Hydrodynamical and Ecological Modelling of the North Sea

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Abstract

The North Sea is one of the most important shelf seas in Europe as it provides important economical resources to the adjacent countries. Using numerical models one can evaluate and predict changes to the system, link cause to effect and enable stakeholders of such resources (countries) to have powerful assessment tools at their disposal in order to manage it with the best approach. Phytoplankton abnormal growth can result in, among other, oxygen deficiency and thus undesirable disturbance to the water quality of a given area, thus OSPAR requires a member state to reduce its nutrients discharge loads to 50% of 1985 levels. MOHID model makes use of a 2D hydrodynamical model to compute tides and a nested 3D ecological model in order to simulate parameters, such as physical, biological and chemical processes. Using the 2D hydrodynamical model, residual circulation and residence time was calculated in a specific region. The validation of the hydrodynamical model was done using tidal harmonic analysis that presented good results. The 3D ecological model simulates phytoplankton (flagellates) and zooplankton (mesozooplankton) and relevant properties in the Channel and Southern Bight. Results show good agreement between the model, field data and satellite imagery. Transboundary nutrient transport fluxes were computed, giving strong confidence that nutrients are transported from the UK to the Dutch coast in an anticlockwise direction, following the circulation pattern. Other findings include phytoplankton growth limitation by light through "self shading", and not nutrient limitation. This alerts one to the possibility that a reduction on nutrients will probably not influence the system and therefore, is a matter to be addressed in future works.

Keywords

North Sea, Modelling, Tidal Harmonic Analysis, Hydrodynamics, Eutrophication, Phytoplankton

1. Introduction

The objective of this work is to study the hydrodynamic circulation of the North Sea, specially the movement of the different water bodies and in addition, to study the primary production, as well as the phosphorus and nitrogen cycles and its relation with the water quality using a mathematical model (MOHID).

It concerns the understanding of eutrophication causes and determining its origin regarding the North Sea. Another goal of this work is to validate the MOHID model in a bigger scale, using the vast amount of data available for the North Sea and compare it with existing models, facilitating this assessment.

1.1. The North Sea

The North Sea is a marginal sea of the North Atlantic situated on the Northwest European Shelf. It is bordered by several countries, namely, England, Norway, Denmark, Germany, the Netherlands, Belgium and France. It is connected to the Atlantic in the North, between England and Norway and the South between England and France/Belgium. To the east, between Norway/Sweden and Denmark it is connected to the Baltic Sea.

Coastal areas are characterised by shallow tidal regions that have high primary productivity often attributed to antropogenic supply of nutrients by the rivers. These areas are very important because they support a number of different ecological habitats, such as migratory birds and they are also a nursery for juvenile fish. Whithin the North Sea, lies one of the most important fishing grounds in the world. Herring, plaice, haddock and cod are the main fish species caught for human consumption (Sündermann *et al*, 2002 and OSPAR, 2000). Furthermore, the offshore oil and gas industry has become a major economic activity in the North Sea since the late 1960s along with some of the busiest shipping routes in the world(OSPAR, 2000).

Land-based activities such as industry, households, traffic and agriculture may have an impact on the ecosystem of the Greater North Sea via riverine or atmospheric inputs of contaminants (Sündermann *et al*, 2002). Substances of concern are the excess of nutrients, which may lead to eutrophication, and hazardous substances which could pose a risk to marine organisms and, via food from the sea, to human health.

For over the last 30 years, the North West continental shelf has experienced increasing eutrophication in the coastal waters: the percentage of riverine input of nitrogen and phosphorus into the shelf seas has increase from 20% and 15% in the 1950s to 52% nitrogen increase and 52% phosphorus increase in 1980 (Patsch *et al*, 1997). Since the oceanic inputs of nutrients do not appear to show an increase, the nutrient supply to these areas is governed by riverine input (Radach 1992), which continuously supply the Sourthern North Sea, that has the highest primary production (Skogen and Moll, 2005).

At the International Conferences on the Protection of the North Sea, commitments were made to reduce inputs of hazardous substances and nutrients into the North Sea by 50% between 1985 and 1995 and also to reduce by 70% inputs of dioxins, mercury, cadmium and lead.

