Modelling the long-term effects of reducing nutrient inputs to the North Sea

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ABSTRACT

The North Sea region is surrounded by highly industrialised and densely populated areas and is thus faced with a number of environmental threats, eutrophication being one of them. This is in particular a problem in the coastal and estuarine areas, which receives large amounts of riverine nutrients. Studies have shown that changing the ratio of nitrogen and phosphorous could potentially lead to a shift in the phytoplankton communities, towards more frequent nuisance algal blooms. The OSPAR Commission, which followed the Paris and Oslo Commissions, drew a set of *Ecological Quality Objectives* (EcoQO's) in order to assess the effectiveness of reducing the river nutrient loads by 50%. All member countries must assess their coastal areas in accordance with the OSPAR Common Procedure and the EcoQO's. The 3-dimensional, coupled physical-chemical-biological model NORWECOM was used in order to assess the long-term effects of reducing riverine DIN and DIP by 50% and 90% on three environmental parameters (N:P, chl a_{max} and O_{min}). The model results showed that there was a decreasing response gradient from near-shore to offshore, where the largest effect for all parameters was identified along the Dutch coast. The EcoQO's of N:P ratio and the chl a_{max} concentrations were achieved for most areas, whereas the O_{min} concentrations had no or very low response to the modelled nutrient reductions. The correlation between large scale meteorology (NAO) and the model parameters seemed to be highest in the German coast and offshore and Dutch offshore, whereas local winds had the highest correlation with the Dutch coast.

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ABBREVIATION LIST

CPR

Continuous Plankton Recorder

DIN

Dissolved Inorganic Nitrogen

DIP

Dissolved Inorganic Phosphorous

DNMI

Det Norske Meteorologiske Institutt

EC

European Commission

ECMWF

European Centre for Medium-Range Weather Forecasts

EMS

European Marine Strategy

EQO

Ecological Quality Objectives (OSPAR)

FRS

Flow Relaxation Scheme

ICES

International Committee for Exploration of the Seas

IFM

Institutt for Fiskeri og Marinbiologi

IMR

Institute of Marine Research (Havforskningsinstituttet)

JCW

Jutland Current Water

NAO

North Atlantic Oscillation index

NCC

Norwegian Coastal Current

ND

Nitrates Directive (European Union)

NORWECOM

NORWegian ECOlogical Model

NSTF

North Sea Task Force

OSCOM

Oslo Commission

OSPAR(COM)

Oslo and Paris Commission

(OSPAR) EUC

OSPAR Eutrophication Committee

PARCOM

Paris Commission

SSS

Sea Surface Salinity

SST

Sea Surface Temperature

UWWD

Urban Waste Water Directive (European Union)

WFD

Water Framework Directive (European Union)

WHO

World Health Organisation

1. INTRODUCTION

The North Sea is one of the most well studied shelf seas in the world (e.g. Brion et al., 2004, Ducrotoy et al., 2000, Jarvie et al., 1997, Reid et al., 1990) and covers the area between the British Isles and the west coast of Norway south of 62°N (Ducrotoy et al., 2000). This shallow sea, average depth ~90m, is surrounded by highly developed and industrialised countries. The shallowest areas are found in the south, the Wadden Sea north of the Netherlands and the German Bight. The deepest part of the North Sea is the Norwegian Trench, reaching down to about 700m (Ducrotoy et al., 2000). The economic and political importance of the sea is evident in the largescale fisheries, aquaculture, shipping and petroleum activities taking place during the last century.

1.1. Nutrient inputs to the North Sea and political management

Nutrient enrichment, due to anthropogenic activities, has been identified as the main cause of eutrophication in coastal areas (Cloern, 2001). This is in particular linked to river discharges and enhanced concentrations of inorganic nitrogen in estuaries. The initial investigations of the coastal systems response to nutrient enrichment was based on knowledge from freshwater eutrophication. Over the past 30 years studies have shown that the coastal zone have a more complex response to nutrient enrichment, with direct and indirect effects (Cloern, 2001). The North Sea is a complex system with large volumes of freshwater entering the coastal zone which is mixed with Atlantic Water further offshore. Although the inflowing Atlantic Water contributes the main portion of nutrients, river loads control the estuarine areas and this nutrient signal can also be identified further offshore (Hydes et al., 1999).

Table 1. 1. Table 1.1 and 1.2 provides an overview of the reported national reductions of N and P and the measured load reductions. There is a clear discrepancy between the reported and the measured loadings of nutrients (OSPAR, 2003a).

Country	Source OSPAR 2001 report 1985-1995 % reduction N	OSPAR 2003 report 1985-2000 % reduction N	Load 1985	2000	% reduction N
Belgium	19	19	NI	58352	NI
Denmark	24	43	60220	47039	22
France	NI	NI	142969	40343	72
Germany	26	38	247410	199250	19
The Netherlands	10	19	455000	372860	18
Norway	20	34	20972	23160	-10
Sweden	22	28	39524	42702	-8
Switzerland	19	27	NA	NA	NA
UK	12	-10 (1985-1996)	319000	355000	-11

Table 1. 2.

Country	Source OSPAR 2001 report 1985-1995 % reduction P	OSPAR 2003 report 1985-2000 % reduction P	Load 1985	2000	% reduction P
Belgium	45	58	NI	4170	NA
Denmark	NI	73	2376	1267	47
France	NI	NI	16604	11867	29
Germany	64	66	16560	8350	50
The Netherlands	NI	71	43300	24250	44
Norway	NI	62	643	1035	-61
Sweden	23	34	880	935	-6
Switzerland	61	63	NA	NA	NA
UK	NI	NI	58400	33000	43

Monitoring of phytoplankton blooms has been conducted frequently in the southern North Sea. Some of the most productive areas are found in this region due to large fresh water discharges and high nutrient availability. A growing concern has recently been how changing nutrient ratios would affect primary production and in particular phytoplankton speciation (Muylaert et al., 2006).

Since the 1980's there has been an abrupt shift in biomass and nutrient concentrations, in particular with regard to nano-flagellates. A shift in phytoplankton speciation could reflect changed N:P ratios due to eutrophication and/or a shift in the hydrodynamic conditions triggered by the NAO (Wirtz and Wiltshire, 2005).
Since 1988 the basic parameters controlling a *Phaeocystis sp.* bloom has been studied through field observations, process-level studies and numerical modelling and experimentations (Lancelot et al., 1997). The main issue in managing the nutrient situation in the North Sea is the paradox of monitoring nutrient input versus monitoring the *effects* of nutrient inputs (de

Jonge, 2006). The only long-term series which monitors the effects of nutrient inputs are the Marsdiep series on the coast of the Netherlands, the Helgoland Road series of Germany and the Continuous Plankton Recorder (CPR) (de Jonge, 2006).

Muylaert *et al* (2006) monitored the spatial variation of phytoplankton communities off the Belgian coast during the spring bloom. The changed nutrient ratios have resulted in a shift from N or P limitation to Si limitation during the diatom spring bloom. As a result large amounts of N and P have thus become available for non-diatom algae growth later in the season (Muylaert et al., 2006). In particular, the undesirable algae *Phaeocystis globosa* frequently forms blooms in the Southern Bight of the North Sea (Muylaert et al., 2006). The *Phaeocystis* species are one of the most widespread marine phytoplankton, forming nearly monospecific blooms in several coastal and oceanic waters (Schoemann et al., 2005). Although the blooms are rarely toxic, the gelatinous colonies can have negative impacts on the ecosystem as well as on commercially important stocks (fish, mammals and crustaceans etc) due to low oxygen levels, net clogging and alteration of fish taste (Schoemann et al., 2005). *Phaeocystis* is thought not to be P limited as they have shown to be able to grow on organic phosphorous, a feat which makes them particularly adapted to grow in high N:P environments such as the North Sea (Schoemann et al., 2005).

The political management of marine eutrophication, defined as *over-enrichment of a water body with nutrients, resulting in excessive growth of organisms and depletion of oxygen concentration*, has historically been closely linked to marine pollution (de Jonge, 2006). The *International Conference on Waste Disposal in the Marine Environment*, held in Berkeley, California, in 1959, initiated national assessments of their sewage treatment based on requirements from the World Health Organisation (WHO). Three years later, in 1962, the *International Conference on Water Pollution Research* was held in London which mainly focused on research related to mixing and dilution of sewage in coastal waters (de Jonge, 2006).

The *Agreement for Cooperation in dealing with Pollution of the North Sea by oil* (the Bonn Agreement) of 1969 marked a turning point in pollution prevention in the Northeast Atlantic and also acted as the starting point for the processes leading to the Oslo and Paris Conventions (OSPAR, 2004). Pollution of the North Sea by human activities was now on the

agenda and in 1972 the Oslo Convention *for the prevention of Marine Pollution by Dumping from Ships and Aircraft* was signed. Two years later, in 1974, the Paris Convention *for the Prevention of Marine Pollution from Land-Based sources* was signed (OSPAR, 2004).
In 1992 there was a ministerial meeting in Paris where the 14 signature states to the Oslo and Paris Conventions were represented. The Ministerial Meeting agreed upon merging the two conventions into the *OSPAR Convention for the protection of the Northeast Atlantic* (OSPAR, 2004). The OSPAR convention did not enter into force until 1998, but was practically functioning straight after the 1992 Ministerial Meeting. The work of the OSPAR Convention is divided into four main areas:

1. Protection and conservation of ecosystems and biological diversity
2. Hazardous substances
3. Radioactive substances
4. Eutrophication

(OSPAR, 2004).

In 1988, the PARCOM Recommendation on reducing nutrients to the North Sea was signed by the contracting parties. This paper outlined that the inorganic nitrogen and phosphorous inputs to the coastal areas should be reduced by 50% of the 1985 concentrations (PARCOM, 1988). In order to combat eutrophication, OSPAR developed the *Common Procedure for the Identification of the Eutrophication Status of Maritime Areas of the Oslo and Paris Convention* (1997) which was updated in 2005 (OSPAR, 2005a). This is a national process where the results are submitted to the OSPAR Eutrophication Committee (EUC). The contracting parties report on source loads and total loads of DIN and DIP in the rivers (see Table 1.1 and 1.2).

The international management of the North Sea basin is a rather complex story, where EU directives, such as the Water Framework Directive (WFD), Nitrate Directive (ND) and the Urban Wastewater Directive (UWWD), to a large extent overlap the governance area of OSPAR. Whereas the OSPAR strategy are more directly pointed at source reduction of nutrients, the new EU WFD have quite ambitious goals of achieving good ecological status in European coastal waters by 2012 (EC, 2000).

1.2. The circulation patterns and environmental conditions of the North Sea

The study of the North Sea dynamics is often thought to have started with the establishment of the International Committee for Exploration of the Seas (ICES) in 1902, but the ICES initiative was based on the work of two Swedish researchers, Ekman and Petterson, who studied the link between herring fisheries and hydrography in the 1890's (de Jong, 2006, Smed, 1983). The ICES work has always been focused on the link between hydrodynamics and biology where one of the main research areas have been the dependence of phytoplankton growth on nutrients, light, vertical circulation and stratification (Smed, 1983).

One of the earliest attempts to visualise the residual currents in the North Sea was done by Böhnecke in 1922 and his charts, deduced from the salinity distributions, have been widely used in the oceanography community (Otto, 1983).

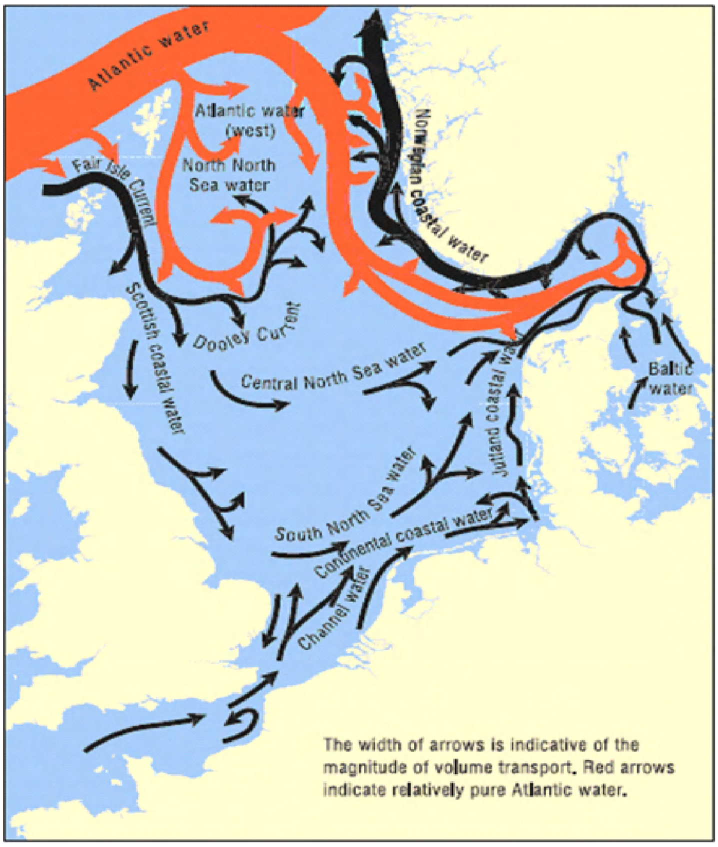


Figure 1. 1. Map of the circulation pattern and a visual overview of the volume transport of the different water masses in the North Sea. The red arrows indicate relatively pure Atlantic water and the width of the arrows indicate the magnitude of the volume transport. Obtained from Turrell (1992).

The Greater North Sea covers an area of approximately 750 000km^2 (OSPAR, 2005c) and the inflow of Atlantic water coupled with the effect of the Coriolis force together drive the cyclonic circulation within the North Sea basin (Otto et al., 1990). The circulation pattern and mixing regime of the North Sea is, in addition to the Atlantic inflow, strongly influenced by fresh water entering from continental Europe, UK, the Scandinavian peninsula and the Baltic Sea (Ducrotoy et al., 2000). About 1/3 of the fresh water entering the basin originate from Scandinavian melt-water. The large European continental rivers which drain into the North Sea include; the Meuse/Rhine, Scheldt, Ems, Elbe, Humber, Thames, Weser and Seine. The discharged river water creates freshwater induced circulation, as is evident in surface plumes of fresher water. Due to the well mixed environment of the southern North Sea, some of these plumes are rather poorly defined (Ducrotoy et al., 2000, Otto et al., 1990).

The fluxes of Atlantic Water into and out of the North Sea vary seasonally. The main controlling factor is the *North Atlantic Oscillation* (NAO) index, which is the pressure difference between the Azores high pressure zone and the Iceland low pressure zone. Positive NAO index causes strong south-westerly winds and thus favours an increased inflow into the North Sea, whereas negative NAO index yields more variable winds and usually colder winter conditions with easterly winds (Winther and Johannessen, 2006). The index is usually stronger during winter than summer, so winters will be associated with higher inflows of Atlantic Water than summer (Winther and Johannessen, 2006).

