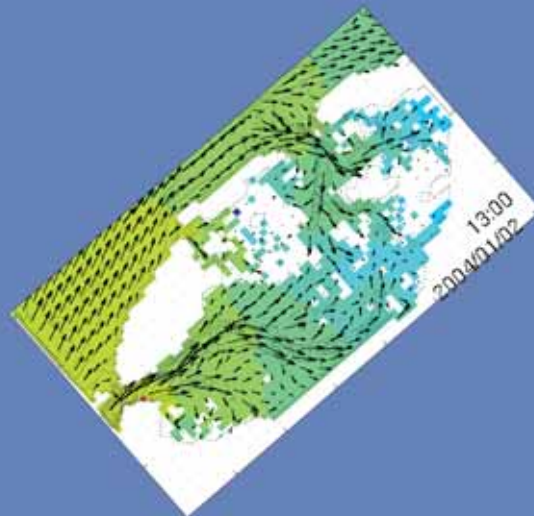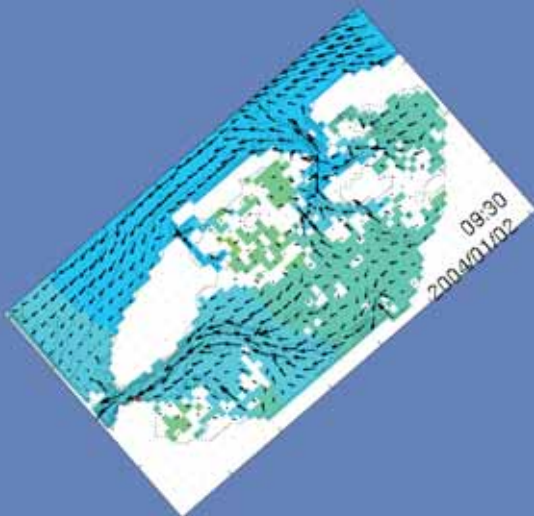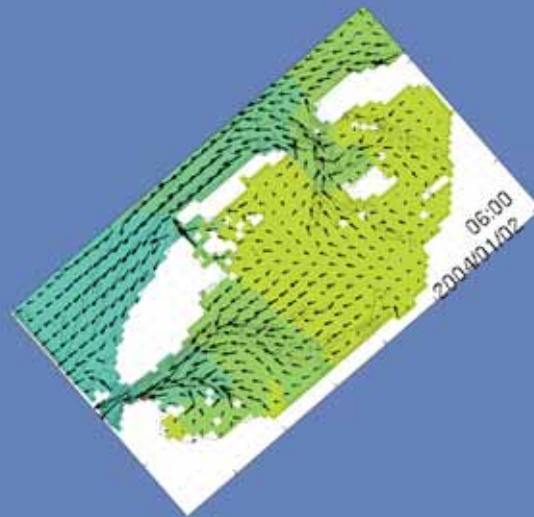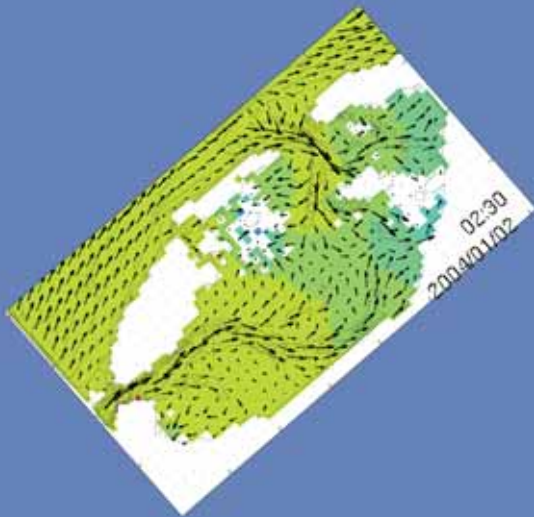# Setup of a 3D hydrodynamic model of the Dutch western Wadden Sea

Janine Nauw

Setup of a 3D hydrodynamic model of the Dutch western Wadden Sea

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Contents

Introduction

The Wadden Sea is a Natura 2000 and UNESCO world heritage area and the biggest nature reserve in the Netherlands. Protection of this heritage is necessary. However, during the last decades many changes have been observed in this area and the nearby coastal North Sea. These changes include drastic decrease of several benthic fauna, fish and bird species and appearance of some new species. Abiotic environmental changes have taken place; particularly nutrient inputs (especially phosphate) were decreased as a result of de-eutrophication measures. Climate change has also had an impact due to increasing water temperatures, atmospheric carbon dioxide and changing wind fields.

Interactions between nutrient and light availability and the amount and type of algae and the timing of algal blooms and shellfish larvae production as well as predation by birds, fish and crabs are highly non-linear interactions containing a suite of feed-back mechanisms which may be susceptible to multiple steady states. To unravel (part of) these interactions, we have coupled a 3D hydrodynamic model to a complex ecosystem model. In-situ observations within this area are present, but temporal and spatial variability are large. Coupled models that cover the relevant ecological processes are very much needed.

This report describes the step taking in setting up the fine-scale 3D hydrodynamic model for the western Dutch Wadden Sea. At the time the proposal was formulated, it was debated whether to use Delft-3D or the GETM-GOTM modeling framework. We chose the General Estuarine Transport Model (GETM, Burchard 2002) coupled to the General Ocean Turbulence Model (GOTM, Burchard 1999). GETM is a 3-dimensional circulation model and it used the 1-dimensional GOTM model, which simulates turbulent velocity structures in the vertical. In GETM special attention is given to flooding and drying, which is very important in the Dutch western Wadden Sea since tidal flats cover roughly 50 % of the area. This was the major reason for choosing GETM-GOTM instead of Delft-3D. Besides that, GETM-GOTM was already open-source at the start of the project, whereas Delft-3D still wasn't.

GOTM

The General Ocean Turbulence Model (GOTM) is a one-dimensional water column model. It is coupled to a suite of traditional as well as state-of-the-art parameterizations for the vertical turbulent mixing. GOTM provides a simple and well-documented tool for learning about the physics of vertical mixing processes, to compare results from different turbulence schemes, to integrate ones data into the simulation and to couple it to other modules and to a 3-D circulation model via a

purpose-built interface. In our case we started out with a simulation of the Rhine Region of Freshwater Influence (ROFI) using the GOTM model only and comparing that with in situ measurements to familiarize ourselves with the model.

Details of the data analysis and model experiments are described in Nauw and van der Vegt (2012). The paper focusses on hydrodynamics of the Rhine ROFI in its most northerly extent near IJmuiden. A bottom-mounted ADCP was deployed near IJmuiden and measured current profiles in east- north and upward direction for almost 6 months. Current velocity profiles in this area are dominated by variation on the M2 tidal frequency having a period of 12:25 hours. Here, tidal currents are not rectilinear, but form ellipses. The ellipticity, defined as the semi-major axis divided by the semi-major axis, is a measure of the effect bottom friction plays on the current. In homogeneous waters, ellipticity near the surface is small and tidal ellipses are almost rectilinear. In stratified waters, counter rotating ellipses are observed in the bottom and top layer. Our observations show that the largest difference in ellipticity between surface and bottom mostly occurred during neap tide, suggesting that the water column was stratified, leading to a cross-shore circulation. However, for 3 out of the 11 neap tides no ellipticity difference was observed and during 1 out of the 10 spring tides a strong ellipticity difference occurred. To understand the causes of these irregularities a model was set up with GOTM. Based on the depth-averaged currents the barotropic pressure gradient is determined. Using a simple advection equation the salinity profile was estimated at the measurement site and used as input for the model. We were able to simulate the overall characteristics of the observed flow patterns. Model results show a strong link between wind stress and a reduced stratification during low energetic neap tides. An increased fresh water discharge was the cause for the strong ellipticity difference during spring tide. The strong effect of wind speed and direction on the onset of stratification of the Rhine ROFI has never been shown before. Furthermore, the results show that during the 150 days of observations the plume always reached IJmuiden.

The data was first rotated over 72.8^0 to derive the alongshore and cross-shore velocity. Moreover, the data was interpolated to σ-coordinates, in which the total depth is divided by an equal amount of layers, leading to a layer thickness variations with the tidal elevation. A running mean least squares harmonic analysis was applied with a window length of 25 hours. Only the M2 tidal constituent was retrieved for each sigma level. The semi-major axis and the ellipticity were determined for the entire 150 day time series. Figure 1 shows a comparison between the data derived between day 275 and 285 and model results using different forcing conditions. The ellipticity showed several events with a large difference between the surface and near bottom value. Such a difference is usually an indication of the presence of stratification [Souza and Simpson, 1996]. In model simulations with only a constant horizontal cross-shore salinity gradient of