Reduction of the inputs of phosphorus was achieved by improvement of urban waste water treatment plants and by the replacement of phosphorus by tensides as detergent in washing powders (Skogen *et al*, 2004). Limited reductions in the inputs of nitrogen were achieved through improvements in sewage treatment; in leaching of nitrate and in farm waste discharges. Little success has been reported in reducing inputs from diffuse sources, i.e. erosion and leaching of arable land (fertilisers), atmospheric deposition (nitrogen), runoff from roads (e.g. wear of tyres) and building materials(OSPAR 2000).

This situation can lead to problems such as toxic algal bloom (Proctor *et al*, 2003) and oxygen deficiency (Tett *et al* 2007), which cause an "undesirable disturbance".

The reduction of phosphorus input by 50% has been achieved by most countries, but no real reduction of nitrogen. The reduction of P has probably lead to a reduced primary production at some times in areas where phosphorus was the limiting nutrient (Skogen *et al*, 2004). Furthermore, the reduction of P has lead to an increase of imbalance between these two nutrients (Skogen *et al*, 2004), which can be the cause of the dominance of *Phaeocystis* (that is sustained by nitrogen excess) in the Southern bight of the North Sea (Lacroix *et al*, 2007).

2. Model Description

MOHID Water is a numerical model included in the MOHID Modelling System (Braunschweig *et al*, 2004a, Braunschweig *et al*, 2004b). The numerical algorithm is based on the concept of finite volume, where the equations are applied macroscopically at each control volume (each cell in the grid), using divergent flux, that assures the conservation in the transport of properties. With the hydrodynamic model solving the 3D incompressible primitive equations (Martins *et al*., 2001), MOHID Water is prepared to simulate properties such as temperature, salinity, cohesive sediments, phytoplankton, zooplankton, nutrients, and metals, in the marine environment.

For this study, a specific MOHID module named Water Quality was used to model the primary production in the North Sea. Fig. 1 shows the relations of the properties and modelled species.

The model considers 18 properties, including nutrients and organic matter (nitrogen, phosphorus and silica biogeochemical cycles), oxygen and organisms. It enables the user to choose between the simulation of one group of phytoplankton or two groups – flagellates and diatoms. The same type of option is made for secondary producers: one generic group of zooplankton or two groups – microzooplankton and mesozooplankton. The model is also able to simulate heterotrophic bacteria in the water column.

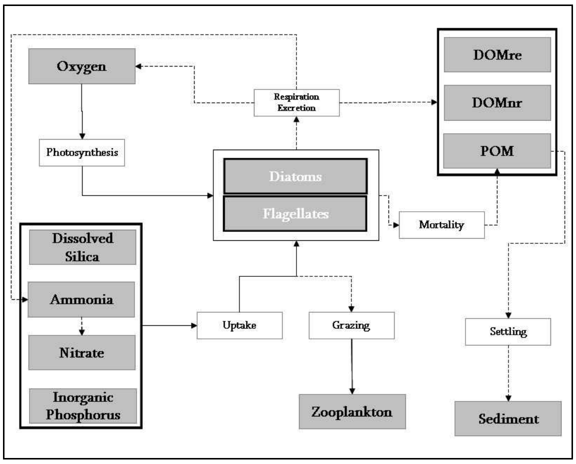

Fig. 1: MOHID Water Quality Module

The model Water Quality is adapted from EPA (1985) and belongs to the category of ecosystem simulations models i.e. sets of conservation equations describing as adequately as possible the working and the interrelationships of real ecosystem components. The pelagic and benthic biogeochemical processes are implemented in the form of sink and sources terms of the transport model (0D). The benthic ecological processes include mineralization of organic matter and oxygen depletion.

In this study, just one group of primary producers and one of secondary producers was chosen: phytoplankton (flagellates) and zooplankton (corresponding to mesozooplankton). Since the as the diatoms were not included, the silica cycle was left out of the model.

MOHID Model has been applied to several water systems, such as, Tagus estuary, Portugal (Portela, 1996; Pina 2001; Braunschweig *et al*., 2003; INAG/Maretec, 2003; Fernandes, L., 2005; Saraiva *et al*., 2007); Guadiana estuary , Portugal (Cunha *et al*., 2000); Douro, Portugal (Pina *et al*., 2003); Westerschelde estuary, The Netherlands (Cancino and Neves, 1999); Gironde estuary, France (Cancino and Neves, 1999); Ria de Aveiro coastal lagoon (Leitão, 2003; Trancoso *et al*, 2005); Coastal systems, such as Estoril Coast (Fernandes, R. *et al*, 2005) and Ría de Pontevedra (Villarreal *et al*., 2002); Ocean: Algarve coastal circulation (Leitão, 2007); Mediterranean outflow (Riflet, 2007); Portuguese coastal current (Coelho, 2002); Slope current along the European Atlantic shelf break(Neves *et al*., 1998); Operational modelling of the Atlantic (Riftlet, 2007); Reservoirs: Roxo, Monte Novo and Alqueva reservoirs (Braunschweig, 2001);

Further detailed descriptions of the structure can be found in Annex II, Leitão(2003), Braunschweig(2004a) or http://www.mohid.com.

