Analysis of velocity field in the eastern Black Sea from satellite data during the Black Sea ‘99 experiment

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[1] Maximum cross correlation (MCC) analysis of National Oceanic and Atmospheric Administration (NOAA) advanced very high resolution radiometer (AVHRR) imagery of the eastern Black Sea in late September 1999 has been used to reconstruct the velocity and vorticity fields of the upper layer of the sea. Analysis revealed the large-scale dynamic features characteristic of the Black Sea, namely the Rim Current, as well as the detailed pattern of mesoscale vortical activity including meanders, eddies, and dipoles, which are often observed on satellite visible, infrared, or sea color imagery. The dynamical character of the pronounced dipole structure in the northeastern part of the Black Sea was determined by comparison with satellite IR images, geostrophic velocities calculated on the basis of conductivity-temperature-depth (CTD) casts performed and trajectories of six Argos-tracked surface velocity program (SVP) drifters deployed during the Black Sea ‘99 expedition onboard R/V Akvanavt on 25–30 September 1999.

INDEX TERMS: 4243 Oceanography: General: Marginal and semienclosed seas; 4520 Oceanography: Physical: Eddies and mesoscale processes; 4275 Oceanography: General: Remote sensing and electromagnetic processes (0689);

KEYWORDS: maximum cross-correlation method, vortex dipole, Rim Current

1. Introduction

[2] The conventional description of the Black Sea general circulation [e.g., Neumann, 1942; Bogatko et al., 1979] as well as more recent descriptions [Ovchinnikov and Titov, 1990; Oguz et al., 1993], are based on decades of hydrographic surveys and include the following main features: a basin-scale cyclonic boundary current over the continental slope, the Rim Current [e.g., Oguz et al., 1992], cyclonic gyres in the basin interior and quasi-stationary or recurrent anticyclonic eddies along the coast. Numerous recent observations [Fedorov and Ginzburg, 1992a; Ginzburg, 1994, 1995; Oguz and Besiktepe, 1999; Ginzburg et al., 2000c] demonstrate that the mesoscale variability is very important in the transport of scalars especially in the coastal-deep basin water exchange across the Rim Current. Satellite imagery, which has been used to investigate the Black Sea surface circulation since 1981 [see Kazmin and Sklyarov, 1982], has made possible the detection of the various nonstationary mesoscale dynamical features (see, e.g., Figure 1) that contribute to this exchange. The observed mesoscale eddy variability is presented by meanders, anticyclonic and cyclonic vortices, pinched off eddies, vortex dipoles, filaments and jets [Kazmin and Sklyarov, 1982; Grishin et al., 1990; Grishin and Subbotin, 1992; Grishin, 1993; Ginzburg, 1994, 1995; Sur et al., 1994, 1996; Sur and Ilyin, 1997; Ginzburg et al., 1996, 1997, 1998a, 1998b, 1998c, 2000a, 2000b, 2000c, 2000d].

[3] Nearshore anticyclonic eddies (NAEs), of approximately 40 km in diameter, are a characteristic feature of the circulation in the northeastern Black Sea. They were regularly observed in standard hydrographic measurements performed by the Southern Branch of the P. P. Shirshov Institute of Oceanology in Gelendzhik [Krivoshaya and Prokopov, 1997; Krivoshaya et al., 1997, 1998a, 1998b]. Remote sensing contributed significantly to the studies of this form of the mesoscale variability [Ginzburg et al., 2000a, 2000c, 2000d]. These observations gave typical translation velocities of 15–17 cm s \(^{-1}\) (three times larger than the velocity estimated from the conductivity-temperature-depth (CTD) casts) and the values of orbital velocities of 30–40 cm s \(^{-1}\). Seasonal variability was clarified, and the role of the eddies in the distribution of chlorophyll \(a\) concentration was described [Ginzburg et al., 2000a, 2000c, 2000d].

2000a, 2000b, 2000c, 2000d]. A movie based on satellite images, however, shows a continuous integrated transport of water directed cyclonically along the coast. Although the eddy variability is so large that it masks the Rim Current, it can clearly be defined as a persistent feature in terms of the statistically defined transport.

