INTRODUCTION TO GENERAL PHYSICAL OCEANOGRAPHY OF THE BLACK SEA

Review by A. Ostrovskii and A. Zatsepin

1. Bathimetry

The Black Sea is about 2000 m deep basin with zonal and meridional dimensions of ~1000 km and ~400 km, respectively, located roughly between 28° and 42°E longitudes, 41° and 46°N latitudes (Fig. 1). It has only a narrow opening to the shallow (less than 75 m deep) Bosphorus Strait restricting exchange with the Mediterranean Sea; it is almost enclosed mid-latitude marginal sea. The Black Sea bathymetry is characterized by a flat abyssal plain (with a maximal depth of 2200 m) in the central area and a continental shelf with varying offshore extension between 5 km (off the western Turkish and Caucasian coasts) to near 200 km in the northwestern area. The Crimean Peninsula to the north and the central Turkish coastline to the south separate the sea into two sub-basins.

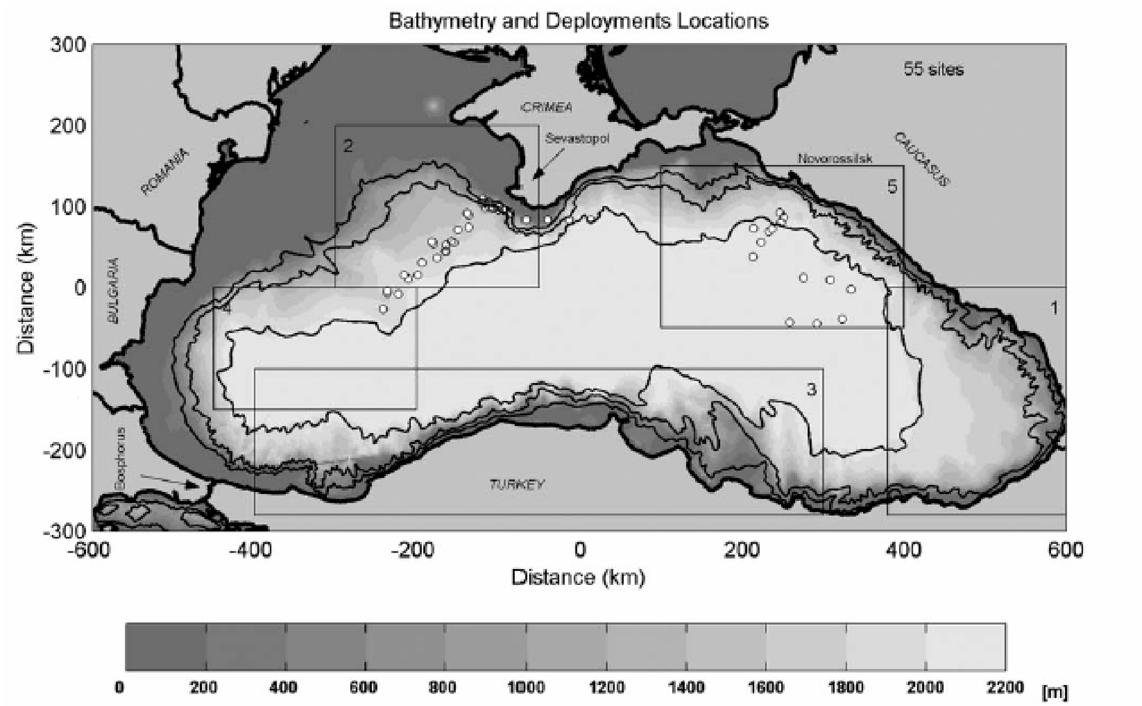

Fig. 1. Black Sea bathymetry (gray shades), drifter deployment locations (circles) and areas (1–5) used to calculate the Lagrangian statistics (rectangles) – see subsection 5. The 200, 1000 and 2000m isobaths are overlaid.

2. Water masses and vertical stratification

Unlike the Mediterranean, the Black Sea is an estuarine type basin (or dilution basin) due to the large river discharge, especially on its northwestern shelf area. A major Danube River accounts for about 50% of the river freshwater influx. According to observations during 1860-1989, the Danube River flow varied from 4×10^3 to 9×10^3 m^3/s (Bondar 1989). The seasonal change in the Danube River flow reaches 1/3-rd of the annual mean value. Also, this flow undergoes substantial interannual fluctuations. The Danube River discharge is correlated with variations of the sea level on interannual scales, as a result of the controls exerted by the Bosphorus.

The low salinity surface waters reach the Anatolian coast in modified form due to mixing; the travel time needed for low salinity waters to move from the Danube River mouth to the Bosphorus Strait lies in the range of 1-2 months. Throughout the Black Sea, the low salinity surface waters of riverine origin overlay salty deep waters of Mediterranean origin. According to Ozsoy and Unluata (1997), the outflow of the Black Sea water through the Bosphorus Strait equals to 20×10^3 m^3/s, by contrast the inflow of the Marmara Sea water was estimated to be to 10×10^3 m^3/s. Water exchange through the Bosphorus Strait has a two-layer structure: the Marmara Sea water of higher salinity is transported to the Black Sea along the bottom of the strait. Ozsoy and Unluata (1997) pointed out that the exchange flows at any instant of time greatly differ from these estimates, as a result of the time-dependent meteorological and hydrological forcing originating from the adjacent basins. Blocking of the flows in either layer occurs during extraordinary events lasting for a few days.

Inflow of the salt water through the Bosphorus Strait determines the density stratification of the sea. The permanant pycnocline is maintained at 100–150 m depth between the surface waters and the deep saltier waters: the deep layer salinity is ~22.5 ‰, as compared with 18–18.5 ‰ in the surface layer. A pronounced permanent pycnocline is situated at a depth of 150–300 m, making the internal Rossby radius equal to 25 km. The seasonal pycnocline usually develops in summer between 10 and 40 m (Oguz et al., 1992).

The main pycnocline coincides with the lower boundary of the Cold Intermediate Water (CIW) which limiting isotherm is 8°C. The layer filled with CIW is called Cold Intermediate Layer (CIL). The lowest CIL core temperature is about 8°C.

According to Ozoy et al. (1993), seasonal and interannual signals extend to depths ~500 m i.e., below the pycnocline, where intrusions of Mediterranean Water entering the Bosphorus drives the interior circulation and mixing.

The waters situated deeper than 500 m are essentially stagnant in the Black Sea (Ozoy et al., 1991, 1993), except near the boundaries, where local instabilities are able to produce fine structures (Ozsoy and Besektepe, 1995). Below 1700 m, a bottom convection layer of thickness ~400 m is driven by geothermal heating from the sea floor (Ozoy et al., 1991, 1993, Ozsoy and Besektepe, 1995).

3. General circulation

The Black Sea is characterized by a predominantly cyclonic and strongly time-dependent basinwide circulation that follows approximately the continental slope around the basin (Fig. 2). Known as the Rim Current, this unique circulation feature is essentially driven by the mean cyclonic wind pattern that prevails over the sea and by strong buoyancy input (Stanev, 1990; Oguz et al., 1995). The Rim Current is a 40–80km wide slope current locked to the steep continental slope (Korotaev et al., 2001). Model simulations (Oguz et al., 1995) have shown that, regardless of the forcing mechanism, the Rim Current is absent if the topography is not included. Changes in bottom slope and coastline orientation along the Turkish and Caucasian coasts generate Rim Current meanders and instability features on a wide range of space and time scales (Oguz et al., 1993).

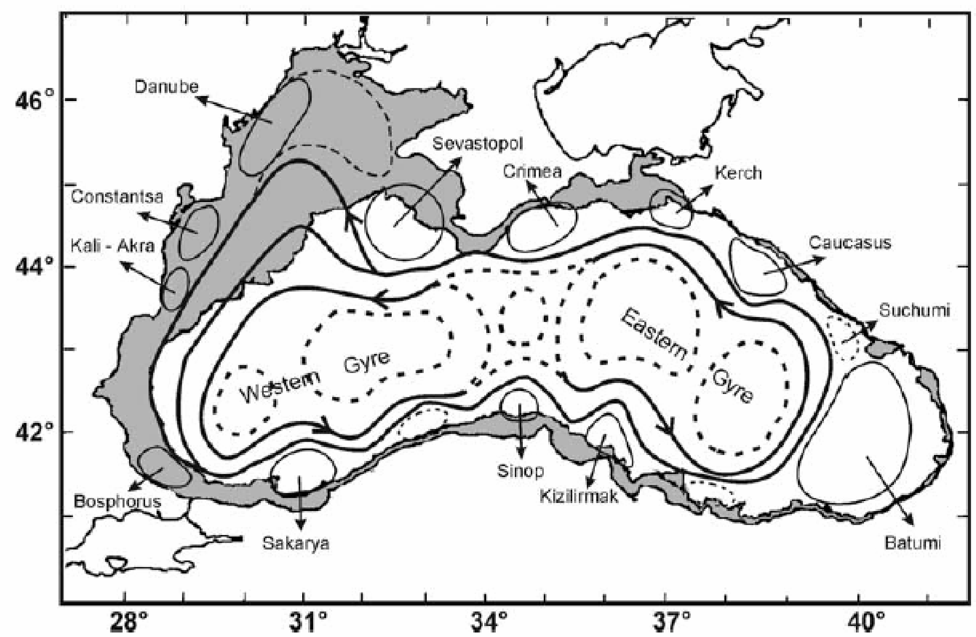

Fig. 2. The schematic diagram for the main features of the upper layer circulation in the Black Sea (Korotaev et al., 2003).

