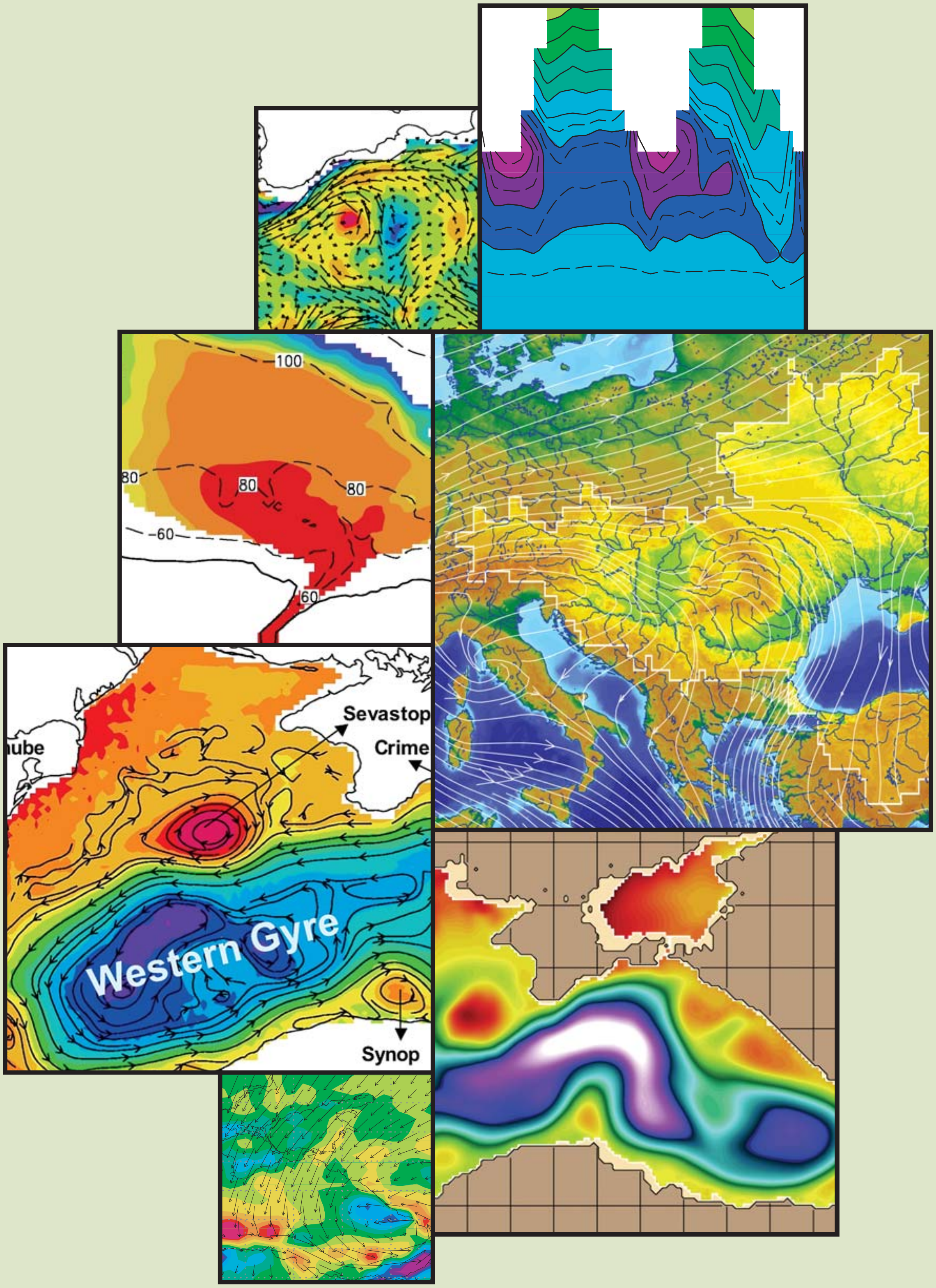
Understanding BLACK SEA DYNAMICS

An Overview of Recent Numerical Modeling

BY EMIL V. STANEV

The importance of the Black Sea extends far beyond its regional role as a mixing body where Mediterranean water is diluted. This sea's marine environment acts as a small-scale laboratory for investigating processes that are common to different areas of the world's oceans. In particular, research on deep ventilation could facilitate understanding of similar controlling processes in the paleocean when the ocean's conveyor belt was shallower. Because water and salt balances are easily controllable and the scales are smaller than in the global ocean, this basin is a useful test region for developing models, which can then be applied to larger scales. Moreover, studying outputs from numerical models is an important complement to sparse observations and extends our knowledge. The major purpose of this paper is to demonstrate this possibility, using Black Sea physical oceanography examples based on numerical modeling results.



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INTRODUCTION

The Black Sea is a nearly enclosed basin connected to the Sea of Marmara and the Sea of Azov by the narrow Bosporus and Kerch Straits, respectively. Its catchment area covers large parts of Europe and Asia (Figure 1), providing a total freshwater supply of 3 x 10^2 km^3 per year[1]. Although evaporation exceeds precipitation, the freshwater flux (river runoff, plus precipitation minus evaporation) remains large in comparison to basin volume (~5.4 x 10^5 km^3), making the Black Sea a typical estuarine basin. Because of the large freshwater flux and the narrow opening in the strait of Bosporus, the exchange between the Black and Marmara Sea is asymmetric: the volume of water transported by the outflowing surface current is two times larger than the inflowing deep counter-current, thus the Black Sea's surface salinity is about half that of the Mediterranean's.

Unlike other large estuarine basins (e.g., the Baltic Sea), the Black Sea is a deep basin (maximum depth of ~2200 m) with a large shelf. A distinct vertical layering is created between the surface waters in the upper 100 m and the deep waters, limiting the vertical exchange and creating a unique chemical and biological environment (see Konovalov, this issue). The cold intermediate water (CIW) mass, with temperatures lower than the mean annual temperature of the surface and deep layers, is a consequence of extremely stable stratification. This cold intermediate layer (CIL) is formed by winter cooling followed by spreading of CIW throughout the sea in a layer approximately 50 to 100 m below the surface. It acts as a boundary between surface and deep waters.

The Black Sea is where most kinds of numerical models based on primitive equations have been used to simulate circulation and transport of matter (see Box 1). This sea provides optimal possibilities, using easily manageable models and observational data to address a wide spectrum of processes observed in the ocean. The Black Sea also has unique oceanographic conditions maintained by strong stratification, river runoff, and inflows.

There are more than 25 peer-review papers in English dealing with different aspects of modeling Black Sea circulation. Extended references on modeling and observations are provided in several reviews (Stanev, 1990; Stanev et al., 2002; Kara et al., 2005a). In this paper we will refer only to well-documented (and in most cases freely available) models applied to the Black Sea. More details about the individual applications as well as about the strengths of different models are given in the papers of Stanev (1990), Oguz and Malanotte-Rizzoli (1996), Staneva et al. (2001), Stanev et al. (2003) and Kara et al. (2005a). This paper does not summarize all major results of these reviews and original publications, rather it reports on new developments and perspectives.

There are many examples in oceanography of fundamental processes that had been first described by theory and later supported by observations. Numerical modeling also provides a powerful tool for estimating fundamental ocean characteristics that cannot be directly measured. The aim of this paper is to demonstrate that studying outputs from numerical models is an important complement to sparse observations and provides important scientific guidance.

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CIRCULATION

Numerical modeling made it possible, for the first time, to quantify the individual impact of mechanical and thermohaline forcing in the Black Sea (Stanev, 1990; Oguz and Malanotte-Rizzoli, 1996), revealing wind as the main driving force in creating a cyclonic general circulation. The haline buoyancy anomalies at the sea surface enhance the cyclonic circulation because most of the freshwater enters the sea in the coastal area. The circulation is structured usually in two connected gyre

[1]In view of the great interannual variability during the last 50 to 100 years (Stanev and Peneva, 2002; Oguz paper 2, this issue), errors of observations and non-steady state conditions, these numbers, as well as some other budget numbers in this paper, give a very rough estimate of the climatic state.

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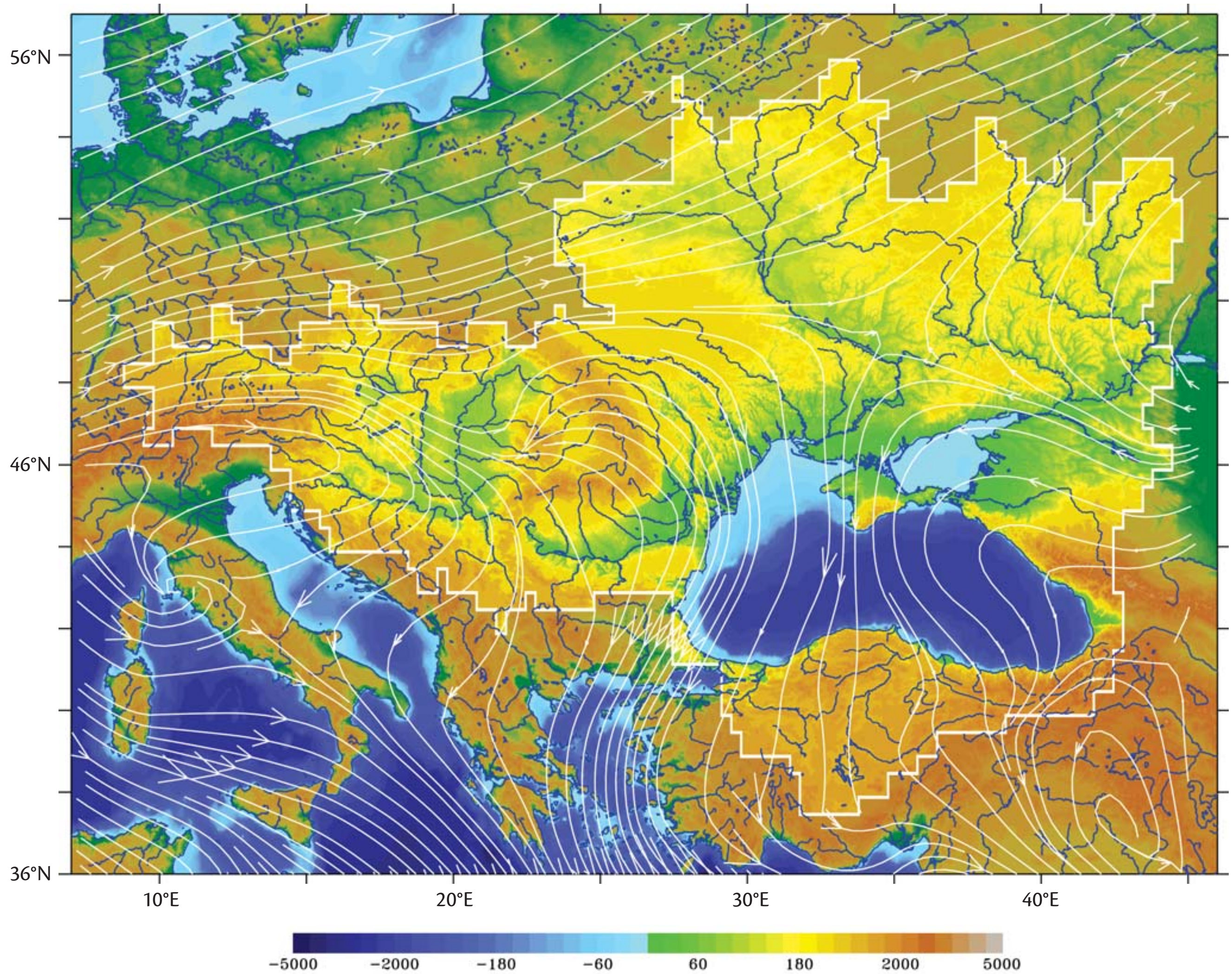
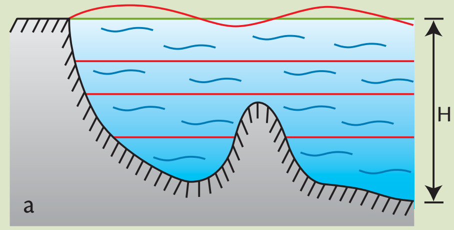