[5] The small spatial scale (less than 30 km in certain cases) and short temporal scale (several days to 1 month) of the vortical features superimposed on the general along-coast flow of 10–30 km d⁻¹ make it practically impossible to monitor their generation and evolution by hydrographic surveys. Therefore, it is no surprise, that only the averaged transport, that is the Rim Current, is displayed on maps of geostrophic currents calculated on the base of CTD surveys which are usually performed during a period of a few days, with stations being located 30–50 km apart. Temporal and spatial averaging hides and/or changes the level of vortical activity which is present, and results in a well-defined boundary current of a statistical nature. Time-dependent features of the circulation in the Black Sea still remain mainly unexplored.

[6] Satellite data (visible, IR, and sea color) with a spatial resolution of ~1 km and a temporal resolution of a few hours (up to six images per day) are necessary for studies of dynamics of mesoscale and small-scale structures. Daily satellite monitoring of the Black Sea, which has been performed since 1994 by the Remote Sensing Department (RSD) of the Marine Hydrophysical Institute (MHI) in Sevastopol (Ukraine), have already produced interesting results on specific features of local circulation in the northwestern, southeastern, and northeastern Black Sea in summer-autumn seasons [Ginzburg et al., 1996, 1997, 1998a, 1998b, 1998c, 2000a, 2000b, 2000c, 2000d].

[7] The Black Sea '99 drifter experiment [Motyzhev et al., 2000; Zatsepin and Flint, 2001] was organized as a part of a complex study of the Black Sea ecosystem and of the shelf-deep basin interactions which were conducted in August-November 1999 by oceanographers from the P. P. Shirshov Institute of Oceanology (SI0), Russian Academy of Sciences (Moscow) on the R/V Akvanavt in collaboration with scientists from the Marine Hydrophysical Institute of National Academy of Sciences of Ukraine (MHI NASU, Sevastopol). The main strategy of the Black Sea '99 expedition was based on the joint application of satellite imagery, satellite-tracked drifters and hydrographic, chemical and biological surveys of selected mesoscale structures. The analysis of the satellite SST images from August-September 1999 revealed an unusual anticyclonic circulation feature in the center of the eastern part of the sea. This rare event was previously observed only once in autumn 1997 [Ginzburg et al., 2000a, 2000b, 2000c]. The anticyclonic eddy formed a large vortex pair (about 150 km in the cross section) together with a cyclonic eddy which was located to the north of it and closer to the Rim Current (Figure 2). Our intention herein is to focus on this interesting feature of the circulation. We have used the maximum cross correlation (MCC) method to obtain velocity fields from the sequential satellite images of the sea. The method is described in section 3.

[8] Vortex pairs (dipoles) or mushroom-shaped currents are regularly observed on thermal and color imagery of the coastal ocean. Many observations of the dipoles have been reported by Fedorov and Ginzburg [1986, 1992a, 1992b]. It was determined that the formation of a dipole at the sea surface is due to a uniform reaction of the upper layer to any spatially localized forcing from the atmosphere (wind-forcing) or due to the oceanic dynamics itself (e.g., instability of currents, pulsing exchange through the straits). One of the first satellite observations of a dipole in the ocean was made in the eastern Black Sea [Kazmin and Sklyarov, 1982]. Over the last decade a series of such observations in the Black Sea

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**Figure 1.** General view of the Black Sea: Processed NOAA AVHRR image for 2 December 1999 with drifters (1–4) trajectories for the period 29 September to 31 December 1999. Drifter numbers are posted near the deployment sites. Light and dark colors correspond to relatively warm and cold surface waters, respectively.
transport from the coastal zone to the deep basin. Other
1996 was oriented from east to west, and provided water
and mass in the region. A dipole observed in November
1998c]. These deep-basin dipoles represent the main effec-
tive mechanism of horizontal mixing and transport of heat
satellite IR imagery in November 1996 [Ginzburg et al.,
1994, 1996; Sur and Ilyin, 1997; Ginzburg et al., 1998c,
structure were 3–5 times weaker.
Figure 2. IR processed image of the northeastern Black
Sea derived from NOAA 14 AVHRR on 29 September
1999, 16:36 MSK (local time). Light and dark colors
correspond to relatively warm and cold waters, respectively.
Black points with numbers show position of CTD stations.
Straight lines between stations show the ship track.
Trajectories of six Argos-tracked SVP drifters during the
first 4 days of the experiment deployed at CTD stations 24–
29 on 28–29 September 1999 are superimposed on the
image (white and black tracks).
has been reported [Fedorov and Ginzburg, 1992a; Grishin,
1993; Ginzburg, 1994; Sur et al., 1994, 1996; Sur and Ilyin,
1997; Ginzburg et al., 1998c, 2000c, 2000d]. Ginzburg
[1995] first reported an observation of a mushroom-like flow, which transported surface water from the shelf near the
Bosphorus Strait toward the center of the western Black Sea
gyre, in the direction opposite to the surface exchange in the
strait. This phenomenon may explain the penetration of
Mediterranean Sea plankton directly to the western gyre
and further. Mediterranean plankton have been observed in
Sevastopol Bay [Bogdanova and Shmeleva, 1967]. Dipoles,
as large as 80–100 km, are often observed in the south-
eastern corner of the Black Sea near the so-called Batumi
eddy. One such dipole was traced in detail using daily
satellite IR imagery in November 1996 [Ginzburg et al.,
1998c]. These deep-basin dipoles represent the main effec-
tive mechanism of horizontal mixing and transport of heat
and mass in the region. A dipole observed in November
1996 was oriented from east to west, and provided water
transport from the coastal zone to the deep basin. Other
possible configurations, such as a cyclone located north of
an anticyclone [Bibik, 1964] or a system of two mushroom-
like structures [Fedorov and Ginzburg, 1992b] can result in
transport between the deep basin and the coastal region.

