) for Scenario 2 (increased wind speed), Scenario 5-down (decrease in SWR with the lowest production) and Scenario 6 (combined with the highest production) for 2003 are shown in Figure 3.3.4 (upper panels) together with the relative (mid panels) and the absolute (lower panels) change from the reference run. The figure shows that the main patterns from the reference run (Figure 3.3.2) are unchanged. The increased/decreased production is to a large extent uniform over the whole model domain. The main exception is the decrease in primary production in the German Bight and along the Danish coast with the increased wind speed. It is also noticeable that the increase in the north-western North Sea are higher than in the south-eastern parts and Skagerrak with the change in wind. In the combined simulation there are a east-west difference.

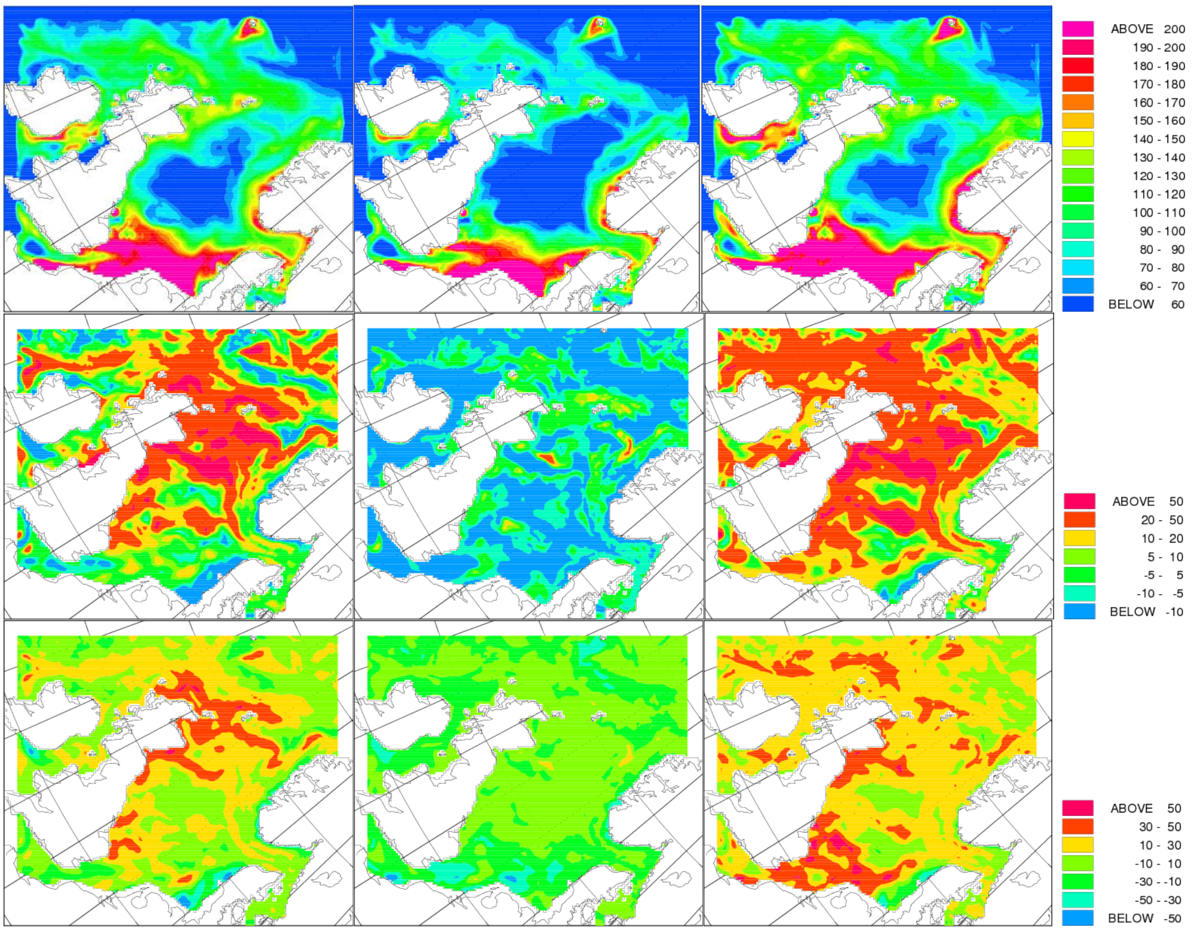

Figure 3.3.4. *Annual depth integrated primary production (gC/m2/year) for Sc2 (increased wind speed) – upper left, Sc5-down (20% reduced Short Wave Radiation) upper middle and Sc6 (combined) upper right. The respective relative changes from the reference (in percentage) are given in the mid panels and the absolute (gC/m^2/year) in the lower panels*