Among many factors that affect the horizontal circulation of water and internal water exchange in the Black Sea, the three most important ones can be highlighted. They are the stable quasi-twolayered density stratification of the water, unsteady and spatially irregular wind forcing, and the characteristic features of topography of the continental slope.

The density stratification in the Black Sea is characterized by the presence of a sharp pycnohalocline that separates an oxygen-containing top layer, whose thickness does not exceed 200 m, and a bottom hydrosulfide layer, whose thickness over the abyssal is greater than that of the top layer by an order of magnitude. The pycnohalocline determines the depth of penetration of the winter convective mixing and limits the oxygen supply to the water column. In addition, it prevents momentum that is transported from the atmosphere owing to the wind forcing against downward propagation. As a result, the currents induced by the wind are localized in the upper layer of the sea and are mainly baroclinic. The facts that the Black Sea is relatively small, the water exchange between the Black and Mediterranean seas via the Bosporus Strait is weak, and the water exchange inside the basin is high may explain the rather regular density stratification throughout the sea area, excluding the vast northwestern shelf that is strongly affected by the riverine runoff.

One of the important characteristic features of the horizontal water circulation in the Black Sea is the general cyclonic gyre in the upper layer, i.e., the contour current, which flows counterclockwise along the coast. On the average, the mainstream of the Rim Current is located over the continental slope (Blatov et al., 1984, Ovchinnikov et al., 1993). According to conventional point of view, the topography of the continental slope significantly affects the structure and stability of the boundary currents, in particular, the Rim Currrent (Koblinsky, 1990, Korotaev et al., 1999). It is known that, owing to the conservation of the potential vorticity, large-scale boundary currents flow mainly along the depth contours (Koblinsky, 1990). Hence one may expect that the steeper the slope, the better the current traces the depth contour. However, when the width of the slope is substantially smaller than the horizontal size of the current, the current has to respond to a steep slope as if it were a vertical wall, and, in this case, it is barely affected by the topography. When the slope width is comparable to or exceeds the horizontal size of the current, we should assume that the effect of the topography on the dynamics and structure of the current is substantial. Therefore, in addition to the slope steepness, the ratio between the width of the slope and the horizontal size of the current should be a key parameter that defines the topographic effect.

It should be noted that the density stratification to some extent "shields" usually most energetic upper sea layer from the effect of the bottom topography. However, even in the presence of a strong stratification, the continental slope can affect the dynamics, structure, and stability of the near-shore current as well as the processes of the generation, movement, and transformation of eddies, particularly over the shelf edge and the top part of the continental slope, where the sea depth is comparatively low. Since eddies are one of the main mechanisms of the interaction of the near-shore zone with the deep sea (Zatsepin et al., 2003), the character and intensity of the water exchange over the slope must be affected by the topography of the continental slope.

Common sense suggests that the effect of the continental slope on the Rim Current should be different for slopes with different steepness and width as well as with different curvature of the depth contours, whose outlines follow the coastline rather well. The topographical features of the continental slope of the Black Sea are well seen in Fig. 1. The distance between the 100-m and 1500-m isobaths characterizes the width of the slope in different areas of the basin. The dimensionless width of the continental slope zone ("width index") is assumed as the ratio L_s / R_d , where L_s is the minimum horizontal distance between the 100-m and 1500-m depth contours and R_d = 18 km is the value of the baroclinic Rossby deformation radius characteristic of the abyssal areas of the sea (Zhurbas et al., 2004), which is a "measure" of the width of the Rim Current. In the northeastern and southwestern areas of the sea, the continental slope is rather narrow ($L_s / R_d \sim 1$), whereas in the northwest, the slope is rather wide ($L_s / R_d \geq 4$). Therefore, it can be expected that the character and extent of the effect of the slope on the structure of the Rim Current in the northwest as well as in the northeast and southwest of the basin should be different.

The wind effect seems to be the most important factor that determines both the structure and the intensity of the horizontal water circulation. The main characteristics of the wind effect on the sea surface are the wind friction stress τ and the vertical component of its vorticity $curl_z\tau$. Owing to the mechanism of Ekman excitation (Zatsepin et al., 2002b), favorable conditions are realized for the onset of the total horizontal water circulation in the basin, which should have the same sign as the friction stress vorticity. It is known that the annual mean vorticity of the wind field in the Black Sea is positive (Stanev 1990). The total water circulation is also cyclonic (Blatov et al., 1984). It was also found that τ and $curl_z\tau$ reach their maxima in the winter period and their minima in the summer. Hence, the general cyclonic water circulation in the Black Sea should be enhanced in the winter and weakened in the summer. This assumption was supported by an analysis of the Black Sea level from the satellite altimetry carried out from 1992 to 1997 (Korotaev et al., 1999, Korotaev et al., 2003). It was revealed that, in the winter, the Rim Current intensifies, whereas in the summer it decays. The winter circulation regime is characterized by a coherent stream of the Rim Current that is "pressed" towards the continental slope, whereas in the summer, the mesoscale eddy structures prevail on the background of the weak general cyclonic water circulation. In addition to the seasonal variability of the circulation in the Black Sea (see section 5 below), there is a variability with higher frequencies (with a period of one to two months) also caused by the variability of the Ekman excitation.

An analysis of the field observations showed that the regime of the Rim Current in the northeastern part of the sea (where $L_s / R_d \sim 1$) is well determined by the level of intensity of the wind forcing of the circulation assessed over the month before the ship observations (Zatsepin et al., 2002a, Zatsepin et al., 2002b). When the wind forcing during this period is substantially higher than the mean level, the Rim Current, as a rule, is represented by a coherent stream pressed to the continental slope. When the wind forcing throughout the previous month is weak or completely absent, a circulation regime is characterized by the domination of mesoscale eddy structures and a barely recognizable stream of the Rim Current is observed.

In the sea northwestern region, where the continental slope is gentle and rather wide ($L_s / R_d \geq 4$), anticyclonic eddies move southwestward (cyclonically) strictly following the depth contours and do not deviate toward the abyssal zone (Ginzburg et al., 2002). The frequent generation of intense and long-lived anticyclonic eddies in the sea northwestern region, in particular Sevastopol Eddy (see Fig. 2), seems to be associated with both the characteristic features of the rough topography of the continental slope west of the Crimean Peninsula and the vorticity of the wind field, which has predominantly negative (anticyclonic) sign over the northern part of the sea.

4. The eddies

Hydrographic observations (Oguz et al., 1993, 1994) and satellite data (Oguz et al., 1992; Sur et al., 1994; Stanev et al., 2000; Ginzburg et al., 2000b; Korotaev et al., 2001, 2003) have revealed the existence of a series of quasi-stable/ recurrent near-shore anticyclonic eddies on the coastal side of the Rim Current and several cyclonic gyres in the central part of the basin. The two most pronounced and persistent near-shore anticyclonic eddies are the Batumi Eddy in the Black Sea southeastern corner and the Sevastopol Eddy over the smooth continental slope west of the Crimean Peninsula (see Fig. 2). The interior of the Rim Current is formed either by one elongated basin-wide cell or by two separate cyclonic gyres in the western and eastern parts of the Black Sea. The interiors of these gyres include recurrent mesoscale eddies which are in contact with each other by a recurrent anticyclone called the Central Basin Eddy (Oguz et al., 1993). The central eddies and gyres have scales from a few tens to a few hundreds of kilometers, and their number, morphology and position vary seasonally.

Spatially and temporally evolving Rim Current meanders and sub-basin scale eddies typically have scales of about 125km along the western and southern coasts and about 250 km along the northern coast (Oguz et al., 1994; Rachev and Stanev, 1997). Models have shown that in spring and summer, the weakening of the wind stress leads to a decrease in intensity of the mean currents (Gre´goire et al., 2004; Stanev, 1990). As a result, the Rim Current meandering observed along the Turkish and Caucasian coasts intensifies, and large meanders are created (100–200 km).

Recently, by using a joint application of satellite imagery, Argos-tracked drifters and hydrographic, chemical and biological surveys focused in the northeastern Black Sea, Zatsepin et al. (2003) have provided observational evidence that: (1) anticyclonic eddies are observed not only in the nearshore and Rim Current zones but also in the central Black Sea; (2) these anticyclones (80–100 km) penetrate the pycnocline. Orbital velocities can reach 50 cm/s (same order of magnitude as the Rim Current speeds); (3) they can interact with the Rim Currrent, which is deflected away from the coast and separates into several jets causing advection and mixing of coastal waters. This transport is comparable to that produced by the detachment of near-shore anticyclonic eddies from shore; (4) long-lived anticyclones in the central eastern Black Sea do not correlate with the severity of the preceding winter. But the interannual, seasonal and synoptic wind forcing variations are determining factors; and (5) eddy dynamics appear to be one of the major factors for the shelf/deep basin exchanges in the Black Sea.

