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Abstract

The Northwestern Black Sea shelf dynamics are studied with numerical simulations based on the Princeton Ocean Model. The study focus is on buoyancy and wind driven flows and on the transport and fate of low-salinity waters that are introduced through riverine sources (the Danube, Dnestr and Dnepr Rivers), under the seasonal changes in atmospheric forcing. The study is part of the DANUBS project (NUtrient management in the DAnube basin and its impact on the Black Sea).

The numerical simulations show that the coastal circulation is greatly influenced by river runoff and especially that of the Danube, which is dominant with monthly averaged values ranging from 5,000 m^3/s to 10,000 m^3/s. The transport of low-salinity waters associated with the Danube runoff is greatly influenced by wind stress, topographic effects and basin-scale circulation patterns, such as changes in the position of the Rim Current.

Keywords: Shelf dynamics; River plume dynamics; Numerical modeling; Black Sea; Danube River.

Introduction

The Black Sea can be viewed as a component of the Mediterranean Sea system, with particular dynamical characteristics that are dictated by the delicate connection with the Mediterranean basin. The link is established through the narrow Strait of Bosphorous (~ 1 km), which imposes a strong hydraulic control on the inflow of salty Eastern Mediterranean water and outflow of fresher Black Sea water. The vast area of the Black Sea (over 4x10^5 km^2) and the restricted water exchange at the Bosphorous result in unique hydrodynamic and biogeochemical conditions in this basin. The most pronounced characteristic in the Black Sea hydrodynamical structure is the remarkable stability in stratification. A thin upper layer with low-salinity (generally not exceeding ~ 18 psu) is superimposed on the Cold Intermediate Layer (CIL), while the greatest part of the water column is occupied by a deep water mass that is almost uniform in the vertical. It is well established by now that the stable stratification is largely due to river runoff, which provides a continuous source of freshwater, diluting the upper basin layers and overwhelming the supply of salty waters of Mediterranean origin through the Bosphorous. One of the direct consequences of restricted mixing between the brackish surface layers and the deeper, denser waters is the prevailing anoxic conditions, which make the Black Sea the world's largest anoxic basin.

The majority of freshwater discharge takes place on the North Western Shelf (NWS), which occupies most of the western Black Sea (taken here as west of the narrowest width of about 250km, between the Crimean peninsula and the Turkish coast, Fig. 1). The major rivers are the Danube, Dnestr, Bug and Dnepr, shown in Figure 1. They have strong flow rates, especially the Danube, which is one of the largest rivers of the world and the strongest single source of freshwater for the Mediterranean Sea / Black Sea system. A number of studies, especially within the framework of large international efforts, such as EROS2000 and EROS2001, demonstrated that the low salinity waters and associated sediments, nutrients and pollutants that originate from the Danube runoff have a significant impact in the hydrodynamic and biogeochemical processes of the western Black Sea, while governing the shelf to open sea exchanges in the region (STANEV *et al.*, 2002; OGUZ *et al.*, 2002). Previous studies have also shown that river runoff has a profound influence on the formation of CIL. As discussed in STANEV *et al.* (1995) and OGUZ AND MALANOTTE-RIZZOLI (1996), the formation of dense water, which takes place on the NWS, is greatly influenced by the inter-annual variability in river runoff, particularly that of the Danube. A prominent feature in the upper layer circulation in the Black Sea is the so-called Rim Current, a cyclonic current that follows the abrupt continental slope and encompasses a cyclonic cell that occupies the basin interior (OGUZ *et al.*, 1993; OGUZ *et al.*, 1994; KOROTAEV *et al.*, 2003).