3. Model Setup

The implementation consists of a 2D hydrodynamical model that encompasses the whole North Sea and a nested 3D ecological (and hydrodynamical, for that purpose) model covering the English Channel and the Southern bight. Fig. 2 illustrates the coupling between the models.

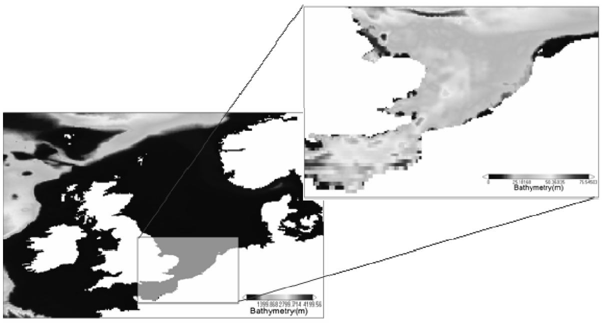

Fig. 2: Coupling between the 2D hydrodynamical and 3D ecological model

Both models have the same irregular bathymetry, which was provided by CEFAS from different sources available. It has a resolution ranging from 0.04º (~4km) at nested model domain, to 0.1º (~11km) at the de boundaries. The domain was chosen to include some of the OSPAR problem areas (Mills *et al*, 2007).

3.1. 2D Model

The 2D hydrodynamical model grid has 436 by 250 cells.

It is forced with wind from ERA 40 dataset which is a 2.5º resolution, four times daily surface dataset. Tidal forcing is made by FES2004 global solution (Lyard *et al*, 2006) that inputs 11 tidal harmonics at the model's boundaries, including the Baltic Sea. 152 river discharges were setup, with daily flow means.

3.2. 3D Model

The 3D ecological model has a 196x106 grid cells. Its depth varies from the shallow 5m in the Wadden Sea to about 75m in the northern part, south of the Dogger Bank.

For the Z coordinate, there are 10 Cartesian layers (fixed along the bathymetry) with different thicknesses (5m to 10m).

The meteorology data (air temperature, wind velocity, cloud cover, relative humidity) for the model application was retrieved from the ECMWF ERA-40 reanalysis dataset. The Solar Radiation data was retrieved from NCEP/NCAR 40-year reanalysis (Kalnay, 1996).

The river discharges data used is the same as the 2D model with the addition of riverine nutrient data. In this case, there are 29 river discharges with daily flow and nutrients. For some properties which were not in the discharges' dataset, a monthly reference was used, based on the Wissenkerke station. Furthermore, a table of correspondence (based on Tchobanoglous, 2003) between the available nutrients and the full set of nutrients used by the model is used. The main river discharges are configured in such a way that it is discharged into a channel before entering the coastal area.

The initial condition is the property dataset field at the model start-up time.

The sea surface temperature field was retrieved from the OISSTv2 (Reynolds *et al*, 2002) dataset. For the salinity, the data was retrieved from the Levitus World Ocean Atlas 1994. The nutrient data input was retrieved from the World Ocean Atlas 2005. The nutrients that are not included in the World Ocean Atlas dataset and are used by the model were obtained by a table of correspondence.

4. Results & Discussion

The results are shown according to the model setup: first for the 2D hydrodynamical model, then for the nested 3D ecological model.

4.1. 2D Model

Circulation

To better understand the transport processes inside the North Sea, the model is able to compute the residual circulation. We present the residual specific flux (m2/s) and the residual velocity (m/s).

Fig. 3 shows the residual flux at the area of interest of the North Sea. In the Skagerrak region, where the depths reach over 500m, the water flows in the direction east-west near the coast, but it flows in the opposite direction some 50km southerly. In the northern boundary, the residual flux is much higher than in the central-southern part of the North Sea. Also, in the Irish seas, as picture in the previous point, the residual flux is much higher than in the rest of the North Sea.