S_y=3.75·10^{-4} m^{-1} (second panel of Figure 1) an event with an ellipticity difference between surface and bottom is reproduced, but the negative values of the ellipticity at the surface are too large compared to observations (top panel). The period with large ellipticity differences started earlier and continued longer compared to the measurements. Moreover, the semi-major axis showed that the velocities throughout the entire spring-neap tidal cycle and at every sigma level were underestimated by the model. The model output indeed showed a relation between the ellipticity difference and a periodic (salinity) stratification with a maximum difference of ΔS_{max}=1.6 PSU. Imposing a realistic meteorological forcing (third row of panels in Figure 1) resulted in improved correspondence between modelled and observed semi-major axis. The ellipticity difference became much more comparable to those in the measurements, however the timing of the event was still wrong. In fact, the event seemed to split up into two different events. The periodic stratification became stronger, ΔS_{max}=2.2 PSU, and is still correlated with the ellipticity event(s). When the model was forced by the observed salinity and temperature gradients (bottom panel of Figure 1), the timing and duration of the ellipticity event corresponded much better to the measured ones, although the modeled values of the ellipticity are a little too small, which suggests that the horizontal gradients are slightly different from the ones found in Figure 1. The periodic salinity stratification still only occurs during the ellipticity event and was slightly larger, ΔS_{max}=2.4 PSU. Now also a periodic pattern was observed before and after the event, but with salinity values being constant throughout the entire water column. Overall, the model was quite sensitive to the forcing and best model-data agreement was obtained when the model had the most realistic forcing. The results indicate that the GOTM model is well capable of reproducing the hydrodynamics of the Rhine ROFI as observed just North of IJmuiden.
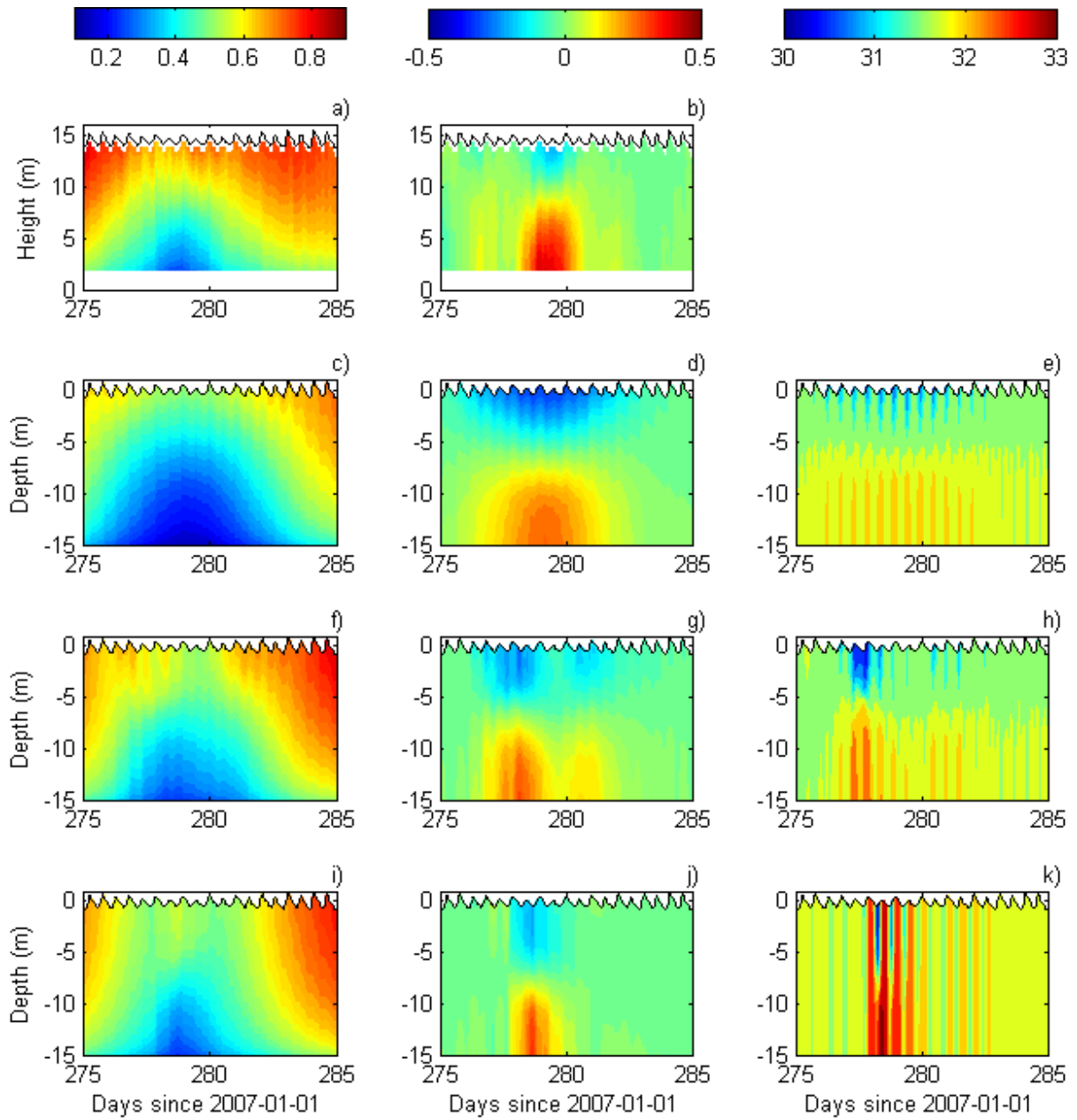
Figure 1: Left: Semi major axis (m/s), middle: ellipticity and right: salinity as a function of depth and time from the measurements (top panel) and the model simulations with constant $S_y=3.75 \cdot 10^{-4}$ m^{-1} (second panel), with realistic wind stress forcing (third panel) and with horizontal gradients from Figure 3 (bottom panel).

Additional experiments have been performed with the model and are described in detail in the above mentioned paper.

GETM

The General Estuarine Transport Model (GETM) is a 3D numerical hydrodynamical model including flooding/drying and is interfaced to the General Ocean Turbulence Model (GOTM) to incorporate a choice for a suite of turbulence closures. GETM is still being developed today, incorporating state-of-the-art numerical methods and adding modules to be able to describe more-and-more complex dynamics.

A complex 3D hydrodynamic setup of the Dutch Western Wadden Sea was created and tested. This first setup described a large part of the North Sea and the Dutch Western Wadden Sea. However, it was known beforehand that we would be unable to couple this one to the complex ecosystem model. Adding some 80 variables to the 8 ones describing the hydrodynamics per gridbox would be to cost-inefficient. Several intermediate steps were planned to arrive at a model that both gave realistic results in terms of hydrodynamics, but would still be cost-efficient in terms of computer time. After this, we started out with a very small basin representing the Marsdiep basin with a closed inlet in which the wind stress was the only forcing. After a successful coupling to the complex ecosystem model and a successful run of the simulation, the inlet was opened by applying boundary conditions to the three points in the inlet forming the boundary. Boundary conditions were derived from a larger model of the entire North Sea. This step also turned out to be successful and let to the next and final step. The Marsdiep has a strong connection to the Vlie basin and inlet. A significant amount of water is exchanged in the channels connecting the basins and over the tidal watershed at high water. In the Marsdiep setup the tidal watershed acted as fixed non-permeable boundary. As already mentioned before, the large setup including a large part of the North Sea should be to computational inefficient when coupled to the complex ecosystem model. From a biological point of view, the North Sea is nothing more than a large container of water and substances; any changes in the much smaller and shallower Wadden Sea in terms of population dynamics or concentrations will have no effect on the North Sea. However, as seen from a physics point of view, the strong depth changes between the Wadden Sea and the North Sea can introduce quite complicated non-linear behavior, which will have an effect on the exchange of water (including dissolved and non-dissolved substances). Therefore an intermediate setup was made in which the Dutch western Wadden Sea was rotated at an angle in such a way that the enclosure dike formed a straight horizontal bottom boundary.

In general, the startup phase of a GETM model run consists of three steps, called bases. In any setup the simulation starts at rest and the system is evolved towards climatology in base 1. Then in the second base, 2D and 3D boundary conditions are added to the open boundaries and a tidal wave starts to move through the simulated area. In base 3, the remaining forcings are added such as meteorology

(wind stress and evaporation minus precipitation) and freshwater inflow into the domain. Below we will describe in detail the procedure followed to run the setups within each base.

BASE 1

In Base 1 all variables should get a small value away from zero. It is not possible to just simply put 2D and 3D boundary conditions on the open boundaries, because that would certainly crash the model. Therefore, in base 1 the run the model towards climatology. For this purpose two input files are essential, being a file containing the bathymetry, H, and one with climatological values for salinity and temperature, S and T.

Bathymetry

Bathymetric data from Emodnet (http://www.emodnet-hydrography.eu/) was downloaded for the North Sea and Rijkswaterstaat vaklodingen (depth soundings) were used for the Wadden Sea. The former has a resolution of 1km and the latter of 50 meters and thus both need to be regridded in some way. The bathymetry at 50 m resolution is shown in Figure 3 and is way too fine for the purposes intended in this study. A method is developed to derive the bathymetry on subsequently coarser resolution being an integer factor larger than the original. Examples are given of the results for a factor of 2 (Figure 4), 4 (Figure 5) and 6 (Figure 6), but with this method also bathymetries on 150x150 (factor 3) and 250x250 (factor 5) easily determined.

At first instance, the following method is used to derive the depth at the new grid. For instance, with a factor two the original grid is subdivided in 2x2 gridpoints. The depth is taken to be the average between each of the four gridpoints and projected to the central point. This is indicated in the schematic representation in Figure 2 (left panel); the similar averaging for a 3x3 gridpoint case is shown in the right hand panel. This provides a depth estimate at locations in the original bathymetry that also contained water depths. This method is different from subsampling, in which every second, third (or whatever integer number) is taken to be the new coarser bathymetry, as this leads to very steep gradients in the bathymetry, that can cause severe numerical problems.

"Land"-points (part of the original 50x50 m gridcell is land and thus never submerged) introduce another challenge. Two options can occur with different outcome:

1. If less than half of the points of the original grid that are to be averaged are "water" points, the new grid point is assumed to be a land point.
2. If more than half of the points of the original grid (or exactly 50 %) are "water" points, the depth is the average over all water points in the new grid.

Each of the coarser grids is being deduced from the original data at 50x50 m. Several examples show that the contours of the land remain the same and that the resulting bathymetry is smooth and agrees well with the original.
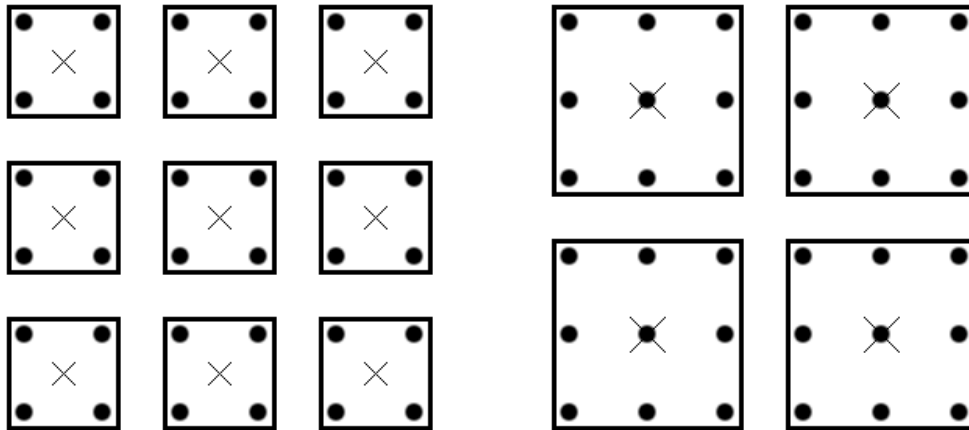

