Scenarios of multi-annual simulations of the coupled North Sea – Baltic Sea system

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ABSTRACT
The Baltic Sea is a brackish semi-enclosed sea having a very limited water exchange with the more saline North Sea. The limited water exchange and large river runoff lead to typical two-layer salinity stratification with a permanent halocline located at about 60-70 meters below the sea surface.

The aim of the present study is to make scenario simulations of the coupled North Sea - Baltic Sea system using the GETM (http://getm.eu) hydrodynamic model. Specifically we want to test the influence of different model settings, parameterization schemes, initial conditions and of a variety of forcing conditions on the occurrences and strength of salt water inflows. The model area covers the connected Baltic Sea and North Sea, therefore no prescribed barotropic sealevel forcing in the Kattegat area is applied. Initial conditions and 3D boundary conditions are derived from climatological data. The tidal forcing is applied at the open boundaries in the English Channel and at the open North Sea. Different relatively coarse data sets for the meteorological forcing were used (ERA40, ERAIN, CLM). Despite of that coarse spatial resolution the main features of the inflow dynamics could be qualitatively reproduced. For the river inflow we used climatological data for the 30 most important rivers within the model area.

Factors that influence the water exchange comprise the large scale air pressure fields, the corresponding wind fields specifically in the channel area, the fresh water run off to the Baltic Sea, water level (filling state) of the Baltic Sea, tides, the exact bathymetry determining the cross sectional area and the related bottom friction as well as the vertical and horizontal mixing processes.

A first assessment of the long term effect of the saltwater exchange is performed by comparing the salinity changes at the Gotland Deep from the different simulations. We established that the most critical forcing component is the strength of the actual wind forcing, followed by the importance of the fresh water flux. The role of the air pressure field and of the tidal forcing is smaller, but they cannot be neglected for achieving realistic simulations.

The most important GETM internal model characteristic appeared to be the used internal pressure gradient parameterization scheme, followed by the turbulence parameterization and the applied advection scheme.

KEYWORDS
Hydrodynamic modelling; Baltic Sea; density inflow.
INTRODUCTION
The Baltic Sea is a salinity stratified semi-enclosed basin located in Northern Europe. The permanent salinity stratification is maintained by the surface freshwater supply from rivers and precipitation and by the bottom inflow of high saline water from the North Sea. Until recently it was believed that the bottom water in the deep sub-basins is only replaced after large storm forced mainly barotropic inflow events, so called Major Baltic Inflows (MBIs, Matthäus et al. 1992). The importance for the renewal of intermediate layers in the halocline of small and medium strength baroclinic inflows has been demonstrated by (Feistel et al. 2006). Mohrholz et al. (2006) have shown, that during the past 2 decades the frequency of large barotropic inflows has decreased, whereas the frequency of medium intensity baroclinic inflows has increased.

Many different factors are influencing the water exchange between the North Sea and the Baltic Sea and specifically the inflow of salty and oxygen rich water to the deeper Baltic basins like the Gotland Sea. These factors comprise the large scale air pressure fields over the entire area, the resulting wind fields specifically in the channel area, the fresh water run off to the Baltic Sea, water level (filling state) of the Baltic Sea, tides, the exact bathymetry determining the cross sectional area and the related bottom friction as well as the vertical and horizontal mixing processes which are diluting the inflowing water masses.

Conceptual models (Lass et al. 1996 and Gustafsson et al. 2001) could qualitatively show that the two major factors determining the occurrence of MBIs are the filling state of the Baltic Sea (as represented by the Landsort sealevel) and the large scale pressure field over the North Sea and Baltic Sea area which determine the strength of the barotropic pressure gradient. Only recently the smaller but nevertheless important role of the baroclinic pressure gradient in driving small salt water inflows was experimentally discovered by Feistel et al. (2003)

Contrary to the general understanding of the main processes achieved, until recently the detailed 3D hydrodynamic modeling of salt water inflows was not completely satisfactory. In most personal communications from model studies it was told that despite the adequate reproduction of the general features the inflowing salt water along its way through the different basins (from the Belt Sea via Arkona Sea, Bornholm Sea into the Gotland Sea) became too diluted and therefore lost its density and finally could not enter in sufficient amounts or not deep enough into the Gotland Basin.