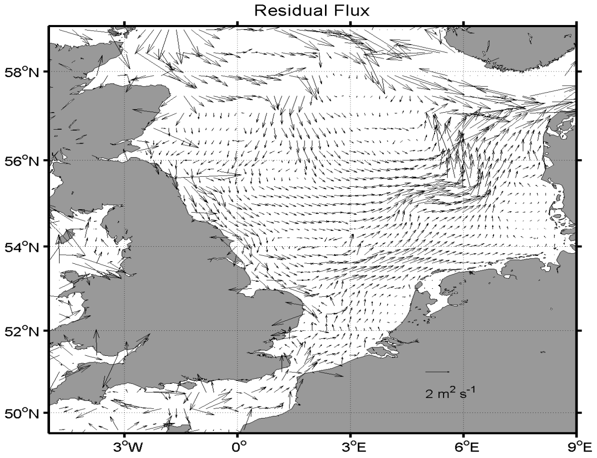

Fig. 3: Residual flux in the North Sea

Analysing the residual circulation, it is possible to deduce that the circulation in the North Sea has a counter clockwise direction. The water enters the shelf in the northern boarder, and circulates southerly, from the UK to the Netherlands, Germany and Denmark. Then it leaves the shelf on the Norwegian trench. Moreover, the water flux passing through the Straight of Dover is significant, although the tidal influence of the English Channel in the North Sea is small.

Harmonic Analysis

The harmonic analysis is an important part of model validation, as it can say much about the hydrodynamical precision of the model.

For the comparison of the model results with measured sea levels, an analysis is made with data from several tidal gauges from around the North Sea (Fig. 4). The data was retrieved from the XTIDE database (XTIDE, 2004), using the interface from T_TIDE (Pawlowicz, 2002).

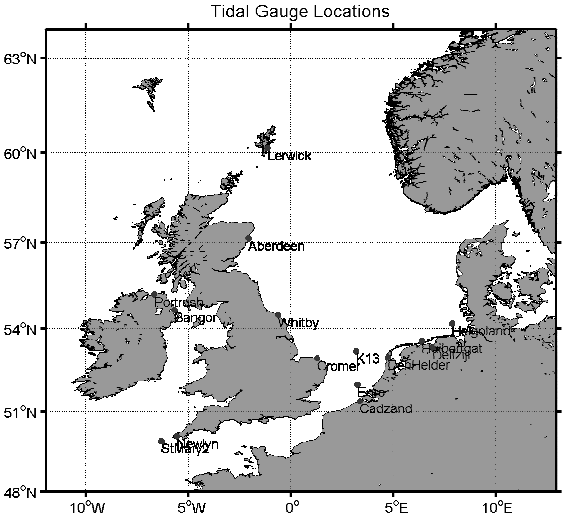

Fig. 4: Map of the tidal gauges analysed

In order to compare the model's result with the XTIDE database, which has only tidal data, one has to remove the non-tidal interactions from the model's timeseries to be able to compare solely the tide. This procedure is done by performing a harmonic analysis on the model's timeseries, and then reconstruct it based on the resulting harmonic components.

From the resulting two timeseries, a statistic analysis was made using several descriptors. The descriptors are based on Chambel-Leitão (2007) from Evans (2003).

The following figure (Fig. 5) shows the mean and standard deviation (error bars) of the descriptors, for all 15 tidal gauges analysed (map from Fig. 4).

The model generally agrees with the observations. It presents a good correlation coefficient (90-99%), indicating that the timing of the tides are correct (Fig. 5). From the results, it is possible to conclude that the accuracy of the model's timeseries decreases when a particular tidal gauge is further away from the tidal forcing on the Atlantic boundaries.

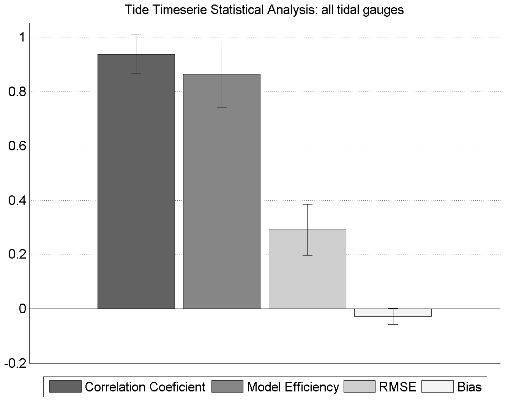

Fig. 5: Model vs XTIDE timeseries statistical analysis for all locations [adim], except for Bias[m] (error bars are standard deviation)

A comparison between the model's harmonic components and the XTIDE database's is done, giving out 8 main harmonic components (based on the model's amplitude).

