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Numerical modeling of physical processes in the North Sea and Wadden Sea with GETM/GOTM

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ABSTRACT

At the Royal Netherlands Institute for Sea Research (NIOZ), several research projects are carried out on the concentration and transport of Suspended Particulate Matter (SPM) in the Southern North Sea and Wadden Sea. So far the focus has been on field data collection and analysis, but in recent years a numerical modeling capacity has been set up, using the GETM/GOTM model. The underlying purpose is twofold. Firstly, a numerical model can provide insight into the hydrodynamics and SPM transport, complementing field observations, helping to interpret and identify the key physical mechanisms. Secondly, it provides a much-needed tool in ecological studies, forming the basic physical core on which the transport of for instance nutrients and larvae depends; thus, these kinds of numerical models provide a valuable bridge in interdisciplinary studies. First steps in the use of the model are reported here, offering a synopsis of its potential.

INTRODUCTION

The historical focus of research carried out at the NIOZ has been towards monitoring physical, biological and geological processes in the North and Wadden Sea. Modeling of physical processes has mainly been used as an additional tool to facilitate the analysis and interpretation of data collected in the field.

Field data are inherently limited in duration and spatial scale. Generally, only specific locations can be studied. Recent developments in remote sensing [as for instance in: *Pietrzak et al., 2011*] and in-situ data collection [as presented in *Nauw et al., 2012*] are greatly expanding the capabilities in data collection. However, the basic limitations still apply to a significant extent. Numerical modeling, on the other hand, can give predictions on wide spatial and temporal scales. However, this type of research can only provide coarse information, lacking the level of detail provided by field data. Moreover, the accuracy of model predictions is greatly dependent on the correctness of the initial model input. By combining field data with numerical modeling, the level of detail obtained by field data could be used to provide more accurate and detailed numerical simulations. The present paper provides an overview of the recent work carried out at the NIOZ in which a numerical modeling techniques are used to study a variety of different physical processes.

The complex circulation pattern in the North Sea mainly arises from the interaction between tides and atmospheric conditions [*Otto et al., 1990*]. The residual current pattern and annual variability in forcing conditions are significant factors determining the sediment transport, distribution of nutrients and pollutants and thus biological development [*Otto et al., 1990; Dyer and Moffat, 1998*]. Furthermore, fresh water inflow from rivers around the North Sea causes stratification and affect the water motion on small and intermediate scale [*De Boer et al., 2006*].

The adjacent Wadden Sea forms a complex estuarine system behind various barrier islands. Several semi-separated tidal basins are drained through tidal channels that are located in between these islands. The dominant tidal behavior is on the semi-diurnal M2 tidal frequency, leading to flooding and drying of large parts of the tidal basins [*Zimmerman, 1976a*]. The tidal currents, along with freshwater inflow from the mainland give rise to complex mixing processes and residual current patterns [*Zimmerman, 1976b*], which have been observed in the field as well as described using computer models over the last decades [*Postma, 1981; Ridderinkhof and Zimmerman, 1992; Stanev et al., 2007; Burchard et al., 2010*].

Suspended Particulate Matter (SPM) is a bulk term encompassing fine-grained substances of organic and inorganic nature, such as silt. It is transported along with the flow while in suspension, but may sink to the bed during calm conditions. High concentrations of SPM can impede sunlight to penetrate the water column, and therefore limit primary production. Moreover, especially in estuarine environments and tidal basins, SPM forms a considerable fraction of the total sediment supply and is therefore of great importance for erosion and accretion of morphological features and their change of form. The transport and concentration of SPM is determined by the prevalent hydrodynamics. Therefore, to understand SPM characteristics, physical aspects such as tides, waves, net currents, and density gradients are of great importance.

Sediment is transported into the North Sea from the English Channel, but also as a result of cliff erosion along the British East coast and river outflow [*Eisma and Kalf, 1987*]. Furthermore, re-suspension of deposited sediments occurs locally as a result of strong currents, due to storm events or during spring tides, for instance at the Flemish Banks [*de Kok, 2004*]. Plumes of sediment can be observed along the coastlines bordering the North Sea captured by estuarine type of circulation due to river outflow, as well as crossing the North Sea [*Pietrzak et al., 2011*].