Figure 2: Schematic representation of the method to regrid the bathymetry on a coarser grid. The black dots indicate the original grid and the crosses the new coarser grid. The squares indicate the data that was averaged and projected on the central point.
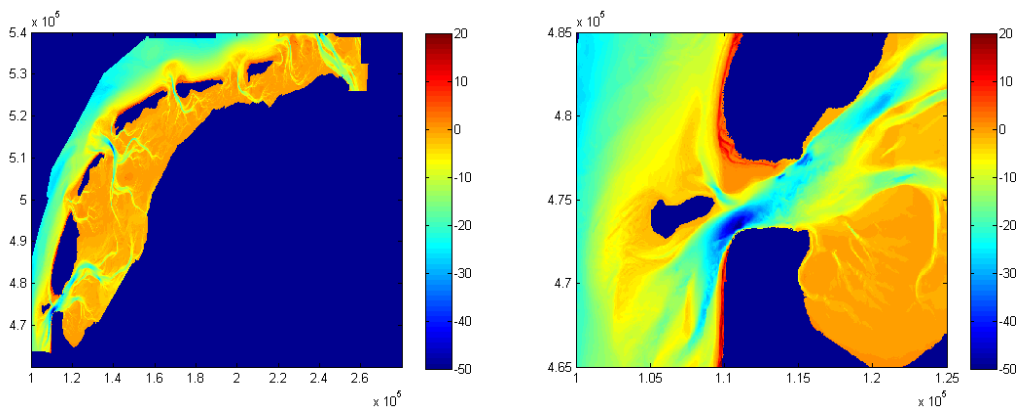

Figure 3: Original bathymetry on a 50x50 m grid. Left all Rijkswaterstaat vaklodingen data and right: zoomed in on the Marsdiep inlet.
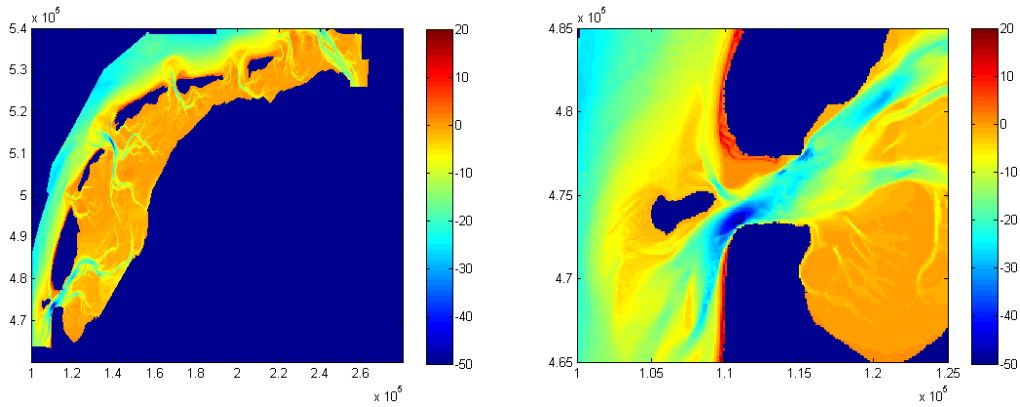
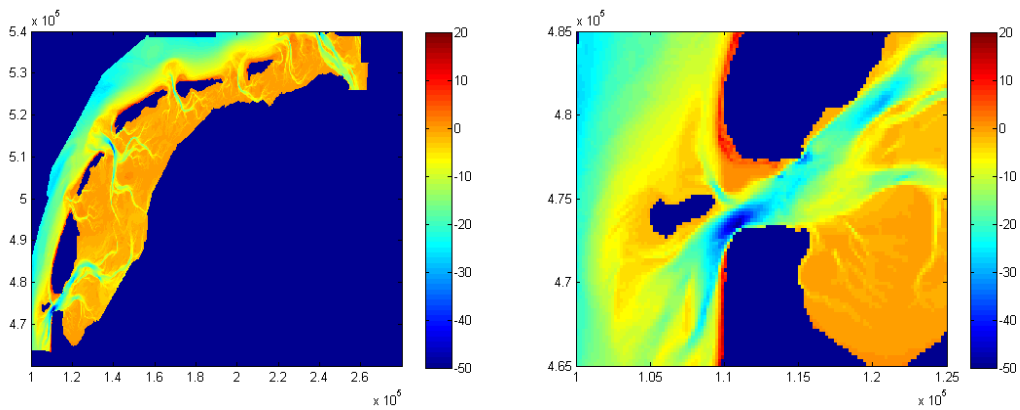Figure 4: Bathymetry on a 100x100m grid derived from the original data.

Figure 5: Bathymetry on a 200x200m grid derived from the original data.
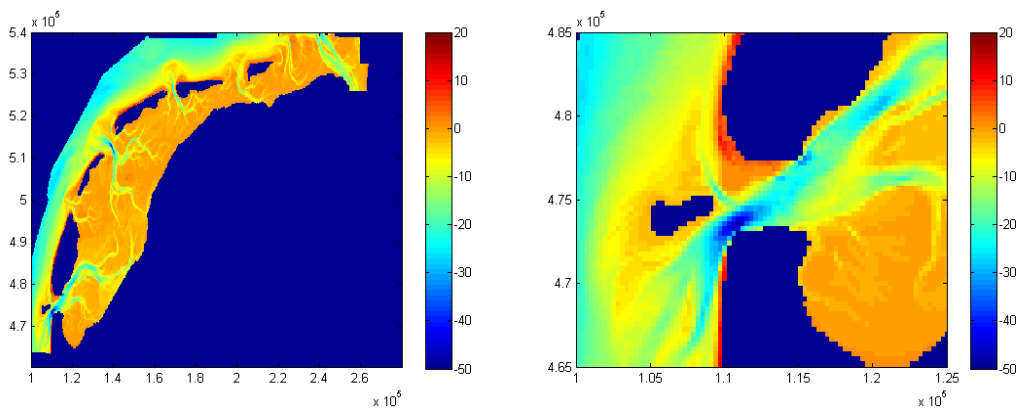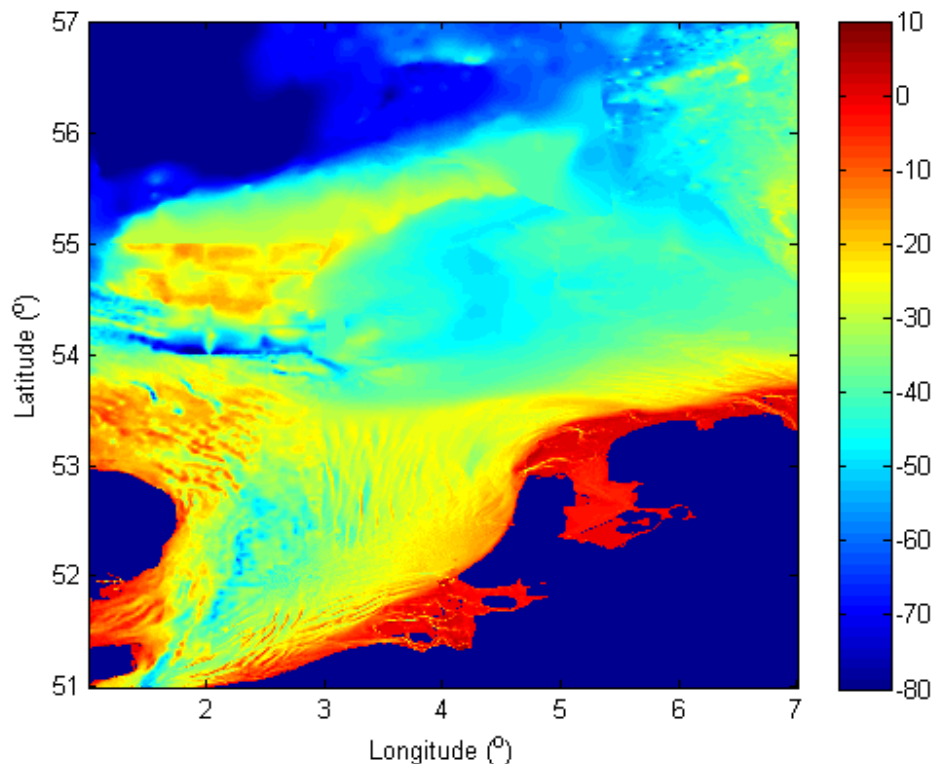

Figure 6: Bathymetry on a 300x300 m grid derived from the original data.

For the area in the Northwestern corner of the domain, which is not sampled in the program by Rijkswaterstaat, we used the EMODNET data (http://www.emodnet-hydrography.eu/) for the larger part of the North Sea as shown in Figure 7.

Figure 7: Bathymetry of the southern part of the North Sea derived from EMODNET at 0.25'x0.25' resolution.

Clearly, the data doesn't contain the islands in the Wadden Sea, nor in the southern part of the Netherlands (the province of Zeeland). Some overlap occurs between this data set and the vaklodingen data. However, the depth estimates within the overlapping part do not match up. To compensate for that the median difference between the EMODnet data and the vaklodingen in the overlapping area is subtracted from the EMODnet data and is 1.56 meters. Then the parts that are not covered by the vaklodingen are filled with EMODnet data. The bathymetry is written in NetCDF format, such that the model is able to read the values.

Climatology (T, S)

The climatology for the North Sea and Baltic Sea is used from Janssen (F. Janssen, C. Schrum and J.O. Backhaus, 1999). They are obtained from http://mersea.dmi.dk/thredds/CatalogFiles/CLIMATOLOGY.html?dataset=Baltic%20Climatology:%20monthly%20means%20of%20salinity%20and%20temperature%20at%2018%20depth%20levels.

The climatology in interpolated to the same horizontal grid as the bathymetry and written in NetCDF format, such that the model is able to incorporate it. We start the

model run on the first of September 2003 and run it for a month. The model is run towards climatology.

BASE 2

In base 2, 2D and 3D boundary conditions are applied to the open boundaries. 2D boundary conditions involve imposing the sea level height, h, to the locations on the boundary; this causes the tidal wave to enter the domain. 3D boundary conditions consist primarily of temperature, T, and Salinity, S. These variables have significant impact on the dynamics locally in the Wadden Sea and are essential to set up an estuarine like circulation. Both the 2D and 3D boundary conditions are multiplied by a factor increasing from 0 to 1 over a 10000 time steps leading to their final realistic value after a few days of simulated October 2003.