Rachev and Stanev (1997) have shown that Black Sea eddies tend to form in the eastern basin and propagate westward as Rossby waves with speed of approximately 3 cm/s. The narrow Black Sea section south of the Crimean Peninsula strongly affects that eddy propagation. Dissipation increases in the western basin where eddies slow down and their scales become smaller. This process is dependent on topography. This westward phase propagation was confirmed using sea level data obtained from satellite altimeters (Korotaev et al., 2001).

Zatsepin et al. (2003) observed mesoscale anticyclonic eddies not only in the near-shore zone and Rim Current region but also in the central part of the Black Sea. Both anticyclonic and cyclonic mesoscale eddies, long-lived (about 3–8 months) and relatively short-lived (less than a month), occupy the basin interior. The existence of such eddies, particularly anticyclones (as the most striking dynamical features with regard to the cyclonic sign of macroscale circulation in the Black Sea), was documented by means of hydrographic data and satellite information in 1984, 1993, 1997, 1998, and 1999. These anticyclones usually have diameter of about 80–100 km and they penetrate deeply into the pycnocline (at least down to 300–400 m). Typical orbital velocity of such eddies near the sea surface is about 0.15–0.50 m/s, which is on the same order of magnitude as the velocity of the Rim Current jet.

The main origin of anticyclonic eddies in the central region of the Black Sea is the detachment of NAEs from the Caucasian, Turkish, and southeastern Crimean shores, and their transformation into open sea eddies (Zatsepin et al., 2003). A compilation of the observations related to different years allowed the authors to conclude that open sea anticyclonic eddies in the eastern basin are most often detected in two areas centered at about 43°N, 37°–39°E and 44_N, 35°–37°E. The contributors of such eddies to the former area are NAEs detached from the Sochi-Sukhumi region, southeastern part of the sea and the Turkish coast, to the latter area: those detached from the Novorossiysk region and southeastern Crimea. Coupling with the adjacent cyclone into dipole vortex structure, favorable wind conditions, and bottom/ shoreline relief may contribute to the detachment of NAEs from the shore. Long lifetime of open sea anticyclonic eddies is likely determined by their large store of potential energy, and by replenishment of their energy and vorticity due to interaction with neighboring eddies and currents.

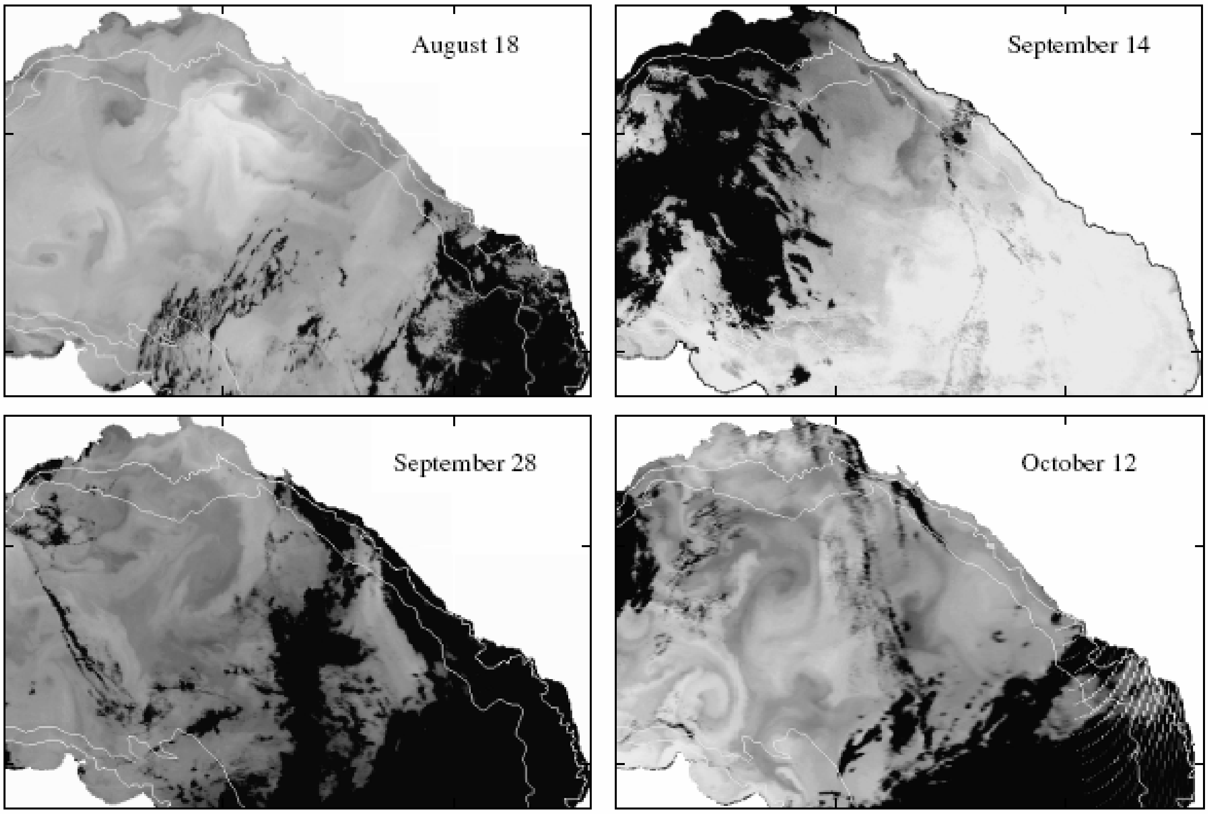

Fig. 3. Space born NOAA AVHRR IR images of the sea surface as of August–September 2003. The thin white lines are the 200- and 1500- m isobaths. This set of the IR imagery demonstrates evolution of the anticyclonic eddy generated in the near-shore zone in the northeastern region of the Black Sea. The eddy moved to the abyssal zone (beyond the 1500-m depth contour).

As it was mentioned above, in the northeastern Black Sea, with the decrease in the wind forcing, not only the Rim Current weakens, but also its midstream is detached from the continental slope toward the abyssal area to a distance of 40 miles from the coast. Such an effect is associated with the generation of the near-shore anticyclonic eddies that displace the stream of the boundary current toward the abyssal region. The detachment of the NAEs from the coast and their conversion into the eddies of the open sea (Ginzburg et al., 2002, Zatsepin et al., 2003) are the result of weakening of the Rim Current and its disintegration into eddies. An example of such a behavior is presented in Fig. 3, where the process of the offshore movement of a near-shore anticyclone is traceable in a set of satellites images of the surface temperature in the northeastern part of the sea.

In the northwestern part of the sea, where the wide continental slope is gently sloping, anticyclonic eddies move southwestward (cyclonically) strictly following the depth contours and do not deviate toward the abyssal zone (Ginzburg et al., 2002). An example of such a behavior is presented in Fig. 4, where movement of two anticyclonic eddies can be tracked, - the eddy pathways closely follow the bathymetry for several months. The frequent emergence of intense and long-term anticyclonic Sevastopol eddy here seems to be associated with both the particular features of the continental slope topography west of the Crimean Peninsula and the wind field vorticity, which is predominantly negative (anticyclonic) over the northern Black Sea (Zatsepin et al., 2002b).