The most important inflow area of the Northern North Sea is the subsurface inflow occurs along the western edge of the Norwegian Channel followed by the Orkney-Shetland passage (the "Fair Isle current") and then the Pentland Firth inflow between Scotland and Shetland (Prandle, 1980, Turrell, 1992). The main outflow of North Sea waters occurs along the Norwegian Coastal Current (NCC) (Otto, 1983). The exchange between the Skagerrak and the Kattegat are highly affected by the wind conditions. The net inflow from the Baltic Sea into the Kattegat has its maximum in spring and minimum in late autumn, and the net inflow from the Kattegat to the Skagerrak has its maximum in summer and minimum in winter (Svansson, 1980). These patterns suggest the importance of the seasonal variations in freshwater runoff in the Baltic Seas.

Backhaus and Maier-Raimer (1983) compared the residual currents in the North Sea in March and August, where the model simulations looked at the patterns with and without the wind-stress component. They found that the circulation pattern of the North Sea had a strong seasonal signal, where the most pronounced difference was found in the northern North Sea in late winter (March). In addition they concluded that density gradients and wind-stress were more important than the tidal component when looking at the total residual currents in the North Sea basin (Backhaus and Maier-Raimer, 1983).

1.3. Ecosystem modelling

Pelagic eutrophication modelling should focus on nutrient enrichment relative to dilution and losses, increases in biomass and primary production and ultimately the consequences of such developments. Some of the main modelling issues are related to the complexity of the physical and biochemical environments. In particular the complexities involved with chemical and biological parameters are crucial in order to simulate the real-world effects of nutrient-enrichment.

An important tool for monitoring nutrient and ecosystem dynamics are 3D models. *Moll and Radach* (2003) made an extensive overview if the existing 3D ecosystem models which have been developed for the North Sea shelf (Moll and Radach, 2003). The first ecosystem model to be tested for the North Sea was the NORWECOM model in 1993. Several other well-known models; ERSEM and ECOHAM (1995), COHERENS (1999) and POL3dERSEM (2000) followed, all focusing on slightly different parts of the system (Moll and Radach, 2003). Common for the 3D models was that they initially addressed the pelagic systems but were later extended to include benthic re-mineralization and sedimentation (Moll and Radach, 2003).

The NORWECOM model was first applied to simulate mesocosm experiments and then to simulate the spring bloom of the North Sea. The simulations were verified by field data and proved to be able to predict several features of the spring bloom (Moll and Radach, 2003). In recent years the NORWECOM model has been applied for ecosystem simulations at several occasions, for the whole North Sea system or more localised scenarios such as floods (Skogen and Moll, 2005, Skogen et al., 2004, Skogen, 1998). NORWECOM is a coupled physical-chemical-biological model, where the basis of the model is a 3D physical model to best try and simulate the complex hydrodynamic environment of the North Sea (Skogen et al., 1995b).

Modelling is an efficient tool for simulating biological effects of nutrient enrichment, but there are major drawbacks to the method. Most models have a fairly simple biological model which may or may not include grazing. There are no ecosystem models which simulates all the interacting trophic levels, as the uncertainties related to these parameters would be too large to account for by mathematical equations. The physical models also have their limitations due to the spatial resolution. A 10 x 10 km grid net, such as used by the NORWECOM in the North Sea, is far to coarse to simulate the processes occurring near shore. Newer physical models, such as ROMS, enables much finer resolution, but the problem still arises when larger areas are to be covered (Skogen, 2006, pers.comm.). As pointed out previously, the NAO has a substantial impact on the circulation pattern of the North Sea. Attempts have been made to downscale atmospheric models and couple them with physical models already existing for the North Sea (Ådlandsvik, 2006). The coupling of atmospheric and oceanic models might be the beginning of a new era in regional ecosystem modelling.

1.4. Aim and Objectives

The short term effects of reducing nutrient loads in the North Sea have been extensively modelled and studied (e.g. Byun et al., 2005, Lenhart, 2001, Lenhart et al., 1997, Skogen and Moll, 2000, Skogen et al., 2004, Skogen et al., 1995a, Wirtz and Wiltshire, 2005). A study by Lenhart *et al* (1997) showed that when reducing the river DIN and DIP loads by 50% the largest effect could be detected in the coastal areas (15% reduction in primary production) whereas the offshore areas had little or no response to these reductions. The model was only run over a two year period (1988-1989) (Lenhart et al., 1997).

The aim of this study is to identify the *long-term* effects of reducing the nutrient loads to the North Sea. In order to achieve an understanding of how the system responds to inorganic nutrient reductions, the analysis is based on seven boxes scattered around the North Sea over a period of ten years (1985-1995),. Moreover the results will be linked to existing environmental targets set by OSPAR, in order to say whether the reductions are sufficient to achieve the management goals.

As meteorology has been identified as the main forcing in the North Sea, comparisons between larger scale meteorology and the local meteorology used in the model will be made. This might give an indication of the importance of larger scale meteorology in the different regions of the North Sea and whether this influences the modelled parameters.

2. MATERIALS AND METHODS

The NORWECOM model has generated the simulation data. Morten Skogen and Henrik Søiland at the Institute of Marine Research, Bergen, have developed this model in collaboration with the Institutt for Fiskeri og Marinbiologi and Det Norske Meteorologiske Institutt. It has been used for various studies regarding primary production, nutrient budgets and the transportation of particles in the North Sea basin (Skogen et al., 1995a, Skogen et al., 1998a). It has especially been adapted to model the nutrient-primary production link, as has been described in several articles and reports (e.g. Skogen and Moll, 2005, Skogen et al., 2004, Skogen et al., 1995a).

2.1 The NORWECOM model

The NORWegian ECOlogical Model system (http://www.imr.no/~morten/norwecom.html) is a coupled physical, chemical, biological model system (Aksnes et al., 1995, Skogen et al., 1998a, Skogen et al., 1995a) and has been validated by comparison with field data in the North Sea/Skagerrak in various studies (Skogen et al., 1997, Svendsen et al., 1996).

The physical model is based on a three dimensional, wind and density driven Princeton Ocean Model (Blumberg and Mellor, 1987). In the present study the model is used with a horizontal 10 x 10 km resolution in an area covering an extended North Sea (Figure 2.1). In the vertical direction 21 bottom following sigma layers are used.

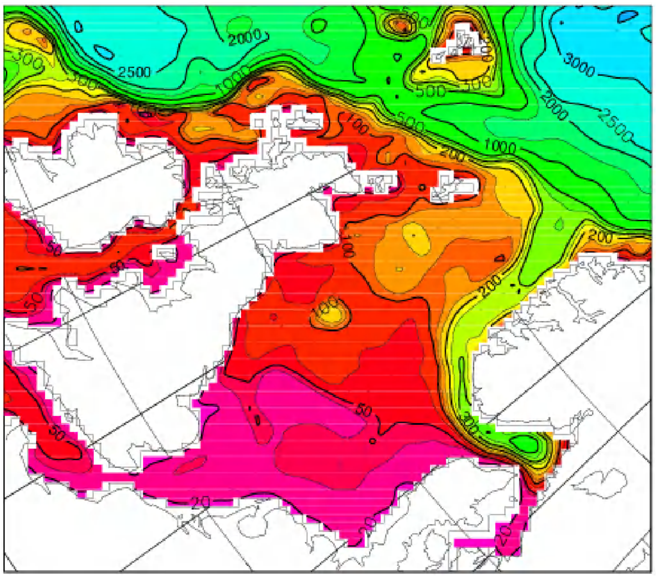


Figure 2. 1. Overview of the model domain and the bathymetry of the NORWECOM model. The horizontal resolution is 10 x 10km and the vertical resolution is 21 bottom-following sigma layers.

The chemical-biological model is linked to the physical model through the subsurface light, the hydrography and the horizontal and vertical water movement (see Figure 2.2). The prognostic variables in the model are dissolved inorganic nitrogen (DIN), phosphorous (PHO) and silicate (SI), two different types of phytoplankton (diatoms and flagellates), two detritus (dead organic matter) pools (N and P), diatom skeletals (biogenic silica), inorganic suspended particulate matter (ISPM) and oxygen. A complete description of how the NORWECOM model is set up can be found in Skogen and Søiland (1998).

The processes that are included are primary production respiration, algae death, remineralization of inorganic nutrients from dead organic matter, self shading, turbidity, sedimentation, resuspension, sedimental burial and denitrification (Skogen and Søiland, 1998).

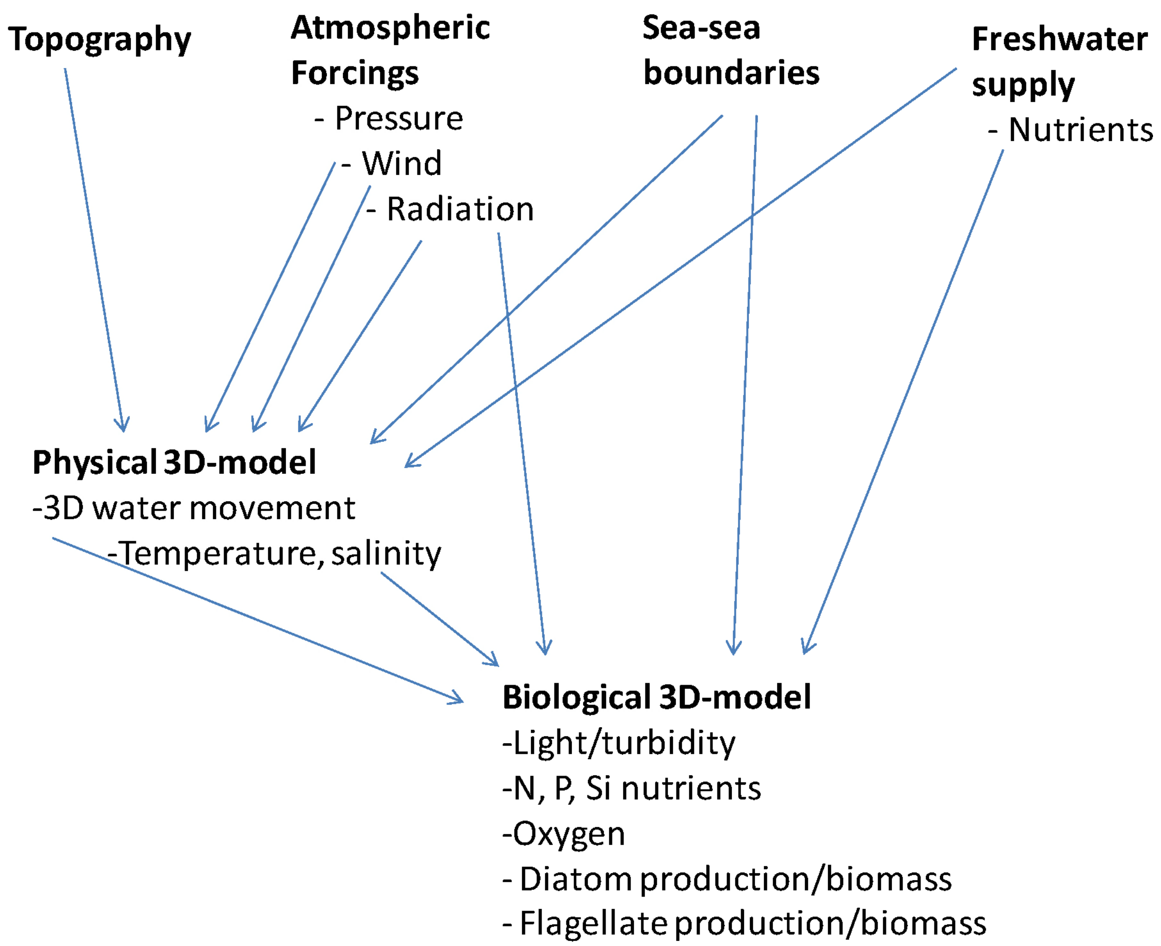


Figure 2. 2. Main components of the meteorologically driven simulation model for phytoplankton production. Modified from *Aksnes, et al (1995).*

Phytoplankton is expected to have an exponential growth under optimal conditions and mortality is given as a constant fraction (10 % day^{-1}) which is assumed to also include zooplankton grazing. Small fractions of the dead material are instantaneously regenerated as DIN and DIP (10 % and 25 % respectively) which are then automatically available for uptake by phytoplankton (Bode et al., 2004, Garber, 1984).

The sedimentation and re-suspension of particulate matter both depend on the bottom stress, and in the shallow North Sea this is a function of both internal currents and waves (Skogen and Søiland, 1998). The wave component of the bottom stress is calculated based on data from the operational wave model (WINCH) run by Det Norske Meteorologiske Institutt (DNMI) (Reistad et al., 1988, SWAMP-Group, 1985).

2.1.1. Model set-up, forcing and initialisation

Five different simulations were done with identical forcing and set-up except for the river nutrient loads. All simulations started on January 1, 1985 and were then run progressively through to 1995. The model was spun up by running 1985 four times. This is done to ensure that the model is in equilibrium with the boundary conditions and river loads and thus eliminate the effect of the initial conditions.

The five simulations include

1. Fixed river nutrient loads to 1985 values (reference run)
2. 1985 values (fixed) but DIN and DIP reduced by 10 %
3. 1985 values (fixed) but DIN and DIP reduced by 50 %
4. 1985 values (fixed) but DIN and DIP reduced by 90 %
5. Actual 1985-1995 river loads

The forcing variables were atmospheric pressure and wind stress, obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF), four tidal constituents, evaporation, precipitation and freshwater runoff. The surface heat fluxes were calculated on the basis of data from the ECMWF (M. Skogen, 2007. pers. comm).

A Flow Relaxation Scheme (FRS) has been used in the model along the boundaries of the model area. This acts as a buffer zone where the prognostic values near the boundaries are forced to relax towards monthly climatological fields for the Northeast Atlantic in the NORWECOM model. The buffer zone is 7 grid cells wide.

In order to keep the model simulations stable a weak relaxation towards climatological sea surface temperatures (SST) and sea surface salinities (SSS) is done. This implies that during calm meteorological conditions the surface values will adjust to the climatological values after about 30 days.

River data (freshwater discharges and nutrient loads) originates from national authorities of the North Sea countries; *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 State Pollution Control Authority* (Norway). Data from the United Kingdom are processed from raw data provided by the Environment Agency.

2.2. The North Sea Task Force Sub-regions and model boxes

The model grid covers the entire North Sea, but in order to assess the expected varying effects of reducing nutrient inputs it is more feasible to look at smaller areas.

In the present study seven boxes, from which data from the model have been extracted, have been chosen to be used. Five of these are located in the southern and central North Sea and two are located in Skagerrak (see Figure 2.3).
The five southern North Sea boxes have been used in previous reports produced by the *OSPAR Workshop on eutrophication modelling* (OSPAR, 2005b). These boxes were chosen as they were already defined within the North Sea eutrophication management programme of OSPAR and their strategic location in relation to the main European rivers (G-C1, NL-C1 and NL-C2). The offshore boxes (G-O1 and NL-O1) were chosen as they would reflect the system response of areas which are not immediately influenced by the river nutrient loads.
The self-defined Skagerrak boxes (SK-1 and SK-2) were chosen in order to assess the system response of this area to nutrient reductions. The hydrological conditions of the two boxes are very different and they are thus expected to display distinctive responses.

