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The water circulation near the Danube Delta and the Romanian coast modelled with finite elements

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ABSTRACT

A numerical model, based on a finite element discretisation technique, was used to study water circulation in the Black Sea's north-western shelf, particularly near the Danube Delta and the Romanian coast. The numerical grid covers the entire Black Sea and the model resolution is gradually increased versus the Romanian coast to resolve both mesoscale and microscale hydrodynamic features. Sea level, water temperature and CTD profiles, collected in the north-western shelf, were used to validate the model. The seasonal and daily coastal hydrodynamics, in 2009, were studied using 3-D water current and salinity fields. Moreover, different numerical tracers were released on the Danube's arms to characterise the Danube's plume extension. Results show that near the Danube Delta the strong salinity stratification confines most of the wind momentum input to the surface water layer, while the subsurface current is mostly influenced by the open sea circulation. In the southern Romanian coast, the vertical salinity gradient is weaker and the action of the wind can reach deeper layers. The numerical tracers show a net predominance of the Kilia branch and how coastal anticyclonic eddies can trap the river freshwater, carrying it away from the coast. This happens especially in spring, when the Danube's discharge is high and a large eddy is active in front of the Kilia branch.

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1. Introduction

The Black Sea is a nearly closed deep basin, which falls to a depth of 2212 m at its centre, while the continental shelf extends widely on the north-west area, ending with a sharp slope (Dinu et al., 2005). It communicates with the Marmara Sea through the narrow strait of the Bosporus. Here a double vertical circulation is frequent (Özsoy et al., 2001; Jarosz et al., 2011) and can be explained by the excess of low-salinity water in the Black Sea compared with the saltier water in the Marmara Sea. The Black Sea's total freshwater inflow (352 $km^3\,y^{-1}$) almost equals evaporation, so that the rainfall contribution is not balanced and the surface outflow in the strait is almost double that of the deeper inflow coming from the Marmara Sea (Besiktepe et al., 1994).

In the western shelf region the depth is less than 100 m and freshwater runoff is high, as the two major rivers of the Black Sea, the Danube and the Dniepr, flow into this area. The first accounts alone for 57.5% of the Black Sea's river runoff, while the second contributes 12.5%, giving a total of 70% (Jaoshvili, 2002).

The general circulation of the Black Sea often presents a cyclonic basin wide stream, called the Rim Current, which is mainly driven by wind and enforced by river runoff. This current is not stable and is subject to perturbations due to baroclinic instabilities which split it into smaller meanders with a period of about 20 months (Stanev and Staneva, 2000).

Nearer to the coast mesoscale anticyclonic eddies are often present, especially in summer, when they are more active (Staneva et al., 2001; Stanev, 2005). These eddies interact with the brackish water near the river estuaries and spread out towards the centre of the basin. When the coastal brackish water, however, is sufficiently cold, as can happen in the shelf during winter, this water can sink to the bottom and feed a middle layer called the Cold Intermediate Layer (CIL)[1]. This layer inhibits vertical motion and strongly limits the ventilation of the deeper region of the basin

[1] Some works showed that even the water convection from the surface happening in the cyclonic eddies could have an important role on the CIL formation (Kaminskii et al., 1989).

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(Oğuz and Malanotte-Rizzoli, 1996; Stanev and Beckers, 1999), making the Black Sea the world's largest anoxic basin.

Due to the strong river inflows the shelf is also rich in nutrients which boost biological production. The biological components are then exported from the shelf to the intermediate layer of the continental slope (Grégoire and Lacroix, 2003). The water dynamics in the shelf and the patterns of the Danube's plume are of primary importance for biogeochemical investigations. For example, Grégoire and Friedrich (2004) found out that the shelf acts as an efficient sink for riverine nutrients, while Tsiaras et al. (2008) studied the seasonal phytoplankton variability, which is strongly influenced by the evolution of the Danube plume.

Water circulation in the north-western shelf has been investigated in a number of studies. Lozovatsky et al. (1999) showed the effect of storms on the temperature and salinity structures during autumn cooling, while Ginzburg et al. (2002) and Shapiro et al. (2010) used satellite data to detect and study the evolution of anticyclonic eddies in the western shelf. Karageorgis et al. (2009) used salinity and water temperature measurements from two oceanographic surveys to investigate the zone in front of the Danube Delta, while Yankovsky et al. (2004) combined ocean surveys and satellite data to investigate the Danube freshwater plume and its interactions with the offshore circulation. The water circulation in the western shelf was studied, with a modelling approach, in some important works. Beckers et al. (2002) showed the importance of model resolution and of the use of at least 6-h forcing fields, while Kourafalou and Stanev (2001) studied the seasonal patterns of the river induced low-salinity water.

This work is focused on the coastal water dynamics in the shelf zone near the Danube Delta and the Romanian coast. The use of a finite element model allows to increase the spatial resolution near the coasts and to accurately represent the complex coastline in the Danube Delta region. The resolution gradually decreases offshore, but is kept high enough to reproduce the mesoscale dynamics of the open sea.

Our purpose here is to investigate the coastal circulation, to determine what are the factors that influence it and to understand the role of the mesoscale water circulation near the coast. Moreover, we made some simulations with passive tracers in order to study the Danube's plume patterns with a modelling approach.