The changes in the monthly North Sea primary production is examined in Figures 3.3.5 and 3.3.6. For all scenarios the peak 2003 production is seen in May, varying from about 22 (Sc5-down) to 35 (Sc6) gC/m^2/month (Figure 3.3.5). 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 delayed bloom into June, when the primary production with a decrease in SWR is higher than that with an increase. This is also seen in the monthly differences in Figure 3.3.6, where the amplitude (in difference between reference and scenario) of Sc2 and Sc6 are almost identical (but in different months – 6 and 5 respectively), and that Sc5-down both have periods when it is lower and higher than the reference. This is also the case with Sc1 (increased air temperature) and Sc5-up (increased SWR).

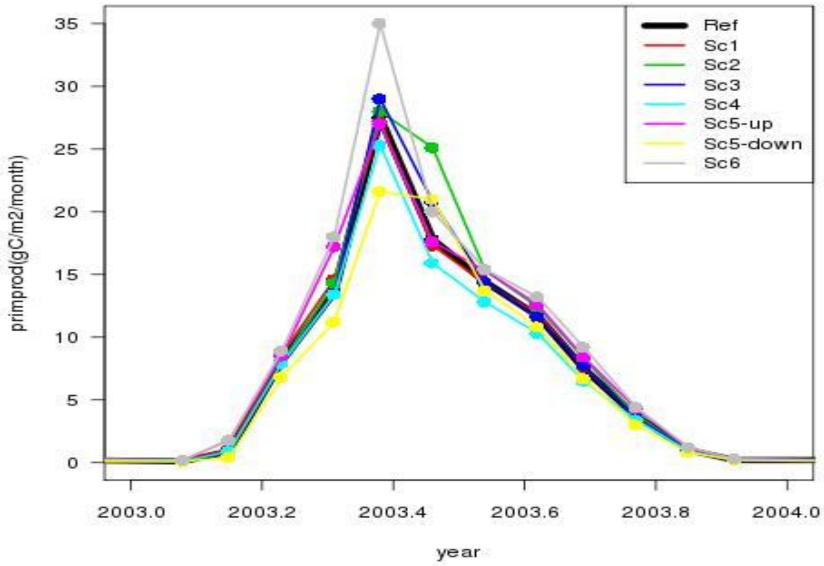

Figure 3.3.5. *Monthly mean North Sea depth integrated primary production (gC/m²/month) in 2003 for the reference and sensitivity simulations.*

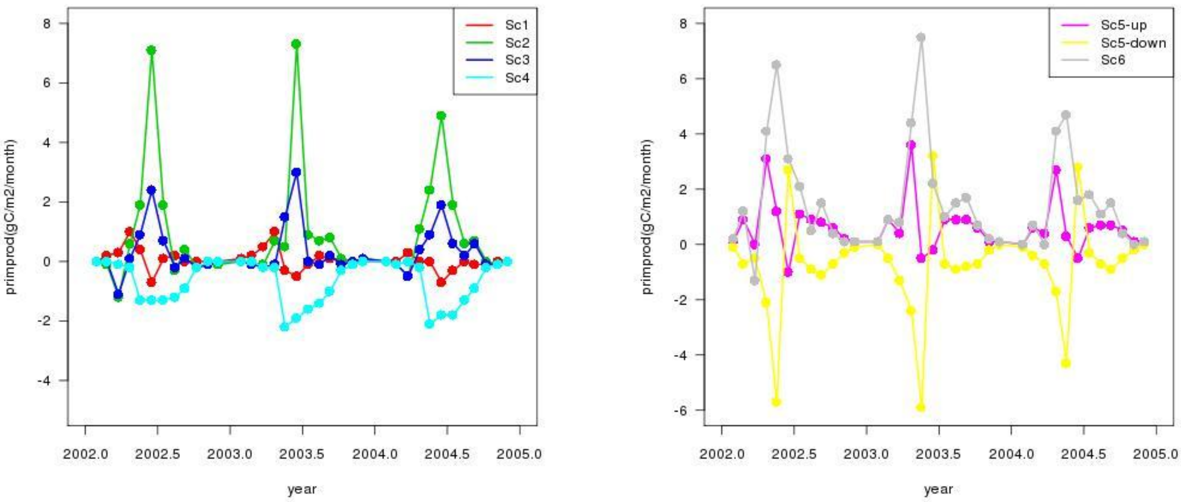

Figure 3.3.6. *Monthly mean North Sea depth integrated primary production difference (gC/m²/month) between the reference run and the sensitivity simulations*.