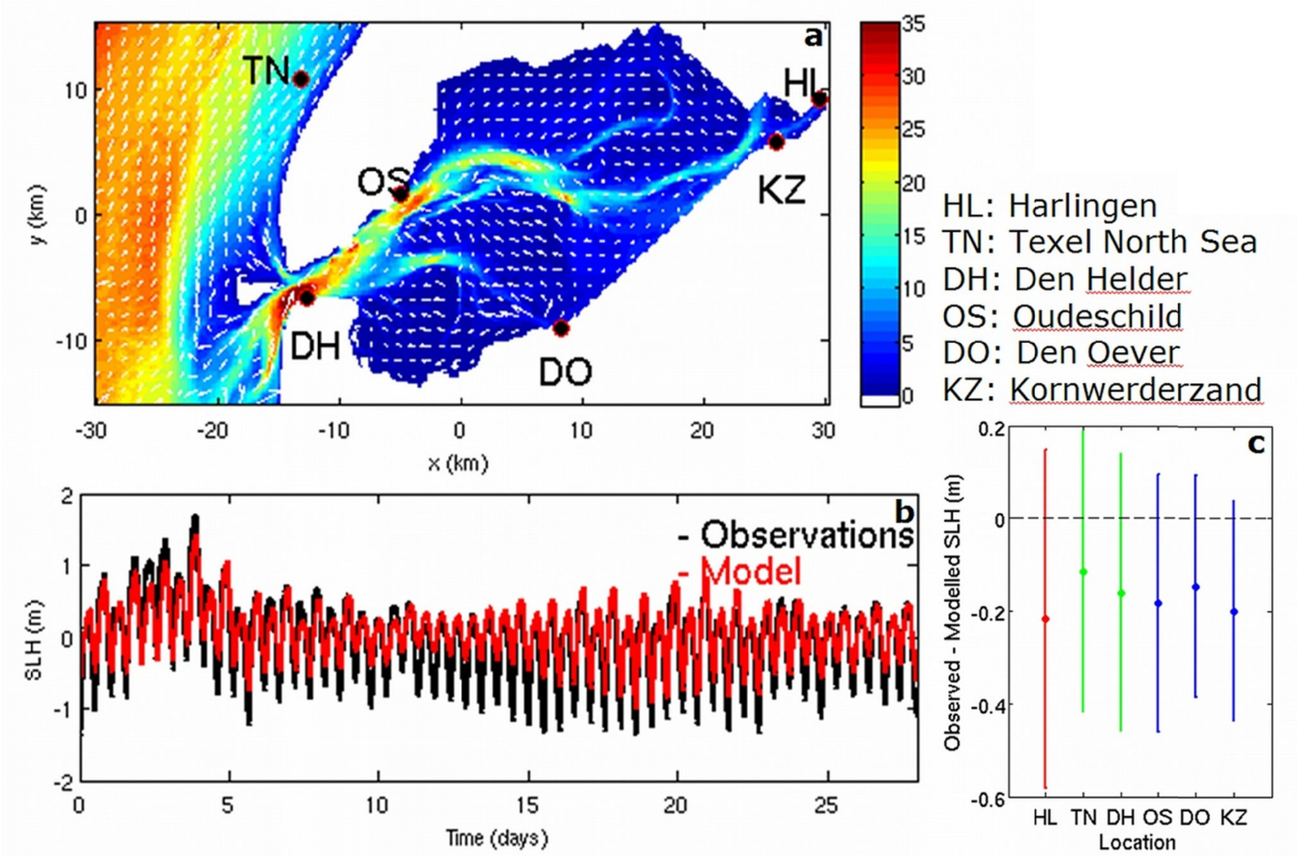

Figure 1. Model set-up for the Marsdiep inlet system: a) Top-view of the bathymetry along with the locations of field-data stations. Sea Level Height (SLH) data from these stations is compared with model predictions (the white arrows indicate the modelled residual current circulation pattern). b) Comparison between predicted (in red) and observed (in black) sea level height over time at Den Helder (DH). c) The mean difference and RMS error between the observed and predicted sea level height for the different stations along the basin-edge.

The transport of nutrients along with favorable water conditions (such as temperature) can give rise to blooms of plankton [*Baars et al., 2002*]. Also, transport of fish-larvae from spawning grounds towards nursery areas is largely driven by flow patterns [*Van der Veer and Witte, 1999*]. Hence, knowledge of the underlying current patterns and their variability is of great importance.