As the main reason for this dilution process an unrealistically high numerical diffusion of current state of the art models is suspected (Burchard and Rennau, 2008). Depending on the characteristics of the model used there are at least two different reasons proposed for the occurrence of this excessively high mixing: firstly artificial mixing at the step like bottom topography for z-coordinate models and secondly pressure gradient errors for $\sigma$-coordinate models.

Despite the fact that this problem has been known for many years and is investigated by several different research groups extended and systematic studies of the importance of the different factors influencing the salt water inflow to the Baltic Sea have not been done. Even very fundamental questions about the role of the local wind field in driving or preventing salt inflows to the Baltic proper have not been well investigated. Here we will present a first attempt to separate the importance of the different processes and parameters. For doing that we are applying the public domain General Estuarine Transport Model (GETM, Burchard and Bolding, 2002, www.getm.eu), which had been used successfully for performing realistic simulations Stips et al. 2004.
MODEL IMPLEMENTATION

General features
GETM solves the three-dimensional hydrostatic equations of motion by applying the Boussinesq approximation and the eddy viscosity assumption. Vertical subgrid scale mixing is parameterized using a turbulence closure with flux boundary conditions. The turbulence scheme for vertical mixing in GETM is selected via the GOTM (General Ocean Turbulence Model, www.gotm.net) turbulence model. In this study we applied the standard k-ε turbulence closure. A simple parameterization for considering the additional mixing effect of breaking internal waves can be included. The model allows the application of different schemes for vertical as well as for horizontal coordinates. Different numerical schemes for tracer advection are implemented and can be used. For this study we mainly used the ULTIMATE quickest algorithm, but we also compared to the simple upstream advection scheme. A background harmonic diffusion of $AH=10$ m$^2$ s$^{-1}$ is applied. For details of the model the reader is referred to Burchard and Bolding, 2002.

Implementation details
The GETM model was implemented for the coupled North Sea Baltic Sea area using different grid sizes of 6 nm, 3 nm and 2°x3’ applying cartesian or spherical coordinate systems respectively. These grids have been generated from different sources of bathymetric data, comprising the DYNOCS bathymetry, the IOWTOPO data (Seyfert and Kayser, 1995) and the GEBCO global 1° topographic data set. Further different filters were applied for smoothing the bathymetry, as this is required for terrain following coordinates which have been used for these simulations. As an example the 3°x2’ bathymetry generated in such a way is shown in Fig. 1, which also provides an impression of the model area. It should be mentioned that the difficulty of simulating salt water inflows using such a large coupled domain is considerably increased, as the very important Kattegat water level which is determining the barotropic pressure gradient cannot be prescribed. The barotropic time step had to be adjusted to the respective horizontal resolution. The split factor between barotropic and baroclinic mode was typically 30. Open boundaries of the model domain are existing between the North Sea and the North Atlantic and the English Channel. Climatological river runoff from 33 major rivers was used for the fresh water input. The model was initialized using the climatological temperature and salinity data compiled by Jannssen et al. 1999. For the open boundary conditions at the Atlantic these climatological data were also applied via a sponge layer formulation. Meteorological forcing data were provided by the European Centre for Medium Range Weather Forecasting (ECMWF, www.ecmwf.int). The following basic data were extracted from the ECMWF data base: air pressure, air temperature, total cloud cover, wind speed (east and north component), dew point temperature, precipitation and evaporation. The time step of the data is 6 hours and the downscaled spatial resolution is approximately 0.5 degrees. The data are interpolated in space and time to the respective model grid. For the tidal forcing at the open boundaries the parameterization derived from the TOPEX-POSEIDON data set has been used, see podaac.jpl.nasa.gov/cdrom/tide. The extracted data are linearly interpolated in time and space to the open boundary elevation points.
Scenario simulations

The main characteristics of the simulations here presented are summarized in Table 1. The standard setup (Run0, r0) used 30 vertical layers, fresh water flux (FWF) from rivers and from the atmosphere, tidal forcing at the open boundaries, complete meteorological surface forcing and a smoothed bathymetry. For the calculation of the internal pressure gradient (IP) the Blumberg-Mellor scheme (Blumberg and Mellor, 1987) was used. For the different scenarios (run1 to run19 here) selected forcings or other features were deactivated, to assess their relative importance to the overall quality of the simulation. For run r4 the number of vertical layers was reduced to 15 and for run19 it was increased to 45.

