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Sensitivity of the Baltic Sea level prediction to spatial model resolution

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ABSTRACT

The three-dimensional hydrodynamic model of the Baltic Sea (M3D) and its new parallel version (PM3D), developed at the Institute of Oceanography, University of Gdańsk in Poland, was tested to establish a grid resolution adequate for the Baltic Sea level prediction. Four outputs of the M3D/PM3D, calculated with spatial resolution varying from 3 NM to 0.5 NM, were validated by comparing the results with hourly sea level readings collected at 9 Baltic gauges in 2010–2015. The spatial resolution of 1 NM applied to the Baltic Sea resulted in a distinct improvement of agreement between the calculated and observed distributions of data. An increase in the resolution to 0.5 NM in the southern Baltic Sea improved the model quality further, as indicated by the lowest variability, the highest correlation and the highest percentage of water level simulations within the range of ±0.15 m difference relative to readings. The increase in horizontal resolution allowed to improve the fit between the observed water levels and those calculated by the PM3D in the cases of rapid sea level fluctuations, such as those registered in January 2012. The model performed slightly worse for stations with larger ranges of water level oscillations. As parallel calculations were used in the PM3D, the time necessary for computing the simulations was significantly reduced, which allowed to apply the high-resolution grid also to the operational version of the model.

1. Introduction

The Baltic Sea is a shallow intra-continental sea of the Atlantic Ocean of 392,978 km^2 surface area. Its mean depth is only 54 m; areas with depths of 50 m or less cover about 50% of the Sea, the largest depth (in the Landsort Deep) measuring only 459 m (Leppäranta and Myrberg, 2009). The Baltic Sea is connected to the North Sea through the Danish Straits, which - due to the limited transport capacity - restrain the water exchange between the two seas, influencing sea level variability on time scales longer than one month (Samuelsson and Stigebrandt, 1996).

The fresh water supply into the Baltic and inflows of more salty waters through the Danish Straits result in the mean salinity decreasing northward and eastward from the Kattegat, thus causing the sea surface height to increase. According to Ekman and Mäkinen (1996) the height difference between the ends of the Gulf of Bothnia and the Skagerrak amounts to 0.35–0.40 m. The annual course of sea level fluctuations, influenced by the seasonal variability of atmospheric conditions, shows a seasonal cycle, with the maximum level in winter months and the minimum level in May (Lehmann and Hinrichsen, 2000; Stramska et al., 2013). It is in contrast to the annual pattern of riverine runoff into the Baltic Sea, the largest in May and the lowest in December (Cyberski and Wróblewski, 2000).

As a result of the choking effect in the narrow and shallow Danish Straits, tides in the Baltic Sea are very small, on the order of a few centimetres only (Fennel and Seifert, 2008). Their impact decreases from the western part of the Baltic Sea to the Baltic Proper (Novotny et al., 2006). In the Gulf of Finland, tidal fluctuations are higher to reach 0.17–0.19 m in the Neva Bay (Medvedev et al., 2013). In turn, seiches in the Baltic Sea are of the order of 0.05–0.1 m in the open basins up to 0.3–0.4 m in the western part of the Baltic, the Gulf of Bothnia and in the eastern part of the Gulf of Finland (Fennel and Seifert, 2008). Induced mainly by air pressure gradients and then by wind impacts, they are greatly influenced by the bathymetry and the geometry of the basins (Metzner et al., 2000).

The sea level in the Baltic is strongly influenced by wind forcing (Johansson and Kahma, 2016). Persistent winds from the south-west or north-east push the water into or out of the Baltic Sea, respectively, resulting in a rise or drop in the mean sea level (Hünicke et al., 2015). According to Fennel and Seifert (2008), the level of filling of the Baltic Sea basin may thus change by ±0.5 m on the average. Short-term sea level variations result mainly from temporary winds which redistribute water within the Baltic Sea, affecting primarily the northern, eastern and south-western coasts (Ekman, 2009).