Figure 1. The Black Sea system is coupled with the atmospheric and hydrological systems over Europe and Asia Minor. The excess freshwater at the sea surface, along with the basin shape and topography and meteorological forcing, make the Black Sea a good overall integrator of the various kinds of processes that act over large continental areas. There is a clear correlation between North Atlantic Oscillation and sea-level variability (Stanev and Peneva, 2002; Oguz, paper 2, this issue). The orography of the Black Sea catchment area (m) is plotted in this figure with brighter colors. Streamlines illustrate the annual mean surface wind computed from the ERA-40 data.

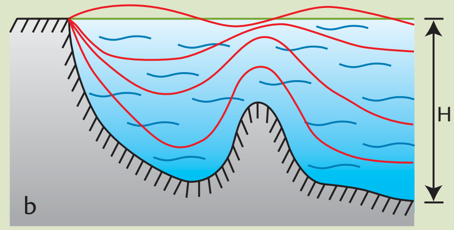
systems encompassing the basin (the Rim Current) (Figure 2). Simulated velocities of ~0.5 m/s, and greater than 1 m/s in some areas (Staneva et al., 2001), compare well with the observations of Oguz and Besiktepe (1999).

The Rim Current is associated with a difference of ~0.2 m between sea level in the coastal and open sea (Figure 2). Similar to many oceanic systems, Black Sea dynamics is controlled by topography, where the largest slope of sea level is located along the continental slope. However, the topographic slope is gentle in the northwestern and western Black Sea, where the width of slope area is ~80 to 160 km, and abrupt along the southern and eastern coasts (Figure 1). Different physical controls are thus possible depending upon the geometric and physical scale. The former is measured by the width of slope area, the latter by the Rossby radius (this physical scale depends upon vertical stratification and planetary rotation and is used in oceanography as a measure of the size of ocean eddies). In the area of abrupt slope, the

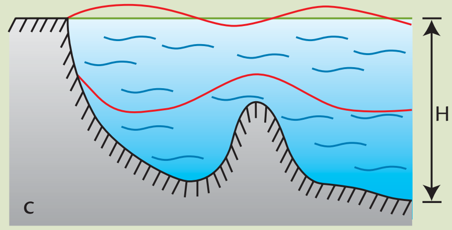
BOX 1: NUMERICAL MODELS AND THEIR APPLICATION IN THE BLACK SEA



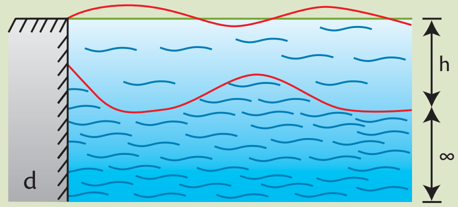
z-Coordinate Model



σ-Coordinate Model



Layered/Isopycnal-Coordinate Model



Reduced Gravity-Coordinate Model

The hydrodynamic equations solved by the ocean models are discretized vertically and horizontally in a finite number of grid elements with different shapes. The horizontal grid resolution has to be sufficiently fine to be able to resolve all of the important processes. However, using a very-fine-resolution grid over large areas is not possible because of the limitation of computational resources. At a minimum, horizontal resolution has to be fine enough to sufficiently resolve ocean eddies ("eddy-resolving models"), which have spatial scales of several tens of kilometers.

Different vertical resolutions are used when modeling different ocean regimes (e.g., surface, coastal, or deep ocean). This figure represents four different examples of vertical resolution. Undisturbed sea level is schematically given by the green line. The free ocean surface and surfaces between model layers are plotted with red lines, H is ocean depth. (a) The simplest vertical resolution is given if horizontal surfaces follow geopotential lines, which are almost horizontal. In these z-coordinate models, the surface layer's vertical resolution is usually finer in order to resolve fine-scale, upper-ocean processes. (b) In σ-coordinate models (terrain-following models) there are always an equal number of layers between the ocean surface and bottom. Thus, the vertical resolution is better in the shallower shelf and coastal ocean, but not very good in the deep ocean. (c) In isopycnal-coordinate models, vertical discretization follows isopycnal surfaces, where density plays the role of vertical coordinate. (d) There are also simpler and computationally efficient models consisting of only: surface one with thickness h and motionless deep layer with infinite thickness. The density difference between two layers reduces the gravity with respect to the interface, therefore, these types of models are known as reduced gravity-coordinate models. Substantial decrease of computations could be reached if one assumes that sea surface is motionless (horizontal green line in the figure). This figure is modified from the Computational Science Education Project figures available online at http://csep1.phy.ornl.gov/CSEP/OM/OM.html. This site also has a good introduction to ocean models.

The very early version of the eddy-permitting Black Sea model Stanev (1990) used the Modular Ocean Model (MOM) (see http://www.gfdl.noaa.gov/~smg/MOM/MOM.html for more information), which is a z-coordinate model based on the so-called "box-concept." This study has been followed by a few other eddy-resolving ocean general circulation models (OGCMs). One of them is the Princeton Ocean Model (POM) (see http://www.aos.princeton.edu/WWWPUBLIC/htdocs.pom for more information), which uses σ-coordinates. Its application to the Black Sea is documented by Oguz and Malanotte-Rizzoli (1996). The Dietrich Center for Air Sea Technology (DieCAST) (see http://www.ssc.erc.msstate.edu/DieCAST/ for more information) model was set up for the Black Sea by Staneva et al. (2001). The high-order numerics employed in this model made it possible, for the first time, to resolve all important mesoscale features of Black Sea circulation. In the study of Beckers et al. (2002) the GeoHydrodynamics and Environment Research (GHER) (see http://modb.oce.ulg.ac.be/GHER/Beckers.html/publications/gherm.pdf for more information) model (horizontal resolution of 5 km) demonstrated, for the first time, the potential of nested modeling. The finest available resolution basin wide has been reached by the modeling efforts of Kara et al. (2005a) and Peneva and Stips (2005). The former authors set up, for the first time in the Black Sea, the Hybrid Coordinate Ocean Model (HYCOM) (see http://hycom.rsmas.miami.edu/ for more information) with 3.2-km resolution. The hybrid coordinates allow the model to behave like a conventional sigma (terrain-following) model in very shallow oceanic regions, like a z-level coordinate model in the mixed layer or other unstratified regions, and like an isopycnic coordinate model in stratified regions. Peneva and Stips (2005) set up, for the first time, the General Estuarine Transport Model (GETM) (see http://www.bolding-burchard.com/html/GETM.htm for more information) with ~ 3.7-km resolution for the coupled system Black Sea-Azov Sea. Recently, there have been a number of efforts towards operational oceanography in the Black Sea (Korotaev et al., 1999). One such effort is due to Besiktepe (2003), who made extensive use of the Harvard Ocean Prediction System (HOPS) (see http://oceans.deas.harvard.edu/HOPS/HOPS.html for more information). This is a system of integrated software for multidisciplinary oceanographic research and forecasting that is built on the Geophysical Fluid Dynamics Laboratory primitive equation model. Most models use rich physical parameterizations (e.g., turbulent schemes, bottom layers, overflows, upper layer physics, and radiation schemes).