2D and 3D boundary conditions for hydrodynamics (h, T, S)

The boundary conditions are derived from model output using the same model for the entire North Sea at a resolution of 10' in longitude and 6' in latitude. The bathymetry locally in the Wadden Sea is depicted in Figure 8.
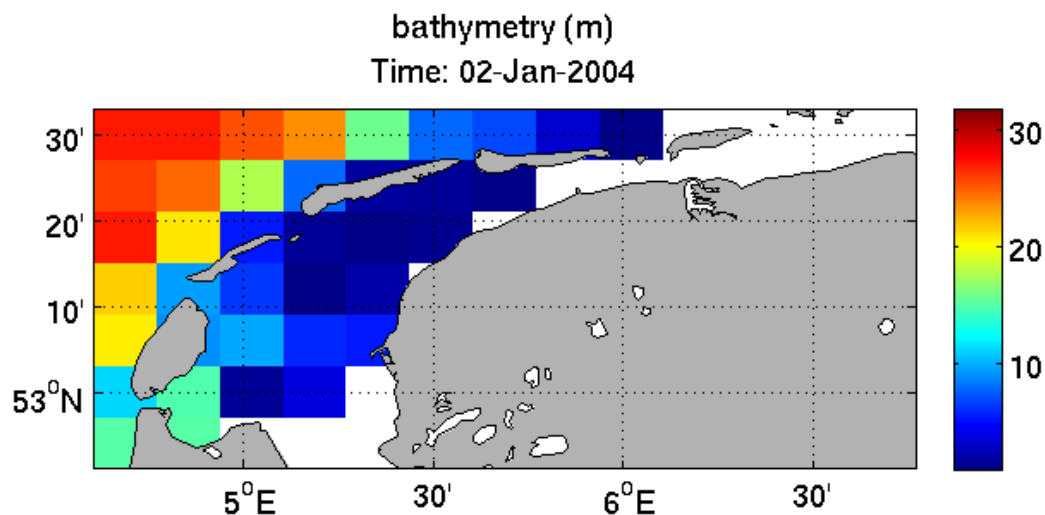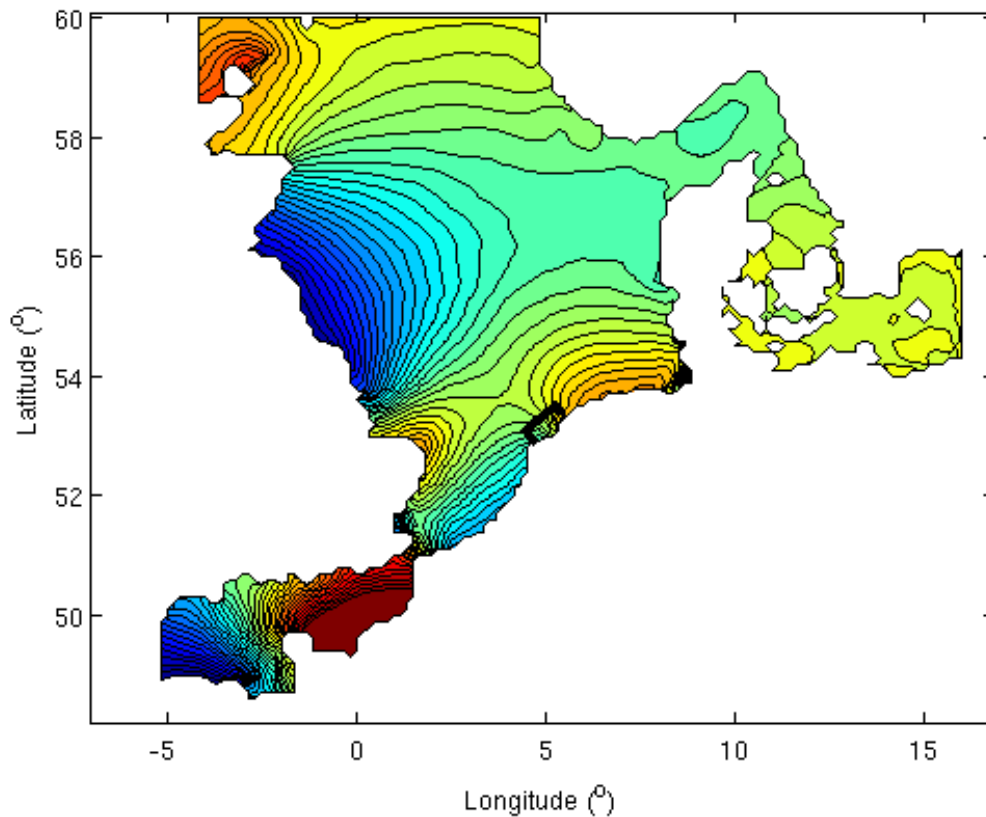

Figure 8: Bathymetry of the large scale North Sea model zoomed in on the Wadden Sea area. Even though the Dutch Wadden islands are depicted, they are actually not present in the model due to the coarse resolution.

Figure 9: Sea level elevation at some instance from the North Sea model and the location of the open boundary (black dots) for the final setup (Figure 16) is shown as an example.

The sea surface elevation, h, is interpolated to the locations of the boundary points using a bilinear interpolation. This is done for all North Sea model data from 2003-08-01 until 2004-12-31 for each month of data separately. The sea level elevations at the boundary points are saved in NetCDF files and afterwards merged into one single file.

A similar procedure is applied to obtain the 3D boundary conditions for salinity and temperature. The bathymetry file of the Wadden Sea model is used to obtain both the latitude and longitude of the boundary points (just as in the 2D case), but also the depth of the bathymetry, H.

Daily 3D data from the large scale North Sea model is read for each month separately, including local depth, H, and the sea level height, h, because the latter is needed to calculate the layer depths from the large scale North Sea model, which is in terrain following σ-coordinates. For each layer the temperature, T, and salinity, S, is horizontally interpolated as was done for sea level height, h, for the 2D case. In a next step, both variables are interpolated in the vertical to a regular grid between 0 and 40 meters with a grid-spacing of 5 m. Values in the near surface

(below bottom) part of the matrix is assumed to be equal to those in the topmost (lowermost) layer containing data; NaN in the boundary file will crash the model. For each month, a file is written in NetCDF format and in a final step the monthly 3D boundary files are merged into one single file.

BASE 3

In base 3, meteorology and fresh water river inflow is finally imposed in the modeled month of November 2003.

Meteorology

Meteorology is taken from the NCEP Climate Forecast System Reanalysis (CFSR). It contains information on precipitation, surface heatflux, sea level pressure, total cloud cover, and the wind velocity measured at 10 m above sea level. The resolution is 0.3125° in longitudinal direction and 0.3122° is latitudinal direction. The model itself performs the gridding of the data on the imposed grid.

River inflow from the sluices in the Enclosure dike

In the database of Rijkswaterstaat: www.waterbase.nl, one can find daily averages of the freshwater discharge at the sluices in the enclosure dike (Afsluitdijk). The total discharge of the previous day is summed and then averaged over 24 hours and put at 08:00 AM (local time). However, the sluices only discharge during several hours around low tide, when the water level in Lake IJssel is higher than in the adjacent Wadden Sea. Moreover, the optimal sea water level in Lake Ijssel is different for the summer and winter season. During summer the optimal level is 20 cm below NAP (Normaal Amsterdams Peil, or standard Dutch ordinance level) and in winter it is decreased to 40 cm below NAP.

We've put in a lot of effort to get information regarding the discharges at the sluices at Den Oever and Kornwerderzand. From Harry Oudevoshaar (Rijkswaterstaat) provided data for both sluices about the lowest low water per tide, the measured or mean level within lake Ijssel, the time when the sluice was opened and closed again in local winter time (=UTC+1) , the number of groups that were opened, which is maximally 3 for Den Oever and maximally 2 for Kornwerderzand. The amount of time the sluices were open is provided, the averaged discharge in m³/minute/group and the discharge per tide in 10^6 m³ is given. These data are combined with the 10-minute sea level measurements locally inside in lake Ijssel and outside in the Wadden Sea obtained from www.waterbase.nl.

The sluice gates are 12 m wide and each group consists of 5 gates. The depth of the sill beneath the sluices is 4.4 m below NAP. We use Bernouilli's equation to estimate the velocity through the gates:

$$v(t) = sign(h_1(t) - h_2(t))(\sqrt{2g|h_1(t) - h_2(t)|} \qquad (1)$$

In which v is the velocity, g is the gravitational acceleration and h_1 and h_2 are the water level in Lake IJssel and sea level height in the Wadden Sea, respectively. The absolute value is taken, since in some occasions the water level in the Wadden Sea is higher than in Lake Ijssel, indeed leading to an (unintentional) import of salt water into Lake Ijssel, sign($h_1(t)-h_2(t)$) is therefore incorporated to give a negative discharge.

The total discharge per tide, Q_{tide}, is simply derived by taking the integral over the width of the gates, B, times 5 (amount of gates per group), times the amount of groups that were opened, grp(t), times the sea level above the sill, $H+h_2(t)$, integrated over the time between opening and closing.

$$Q_{tide} = 5B \int_{t_{open}}^{t_{close}} v(t)\big(H + h_2(t)\big)grp(t)dt \qquad (2)$$

This is then linearly correlated with the discharge per tide given in the table leading to a discharge coefficient, μ, which is non-equal to one and different for both sluice complexes. It turns out that μ=1.09 for the complex at Den Oever and μ=1.02 for the complex at Kornwerderzand (Figure 10). The reasons for this are summed in a study on the design of the enclosure dike on the calibration of the discharges at the sluices (in Dutch, Vlag and Ytsma, 2001 and 2002). These studies suggest that it is related to the relatively small difference in level between Lake Ijssel and the Wadden Sea and interaction between the currents in the gates, density differences between Lake Ijssel and the Wadden Sea and measurement errors.
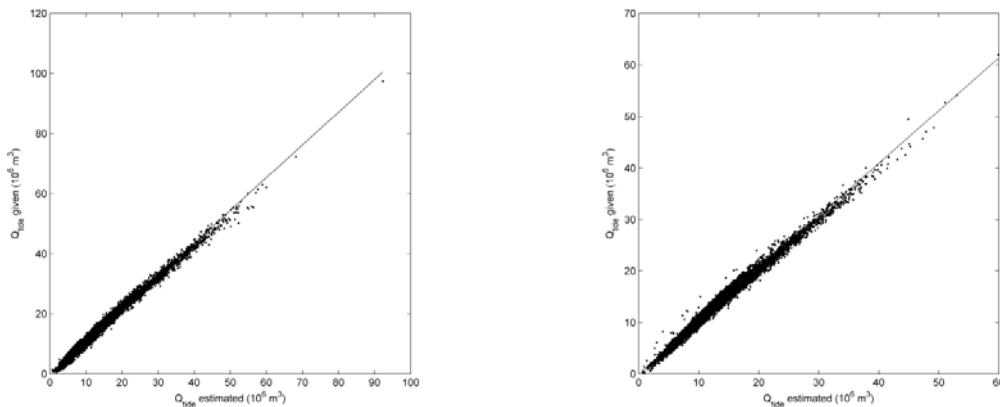
Figure 10: Q_{tide} given as a function of the Q_{tide} estimated from equations (1) and (2) for the sluicecomplex near Den Oever (left0 and Kornwerderzand (right).