In 1987 a request from the Second Ministerial conference on the Protection of the North Sea was directed to the International Council for the Exploration of the Sea (ICES) and OSPARCOM. The request regarded the establishment of a task force who should *carry out work leading, in a reasonable time-scale, to a dependable and comprehensive statement of circulation patterns, inputs and dispersions of contaminants, ecological conditions and effects on human activities in the North Sea* (NSTF, 1993a). The resulting reports have been used to describe the physical and environmental conditions of the model box areas. In 1993 the North Sea Task Force (NSTF) published 13 Quality Status Reports, which aimed to provide an overview of the *circulation patterns, inputs and dispersions of contaminants, ecological conditions and human activities in the North Sea* (NSTF, 1993). The descriptions of the physical and environmental status of the modelled boxes are mainly based on these reports.

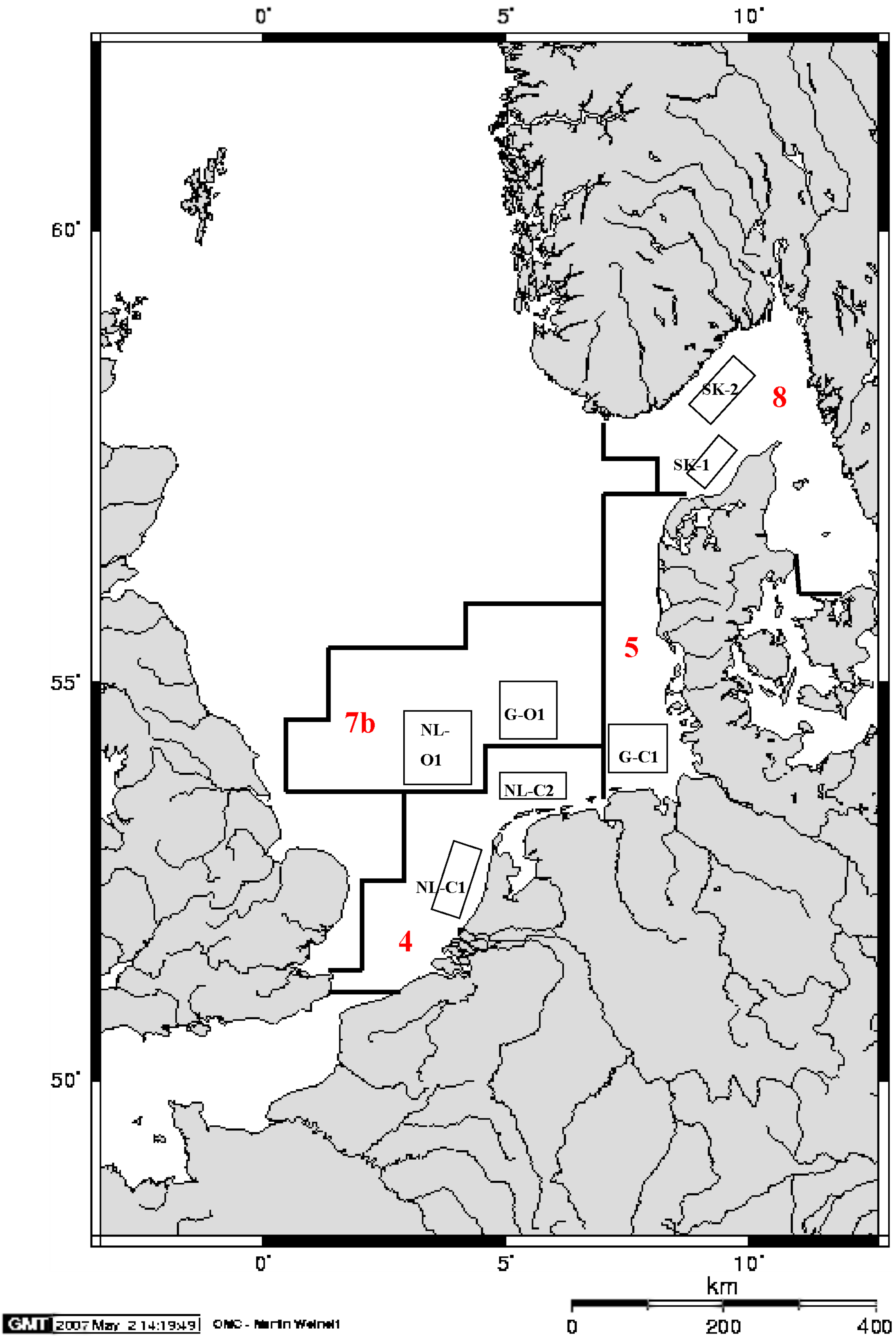


Figure 2. 3. The map shows the model boxes and the NSTF boxes used for North Sea management purposes. See Table 2.1 for further information on the NSTF boxes.

Table 2. 1. Overview of the NSTF sub-regions and the boxes within the sub-regions

NSTF Sub-region	Box number and description
4	NL-C1: Rhine Plume NL-C2: Frisian Island, coastal
5	G-C1: German Bight
7b	G-O1: German Offshore NL-O1: Oyster Ground
8	SK-1: Jammerbugt, Denmark SK-2: The Norwegian Trench, Arendal-Porsgrund (Norway)

2.2.1 Sub-region 4: Rhine Plume and Frisian Island, coastal

Sub-region 4 covers the two Dutch boxes NL-C1 (Rhine plume) and NL-C2 (outside the Frisian Islands), the Belgian coast and the Strait of Dover. The maximum water depth of this region is very shallow, only reaching down to 40 metres, which makes this a well-mixed environment (NSTF, 1993a). The two most predominant estuarine systems in this region are the Rhine (average discharge of 2200 m^3s^{-1}) and the Scheldt, which drain densely populated, farmed and industrialised areas (NSTF, 1993a). Freshwater outflow into the estuaries are regulated by man which leads to alterations of the upstream tidal surge to some extent (NSTF, 1993a).

The bottom topography is characterised by numerous sandbanks which are strongly influenced and influencing the hydrographical conditions, such as strong tidal currents (NSTF, 1993a).

The general circulation of the area is defined as anti-clockwise where Atlantic water enters trough the English Channel and is then mixed with freshwater entering from the rivers. Water transport and circulation is influenced by the wind direction. Along the Dutch coast the prevailing wind direction is from the south-west, except April-June where the mean wind direction is from the northwest (NSTF, 1993a). The residual current has a NE component due to the Coriolis force confining the Rhine outflow to follow the shoreline and thus allowing for other driving forces to influence the circulation patterns. The flushing time of this region is about three months (NSTF, 1993a). The hydrodynamic processes of this region are dominated by tidal currents which lead to vertical stirring and well mixed conditions of the water column (NSTF, 1993a).

Density stratification plays an important role in the front formation in the transition zone between low-salinity coastal water and the saline Atlantic water (NSTF, 1993a). Thermal stratification only occur at the northern boundary of the region and low oxygen concentrations have been observed in the Oyster Ground area in relation with prolonged periods stratification (NSTF, 1993a). This is a direct result of meteorological conditions as warm weather creates deeper thermal stratification and thus inhibits both vertical mixing of water and oxygen in the water column and oxygen production in the bottom mixed layer (BML).

Nutrients in the region originate both from riverine inputs and oceanic input, where the inflow of Atlantic water through the English Channel is the largest source of inorganic nitrogen and phosphates (NSTF, 1993a). The riverine inputs of N and P from the Rhine and Meuse systems were during the period 1985 and 1990 reduced by 40% (P) and 20% (N). For the Western Scheldt the reductions of N and P were 39% and 64%, respectively. These values were calculated using the PARCOM method and only accounts for the inputs into the estuary and not the actual concentrations in the estuary. They should therefore not be considered absolute values, as the inter-annual freshwater loadings varies a lot and also because the numbers do not account for the biochemical processes in the estuary (NSTF, 1993a).

2.2.2 Sub-region 5: German Bight

The G-C1 (German Bight) box of the model is situated in the area defined by the NSTF as *sub-region 5*. It covers an area of 32000 km^2 in the southeastern part of the North Sea.

The box covers the north coast of Germany and the western coast of Denmark. The main freshwater influence comes from the German rivers Elbe, Weser, Ems and Eider, where Elbe and Weser contributes the largest freshwater volumes.

The thermohaline circulation is influenced by Central North Sea water flowing in from the north, and Continental Coastal water that is transported northeast from the English Channel. The water from the German Bight influences the Skagerrak/Kattegat area and can also be found off the south and south-west coast of Norway.
The mean long-term circulation within the sub-region is a coastal northward flow. (tidal influenced bottom and vertical stirring)

There is a tendency towards nitrogen eutrophication the last couple of decades related to the Elbe outflow. Inorganic nitrogen concentrations increase during flooding events, indicating increased runoff from agricultural land and other nitrogen-rich soils. The phosphorous on the other hand is added to the river water from fixed point sources and during floods the P concentrations will decrease due to dilution. The coastal plume, resulting from the Elbe floods of 87-88, reflected this high N:P ratio which makes P the limiting nutrient.
Phaeocystis blooms coincided with periods of phosphorous limitation.

The German Bight is particularly prone to eutrophication due to the shallow seas which leads to a small volume to discharge ratio. Helgoland Data shows an increase in phytoplankton stocks that is probably due to eutrophication. The light conditions are more important for bloom development than nutrients, so high nutrient concentrations in the German Bight might not be reflected by elevated primary productivity due to the turbidity of the water.
The depth range of Eelgrass is a good indicator of ecological status in near shore areas and along the Jutland coast the potential depth has been considerably reduced. This reflects a general deterioration of benthic flora in the German Bight area.

2.2.3 Sub-region 7b: German Offshore, Oyster Ground

Region 7b covers the south central parts of the North Sea. The water enters from the north (the “Fair Isle”-current), along the English coast. The area is strongly influenced by the Flamborough front that stretches down to Flamborough Head (UK) where it branches off and one part flows east towards the German Bight. (NSTF, 1993a).
The region is overall shallow, dominated as it is by the Dogger Bank, and wind is the main factor influencing the circulation (NSTF, 1993a). The assessment report stresses the point that the circulation pattern in this region is not very well understood. In *Otto et al* (1990) the southern and central North Sea hydrological conditions have been descried in depth. As this is a relatively shallow area overall, wind and tidal movements are the main influencing factors (Otto et al., 1990).

There is a general lack of data concerning offshore nutrient concentrations. It is not a straightforward assumption that the input into estuaries will be reflected in the coastal waters due to the complex biogeochemical interactions in the estuary. In addition along-shore currents may prohibit the anthropogenic signal reaching offshore (NSTF, 1993a). Based on Continuous Plankton Record (CPR) data, the NSTF for sub-region 7b was not able to find any temporal trend in inorganic nutrients offshore. There are minor spatial differences between the Dogger Bank area and the Oyster Grounds due to the lack of direct nutrient inputs to the regions. The report thus suggests that new regions should be made on the basis of the actual biogeography (NSTF, 1993a).

The spring bloom seems to start earlier in this region than the rest of the North Sea (NSTF, 1993a). According to the nutrient data, prior to 1993, there were no indications of eutrophication in the region, but an investigation of the benthos showed a reduction in species diversity and a shift from long-lived to short-lived species. Whether this is a sign of eutrophication or of natural variations was not established by the assessment report (NSTF, 1993a).

2.2.4 Sub-region 8: SK-1 (Jammerbugt, Denmark) and SK-2 (Norwegian Trench, Norway)

Skagerrak is the link between the North Sea and the Baltic Sea. The hydrographical characteristics of the area are complex due to the mixing of saline Atlantic water flowing in from the north through the deep Norwegian Trench and the relatively fresh Baltic water entering from the Kattegat area (Smed, 1983).

Atlantic water is the largest volume of water entering Skagerrak and the AW^h (shallow water) is the most interesting with respect to biology due to its high N, P and Si concentrations (Table 2.2) (Skogen et al., 1998a). This water enters typically at the Danish borders of the Norwegian Trench at a depth between 200 to 500 metres (Skogen et al., 1998a). Water entering from the Southern North Sea is usually very low in nutrients, especially nitrate, when they reach Skagerrak due to the high production off the Belgian and Dutch coasts, even in winter (Skogen et al., 1998a).

Table 2.2. Overview of the main water masses in the Skagerrak distinguished during SKAGEX I. Obtained from the SKAGEX report by Danielssen et al. (1990)

WATER MASS	SALINITY	TEMPERATURE	COMMENTS
SW, surface water	15-32	10 - 15	Low nutrients, outgrown; thickness 5-20m
JCW, Jutland coastal	32-34	10 - 15	High nitrate, low phosphate; thickness 35m
SNSW Southern North Sea Water	34.8-34.9	8 - 9	Low nitrate, (0 - 1 μmol/l)
CNSW, Central North Sea Water	34.8-35.0	8 - 9	Subsurface nitrate, (2 - 5 μmol/l)
AW^h, Atlantic water high	35.0-35.15	8 - 10	Nitrate (0 - 7 mmol/l), nutrients increasing with depth
AW^l, Atlantic Water low	35.18-35.32	7.2 - 8	Nitrate (10 - 15 μmol/l)

Alongside the SNSW flows the Jutland Current Water (JCW), originating in the German Bight, and is typically characterised by high nitrate concentrations (high NP ratio). The salinity increases as this water is mixed with CNSW and AW^h (Skogen et al., 1998a).

The Baltic water that enters through Kattegat (at about 56°N) is rapidly mixed to form a surface layer down to a depth of approximately 10m. This is gradually mixed (both vertically and horizontally) with water of higher salinities. By the time this water enters the Norwegian coastline it turns westwards and become Norwegian Coastal water, with surface salinities of around 25-32 in the upper 10-20 metres (Skogen et al., 1998a).

Wind driven Ekman transport is very important for the circulation of the water masses in Skagerrak. The inflow of Jutland Current Water (JCW) are frequently blocked from the Norwegian Skagerrak coast by Atlantic Water forced down by northerly winds (Skogen et al., 1998b).

The oxygen concentrations and water exchange at depth varies a lot between the two the Skagerrak boxes. The deep water of the Norwegian Trench are only exchanged due to an overflow of North Sea Shelf water during cold winters or due to the inflow of Atlantic water (NSTF, 1993a). After 1987 there were several mild winters that prevented sufficient cooling of the shelf water and thus restricted the mixing of deep water, which in turn lead to stagnation and low oxygen concentrations. Then, in 1991, there was an inflow at depth of high salinity Atlantic water and the oxygen concentrations increased again (NSTF, 1993a). Measurements along the Danish coast have revealed a decreasing oxygen trend, but no serious deficiency. As expected, there is a seasonal signal with the lowest measurements taken in late summer or early autumn with values varying between 4.5 – 7.5 ml/l (NSTF, 1993a).
Along the Swedish Skagerrak coast and the Kattegat a decrease in oxygen has been linked to increased nitrogen input and primary production, which leads to higher oxygen consumption (NSTF, 1993a).

The mean winter concentrations of nitrates and phosphates in Atlantic Water amounts to about 15:1 at the surface, and the deeper water (200-300m) have a ratio of approximately 13:1. The background levels of nutrients are assumed to be equal to that of the southwestern

Norwegian coast, with N and P at 8-10 and 0.7-0.9 μmol/L, respectively (or a ratio of about 11:1) (NSTF, 1993a).

Nitrate concentrations in the German Bight have tripled the last 30 years, with the largest increase during the 1980's. This was reflected in 1988, prior to the *Chrysochromulina polylepis* bloom, when water from the German Bight and Southern North Sea was identified in the Skagerrak on the basis of its high N:P ratio (NSTF, 1993a).