In section 2, we describe in detail the available data. In
section 3, the MCC method is described and the results on
drifters as well as on geostrophic currents calculated from the
data of the CTD survey performed during the expedition
Black Sea ’99 are compared with a velocity field given by the
MCC method. We conclude with discussion of our results.

2. Data

In September 1999 a large dipolar structure (Figure 2)
was detected by remote sensing in the southwestern part of
the Black Sea. The size and quasi-stationary character of the
dipole were unusual. Moreover, by 25 September the Rim
Current was effectively blocked by the dipole, a significant
part of the current being entrained into the cyclonic part of
the dipole. It was decided that the Black Sea ’99 expedition
would focus on this vortex dipole. During the first phase of
the expedition (25–30 September) a hydrographic (physical,
chemical, and biological) survey of this dipole structure and
adjacent areas was carried out (see map of CTD stations in
Figure 2). During the survey six surface velocity program
(SVP) drifters [Sybrandy and Niler, 1991] have been
drogued at 15 m nominal depth. They were deployed into
and near the dipole: two in the anticyclone (drifters 1 and 5,
stations 24 and 25), two in the cyclone (drifters 2 and 3,
stations 28 and 29) and the last two drifters just in front of
the structure (drifters 4 and 6, stations 26 and 27). Thus, half of
the drifters were located on the right side from the dipole axis
(white tracks in Figure 2), the rest on its left side (black
tracks). During the first four days after deployment, all six
drifters were successfully tracked by the Argos satellite
system. Two drifters (5 and 6) failed to transmit four days
after the deployment date. The deployment locations and the
4 day long trajectories are shown in Figure 2, superimposed
on the advanced very high resolution radiometer (AVHRR)
channel 4 image of 29 September. The regions of anti-
cyclonic and cyclonic rotation are clearly seen in the satellite
image by the thermal field and by the trajectories of the
drifters. According to the drifters the typical orbital velocities
in the anticyclone were 15–20 and 25–30 cm s
−1 in the
cyclone (velocity reached 35 cm s
−1 at the outer edge, near
the Rim Current). The currents just in front of the dipole
structure were 3–5 times weaker.

Approximately the same velocities in the dipole were
estimated using the geostrophic approach based on CTD
data (Figure 3). Only the cyclonic part of the dipole was
covered by the survey (Figure 3) in a region delimited by
the Russian economic zone. Dynamic heights clearly show
the center of the cyclone located between stations 18, 29,
and 30. This velocity map corresponds well to the satellite
image for September 29, including the deflection of the Rim
Current to the southwest and splitting of a small part of the
current which continues to move along the coast.