Several recent modeling studies have elucidated the inter-annual and seasonal variability of the general circulation (OGUZ *et al.*, 1995; STANEV *et al.*, 1995, 1996; OGUZ AND MALANOTTE-RIZZOLI, 1996; KOROTAEV *et al.*, 2003). The coastal dynamics on the NWS have received less attention, although the shelf contribution on distinct general circulation features has been shown by RACHEV AND STANEV (1997), in terms of causing eddy dissipation and by

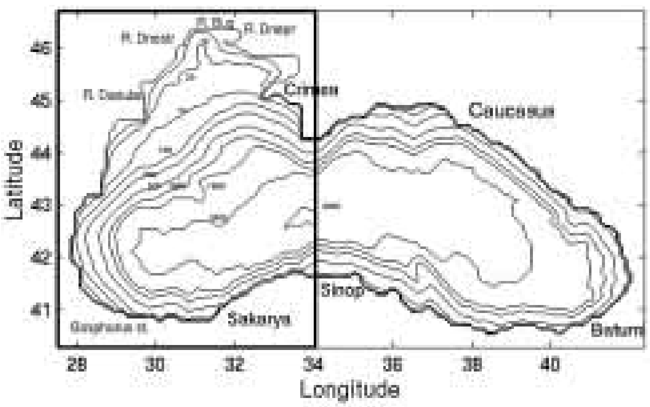

Fig. 1: The Black Sea, major rivers and the Northwestern Black Sea shelf model domain (left box).

OGUZ *et al.* (1995) in terms of maintaining the basin-wide cyclonic circulation.

Model development on the Northwestern Black Sea in the framework of the EU DANUBS project (NUtrient management in the DAnube basin and its impact on the Black Sea) aims toward the development of the necessary tools for the integrated study of the physical and ecosystem dynamics in the Northwestern Black Sea shelf. The processes of interest include river plume dynamics and the related coastal frontal structures, air-sea interaction and basin-wide circulation influence on the transport of low salinity waters and associated nutrients that are introduced at the Danube delta.

Materials and Methods

The methodology is numerical simulations based on the Princeton Ocean Model (BLUMBERG AND MELLOR, 1983), a 3-dimensional, primitive equation, free surface and sigma-coordinate hydrodynamic model. The model has been modified to include river plume dynamics, following the approach developed by KOURAFALOU *et al.* (1996a), where a source term is added in the continuity equation, representing the volume of the river input. This approach allows for the numerical description of the phenomena associated with river runoff, based on model input of the river discharge rate and the salinity of the incoming water. The value of salinity near the mouth is thus time and space varying and determined according to the mixing conditions.

The horizontal mixing depends on the grid size and the velocity field, as the horizontal eddy viscosity / diffusivity parameter is given by the SMAGORINSKY (1963) formula. The vertical eddy viscosity / diffusivity parameter is calculated according to the MELLOR AND YAMADA (1982) turbulence closure scheme, which solves the equations for turbulent kinetic energy and turbulence macroscale and provides a realistic simulation of the mixed layer taking account of the wind stirring and the stability induced by stratification. In the vertical the model uses a bottom following sigma coordinate system. Thus all vertical levels are maintained throughout the model domain permitting a better resolution of the bottom boundary layer, which is particularly suitable for coastal regions where bathymetric effects are important. The model can successfully represent the dynamics of a freshwater plume, as was shown in previous studies of river plumes, in semi-enclosed Mediterranean basins (KOURAFALOU, 1999, 2001) and in the open ocean (KOURAFALOU *et al.,* 1996b).

Two model domains have been used: a basin-scale domain that covers the entire Black Sea and a shelf model domain that encompasses the northwestern Black Sea shelf, approximately between 28° and 34° East and 41° to 46° North (Fig. 1). Horizontal resolution of the two models is ~ 10km ('coarse') and ~ 5km ('fine'), respectively. Sixteen sigma-levels are resolved in the vertical, with logarithmic distribution approaching the surface in order to achieve a better resolution of the upper layer. Realistic bathymetry is used and minimum depth is set to 5m.

The river sources are represented by an 8-point source for the Danube, a 2-point source for the Dnepr and single point sources for the Bug and Dnestr rivers.

The surface boundary conditions, which account for momentum, heat and water input at the sea surface, represent air-sea interaction processes, employ the vertical mixing coefficients K_M, K_H and are specified as follows.

Momentum:

$$K_M \left(\frac{\partial U}{\partial Z}, \frac{\partial V}{\partial Z} \right) = \left(\tau_x, \tau_y \right)$$

where (τ_x, τ_y) is the wind stress.

Temperature:

$$K_H \left. \frac{\partial T}{\partial Z} \right|_{z=0} = Q_{tot}$$

where Qtot is the net heat flux at the sea surface.