2.3. Assessment methods, OSPAR

Category	Assessment Criteria
Degree of nutrient enrichment (I)	Winter N/P ratio (Redfield 16:1)
Direct effects (II)	Maximum chlorophyll a
Indirect effects (III)	Oxygen deficiency

Table 2. 3. Assessment criteria based on the OSPAR *Common Procedure* (2005a).

Assessing the eutrophication status of the North Sea is a very complex operation, where several considerations need to be taken into account. A complete assessment of all system parameters would be far too time and labour consuming to be desirable and thus a few parameters have been accepted by researchers as indicators for the eutrophication status.
In accordance with current management practices, the OSPAR criteria (Table 2.3 and 2.4) for eutrophication assessment have been investigated using the NORWECOM model for simulating the condition of seven North Sea boxes, of which 5 are already defined and used by OSPAR.

The criteria include winter N and P values (in this work looking at the ratio between N and P), chlorophyll maximum (Chl a $_{max}$) and minimum oxygen values.

Table 2. 4. The Ecological Quality Objectives from the OSPAR Common Procedure (OSPAR, 2005a).

	Background				Elevated values		
BOX	N:P	Chl a $_{mean}$ µg/l	Chl a $_{max}$ µg/l	O_{min}	N:P	Chl a $_{mean}$ µg/l	O_{min}
G-C1	16	2-4	13-18	> 6 mg/l	>24	3-6	4-6 mg/l
G-O1	16	2	10-13	> 6 mg/l	>24	3	4-6 mg/l
NL-C1	16	10	10	> 6 mg/l	>24	>15	4-6 mg/l
NL-C2	16	N/A	16	> 6 mg/l	>24	>22-24	4-6 mg/l
NL-O1	16	2-4	N/A	> 6 mg/l	>24	>4.5	4-6 mg/l
SK-1	16	N/A	N/A	> 6 mg/l	>24	N/A	4-6 mg/l
SK-2	16	N/A	N/A	> 6 mg/l	>24	N/A	4-6 mg/l

Table 2.4 provides an overview of the assessment levels which have been set out in the OSPAR *Common Procedure*. The background levels refers to the desirable levels of the N:P ratio (± 50%), chl $a_{mean/max}$ and O_{min}. The chlorophyll mean levels refer to the mean concentrations during the growth period, whereas the maximum levels refers to the expected maximum concentrations during the growth period. The elevated concentrations of chlorophyll mean are a measure of undesirable levels during a growth period, or an indicator of eutrophication (OSPAR, 2005a). It should be pointed out that the elevated chlorophyll mean concentration of the NL-C2 have not been verified by OSPAR (OSPAR, 2005a).

The Redfield ratio for N and P is a very useful tool for quantifying the nutrient consumption due to biological uptake (Redfield et al., 1963). The model N:P ratio was based on mean January-February nutrient concentrations for each box. Winter concentrations of N and P are good indicators for the nutrients available for the springbloom. However, it has been pointed out that the winter ratio between N and P is more relevant for bloom development than the concentrations (OSPAR, 2005c). In the present study the N:P ratio from the surface layer (upper 5 metres) will be used.

Chl a $_{max}$ is a parameter used as an indication for the quantity of plankton biomass. It is in reality a measurement of the green pigment in phytoplankton. This is not the most accurate method for determining the standing stock of phytoplankton, and it does not distinguish between different species. Nevertheless it is a widely used assessment method due to its rather simple interpretation. The chl a_{max} values are based on averaged May values of the flagellate component in the model.

Oxygen minimum (O_{min}) is the third and last parameter investigated in this study. This is an indirect effect of plankton blooms, as respiration further down in the water column will increase with increasing amounts of organic debris falling out of the surface layer. If the water column is stratified the effect of such oxygen demand, and possible deficiency, will be enhanced as deeper water and especially bottom water will become inhibited from exchange with the oxygen-rich surface layer (Andersson and Rydberg, 1988).

The eutrophication status of the North Sea has been outlined through several reports and articles by independent researchers and by the OSPAR working groups. The status of the sub-regions has been assessed using the *Common Procedure* (OSPAR, 2005a).

2.4. The Cost function

The cost function aims to quantify the discrepancy between models and observations and was initially intended as a tool for model validation (Berntsen et al., 1996). The function is defined as

Equation 2.1

$$D_F = (F_{model} - F_{data})/SD_{data}$$

Where D_F is the area average of the absolute values of the cost function field (the model grid), F is the temporal model or data field and SD_{data} is the standard deviation of the temporal average of the measured field (data) (Søiland and Skogen, 2000, Berntsen et al., 1996).
The cost function values are interpreted such that

$0 \leq D_F < 1$ = low discrepancy
$1 \leq D_F < 2$ = medium discrepancy
$2 \leq D_F$ = high discrepancy
(Skogen et al., 2006).

In this study, the cost function will be used to quantify the discrepancy between the three different reduction scenarios (10, 50 and 90%) and the 1985 reference run. F_{data} is thus defined as the temporal average of the 1985 reference run and F_{model} is the temporal average of the 10, 50 and 90% reductions. The resulting values will function as an indicator of the actual effect of each reduction scenario in relation to each other.

2.5. The Pearson Correlation

The Pearson correlation (r) has been used in this study to identify different relationships between the model results and external forcing, such as river nutrient loads and meteorology. The Pearson correlation is a measure of the correlation between two variables (x and y). The resulting relationship can either be positive or negative, where (±) 1 indicates full correlation and 0 indicates no correlation (Wikipedia, 2007).

The correlation has been calculated between all parameters of the 1985 reference run and the NAO index, the O_{min} concentrations of the 1985 reference run and local wind speeds and finally between the N:P ratio of the realistic run and measured riverine N:P ratios. In addition a correlation test was run between the three parameters in order to identify to which extent they influenced eacother.

3. RESULTS

3.1. Description of the simulations

The NORWECOM model has been run for five different scenarios. The most interesting ones, from a management point of view, are the 90 % and 50 % reduction runs. These give an impression of how the coastal systems would respond to such reductions of the *total nutrient load* entering the estuaries.

The 1985 reference run is in reality a representation of the systems response to changing meteorological conditions as the nutrient loading stays at a constant 1985 level throughout the ten-year period. This simulation is thus useful as an indicator of the annual natural fluctuation of the systems and to which extent the reduction scenarios are influenced by these variations. The simulations also include a realistic run, where the actual riverine loadings have been modelled for the ten-year period. The 10 % run appears to be similar to the 1985 reference run and the two will thus not be described in separate terms.

When analysing the model simulations one of the striking features is that for the NP ratio, and to some extent the Chl a_{max}, the effect of the 50 and 90 % reductions seems to stabilise after the two first years. The oxygen minimum simulations demonstrate that the reductions have less effect here than in the N:P ratio and chlorophyll maximum simulations.

3.2 The box results

3.2.1. The Southern coastal boxes, NL-C1, NL-C2 and G-C1

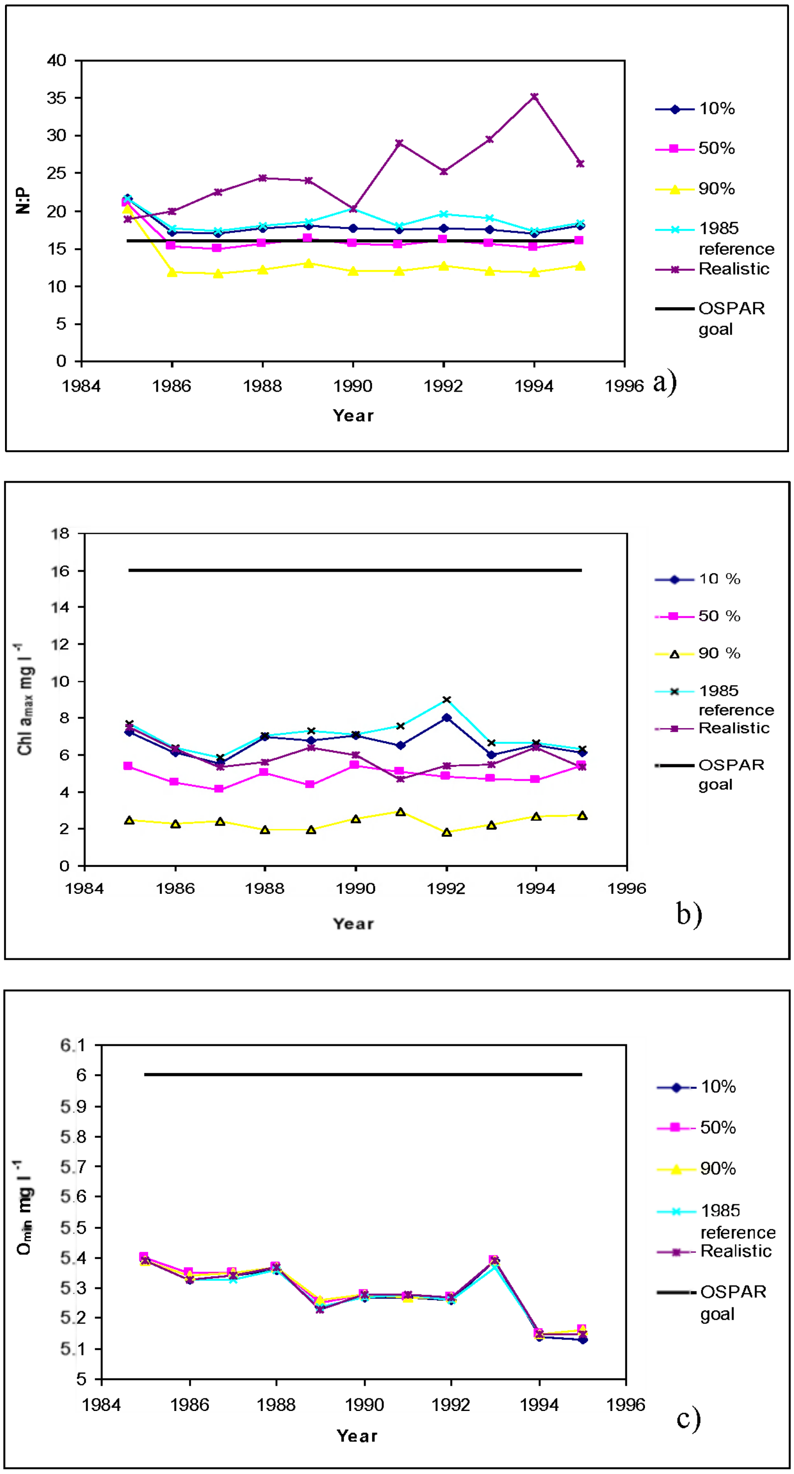


Figure 3. 1. The Rhine Plume box (NL-C1); a) N:P ratio; b) chl a_{max} concentrations; c) O_{min} concentrations

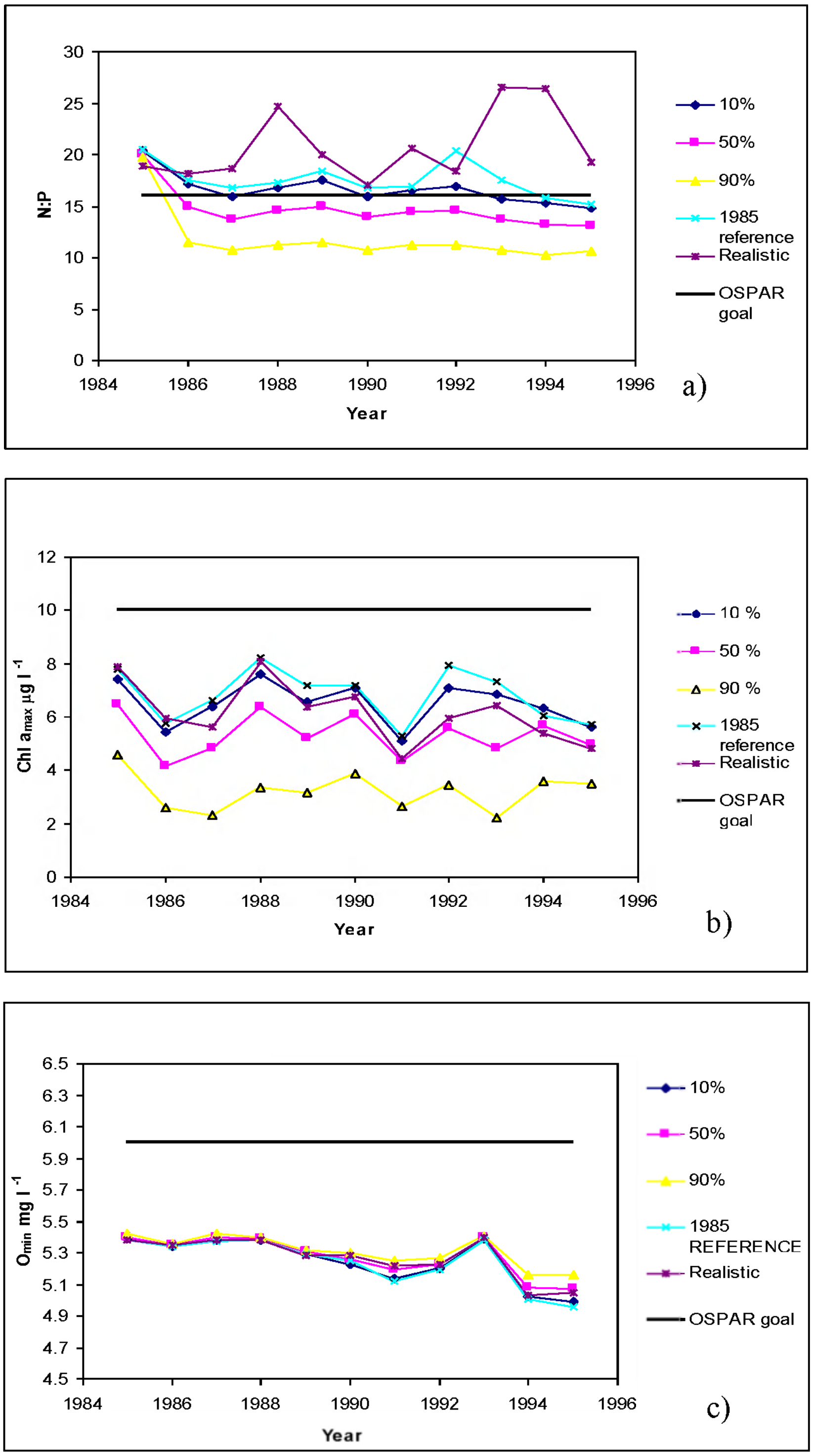


Figure 3. 2. The Frisian Island Coastal box (NL-C2); a) N:P ratio; b) chl a_{max} concentrations; c) O_{min} concentrations