3. MCC Analysis

The MCC method [Emery et al., 1986; Kelly and
Strub, 1992] is a procedure for reconstructing velocity fields

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associated with the surface circulation. In this procedure the displacements of small regions of the patterns of passive tracer are estimated between sequential images using cross correlations between small rectangular sections from each image. Similar techniques are widely used in experimental fluid dynamics. Collectively these techniques are known as Correlation Imaging Velocimetry [see, e.g., Fincham and Spedding, 1997]. The name particle imaging velocimetry (PIV) is commonly used when small particles of neutral density are seeded in the fluid. However, any passive tracer that provides image texture and follows the flow may be used. The scalar field of sea surface temperature (SST) is often used for oceanographic applications. SST is generally not a passive tracer though, because of heating and cooling at the surface. The lack of conservation of temperature applies additional restrictions on the choice of pairs of SST images (nighttime, intervals of only a few hours) to be used for the analysis and on the interpretation of the results obtained. MCC generally gives poor results when used to estimate the velocities along the front of the scalar field due to poor correlations, if there is no contrast pixel patchiness along the front. This is a serious disadvantage of the method which can be reduced somewhat by application of objective interpolation technique which uses dynamical constraints. We used the variational method [Panteleev et al., 2002] to interpolate the velocity field obtained by MCC. The basis of this method is to apply the appropriate dynamical constraints to the original velocity field. The obvious advantage of the MCC method, on the other hand, is that this method provides nearly instantaneous estimates of the currents over a large area (over the large portion of the Black Sea in our case). It is impossible to obtain this important information on the surface layer dynamics over all regions of the sea by any other means.

[13] Initial processing of the pairs of satellite images was performed using software originally developed for PIV analysis. A description of the algorithm is given by Pawlak and Armi [1998]. In this procedure cross-correlations between rectangular sections from each image are estimated while searching for the location in the second image which gives the maximum cross-correlation coefficient. The displacement of the section is then calculated. We used square regions 24 by 24 pixels, at intervals 6 pixels in both directions. These sections were small enough to resolve the mesoscale features having a size of approximately 30 km. On the other hand, the correlation region was large.

Figure 3. Dynamic heights in cm (solid lines) and geostrophic velocities in cm s\(^{-1}\) (arrows) at the sea surface calculated relatively to 500 dbar basing on the CTD survey (36 stations) made by R/V Akvanavt on 25–30 September 1999. Arrow in the upper left corner of the image shows the velocity scale 50 cm s\(^{-1}\). See color version of this figure at back of this issue.
enough to contain a number of small-scale distinctive features which create the texture of the image. The velocity field obtained by the MCC procedure was then interpolated using the variational method developed by Panteleev et al. [2002]. This method is designed to determine a stationary two-dimensional circulation from estimates of horizontal velocities by minimizing the functionals which represent different hydrodynamical constraints on the flow field. We used in particular the following integral constraints:

\[
I_1 = \int \left( u_{xx}^2 + u_{yy}^2 + v_{xx}^2 + v_{yy}^2 \right) / g_1 \, dxdy \\
I_2 = \int (u, v) / g_2 \, dxdy.
\]

Here \( I_1 \) and \( I_2 \) are the smoothness and the divergence of the velocity field \((u, v)\), respectively. The values of the weight functions \( g_i \) were chosen to produce a smooth and almost divergence-free flow field keeping the correspondence of original and modified data in reasonable limits. The realistic coastline was also taken into account in these calculations. The velocity field near the boundaries was modified to satisfy the free-slip boundary conditions. As a base for MCC analysis we used National Oceanic and Atmospheric Administration (NOAA) AVHRR IR images (1.1 km resolution) regularly received during the expedition. In order to have a good reference with field data (drifters and CTD) we first chose a pair of nighttime images (time interval of 2 hours 28 min) for 30 September to reconstruct the velocity field in the dipole area. Analysis of other available pairs of images showed that this particular time interval between the images is optimal for the MCC procedure. The time interval is short enough for the temperature to remain an approximately conserved quantity, while it allows the water parcels to move by an appreciable distance (1–3 pixels).

[14] The velocity field obtained by the application of the MCC procedure and the modified velocity field obtained by further application of the interpolation/smoothing procedure are shown in Figure 4 for comparison. Two dipoles sharing one vortex are clearly seen in the satellite images. One of the dipoles, namely the one composed of relatively warm water from the Rim Current, deflects from the coast in the westward direction. The intense jet of the Rim Current flow is deflected by this coastal feature and forms the dipole. This jet is well resolved in the MCC map (Figure 4a). The