The simulation r0, starting from climatology in January 1997 represents the basic reference run. The runs usually extend from the year 1997 until the end of 2007, but some runs (r9) were started already in 1986. During the first year (1997) the model has to adapt to the artificial initial density stratification taken from the climatological data. During the first phase of this process the salinity is decreasing at an unrealistically high rate, resulting from strong transport and exchange processes. This adaptation process seems to last about one year for the GETM model. At the end of the first year the bottom salinity in the deep basins has approached the original starting value again.

For the purpose of this investigation we use as a simplified measure of model performance the change of the salinity in the bottom layer at the central station BY15 (57.3° N, 20° E, see Fig. 1) in the Gotland basin. The total change of bottom salinity after 10 years of simulation for the different runs is given in Table 2. In the reference run the salinity increased during these 10 years by 0.34 PSU, which is slightly less than the 0.5 PSU increase resulting from the measured data taken from the monitoring programme. Changing now different components of the forcing and the setup we compare their relative influence with respect to the reference run.

Figure 1. Bathymetry of the coupled North Sea - Baltic Sea setup. The monitoring station BY15 in the central Baltic Proper (Gotland Sea) is indicated by a circle.

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The expected high importance of the riverine fresh water input not only for the surface salinity, but also for the bottom salinity is evidenced by run r1 (Table 2). The bottom salinity increases after the usual initial drop in almost all the years, with a rate of 2.9 PSU in 10 years, which is about 7.6 times more than the reference run r0. From this high sensitivity it is therefore clear that the usage of the best available river runoff data is essential for adequately simulating the Baltic Sea salinity. This was already shown by Lehmann and Hinrichsen, 2000. The importance of the applied wind forcing is investigated by the runs r5, r17 and r18 applying either no wind or increased/reduced wind during the simulation. The highest overall value for the bottom salinity is achieved by switching off the wind forcing completely (r5), which results in about 9 times higher increase compared to the reference run (Table 2). Figure 2 is showing a visualization of the temporal development of the bottom salinity at BY15 from run r17 using an increased wind speed and run r18 using a decreased wind speed compared to