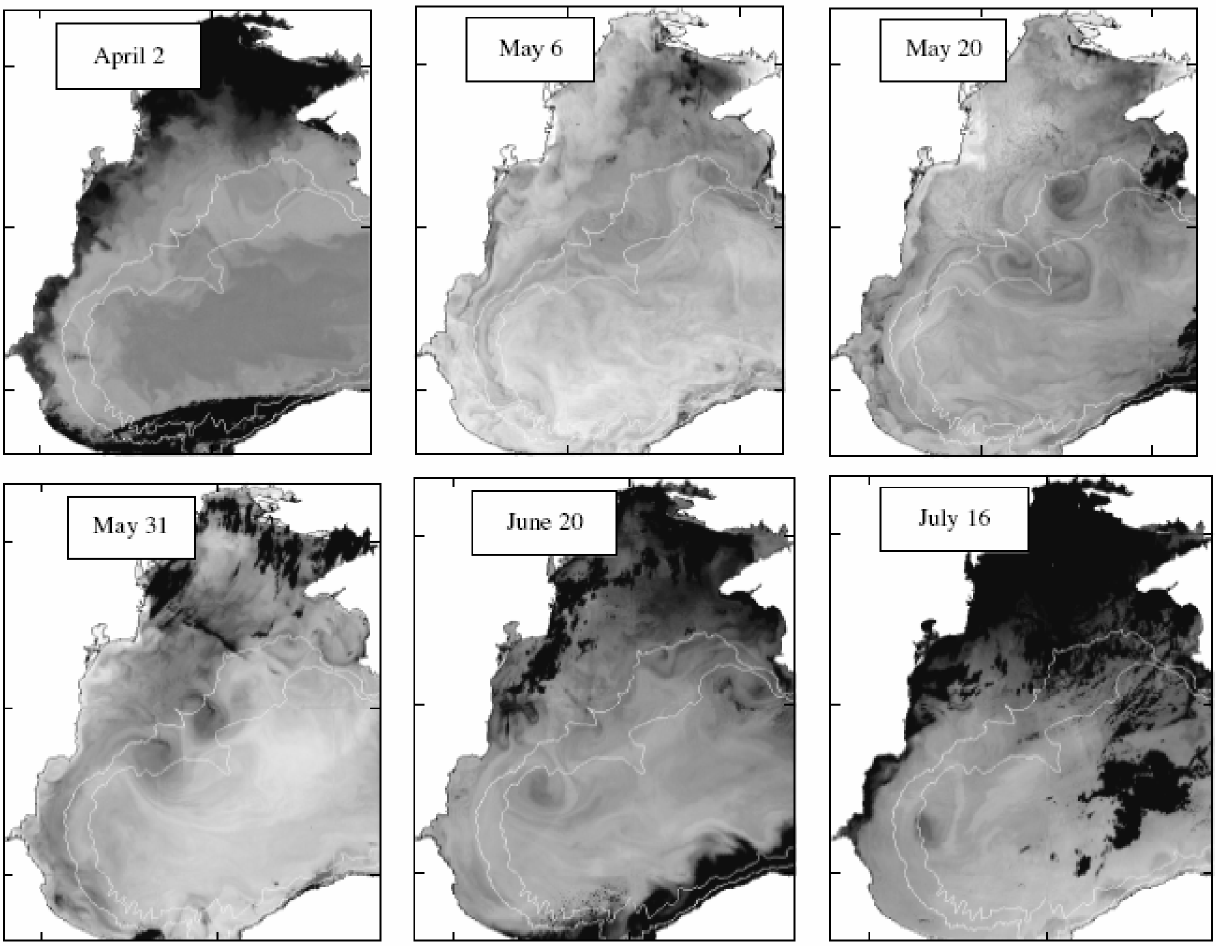

Fig. 4. Space born NOAA AVHRR IR images of the sea surface as of April–July 2003. The thin white lines are the 200- and 1500- m isobaths. Two anticyclonic eddies were generated in the near-shore zone in the northeastern region of the Black Sea and moved southwestward along the slope.

There are indications (Zatsepin et al. 2003) that the existence of longlived anticyclonic eddies in the eastern deep basin does not correlate with the severity of the preceding winter: such eddies were observed after both cold winter of 1992–93 and warm winter of 1998–99. The observations during the summer-autumn of 1993 and 1999 suggested that there can be a positive correlation between the intensive mesoscale eddies formation and low atmospheric wind forcing. It should be stressed however that most of the observations of the open sea anticyclonic eddies relate to warm season, from April to December when cyclonic vorticity of the atmospheric circulation and the strength of winds are usually lower than in winter (Korotaev et al., 1999; Staneva and Stanev, 1998). But even during the winter season wind forcing may be weak or have anticyclonic sign in some parts of the Black Sea area (Zatsepin et al., 2002b). So it is quite possible that interannual, intraseasonal, and synoptic/local variability of wind forcing, and the stability of the Black Sea macroscale circulation associated with it, are the governing factors for the mesoscale structure generation.

More recently, by using the satellite tracked drifter data (see section 3.2 below), Poulain et al. (2005) showed that near-shore anticyclonic eddies, including the Batumi and Sevastopol eddies, prevail inshore of the Rim Current. In addition, they proved for the first time that both cyclonic and anticyclonic mesoscale features are ubiquitous throughout the basin. These eddies contribute significantly to the horizontal mixing, especially between the coastal zones and the deep sea (Zatsepin et al., 2003). It is interesting to note that, besides the Batumi and Sevastopol eddies, the drifters did not provide any strong signature of other persisting near-shore anticyclonic eddies. The strong recurring Batumi and Sebastopol eddies are located in areas where the mean annual wind curl is negative (Zatsepin et al., 2002), so these two eddies may be formed and sustained under the direct influence of wind forcing. The other near-shore anticyclonic eddies seem to be non-permanent eddies, produced mostly by the instability of the flow.

5. Near-surface currents and horizontal diffusion

Direct Lagrangian observations of near-surface currents in the Black Sea date back to the late 1980s (Motyzhev et al., 1987, 2000). A total of 14 satellite tracked drifters were used between 1987 and 1997 to measure the Rim Current spatial structure and temporal variability. The drifters confirmed the strong seasonality of the Black Sea surface dynamics with a well-pronounced and strong (with surface speeds up to 1m/s; Korotaev et al., 2001) Rim Current in winter, and with high eddy activity and a weak and intermittent Rim Current in summer. The data from two drifters in summer 1987 were incorporated with climate data and numerical modeling results to reconstruct the circulation in the western Black Sea (Eremeev et al., 1992) suggesting seasonal inversion of the large-scale circulation. A new phase of drifter experiment in the Black Sea started in September 1999, when 6 drifters were deployed in the northeastern region to study near shore–deep sea exchange processes (Motyzhev et al., 2000; Afanasyev et al., 2002; Zatsepin et al., 2003). This marked the start of international collaboration between Ukrainian, Russian, American and European scientists to study the Black Sea surface dynamics with satellite-tracked drifters. More drifters were launched in the falls of 2000 and 2001. Thanks to additional releases from ships of opportunity, the Black Sea was sampled continuously by drifters (at least 2 units) from October 2001t o August 2003.

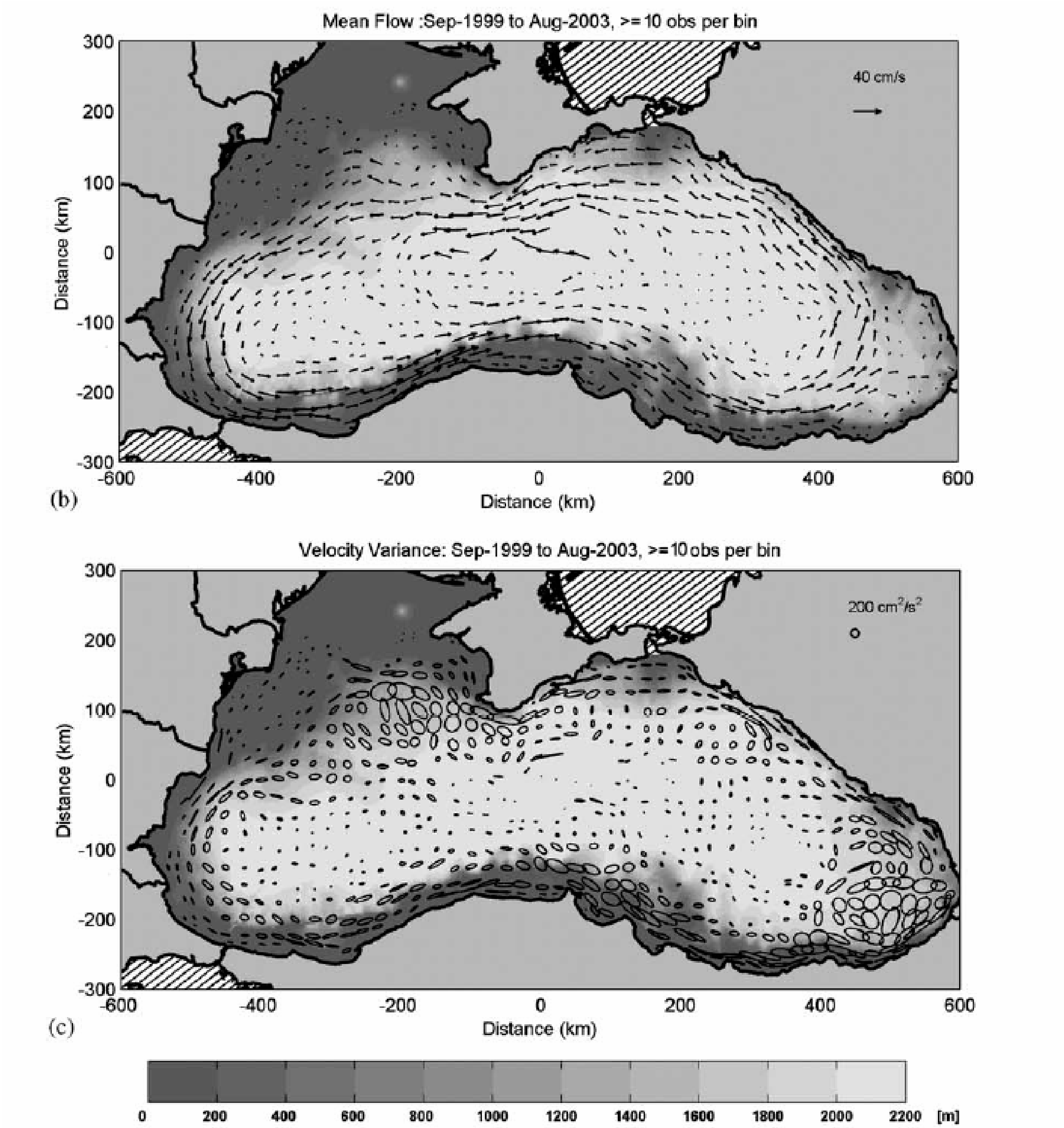

Fig. 5. The mean near-surface circulation (top) and sub-inertial velocity variance ellipses (bottom) as calculated in bins with 25km radius. Arrows and ellipses are drawn (at the data center of mass) for bins with more than 10 drifter observations. Bins The Black Sea bathymetry is shown with gray shades.