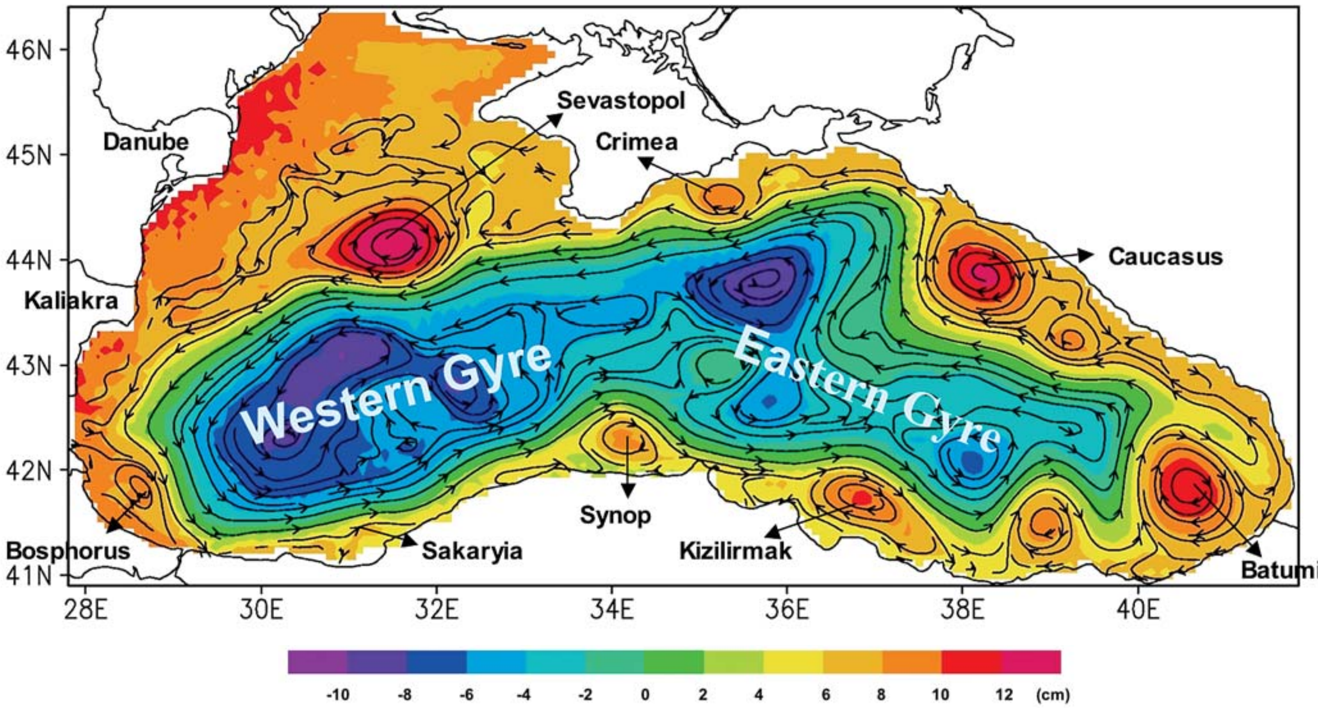


Figure 2. Snapshot of sea level and surface streamlines simulated by the DieCAST model (for more details, see Staneva et al., 2001). Note the existence of the eastern and western gyres, coastal eddies (most of them anticyclonic), the major sub-basin gyres (known as Batumi and Sevastopol eddies), and the bifurcation of the Rim Current east of Cape Kaliakra. This plot compares well with the scheme of the Black Sea surface circulation based on a synthesis of dynamic height derived from hydrographic observations by Oguz et al. (1993). The names of major coastal eddies as known from observations (usually, associated with geographic names, for example, capes and towns) are also given.

Rossby radius (~20 to 30 km in the Black Sea) is comparable to the width of the slope area. Thus, an interesting phenomenon occurs, which is well traced both in simulations (Figure 2) and in observations (Figure 3): the mean position of Rim Current follows the continental slope in the northwestern and western parts of the Black Sea and is displaced seawards elsewhere, revealing that very steep topography does not efficiently control the current. The above results from modeling and observations are consistent with the laboratory experiments of Zatsepin et al. (in press), which demonstrate that for very steep slopes, the current interacts with the bottom slope zone approximately as a vertical wall, and the eddy field becomes highly unstable and meandering. A similar increase in instability (Figure 4) had been first observed in the numerical experiments of Stanev and Staneva (2000), which were designed to demonstrate the "competition" between controls of the planetary and topographic β-effects (i.e., the slope of topography acts in a similar way as the change of Coriolis parameter with latitude [the β-effect]).

In the Black Sea, like in other estuarine basins (e.g., fjords), strong stratification dynamically isolates deep layers from surface and intermediate ones. Numerical simulations of Stanev (1990) demonstrated that in strongly stratified geophysical fluids, the joint effect of baroclinicity (density is a function of more than just pressure) and relief is substantially reduced. This is a typical case in the Black Sea, and possibly in the paleooceans when the freshwater fluxes were larger and the stratification was much stronger than today. Data from the above-cited numerical simulations demonstrated that currents in the deep layers reach several cm/s, revealing a highly barotropic structure (very small change of currents with the depth). This result was supported recently by observations with profiling floats (Gennady Korotaev, Marine Hydrophysical Institute of the Ukraine Academy of Science, Ukraine, pers. comm., 2005) showing that currents in the barotropic layers can reach ~5 cm/s.

There have been long-lasting debates among Black Sea oceanographers about whether or not circulation in the deep layers is opposite that of the surface layer. In the last decade, numerical modeling consistently supported the idea that there was no reversal; however, there were theories based on laboratory experiments (e.g., Whitehead et al., 1998), which demonstrated that buoyant plumes originating from straits could drive anticyclonic circulation in the deep sea. Very recent observations from profiling floats (Gennady Korotaev, Marine Hydrophysical Institute of the Ukraine Academy of Science, Ukraine, pers. comm., 2005) clearly support the numerical simulations—circulation is not reversed in the deep layers. This conclusion helps us to answer the fundamental question about whether positive buoyancy provided by the Bosporus plume, or wind, is more important in driving deep Black Sea circulation. The answer: wind is the major control on the dominant Black Sea cyclonic circulation throughout the water column (including the deep layers).

Although horizontal circulation, which can be reconstructed from observations, has been studied for many years, the equally important vertical circulation was completely unknown until recently. In particular, the quantitative characteristics of vertical circulation

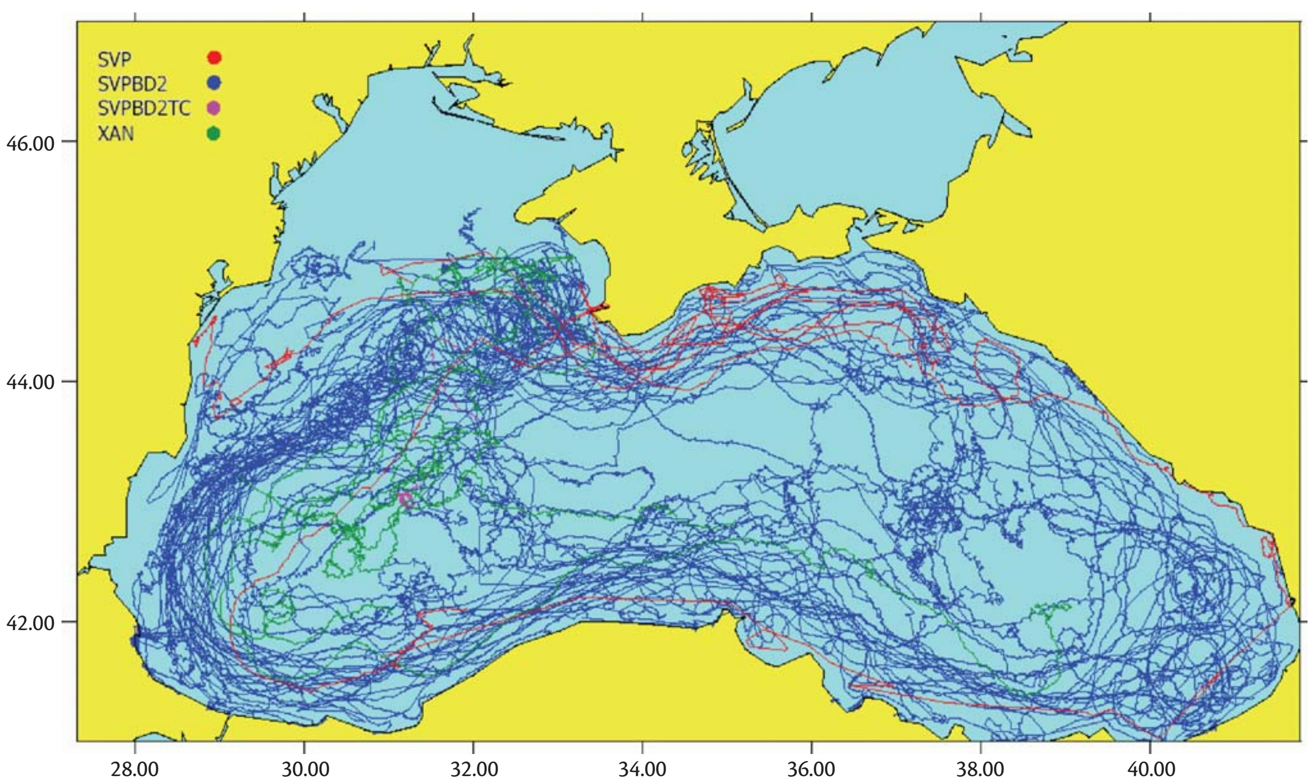


Figure 3. Numerical simulations (Figure 2) and Lagrangian drifter observations (Zhurbas et al., 2004) show that, depending on the trajectory, it takes about three to six months for surface currents to make one loop around the basin. The looping trajectories are best pronounced in the area of Batumi and Sevastopol eddy. This figure shows trajectories of Lagrangian (SVP, SVPBD2), quasi-Lagrangian (SVPBD2TC), and non-Lagrangian (XAN) drifters launched in the Black Sea in 1999-2004. Figure courtesy of Sergey Motyzhev, Marine Hydrophysical Institute NASU, Sevastopol, Ukraine.

were unknown because they cannot be easily measured. Numerical simulations (Stanev, 1990; Stanev et al., 2002) demonstrated that vertical circulation (~10^5 m^3/s) is much weaker than horizontal circulation (~5 x 10^6 m^3/s). The vertical circulation cell includes the coastward transport of surface waters due to cyclonic wind stress and compensating inward transport in the deep layers. This cell is closed in the vertical by upward motion in the basin interior and downward motion in the coastal regions.

The intensity of vertical circulation estimated from numerical models is comparable with the amount of water entrained by the Mediterranean plume in Black Sea surface and intermediate water. These models indicate that the inflow from the Bosporus Strait plays an important role in controlling vertical exchange. What has not been understood until very recently is that the outflow from the Bosporus Strait does not only propagate into a fixed ambient water column, but also changes the water's vertical stratification. By unifying downward motion in the coastal zone (caused by slope currents and coastal anticyclones) and upward motion in the basin interior (associated with wind forcing), vertical circulation regulates the impact of different dynamic controls on stratification (Stanev et al., 2004).