Salinity:

$$K_H \left. \frac{\partial S}{\partial Z} \right|_{z=0} = (E - P) \cdot S_{surf}$$

where E, P are the evaporation and precipitation rates.

The lateral boundary conditions for the shelf model are provided by the basin scale model. Temperature and Salinity along the eastern boundary are calculated from their upstream values during outflow and prescribed boundary values from the basin model during inflow, using an advection equation. The external (depth averaged) velocity is calculated from a FLATHER (1976) type radiation condition using the prescribed boundary value. In order to preserve the mass balance during the model integration the average boundary velocity is subtracted from the prescribed boundary value so that the total mass transport along the boundary is zero (or equal to the net mass increase). This volume constraint introduces a small correction, which is assumed not to appreciably affect the resulting flow. The Bosphorus strait is kept closed, as the exchange with the Sea of Marmara is beyond the scope of this study. Internal velocities are obeying a Sommerfeld type radiation condition with constant internal wave phase speed.

Results and Discussion

A climatological type simulation took place that employed the important circulation forcing mechanisms: buoyancy (due to river discharge), wind stress, heat and salt fluxes at the air-sea interface and interaction between shelf and basin flows. The simulations were carried out on both the basin-scale and shelf model domains and they lasted for 2-3 years.

Forcing

The air-sea interaction parameters are based on STANEVA AND STANEV (1998). They have examined various climatological wind data sets and they have incorporated additional data from ship observations to prepare a new data set that is downscaled and representative of the local basin dynamics, including the shelf area.

a) Wind stress

An example of the monthly wind data set, imposed on the model grid is shown in Figure 2 for February (winter), May (spring), July (summer) and October (autumn). The monthly averaged wind stress has been computed, showing the intensity and the spatial variability of the wind forcing for each month. The changes in the magnitude and the direction of the wind force are pronounced over the different domain areas and from season to season. The winds are strongest in winter, while the maximum wind curl (not shown) is usually found near the Danube delta, due to the abrupt change in coastline orientation. For the western part of the domain and especially for the vicinity of the Danube River plume, winds are usually downwelling-favorable (strong northerly or easterly component), but periods of upwelling-favorable conditions also exist (strong southerly or westerly component, as in July). Periods of relaxation in the wind field are also observed, as in May, when winds near the Danube are almost negligible. During the simulation, the wind changes in the middle of each month, bearing a weighted influence for two consecutive months.

b) Heat and salt fluxes

We use 10-day averages for the (net) surface heat fluxes. For solar radiation which is explicitly included in the model, we use monthly mean averages; evaporation and

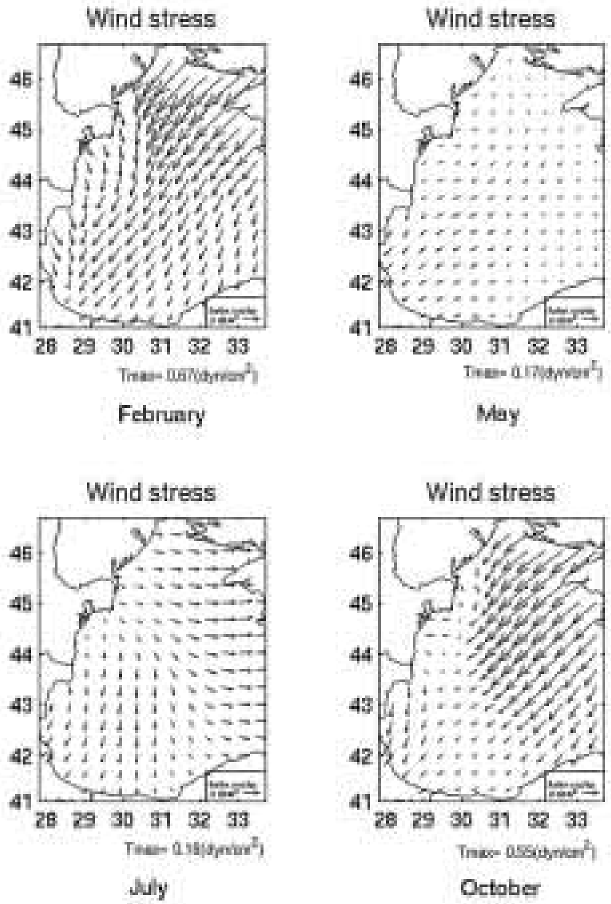

Fig. 2: Monthly averaged wind speed during four different seasons.