More recently, Poulain et al. (2005) used a comprehensive drifter data set spanning 1999–2003 to describe quantitatively the near-surface circulation in the Black Sea. They presented statistical results mostly for 2002–3, as the majority of the drifter observations were concentrated in this period. Pseudo-Eulerian statistics in 50-km bins (Fig. 5) showed that the Rim Current is intense and highly fluctuating mostly in the direction of the strong mean currents. The kinetic energy was found to be mainly in terms of mean current for the Rim Current and in terms of velocity fluctuations elsewhere. Enhanced isotropic variability was associated with the Batumi and Sevastopol eddies.

The bifurcation of the Rim Current southwest off the Crimean Peninsula indicated by drifters possibly has a physical nature different from that described by Korotaev et al. (2003). The explanation follows from the comparison of drifter trajectories in the fall of 1999 and 2000 together with the wind stress curl over the region. It was shown by Zatsepin et al. (2002) that the drifters tend to follow the isolines of the seasonally averaged wind stress curl. In the fall of 1999 the northeastern zone of the cyclonic wind curl was stretched just to the south of the Crimean Peninsula. In contrast, in the fall of 2000 the region around Crimea was under the influence of anticyclonic wind curl. Correspondingly, in 1999 the drifters turned to the south (to the center of the western part of the sea), and in 2000 they moved to the northwest (toward the northwestern shelf) after passing the tip of Crimea. Hence, the branching southwest of the Crimean Peninsula, which is striking in the summer/fall mean circulation, is not necessarily simultaneous but includes the contribution of the interannual variability related to the different wind forcing regimes between 1999 and 2000.

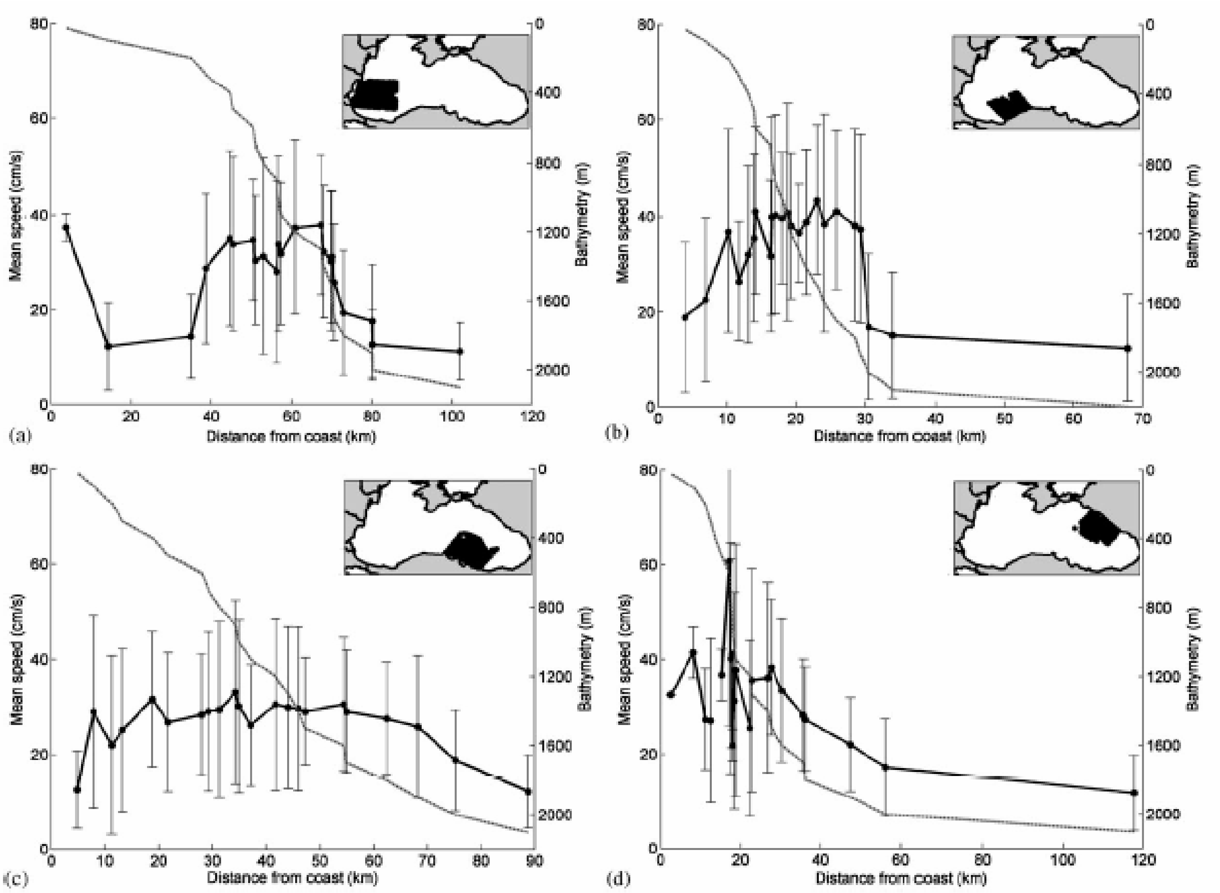

Fig. 6. Mean speed (solid black with standard deviation as gray bars), depth (dashed gray) as a function of distance from shore in selected areas of the Black Sea (depicted in inserted panel): (a) southwest corner (off Bulgaria), (b) off Turkey (western portion), (c) off Turkey (eastern portion) and (c) northeastern area (off Caucasus).

In agreement with previous works, and especially those based on satellite altimeter data (Stanev et al., 2000; Korotaev et al., 2001, 2003), the Rim Current was found as a swift surface current with sub-inertial speeds reaching 1m/s along the entire periphery of the Black Sea, including some branching into two pathways southwest of the Crimean Peninsula. Its strengthening in winter/spring was confirmed by the drifters. The Rim Current main core is trapped to the continental slope in water depths ranging between 400 and 1800 m and at distances from the coast varying between 10 km (off central Turkey and the Caucasus area) and 40 km (off Bulgaria and eastern Turkey) (see Fig. 6). Its width varies between 20 and 80 km, which agrees with the values reported by Korotaev et al. (2001). The Rim Current is faster (maximum value of 40–50 cm/s of mean long-shore current), thinner and closer to the coast (maximal speed less than 30km from the coast) off western Turkey and off the Caucasian coast (Figs. 6b and d). In contrast it is weaker (maximum speed of 25–25 cm/s), wider and father from shore (~45 km) off Bulgaria and eastern Turkey. These differences are due mainly to the varying profiles of bottom topography. It was found that a surface drifter typically completes an entire loop with the Rim Current around the Black Sea in 90–180 days, depending whether or not it spends some time in adjacent eddies.

Poulain et al. (2005) have found that mean currents, MKE and EKE levels, one-particle diffusivities and Lagrangian integral scales are generally larger in the zonal direction than in the meridional direction. This is due mainly to the fact that the Black Sea, and its bathymetric contours, is more elongated in the east-west (~1200 km) than in the north-south (~400 km) direction and because the steep continental shelf slope is more oriented in the zonal direction (especially the steep slope off Turkey).

Horizontal mixing and diffusion in the Black Sea are enhanced in the zonal direction by the faster currents, higher variability and longer Lagrangian scales in that direction. The numerical values for the Lagrangian statistics obtained by Poulain et al. (2005) are similar to those of Zhurbas et al. (2004), despite the different methods adopted to estimate them. Even though shear dispersion effects were reduced by removing the mean circulation of Fig. 5 before calculating the Lagrangian statistics, the results by Poulain et al. (2005) prove that mixing and diffusion processes are strongly non-isotropic. This is in slight disagreement with Zhurbas et al. (2004), who argue that zonal diffusivity is overestimated because of the effects of shear dispersion and that the ‘‘true’’ exchange coefficient is the one calculated in the meridional direction. The non-isotropic character of the diffusion is even more pronounced in the region off central Turkey, where the diffusivity values vary between $1 \cdot 10^7$ and $8 \cdot 10^7$ cm^2/s with the direction. In the region off the Caucasian coast, the meridional diffusivity ($2 \cdot 10^7$ cm^2/s) and related integral scales (~2 days and ~20 km) correspond to the eddy transport/ mixing between the coastal areas and the open sea described by Zatsepin et al. (2003) and Zhurbas et al. (2004). In most areas, along-slope dispersion appears to dominate, but across-slope mixing, although smaller, remain important.

6. Shelf/open sea water exchange

The Black Sea poor ecological conditions are a result of its limited water exchange with the open basins, weak vertical mixing (due to the strong density stratification and weak tides), and enhanced contamination by river discharges, city and tourist resort wastes, oil and other discharges from shipping and oil terminals. Because most of the contamination comes from the shore and near-shore regions of the sea, the processes of horizontal mixing and shelf/open sea water exchange are of the great importance.

The commonly assumed scheme of the Black Sea general circulation (Knipovich, 1932; Neumann, 1942; Bogatko et al., 1979; Ovchinnikov and Titov, 1990; Altman et al., 1990; Oguz et al., 1993; Titov, 1999) includes a basinscale boundary current cyclonically flowing along the continental slope (the Rim Current), western and eastern cyclonic gyres in the open sea, and nearshore anticyclonic eddies (NAEs) between the Rim Current and the shore. From such a circulation scheme it is unclear, however, how horizontal mixing and water mass transformation

process (e.g., fresh coastal water becoming saltier) occur.

