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Evaluating hydrography, circulation and transport in a coastal archipelago using a high-resolution 3D hydrodynamic model

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ABSTRACT

We used a 3D hydrodynamic model, COHERENS, to simulate the temperature, salinity and currents in an extremely complicated area, the Archipelago Sea in the Baltic Sea. The high-resolution model domain with approximately 460 m resolution was nested inside a coarser resolution (~3.7 km) grid covering the entire Baltic Sea. The verification of the model results against temperature and salinity measurements showed that the model well captured the seasonal temperature cycle in the surface layer, both in the inner and outer archipelago. In the inner archipelago, the model tended to reproduce higher temperatures in the bottom layer than were measured. The modelled vertical temperature and salinity stratifications were not as pronounced as the measured ones but did describe the overall vertical structure. There was large year-to-year variability in the annual mean surface circulation, both in direction and magnitude. In the deeper channels crossing the Archipelago Sea, there were some year-to-year differences in the magnitudes of the bottom layer currents, but there was very little difference in the directions. These differences were studied by introducing passive tracers into the model through river discharge and as point sources. The results showed that the prevailing wind conditions resulted in southward net transport from the Bothnian Sea towards the Baltic Proper. However, due to the variability in the wind conditions in some years, a significant proportion of transport can also be towards north, from the Baltic Proper to the Bothnian Sea.

1. Introduction

The modelling of the state of coastal waters is a very important and topical issue. Coastal seas are facing multiple stressors and in many places are suffering from heavy eutrophication and pollution. The European Union (EU) Marine Strategy Framework Directive binds EU member countries to introduce measures to achieve and maintain the good environmental status of the European seas. To cost-effectively monitor the environmental status of the seas at regional and national levels, monitoring programmes are currently being evaluated and updated.

In the Baltic Sea, eutrophication is considered one of the main threats to biodiversity (e.g., HELCOM, 2009). The status of the Baltic Sea has been monitored since 1979 via the HELCOM monitoring programme that includes, for example, measuring physical, chemical and biological variables. Although the monitoring programme includes measurements at several stations, the temporal frequency of the visits and the locations of the stations do not provide enough data to adequately resolve the physical characteristics of the Baltic Sea as an entity. The number of automated buoys, floats and gliders in the Baltic Sea (e.g., Alenius et al., 2014; Westerlund and Tuomi, 2016) is continuously increasing and supporting traditional monitoring in open sea areas. Additionally, coastal observatories are being implemented in several countries, for example the German FINO2 research platform (http://www.fino2.de) and the Finnish Utö station (http://en.ilmatieteenlaitos.fi/Uto). There is, however, still a need for more data to evaluate the state of the Baltic Sea and to evaluate the effect of the measures taken (for example those taken to reduce the external inputs of nutrients to the sea) on the health of the Baltic Sea ecosystem.

To improve the ecological state of the Baltic Sea, Helsinki Commission (HELCOM) has set country-vice allocated reduction targets in the Baltic Sea Action Plan (HELCOM, 2013). As modelling is considered to be a good tool for evaluating the effect of the actions on the state of the sea in the future, the Baltic Nest Institute has calculated the maximum allowable annual inputs of nutrients (nitrogen and phosphorus) using the Baltic Sea long-term large-scale eutrophication model (BALTSEM, Savchuk et al., 2012). Although, BALTSEM is a relatively good tool for evaluating the basic nutrient dynamics in the open sea

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areas, more sophisticated tools are needed to evaluate the dynamics of the coastal areas. This can be done by utilising coastal high-resolution models which are able to evaluate the nutrient retention and water exchange between coastal and open sea areas – until now, the latter has not been frequently mentioned.

Model systems that are carefully implemented in coastal regions and verified against a sufficient amount of measurements can bring added value in the evaluation of the Baltic Sea state in the past, present and future, and thus result in a more comprehensive view of the state of the sea. The modelling of the coastal archipelago areas where the topography is extremely complex is a challenging task. Often, the adequate bathymetric data are not available; additionally, the compilation of a model grid in such areas is not an easy task (Tuomi et al., 2014). The large computational cost of high-resolution coastal models also often limits their use. Different solutions have been studied to enable modelling in such areas. For example, Engqvist and Andrejev (2003) used a 0.5 nmi horizontal resolution to model the outer archipelago of Stockholm, but for the inner archipelago, they used a discrete basin model, where the coastal areas were divided into sill-delimited basins of varying size. This type of approach is computationally less demanding than modelling the whole area with a resolution high enough to adequately describe the bathymetry in the inner archipelago and still provides usable information on the dynamics between the inner and outer archipelago. However, the spatial characteristics in the basins of the inner archipelago cannot be reproduced with this method. Additionally, in many areas, unstructured grids can be applied to provide a higher resolution where it is needed. For example, Aleynik et al. (2016) have shown that this type of model was able to give much more accurate and detailed results than the coarse resolution basin-scale models.