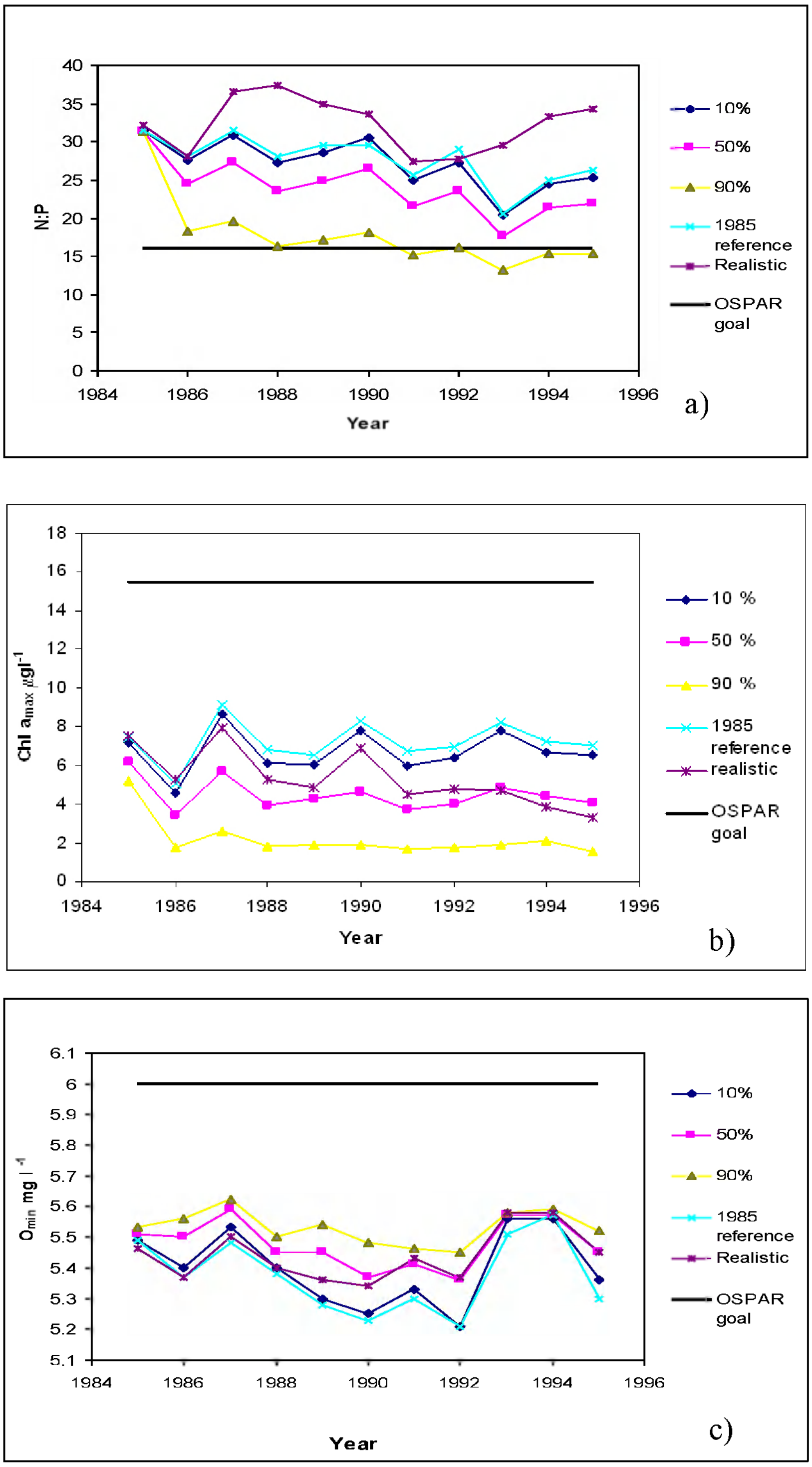


Figure 3. 3. The German Bight box (G-C1); a) N:P ratio; b) chl a_{max} concentrations; c) O_{min} concentrations

The Rhine Plume (NL-C1)

The N:P ratio (Figure 3.1a) stabilises for all the reduction scenarios after just one simulation year, of which the 90 % reduction is consistently lower at a stable ratio of around 12. The realistic run fluctuates more and does not seem to have a particular trend apart from an increase towards the end of the simulation period. This is not strongly reflected in the chlorophyll data (Figure 3.1b), but in the oxygen data (Figure 3.1c) minimum values are reached in 1994, which is the same year as the peak in the N:P ratio.
This should possibly be discussed in the light of the parameters used to determine Chl a_{max}.

The Frisian Island, coastal (NL-C2)

The N:P ratio (Figure 3.2a) for all runs, except the realistic, stabilises after the second simulation year. The realistic run peaks in 1993/1994 then drop slightly in 1995.
There is a general negative trend in the oxygen results (Figure 3.2c) and minimum levels are found in the two final simulation years for all scenarios. The simulations all display the same pattern apart from the 50 and 90 % runs that deviates the most from the realistic run the two final years. There is no apparent trend in the chl a_{max} (Figure 3.2b) time-series, but similar to the N:P ratio simulations the chl a_{max} reduction scenarios seem to reach maximum effect rather rapidly (minimum values after two simulation years). In contrast to the N:P data the reductions seems to have an immediate effect on reducing the biomass (chl a_{max}).

The German Bight (G-C1)

The German Bight represents an area that is strongly influenced by nutrient loadings from the major German rivers: Elbe, Weser, Ems and Eider. The model results clearly show that reductions, both 50 and 90 %, have an effect on the system for all parameters (Figure 3.3a, b and c). The temporal N:P ratio (Figure 3.3a) reveals a decrease after the first year for all simulations, and a slight increase again the next year. There is a relation in the fluctuations between the reduction scenarios and the reference run.

3.2.2. The Southern offshore gradient, NL-O1 and G-O1

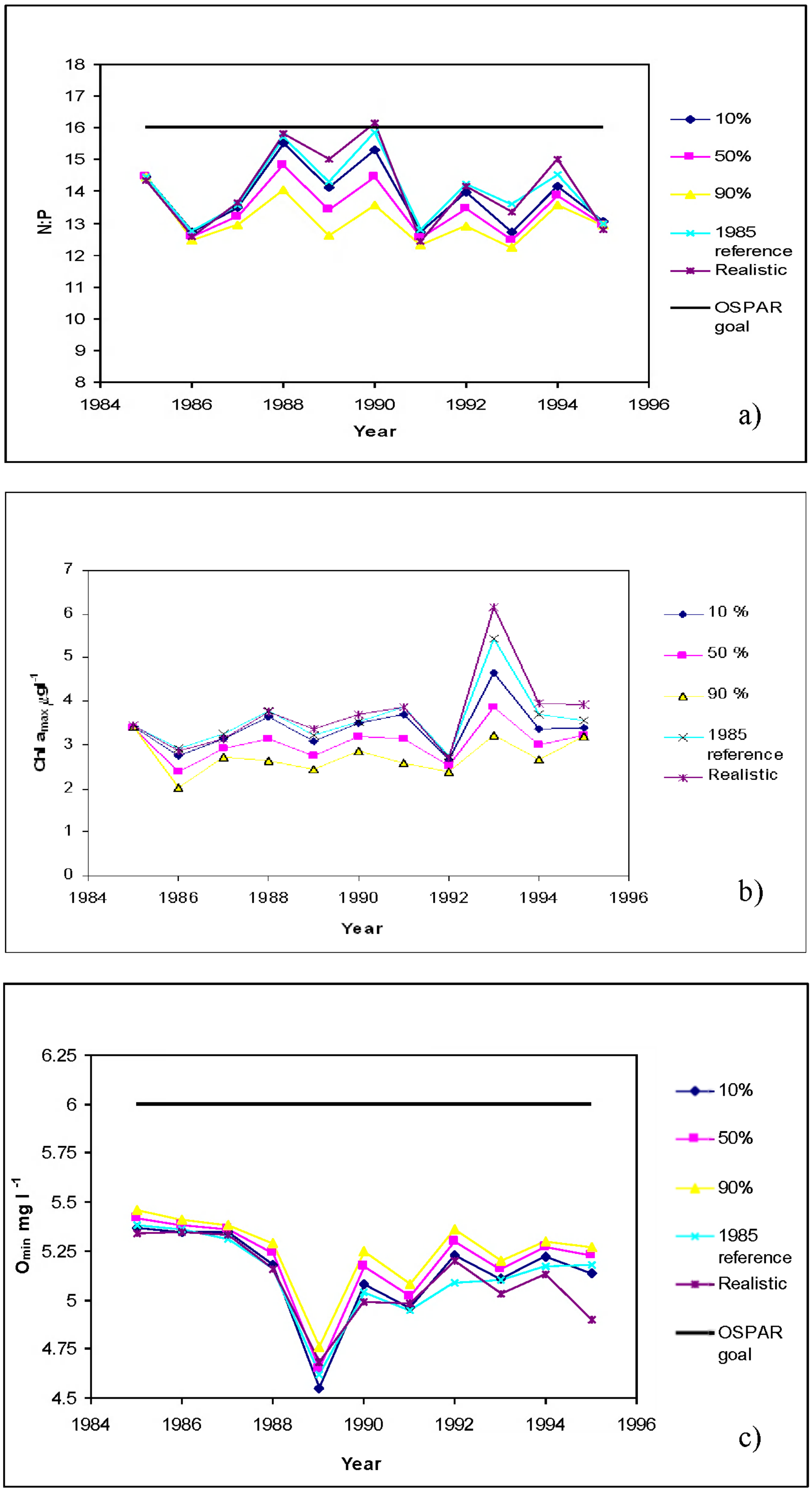


Figure 3. 4. The Oyster Ground (NL-O1) ; a) N:P ratio; b) chl a_{max} concentrations; c) O_{min} concentrations

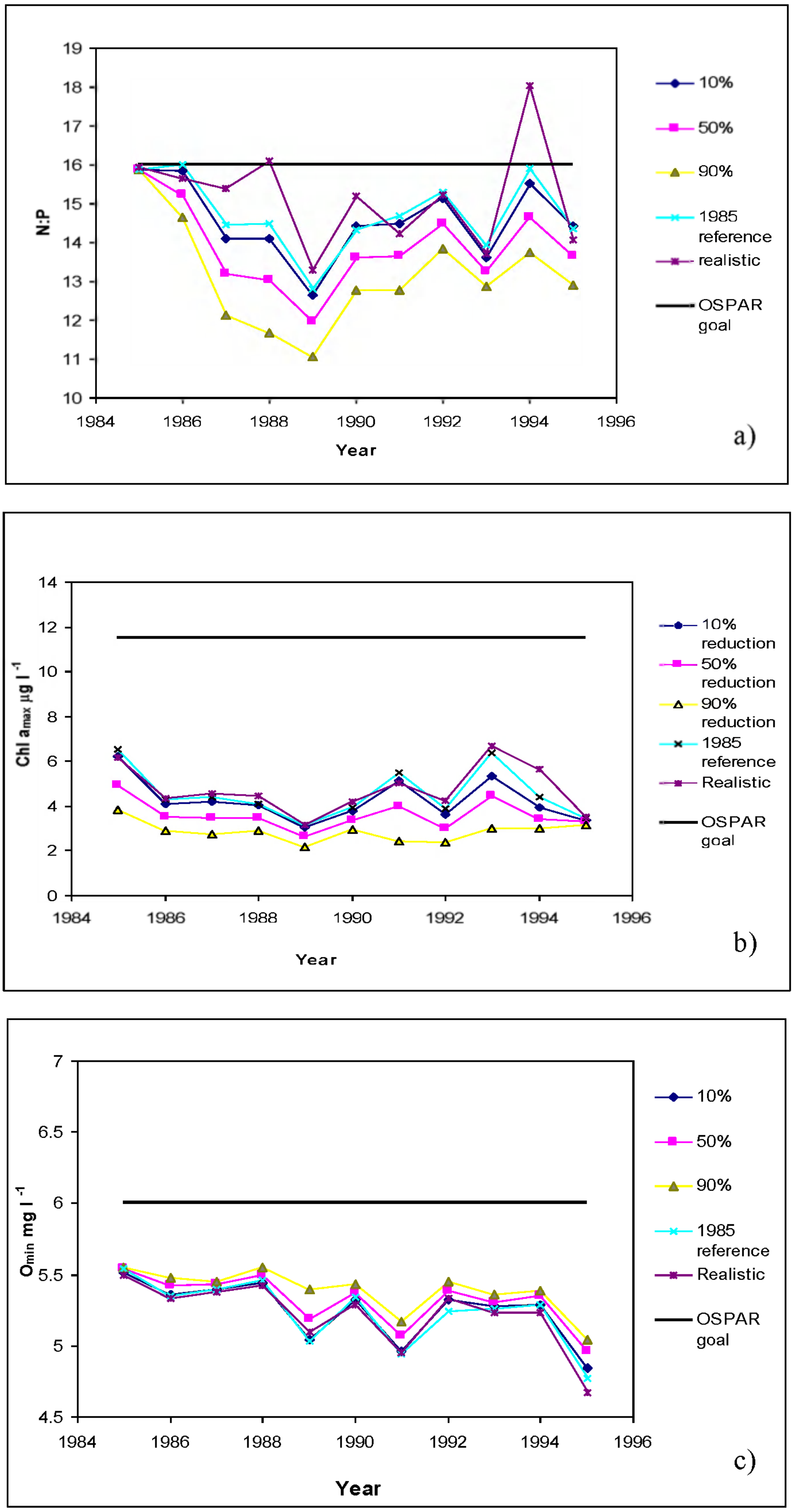


Figure 3. 5. The German Offshore box (G-O1); a) N:P ratio; b) chl a_{max} concentrations; c) O_{min} concentrations

Oyster Ground (NL-O1)

In the N:P ratio (Figure 3.4a) the 50 and 90 % reductions does not appear to deviate significantly from the realistic run and there is no defined trend.
The same pattern is found for oxygen minimum (Figure 3.4c), where a minimum value for all parameters is found in 1989. Here the 50 and 90 % simulations have a consistently higher value than the realistic run.

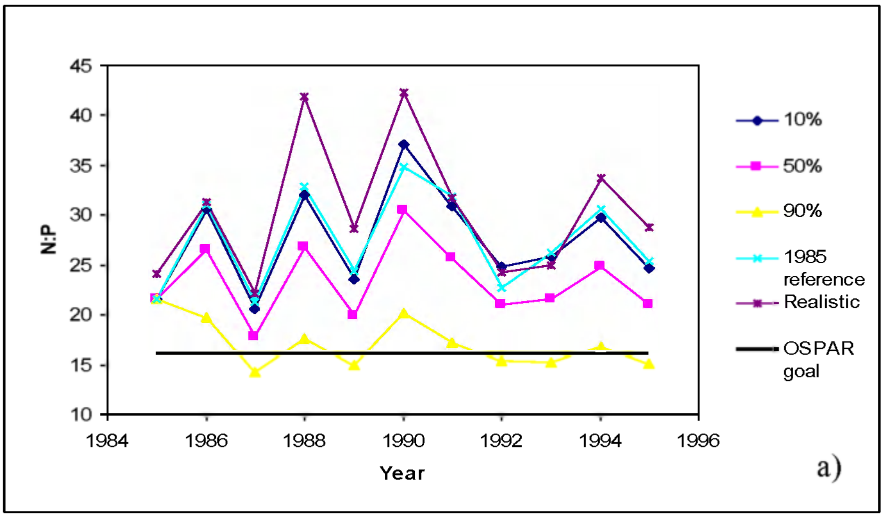
The chl a_{max} (Figure 3.4b) results were very stable for all simulations, with only one peak deviating from the rest of the data set. The peak occurs in 1993 and is especially marked in the realistic, reference and 10 % runs.