precipitation values are also monthly averages. To avoid drifting from climatological values, we introduced a relaxation of the surface temperature to the climatological one with a restoring coefficient g=0.5m/day (~ 25W/m^2). Surface salinity was also relaxed towards climatology with a weaker restoring coefficient g=0.25m/day.

c) River Discharge

The adopted climatic values of river runoff for the Danube, Dnestr, Bug and Dnepr rivers are shown on Fig. 3. The monthly mean data for river discharge are taken from ALTMAN AND KUMISH (1986) and are further prepared and analysed by STANEVA AND STANEV (1998). The intense seasonal variability is evident here, as well, with maximum runoff during the late spring to early summer period. It is obvious from Figure 3 that the Danube runoff far exceeds that of the other rivers, generally more than 5.000 m^3/s and reaching as high as 10.000 m^3/s during the peak season. This reflects the enormous drainage area for the Danube that covers a vast area of Europe. Such discharge values put the Danube River in the same category as the Mississippi (Gulf of Mexico), the Amazon and the La Plata (South Atlantic) i.e., rivers with discharge values in the order of $10^4 m^3$/s.

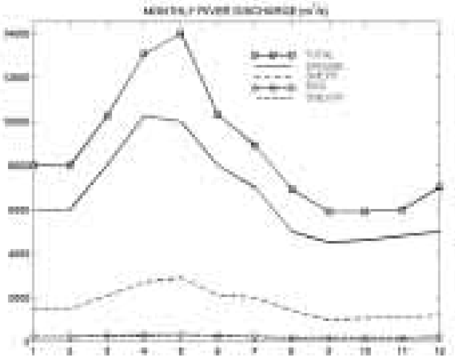

Fig. 3: Climatological values of discharge rates for major rivers.

Basin-wide simulation

The initial conditions were based on a 30-day simulation that started with climatological values of temperature and salinity with the addition of river discharge that allowed for the development of river plumes in the vicinity of the major rivers. The Danube River plume was strongest, but a Coastal Low Salinity (CLS) band was formed from the blending of all major river plumes, as discussed in KOURAFALOU & STANEV (2001). In agreement with their findings, we observed a dominant anticyclonic bulge offshore of the Danube delta with a buoyancy-driven current that is subject to intense interaction with the prevailing wind forcing.

An example of the model computed, near surface salinity fields for the months of February, May, July and October during the third year of simulation are shown in Figure 4. The CLS is narrowest in winter, due to the prevailing downwelling-favorable winds (for the western coast) that prohibit cross-shore exchange and strong winds that induce mixing. There is considerable offshore spreading in late spring, when the winds are weak and in summer, when stratification due to heat flux allows for faster wind-driven transport on the upper part of the water column. The velocity field (not shown) exhibits a well-pronounced

