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Variability of bottom friction velocity along the inflow water pathway in the Baltic Sea

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ABSTRACT

Using a regional circulation model of the Baltic Sea with the horizontal resolution of 0.5 nautical miles and with an open western boundary, time series of bottom friction velocity and bottom salinity were simulated for the period of April 2010–July 2016 and analysed at specific points of interest along the inflow water pathway. The model reproduces reasonably well observations of the bottom currents and salinity at monitoring stations in the Bornholm and Gotland deeps. The bottom friction velocity at chemical warfare dumpsites in the Bornholm and Gotland basins was found to be permanently below the resuspension thresholds for the suspended particulate matter and fine sand, and even the Major inflows could not violate the balance. Occasionally the bottom friction velocity may exceed the resuspension threshold for the fine biogenic material (fluffy layer and cysts) almost everywhere in the deep Baltic basins, though additional studies are necessary to assess the likelihood of potential transport and dispersion of the chemical warfare by-products due to high sorption ability of the fine biogenic material.

1. Introduction

Bottom shear stress, τ, or bottom friction velocity $u_* = (\tau/\rho)^{1/2}$, where ρ is the water density, is a key parameter responsible for the intensity of resuspension/deposition of sedimentary material in the sea or river flows. Matter flux Q describing the quantity of sediment per unit area and time which is resuspended or deposited at the bottom can be parameterized as follows (Puls and Sündermann (1990))

$$Q = \left\{ \begin{matrix} w_{sink} c_B, & u_* \le u_{*d} \\ 0, & u_{*d} < u_* \le u_{*r} \\ M\rho(u_*^2 - u_{*r}^2), & u_* > u_{*r} \end{matrix} \right\}, \tag{1}$$

where u_{*d} and u_{*r} are critical friction velocities (thresholds) for deposition and resuspension, respectively, w_{sink} and c_B are settling velocity and near-bottom concentration of sedimentary matter, respectively, and M is a material-specific dimensional constant [s/cm]. The settling velocity w_{sink} varies from $4 \cdot 10^{-4}$ cm/s for the suspended particulate matter to $4 \cdot 10^{-1}$ cm/s for fine sand, while the material-specific constant M is estimated within a narrow range of $(1\text{–}2) \cdot 10^{-5}$ s/cm for all types of sedimentary material (Kuhrts et al., 2004). For the bottom friction velocity below the deposition threshold, $u_* \le u_{*d}$, matter flux Q across the bottom is negative implying the deposition of suspended matter, and the other way around, for the bottom friction velocity above the resuspension threshold, $u_* > u_{*r}$, matter flux Q across the bottom is positive implying the resuspension of bottom sediments. In between, for $u_{*d} < u_* \le u_{*r}$, a dynamical balance between the deposition and resuspension processes occurs. Typical values of resuspension threshold are $u_{*r} = 2$, 1.4, and 0.5 cm/s for the suspended particulate matter, fine sand, and fine biogenic material (fluffy layer and cysts), respectively (Kuhrts et al., 2004). The bottom shear stress is caused by near-bottom currents and waves; in the shallow water the contribution of surface waves can dominate, while in the deep sea, along the pathway of inflow waters, the contribution of near-bottom gravity flows and internal waves with near-inertial frequency to the bottom friction can be essential.

This work is aimed to study the variability of bottom shear stress along the pathway of inflow waters in the Baltic Sea by means of numerical modelling. In particular, it would be interesting to find out if the Major Baltic Inflows (MBI's), i.e. the rare events (recently one or two events per decade (Mohrholz et al., 2015)) that ventilate the deepest Baltic basins, are able to largely enhance the bottom shear stress relative to the typical background values. Note, that along the Baltic inflow pathway, there are two dumpsites of chemical weapons (CW), one in the Bornholm Deep and the other in the Eastern Gotland Basin (HELCOM, 1994; Sanderson et al., 2010), and the enhanced bottom shear stress could potentially reinforce the transport of bottom

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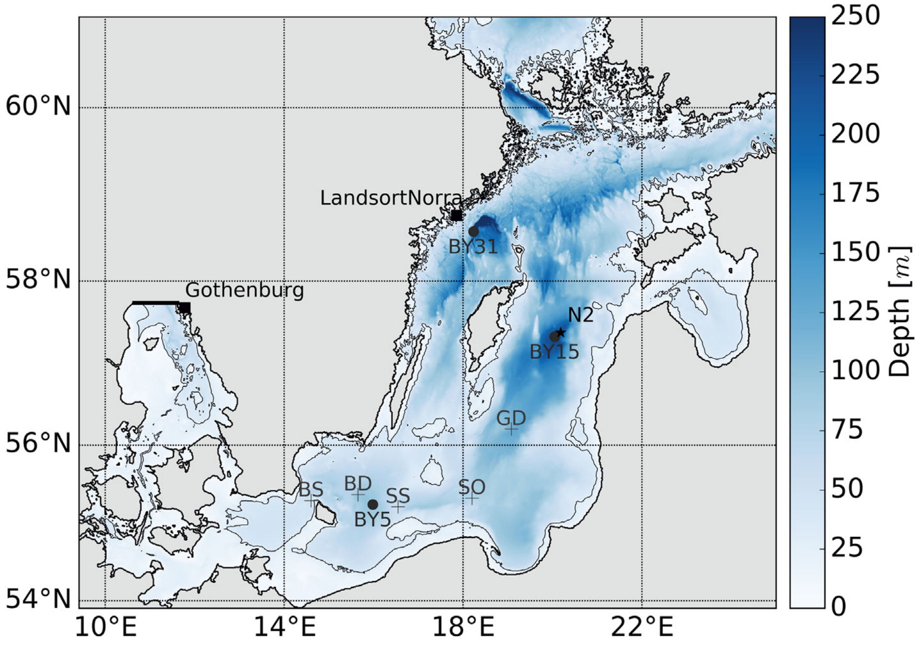