### Table 1. Summary and characteristics of the analyzed runs for the scenario simulations.

<table>
<thead>
<tr>
<th>Run</th>
<th>Forcing</th>
<th>Start year</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run00 (r0)</td>
<td>FWF, rivers, tides, wind, air pressure, smoothed, 30L</td>
<td>1986</td>
<td>Reference run</td>
</tr>
<tr>
<td>Run01 (r1)</td>
<td>FWF, no rivers, tides, wind, air pressure, smoothed, 30L</td>
<td>1997</td>
<td>No rivers</td>
</tr>
<tr>
<td>Run02 (r2)</td>
<td>FWF, rivers, no tides, wind, air pressure, smoothed, 30L</td>
<td>1997</td>
<td>No tides</td>
</tr>
<tr>
<td>Run03 (r3)</td>
<td>FWF, rivers, tides, wind, air pressure, unsmoothed, 30L</td>
<td>1997</td>
<td>Unsmoothed bathymetry</td>
</tr>
<tr>
<td>Run04 (r4)</td>
<td>FWF, rivers, tides, wind, air pressure, smoothed, 15L</td>
<td>1997</td>
<td>Only 15Levels</td>
</tr>
<tr>
<td>Run05 (r5)</td>
<td>FWF, rivers, tides, no wind, air pressure, smoothed, 30L</td>
<td>1997</td>
<td>No wind</td>
</tr>
<tr>
<td>Run06 (r6)</td>
<td>FWF, rivers, tides, wind, no air pressure, smoothed, 30L</td>
<td>1997</td>
<td>Constant air pressure</td>
</tr>
<tr>
<td>Run07 (r7)</td>
<td>FWF, rivers, tides, wind, air pressure, smoothed, 30L</td>
<td>1997</td>
<td>Different IP scheme 4</td>
</tr>
<tr>
<td>Run08 (r8)</td>
<td>FWF, rivers, tides, wind, air pressure, smoothed, 30L</td>
<td>1997</td>
<td>Different IP scheme 6</td>
</tr>
<tr>
<td>Run09 (r9)</td>
<td>No FWF, rivers, tides, wind, air pressure, smoothed, 30L, starting earlier</td>
<td>1986</td>
<td>Starting earlier</td>
</tr>
<tr>
<td>Run13 (r13)</td>
<td>FWF, rivers, tides, wind, air pressure, smoothed, 30L</td>
<td>1997</td>
<td>Simple turbulence</td>
</tr>
<tr>
<td>Run16 (r16)</td>
<td>FWF, rivers, tides, wind, air pressure, smoothed, 30L</td>
<td>1997</td>
<td>Simple advection (Upstream)</td>
</tr>
<tr>
<td>Run17 (r17)</td>
<td>FWF, rivers, tides, wind, air pressure, smoothed, 30L</td>
<td>1997</td>
<td>Wind=Wind*1.3</td>
</tr>
<tr>
<td>Run18 (r18)</td>
<td>FWF, rivers, tides, wind, air pressure, smoothed, 30L</td>
<td>1997</td>
<td>Wind=Wind*0.7</td>
</tr>
<tr>
<td>Run19 (r19)</td>
<td>FWF, rivers, tides, wind, air pressure, smoothed, 30L, 45Levels</td>
<td>1997</td>
<td>45Levels</td>
</tr>
</tbody>
</table>
run r0. The reason for the increased bottom salinity without wind or reduced wind is the strongly suppressed vertical mixing, which allows the high saline water to inflow without much dilution.

![GETM 3nm Bottom Salinity BY15](image)

**Figure 2.** Temporal development of the bottom salinity at station BY15, reference run r0, increased wind speed r17 and decreased wind speed r18.

Usually the role of tides in the Baltic Sea is considered to be small. As can be seen in Table 2 for the run r2 the tidal forcing at the open boundary of the North Sea was switched off. The salinities are increased when switching the tidal forcing off and have a tendency to increase further (increase about 0.5 PSU in 10 years). This underlines the fact that despite the small influence of tidal mixing in the Baltic proper, it cannot be ignored for long term (decadal) simulations. This also demonstrates that doing simulations with all settings being equal but just not applying tidal forcing would give slightly more realistic results, then with tidal forcing, because of the reduced mixing.

The sensitivity of the bottom salinity to the complete ignorance of air pressure fluctuations (at least over such long time scales as considered here) and to a 50% reduction of the number of used layers is surprisingly small (Table 2). In both cases the simulations follow the reference run rather close.

General vertical coordinates as used in this study are terrain following and therefore allow a good representation of dense water inflows Burchard *et al.* 2005, whereas special measures must be applied to achieve equally good results in z-level models Meier, 2007. Unfortunately the disadvantage of using terrain following coordinates is often increased artificial mixing due to numerical errors in the calculation of the internal pressure gradient over steep topography Mellor et al. 1998. Therefore the realistic rough bottom topography is usually smoothed before doing simulations with terrain following models (Martinho and Batteen, 2006). Not applying the normal smoothing will lead to a little increased mixing in the model domain and therefore the bottom salinities are reduced, as can be seen in Table 2 run r3.

The simulations are very sensitive to changes in the applied advection scheme. Instead of the total variance diminishing (TVD) scheme used for the reference run we used a simple upstream advection scheme for run16. For a visual impression of the result the temporal changes of the bottom salinity are also shown in Figure 3. Due to the high diffusive character
of the upstream advection scheme the bottom salinity is decreasing quite strong during the simulation period.