The following figure (Fig. 6) shows the harmonic analysis for the Euro Platform tidal gauge. Taking into account the error (error bars), the differences between the model and the XTIDE database are quite satisfactory for most tidal gauges. From the results it is possible to conclude that there are some phase differences on the tidal gauges near the Dutch and German coasts, which can explain the inferior performance of these gauges. The bathymetry resolution can be blamed for these discrepancies, as later discussed.

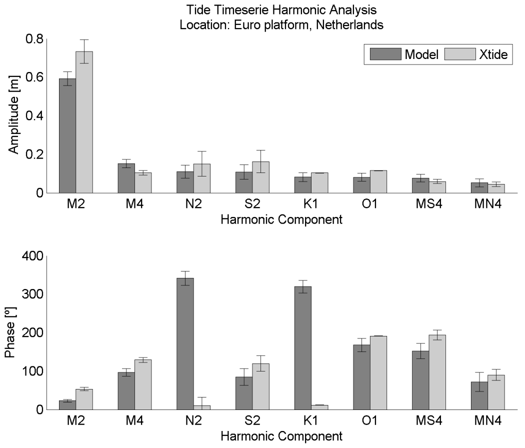

Fig. 6: Euro platform tidal gauge harmonic analysis

A wider outlook of the whole North Sea can be obtained if the harmonic components for each cell in the model grid are computed. This outputs two maps, one for the amplitude and one for the phase, for each harmonic component, for the entire grid.

For the M2 harmonic component, Fig. 7 shows the amplitude and Fig. 8 shows the phase. From Fig. 8 it is possible to perceive the two amphidromic points: one halfway between England and the Netherlands and the other, just north from the Netherlands, west of Denmark.

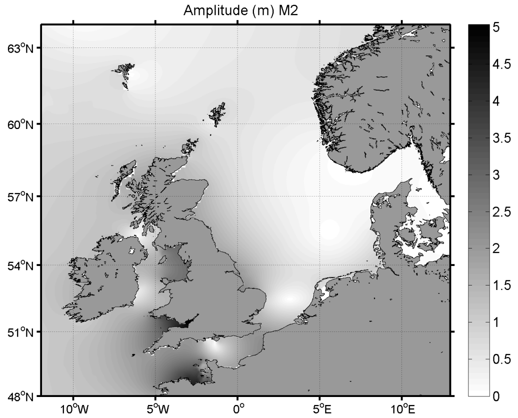

Fig. 7: M2 tidal harmonic component: amplitude (metres)

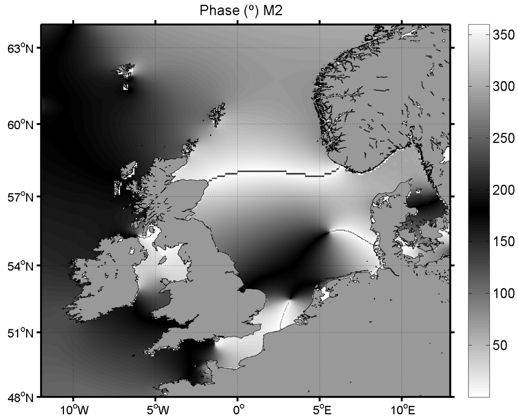

Fig. 8: M2 tidal harmonic component: phase (degrees)

Comparing the MOHID model's results with other published materials, for example Davies(1986), Helleiner(1997) and Anderson(2006), we can observe that there is a visual correspondence in amplitude and phase for a variety of components(for e.g.M2 and M4). In addiction, the position of the amphidromic points is correct.

In order to check if the model is not generating fake tides, the model was compared to the forcing dataset, which is from FES2004. This comparison shows that the model is correctly simulating the tide along the domain with the forcing based on the boundary conditions. However, there are some differences, mainly in shallow water areas, where the harmonic components interact with the bottom and generate non-linear harmonic components. On such locations (Bretagne/Normandy and in Wales) the model M2 component has distinctively different shapes. Here, the tidal amplitude ranges from -6 to +6m in spring tide. For that reason, the bathymetry used in the simulation can have significant errors (T. Letellier, 2004) because it is difficult to accurately determine the depths without having tidal influence in the measurements. Thus, there are significant differences between the model and the FES2004 solution for the M2 tidal component.

