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Optimising the vertical grid for numerical simulations of the Black Sea dynamics

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In contrast to analytical methods which deal with continuous functions, solutions obtained using numerical methods depend on the type of discretisation used in the model. It is known that not only different classes of discretisation (such as finite difference, finite element, finite volume etc.) result in different numerical outputs but also variations within the same class may have significant effect on the quality of simulation. When it comes to discretization in the vertical, examples include z- or terrain-following coordinate systems all of which have their advantages and disadvantages.

The aim of this study is to identify how sensitive modelling results are to changes in the vertical grid structure, under condition that all other parameters, both physical (e.g. initial temperature and salinity field and meteo forcing) and numerical (e.g. time step, horizontal resolution, number of vertical layers) are kept the same. The simulations were carried out using the NEMO ocean model at 6 km resolution for the Black Sea which has both deep (more than 2 km) areas and an extensive (hundreds of kilometres) continental shelf. The shelf break, where the slope changes abruptly, is traditionally a difficult location for many types of models. The terrain-following coordinate systems (such as s- and sigma-) are prone the pressure gradient (PG) errors, while z-coordinate systems create a serrated edge near the bottom. Some improvements are provided by z-coordinates with partial steps; however this approach has its own limitations.

In this study we compare 4 vertical coordinate system: z-, s-, hybrid (s- on top of z-), and advanced hybrid (modified s- on top of z-). The latter two are the new systems, not yet implemented in the standard NEMO code and developed specifically for this study. The hybrid system uses s-coordinates in the upper layer of the ocean, from the sea surface to the depth of the shelf break and z-coordinate below this level. Such configuration minimizes the PG error as the terrain-following coordinates are only used over a gently sloping bottom. At the same time it allows us to resolve the details of near-bottom circulation which is important for understanding dense water cascades from the NW Black Sea shelf and formation of the Cold Intermediate Layer (CIL). However the disadvantage of this scheme is that the depth and the width of the shelf break is different at different locations of the Black Sea. In some places the shelf is so narrow that it is not properly resolved horizontally. The advanced hybrid system rectifies this issue, and combines the ideas which underpin the partial steps and s-coordinate systems.

Simulations have been carried out for a number of initial temperature (including idealised) and salinity fields and meteo forcings. The idealised fields have been set as follows: (i) completely homogenous T and S, (ii) horizontally homogenous 4-layer in the vertical, (iii) horizontally homogenous vertically continuously stratified and (iv) two layer with sloping interface (tilted ‘Margules’ fronts). The real 3D initial fields were taken from the Black sea climatology. Meteo forcing was acquired from the NCEP database. Results have shown that z-coordinate produces zero spurious currents for horizontally homogenous fields (i-iii) but created significant errors for the tilted fronts (iv). As the real structure of the Black sea waters is dome like (the CIL is shallower in the centre of the sea), the errors generated by z-coordinate system may force introducing more vertical layers which makes the computation slower. Full s-coordinate system produced large spurious currents in the areas of continental slope and rise, where the PG errors were quite large and the Hayne condition was not satisfied. The hybrid scheme produced small spurious currents in all idealised cases, however they were quite small (<1 cm/s) except a few locations neat the Turkish coast. The advanced hybrid scheme produced the smaller spurious currents than the s- and hybrid schemes for all initial settings, and smaller errors than the z-coordinate system for the most realistic, while still idealised, case of tilted fronts (case iv). For the real initial conditions the hybrid scheme produced realistic circulation pattern over the NW and NE shelf and the deep sea, however it generated unrealistically fast currents at some locations near the Turkish coast. The advanced hybrid scheme coped much better with these locations thus providing an efficient approach to improving the quality of modelling the Black Sea circulation.

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