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The Baltic Sea level is significantly influenced by large-scale atmospheric pressure patterns over the North Atlantic Ocean. The impact of the North Atlantic Oscillation is particularly distinct during winter months (Andersson, 2002; Jevrejeva et al., 2005; Hünicke and Zorita, 2006; Dailidienė et al., 2011). Other factors affecting the sea level embrace atmosphere forcing over the western Baltic Sea (Lehmann and Post, 2015), precipitation and temperature (Chen and Omstedt, 2005; Hünicke and Zorita, 2006).

Storm surges in the Baltic Sea are associated with low-pressure systems travelling east from the North Atlantic, sometimes to the north from the Mediterranean Sea or to the south from the Arctic Seas (Jensen and Müller-Navarra, 2008). Storm surges are induced mainly by wind activity. Other determinants include standing and long waves as well as inverted barometer effects (Ekman, 2009; Kowalewska-Kalkowska and Wiśniewski, 2009; Hünicke et al., 2015). The highest surges are recorded at the north-eastern and the south-western coasts of the Baltic Sea. In 1824, the surge level in the Neva Bay reached 4.21 m (Averkiev and Klevanny, 2010), whereas in 1872, the sea level at the Schleswig coast rose up to 3.30 m (Richter et al., 2012). The highest surge (2.75 m) at the Gulf of Riga coast was recorded in 2005 (Suursaar and Kullas, 2006), while in the Gulf of Bothnia the level of 2.01 m was registered in 1984 (Averkiev and Klevanny, 2010). The surge levels in the central part of the Baltic Sea usually are lower than 1 m.

Over the recent years, the Baltic Sea hydrodynamics has been a target of many numerical studies, involving the whole basin (Lehmann, 1995; Schmidt et al., 2008; Omstedt et al., 2014) and its individual regions (Lass et al., 2001; Suursaar et al., 2002; Myrberg et al., 2010; Burchard et al., 2009). Several numerical models cover both the North and the Baltic Seas systems (Zhuang et al., 2011; Zhang et al., 2016). Numerous studies were dealing with modelling of extreme water levels in the Baltic Sea (Suurssar et al., 2003; Averkiev and Klevanny, 2010; Gräwe and Burchard, 2012; Weisse et al., 2014). Mathematical modelling has also become an essential tool in the Baltic Sea level forecasting. In the 1990s, the 3D operational model BSHcmod was developed in Bundesamt für Seeschiffahrt und Hydrographie (BSH) (Kleine, 1994; Dick et al., 2001). It became a core of the High Resolution Operational Model of the Baltic Sea (HIROMB), provided then by the Swedish Meteorological and Hydrological Institute (SMHI) (Funkquist, 2001). Moreover, the BSHcmod was run and further developed at the Danish Meteorological Institute (DMI) as the DMI-BSHcmod (Gästgifvars et al., 2008). The sea surface elevation output from these models was validated for different parts of the Baltic (Kałas et al., 2001; Filinkova et al., 2002; Gästgifvars et al., 2008; Lagemaa et al., 2011). Recently, a new forecasting system for the North and Baltic Seas called the HIROMB-BOOS-Model (HBM) has been developed by the BSH, DMI, the Finnish Meteorological Institute (FMI) and the Marine Systems Institute (MSI) at Tallinn University of Technology (Brüning et al., 2014). This system is a part of a multiple model ensemble (MME), involving thirteen different operational ocean forecasting models covering either the North Sea or the Baltic Sea or both regions, built in the framework of the MyOcean project (Golbeck et al., 2015). Another model, the BSM (Baltic Sea model), constructed with the modelling system CARDINAL (Coastal ARea Dynamics INvestigation ALgorithm), has produced water level forecasts for the eastern part of the Gulf of Finland (Klevanny et al., 2001). The BSM proved successful in research on extreme sea levels in the Neva Bay (Averkiev and Klevanny, 2010).