The high horizontal (isopycnal) homogeneity of the Black Sea water masses even in the upper layer (Dobrovolskii and Zalogin, 1982) may be regarded as the indirect evidence of intensive horizontal water exchange. The argument is the following. The Black Sea is characterized by large freshwater input due to the river discharge, about 80% of which is concentrated in the northwestern shelf. The Black Sea level due to the river input should be increased by a value of about 1 m/yr which is an order of magnitude larger than for the World Ocean (Stepanov, 1983). If horizontal mixing was weak and the Rim Current existed permanently, a belt of low-saline water mass at the periphery of the Black Sea should be formed. In particular, it is sometimes argued that the central part of the sea and the near-shore region are separated by a frontal zone associated with the Rim Current that inhibits water exchange between these two regions (Sapozhnikov, 1991). However, the river water is not concentrated near the shore, but spreads and mixes well with the upper layer water forming the entire Black Sea surface water mass, except the northwestern shelf (Filippov, 1968; Dobrovolskii and Zalogin, 1982). It is remarkable that the average salinity difference between the surface water in the central part of the Black Sea (18.3) and on its shelf (17.9) is only about 0.4 (Blatov and Ivanov, 1992). The concentration of various admixtures and supply of nutrients in the surface layer are controlled by mesoscale eddy structures (vortices, vortex dipoles, and associated eddies), filaments, and jets that carry out the exchange between the shelf region and central part of the sea.

The mesoscale eddy dynamics (particularly NAE's dynamics) plays a significant role in the water exchange and mixing between the shelf zone and deep-sea regions of the Black Sea. The contribution of an anticyclone detached from the coast to the shelf/deep-sea water exchange is due to both entrainment/transport of coastal water and generation of associated cyclones and jets at its periphery (Ginzburg et al., 2001a). For example, in the northeast Black Sea, water with relatively low salinity of obviously coastal origin (18.15 as compared to 18.25 in the surrounding waters) was observed at the center of the eddy in November 1993 (Krivosheya et al., 1997), 3 months after its separation from the coast. Also, it should be stressed that the advection of the surrounding water at the periphery of an eddy (Fig. 7a) is an important mechanism of shelf/deep sea interaction. One of the examples of this type is an entrainment of cold coastal water by the eddy after wind-driven upwelling in September 1993 and its transport about 100 km offshore (Ginzburg et al., 2001a). Besides, the mesoscale structures condition patchiness in distribution of chlorophyll a and macroplankton concentration in both the coastal zone and open sea. For example, in October 1997, during the period of location of maximum of chlorophyll a concentration below the upper mixed layer at a depth of about 35–40 m (Vedernikov and Demidov, 1997), the increased chlorophyll concentration was observed in ‘‘young’’ anticyclones (NAE-2-NAE-5 in Fig. 7b) likely due to the entrainment of nutrient-rich coastal waters after heavy rains and increased river discharges (Ginzburg et al., 2000a). Low chlorophyll concentration (relative to the surrounding water) was observed in ‘‘old’’ NAE (1-month-old) separated from the shore, in the absence of supply with coastal waters. In the 1999 case, at the center of anticyclone, the maximum open sea concentrations of ctenophores Beroe ovata and Mnemiopsis leidyi were associated with the capture of macroplankton-rich coastal waters by the eddy in the process of its formation and separation from the coast (Ginzburg et al., 2001b).

Quantitative estimation of the cross-shelf water exchange induced by Black Sea mesoscale eddy-like structures is a difficult task. However, it is important to know the water fluxes between the near-shore area and open sea because they control the ventilation of the shelf zone by relatively pure seawater and produce the transport of nutrients from the shelf to the open sea. The latter transport has a positive influence on the productivity of Black Sea pelagic plankton (Arashkevich et al., 2002). An attempt to obtain an integral (for the whole Black Sea) estimation of water transport from the shelf to the open sea and vice versa has been recently made by Dikarev and Poyarkov (2000). Their stationary two-layer box balance model included three blocks: near Bosphorus, shelf, and open sea. Balance relations of water volume, salt content, and upper layer turbulent mixing energy were used for each box. Volume and salt fluxes between the boxes and the characteristic thickness of the upper quasi-homogeneous layer were obtained as the solutions of the algebraic equations. Water volume fluxes from the shelf to the open sea and in the opposite direction (not equal but close to each other values) were estimated as $(4 \div 6) \times 10^3$

km^3/yr. The values are 20 times greater than river input: (2÷3) × 10^2 km^3/yr (Altman et al., 1990; Ozsoy and Unluata, 1997).

Taking into account that typical NAE has a diameter near 50 km and the upper layer thickness is about 50 m, one may estimate that (4÷6) × 10^3 km^3 of water is contained in the upper layer of 40–60 NAEs. Although the statistics for annual amount of NAEs' detached from the shore in the whole sea scale is not complete, it is reasonable to estimate it as several tens at least. So NAEs' detachment should considerably contribute to the integral cross-shelf water transport.

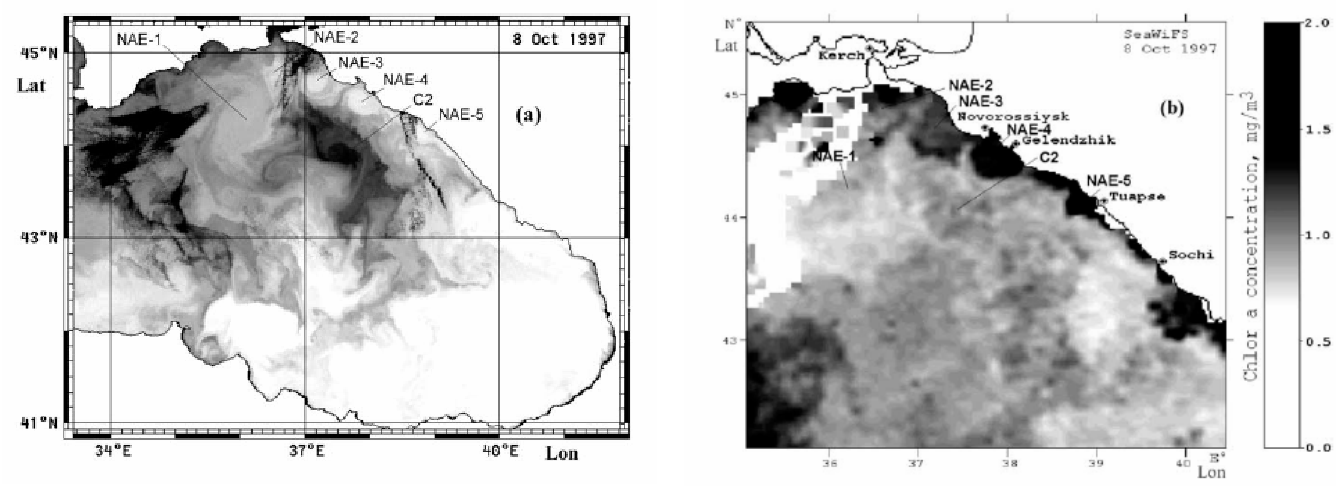

Fig. 7. (a) IR image (8 October 1997 at 1214 UT) of the northeastern part of the Black Sea with marked positions of the eddies (NAE-1, NAE-2, etc.). Dark areas southeast of the Kerch Strait and to the west of NAE-1 are clouds. (b) SeaWiFS image (8 October 1997 at 1027 UT) of chlorophyll concentration in mg/m3 in the northeastern part of the Black Sea (light, low chlorophyll concentration; dark, high chlorophyll concentration) with marked positions of the eddies (NAE-1, NAE-2, etc.).

However, the cross-shelf water exchange processes are more complicated and not all of them are related to NAEs' detachment and even to the mesoscale dynamics. Turbulent entrainment of the shelf water into the Rim Current jet, and on the contrary, the detrainment of the Rim Current water into the shelf zone may be an effective mechanism of the shelf zone ventilation, particularly, in the cases when the Rim Current is intensive and compressed to the shelf edge. Another mechanism that may play a significant role in the cross-shelf water exchange is the intermittent, in space and time, wind action. All of these mechanisms should be studied in future both experimentally and on the base of numerical modeling.

7. Seasonal and interannual variabilities

The Black Sea near-surface circulation is dominated by eddies with variations at the interannual and seasonal scales. Mesoscale features characterize the near-surface layers, whereas larger and quasi-permanent features (e.g., the Rim Current, some near-shore anticyclonic eddies and central gyres) can penetrate down into the permanent pycnocline to 500m depth, with some reduction in strength (Oguz et al., 1994). Near-surface geostrophic currents of 20–50 cm/s in the Rim Current core and strong eddy features have been estimated (Oguz et al., 1994; Afanasyev et al., 2002; Zatsepin et al., 2003).