Using these coefficients, the discharge can be calculated from the original sea level measurements in Lake IJssel and the Wadden Sea, which are collected every 10 minutes.

There were two very obvious typos in the original excel files in which the openings and closings of the sluices were given. These were a closing of the KZ sluice on 25 December at 20:40, which should have been 8:40 and a closing of KZ sluice on 10 January at 10.30, which should have been 19.30. These have been changed manually. There are more intervals longer than an hour during which the discharge was negative, which could either be due to a typo in the excel file of the closing or opening of either of the sluice, but it could also be an error in determining the closing or opening of the sluices and an actual import of Wadden Sea water into Lake Ijssel. We assumed the latter and left the discharges to be negative.

The resulting discharges for the period between 2000 and 2012 are provided in Figure 11 for both different sluices. The instantaneous discharge can be as much as 3000 m^3/s for the Den Oever sluice complex and about 2000 m^3/s for the Kornwerderzand complex. This reflects the number of sluice gates in each complex, being 3 and 2, respectively. Also, a clear seasonal cycle can be observed with lower discharges during summer than during winter.

The average time that the sluices in Den Oever were opened is 238±70 minutes per low tide, if they were opened. This is 255±71 for the sluices near Kornwerderzand. The mean amount of groups that are opened is 1.65 in KZ and 2.21 in DO. Generally, the total discharge between the sluices is divided in such a way that about 41% is discharged at Kornwerderzand and about 59% at Den Oever.
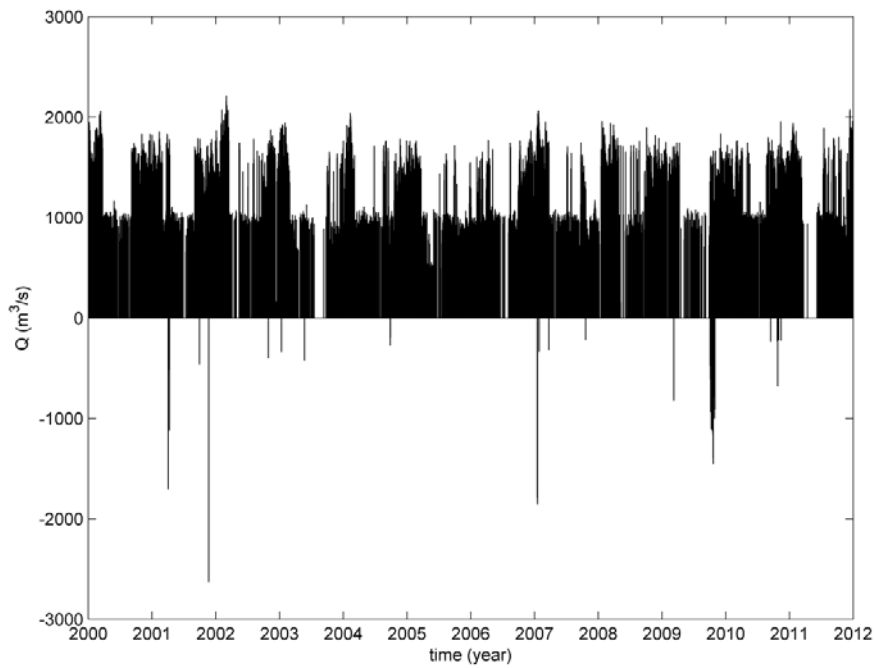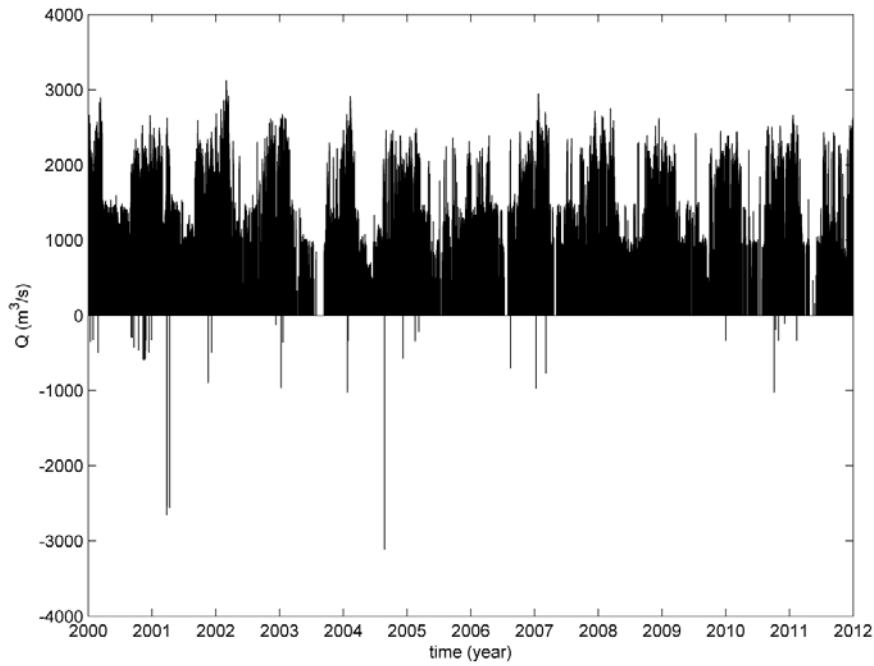
Figure 11: Estimated discharge at Den Oever (top) and Kornwerderzand (bottom) for the years 2000 to 2012 based on 10-minute sea level measurements inside Lake Ijssel and outside in the Wadden Sea (m³/s).

Towards coupling to the complex ecosystem model

Additional 3D boundary conditions need to be applied to the open boundary for nutrients and diatoms concentrations in order to run the model coupled to the complex ecosystem model. These biogeochemical constituents are given in the appendix.

3D boundary Conditions for biogeochemical constituents (55 variables)

A list of 55 state variables is provided in Table 1 in **Error! Reference source not found**.. These should be imposed to the boundary as well. Deriving files for these constituents is performed in the same way as done for T and S. A program is written which reads the list with the 55 variables and checks whether these are available in the model output from the large scale North Sea model. Then the 3D boundary data for T and S and the 55 biogeochemical state variables are written to a NetCDF file for each month separately and later merged into one file for the whole period 2003-08 to 2004-12.

Creating porosity file in NetCDF

Information on porosity is necessary to describe the behavior of the sediment and diatoms on the sea floor in the western Wadden Sea. A short paper describes how the sediment characteristics of the Dutch western Wadden Sea were derived from the limited data set available (Brinkman, 2013). A list of variables is given in

Table 2. The original ascii file used the Dutch local coordinate system (Rijksdriehoeksystem). These coordinates were first transformed into latitudes and longitudes and the total data set was written in NetCDF format for the model to be able to read it.

Subdomain decomposition

The numerical model is solved on a parallel system, because due to the additional state variables it no longer runs on a single processor within a descent amount of time. Therefore we have split the domain into smaller boxes and divided the model computation over the different nodes of the system. Dividing the numerical simulation over different nodes will improve the speed of the calculation, however the interaction between the boxes (and thus between the nodes) decreases speed. This leads to an optimum subdomain division. This optimum depends on whether the model runs for hydrodynamics only, or is coupled to the complex ecosystem model with the additional 55 state variables. Therefore, a set of subdomain divisions was constructed, so that it could be tested for hydrodynamics coupled to ecosystem dynamics; 2 examples are shown in Figure 12.
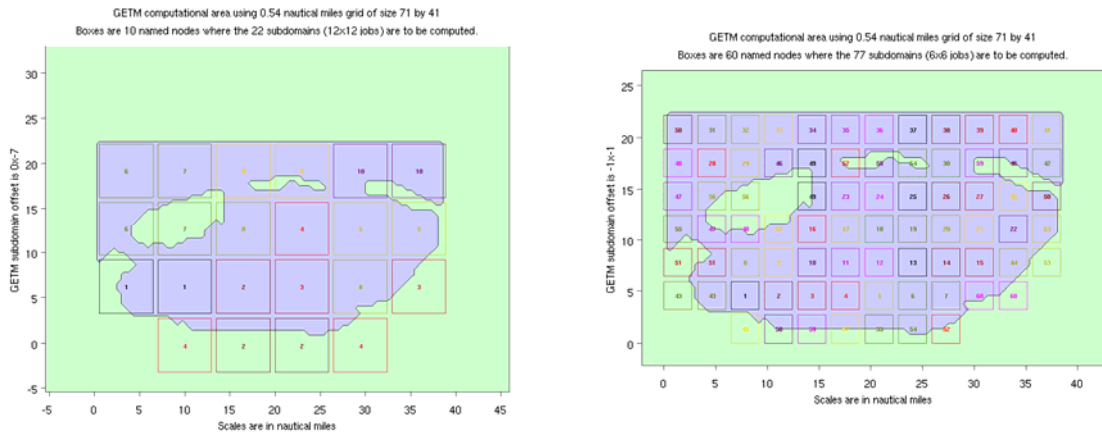
Figure 12: Two examples of subdomain divisions; left: 12x12 boxes divided over 10 nodes; right: 6x6 boxes divided over 60 nodes.