NUMERICAL MODEL

The General Estuarine Transport Model (GETM) is a three-dimensional hydrodynamic model, which is coupled to GOTM (General Ocean Turbulence Model) that includes a variety of vertical turbulence schemes. This public domain model was developed by *Burchard and Bolding [2002]* with an initial focus on estuarine systems, where drying and flooding of parts of the domain are of great importance. However, later also coastal seas (such as the North Sea and the Baltic Sea) were investigated by different research groups using this model. Continually, new modules are being added by the user community. The model can implement the inflow of fresh water and describe the development of stratification in the domain, both as a result of salinity and temperature gradients. The vertical tides and meteo-forcing are prescribed at the open boundaries. Recently, a module for the transport of fine sediments (SPM) has been added to the GETM/GOTM system which is still under development. Initially

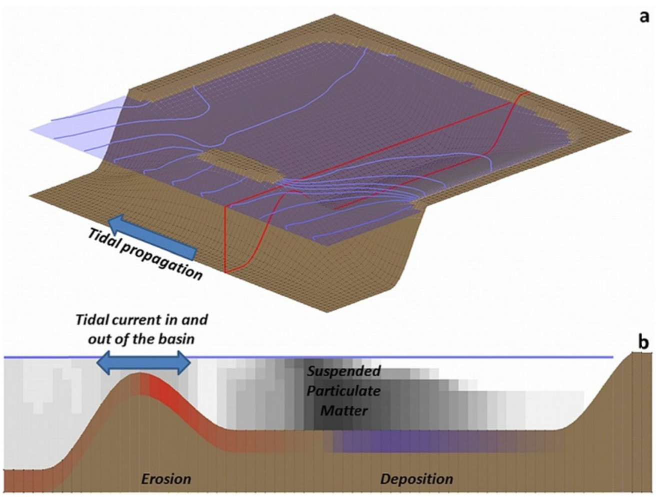

Figure 2. An idealized model set-up of a barrier-island coastline: A tidal wave propagates along the open end of the domain, creating a tidal current in and out of the basin behind the island. b) The strong current results in sediment being eroded from the inlet and transported into the basin, where it deposits.

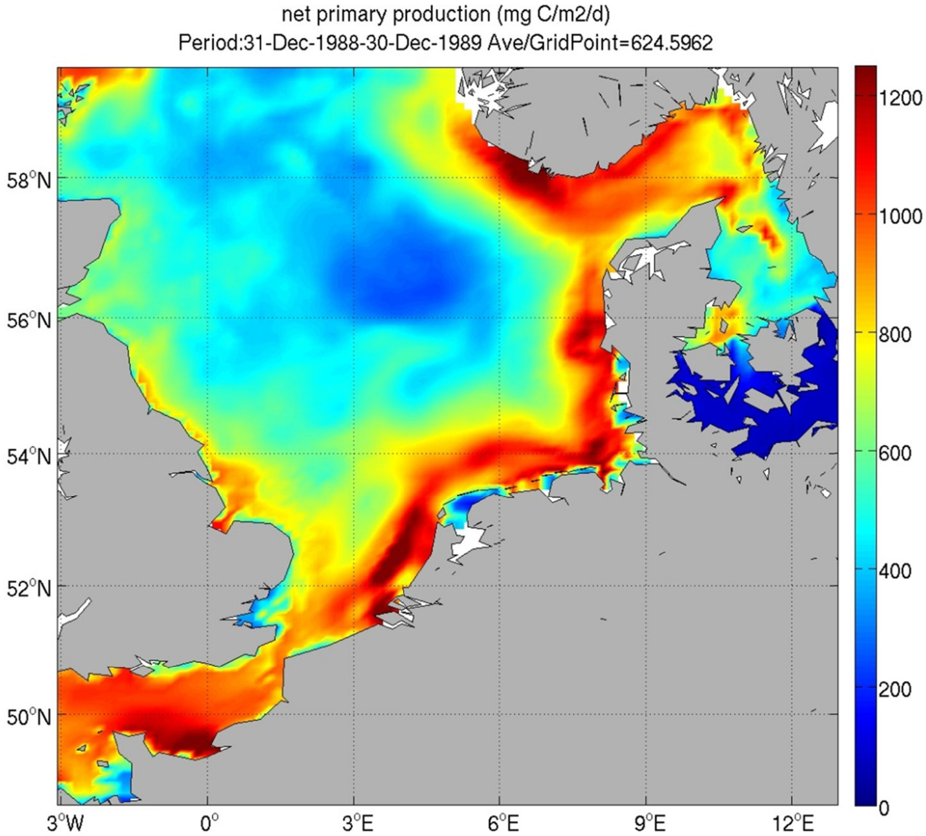

Figure 3. Depicted is the net primary production o of phytoplankton biomass in 1989, calculated with GETM/GOTM and a coupling to ERSEM/BFM, see www.nioz.nl/northsea_model for more results.

the model will be used to describe the hydrodynamics, but subsequently it will be applied to study SPM transport and concentration.