Residence Time

Residence time is an important indicator for understanding the study region. This is particularly important in the case of algal blooms. Regions which have very short residence times are expected to have much lower algal blooms than regions with higher residence times. In this case, the problematic region is the UK/Netherlands/Belgium region (Mills *et al*, 2007) which will be specifically studied in the 3D model.

The residence time is defined as the time required by water to leave a region and is computed using lagrangean tracers, which are used to label the water and to monitor its location and movements. The lagrangean module in MOHID is used to compute the tracers.

Different regions inside the domain are identified by boxes, which are uniformly filled with lagrangean tracers. 10 boxes were considered, each one filled with a variable number of particles, each one with fixed volume.

From the results it is possible to conclude that, after 1 year, the particles belonging to French, Southern English, Belgium and Dutch boxes are all spread over the Netherlands, German and Danish coasts. The particles that were inside the English Channel have travelled westerly around the UK to the Irish Sea. The outflow of particles occurs northerly along the Norwegian coast.

The evolution of the fraction of the tracers inside the domain (volume of all tracers inside the domain divided by the total volume of water in the domain in the same instant) is shown in Fig. 9. After 1 year of simulation, about 75% of the initial volume remains inside the domain, which is a relatively long residence time.

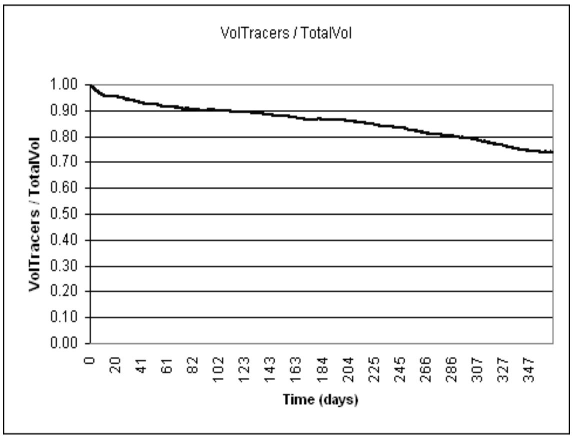

Fig. 9: Evolution of the ratio between the volume of lagrangean tracers inside the boxes and the total volume as a function of the time.

4.2. 3D Model

In order to evaluate if the model is correctly simulating the different variables, a comparison with field data has been made. The data was retrieved from the Dutch monitoring system in the North Sea (Rijkswaterstaat). Moreover, an analysis of satellite imagery spatial was done.

As for temperature, the model reproduces the evolution correctly over the year. Since, many important physical and biological processes are linked to the temperature, the model has to simulate it accurately.

The differences of salinity on the plumes from the Rhine and Scheldt rivers between winter and summer due to the riverine flows variability are particularly interesting.

The model's domain area is only thermal stratified during short periods of time in the summer, at the expected sites, on the northern boundary (Pingree, 1978; Pohlmann, 1996; van Haren, 2004; Beusekom, 2007).

Nutrients

The model overestimates nutrients (shown in Fig. 10. This can be explained by the high values found on the boundary conditions that propagate to the inner domain and due to an underestimation of primary production (presented ahead). Since the model's riverine nutrient inputs are assumed to be correct (apart from Lake Ijssel), the WOA05 dataset used to ensure nutrient boundary conditions has higher values. These boundary condition imposed had to be interpolated to the model grid. Given that the dataset's grid has a resolution of 1º, it averages the coastal levels (that are typically higher due to discharges) with the offshore levels (lower), giving higher values.

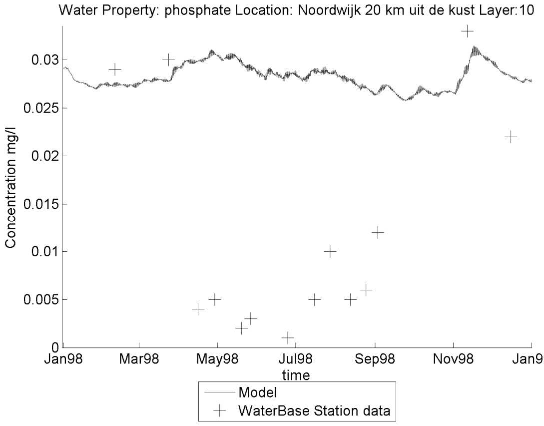

Fig. 10: Inorganic phosphorus, model vs field data at station Noordwijk 20

The oxygen levels are important because it is considered an effect of eutrophication. The model's result in this matter is quite good, matching the evolution of station data.