2. Methods

2.1. Model description

The hydrodynamic model used in this work is SHYFEM (Shallow water HYdrodynamic Finite Element Model)[2]. SHYFEM is an open source hydrostatic model which solves the shallow water equations, in a 3D formulation, using a finite element technique. The equations for an arbitrary vertical layer l are the following:

$$\frac{dU_l}{dt} - fV_l = -h_l\left[g\frac{\partial\zeta}{\partial x} + \frac{g}{\rho_0}\frac{\partial}{\partial x}\int_{-H_l}^{\zeta}\rho'\,dz + \frac{1}{\rho_0}\frac{\partial p_a}{\partial x}\right] + A_H\Delta U_l + \frac{1}{\rho_0}(\tau_x^{l-1} - \tau_x^{l})$$

$$\frac{dV_l}{dt} + fU_l = -h_l\left[g\frac{\partial\zeta}{\partial y} + \frac{g}{\rho_0}\frac{\partial}{\partial y}\int_{-H_l}^{\zeta}\rho'\,dz + \frac{1}{\rho_0}\frac{\partial p_a}{\partial y}\right] + A_H\Delta V_l + \frac{1}{\rho_0}(\tau_y^{l-1} - \tau_y^{l})$$

$$\frac{\partial\zeta}{\partial t} + \sum_l\frac{\partial U_l}{\partial x} + \sum_l\frac{\partial V_l}{\partial y} = 0 \tag{1}$$

with U_l, V_l the water transports in the layer l (vertically integrated velocities), f the Coriolis parameter, g the gravity acceleration, ζ the surface water level, H_l the depth of the bottom of the layer l, h_l its thickness, ρ_0 the undisturbed water density, $\rho' \equiv \rho - \rho_0$ the residual water density with ρ the water density, p_a the atmospheric sea level pressure, A_H the horizontal turbulent diffusion parameter and $\Delta[\cdot]$ the Laplace operator. τ_x^{l-1}, τ_y^{l-1} are the shear stress components at the upper interface of the layer and τ_x^l, τ_y^l at the lower one. Tidal forcing in the Black Sea is negligible (see e.g., Stanev and Staneva, 2000) and was not considered.

A finite staggered element technique is used for the horizontal space discretisation, with water levels computed in the triangles' vertices and velocities in the centres. This formulation allows mass conservation using a semi-implicit time integration scheme (Umgiesser et al., 2004). Maximum time step is 50 s and can vary at each iteration, depending on the computational stability. Z levels are used for the vertical discretisation.

The divergence terms in the continuity equation are summed over the whole water column. Layers are counted from the surface (1), where the wind stress is prescribed, to the bottom (L), where the bottom stress formulation is used. The wind stress for the x-component is

$$\tau_{wx} = \rho_a C_D u_w\sqrt{u_w^2 + v_w^2} \tag{2}$$

and similarly for the y component. Where u_w and v_w are the zonal and meridional wind components respectively and ρ_a the surface air density. C_D is set to a rather high value of 2.5×10^{-3} in order to compensate the real wind underestimation made by the ECMWF analysis fields (Stanev, 2005).

The bottom stress formulation is

$$\tau_{bx} = \rho\frac{C_b}{h_L^2}U_L\sqrt{U_L^2 + V_L^2} \tag{3}$$

and similarly for the y component. U_L and V_L are the transports in the last layer, h_L the thickness of the last layer and C_b the bottom drag parameter, set to 2.5×10^{-3}.

Turbulent diffusion is computed horizontally with a formulation proposed by Smagorinsky (1963), using a parameter value of 0.3, and vertically by the GOTM (General Ocean Turbulence Model) model, through a k–ϵ scheme (Burchard and Petersen, 1999).

The dispersion of temperature, salinity and any conservative numerical tracer is computed with the advection–diffusion equation, which uses a total variational diminishing (TVD) numerical scheme. Different source/loss terms are used for temperature and salinity to take into account of boundary conditions. In case of salinity the source/loss term is the difference between evaporation and precipitations (unit: $\mathrm{kg\,m^{-2}\,s^{-1}}$). The evaporation rate is determined by the bulk aerodynamic transfer method (Ham, 1999) using air temperature, relative humidity, wind speed, air pressure and simulated water temperature.

In case of water temperature, the source/loss term represents the heat source through the water surface, $Q/\rho c_w H$, where c_w is the specific heat of the water ($c_w = 3991\ \mathrm{J\,kg^{-1}\,{}^{\circ}C^{-1}}$) and H is the thickness of the surface water layer. Q is the heat flux ($\mathrm{W\,m^{-2}}$) between the atmosphere and the sea, computed by the thermal radiative model.

Finally, water density is computed from temperature, salinity and pressure with the UNESCO equation of state.

2.2. Model set-up

Computational grid: In order to avoid the prescription of uncertain conditions to wide boundaries, the computational grid was extended over the entire Black Sea. The grid has 43,823 nodes and 83,938 triangular elements. Mesh resolution varies from 1.5 km near the coasts to less than 10 km in the central Black Sea to correctly reproduce the baroclinic circulation (the first baroclinic Rossby radius is around 30 km, Oğuz et al., 1995; Stanev and Rachev, 1999). Near the Romanian coast and the Danube Delta resolution

[2] http://www.ismar.cnr.it/shyfem.

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