Phased setups, from simple to increasingly complex

The intention was to make different setups starting with a very simple setup of only the Marsdiep with closed boundaries as shown in Figure 14 all the way to the realistic setup of Figure 13. Then we would first be able to test the coupling between the hydrodynamics and the ecosystem model, before moving bigger. However, eventually we ended up in a compromise between realism and size of the domain as shown in Figure 16.
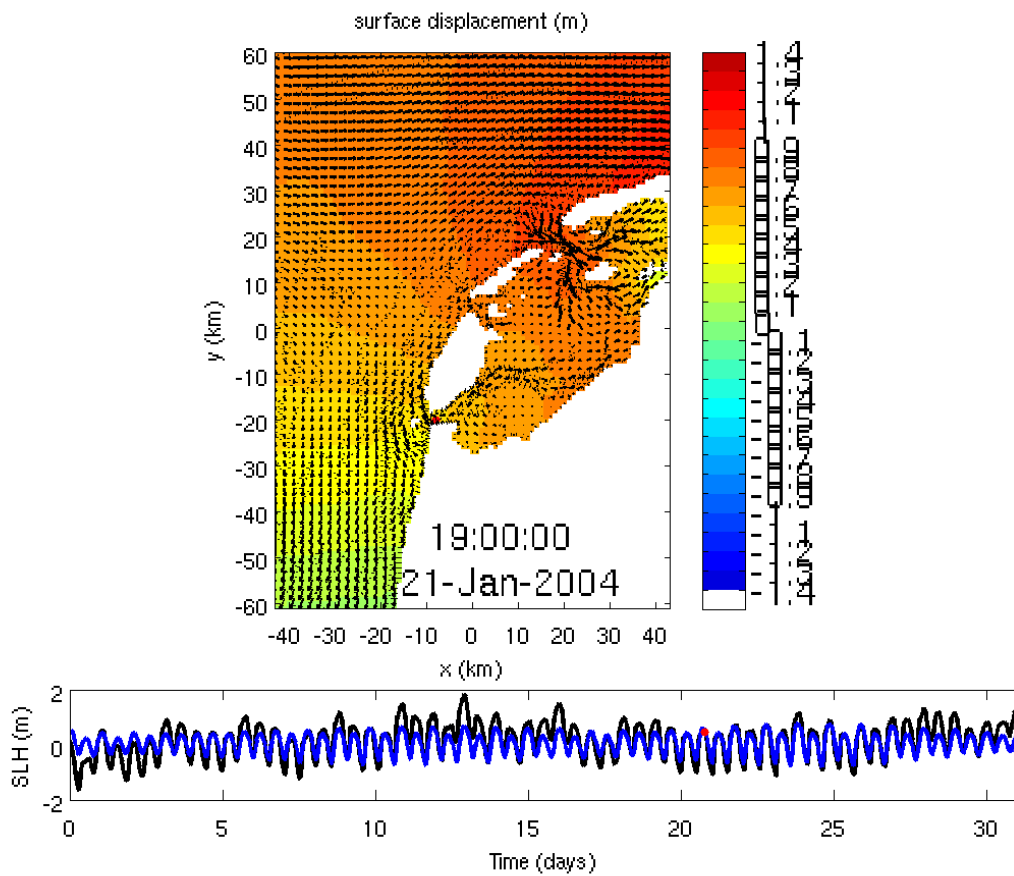
Figure 13: Top: Colors show the sea level elevation (m, relative to Dutch ordinance level) on 21-Jan-2004 19:00:00 and arrows the depth averaged current velocity and direction. Bottom shows the time evolution for the sea level height as a function of time in days since 1-Jan-2004. Black shows the measurements and blue the simulation.

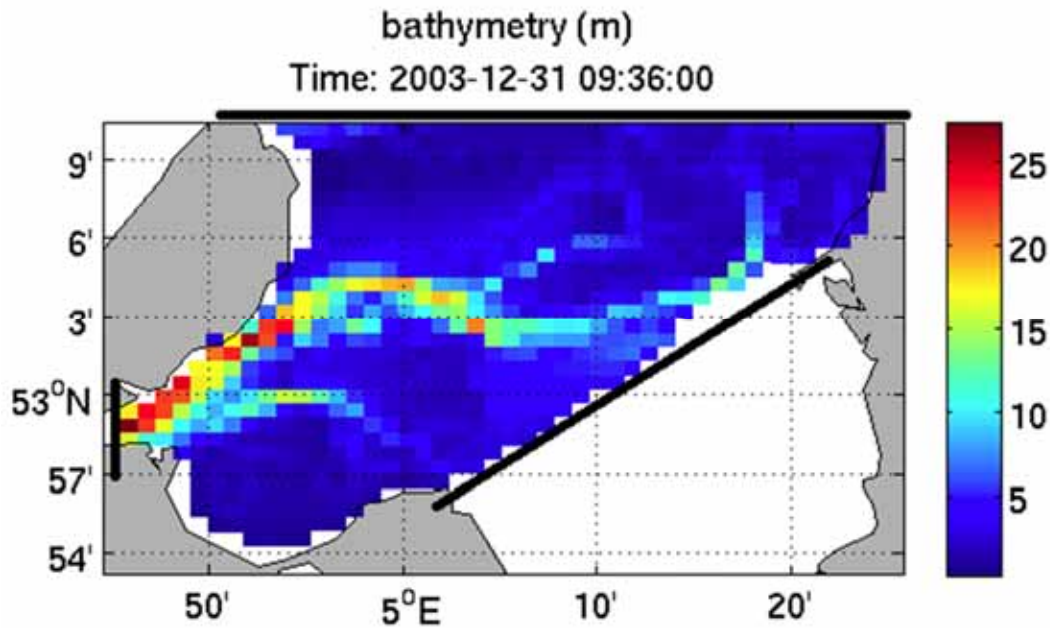## Phase 0 – Marsdiep basin with closed boundaries (wind only)

Figure 14: Bathymetry of phase 0 and 1 of the Marsdiep basin. The three boundaries indicated with thick black lines are assumed to be closed in phase 0 and no river inflow was imposed at the sluices in the enclosure dike. Meteorology (wind, evaporation minus precipitation and solar radiation) drives the hydrodynamics in this setup.

Phase 1 – Opening the Marsdiep inlet (tidal flow and fresh water river inflow)

Phase 1 has essentially the same setup as phase 0, but now the western boundary is opened and the basin is forced with sea level elevation, temperature and salinity at the open boundary. Also fresh water discharge is imposed at the sluices in the enclosure dike near Den Oever and Kornwerderzand in the way as described earlier.

Phase 2 – Including the Vlie inlet

In phase 2, we intended to include the Vlie inlet as demonstrated in Figure 15. In the process of working towards this still intermediate phase between the full-blown version of the Marsdiep-Vlie inlet, which we hoped to achieve, we concluded that it would not be possible to run the latter within a reasonable amount of time. We discussed the options of having the setup as in Figure 15 as the final product. However, that would have led to serious errors in the inflow conditions at the inlets, as boundary conditions imposed at the open boundaries are retrieved from the large scale model (Figure 8), which doesn't even contain the inlets. This would lead to unsatisfactory results in terms of hydrodynamics.
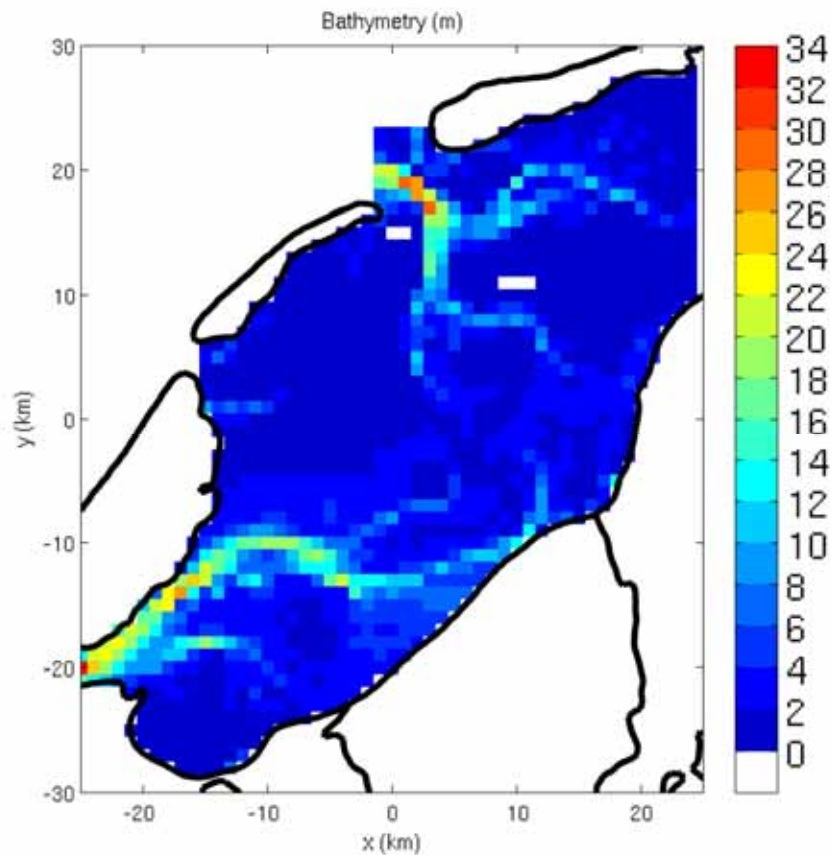
Figure 15: Bathymetry intended to be used in phase 2. The Marsdiep inlet, Eierlandse gat and Vlie inlet are assumed to be open and the tidal water shed between the main land and Terschelling is assumed to be a closed boundary. Fresh water discharge is imposed at the sluices in the enclosure dike.