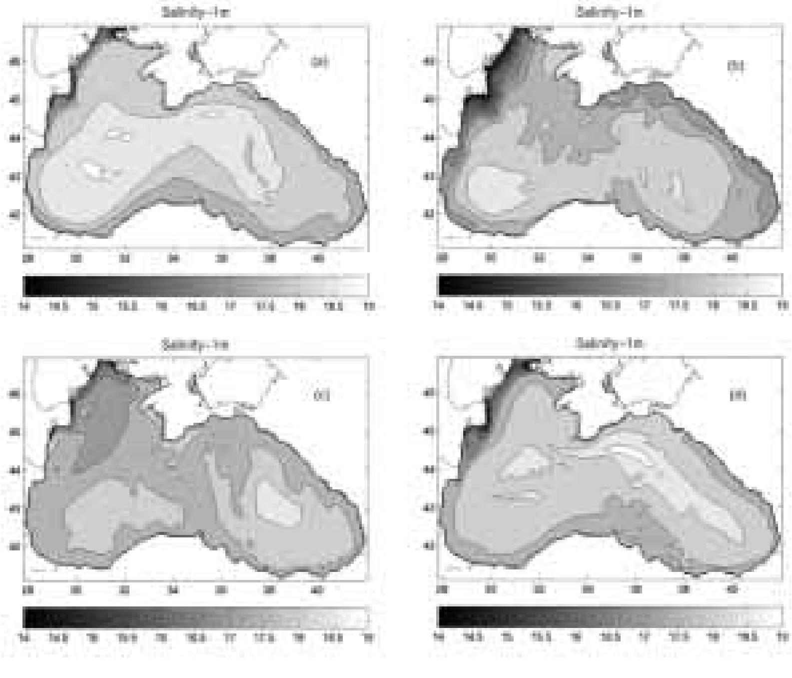

Fig. 4: Monthly averaged near-surface salinity patterns for the entire Black Sea, calculated by the coarse resolution, Black Sea POM model: (a) February; (b) May; (c) July; (d) October.

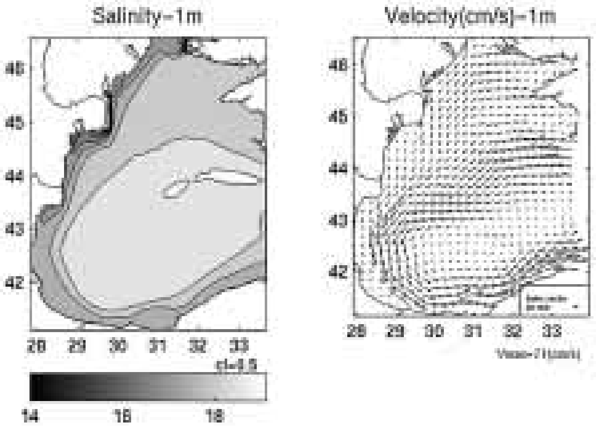

Fig. 5: Monthly averaged (February) near-surface salinity and velocity patterns for the western Black Sea, calculated by the fine resolution, western Black Sea POM model.

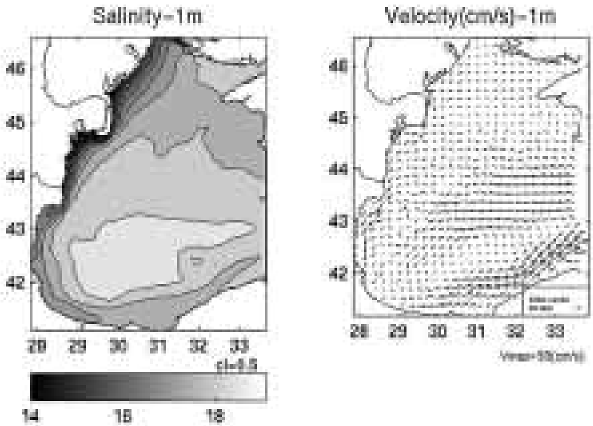

Fig. 6: Monthly averaged (May) near-surface salinity and velocity patterns for the western Black Sea, calculated by the fine resolution, western Black Sea POM model.

Rim Current flowing cyclonically along the continental slope and a two-gyre system in the deep interior (see ‘east’ and ‘west’ high salinity cells in Fig. 4), as is known from in-situ and altimeter data based studies (OGUZ *et al.*, 1994; KOROTAEV *et al.*, 2003).

Shelf model simulation

The shelf model is initialised by the third year results of the climatological basin-wide simulation described in the previous section. A two-year simulation follows and an example of monthly averaged results is shown on Figures 5-8.

The computed velocity and salinity fields on the Northwestern Black Sea shelf are dominated by the river plume dynamics and the interaction with large scale flows. The wind forcing (Fig. 2) has a prominent role in the transport of low-salinity waters. The CLS band is even more pronounced than in the basin-scale run, due to the higher resolution that allows the better description of topography and better definition of plume dynamics.