The Black Sea's general circulation is subject to pronounced seasonal variations. Sea level responds to meteorological forcing of a different kind; its seasonal amplitudes are ~10 to 20 cm, and the amplitudes of interannual variations are ~5 to 10 cm (Stanev and Peneva, 2002). The seasonal amplitude of the difference between sea-level height in the coastal

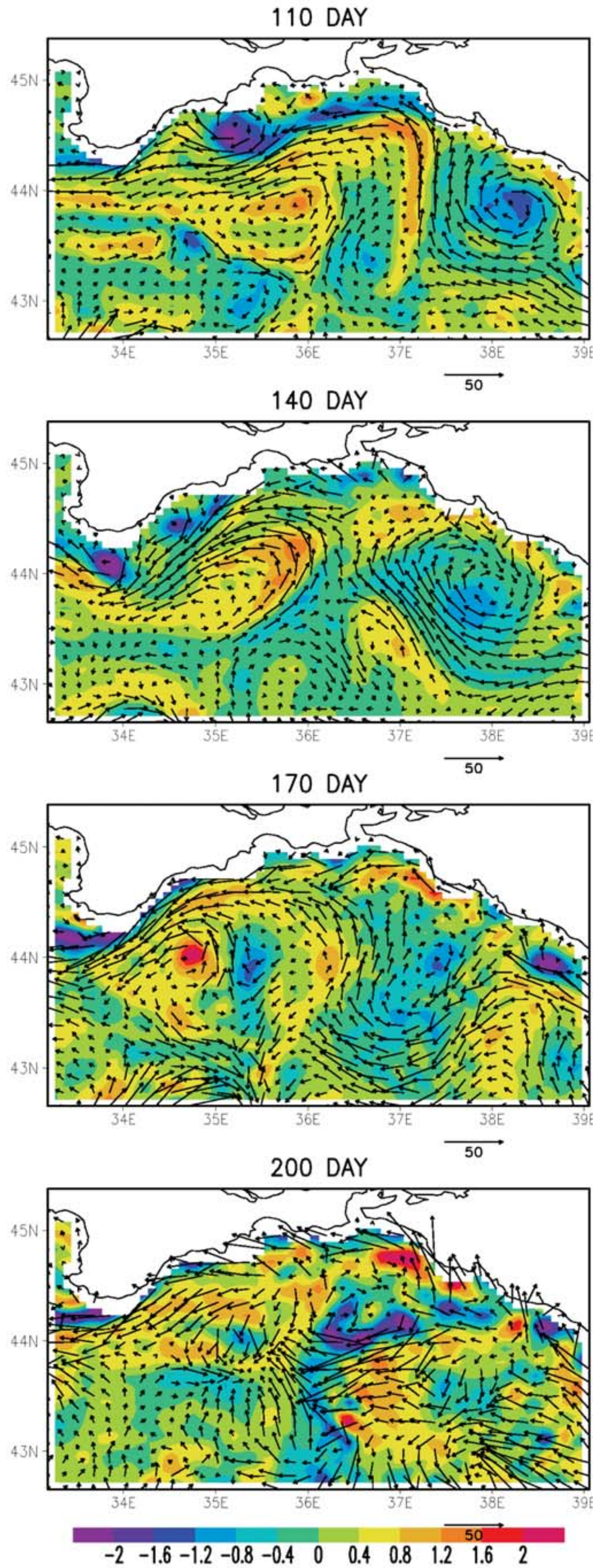


Figure 4. The Rim Current is accompanied by a series of anticyclonic mesoscale eddies between the continental slope and the coast (typical radius between 50 and 100 km). Their growth gives rise to large meanders that could either detach and propagate in the open sea or stagnate for some time in coastal areas feeding sub-basin-scale eddies (Batumi and Sevastopol eddy). This figure shows simulations with the DieCAST model in the area off the Caucasus coast. Colors give the relative vorticity normalized by the Coriolis parameter and multiplied by 10. In vast areas, relative vorticity is only ~ 5 times smaller than planetary vorticity. The evolution of eddies compares well with the observations of vortex dipoles (Zatsepin et al., 2003), including lifetimes (several months), deflection of Rim Current to the southwest, and entrainment of coastal water into the open sea (see also Figure 9 of Korotaev et al., 2003).

and open ocean, estimated from numerical simulations and altimeter data (Stanev et al., 2003), reaches half of the annual mean value (see Figure 2 for the sea-level slope). This sea-level information demonstrates that horizontal transport almost doubles in winter, which is the season of more intense circulation. During this season, the circulation is organized in one gyre system encompassing the entire basin (the Batumi sub-basin gyre is absent). In the warm part of the year, anticyclonic sub-basin-scale eddies are more pronounced (Stanev, 1990). It follows from the numerical simulations of Stanev and Staneva (2000) that the transition between summer and winter circulation is controlled by baroclinic eddies and is well revealed by the changing balance between vorticity in the open ocean and coastal sea. Because potential vorticity (i.e., vorticity of a water parcel normalized by depth or layer thickness) depends upon stratification, the transition between different circulation states (one-gyre circulation in winter and multiple sub-basin-scale eddies in summer) is enhanced by the large seasonal stratification cycle above a relatively shallow and strong pycnocline as in the Rim Current (Staneva et al., 2001).

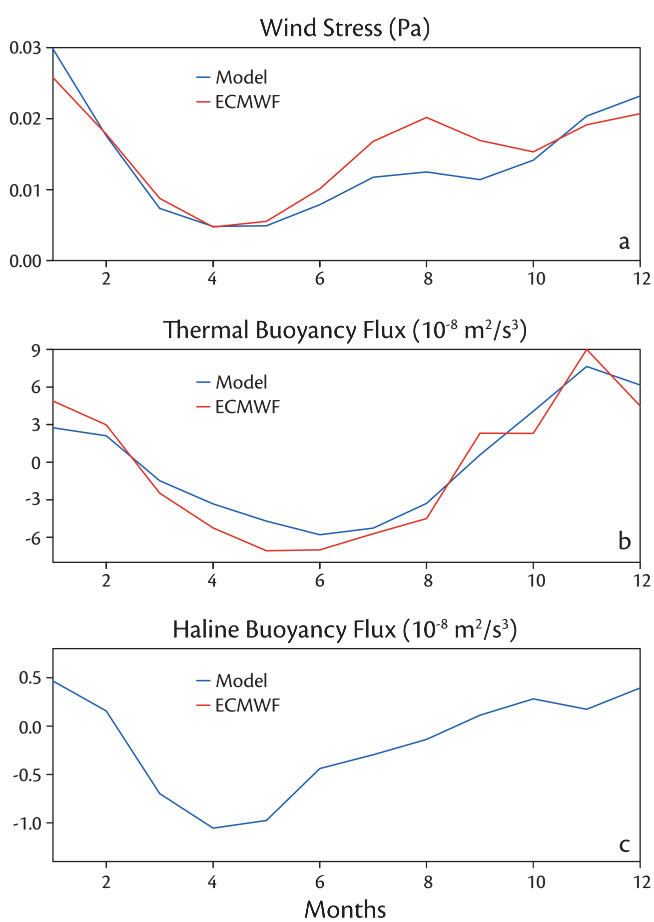


Figure 5. Temporal variability (mean year) of (a) wind stress, (b) thermal buoyancy flux, and (c) haline buoyancy flux. These results are diagnosed from simulations carried out with the 5-minute-resolution Black Sea Modular Ocean Model (MOM) (Stanev et al., 2003). Also shown are the corresponding curves calculated from the ECMWF-reanalyzed data (stands for European Centre for Medium-Range Weather Forecasts) using aerodynamic bulk formulae, air and sea surface temperature, relative humidity, and winds.

AIR-SEA EXCHANGE

Numerical simulations provide valuable information about air-sea exchange, which cannot easily be measured over vast ocean areas. To enable such diagnostics, one needs outputs from coupled ocean-atmosphere models, or at a minimum to be able to specify surface forcing in ocean models through a combination of data from atmospheric analyses, model-simulated sea surface temperature, and specific parameterizations called bulk aerodynamic formulae. The diagnostics of numerical simulations (Stanev and Staneva, 2001) demonstrate that the largest heating of ~2 x 10^2 W/m^2 is reached in June and the largest cooling of ~-3 x 10^2 W/m^2 is reached in early winter. Furthermore, the amplitude of the seasonal thermal buoyancy flux exceeds that of the haline buoyancy flux by an order of magnitude (Figure 5). However, the net thermal buoyancy flux is about four times smaller than the net haline flux. Because buoyancy fluxes control the density field, we conclude that the annual mean stratification in the Black Sea is dominated by dilution of surface waters by rivers, while the seasonal variability is created mostly by air-sea heat exchange. The contribution of Ekman pumping (which measures the vertical velocity resulting from the wind stress curl) is comparable to the one of haline buoyancy flux (Stanev et al., 2003). This specific combination of different forcing mechanisms tends to create a stable salinity stratification, which changes very little through time; however, there is an extremely high variability in the upper ocean thermal structure. The formation and character of the CIL is one of the main consequences of the present-day balances of buoyancy.

MIXING AND WATER MASS FORMATION

In contrast to the neighboring Marmara Sea, which has relatively young water, the deep water in the Black Sea is characterized by slow renewal (longer than 10,000 years). It is commonly accepted that the Black Sea's water was formed over a long time period, and perhaps under different condition than today's climate. These stagnant conditions are well illustrated by the fact that temperature signals in the numerical simulations (Figure 6) and observations cannot be traced much deeper than 200 to 400 m. Furthermore, numerical simulations and the limited number of observations reveal the slow penetration rates of passive tracers (Figure 7): the concentration of CFC-12 at 400 m in 1988 is less than 1 percent of surface values, which is not the case in the ocean, nor in the neighboring Marmara Sea, where the vertical exchange is much faster. This unique feature of the Black Sea is explained by the fact that vertical mixing in strongly stratified fluids tends to molecular values (Stanev, 1990; Gregg and Özsoy, 1999).

It follows from the numerical simulations of Stanev et al. (2004) that the horizontal contrasts in concentration of CFCs as seen on density surfaces are ~70 times smaller than the contrasts on z-surfaces (Figure 7). This trend, which has also been found for other geochemical tracers in the Black Sea, is consistent with the theory of homogenization of potential vorticity, indicating that tracers tend to align themselves along isopycnal surfaces (Figure 6; see also Box 1).

