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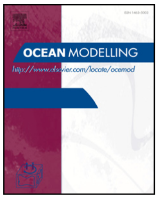

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Unstructured-grid model for the North Sea and Baltic Sea: Validation against observations

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ABSTRACT

A new unstructured-grid model and its application to the North Sea and Baltic Sea are described. The research focus is on the dynamics in the two basins and in the multiple straits connecting them and more specifically on how the model replicates the temporal and spatial variability of physical processes. The comparison against observed data indicates the realism in the simulations of the exchange flows. The simulations demonstrated that in contrast to the tidal variability which decreases in the strait, the role of the barotropic forcing due to weather systems increases. In this zone reversal of transport is well manifested by the increased difference between the surface and bottom salinity values. Small sub-basins like Arkona and Bornholm play the role of reservoirs for denser water which under specific conditions cascades on its way to the Gotland Deep. Unlike the intermediate and deep water salinity in the Baltic Sea, which is strongly affected by fluxes in the straits, the simulated winter-refill and evolution of cold intermediate water are rather driven by surface cooling and processes in the upper mixed layer.

1. Introduction

The North Sea and Baltic Sea (Fig. 1) represent coupled tidal and non-tidal basins of approximately equal size connected through a system of straits. This straits system (hereafter the North Sea–Baltic Sea Transition Zone (NBTZ)) includes the Kattegat, Danish straits and the western part of the Baltic Sea. The surplus of fresh water in the Baltic Sea and the limited water exchange with the North Sea support a two-layer exchange flow in the NBTZ and explains the low salinity (brackish water) of the Baltic Sea. The deep part of the Baltic Sea known as the Baltic proper is separated from the straits area by a number of sills: the Darss Sill (depth of 18 m), the Drogden Sill (depth of 8 m) and the Stolpe Channel (depth of 63–64 m) further east. In these shallow areas the inflowing North Sea water is subjected to substantial mixing with the highly stratified Baltic Sea water.

The North Sea–Baltic Sea system represents a challenge for the numerical modelling because of several reasons. The first one is that it consists of a tidal and non-tidal basin with different dominating balances in each individual basin. The tidal one (the North Sea) is very shallow, except for the Norwegian trench. The relatively high salinity values in the North Sea are typical for the ocean; the vertical mixing which is mostly due to tides dominates the hydrophysical fields. The second basin (the Baltic Sea) can be considered as a huge estuary with extremely strong vertical stratification, which inhibits the vertical mixing. The diffusion coefficients approach to their molecular values, resulting in the extremely weak mixing between the surface and deep layers. This specific vertical stratification is maintained by two major factors: (1) the river runoff and precipitation–evaporation balance at sea surface, and (2) periodic intrusions of saltier North Sea water triggered by extreme atmospheric conditions with an approximately decadal periodicity.

The second challenge in the modelling of Baltic Sea and the area of Skagerrak and Norwegian Trench stems from the fact that the processes there are strongly dependent upon the exchanges in the NBTZ. Compared to other similar transition zones (e. g. Mediterranean–Atlantic Ocean or Black Sea–Mediterranean; Sannino et al., 2009, Stanev and Lu, 2013), the NBTZ is more complex because of the presence of multiple straits. Under different weather or circulation conditions their individual contribution to the exchange between the basins varies (Stanev et al., 2015). Thus the partitioning of flows and recirculation in the belts (which includes 3 major waterways: Great Belt, Little Belt, and Oresund) are central to the problem of the ventilation of deep Baltic basins by the North Sea water (see also, Meier, 2005, 2007). Extremely high resolution

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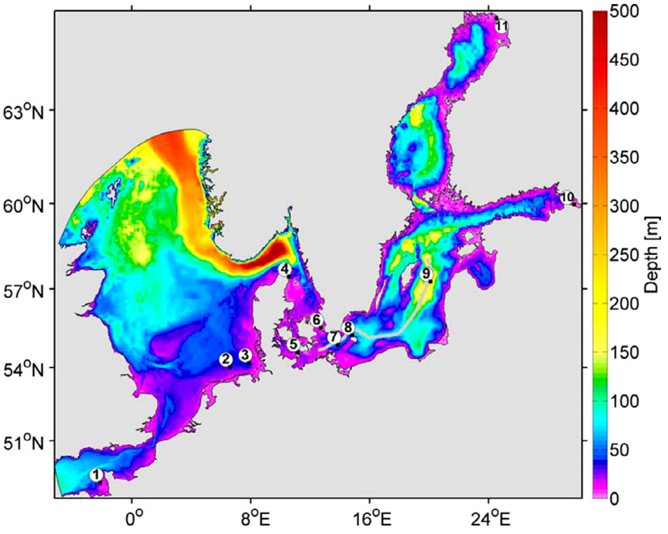

Fig. 1. North Sea and Baltic Sea topography. The colour scheme was chosen to better illustrate the bottom relief in the deepest parts of the two basins. The positions of the following stations used in model validation are also shown: (1) Jersey, (2) FINO-1, (3) Helgoland, (4) Frederikshavn, (5) Fehmarn Belt, (6) Drogden, (7) Arkona Basin, (8) Tejn, (10) Kronstadt and (11) Kemi. Analyses of numerical simulations are presented further in the paper at location (9) and along the transect line starting in the western Arkona Basin and ending in the northern Gotland Deep (grey line).

is needed there in order to resolve the complex coastal line as well as the bottom topography found in the three straits (note that the Little Belt is only 1 km wide). Without an adequate resolution the hydrodynamics of the inflow–outflow system cannot be accurately simulated.