The strong signal formed mostly by river discharges, along with the seasonal variability in wind forcing and the local dynamics, creates a significant interannual variability of the Black Sea circulation (Stanev et al., 1995; Stanev and Beckers, 1999). The best description of the interannual and seasonal variabilities was recently obtained with satellite altimetry observations (Stanev et al., 2000; Korotaev et al., 2001, 2003). Using TOPEXPOSEIDON altimeter data for about 5 years (1992–1997), Stanev et al. (2000) pointed out that the general cyclonic circulation intensifies in winter and spring corresponding to pronounced positive sea level anomalies in the coastal areas. They also explained that the wind is the major force driving the seasonal intensification of the circulation. The intraannual (mesoscale) variations are strongest in the Rim Current and in large quasi-permanent near-shore anticyclonic eddies, such as the Batumi and Sevastopol eddies. The Batumi Eddy has clear seasonal modulation with intense cyclonic circulation in winter and weaker (sometimes anticyclonic) rotation in summer–fall. It also has substantial energy levels at shorter intra-annual scales, supporting the theoretical results of Rachev and Stanev (1997) that the oscillations in the eastern Black Sea are the major source of disturbances that propagate farther westward. In contrast, the Sevastopol Eddy is not clearly resolved in the seasonal variability and has large sea level oscillations at the inter- and intra-annual scales.

Combined TOPEX-POSEIDON and ERS-1data confirm that the Black Sea circulation has a strong seasonal variability, with attenuation in summer– fall and intensification in winter–spring (Korotaev et al., 2001). The combined data demonstrate that the strongest mesoscale oscillations have periods of about 120 days and are located in the southeastern part of the basin, where the Rim Current bifurcates, and off the Crimean Peninsula, where the Rim Current meanders as a result of the interaction with the local bathymetry. Seven years (1992–99) of TOPEX-POSEIDON and ERS-1sea level data assimilated into a reduced gravity model illustrate that in winter the Black Sea general circulation has a two-cyclonic gyre structure that transforms into one composite cell surrounded by a broader and weaker Rim Current in the summer. The circulation eventually disintegrates into a series of interconnecting eddies later in the summer and in fall, when the Rim Current exhibits more pronounced and complex mesoscale activity (Korotaev et al., 2003). The model simulation also reveals that anticyclonic gyres prevail in summer and fall in the southeastern (Batumi Eddy) and northwestern Black Sea corners. They showed that the Batumi Eddy is the most intense and persistent of the Black Sea nearshore anticyclonic eddies and that it regularly prevails between March and October (~210 days per year). They also explained that winter and summer are the most preferred periods for the formation of the Sevastopol Eddy. This feature has a mean lifetime of about 50 days and is generated as a byproduct of an intense meander of the Rim Current or as part of the bifurcation of the Rim Current along the western coast of Crimea.

Poulain et al. (2005) assessed seasonal variability by computing the pseudo-Eulerian statistics derived from the satellite tracked drifter data in two extended seasons: winter/spring and summer/fall (Figs. 8 and 9). The Rim Current tends to form a stronger single loop trapped on the continental slope in winter/spring, whereas in summer/fall the mean circulation is more meandering, recirculation cells appear in the central areas and the bifurcation southwest of Crimea is enhanced. The drifters did not confirm the possible separation of the Rim Current into two cyclonic cells in the west and east sub-basins, neither the existence of the Central Basin Eddy proposed by Oguz et al. (1993). There is some evidence of the reversal of sense of rotation of the currents in the Batumi Eddy region, changing from mainly anticyclonic in summer/fall to cyclonic in winter/spring, in good agreement with satellite altimetry results (Stanev et al., 2000). Significant variability at intraannual (mesoscale) scales is observed in both the Batumi and Sevastopol eddy areas.

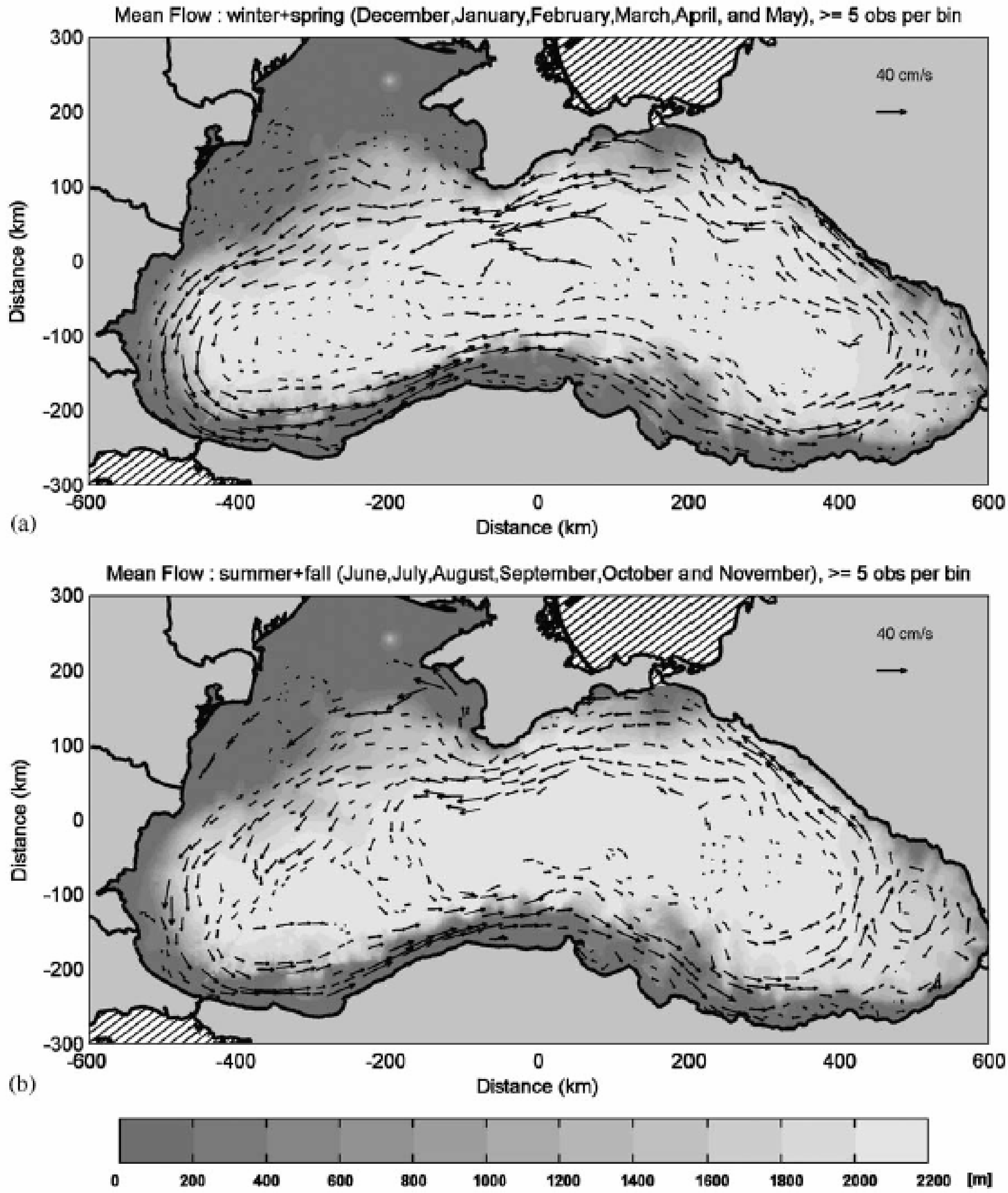

Fig. 8.

Map of mean surface circulation but for the combined seasons (winter/spring–top and summer/fall–bottom). Arrows are drawn (at the data center of mass) for bins with more than 5 drifter observations. The Black Sea bathymetry is shown with gray shades.

