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The performance of the parameterisations of vertical turbulence in the 3D modelling of hydrodynamics in the Baltic Sea

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ABSTRACT

This paper is devoted to a study on the effects of different parameterisations of vertical turbulence – with a 3D hydrodynamic model COHERENS – on the accuracy of calculated temperature and salinity fields in a hydrodynamically complex test area – the Baltic Sea, Gulf of Finland. Two algebraic parameterisations and k–ε and k-models were used. For k-model four different sets of stability functions were used. Calculated vertical profiles of temperature and salinity were compared against CTD-profiles collected during a measurement campaign in the Gulf of Finland in summer 1996. The dataset has an outstanding spatial and temporal coverage including over 300 measured CTD profiles. The thermocline depth was underestimated throughout summer by all the vertical turbulence schemes. The selection of stability functions had significant effect on the accuracy of the k-model. Generally k-model performed better when the limiting conditions for mixing length were not applied. The k-model with stability functions based on the Munk–Anderson relation without limiting condition for mixing length showed best accuracy in the calculated profiles of temperature and in the thermocline depth. The improvement of the meteorological forcing had an impact on the exactness of the calculated thermocline depth. However, sensitivity tests showed that this impact was relatively small. Generally, calculated salinity was overestimated in the surface layer and underestimated in the bottom layers. Algebraic parameterisations had highest accuracy in the vertical salinity profiles. In the eastern Gulf of Finland the calculated values of salinity were overestimated. The accuracy of initial conditions, river runoff and bathymetry had significant effect on the accuracy of calculated salinity fields.

1. Introduction

Vertical mixing plays a key role in the ecosystem processes in the oceans. It has e.g., an important role in the vertical distribution of nutrients and especially keeping deep chlorophyll maxima, zones of relatively high phytoplankton abundance which is fed by nutrient fluxes through the thermocline when there is depletion of nutrients in the upper mixed layer (see e.g., Reissmann et al., 2009) and affecting the overall stratification conditions considerably. The strong dependency of the accuracy of modelled biogeochemical parameters on the selection of the vertical turbulence closure scheme in a hydrodynamic model has been shown for instance by Burchard et al. (2006). Selection of turbulence closure scheme has also been shown e.g., by Amoudry and Souza (2011) to have effect on the sediment transport. Vertical mixing is very variable in different parts of the World Ocean, this being related to the various forcing functions and internal dynamics; like wind and tidal forcing, topographic and stratification conditions and e.g., frontal activity (see e.g., Large et al., 1994). Extremely complex mixing conditions are found in such basins like the Baltic Sea where the spatio-temporal changes in stratification are pronounced (see Reissmann et al., 2009 for details).

The Baltic Sea (Fig. 1) is a semi-enclosed brackish water basin where stratification, and accordingly mixing dynamics, is specific compared with the overall conditions in the World Ocean. This makes it an excellent test area e.g., for the validation of commonly used parameterizations for physical processes such as the vertical turbulence in numerical models. In the Baltic Sea a specific physical feature compared to oceans is that salinity mostly determines stratification (density) of the water masses (see e.g., Leppäranta and Myrberg, 2009). The inflowing water masses, including episodic major Baltic inflows, from the North Sea enter the Baltic Sea through the Danish Straits, move further in, sink and fill the deep water

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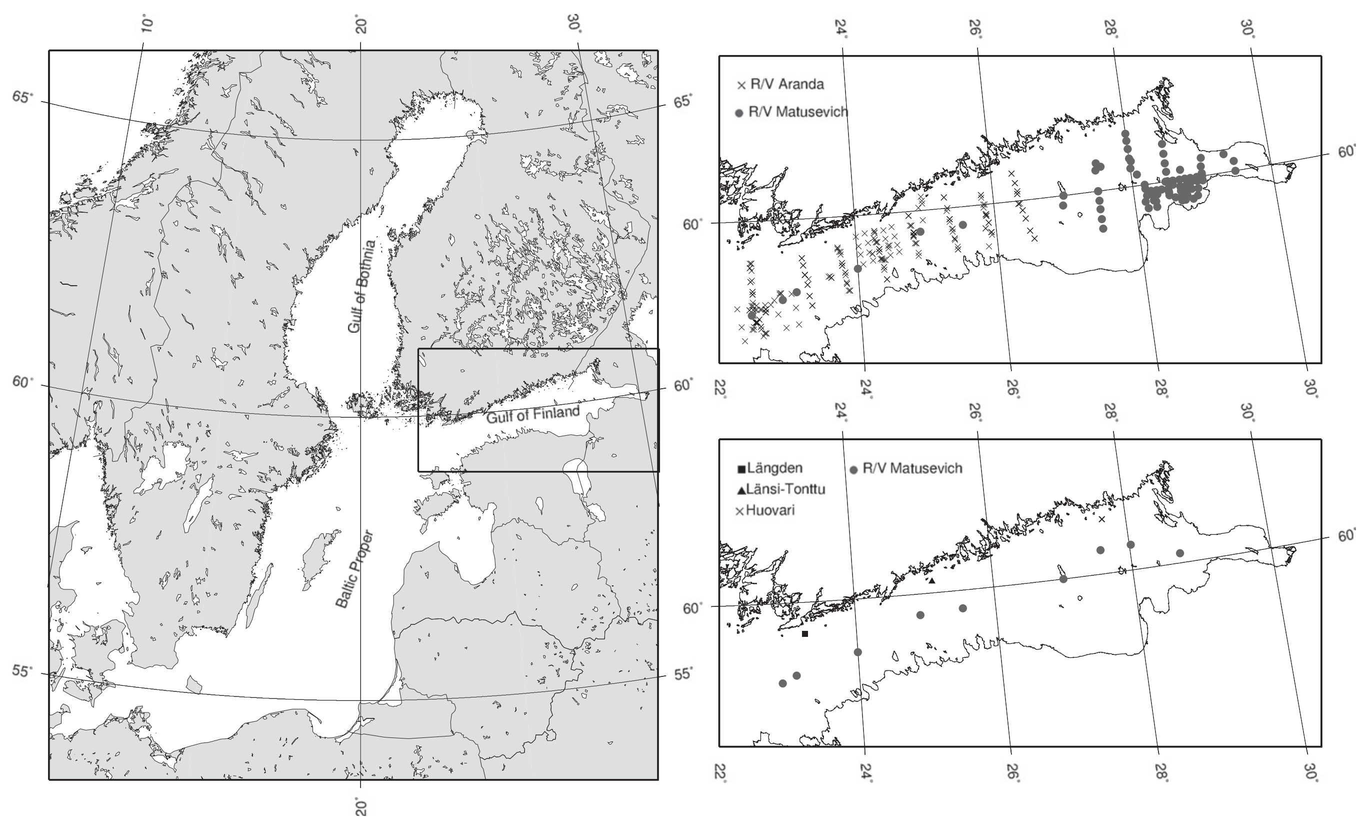