Therefore, we compromised between the intended full-blown version of the Dutch western Wadden Sea (Figure 13) and the version depicted in Figure 15 leading to the bathymetry indicated in Figure 16, which is the bathymetry rotated -41 degrees. This ensured that the enclosure dike was a more-or-less straight line along the rotated x-axis. Meteorological forcing was rotated accordingly. The domain contains 71x41 grids of 1x1 km in the horizontal and has 5 levels in the vertical, this leads to a total of 14555 gridboxes. The domain is chosen in such a way that the open boundaries are not too close to the tidal inlets (except for the Marsdiep inlet), but that the amount of gridboxes covering the North Sea are less than the ones inside the basin, as the deeper North Sea is biologically less interesting than the shallower Wadden Sea in terms of primary production.
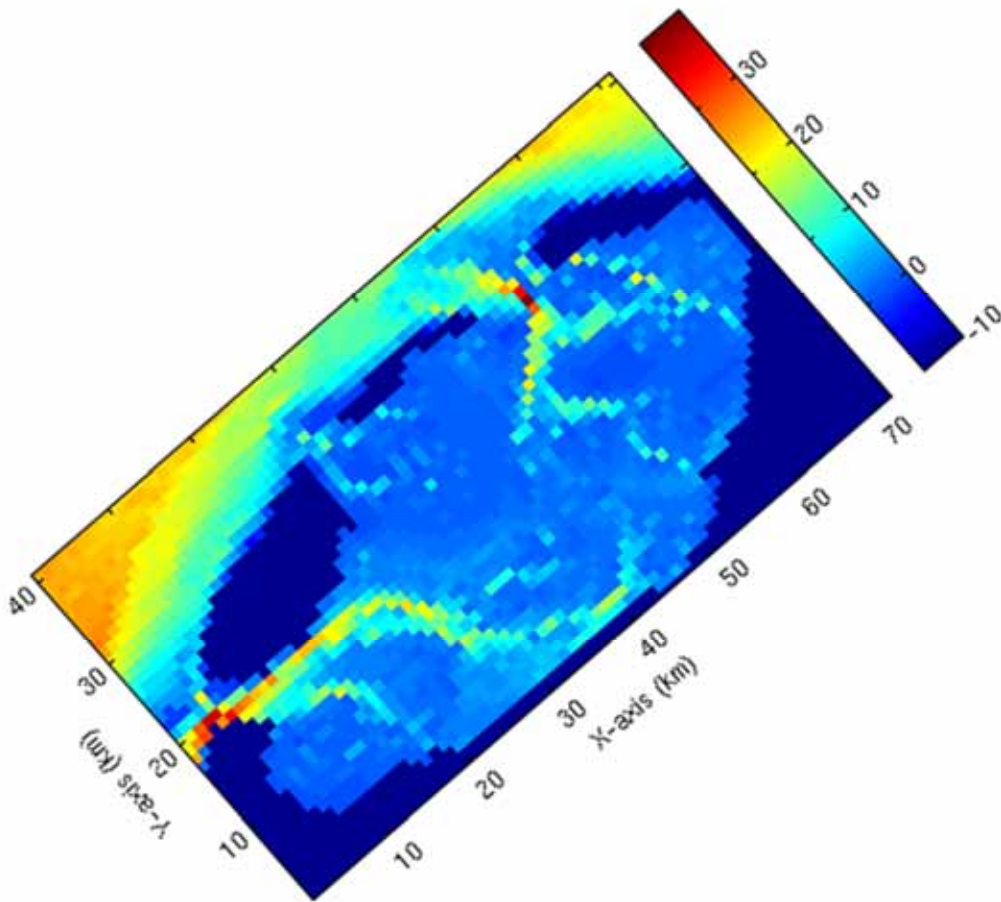
Figure 16: Bathymetry of final phase rotated of -41 degrees as that led to a more-or-less straight enclosure dike. Fresh water discharge is imposed at the sluices in the enclosure dike. Boundaries on the North Sea are open and boundary conditions derived from the large scale North Sea model are imposed.

Figure 17 shows four snapshots of the sea level elevation and the depth averaged velocity vectors throughout the tidal cycle. The drying can clearly be observed during low-tide. Then tidal flat in the western Dutch Wadden Sea are exposed. The time-series of the sea level height at Den Helder shows correspondence between the simulated and in-situ measured values.
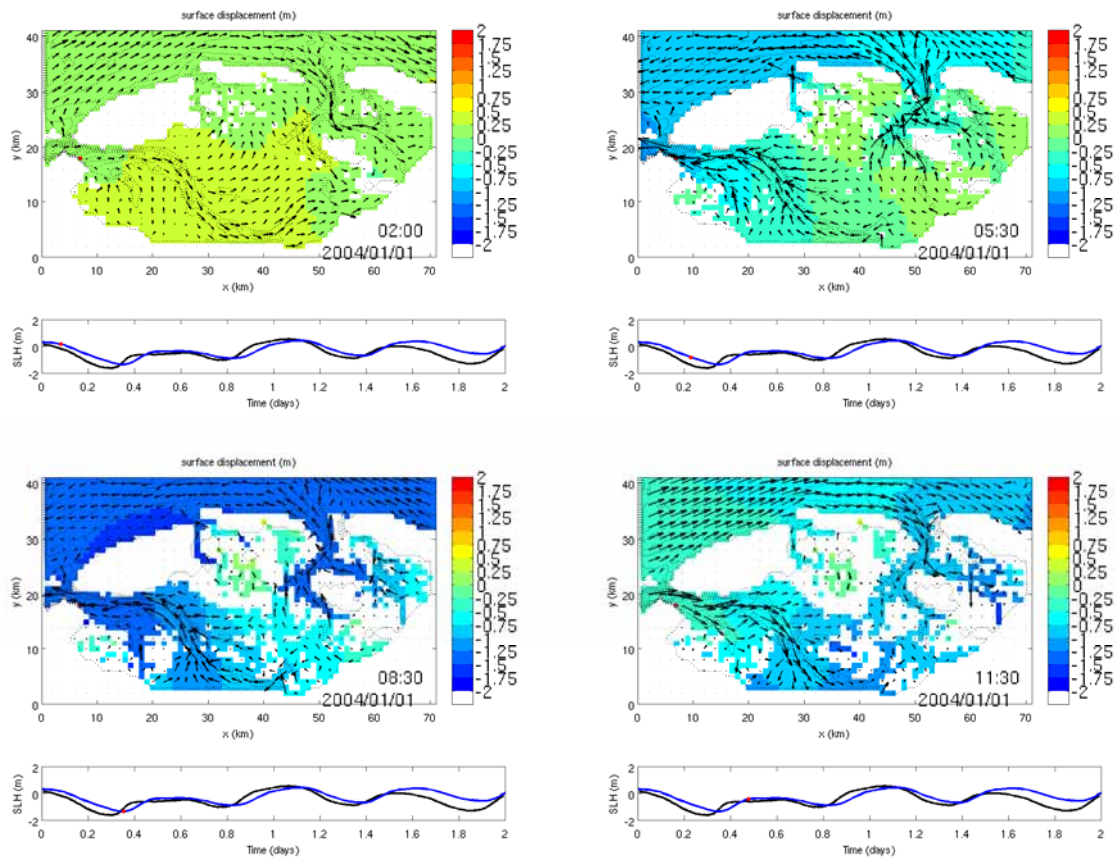
Figure 17: Sea surface elevation (colors) and depth averaged velocity (arrows) at four stages throughout the tidal cycle. Bottom panels show the sea level elevation in Den Helder (at the location of the red dot in the top panels); black shows the in-situ measurements and blue the simulated value. The red dot in the bottom panels indicates the time at which the snapshot in the top panels is given. A movie "data1.wmv" is also available for 1 and 2 January 2004.

Figure 18 shows the salinity in the surface layer at two different times (snapshots). The left hand panel shows a situation with strong discharge at the sluices in the enclosure dike; the sources at Den Oever and Kornwerderzand are easily discriminated. The situation in the right hand panel is shown during a period with low discharge. Most of the fresh water is removed from the system. The correspondence between the in-situ measurements at the jetty (indicated with a blue dot) and the simulated values seems to be off during the high discharge period. However, during other periods in December 2003, values are quite similar.
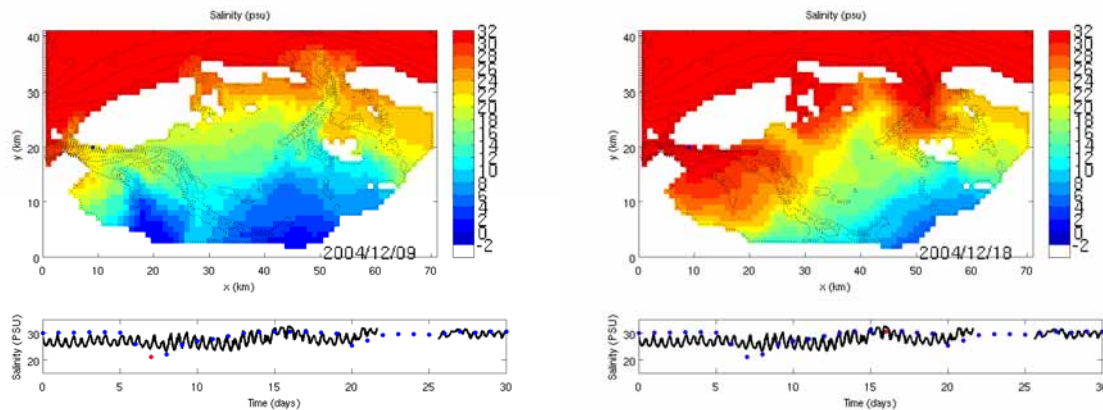
Figure 18: Snapshots of the salinity in the top layer (top panels). Bottom panels show the time evolution of the salinity at the location of the NIOZ jetty (blue dot in top panels). The black line shows the in-situ measurements and the blue dots the instantaneous values at that location in the simulation. The red dot indicates the time of the snapshot in the upper panel. A movie "data2.wmv" is also available for the entire month of December (2004).

Summary and Discussion

The setup of a 3D hydrodynamic model for the Western Dutch Wadden Sea was described in this report. It took a large number of steps to get to the final product of which the results were shown in Figure 16, Figure 17 and Figure 18. It started with familiarizing with General Ocean Turbulence Model (GOTM). The results on modeling the Rhine Region of Fresh Water Influence led to an award winning paper (Nauw and van der Vegt, 2012) in the jubilee conference proceedings of the NCK.

The next step was setting up a model for the Dutch western Wadden Sea. The General Estuarine Transport (GETM) model was used and several input files had to be generated and running the model was approached in three bases. For base 1, a bathymetry file needed to be constructed for which the Rijkswaterstaat vaklodingen were used and averaged to obtain a coarser grid. Besides that, a climatology file was needed which was derived from Janssen (1999) climatological values. Running base 1 pushed the currents away from zero value without crashing the model instantly. In base 2, 2D (thus sea level elevation) and 3D (temperature and salinity profiles) boundary conditions had to be constructed for the open boundaries. They were derived from a larger coarser scale simulation of the North Sea. The result is a tidal wave propagating through the domain and salinity and temperature values changing according to what is prescribed at the open boundary. In base 3, meteorological forcing, such as wind stress and evaporation minus precipitation, is added to the simulation, as well as fresh water river inflow. Particular attention is given to the river inflow at the sluices, which is only available in 24-hour sums, which doesn't seem representative for a discharge that only takes place during low tide.

All of the above is necessary to run the model for 3D hydrodynamics. If coupled to a complex ecosystem model, additional information is needed such as 3D boundary conditions for the biogeochemical constituents as shown in Table 1. Moreover, a porosity file is needed to accurately describe benthic processes. Adding the complex ecosystem model adds to the computational demand. Therefore, the domain needs

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to be subdivided into smaller coupled basins, which were run in parallel on different nodes of a cluster.

Several setups were created from simple configurations to increasingly complex ones to test the coupling between the hydrodynamics and the ecosystem dynamics. We started with a small closed basin representing the Marsdiep. It was closed, so there was no tidal wave entering the domain. Once this setup ran, the boundary at the inlet was opened. Tidal flats were now exposed during low tide.
The next step was to add the Vlie inlet to the domain and have the boundaries open at the inlets. However, to be able to simulate the hydrodynamics well, a small portion of the North Sea had to be added to the domain. The boundary conditions from the larger scale North Sea model are slightly wrong, because the depths of at the boundaries do not coincide exactly. The setup as in Figure 13 would not be useful when coupled to a complex ecosystem model as the computational demand (even with parallel computing) with be way too large to derive any substantial amount of simulated time. Therefore, the intermediate option was chosen as displayed in Figure 16, Figure 17 and Figure 18. Results of the hydrodynamics turn out to be quite similar to local in-situ observations, which gave us confidence in the overall hydrodynamic performance of the model, when coupled to a complex ecosystem model and focus is on the latter.