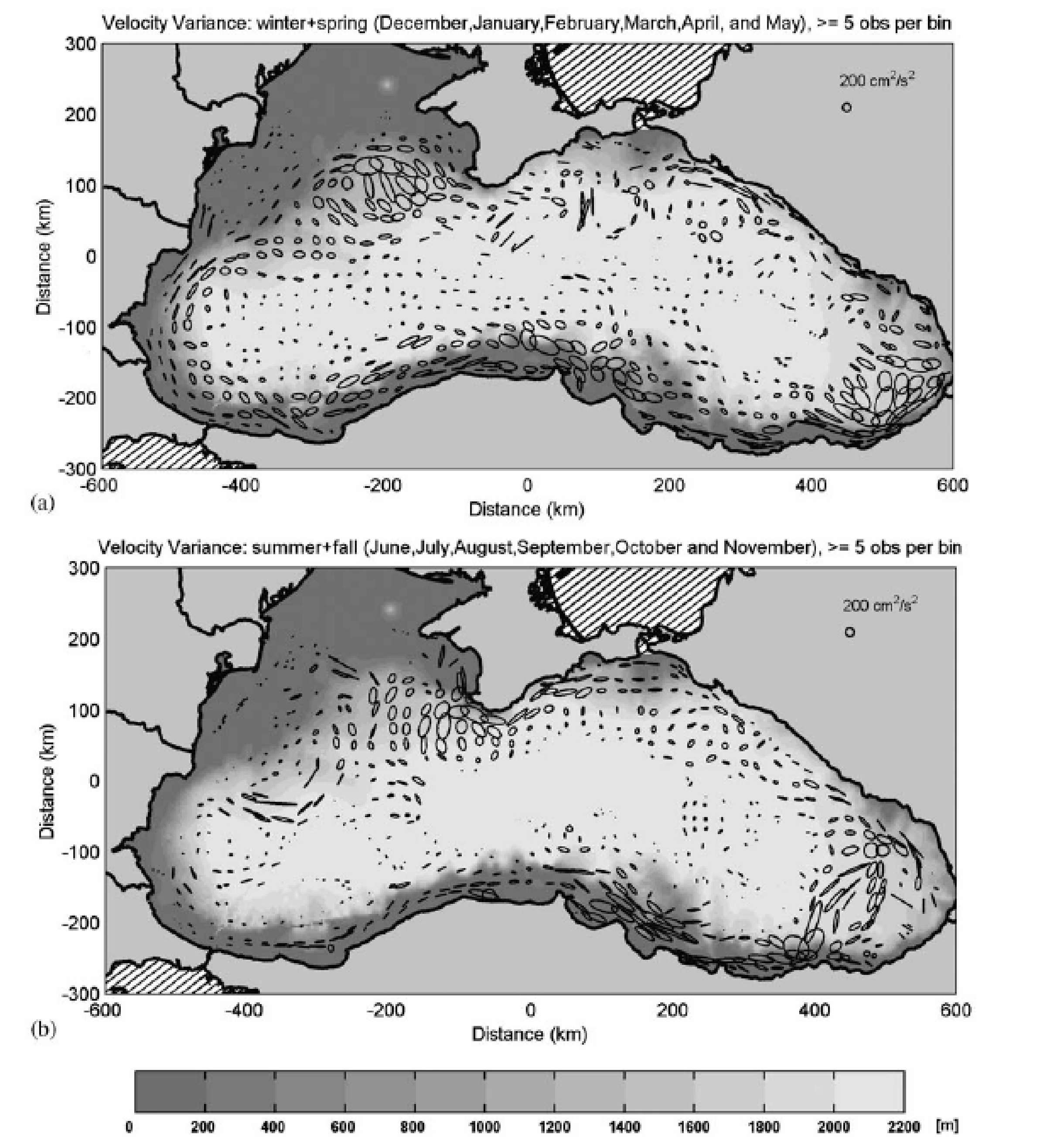

Fig. 9. Same as in Fig. 5 but for the sub-inertial velocity variance ellipses.

By analyzing the satellite tracked drifter data Poulain et al. (2005) have found that statistically significant maxima in EKE is observed in the early spring time (Fig. 10) but not in the winter as is suggested in Filippov (1968). The second maximum in August, although not statistically robust because of the low number of observations, might be related to the enhancement of the basin scale cyclonic circulation that occurs in August– September (Cheredilov, 1967; Bogatko et al., 1979). Also, the high zonal diffusivity is larger in winter/spring (~$5 \cdot 10^7$ cm^2/s) and lower (~$3 \cdot 10^7$ cm^2/s) in summer/fall, compared to $1 \cdot 10^7$ cm^2/s for both seasons in the meridional direction. Thus, the seasonal variability of the Black Sea upper layer circulation might not be so simple.

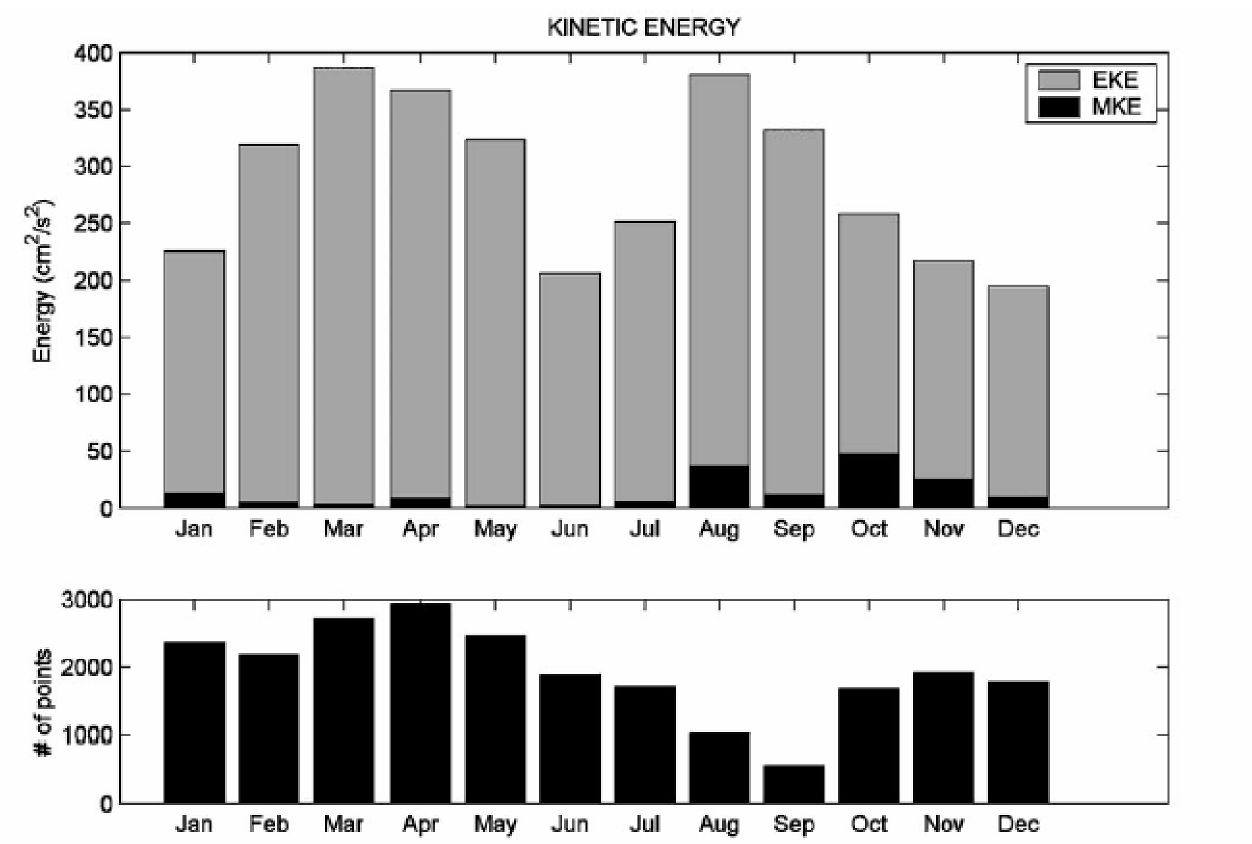

Fig. 10. Energy levels (MKE and EKE) for the entire Black Sea calculated for the individual months of the year between 1999 and 2003 (top). Corresponding number of drifter observations (bottom).

It has been noticed (e.g., Ozsoy and Unluata, 1997) that the Black Sea is responds sensitively to interannual and longer term climatic variability in atmospheric fluxes, which leave imprints in the structure of its stable pycnocline. In winter season, regional climate anomalies set conditions for deep convection in the Black Sea and in the adjacent seas to the south. For example, an extreme event of cooling occurred in the Black Sea in 1987, when similar effects were noted in the surrounding seas, e.g. dense water intrusion of the Aegean water into the Marmara Sea (Besiktepe et al., 1994), and deep water formation in the Rhodes region (Gertman et al., 1990). The strong cooling event of 1992 changed the structure of the Black Sea main pycnocline (Ivanov et al., 1997). As a result of such a cooling, the CIW inherited extreme properties, which lasted for several years.

In winter season, cooling and convection processes lead to development of 70-80 m deep upper isothermal layer having minimum temperatures of 6-7°C. This minimum temperature can drop to as low as 2-5°C as it happened in March 1962 in the northwestern shelf region (Tolmazin, 1985). In summer season, CIL comprises subsurface temperature minimum capped by a warm surface layer.

Interannual variability of the sea dynamics and the hydrological structure of the upper layer rich in oxygen have been studied during field surveys carried out two to three times every year since 1990 at a hydrographic 100-mile section in the northeastern part of the Black Sea from about 44.5°N 38°E towards 43°N 36.5°E . The observations were analyzed along with the time series of air temperature and wind observations at the Gelendzhik meteorological station located on the northeastern coast of the sea. Over these 15 years, three periods with different meteorological conditions were distinguished in the northwestern part of the Black Sea as follows: 1991 – 94 was a period of cold winters; 1995 - 98 was a period of moderate winters; 1999 - 2001 was a period of warm winters. In 2002, the winter was moderate; in 2003, the winter was cold; and in 2004, the winter was warm.

During the cold winters, the Rim Current, the quasi-stationary anticyclones (Batumi, Kerch, Sevastopol, and other eddies), and the cyclonic gyres in the central part of the sea all were rather active. After the cold winters, the Cold Intermediate Layer (CIL) reaches maximum thickness. In certain years, it gains 80–85 m, while its core minimal temperature drops down to 6.0–6.2°C. When the winters were moderate and particularly during warm winters, the Rim Current was slower as compared to that in the cold winters, while the number of mesoscale eddies (both cyclonic and anticyclonic) increased near the Current. After the warm winters, the thickness of the CIL decreased significantly. In September 2001, it contracted to 30–40 m along the 100-mile section, while the CIL core temperature rose to 7.8– 7.9°C.

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