HYDRODYNAMICS

Using long-term ferry based observations, the net SPM transport in the Marsdiep inlet is estimated to be 5 to 10 Mton/year into the Wadden Sea [*Nauw et al., 2012*]. A question that arises from these findings is what happens with this sediment within the Wadden Sea. After all, the Marsdiep inlet forms one of the two main inlets of the Western Wadden Sea, the other one being the Vlie, and so one may expect that part of the imported sediment is partly exported again through the other inlet. As field data is only available from a limited number of stations, numerical modeling results should give a more comprehensive insight into the sediment transport within the Wadden Sea. For the description of SPM characteristics from a numerical model, an accurate description of the hydrodynamics is a prerequisite. An initial set-up can be seen in Fig. 1; here, for simplicity, the Marsdiep basin is taken in isolation, ignoring the neighboring Vlie basin by imposing a 'wall' along the watershed between the basins. Despite these simplifications, a comparison between modeled tidal elevation and data from coastal stations already shows a reasonable correspondence. In the near-future, a similar set-up will be developed for the entire Western Dutch Wadden Sea to investigate the interaction between the Marsdiep and Vlie inlets.

SUSPENDED SEDIMENT TRANSPORT

The transport of fine sediments is important both in relation to biology, and because of bed pattern formation. Currently, a simple experimental version of an SPM-module is available within the model; however this has not yet been applied to actual field-locations. The sensitivities of this sediment module are currently investigated using idealized set-ups; as shown in Fig. 2, where a tidal wave propagating along a coastline passes an idealized estuary. The resulting tidal wave into the estuary causes erosion of the fine sediments at the entrance. This suspended material subsequently deposits further into the estuary. Once a more comprehensive description of the suspended sediment dynamics is developed (involving for instance different sets of grain sizes with their corresponding settling velocities), this module can be applied to a range of different coastal seas and estuaries to investigate the SPM dynamics. Future plans will see the GETM/GOTM model to be applied not only to investigate the SPM transport within the Wadden Sea, but also the dynamics and driving forces behind the East Anglia Plume and plumes along the Dutch coast.

COUPLING TO ECOLOGY

The GETM model is currently already linked to a biological model developed at NIOZ, in collaboration with CEFAS (UK), to study biological processes in the North Sea. The latest version is called BFM, Biogeochemical Flux Model, used to investigate the causes and variability in sub-surface oxygen minima at the Oyster

Grounds, and C and N cycling. An example for the North Sea as a whole is shown in Figure 3: the net primary production (production of new phytoplankton biomass). Fig. 3 shows that the primary production is higher near the coast than in off-shore areas. The high production in the Southern North Sea along the coast is caused by Phaeocystis. These algae can reach very high concentrations through colonies formation which are too large for grazing by mesozooplankton. The relatively high production south of Norway is caused by local conditions in the Skagerrak and the Norwegian Trench and the fact that we dynamically modeled the chlorophyll content, resulting in primary production down to 50 meter. The low production in the Northern off-shore part of the North Sea is caused by relatively low nutrient concentration, a smaller growing season and the stable vertical stratifications.

A second ecological study at NIOZ focuses on the transport of plaice eggs and larvae. Spawning grounds are located in the central (and northern) parts of the North Sea. Residual currents transport the eggs and larvae towards nursery grounds located in the Wadden Sea. Field studies in the Marsdiep inlet have shown strong variability of the plaice concentration over the years. This behavior is partially the result of prevalent forcing conditions, but is also affected by active behavior exhibited by the plaice larvae, such as changing their vertical position in the water column. The transport patterns and inter-annual variability in plaice in the nursery areas forms the basis for this second project. The use of a 3D hydrodynamic model coupled with a particle tracking module (developed at CEFAS [*Van der Molen et al., 2007*]) that can implement active behavior of plaice, can give new insights into the transport routes taken by plaice eggs and larvae. Secondly, the inter-annual variability in forcing conditions will be studied, to identify potential sources of the changes in plaice concentrations in the Marsdiep nursery ground. Additional processes will be studied in a sensitivity analysis, such as water temperature (which might affect plaice development and mortality) and various active behavioral concepts.

CONCLUSIONS

The use of a hydrodynamic model, coupled with various additional components and modules, such as a particle tracking and the SPM module, can give great insights into different processes occurring in the North and Wadden Sea. The large quantity and quality of field-data collected at NIOZ and elsewhere, both of physical processes as well as biological characteristics, can be used to drive model parameters, as well as to judge accuracy of model predictions. Secondly, model predictions can cover large areas and durations that are not covered by the extensive field data-bank. These model data can be used as a basis to study biological, geochemical and ecological processes; the study of SPM in the Wadden Sea, and coupling with primary production being examples of this.

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