Although the diapycnal mixing is quite small, it is very important to Black Sea thermodynamics and its origin needs

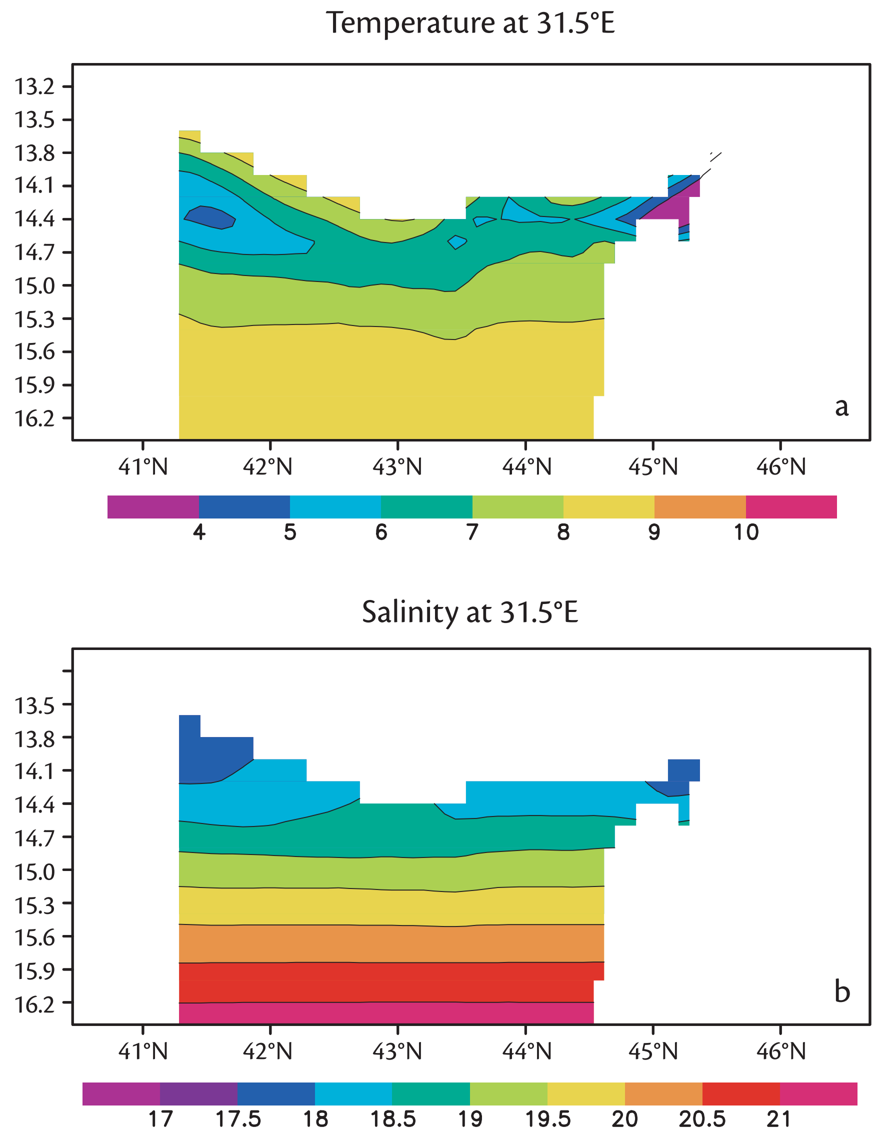


Figure 6. Meridional cross sections of simulated (a) temperature and (b) salinity in density coordinates at 31.5°E during April 1993. The simulations have been done with the 5-minute-resolution Black Sea Modular Ocean Model (MOM). Its setup, forcing, and other technical details are described by Stanev and Staneva (2001) and Stanev et al. (2003). The upper panel represents the CIL. The larger "depth" of CIL in the interior Black Sea seen in isopycnical coordinates is due to upwelling (causing shallower isopycnals). The bottom panel demonstrates, that below σ_t = 15.5 (density layer in kg/m^3), stratification is entirely dependent on salinity, and isohalines coincide with the isopycnals.

to be explained. Breaking internal waves are one of the candidates, as demonstrated in the numerical simulations of Stanev and Beckers (1999) where the oscillations of pycnocline produce mixing in the area of shelf edge, enhance the entrainment of surface water into the intermediate layers, and affect vertical stratification. This mechanism is reminiscent of the "manganese pump." The "manganese pump" hypothesis is a fundamental idea in the biogeochemistry of the Black Sea, suggesting that most of the important interactions and mixing over the continental slope and shelf edge are due to oscillations of the pycnocline and the signals ("mixtures") propagate along isopycnal surfaces into the open sea. These processes are still not well explored, and there is a need for dedicated observations to support the above concepts.

Mixing originating at the sea surface is better studied than deep mixing because at the sea surface, signals are stronger, there are more observational data, and numerical modeling has been successful. The Black Sea once again provides an interesting case study—this time in ventilation of the pycnocline. As demonstrated in the numerical study of Stanev et al. (2003), ventilation occurs only during certain parts of winter, unlike the ocean, where seasonal variability is manifested by the north-south excursions of outcropping isopycnal surfaces during the whole year. The above considerations become clearer if we remember that in the Black Sea, the ratio of the net heat flux through the ocean surface to its seasonal amplitude is a small number (~10^{-2}) (Stanev et al., 2003). Therefore, ventilation of the intermediate layer is maintained by the seasonal signal (not by permanent structures of isopycnal surfaces), which pumps cold water periodically into the CIL (Figure 8). The replenishment time of the CIW of about five years estimated by the model supports the estimates based on sparse observations.

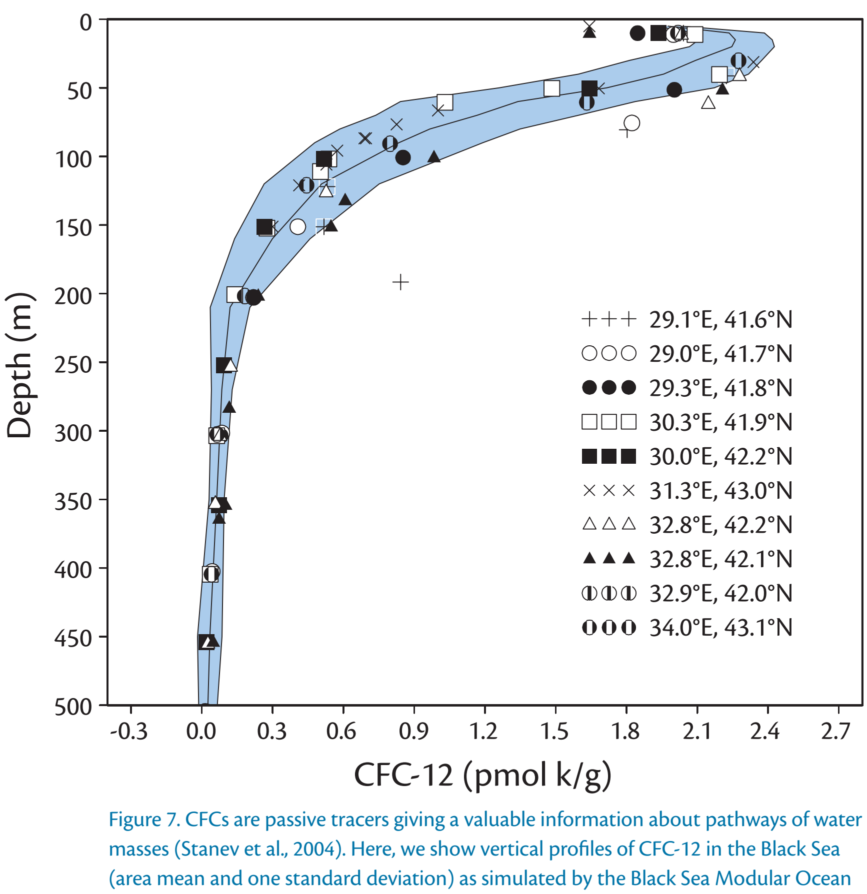


Figure 7. CFCs are passive tracers giving a valuable information about pathways of water masses (Stanev et al., 2004). Here, we show vertical profiles of CFC-12 in the Black Sea (area mean and one standard deviation) as simulated by the Black Sea Modular Ocean Model (MOM). The accuracy of simulations in replicating the penetration of surface signals is supported by comparisons with field observations. Data from the R/V *Knorr* 1988 cruise (for more details see Stanev et al., 2004) are plotted by symbols. The legend gives the correspondence between symbols and station numbers. The outlier at 200 m is from measurements very close to the strait, thus, this value is higher, displaying deep ventilation by the buoyant plume.

Ocean mixing is intimately related to water mass formation, the latter being generally associated with air-sea exchange. There is a long-lasting debate in the Black Sea oceanography community about the relative importance of different mechanisms contributing to water mass formation: cooling of shelf waters and their advection, or convection in the open sea enhanced by mesoscale eddies. Using results from numerical simulations we show that the main issue here is, instead, to what extent air-sea exchange (Figure 9) is dominated by dynamics.

It follows from the results of numerical simulations that not much CIW intrudes the pycnocline south of Kerch Strait (Figure 10) where air-sea exchange is strongest in winter (Figure 9). The explanation of this "discrepancy" is that atmospheric cooling in this area is almost completely compensated by advection of warm water by the Rim Current, thus dynamics reduces the water mass formation rates. Just the opposite situation is observed in the western Black Sea, where the Rim Current transports cold water originating from the northern shelves over the continental slope. Mixing with more saline open ocean water enhances convection rates.

What was not realized in the earlier studies was that water mass formation is localized over a very narrow band along the shelf edge of the western Black Sea. This oversight could have been due to the coarse space/time resolution of the climatic data, precluding detection of such small-scale features. As demonstrated by the numerical experiments of Stanev and Staneva (2001) small-scale processes govern the ventilation regime not only in the bottom layer, but also at the fringe of the mesoscale eddies.