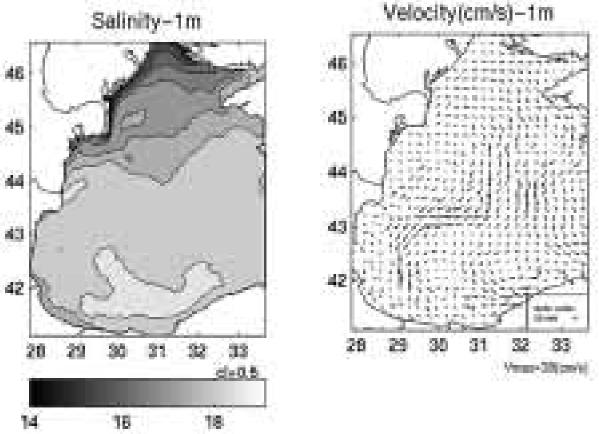

Fig. 7: Monthly averaged (July) near-surface salinity and velocity patterns for the western Black Sea, calculated by the fine resolution, western Black Sea POM model.

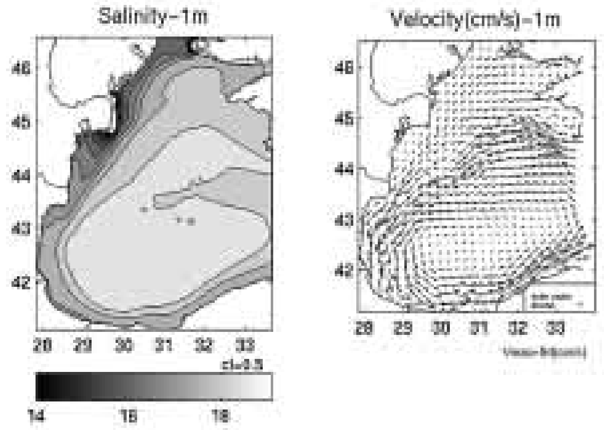

Fig. 8: Monthly averaged (October) near-surface salinity and velocity patterns for the western Black Sea, calculated by the fine resolution, western Black Sea POM model.

During winter, winds are mostly downwelling-favorable in the Danube area and the CLS band is constrained near the coast. In February (Fig. 5), the water column is well-mixed and this condition is maintained by the strong winds. Therefore, buoyancy effects are diminished, even in the vicinity of the Danube, where river runoff is strongest. A well pronounced southward jet is formed along the western coast, which is largely barotropic (wind-driven). By March, the diminishing winds allow for the formation of the CLS band along the west coast, as the result of the blending of the amplified individual river plumes. The strongest salinity gradients are near and to the south of the Danube delta, where buoyancy effects are dominant. Consequently, the southward coastal current is mainly baroclinic (buoyancy-driven). As the water column begins to stratify and the winds remain light, the river plumes strengthen. In May (Fig. 6), the wind stress is greatly reduced in the plume area, so that a strong offshore bulge develops that contains low-salinity waters (mainly of Danube origin) and occupies most of the Northwestern Black Sea shelf. A southward propagation of riverine waters is also found, immediately south of the delta. The northward winds in the southern part of the domain during June (not shown) reverse the southward propagation of the coastal current, but low-salinity waters still reach the coast south of the Danube delta through the central part of the domain (part of the bulge anticyclone). Winds are slightly stronger in July (Fig. 2), when the water column is more stratified, due to the onset of heat induced stratification. The westerly component of the wind stress in the northern part of the shelf causes spreading of low salinity waters across the shelf, with a largely spread anticyclonic flow that produces a mid-shelf southward jet (Fig. 7). The weak Rim Current further favors the offshore spreading of low salinity coastal waters. By October (Fig. 8), the Rim Current has gained strength, the seasonal vertical stratification starts to diminish and the CSL retreats near shore.

Conclusions

A hydrodynamic model has been developed that focuses on the Northwestern Black Sea shelf and it also includes the effects of the basin scale circulation. The performed simulations have elucidated the role of the major circulation forcing mechanisms, namely air-sea interaction and buoyancy-driven flows due to the discharge of the Danube and other major rivers. It was shown that the prominent basin-scale flow of the Rim Current may influence the offshore removal of the coastal low-salinity waters. We conclude that strong shelf to open sea interactions are taking place with pronounced seasonal variability. As the Danube River drains a vast area of Europe, introducing nutrient and sediment loads in the Black Sea, we expect that the circulation patterns simulated by the hydrodynamic model can serve as a basis for the study of transport pathways of river-borne materials.

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