Tables

abbreviation	Name	unit
R9x	Suspended sediment	mg/m3
O2o	Oxygen	mmol O2/m3
N1p	Phosphate	mmol P/m3
N3n	Nitrate	mmol N/m3
N4n	Ammonium	mmol N/m3
N5s	Silicate	mmol Si/m3
N6r	Reduction Equivalents	mmol S--/m3
B1c	Pelagic Bacteria	mg C/m3
B1n	Pelagic Bacteria	mmol N/m3
B1p	Pelagic Bacteria	mmol P/m3
Bac	Pelagic Nitifying Archea	mg C/m3
P1c	Diatoms	mg C/m3
P1n	Diatoms	mmol N/m3
P1p	Diatoms	mmol P/m3
P1l	Diatoms	mg Chl/m3
P1s	Diatoms	mmmol Si/m3
P2c	Flagellates	mg C/m3
P2n	Flagellates	mmol N/m3
P2p	Flagellates	mmol P/m3
P2l	Flagellates	mg Chl/m3
P3c	PicoPhytoPlankton	mg C/m3
P3n	PicoPhytoPlankton	mmol N/m3
P3p	PicoPhytoPlankton	mmol P/m3
P3l	PicoPhytoPlankton	mg Chl/m3
P4c	Dinoflagellates	mg C/m3
P4n	Dinoflagellates	mmol N/m3
P4p	Dinoflagellates	mmol P/m3
P4l	Dinoflagellates	mg Chl/m3
P5c	Resuspended Benthic Diatoms	mg C/m3
P5n	Resuspended Benthic Diatoms	mmol N/m3
P5p	Resuspended Benthic Diatoms	mmol P/m3
P5l	Resuspended Benthic Diatoms	mg Chl/m3
P5s	Resuspended Benthic Diatoms	mmmol Si/m3
P6c	Phaeocystis colonies	mg C/m3
P6n	Phaeocystis colonies	mmol N/m3
P6p	Phaeocystis colonies	mmol P/m3
P6l	Phaeocystis colonies	mg Chl/m3
Pcc	Phaeo mass initiating colonies	mg C/m3
R1c	Labile Organic Carbon (LOC)	mg C/m3
R1n	Labile Organic Carbon (LOC)	mmol N/m3

R1p	Labile Organic Carbon (LOC)	mmol P/m3
R2c	TEP (long sugars)	mg C/m3
R3c	TEP in Phaeocystis	mg C/m3
R6c	Particulate Organic Carbon (POC)	mg C/m3
R6n	Particulate Organic Carbon (POC)	mmol N/m3
R6p	Particulate Organic Carbon (POC)	mmol P/m3
R6s	Particulate Organic Carbon (POC)	mmol Si/m3
RZc	FaecelPellet Particulate Carbon (POC)	mg C/m3
O3c	Dissolved Inorganic Carbon	mg C /m3
O3h	Alkalinity	mmol H/m3
Z3c	Carnivorous mesozooplankton	mg C/m3
Z4c	Omnivorous mesozooplankton	mg C/m3
Z2c	Filterfeederlarvae	mg C/m3
Z5c	Microzooplankton	mg C/m3
Z6c	Heterotrophic nanoflagellates (HNAN)	mg C/m3

Table 2: List of data in the porosity file

Col
Row
POINT_X
POINT_Y
MosLitNJ_1
MosLitNJ_2
MosLitNJ_3
MosLitVJ_1
MosLitVJ_2
MosLitVJ_3
SumSubLit_SumBiom
SumSubLit_SumBiom_1
SumSubLit_BiomCons
SumSubLit_BiomCons_1
SumSubLit_BiomHalf
SumSubLit_BiomHalf_1
SumSubLit_BiomNB
SumSubLit_BiomNB_1
SumSubLit_BiomZaad
SumSubLit_BiomZaad_1
VisduurNJ
VisduurVJ
DryPerc
Max_Flow
BottomSS
Cl88_wet
Cl92_dry
OrbitalVel

Depth
Silt_Perc
MedGrainSize
CompNr
MosHabClass
Silt16_Perc
Fe_mg_g
H2O_pct
Porosity
Lutum%
Humus_mg_g
Ca_mg_g
Silt63_Perc
P_mg_g
P_NH4_mg_g
P_NaOH_mg_g
P_HCl_mg_g

Publications

Nauw, J. & van der Vegt, M. Kranenburg, W.; Horstman, E. & Wijnberg, K. (Eds.) Hydrodynamics of the Rhine ROFI near IJmuiden *NCK-days 2012: Crossing borders in coastal research : jubilee conference proceedings*., 2012, 167-172[*]

Nauw, J. J.; Merckelbach, L. M.; Ridderinkhof, H. & van Aken, H. M. Long-term ferry-based observations of the suspended sediment fluxes through the Marsdiep inlet using acoustic Doppler current profilers under revisions for *Journal of Sea Research*, 2013

[*] This paper received the "Best senior paper award" out of all papers submitted to the jubilee conference proceedings of NCK-days 2012.

Presentations

J. Nauw, L. Merckelbach, H. Ridderinkhof, E. Wielsma, M. van der Vegt, B. Brinkman and P. Ruardij (2009) Total suspended matter concentration from acoustic backscatter intensity; Part I: Ferry-based observations of the transport of total suspended matter through the Texel inlet; Part II: Comparison between observations from a bottom-mounted ADCP and GOTM in the North Sea, Internal workshop IMARES-GKSS-NIOZ (Germany - Geesthacht, 2009-08-31)

J. Nauw, L. Merckelbach, H. Ridderinkhof, E. Wielsma, M. van der Vegt, B. Brinkman and P. Ruardij (2010) Hydrography and hydrodynamics in the North Sea near

Ijmuiden a data-model intercomparison, Internal workshop IMARES-NIOZ-GKSS (Texel, 2010-06-21)

Janine Nauw, Meinard Tiessen, Theo Gerkema and Piet Ruardij (2011) A GETM setup for the Western Dutch Wadden Sea, Internal WORKSHOP Coupled BGC + GETM Waddensea Modelling (IMARES Texel, 2011-05-09)

Janine Nauw, Meinard Tiessen , Theo Gerkema & Piet Ruardij (2011) Modelling of physical processes in the North and Wadden Sea, Departmental talk (NIOZ-Physics department , 2011-09-19)

J. Nauw, L. Merckelbach, H. Ridderinkhof and H. van Aken (2011) Ferry-based observations of the transport of total suspended matter through the Texel inlet, International Symposium on the Ecology of the Wadden Sea (Texel, 10-14 October)

Janine Nauw, Meinard Tiessen , Theo Gerkema & Piet Ruardij (2012) Modelling of physical processes in the North and Wadden Sea, Internal workshop on Oceanography and Ecology of the Wadden Sea (IMARES, 13 February)

Janine Nauw and Maarten van der Vegt (2012), Hydrodynamics of the Rhine ROFI near IJmuiden, NCK days (Enschede, 13-16 March)

Posters

Janine Nauw, Theo Gerkema, Evert Wielsma, Maarten van der Vegt, Bert Brinkman en Piet Ruardij (2009) Comparison between ADCP data and GOTM in the North Sea within "Wadden Sea ecosystem data assimilation and integrated modeling", ZKO symposium (Texel, 2009-03-09)

J. Nauw, L. Merckelbach and H. Ridderinkhof (2010) Ferry-based observations of the transport of total suspended matter through the Texel inlet, Noordzeedagen (Texel, 2010-10-07)

M. Tiessen, J. Nauw, T. Gerkema & P. Ruardij (2011) Modelling of physical processes in the North and Wadden Sea, Buijs Ballot Research School Autumn symposium (Oranjewoud, 26-29 October)

J. Nauw, L. Merckelbach, H. Ridderinkhof and H. van Aken (2012) Long-term observations of the SPM transport through the Texel inlet using ferry-based ADCP measurements, PECS (New York, 13-17 August)

J. Nauw, P. Ruardij, D. Gerla and B. Brinkman (2012) Wadden Sea ecosystem modelling: What have we achieved so far?, ZKO symposium (The Hague, 7-8 November)

J. Nauw, P. Ruardij, D. Gerla and B. Brinkman (2012) Wadden Sea ecosystem modelling: What have we achieved so far?, NCK days (The Hague, 13-15 March)

Bibliography

Brinkman, B. Compilation sediment data Wadden Sea, **2013**

Burchard, H.; Bolding, K. & Voillareal, M. R. GOTM–a general ocean turbulence model. Theory, applications and test cases. *European Commission,* **1999**

Burchard, H. & Bolding, K. GETM, a general estuarine transport model. *European Commission, Ispra,* **2002**

Janssen, F.; Schrum, C. & Backhaus, J. A climatological data set of temperature and salinity for the Baltic Sea and the North Sea *Ocean Dynamics, Springer Berlin / Heidelberg,* **1999**, *51*, 5-245

Vlag, D. P. & Ytsma, D. A. Definitiestudie Spui Afsluitdijk : fase 2 : bepaling spuilocatie en capaciteit, **2001**, Ministerie van Verkeer en Waterstaat, Rijkswaterstaat, Rijksinstituut voor Integraal Zoetwaterbeheer en Afvalwaterbehandeling

Vlag, D. P. & Ytsma, D. A Definitiestudie Spui Afsluitdijk : fase 3 : vergelijking ontwerpopties en bepaling meest effectieve locatie, **2002**, Ministerie van Verkeer en Waterstaat, Rijkswaterstaat, Rijksinstituut voor Integraal Zoetwaterbeheer en Afvalwaterbehandeling

Souza, A. & Simpson, J. The modification of tidal ellipses by stratification in the Rhine ROFI *Continental Shelf Research,* **1996**, *16*, 997 - 1007

De missie van het NIOZ is het verkrijgen en communiceren van wetenschappelijke kennis van zeeën en oceanen voor een beter begrip en een duurzaam beheer van onze planeet, het beheren van de nationale faciliteiten voor zeeonderzoek en het ondersteunen van onderzoek en onderwijs in Nederland en in Europa.