Since the end of the 1990s, operational forecasts for the Baltic Sea have been provided by the three-dimensional hydrodynamic model M3D (Kowalewski, 2002). The model, based on the Princeton Ocean Model (Blumberg and Mellor, 1987), was developed at the Institute of Oceanography, University of Gdańsk in Poland (Kowalewski, 1997). The M3D was used then as a base on which to build other modules. Firstly, the ProDeMo (Production and Destruction of Organic Matter Model) ecohydrodynamic model was developed (Jędrasik, 1997; Ołdakowski et al., 2005; Kowalewski, 2015). In 2009, the M3D was strengthened by incorporating procedures for assimilation of measurement data (sea level, temperature, salinity) as well as spatial distributions of sea surface temperature (SST) derived from satellite images. Subsequently, the model was enhanced by adding modules for the sea ice thermodynamics and dynamics (Herman et al., 2011).

The high grid resolution applied to the modelling of the Baltic Sea hydrodynamics has significantly improved the description of processes operating in the sea (Burchard et al., 2009; Andrejev et al., 2010; Myrberg et al., 2010). Although it enables to describe the intricate coastline and bottom topography of the Baltic Sea, the computational costs increase rapidly (Andrejev et al., 2011). To minimize the computational time, nested-grid approaches are often applied. The BSH HBM model involves four grids with different spatial resolution ranging from 10 km for the North-East Atlantic to 90 m for the Elbe Estuary, 5 km resolution being applied to the Baltic Sea (Brüning et al., 2014). The horizontal resolution of the storm surge model DKSS2013 run at the DMI varies from 3 NM in the main domain covering the North and Baltic Seas to 0.5 NM in the Danish Straits (Golbeck et al., 2015). In turn, the General Estuarine Transport Model (GETM) involves spatial spacing of 3 NM applied to the North Atlantic, 1 NM to the North and Baltic Seas, and 600 m in the domain covering the Danish Straits and the western part of the Baltic Sea (Büchmann et al., 2011). The HIROMB simulations are carried out at a resolution of 1 and 3 NM (Gästgifvars et al., 2008), whereas Zhang et al. (2016) used an unstructured grid in their modelling of hydrodynamics of the North and Baltic Seas.

Within the framework of the project "The satellite monitoring of the Baltic Sea environment" (acronym: SatBałtyk) (Woźniak et al., 2011a, 2011b) dealing with remote sensing methods for monitoring of the Baltic Sea ecosystem, hydrodynamic modelling was employed to fill the gaps in SST fields in overcast areas. As a result, several models with different grid resolution have been developed. In this paper, we focus on the assessment of the sensitivity of the Baltic Sea level prediction to the grid size resolution. Section 2 describes a hydrodynamic model of the Baltic Sea (M3D/PM3D). Section 3 provides a detailed comparison of model simulations conducted with different grid resolution. Then, the storm surge projection along the Baltic Sea coast is presented. The last section discusses the results and presents the concluding remarks.

2. Materials and methods

2.1. The M3D/PM3D model description

In this study, the hydrodynamic model of the Baltic Sea (M3D) and its new version (PM3D) was applied to calculate sea level fluctuations along the Baltic coast. The M3D model has been in use for more than 20 years at the Institute of Oceanography, University of Gdańsk in Poland. The tool was based on the coastal ocean circulation model known as the Princeton Ocean Model (POM), described in detail by Blumberg and Mellor (1987). The model was adapted to the Baltic Sea by Kowalewski (1997). The operational version of the M3D model was run in 1999 with two computational domains of different spatial resolution: 5 nautical miles (NM) for the Baltic Sea and 1 NM for the Gulf of Gdańsk (Kowalewski, 2002). In 2004, a new domain covering the Pomeranian Bay and the Szczecin Lagoon was added (Kowalewska-Kalkowska and Kowalewski, 2005, 2006). Calculations in that version of the M3D were performed for three areas using different spatial resolutions: 5 NM (c. 9 km) for the Baltic Sea, 1 NM (c. 1.8 km) for the Gulf of Gdańsk, and 0.5 NM (c. 0.9 km) for the Pomeranian Bay and the Szczecin Lagoon. Recently, the model was extended to cover the Szczecin Lagoon with a resolution of 1/6 NM, i.e., about 300 m (Kowalewski and Kowalewska-Kalkowska, 2011).

At the first stage of SatBałtyk, the operational version of the M3D, including the satellite SST assimilation, was run (version A). The model involved a rectangular numerical grid in geographic coordinates. The horizontal resolution was 3′ along the latitude and 6′ along the