Fig. 1. Bathymetric map of the model domain (except for the Bothnia Sea/Gulf and the eastern part of the Gulf of Finland) with the location of monitoring stations (black dots) and the location of points of interest in the southern Baltic Proper (black crosses). The sea level observations conducted by Swedish Meteorological and Hydrological Institute (SMHI) and provided publicly within the COPERNICUS project from the Gothenburg station were used for the open boundary and from the LandsortNorra station for validation. Long-term current observations from a mooring site N2 (black star) conducted by the Leibniz Institute for Baltic Sea Research (IOW) were used for statistical comparison. Bold black line indicates the location of open boundary. Thin black line is the 30 m isobath.

sediments contaminated by the CW by-products. The latter defines the applied importance of the study.

2. Model setup and validation

2.1. Model setup

The General Estuarine Transport Model (GETM, Burchard and Bolding, 2002) was applied to simulate the bottom boundary currents and the dynamics in the southern Baltic Sea. GETM is a primitive equation 3-dimensional, free surface, hydrostatic model with the embedded vertically adaptive coordinate scheme (Hofmeister et al., 2010; Gräwe et al., 2015). The vertical mixing is parametrized by two equation k-ε turbulence model coupled with an algebraic second-moment closure (Canuto et al., 2001; Burchard and Bolding, 2001). The implementation of the turbulence model was performed via General Ocean Turbulence Model (GOTM, Umlauf and Burchard, 2005).

The horizontal resolution of the model grid is 0.5 nautical miles (approximately 926 m) over the whole Baltic Sea (Fig. 1); there are 60 adaptive layers in the vertical direction. The digital topography of the Baltic Sea was taken from Baltic Sea Bathymetry Database (http://data.bshc.pro/) and adapted for the Gulf of Finland based on the data by Andrejev et al. (2010, 2011).

The atmospheric forcing (the wind stress and surface heat flux components) was calculated from the wind, solar radiation, air temperature, total cloudiness and relative humidity data generated by HIRLAM (High Resolution Limited Area Model) version maintained by the Estonian Weather Service with the spatial resolution of 11 km and the forecast interval of 1 h ahead of 54 h, recalculated for every 6 h (Männik and Merilain, 2007). The wind velocity components at the 10 m level along with other HIRLAM meteorological parameters were interpolated to the model grids.

The model simulation runs were performed from 01 April 2010 to 30 October 2016 covering at least 2 major inflow events into the Baltic Sea. The model domain has an open boundary in the Danish straits. For the boundary conditions the sea surface height measurements from the Gothenburg station and the climatological temperature and salinity profiles along the open boundary were utilized. The freshwater input from 54 largest Baltic Sea rivers together with their inter-annual variability was taken into account.

The initial thermohaline field was generated by COPERNICUS reanalysis of the Baltic Sea for the time period 1989–2014. The product provided the horizontal resolution of 3 n.m. and the vertical resolution from 5 m at the surface up to 50 m in the bottom layers.

Here we analyse the simulated time series of bottom friction velocity at several specific points of interest located in the Southern Baltic along the pathway of inflow waters, in particular, in the Bornholm Strait (14.60°E–55.35°N, denoted by BS in Fig. 1), Słupsk Sill (16.55°E–55.22°N, denoted by SS), Słupsk Furrow outlet (18.20°E–55.33°N, denoted by SO), Bornholm dumpsite (15.65°E–55.375°N (Sanderson et al., 2010), denoted by BD), and Gotland dumpsite (19.08°E–56.20°N (HELCOM, 1994), denoted by GD). The bottom friction velocity, u_*, was calculated as

$$u_* = [(\tau_x/\rho)^2 + (\tau_y/\rho)^2]^{0.25}. \tag{2}$$

Components of the bottom shear stress, τ_x and τ_y, were estimated using an assumption of the logarithmic velocity profile (the von Karman's "law of the wall") as (Blumberg and Mellor, 1983).

$$(\tau_x, \tau_y)/\rho = -C(u_B^2 + v_B^2)^{1/2}(u_B, v_B),\ C = \max\left[\frac{\kappa^2}{[\ln(z_B/z_0)]^2}, 0.0025\right],$$

where u_B and v_B are components of the simulated flow velocity at the level closest to the bottom, z_B is the height of the level relative the bottom (varied in the simulation within the range of $z_B = 0.5 - 3.6$m), $\kappa = 0.4$ is the von Karman constant, and z_0 is the roughness parameter, $z_0 = 0.002$m. The roughness parameter was adjusted to fit simulated and observed time series of bottom salinity, in particular, the arrival time of the 2014–2015 MBI to BY15 (see Fig. 2 and related explanation in Section 2.2). Along with the bottom friction velocity time series, the time series of wind friction velocity, u_{*w}, and bottom salinity, S_B, are analysed.

2.2. Model validation

The model was validated against the time series of bottom and surface salinity from 3 different monitoring stations of the Baltic Sea – BY5, BY15 and BY31 and the time series of the sea surface height at the LandsortNorra station. In addition we have done a statistical comparison of deep current velocities at BY5 and station N2 in the Gotland Deep (see Fig. 1 for the locations).

The time series of surface and bottom salinity at the BY5, BY15, and BY31, both obtained from the Nest Institute's BED (Baltic