A number of numerical models based on primitive equations and finite-difference discretization have been used to simulate the circulation in the coupled North Sea–Baltic Sea; e.g., models of Funkquist and Kleine (2007), She at al. (2007), Fu et al. (2011, 2012), Zhuang et al. (2011). More detailed references are given in Meier and Kauker (2003), Lehmann et al. (2004), Schmidt et al. (2008), Leppäranta and Myberg (2009). However the horizontal resolution in these models did not allow sufficient resolution in the three straits. Burchard et al. (2005, 2009) used a horizontal resolution of 0.5 nm to study the dominant dynamics in the Western Baltic Sea and validated the model performance with a focus on the mixing in the areas of Drogden Sill, Darss Sill and the Bornholm Channel. Although this resolution was not sufficient for the Sound and inadequate for the Little Belt, the idealized simulations of the authors allowed determination of the pathways of salt transport during medium-intensity inflow events (see also Meier, 2007), demonstrating a reasonable consistency with the observations. However in these publications some problems with the open boundary conditions at the Kattegat, and also with the initialization strategy have not been resolved; e.g., forced with the climatological condition, the model did not fully recover this condition in an annual simulation (Meier, 2007).

Motivated by the above challenges we (1) address the resolution problem by enabling sufficient resolution in the straits, and (2) avoid inconsistencies in some earlier studies. Some of these inconsistencies are associated with either the forcing being prescribed in the NBTZ, or with the one-way or two-way nesting techniques, which are not seamless. Therefore we describe in the present paper an application of an unstructured-grid model for the coupled basins starting from the English Channel in the South up to the Shetland Islands to the North. This configuration enables the seamless propagation of the large-scale forcing into the NBTZ (see Danilov, 2013 for a review of recent developments and practices on using unstructured meshes in ocean modelling and for more references). Unlike other applications of unstructured models for this region (e.g. Kliem et al. 2006), we use a 3D baroclinic set up. This presents a third challenge because it has never been shown before how unstructured-grid models can adequately simulate the complex thermohaline structure of two basins. If the adequacy is demonstrated, the model could be used also for other similar ocean areas.

It's our hope that our research will shed new light on the pros and cons of the current model vs. other more traditional models (including both structured- and unstructured-grid models). The major differences include: implicit time step (which avoids splitting errors and enables efficiency and robustness), and treatment of momentum advection with Eulerian–Lagrangian Method (ELM, which further boosts efficiency and robustness) (although central-difference scheme has also been implemented). While the use of Galerkin Finite Element Method (GFEM) is not new, the combination of it with the previous two features seems to have achieved a good balance in terms of numerical diffusion and dispersion, as the numerical diffusion inherent in an implicit method and ELM is balanced out by the numerical dispersion inherent in GFEM. This is very different from other earlier finite-volume models such as ELCIRC (Baptista et al. 2005) where numerical diffusion is dominant (another major advantage in this regard is SCHISM's ability to handle very skew elements and be completely free of orthogonality constraint). As a result, the model can be effectively used to simulate cross-scale processes with both accuracy and efficiency. However, as an unstructured-grid model, it's not immune to some common issues such as sensitivity to grid generation. The latter does not have an easy answer as the quality of model results is clearly tied to the grid used, and while there are some generic guidelines about mesh quality, ultimately the issue is application dependent. We are in the process of carefully testing and documenting this issue for a variety of barotropic and baroclinic applications including baroclinic instability (eddies and meanders), and comparing our results with those from structured-grid models (Zhang et al. 2015).

The research questions and novelties can be briefly summarized as follows:

1. Describe a new model and its application to a very specific region, which is dominated by tides and shelf processes, baroclinic processes driven by fresh water fluxes in the Baltic Sea and very specific (shallow) transition zone. Addressing all these needs good quality of simulation of both barotropic and baroclinic processes.
2. Quantify how well the model replicates the temporal and spatial variability of physical processes in the studied area.
3. Make available a reproducible reference set-up for this model to be used in further studies.

While deeper analysis of processes will be addressed elsewhere, this paper is focused on validating the new model. In Section 2 we describe the model used. Section 3 describes the dynamics of sea level and the inter-comparisons with observations. Section 4 addresses the simulations of thermohaline fields, and Section 5 describes the quality of simulations of water mass structure. Short conclusions are formulated at the end. Because the processes in the two basins differ greatly, the validation presented here is not fully symmetric for the two basins; the baroclinic part of the Baltic Sea is presented in more detail along with the issue of water mass structure.

2. The model

2.1. Model description

SCHISM (Semi-implicit Cross-scale Hydroscience Integrated System Model; Zhang et al. submitted) is a derivative product of