Entrainment of the CIW by the inflowing Bosporus plume is another key mixing mechanism that enables a mixture of surface and intermediate waters (in much larger quantities than the inflow from the strait) to penetrate the pycnocline. Consistent with this general idea, the simulations presented by Stanev et al. (2004) demonstrate that most of the CFCs penetrating the deep layers (Figure 7) have their source at the sea surface within the Black Sea rather than in the Marmara Sea! This penetration occurs in the area of the abrupt continental slope, where dilution of the

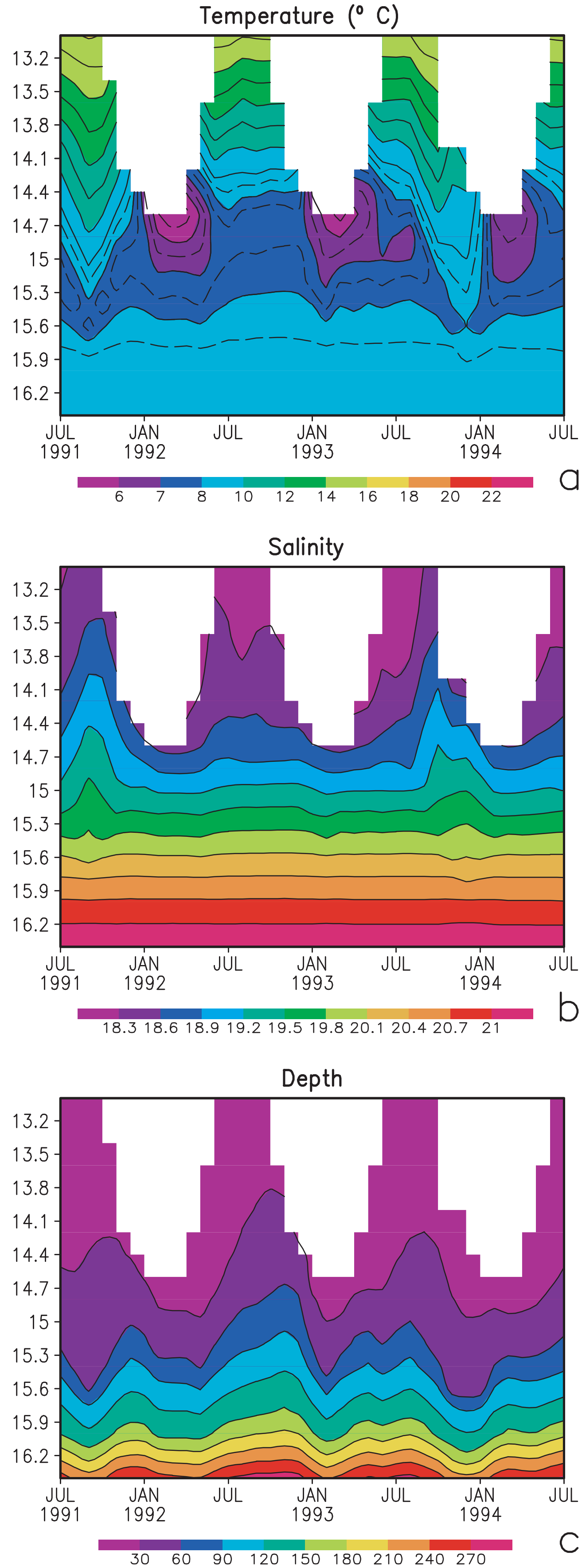


Figure 8. Simulated (a) temperature, (b) salinity, and (c) depth of isopycnic surfaces during 1991-1995 plotted in time-density coordinates. The coordinates of the location are 42.5°N and 31°E, which is in the interior of the western basin. The ventilation in the Black Sea is confined in a very thin surface layer and is manifested by the outcropping isopycnal surfaces in winter, which completely submerge in summer as they are overlain by light surface water. Note also the haline-dominated density in (b) and the up-and-down excursions of isopycnal surfaces (c).

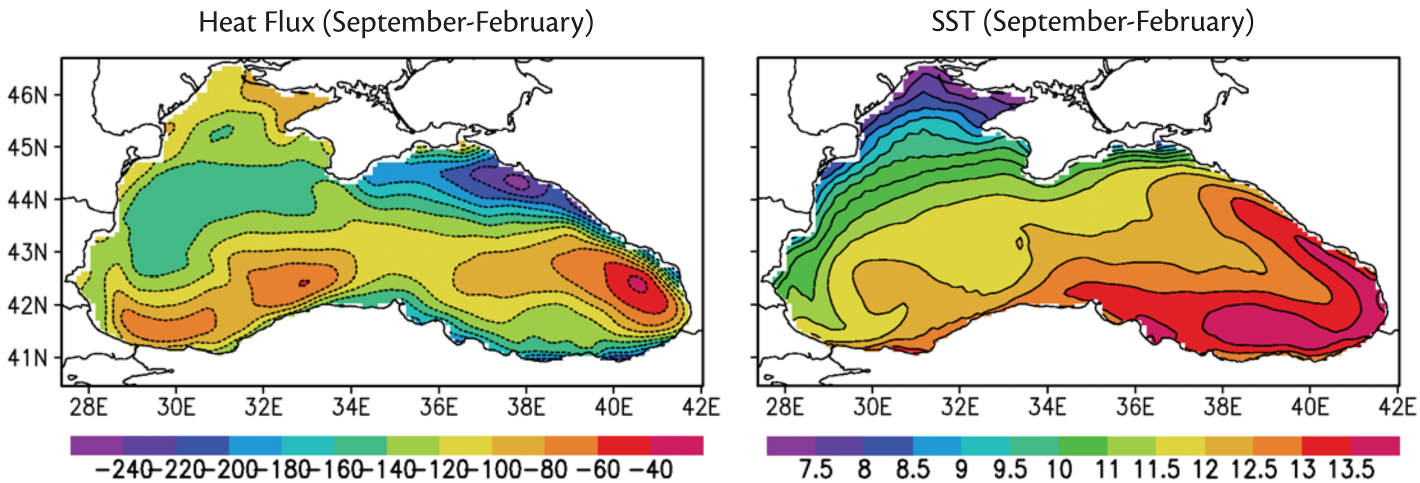


Figure 9. Surface thermal forcing (as diagnosed from the 5-degree-resolution Black Sea Modular Ocean Model (MOM) averaged during the cold part of the year. Left panel: heat flux. Right panel: sea surface temperature (SST). This figure would suggest that the northern Black Sea is the dominating area of water mass formation, the area south of the Kerch Strait providing the largest contribution. However, mixing in the surface layer could bias the estimates based on heat flux data alone.

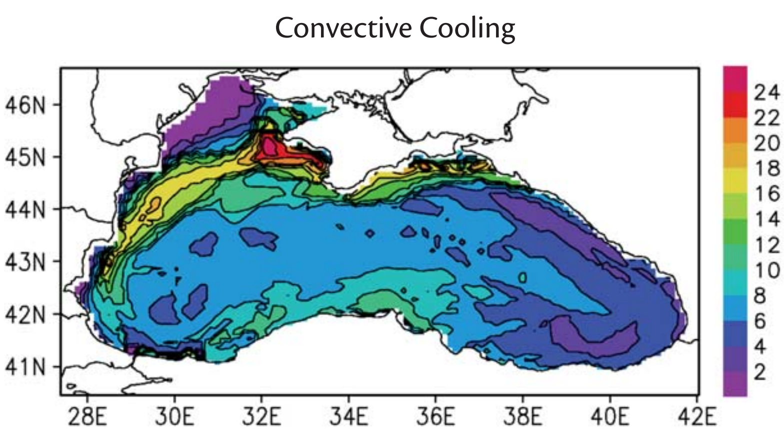


Figure 10. Simulations with the 5-minute-resolution Black Sea Modular Ocean Model (MOM) help to estimate the rates of water mass formation by convective cooling (Stanev et al., 2003). The results here are presented as the thickness of water column (m) intruding the pycnocline every year. Most cold water penetrates the CIL along the northwestern slope area. The advective cooling of the water column in these areas preconditions the penetration of surface cooling down to the CIL. Furthermore, the mixing of cold shelf water with saltier open seawater increases instability and triggers convection along the continental slope. The area of most efficient cooling acts as a small (compared to the basin surface) "throat" where the model predicts maximum penetration of cooled water into the CIL.

effluent is quite strong. The large values of turbulent kinetic energy observed by Gregg and Özsoy (1999) indicate that in this area, entrainment becomes dominant, supporting the simulations of Stanev et al. (2001).

HEAT AND SALT CONVEYOR BELT

Slope (or gravity) currents originating from the Bosporus Strait present a challenge for numerical simulations. Slope currents contribute to the lateral ventilation of the Black Sea because they are the origin of the massive intrusions of oxygen-enriched water that extend to ~200 km from the coast. This situation is highlighted by the outlier seen in Figure 7, and in the more detailed observations by Konovalov et al. (2003). An explanation for these intrusions is given by the numerical simulations of Stanev et al. (2001) (Figure 11).

In a motionless ocean, the "mean for the basin" suboxic layer (a biogeochemical transition zone between oxic surface and sulfidic deep waters) (Murray et al., this issue; Konovalov et al., this issue) would intersect the bottom along a very narrow area, which is illustrated by the red strip in the bottom panel of Figure 11. Numerical simulations demonstrate that the Bosporus plume displaces the ambient water reaching depths of ~250 m (upper and middle panel of Figure 11). Thus, it provides the positive (relative to ambient water) oxygen anomalies in the layer 15 to 16 σ_t (a constant density surface, measured in kg/m^3) (see also Konovalov et al., 2003). Because the ambient water is motionless in the reduced gravity model, the high oxygen signatures extend only to ~50 km from the coast. In the real ocean, oxygenated water is entrapped by coastal eddies (remember the large dispersion of drifters in the Rim Current) (Figure 3) and propagates far from the strait.

The above results lead to a hypothesis about the driving forces behind the Black Sea heat and salt conveyor belt, derived from comparing modeling results and observations. As seen in Figure 10, the heat conveyor belt starts and ends at the Black Sea surface (Stanev et al., 2003); however, only its origin is relatively easily detectable by the large values of CIW intrusions. Because the rate of CIW intrusions is very sensitive to climate change, the amount of CIW can be substantially reduced after several warm winters. This is highlighted in Figure 12, where the good correlation between simulations and observations gives us the confidence to speculate that the thermal conveyor belt gives an integrated response of Black Sea to climate change (see Oguz, paper 2, this issue).