Fig. 1. The Baltic Sea with locations of the sub-basins the Baltic Proper, the Gulf of Finland, and the Gulf of Bothnia on the left panel. Location of CTD-measurements from R/V Aranda and R/V Matusevich are shown on the upper right panel. Location of three Finnish coastal stations of intensive monitoring, Längden, Länsi-Tonttu and Huovari and the section measured by R/V Matusevich on August 11–12 on the right panel.

basins. On the other hand, there is a pronounced surplus of fresh water due to voluminous river runoffs. As a result of these opposite processes the water body of the Baltic Sea has a permanent two-layer structure in salinity, and accordingly in density. The halocline is usually at a depth of 40–80 m. In summer seasonal thermocline develops at depths of 10–30 m and in the autumn it vanishes due to convection caused by the cooling and the strong wind-induced mixing. So, the stratification conditions are extremely complex: as an example of that the thermocline and the halocline are situating at different depths resulting to a layered structure that is a challenge to be accurately described by numerical models.

Our test area, the Gulf of Finland (hereafter denoted as the GoF), is the second largest sub-basin of the Baltic Sea (Fig. 1). It is an elongated basin with a length of about 400 km and a width from 48 to 135 km, having a mean depth of 37 m only. This basin has no sill towards the Baltic Proper and accordingly the water exchange between the Gulf and the Baltic Proper is continuous at all depths. The overall hydrography of the GoF is characterized by large horizontal and vertical variations both in salinity and temperature. The salinity increases from east to west and from north to south. The surface salinity decreases from 5 to 6.5 psu in the western GoF to about 0–3 psu in the easternmost Gulf (Alenius et al., 1998). In the western GoF a quasi-permanent halocline is located at the depth of 60–80 m, and due to that the wind-induced vertical mixing mostly takes in the layer above it. In the western GoF the bottom salinity can reach values up to 8–10 psu due to the advection of saltier water masses from the Baltic Proper. The bottom salinity has an extensive natural variability due to the irregular saline water intrusions as well as to the large seasonal and inter-annual variability in river runoff. Moreover, the changeable meteorological conditions (see e.g., Soomere and Keevallik, 2003) add to this variability. In the eastern GoF the permanent halocline is missing and the salinity typically increases linearly with depth.

The seasonal variations in surface temperature are pronounced in the GoF due to the large variations in solar radiation. In July–August the sea-surface temperature reaches its maximum value: these values being about 15 to 20 °C, at most up to 23 °C. The horizontal gradients can occasionally be large due to local upwelling (Lehmann and Myrberg, 2008). The well-defined seasonal thermocline starts to develop in May and it will reach a depth of 15–20 m in summer time. It starts to erode in late August when the energy balance becomes negative. The general hydrography of the GoF is described in detail by Alenius et al. (1998), by Soomere et al. (2008) and by Leppäranta and Myrberg (2009).

The parameterisations of vertical turbulence developed and verified for Oceans will encounter in the Baltic different type of conditions, where the vertical and horizontal gradients in temperature and salinity are pronounced within a relatively small area and the thermocline and halocline are situating at different depths. This is a challenging environment especially for the standard turbulence parameterisations when thinking about testing their accuracy in describing the vertical mixing in the Baltic Sea.

Which processes then determine the vertical mixing in the Baltic Sea? The review paper by Reissmann et al. (2009) summarizes these different mechanisms. One major mechanism is due to the episodic overflow of water over the sills into the Baltic Sea bringing through bottom currents in more saline waters, this leading to entrainment and interleaving of the incoming water masses to the level of neutral buoyancy (e.g., Lass and Mohrholz, 2003). Through this mechanism the Baltic deep waters are ventilated (e.g., Meier et al., 2006). Because of volume conservation, this process leads to uplift of waters masses in the central Baltic. Mixing due to inertial waves and breaking of internal waves lead to enhanced vertical turbulent transport as does the effect due to Baltic Sea eddies (e.g., Lass et al., 2003). Also the coastal upwelling (Lehmann and Myrberg, 2008) plays a certain role. In addition to that the winter-time convection