Phytoplankton

The model can moderately represent the evolution of phytoplankton, including the spring bloom. The model's bloom occurs around June, although the stations data seem to point it around May. Station Noordwijk 20 (Fig. 11), which has many records in the summer period, shows that the model underestimates the chlorophyll, however, for the satellite does not agree with this data.

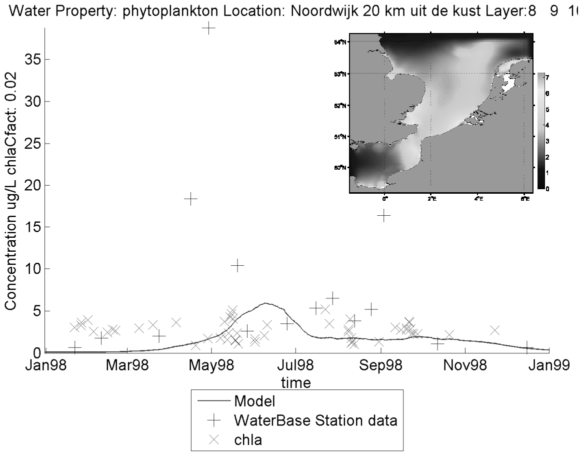

Fig. 11: phytoplankton, model vs field data at stations at Noordwijk 20 (continuous line is model, plus sign is station, cross is satellite). Synoptic view at July 1st 1998 in subset.

Phytoplankton comparison with remote sensing data was made using data from the

SeaWiFS sensor. The following figure shows the differences between the model and satellite chlorophyll concentration at a specific time.

The resulting analysis can only be quality-assessed, since the choice of a chlorophyll-carbon factor is a very influential in these results: they can have 100% variability. Furthermore, the data availability is not good all year round: there are clouds or data errors in almost all images, appearing as white patches.

The resulting analysis shows a big bloom in the centre of the domain that can be seen around 15th May (Fig. 12) and quickly fades away by 18th May. The model could not reproduce this bloom at the centre of the domain, but it produces a coastal bloom days after.

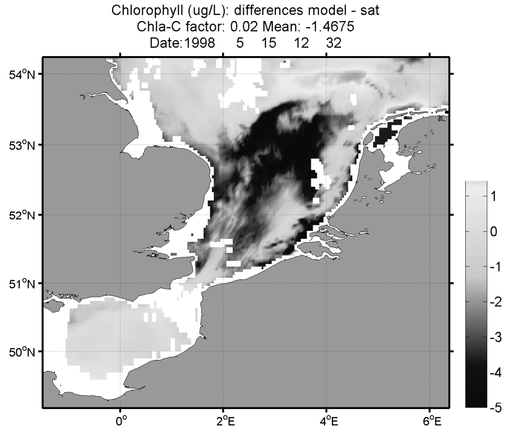

Fig. 12: phytoplankton differences (model – satellite) in ug chla/l, day 134 – 15 May 1998

By checking the original satellite data, we can conclude that the blooms settle in very quickly and rapidly fade away

Nutrient fluxes

A calculation of fluxes between boxes and, when possible, the riverine input aggregated by box was made. These results are hard to compare with reality, because there isn't much data available and, if we employ models, each model has a different way to define the boxes, giving out unrelated results.

From the results (Fig. 13), it is possible to deduce that the water fluxes agree with the residual flux and velocity of the domain, following a counter clockwise pattern in the northern part (from the UK to the Netherlands) and a relatively intense flow from the channel going northerly. For most nutrients, the riverine input is a significant contribution.

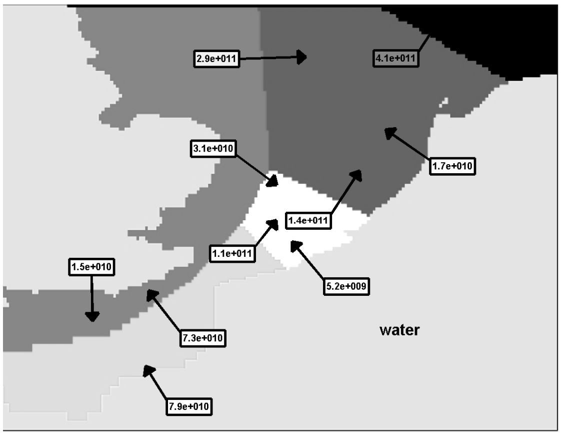

Fig. 13: Annual water fluxes between boxes, including river inputs in [m^3/year]

Limitation of Phytoplankton Growth

The model can output the effect of several properties on the limitation of phytoplankton growth. It outputs the results as an index, ranging from 0 when there is a strong limitation, to 1(one) when there is no limitation.