Our study area, the Archipelago Sea, is located between the Gulf of Bothnia and the Baltic Sea Proper. The area consists of approximately 40,000 small islands, islets and shoals scattered over a relatively small surface area, approximately 8300 km^2, which is only approximately 2% of the surface area of the Baltic Sea. The smallest islets are just a few metres in diameter, and many of the straits between the islands are very narrow. The estimated mean depth of the area is only 19 m, but the deeper areas are typically up to 50 m deep, and there are some fault lines that are partly deeper than 100 m (Fig. 1). The Archipelago Sea is a transition zone between the Gulf of Bothnia and the Baltic Proper, as well as the coastal inner and outer archipelagos. The surface salinity varies from 4 g/kg in the inner archipelago and close to the river mouths, to 6 g/kg in the outer archipelago. Only in a few deeper areas is there a weak halocline. In summer, a seasonal thermocline develops and reaches depths of 10–20 m. Below the thermocline, there is a colder water layer, the so-called old winter water. In shallow areas in the inner archipelago, there is no thermocline, and the entire water column is heated during the summer. The coastal inner-archipelago is ice-covered even in mild winters, and during an average ice season, most or all of the Archipelago Sea is ice-covered (Seinä and Peltola, 1991). Though the Archipelago Sea is in a nodal point of sea level variations, the amplitude of the short-term (mainly inter-annual) sea level variations range from approximately 1.7 m in the southern part to approximately 2 m in the northern part (Johansson, 2014). Sea level variability is mainly driven by meteorological forcing and seiches, and changes in the total water volume of the Baltic Sea. The tides only contribute to the sea level variation in the order of a few centimetres. The deeper channels (mean depths ~40 m) that cross the Archipelago Sea in the north–south direction steer the water exchange through the archipelago between the Bothnian Sea and the Baltic Proper. The relatively shallow depths of the channels only allow the exchange of Baltic Proper and Bothnian Sea upper layer waters above the halocline. There are estimates that approximately 33% of the transport between the Baltic Proper and the Bothnian Sea goes through the Archipelago Sea, and 24% of that is southward transport; the major part, 67% of the water exchange, goes through the Åland Sea (Ambjörn et al., 1983).

There are only a few published studies of the physical oceanography of the Archipelago Sea (e.g., Ambjörn et al., 1983; Suominen et al., 2010). Most of the studies are either limited to a specific area (e.g., Virtaustutkimuksen neuvottelukunta, 1979) or are a small part in studies that actually handle the whole Baltic Sea. The number of marine biological and chemical studies is larger, for example, studies of fish spawning areas (e.g., Snickars et al., 2015) and bottom oxygen conditions (e.g., Virtasalo et al., 2005). In these studies, physical oceanography is acknowledged as one of the important driving factors. The first high-resolution modelling efforts in the Archipelago Sea were made in the BEVIS project (BEVIS, 2007), which aimed at developing a modelling system for decision support in water quality issues. The system was able to simulate the basic characteristics of the water quality in the Archipelago Sea, and it was demonstrated to adequately simulate the effect of fish farms on the nutrient dynamics in areas close to the main island of Åland. The experience gained from this earlier work encouraged the further development of modelling systems in the SEABED project (Jönsson, 2013), and recently in the “Development of Archipelago Sea nutrient load model assembly” project (Lignell et al., 2016).

In our study, we used a high-resolution implementation of the 3D hydrodynamic model COHERENS (Coupled Hydrodynamical–Ecological Model for Regional Shelf Seas) to calculate the hydrography, circulation and transport in the Archipelago Sea. The high-resolution implementation was validated against temperature and salinity observations from the years 2013–2015. The model implementation was then used to evaluate the annual mean currents in the area. The effect of wind conditions on the year-to-year variability of currents was studied. Passive tracers released as riverine inputs and point sources were introduced to the model to study the effect of the yearly variations in the current fields on the transport of substances in and through the archipelago. Finally, the model implementation was evaluated from the perspective of its future use as forcing for a coastal high-resolution nutrient load model.

2. Materials and methods

2.1. The 3D hydrodynamic model COHERENS

We used a three-dimensional hydrodynamic model, COHERENS (Luyten, 2013), to simulate the hydrography, currents and transport in the Archipelago Sea. COHERENS has been used in several modelling studies of the Baltic Sea, and it has been shown to adequately simulate the dynamics of the Baltic Sea, both at basin and coastal scales (e.g., Bendtsen et al., 2009; Myrberg et al., 2010; Tuomi et al., 2012).

COHERENS solves the momentum equation in an Arakawa C-grid using the Boussinesq approximation and the assumption of vertical hydrostatic equilibrium. The equations of momentum and continuity are solved numerically using the mode-splitting technique (Blumberg and Mellor, 1987), where a first-order explicit Euler scheme was used for the barotropic mode and a semi-implicit TVD scheme was used for the baroclinic mode. For the equation of state, a formulation by McDougall et al. (2003) was used. Surface stress and heat flux formulations are calculated according to Large and Pond (1981, 1982). For vertical mixing, the k-ε parameterisation was applied.

The Archipelago Sea was modelled using a one-way nested approach as follows: a coarse resolution Baltic Sea model provides the boundary conditions for a finer-grid coastal application. The Baltic Sea model has a horizontal resolution of 2 nautical miles and 80 vertical layers, and the nested coastal model has a resolution of 0.25 nautical miles and 40 layers (bathymetries shown in Fig. 1). The Baltic Sea bathymetry is based on the IOW (the Leibniz Institute for Baltic Sea Research, Warnemünde) ocean bottom topography (Seifert et al., 2001). The high-resolution coastal grid was compiled from bathymetric data available in coastal nautical charts of the Finnish Transport Agency after some modifications based on the VELMU depth model (http://www.syke.fi/en-US/Open_information/Spatial_datasets).