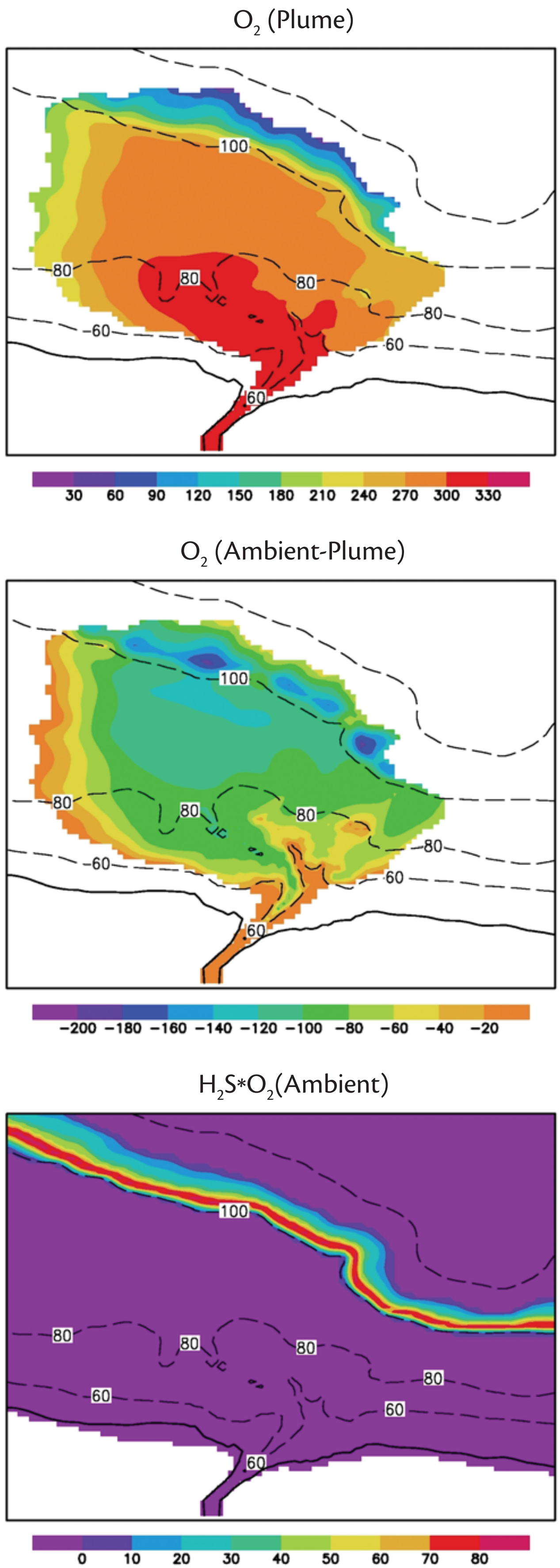


Figure 11. Stanev et al. (2001) developed a reduced-gravity model for the buoyant plume originating from the Bosporus Strait with 600 m horizontal resolution. Unlike the case shown in the Box 1, Figure d, the bottom layer moves and the surface layer is motionless. Stratification of the motionless ambient fluid (including chemical tracers) is prescribed from observations. The model is coupled with a simple chemical model simulating the oxidation of H_2S by O_2. The upper panel gives the distribution of O_2 in the plume, and the middle panel shows the difference between O_2 in the ambient fluid and plume. The bottom panel gives an idea about the projection of the suboxic layer on the bottom represented by the product between H_2S and O_2 (low values are due to either a negligibly small concentration of H_2S in surface layers, or O_2 in deep layers.) The narrow red strip follows a depth of ~120 m, which is approximately the depth of sulfide onset in the open sea (Konovalov et al., 2003). As seen in the upper and middle panels, the plume reaches a depth of ~250 m. The plotted area extends between 28.8°E and 29.51°E and 41.18°N and 41.6°N. Depth contours down to 100 m are plotted with dashed lines with a contour interval of 20 m, the last dashed line is isobath 500 m.

The functioning of the salt conveyor belt is different. Salinity fluxes (in contrast to heat fluxes) are more localized (in the river run-off areas and Bosporus Strait), showing a smaller seasonal buoyancy signal and large annual mean values. The deep branch of the Black Sea conveyor belt is coupled with the Mediterranean Sea surface water; the surface branch exports low-salinity Black Sea water into the Mediterranean Sea. The two branches "meet" in the interior Black Sea. The processes discussed in this paper reveal the multiple mechanisms closing the loop of conveyor belts. There is still much to be studied in the field of theory and observations of the Strait's control. So far, it is known that the sea-level difference between basins controlled by water balance, regional circulation, and direction of wind strongly affects the two-layer exchange; however, modulation of these connected basins' climate by Strait's dynamics and feedback mechanisms are still unclear.

FURTHER PERSPECTIVES

Although recently much has been learned about Black Sea dynamics, there are still many questions and exciting issues to be addressed. We mention four of them.

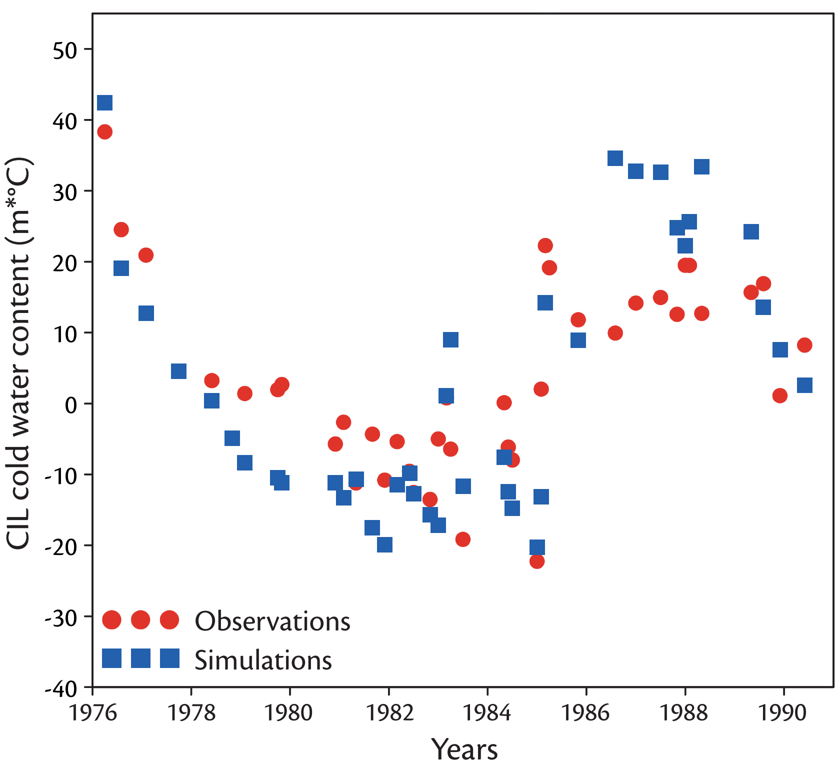


Figure 12. Temporal variability of the cold water content between isopycnal levels σ_t =14.4 and 15.6. Observations and simulations with the Black Sea Modular Ocean Model (MOM) are shown. This variability is triggered by large-scale atmospheric forcing (Stanev and Peneva, 2002; Oguz, paper 2, this issue).

1. Coupled Atmosphere-Ocean Models

Most ocean models are driven by data based on either ocean observations or atmospheric analysis data ("uncoupled" models). These models cannot resolve some very important ocean processes resulting from air-sea exchange because the atmosphere is predetermined. In addition to the inaccuracies caused by lack of interaction between the atmosphere and ocean in uncoupled models, another problem is the insufficient horizontal resolution of available atmospheric data. The dominant processes in the coastal ocean have small scales, which are usually sub-grid scales in global atmospheric models. The question then is this: do simulations from numerical models forced by coarse-resolution data provide reliable estimates for the coastal ocean? One of the problems with using coarse-resolution atmospheric analysis data (Figure 1) to force fine-resolution ocean models (see Kara et al., 2005b) is associated with the errors close to the coasts, which can be attributed to the misrepresentation of the land/sea mask (a matrix that defines which points in the horizontal grid are dry and which are wet). However, with the present-day resolution of available products, this problem can be solved only partially even if the masks are corrected. More important is that in areas of large orographic slopes, coarse-resolution atmospheric models give large errors, highlighted by the fact that in these models, wind crosses steep topography along the southern coast (Figure 13, lower panel), which is not very plausible. Using regional atmospheric models could eliminate errors in regions with complex orography (Figure 13, upper panel).

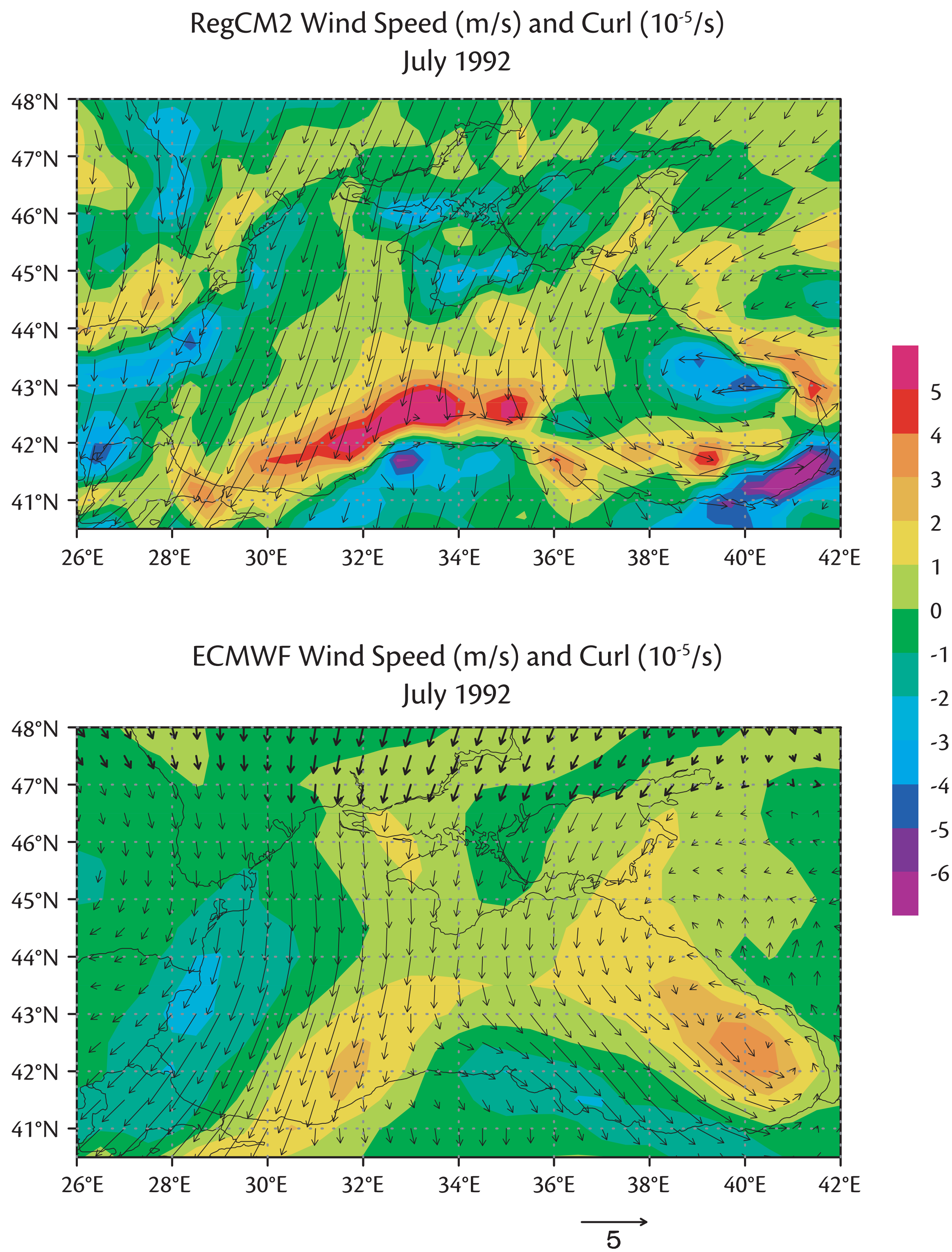


Figure 13. The regional atmospheric model RegCM2 with a horizontal resolution of 30 km has recently been set up by E. Peneva (manuscript in preparation) for an area extending from the Adriatic to the Caspian Sea (the Black Sea is almost in the middle of the area). The model is driven by the ECMWF reanalysis data with 1-degree resolution. The problems with the wind crossing steep orography (lower panel) are removed in the regional simulations. Note the small-scale curl in the wind field (upper panel) emerging in the coastal zone.