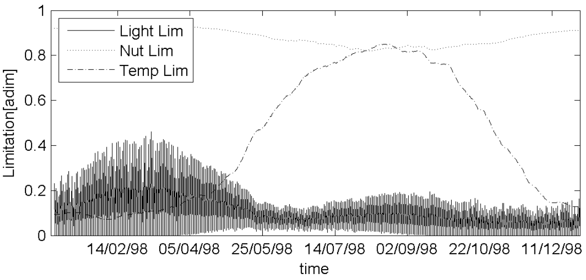

Fig. 14: Phytoplankton Limitation factor

Evaluating the figure above, we can conclude that the phytoplankton is light limited all year round, with a particular temperature limitation during winter.

The light limitation can be caused by reduced solar radiation (during winter), suspended particulate matter (SPM) and the phytoplankton itself causing "shadowing" to the lower levels. Since the light extinction scheme is based on Parsons (1984) for the open ocean, which only considers the effect of phytoplankton self-shadowing, SPM has no influence on phytoplankton growth. Therefore, during summer, the light limitation is due phytoplankton itself, since the solar radiation peak is in this period. This result can also be influenced by the high nutrient concentrations, causing the model to underestimate the nutrient limitation (it is almost irrelevant by analysing Fig. 14).

5. Conclusion

The MOHID modelling system has the capability of coupling a hydrodynamical model with an ecological model enabling a flexible and comprehensive analysis of the model's result, either the ecological or hydrodynamical features. It has been validated in many other applications, so the North Sea application was somewhat a test to its integrity.

The hydrodynamical model performs agreeably with known findings. The general circulation of the wider North Sea is presented in the form of lagrangean tracers, residual circulation and residence times. The tidal harmonic analysis has been made and compared with existing data and it shows that the model performs well, as expected.

As for the ecological model, although the model performs moderately, some difficulties arise from specific options taken during the setup phase. A general comparison of the timeseries and spatial analysis has been made with station data and satellite imagery.

As for the timeseries, the nutrients present a higher level than the field data, but it presents reasonable results for phytoplankton, although it does not simulate the magnitude correctly. The higher nutrients are explained by the use of a climatology that has no sufficient spatial resolution and the underestimation of primary production. Oxygen deficiency is one of the symptoms of eutrophication and regarding this property, the station data fits the model's curve adequately. Satellite imagery is not eligible for a thorough quantitative analysis due to its characteristics, but it reveals that the model is capable of simulating phytoplankton on a wider scale, not specifically in some areas.

Furthermore, a presentation of transboundary nutrient transport has been made, using boxes defining countries maritime areas and that include riverine inputs. Putting these results at the level of the residual circulation, one can conclude that there is a transport of nutrients from the UK to the Netherlands and from the French and Belgium boxes to the North, following the circulation pattern.

One of the most challenging tasks is to know which limiting factor on phytoplankton growth. From the model's result, one can conclude that the system is mainly light limited during the growth phase (temperature limited during the winter). Having in mind that the OSPAR strategy requires a member state to reduce 50% of nutrient discharges, this reduction will probably not have an effect on the system because it is light limited(and not nutrient limited as expected). However, the light limitation has to be carefully analysed: the model does not include realistic SPM discharges, neither a field to which it is forced upon, and its light extinction scheme does not include SPM. Nevertheless, other model's results clearly indicated that SPM and therefore light limitation is a question to be seriously addressed. If this conclusion is to be verified, it could have an important effect on water management policies (for e.g. reduction strategies) that would not have an effect on the system.

Moreover, the model's simple trophic level could be more complex, including diatoms, which are an important part of the biogeochemical cycle of the North Sea.

On the many difficulties encountered one has to mention the availability of data to which compare the model's results: at some times, the data does not have enough temporal resolution, impeding the correct validation of results. Furthermore, to use datasets, these have to be carefully processed since they can have particular characteristics that can put the model's results in question, such as the solar radiation problem that was found while developing of the model's setup.

Although a model implementation is not ever finish, on the whole the objectives of the thesis were achieved: the study of a system that is exceptionally well known.

6. References

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