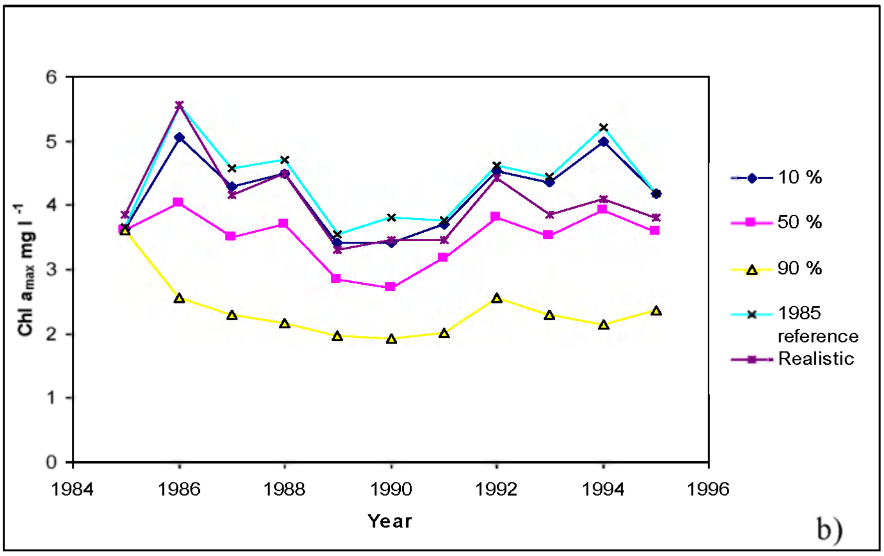
German offshore (G-O1)

No clear trend for N:P ratio (Figure 3.5a) or Chl a_{max} (Figure 3.5b). O_{min} (Figure 3.5c) has a fluctuating, negative trend with minimum values for all runs at the final simulation year (1995). Coinciding with the minimum oxygen values is the biggest spread in the data set. This does not seem to be linked with chlorophyll concentrations, as the 1995 are lower than both 1993 and 1994.

Result values for N:P ratio start to spread after two years (1987) and 90% stays consistently lower in the period 1986-1995.

3.2.3. The Skagerrak boxes, SK-1 and SK-2





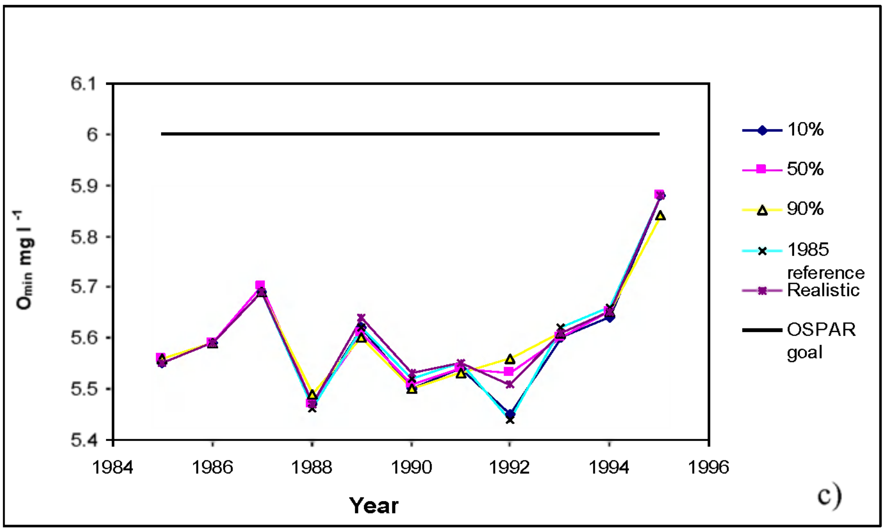


Figure 3. 6. The Danish Skagerrak box (SK-1); a) N:P ratio; b) chl a_{max} concentrations; c) O_{min} concentrations

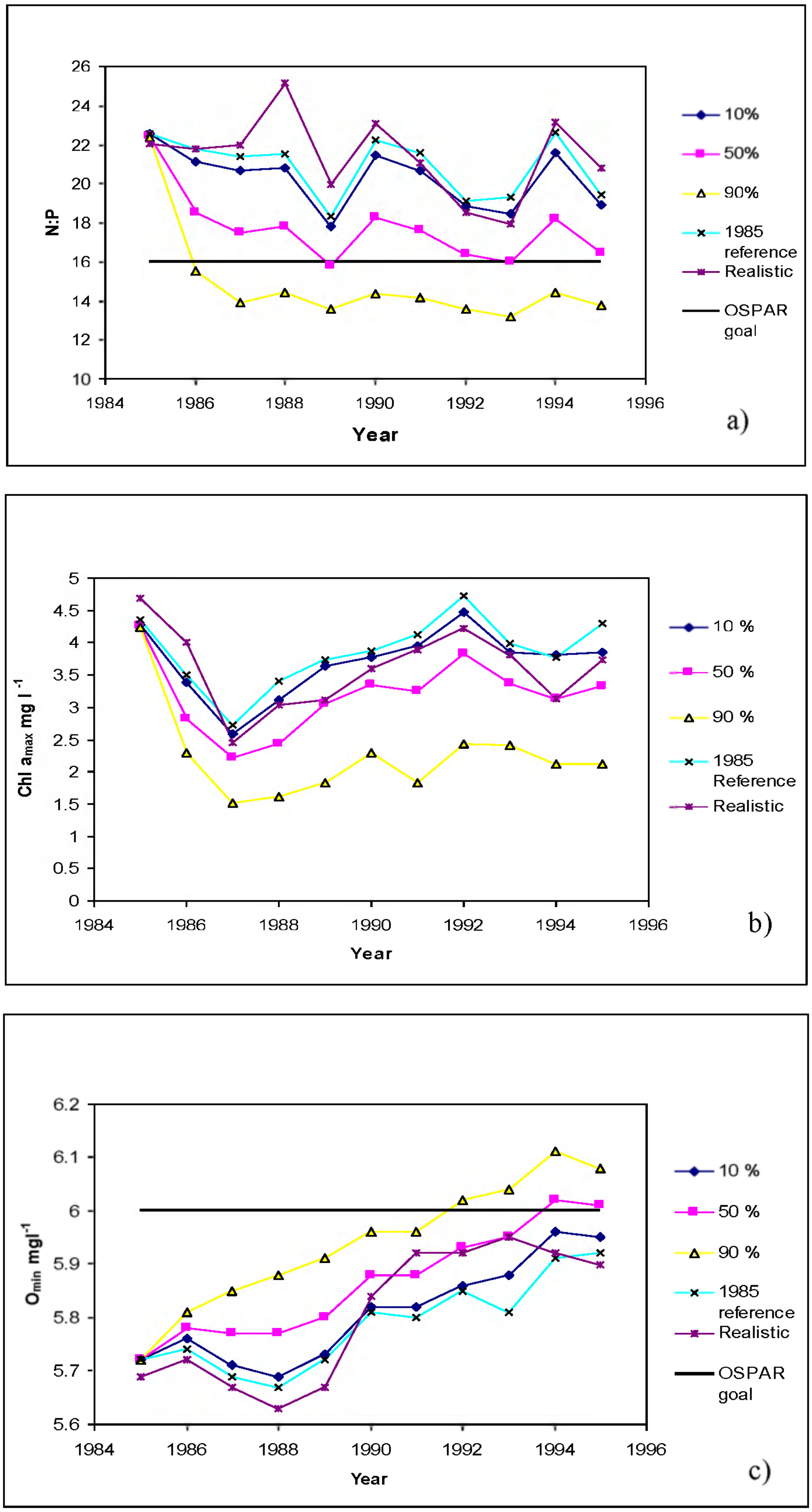


Figure 3. 7. The Norwegian Trench (SK-2); a) N:P ratio; b) chl a_{max} concentrations; c) O_{min} concentrations

Skagerrak, Danish coast (SK-1)

The N:P ratio (Figure 3.6a) fluctuates a lot in the first half of the modelling period and peaks in1990 for all simulations. The 50 % reduction fluctuates from its lowest point at 18 (1987) to its highest point in 1990 at 30 for the N:P ratio, after that the values decrease towards the end of the period. The 90 % reduction peaks the same year as the 50 % reduction, although at a lower level. It fluctuates similarly to the other simulations, but the curve is much smoother. Both reductions are consistently lower than the realistic run throughout the simulation period.

For the chlorophyll results (figure 3.6b), the 50 % reduction appears to have an effect, as this scenario is consistently lower than both the realistic and reference run. Although it stays low in the first half of the simulation period, it increases towards the end of the period and closes in on the realistic values again. The 90 % reduction, on the other hand, stayed consistently lower than the other scenarios throughout the simulation period, where minimum value was reached in 1990.

There is a positive oxygen trend (Figure 3.6c) in the model data in the latter half of the simulation period, but in the beginning of the period there is some fluctuation.
There is little difference between the scenarios; the datasets are more or less identical except in 1992 where the results deviate slightly.

Skagerrak, Norwegian Trench (SK-2)

The reduction scenarios appears to have an effect on the N:P ratio (figure 3.7a), where minimum values are achieved after only two simulation years for both the 50 and 90 % reductions. The 50 % reduction fluctuate more than the 90, but stays well below the realistic run, at a ratio between 15 and 20 throughout the period.

The chlorophyll results (figure 3.7b) display a marked drop in concentration in the first half of the simulation period. Whereas the trend of the scenarios increases, the 90 % stays stable at a low between 1.5 – 2.5 $\mu g l^{-1}$. The trend of the 50 % reduction was also increasing after the low point in 1987, but stayed consistently lower than the realistic run.

The modelled oxygen trend (figure 3.7c) is positive for all scenarios where the 90% run has consistently higher values than the other runs. The realistic run start to increase in 1989 and crosses the 50% series in 1991 then drops below the other runs again.

3.3. Inter-comparison of the model boxes

The N:P ratio of the coastal boxes NL-C1 and –C2 appears to be very similar, in particular the reduction runs. The realistic run of the two boxes seems to differ slightly, but both curves peaks around 1994. The G-C1 box is situated in the vicinity of the two Dutch boxes, but has slightly different response to the reductions. The 50 and 90 % time series of the N:P ratio fluctuates more in G-C1 than in the other two boxes and the realistic run peaks in 1988 rather than in 1994. The oxygen results for NL-C1 and NL-C2 are similar both in trend and concentrations. Maximum values are found in 1993 for both boxes and drop to a minimum level in 1994/1995. There is a larger discrepancy between the simulations of the G-C1 box and the maximum oxygen values for all simulations occur in 1993/1994 before it drops in 1995. The three boxes respond quickly to reductions for chl a_{max}. The fluctuations in the 50 and 90% run smoothen out after the first three years in both G-C1 and NL-C1.

The offshore boxes, G-O1 and NL-O1, do not seem to have a trend in the N:P ratio. There is a greater discrepancy in the N:P ratio data of G-O1 than NL-O1, but the maximum and minimum values stays within a range between 11 and 18 for both boxes.
The O_{min} differ between the boxes, where minimum values of the G-O1 box occur in 1995 and in 1989 for the NL-O1. Similar for both boxes is the low discrepancy between the different simulations. There is a marked reduction in chl a_{max} for the 90% reduction which is visible in both boxes. The 90% results seem to stabilise after the first simulation year. The G-O1 box has higher initial values of chl a_{max}, but both boxes peak in 1993.

There does not seem to be a link between the N:P ratio results of SK-1 and SK-2. Both 50 and 90% reductions seem to be effective in lowering the ratios, but the fluctuations in the SK-1 box are much larger than in SK-2.

There are some similarities in the trends of the chl a_{max} results for the two boxes. The 90% reduction seems to have the largest effect and remains low and stable compared to the other simulations.

Table 3. 1. The **table shows the cost function values and the interpretation for each modelled parameter. The colours refer to the degree of discrepancy between the reduction scenarios and the reference run (red = low discrepancy, blue = medium discrepancy, green = high discrepancy).**

	N:P ratio			Chl a_{max}			O_{min}		
	10 %	50 %	90 %	10 %	50 %	90 %	10 %	50 %	90 %
G-C1	0.26	1.33	3.33	0.98	5.11	9.35	0.15	0.55	0.83
G-O1	0.26	1.18	2.10	0.34	0.76	1.27	0.15	0.47	0.74
NL-C1	1.06	3.22	7.11	0.49	1.85	3.92	-0.04	0.06	0.06
NL-C2	0.63	1.65	3.11	0.24	1.42	3.37	0.08	0.32	0.62
NL-O1	0.40	0.76	1.09	0.28	0.63	0.89	0.73	2.11	3.09
SK-1	0.04	1.20	3.02	0.22	2.05	5.17	-0.04	0.06	0.04
SK-2	0.46	2.20	4.15	0.46	1.87	4.61	0.69	1.93	3.55

An interesting factor, when considering the effect of reducing nutrient inputs, is to compare the response of the different areas of the North Sea and the cost function results provide a simple interpretation of the reduction effects in the different model boxes (Table 3.1). The discrepancy of the near-shore boxes near doubled from 50 to 90% in the N:P ratio and all boxes, except NL-O1, had high discrepancy in their 90% simulation.

The highest discrepancy was found in the 90 % reduction scenario and the lowest was found in the 10 % reduction scenarios for all parameters. The discrepancies in the N:P ratio increased from 10 to 90 % for all boxes. The lowest increase in the discrepancy occurred in the two offshore boxes. Overall the least increase in discrepancy was found for all boxes for the O_{min} parameter.

3.3.1. The realistic runs vs. river discharges

Table 3. 2. The Pearson correlation (r) between the N:P ratio of the realistic runs and the N:P ratio measured in the rivers included in the model. Kanal = Nordsee kanal; Lake = Lake Ijssel; SHK(L) = Scheldt, Haring Vleet, Nordsee kanal, Lake Ijssel; ElWEm = Elbe, Weser, Ems; GlGö = Glomma, Göta. The model box values have been correlated with rivers which are expected to influence that particular model area, based on knowledge of the circulation patterns.

	RIVERS					
	KANAL	LAKE	SHK	SHKL	ElWEm	GlGö
NL-C1	0.61	-	0.8	-	-	-
NL-C2	0.17	0.23	-	0.28	-	-
NL-O1	-0.19	-0.35	-0.12	-0.31	-	-
G-C1	-	-0.52	-	-0.43	-0.21	-
G-O1	-	-	-	-0.16	-0.25	-
SK-1	-	-	-	-	0.15	0.08
SK-2	-	-	-	-	-	-0.18

The N:P ratio trend of the realistic run deviates from the other scenarios with fixed 1985 river loads in all the near-shore model boxes. In the offshore boxes the realistic run usually has higher values although the trends are more or less similar.
Table 3.2 provides an overview of the correlation between the realistic runs and the reported N:P ratios from the rivers. These data have been used in the model as a forcing of the realistic run.

The highest correlation between rivers and the near-shore boxes are found in NL-C1 and the mean value of SHK (r = 0.80) and the Nordsee Kanal (r = 0.61). The offshore boxes had negative correlations for all comparisons, where the highest correlation was found between NL-O1 and Lake Ijssel (r = -0.35). The G-C1 box also had negative correlation for all comparisons and the highest correlation is found with Lake Ijssel and the mean value of SHKL (r = -0.52; -0.43, respectively).