A very similar but even more pronounced effect has the substitution of the two-equation k-ε turbulence model by a simple constant background diffusivity (the canonical value of $10^{-4}$ m$^2$ s$^{-1}$ has been chosen), as can be seen from run r13 in Table 2. Obviously such a simple turbulence parameterization (still often applied in General Circulation Models), leads again to far too high vertical mixing, thereby diluting the inflowing salt water too much.

Finally we present here also results from the run r8, which uses the more sophisticated internal pressure gradient calculation scheme published by Shchepetkin and Mc Williams, 2003. Unfortunately the result is rather disappointing as the lowest overall bottom salinity after the 10 year simulation period is achieved and the reason for this unexpected behaviour is unclear.

**Table 2.** This gives a summary of the change of bottom salinity at the central Gotland Sea station BY15 after 10 years of simulation. Given are the absolute change in PSU and the change relative to the reference run r0.

<table>
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<tr>
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</thead>
<tbody>
<tr>
<td>Run05 (r5)</td>
<td>3.44</td>
<td>3.10</td>
<td>9.1</td>
<td>No wind</td>
</tr>
<tr>
<td>Run01 (r1)</td>
<td>2.92</td>
<td>2.58</td>
<td>7.6</td>
<td>No runoff</td>
</tr>
<tr>
<td>Run18(r18)</td>
<td>1.64</td>
<td>1.98</td>
<td>5.8</td>
<td>Wind*0.7</td>
</tr>
<tr>
<td>Run02 (r2)</td>
<td>0.57</td>
<td>0.23</td>
<td>0.7</td>
<td>No tides</td>
</tr>
<tr>
<td>Run06 (r6)</td>
<td>0.38</td>
<td>0.04</td>
<td>0.1</td>
<td>No air pressure variation</td>
</tr>
<tr>
<td>Run00 (r0)</td>
<td>0.34</td>
<td>0.00</td>
<td>0.0</td>
<td>Reference</td>
</tr>
<tr>
<td>Run04 (r4)</td>
<td>0.31</td>
<td>-0.03</td>
<td>-0.1</td>
<td>15 Levels</td>
</tr>
<tr>
<td>Run03 (r3)</td>
<td>0.24</td>
<td>-0.10</td>
<td>-0.3</td>
<td>No bathymetry smoothing</td>
</tr>
<tr>
<td>Run16(r16)</td>
<td>-0.91</td>
<td>-1.25</td>
<td>-3.7</td>
<td>Upstream advection</td>
</tr>
<tr>
<td>Run13(r13)</td>
<td>-1.29</td>
<td>-1.63</td>
<td>-4.8</td>
<td>Simple turbulence</td>
</tr>
<tr>
<td>Run08 (r8)</td>
<td>-1.78</td>
<td>-2.12</td>
<td>-6.2</td>
<td>Sophisticated pressure gradient</td>
</tr>
</tbody>
</table>
CONCLUSIONS
An attempt was made to investigate some of the factors that influence the quality of multi-annual simulations of the complicated large scale estuarine basin like the Baltic Sea. Despite the fact that many studies have dealt with the circulation in the Baltic Sea experimentally or by simulation, there are still many open questions related to the pathways of the inflowing salt water in the various sub basins. The role of upwelling stirred by the topography and of diapycnal mixing caused by breaking internal waves is still not understood. Here we were able to show that the simulated bottom salinity far away from the Baltic Sea entrance area has its greatest sensitivity with regard to the applied fresh water fluxes, wind field and tidal forcing as external model forcing data. The details of the numerical implementation of the model as the used advection scheme, the turbulence model and pressure gradient scheme are of at least the same importance as the boundary forcing.

It seems still to be necessary to significantly improve current hydrodynamic models to achieve more realistic simulations and to improve the applied boundary conditions. One way in this direction might be to introduce so called adaptive coordinates Burchard and Beckers, 2004, which might be able to avoid some of the major drawbacks of currently used coordinate systems.

ACKNOWLEDGMENT
We thank the GETM development team for their continuous enthusiasm and support in helping to improve and to run the model. The measured data for this study were provided by the Baltic NEST database. Excellent informatics support was given by Philippe Simons and Francesco Andreozzi.
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