Furthermore, comparing these models with Figure 2 demonstrates that the wind patterns resolved by the fine-resolution regional atmospheric model have horizontal scales that are comparable with the scales of the coastal anticyclones. One could expect that comparable oceanic and atmospheric scales in the coastal zone could enhance coupled modes in the regional atmosphere and ocean. The next step towards understanding fine-scale coastal dynamics is coupling ocean and regional atmospheric models.

> The Black Sea is where most kinds of numerical models based on primitive equations have been used to simulate circulation and transport of matter...

2. Cascading Basins

The system of European coastal seas consists of several cascades, the biggest of which includes Azov, Black, Marmara and Mediterranean Seas. (Here we speak about cascades, keeping in mind that the net transport in the straits is comparable to the transports in each layer, which is not the case in the Gibraltar Strait, for example.) The two-layer exchange in the connecting straits modulates short- and long-term climate variability in each basin, introducing a number of feedback mechanisms, which are still largely unknown. Numerical modelling seems to provide a powerful tool to address dynamics of coupled basins, however straits are very narrow, and ultra-high-spatial resolution is needed—a big challenge for numerical models (Figure 14) (see also Peneva and Stips, 2005).

In the Black Sea-Mediterranean Sea cascade, a large amount of freshwater accumulated on land is exported towards the Mediterranean. It is natural to expect that long-term variations of water transport through the straits may be key to understanding climatic controls dominating the European river catchment area and their interaction with the regional and global water cycle. These transports have undergone dramatic evolution caused by global sea-level change. Thus, the Black Sea-Mediterranean Sea cascade provides one more case study, this time in the field of long-term climatic transitions. This case study is actually unique because there were situations in the past when transport in the Bosporus Strait was unidirectional, and other times when it had ceased. These transitions resulted in dramatic transitions between different states of Black and Mediterranean Sea's physical and biogeochemical systems, another exiting problem to be addressed with the help of numerical modeling.

3. Black Sea Operational Oceanography

Although operational oceanography has specific practical goals, it can contribute to further understanding ocean dynamics because (1) operational oceanography needs and develops sound knowledge of natural systems, (2) by bringing modeling and data together (e.g., assimilation of data into numerical models), it results in the best use of theory and observations, (3) operational models produce valuable data sets, analysis of which contributes to scientific development (this possibility has been largely demonstrated in meteorology by the quality of recently available atmospheric analyses and reanalyses, for example, ERA-40 data). Efforts in the field of data assimilation in the Black Sea (Stanev, 1994; Korotaev et al., 1999) have already contributed to studying the Black Sea system and also towards developing operational capabilities (Besiktepe, 2003; Korotaev et al., 2003). The interest is particularly strong in the coastal areas, where most of operational products are needed. Because the Black Sea is a typical coastal sea with many specific features, it can provide an important test region for developing operational models.

We demonstrated in this paper that available numerical models for the Black Sea are well developed and validated (see also the references). Furthermore, the merged products from satellite altimetry provide very valuable data to be assimilated in operational models, with high level and quality of physical signals making it possible to accurately reconstruct both temporal variability and mesoscale circulation. When assimilated in numerical models, these data ensure low errors in simulated fields as shown by comparisons with independent observations (Korotaev et al., 2003). The harmonization between modeling (theory) and monitoring (observations) efforts seems to become a major challenge in the Black Sea oceanography in the years to come.

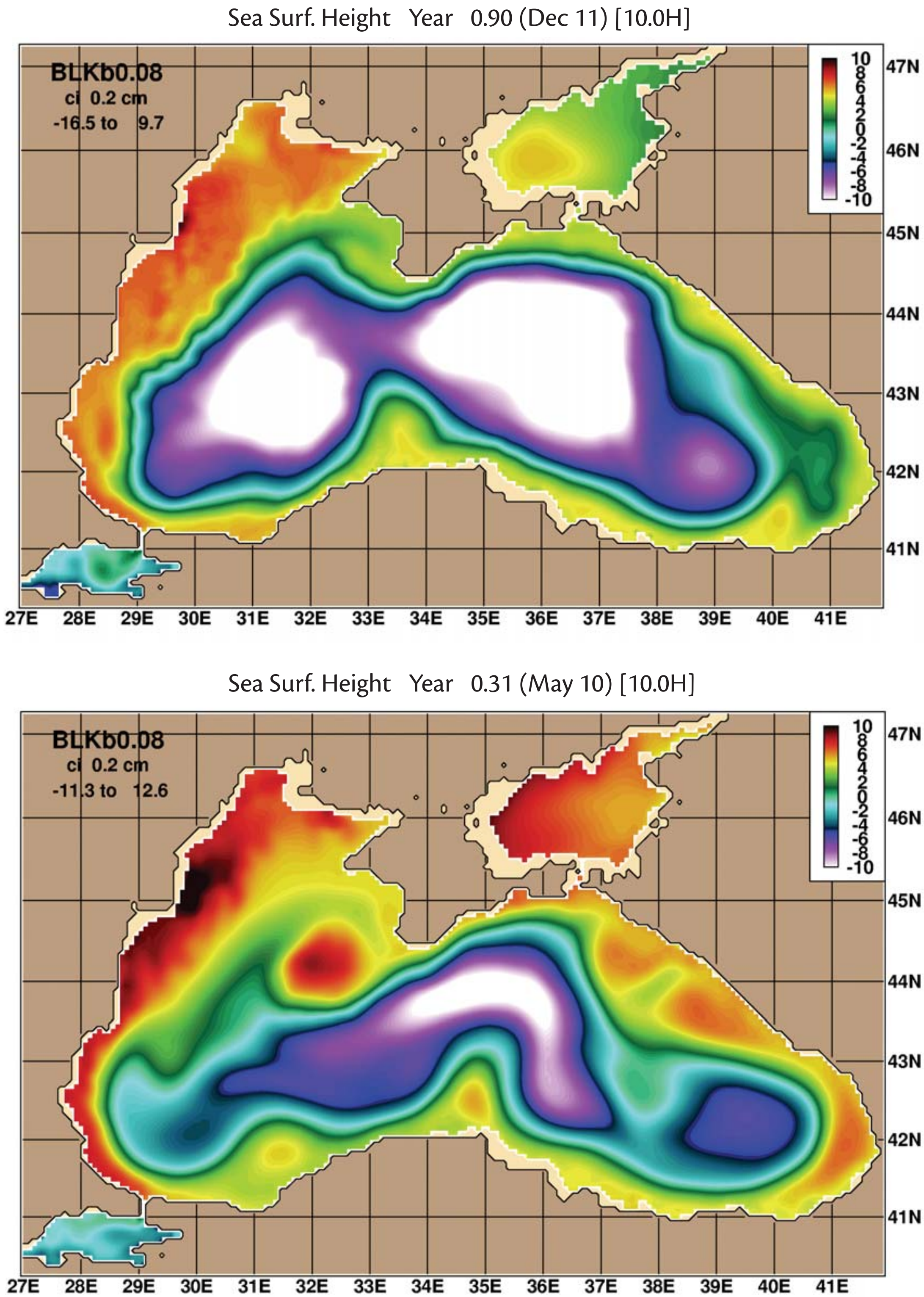


Figure 14. Three cascading basins. In the recent joint effort of the author and H. Hurlburt, J. Metzger, B. Kara, and A. Wallcraft (all at Naval Research Laboratory), the Hybrid Coordinate Ocean Model (HYCOM) was set up for a triple cascade with a resolution of ~ 6 km. The figure shows two snapshots of the simulated sea level: winter (less developed coastal anticyclones) and spring (initiation of anticyclonic circulation). Although the resolution is very coarse for reproducing realistic exchange between basins, the results are encouraging and motivate developing downscaling strategies, which can be applied to similar cases in other areas.

4. Coupling Between Physical and Biogeochemical Systems

Because the mixed layer depth is very shallow, especially in summer, an accurate treatment of insulation penetration is needed. The HYCOM, which includes an up-to-date parameterization of optical processes in the upper layer Kara et al. (2005b,c), proved that the sea surface temperature in the Black Sea is very sensitive to water turbidity. This result is consistent with the evidence that shows that changes of water turbidity can change upper-layer stratification (Gennady Korotaev, Marine Hydrophysical Institute of the Ukraine Academy of Science, Ukraine, pers. comm., 2005). Because turbidity in this sea is large, highly variable, and controlled by external forcing and biological processes, an interesting possibility exists that in this basin, the feedback mechanisms between physical and biological systems could play an important role in the overall Black Sea dynamics. Furthermore, the authors suggest that if the Black Sea turbidity is entirely or largely due to biology, a lack of nutrients (or another cause for a loss of biomass) will have a significant impact on the overall circulation.

The Black Sea is one of the most interesting cases worldwide where one detects high-quality, short-time signals, as well as signals of its paleo-evolution that are well preserved due to the anoxic bottom conditions. This information is not only of regional interest, but can contribute to revealing important changes in the Earth system. The modeling of the biogeochemical process is quite advanced (Oguz et al., 2002), there are promising results in the field of nitrogen cycling in the shelf-continental slope area (Gregoire and Friedrich, 2004), and coupling with advanced circulation models can facilitate the quantification of biogeochemical functioning, in particular if sediment dynamics is addressed properly.

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