The Skagerrak boxes had in general low correlations with the river N:P ratios.

3.3.2. The 1985 reference runs vs. the North Atlantic Oscillation (NAO) and local wind fields

Table 3. 3. The Pearson correlation (r) between the N:P ratio of the 1985 reference run and the NAO index mean of January and February. The O_{min} correlation is based on the NAO index mean of July, August and September. The Chl a_{max} correlation is based on the NAO index in May.

	G-C1	G-O1	NL-C1	NL-C2	NL-O1	SK-1	SK-2
N:P ratio (NAO)	-0.52	-0.58	-0.18	-0.37	0.17	0.52	-0.46
Chl a_{max} (NAO)	-0.30	-0.28	0.46	0.30	-0.53	0.22	-0.08
O_{min} (NAO)	-0.60	-0.40	-0.55	-0.45	-0.61	-0.03	0.21

The 1985 reference run is only forced by the meteorology and it would thus be interesting to see how well the results correlate with a large scale meteorological system such as the NAO index. In Table 3.3 (N:P ratio) the G-O1 box had the highest correlation (r = -0.58), closely followed by SK-1and G-C1 (r = 0.52 and -0.52, respectively). As for the three Dutch boxes, NL-C1/NL-C2 and NL-O1, the correlation was much lower (r = -0.18; -0.37 and 0.17, respectively). The effect of the NAO index on the chl a_{max} seemed to have the highest correlation with NL-C1 and NL-O1 (r = 0.46 and -0.53, respectively). The correlation between the NAO and O_{min} seemed to be relatively high in all boxes except SK-1. The near-shore boxes and NL-O1 appeared to have the highest correlations.

Table 3. 4. The Pearson correlation (R^2) between the O_{min} of the 1985 reference run and two local wind fields, one in the southern North Sea and one in Skagerrak. The correlation is based on weekly means (June – September) of wind speed which coincided with the lowest O_{min} values of the different model boxes.

G-C1	G-O1	NL-C1	NL-C2	NL-O1	SK-1	SK-2
-0.02	-0.03	0.36	0.64	-0.16	-0.17	NA

The correlation between local wind speeds and the O_{min} values (Table 3.4) were absent or very low for most boxes, except NL-C2 (r = 0.64) and to a small extent NL-C1 (r = 0.36).

3.3.3. The relationship between the three parameters

Table 3. 5. the Pearson correlation (r) between the three different parameters for all model boxes.

	G-C1	G-O1	NL-C1	NL-C2	NL-O1	SK-1	SK-2
N:P vs O_{min}	-0.27	0.43	0.33	0.51	-0.14	-0.27	-0.15
N:P vs Chl a_{max}	0.04	0.31	0.55	0.66	-0.02	0.20	-0.28
Chl a_{max} vs O_{min}	0.28	0.36	0.05	0.59	-0.08	0.02	0.58

The highest correlations between all parameters were found in the NL-C2 results (Table 3.5). The two offshore boxes, NL-O1 and G-O1, deviated in their correlation results, where G-O1 had high correlations and NL-O1 had low correlations for all parameters.

4. DISCUSSION

The main findings of this study are related to the modelled effect of the reduction scenarios. According to the OSPAR Eutrophication Strategy (2005) the process of reducing DIN and DIP inputs to the North Sea by 50% should by 2010 have achieved to establish and maintain a healthy marine environment where eutrophication do not occur (OSPAR, 2005a). The definition of a *healthy marine environment* has been defined on an area basis, where background and problem levels for the N:P ratio, oxygen minimum and chlorophyll maximum has been identified (see Table 2.2). The main issue seems to be that the reported values do not seem to coincide with the measured values (see Table 1.1 and 1.2).

The model was run over a 10 year period, which was similar to the time period available to the OSPAR member countries to achieve the desired status. A general trend was that the boxes in the closest vicinity to the major estuaries seemed to respond to both the 50 and 90% reductions rather rapidly (within the first 2-3 years) then stabilise, whereas the offshore boxes were affected by the reductions only to a small extent. This provides an indication of the rapid response time of the North Sea. However, there was a surprisingly low response to the nutrient reductions in the O_{min} concentrations in all boxes. When compared to the NAO index and local winds, it became evident that the modelled oxygen levels were influenced by vertical mixing and climatological conditions to a larger extent than nutrient ratios.

4.1. Limitations

4.1.1. Using the NORWECOM model

A model is the only available tool when trying to predict environmental conditions in a system like the North Sea. However, there are some important limitations linked to this method.

Models can only produce results which are already predetermined by the model equations. This limitation is apparent in the NORWECOM model, which contains a simplified biological model. As indicated in the introduction, one of the motives leading OSPAR to chose the N:P ratio as a eutrophication indicator, apart from the apparent biological availability, was that a shift in the ratio might have triggered the observed phytoplankton regime shift in the late 1980's that favoured the growth of certain species of dinoflagellates (Muylaert et al., 2006). As the model only consider the biomass of two phytoplankton groups, it might be hard to identify a shift in species composition due to eutrophication. There are many studies pointing out the relevance of benthic sedimentation and remineralisation in the different parts of the North Sea (Ehrenhauss et al., 2004, Hall et al., 1996, Johannessen and Dahl, 1996, Kirby et al., 2007), but this process is only represented in the model by a simple remineralisation equation. The lack of a benthic algae component could potentially lead to incorrect retention times of DIN and DIP, particularly in the coastal areas (Cloern, 2001).

Model simulations are completely dependent on observational data for validation and simulation. As is known from empirical data analysis, the quality and accuracy of the collected data is of the utmost importance. If the data does not reflect well enough the situation of the specific area the whole simulation might come out with results completely off the target (ref).

4.1.2. The model input: Using OSPAR data

The model results are based on reported river nutrient loads (DIN and DIP) from the member states of OSPAR. By only using the dissolved inorganic components of N and P, the model might not be able to provide the full extent of the biologically available nutrient pool. A study by Hydes *et al* (1999) showed that during the winter months of 1988/89 the N:P ratio in the southern North Sea was much lower than would be expected from a conservative mixing of river and ocean waters. This was linked to high rates of denitrification of dissolved organic nitrogen (DON). In the German Bight only 50% of the observed changes in the nitrate loads was due to inputs of new nitrogen from rivers and atmosphere, the rest was linked to denitrification of DON (Hydes et al., 1999).

Atmospheric inputs of nutrients in the OSPAR data are only accounted for on a catchment basis (OSPAR, 2005a) and this might pose a problem when comparing model results with realistic results.

Atmospheric inputs of nutrients are both of natural and anthropogenic origin. Dust storms from the Saharan belt can carry large amounts of nutrients into remote areas and thus significantly contribute to the local deposition. Large sand storms have become more frequent since the early eighties as a response to climatic changes in the atmospheric circulation (Dobricic, 1997) this could lead increase in atmospheric deposition over the North Sea. In addition, atmospheric nitrogen deposition may have a substantial impact on a local and regional scale. It was pointed out in the de Leeuw study (2003) that atmospheric inputs added nutrient pressure to already stressed areas of the North Sea (the southern coastal areas). Even short but intense events of deposition can trigger algal blooms during nutrient depleted periods in summer and early autumn (de Leeuw et al., 2003).

Nutrient deposition to the sea has been modelled with atmospheric models, but the chemical processes of coastal systems are rarely included (de Leeuw et al., 2003). The NORWECOM model only considers atmospheric deposition of N in the simulations.

Most OSPAR countries, except Denmark, report their emissions on the basis of a *source oriented approach* (OSPAR, 2003a) due to the management focus on mitigation actions (Borgvang et al., 2006). In general terms these are methods of quantifying nutrient loads through modelling, where loss coefficients and data discharges from point sources are used. The *load oriented approach*, used by Denmark, is based on quantification of nutrient loads through direct measurements of concentrations and transport values in rivers (Borgvang et al., 2006). In addition to this, the member states also report on measured nutrient loads from monitoring stations in the estuaries (Jarvie et al., 1997, OSPAR, 2003a, OSPAR, 2005a). The model results and results measured at monitoring stations along the coast and estuaries do not agree with the nationally reported reductions (see Table 1.1 and 1.2). A study by Jarvie *et al* (1997) analysed the Paris Commission (previous to the OSPAR Commission) data and the national monitoring strategies. One of the main limitations pointed out in their study was that despite the attempts made to standardise the monitoring strategies, some important methodological discrepancies still remained. In the study the location of the sampling site in relation to the saline and tidal limits was identified as the factor which caused the largest discrepancy. The problems with collecting data within the tidal reaches were linked to sedimentation and resuspension as these processes would have implications for the interpretation of the river load data and the consequences for the estuarine and coastal environmental status (Jarvie et al., 1997). This would in turn influence the model output as the values were so strongly linked to the input data.

4.2. The realistic run

The present study focuses mainly on the long-term effects of nutrient reductions, but it is useful to consider the effect on the system from actual river nutrient loads during the model period. The realistic run, which was forced with continuous river runoff and meteorology, deviated quite substantially from the reduction runs particularly in the coastal boxes. By comparing the modelled effects of the realistic river loads with measured values in the rivers an assumption regarding the extent of the riverine impact offshore and along-shore can be made. The N:P ratio was chosen for this comparison as this has been identified by OSPAR as a measure for the degree of nutrient enrichment (OSPAR, 2005a). Of all the model boxes, the NL-C1 box had the highest correlation with the river N:P ratio of the Nordsee Kanal and the mean ratio of Scheldt, Haring Vleet and the Nordsee Kanal (SHK) ($r = 0.61$ and 0.8, respectively). This was not such a surprising result as the box is situated in the Rhine Plume.

The G-C1 box had higher correlation with Lake Ijssel and the SHK+Lake Ijssel (r = -0.52 and -0.43, respectively) than with the German rivers, Elbe, Ems and Weser (r = -0.21). This may indicate the importance of the along-shore current when considering the transport of nutrients. The modelled N:P ratio of the offshore and Skagerrak boxes appeared to be following the fluctuations of the 1985 reference run. As the fluctuations in the reference run are a signal of the meteorological forcing, an initial conclusion may be that these boxes are to a larger extent influenced by meteorology than the nutrient signals from the rivers.

4.3. Inter-comparison of the boxes – The effects of reducing DIN and DIP

From a management point of view, reducing the nutrient load to the North Sea by 50% of 1985 concentrations has been proposed to be sufficient in order to achieve good environmental conditions (OSPAR, 2003a, PARCOM, 1988). As estuaries and near-shore areas are most affected by river water, these areas are of particular interest in management strategies.

When river water enters an estuary it mixes with coastal water and becomes diluted. The signal from the river will become weaker further offshore until it is finally absent (Hydes et al., 1999). This gradient is important as it gives an indication of how large the effects of reducing nutrients will be on the North Sea system going offshore. Likewise, the along-shore gradient would be indicative of how the different nutrient sources influences the coastal boxes and to which extent reducing the nutrient inputs from one river system would impact not only the areas in the immediate distance, but also areas which would be expected to receive water transported from these rivers.

Previous model studies of the North Sea have shown that short term effects of nutrient load reductions only had a noticeable effect on the coastal zone of the North Sea (Lenhart, 2001, Lenhart et al., 1997, Skogen et al., 2004). This was linked to reduced loads of the three rivers Rhine, Meuse and Elbe which to a large extent controlled the nutrient regime of this region during spring and summer (Lenhart et al., 1997).

4.2.1. The southern coastal boxes; NL-C1, NL-C2 and G-C1

The southern coastal boxes, the NL-C1, NL-C2 and G-C1, showed similar patterns for all parameters. The boxes are situated in the immediate distance of large estuaries and would thus be expected to show a response to reduced nutrient input. The results showed that for the N:P ratio, the 50% reduction was sufficient to achieve the desired Redfield ratio (±50%) in all the model boxes after only two simulation years, except G-C1. The German coastal box had an immediate response to the 90% reduction scenario and reached the desired 16:1 ratio the second simulation year. The 50% reduction scenario had a generally decreasing trend, but only reached the Redfield ratio (±50%) in 1991.

The effect of the nutrient reductions was further established through the cost function where there was a clear trend of increasing discrepancy between the reduction runs and the reference run as the reductions increased. The discrepancy of the N:P ratio was significant for all three boxes in the 90% simulation, but only NL-C2 had significant discrepancy in the 50% run. When considering the effect on N:P ratio the reduction potential seemed to be fully utilised after the second year in all three boxes. Over a 10 year period, the fluctuation in the 50% run of the G-C1 and NL-C1 boxes was within a natural fluctuation as the cost function did not exceed 2 standard deviations. The influence of Atlantic Water in the North Sea is to a large extent related to the NAO index but the direction of this water within the North Sea basin is not fully understood (Winther and Johannessen, 2006). In order to analyse the effect on the coastal region a correlation between the model results and the NAO index was performed. The results revealed that the German box, G-C1, had higher correlation ($r = -0.52$) with the NAO than the NL-C1 and NL-C2 ($r = -0.18$ and -0.37, respectively). This indicates that the German Bight is more strongly influenced by the NAO and thus Atlantic Water than the Dutch coast.

The chlorophyll a results indicated a response to both 50 and 90% reduction similar to the effect visible in the N:P ratio. The cost function showed that for all three boxes the 90% run yielded values with a significant discrepancy to the meteorological fluctuations whereas only the G-C1 box achieved this for the 50% run. These results show that near-shore areas, such as estuaries, have a natural variability and that there is a relationship between the N:P ratio and the chl a_{max} concentrations. The correlation between these two parameters were moderate in all three boxes but the peaks in chl a_{max} coincided with the peaks of the N:P ratio. The chlorophyll results were in general closely linked to the meteorological signal and comparison with the NAO indicated some correlation. The highest value was found in NL-C1 ($r = 0.46$), but this was only slightly higher than the NL-C2 and G-C1 results ($r = 0.3$ for both boxes). Compared with the N:P ratio, the NL-C2 box had the highest correlation between the N:P ratio and the chl a_{max} concentrations whereas the G-C1 had very little correlation ($r = 0.04$). This may imply that the phytoplankton biomass is more strongly connected to the nutrient ratios in the Dutch boxes. However, all boxes seem to have similar responses to the climatological signal regarding the chl a_{max} concentrations.

The nutrient reduction's effect on the oxygen conditions was surprisingly low. Apart from the G-C1 box, the southern coastal boxes showed little or no effect in the O_{min} results from neither the 50 nor the 90% run. This was reflected in the cost function where the three boxes all had low discrepancy with respect to the 1985 reference run. In order to quantify the affinity with the meteorological signal the 1985 reference run results were compared to local wind conditions and the NAO index. Of the three boxes, the G-C1 had the highest correlation values for O_{min} with the NAO index ($r = -0.60$), but no correlation with the local wind conditions. The two Dutch boxes, NL-C1 and NL-C2, also showed a fairly good correlation with the NAO ($r = -0.55$ and -0.45, respectively). In contrast to G-C1, NL-C2 had a correlation with local wind conditions of $r = 0.64$. This was the highest correlation of all boxes, both near shore and offshore. It would be expected that due to their vicinity to each other G-C1 and NL-C2 would react similarly to the local wind conditions, but this was not the case.

On the whole the G-C1 box seems to be more influenced by regional climatic conditions than the two Dutch boxes. This is reflected in the correlation between the NAO index and the N:P ratio and between the local wind conditions and the O_{min} concentration.

4.2.3. The southern offshore gradient

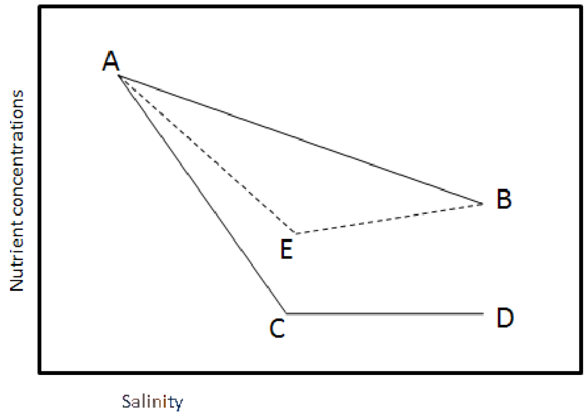


Figure 4. 1. Schematic overview of variations in nutrient concentrations with a dominant riverine source. The letters A, B, C, D and E indicate nutrient concentrations at specific salinities. Line A-B represents steady-state well mixed winter conditions, line A-C-D represents the summer conditions and line A-E-B represents conditions after deep winter mixing off the shelf. From *Hydes et al (1999).*

Moving offshore, the influence from the rivers become weaker and a stronger signal from Atlantic Water can be detected. Figure 4.1 provides a schematic overview of how nutrient concentrations decrease with increasing salinities. To a large extent this theory fits with the reduction scenarios of the two offshore boxes G-O1 and NL-O1. According to the cost function neither of the boxes had a significant response to the 50% reduction and only G-O1 had a significant response to the 90% reduction. These results reflect the theory that the riverine signal is to a large extent confined to the coastal zone and further offshore the signal weakens and finally becomes absent (Lenhart, 2001, Hydes et al., 1999). Instead, the fluctuations of the N:P ratio are similar to that found in Atlantic Water, with values between 11 and 16 (M. Skogen, 2007. pers. comm.). When comparing the N:P ratios with the NAO index, the G-O1 had the highest correlation of the two boxes (r = -0.58). The initial assumption would be that this box is more influenced by the NAO index when it comes to nutrient concentrations than the NL-O1 box.

For the chl a_{max} results, the highest correlation with the NAO index was found in the NL-O1 box (r = -0.53 and -0.61, respectively). It appears that large scale meteorology, and possibly inflow of Atlantic Water, is more important for primary production in this box than in the G-O1. The cost function values for the O_{min} NL-O1 deviated significantly from the 1985 reference run for both the 50 and 90% reduction scenarios. The chl a_{max} concentrations were generally lower for the NL-O1 than the G-O1. This could be linked to the low correspondence of the NL-O1 box to reduced nutrient loadings from the rivers, but rather influenced by water from the central North Sea and the English coast (NSTF, 1993b). The O_{min} correlations were identical for the two boxes (r = -0.6).

When compared to the local wind fields, the two boxes had very little or no correlation for the O_{min} results. In a study by Warrach (1998), the development of thermal stratification in the central North Sea and to which extent the wind speed and direction influenced the depth of the mixed layer, was modelled. For all model scenarios the thermal stratification was evident in the water column until 30th of August and that mean wind speeds below ~6 m s^{-1} were not sufficient to increase the mixed layer sufficiently to break down the stratification (Warrach, 1998). This may support the O_{min} results from NL-O1 and G-O1, where the years of low O_{min} concentrations for both boxes coincided with relatively low weakly mean wind speeds for August. This was especially true for 1995 where mean wind speeds were in the range of 4-5 ms^{-1} for most of August. An additional explanation is that the NAO controlled Atlantic inflow surpasses the signal of local winds over such short time scales.

This study did not analyse the data in relation to atmospheric temperatures and solar radiation. This may be just as important as wind stress in determining the vertical mixing considering the low wind speeds. In addition, the wind speed values are from a non-specified point in the southern North Sea, and may thus not reflect the actual meteorological conditions of the NL-O1 and G-O1 areas.

4.2.3. The Skagerrak boxes; SK-1 and SK-2

The N:P ratio of the two Skagerrak boxes had some similarities in their fluctuations, especially with regard to the peaks of 1988, 1990 and 1994. These peaks were easily identified in both boxes although the magnitude of the SK-1 was nearly twice that of SK-2. The effectiveness of the reductions was most prominent in SK-2, where the 50% reduction scenario achieved the Redfield ratio (±50%) for N:P ratio within the second year. For SK-1 the 50% reduction scenario fluctuated more and it was only the 90% reduction scenario which stabilised around the desired Redfield ratio. This difference in the two boxes was further found in the cost function values, where the SK-2 showed a significant response to the 50% reduction compared to the 1985 reference run whereas the SK-1 stayed within the range of natural variability. A significant response was identified in relation to the 90% reduction in the SK-1 box. The correlation of the N:P ratio and the NAO index yielded similar values for both SK-1 and SK-2 ($r = 0.52$ and -0.46, respectively). This implies that the N:P ratio of SK-1 and SK-2 both respond to the meteorological forcing, but with different outcome.

It might be expected that the fluctuations of Atlantic Water N:P ratio would surpass that of the local inputs, due to the sheer volume of water flushing through the system. The N:P results do not directly support such a straightforward assumption. The different responses may be explained by the fact that the inflowing Atlantic Water is more saline than the surface water and will thus enter Skagerrak at intermediate depths. The surface water originating from the Baltic Sea will thus dominate the upper layer at SK-2 (NSTF, 1993c, Skogen et al., 1998a). In the SK-1 box, the surface layer is a mix of Atlantic Water and the Jutland Current Water, originating from the German Bight and thus reflects the riverine signal of this region (NSTF, 1993c, Gustafsson and Stigebrandt, 1996, Skogen et al., 1997). It appears as if high N:P ratios of the SK-2 box corresponds to low values of the NAO index, whereas the opposite is true for SK-1. A possible explanation to this may be that strong south-westerly winds, associated with high NAO index values, increases the transport of water from the German Bight and along the Danish Coast, whereas the same winds will retard the outflow of Baltic water into the Skagerrak (Rydberg et al., 1996, Winther and Johannessen, 2006). This confines the nutrients in the less saline surface layer to the eastern parts of Skagerrak, and the N:P ratio of SK-2 will to a larger extent reflect the ratio of Atlantic Water.

The chl a_{max} results in both boxes did not seem to have any particular trend. In SK-2 only the 90% reduction scenario indicated a clear decrease which was reflected in the cost function, whereas a significant response was found in the chl a_{max} results for the 50% reduction in SK-1. When comparing the 1985 reference run to the NAO index, the chl a_{max} results show some correlation in the SK-1 box ($r = 0.22$) and no correlation in SK-2. Judging by the low correlation values, it may suggest that the primary production of the Skagerrak area is not fluctuating with respect to the NAO index, at least not the northern parts.

The O_{min} results of SK-1 appeared to have no correlation with the NAO index, but had a slight negative correlation with the N:P ratio ($r = -0.27$). Surprisingly there was no correlation with the chl a_{max} concentrations.

The O_{min} results for SK-2 had a clear positive trend for all simulations, but no correlation analysis was made for these concentrations. The reason for this decision was that these results might not be representative of the actual situation in the deep parts of the Norwegian Trench. The Institute of Marine Research in Flødevigen, Arendal, have long time series of O_{min} measurements from the Torungen – Hirtshals transect, which contradicts the results from the model. The time series does not display any trend, only a slight drop in the concentration in the period 1988 to 1990. This drop was most probably due to warm winters and thus stronger thermal stratification and decreased winter mixing of bottom water (Johannessen, 2007. pers. comm, Johannessen and Dahl, 1996).

4.4. The effects of the management approaches in the North Sea

The North Sea environment is managed through several international institutions conventions, the OSPAR Convention being one of them. In 1988, the PARCOM recommendation on nutrient reductions was agreed upon by the member countries and the goal of reducing N and P by 50% was first proposed (PARCOM, 1988). Later, the PARCOM and OSCOM merged into OSPAR and the 50% reduction goal was transferred to the new commission.

The strength of the OSPAR EcoQO's (OSPAR, 2005c) is their simplicity. From a management point of view this is important due to their clear goals and procedures, but as it has been pointed out in Borgvang *et al* (2006) and Jarvie *et al* (1997) the monitoring procedures might not be sufficient in determining the effect of nutrient reductions in the coastal areas. The realistic model results show that, despite the reported reductions, the nutrient dynamics in the near-shore areas have not responded to these reductions. On the contrary, the model boxes closest to the major river outlets (NL-C1, NL-C2 and G-C1) seemed to have a slight increase towards the end of the modelling period. A changing climate is further complicating the management of nutrient inputs, causing an increase in river run-off to areas which are already stressed by high nutrient loadings. Judging by the model data of Skagerrak and the offshore areas, the realistic run seemed to be controlled by meteorology to larger extent than river runoff.

The 50% reduction scenario was able to meet the EcoQO's for the N:P ratio for most of the coastal boxes within the first two simulation years, except G-C1 and SK-1. Whereas the G-C1 box reached the EcoQO towards the end of the modelling period, the SK-1 box appeared to be more linked to fluctuations in the meteorology. The Danish box receives nutrients from several sources, and the largest contributor is the Atlantic Water which enters at the western edge of the Norwegian Trench. Whereas the quantity of nutrient concentrations due to anthropogenic activities to a certain extent can be identified in river water, this is not a straight forward procedure for the Atlantic Water. Here, atmospheric deposition is a very important anthropogenic signal (de Leeuw et al., 2003, Rendell et al., 1993) and should maybe be accounted for to a larger extent in modelling and the monitoring procedures.

In addition, the appropriateness of using the Redfield N:P ratio (16:1, ±50%) has been debated. Estuaries, and as indicated in this model study; near-shore areas, rarely achieve the desired ratio due to their naturally high N:P ratio, so rather than using a fixed ratio a possibility is to use a sliding assessment level based on salinity (OSPAR, 2003b).

The EcoQO of O_{min} for a healthy bottom environment is set to 6 mgl^{-1} for the whole North Sea region. This goal was not achieved for any of the boxes and surprisingly the nutrient reductions had little or no effect on the minimum values during the duration of the modelling period. The O_{min} parameter is an important indicator of the health state of a system, as hypoxia and anoxia can seriously harm the benthic biota (Cloern, 2001). However, this parameter was clearly controlled by meteorology and long warm summers and insufficient vertical mixing during winter can lead to a more stratified North Sea, with prolonged periods of low oxygen concentrations. It seems that reducing the nutrients will not be sufficient to increase the oxygen concentrations in the North Sea.

The chlorophyll a concentrations did not exceed the background levels for chl a_{max} defined for the different regions in any of the boxes. The EcoQO's are based on national assessments and differs quite a lot from region to region. The most noticeable difference is found in the EcoQO's for elevated levels of the mean chlorophyll a concentration in NL-C2 and G-C1, >22-24 μgl^{-1} and >3-6 μgl^{-1}, respectively. With such large deviance between the assessments levels and the fact that G-C1 is upstream from the NL-C1 box, it may be difficult to achieve the desired goal in the German Bight area.

The quality status reports of the North Sea were based on the spatial restrictions of the NSTF boxes. The regions might be politically practical, but the model results indicated that there might be large intra-regional differences. These differences were identified in region 7b (NL-O1and G-O1) and in region 8 (SK-1 and SK-2). The responses of the Skagerrak area to nutrient reductions are different in the north (SK-2) and the south (SK-1). This is linked to the nature of the surface waters entering the region, where the north-east is mainly influenced by Baltic water whereas the south-west is influenced by the Jutland Current which originates in the German Bight. The southern offshore box, region 7b, also appeared to have different responses to nutrient reductions in the two model boxes. On the basis of these results the appropriateness of the current NSTF regions as management units should maybe be re-evaluated.

After the political agreements in the 1980's on how to handle the eutrophication problem there has been a general decline in the political interest for these issues. The task is now to implement these decision and a shift towards eutrophication management at EU level is becoming more and more prominent (de Jong, 2006). Future management strategies in the North Sea include a harmonisation of the OSPAR Eutrophication Strategy and the EU directives relating to marine eutrophication. As stated in the *Strategy for a Joint Assessment and Monitoring Programme* (JAMP) (2006):

"It is particularly important that synergy is achieved between the monitoring activities under the JAMP and the requirements of EC Directives (such as those relating to the Water Framework Directive (WFD) and the Habitats Directive). So far as there is a spatial overlap in coastal waters between OSPAR and the WFD and an overlap in the issues addressed, there is a need to ensure a consistent approach in both organisations, and for each to prevent duplication by making the best use of the expertise and tools developed by the other." (OSPAR, 2006).

Previously, the EU directives (ND, UWWD) have mainly focused on continental and estuarine environmental impacts of increased nutrient loadings, but with the WFD and the new European Marine Strategy (EMS) the marine engagement is extended into areas already covered by OSPAR. With this extension it has become increasingly important to harmonise the management approaches. In general, the OSPAR assessment and classification strategies are more clearly defined than both the UWWD and WFD (OSPAR, 2005d). One of the most important features in the OSPAR assessment is the inclusion of "transboundary affected" problem areas. These are areas where the nutrient loadings have not increased, but where direct and/or indirect effects of eutrophication can be identified (OSPAR, 2005d). As has been pointed out in this study, the transboundary transport of nutrients can affect areas which may not naturally be subjected to eutrophication. This is thus a very important element which should be included in any future harmonised eutrophication approach.

One of the largest challenges for future North Sea management is to harmonise the eutrophication strategies of OSPAR, the WFD and the EMS. As the WFD and the EMS are legally binding instruments it becomes increasingly important to establish an international nutrient monitoring programme, identify suitable EcoQO's and have a common classification strategy of marine areas (de Jong, 2006).

5. CONCLUSIONS

Previous studies have focused on modelling the short-term effects of reducing the nutrient loads to the North Sea system. These studies revealed that the only noticeable effects occur in the near-shore areas of the North Sea.

This study, which had a span of 10 years, that the largest and most rapid response was found in the N:P ratio for all model boxes. All three parameters (N:P, chl a_{max} and O_{min}) in the G-O1 and NL-O1 boxes had the largest correlations with the NAO index. The highest correlations with the local wind field, which was compared to the O_{min} concentrations, were found in NL-C2 and NL-C1. These results indicate that the offshore areas seem to be more strongly influenced by the large scale meteorology than the near-shore boxes, in particular along the Dutch coast, which are influenced to a larger extent by the riverine nutrient loads. This study supports previous studies on the short-term effects of nutrient reductions and also predicts a rapid response time of the North Sea coastal areas. Another interesting result is the importance of large scale meteorology, such as the NAO index, in the region and how this affects the fluctuations in nutrient and oxygen concentrations.

The only modelled parameter which did not seem to be influenced by reduced nutrient loads in any of the boxes, except the Dutch offshore box (NL-O1), was O_{min}. Perhaps this parameter, rather than having a fixed minimum value for the whole North Sea region, should be defined on a more region specific basis, as it appears to be quite closely linked to meteorological conditions.

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