**Figure 4.** (opposite) Velocity field in the region of the dipole in the central Black Sea: (a) reconstructed by the MCC analysis of two subsequent NOAA IR images derived on 30 September 1999, 03:58 MSK and 06:46 MSK, (b) interpolated/smoothed by application of the variational procedure, and (c) vorticity field is nondimensionalized by the Coriolis parameter \( f = 9.92 \times 10^{-5} \, \text{s}^{-1} \) estimated for the latitude of 43°. Contours are given with the interval of 0.015 starting from \( \pm 0.015 \). Solid and dashed lines represent cyclonic and anticyclonic vorticity, respectively. The velocity and vorticity maps are superimposed on the image of 06:46 MSK. Light and dark colors correspond to relatively warm and cold waters, respectively.
values of velocity in the jet exceed 20 cm s$^{-1}$. For comparison the value of geostrophic current velocity at station 9 was approximately 26 cm s$^{-1}$ (see Figure 3 and Table 1). The second dipole is formed from the entrained relatively cold water. The jet between the vortices of this dipole is directed to the east and is also well resolved by the MCC procedure. In Table 1 we compare the values of speed and direction of current obtained by the MCC analysis (before application of the variational procedure) with the values obtained from the analysis of field data at the selected locations inside both dipoles (see Figure 4a). The error in velocity magnitude is estimated to be 11% when the MCC currents and the drifter data are compared. The values of direction of velocity agree well between both the MCC and the geostrophic currents (the error $\theta = 45^\circ$) as well as between the MCC and the drifters data ($\theta = 32^\circ$). The MCC estimates of the absolute values of velocity agree reasonably well with both sets of field data in the region of intense flow in the cold dipole (stations 23–30) while being lower in the warm dipole (stations 3–19) where the overall flow was weaker as compared to the cold dipole. Clearly the discrepancies between the MCC velocities and geostrophic velocities are partly due to the nature of geostrophic approach itself, the fact that the results of the CTD survey performed during six days are regarded as an instant field. The MCC procedure gave poor results for the velocity magnitude in the Rim Current. The images were almost uniform at the latitude of 43°C 04:21 MSK. The time interval between the images was more than 12 hours. The images were relatively cloud free with the exception of the region around the Crimean peninsula and the region in the southeast. Maps in Figures 5a and 5b show the velocity and vorticity fields obtained by both the MCC analysis and by further application of the variational procedure. The currents along southern coast as well as the currents in the central part of the Black Sea (including the region of the dipole) are well resolved by MCC. Interesting spatial features including the meanders of the Rim Current along the southern coast are clearly visible both in the satellite images and on the flow map obtained. Note that the flow field west of the Crimean peninsula, as well as in the south-eastern region of the sea, can hardly be reliable because of the clouds, and must be disregarded.

### Table 1. Sea Surface Currents at Locations of CTD Stations of the Hydrographic Survey Performed on 25–30 September 1999 Calculated by Different Methods

<table>
<thead>
<tr>
<th>CTD Station$^a$</th>
<th>MCC currents on 29 September 1999</th>
<th>Geostrophic Currents on 25–30 September 1999</th>
<th>Drifters data on 29 September 1999</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Velocity, cm s$^{-1}$</td>
<td>Direction, deg</td>
<td>Velocity, cm s$^{-1}$</td>
</tr>
<tr>
<td>3</td>
<td>1.2</td>
<td>360</td>
<td>15.5</td>
</tr>
<tr>
<td>5</td>
<td>2.6</td>
<td>244</td>
<td>10.5</td>
</tr>
<tr>
<td>7</td>
<td>1.8</td>
<td>200</td>
<td>5.8</td>
</tr>
<tr>
<td>9</td>
<td>0.9</td>
<td>231</td>
<td>26.2</td>
</tr>
<tr>
<td>17</td>
<td>1.7</td>
<td>267</td>
<td>10.0</td>
</tr>
<tr>
<td>19</td>
<td>1.4</td>
<td>168</td>
<td>2.5</td>
</tr>
<tr>
<td>23</td>
<td>8.1</td>
<td>126</td>
<td>11.1</td>
</tr>
<tr>
<td>24</td>
<td>11.5</td>
<td>119</td>
<td>4.4</td>
</tr>
<tr>
<td>25</td>
<td>22.7</td>
<td>167</td>
<td>8.5</td>
</tr>
<tr>
<td>26</td>
<td>0.7</td>
<td>256</td>
<td>4.0</td>
</tr>
<tr>
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<td>1.9</td>
<td>13</td>
<td>12.3</td>
</tr>
<tr>
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<td>12.9</td>
<td>85</td>
<td>10.9</td>
</tr>
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<td>14</td>
<td>112</td>
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</tr>
<tr>
<td>30</td>
<td>0.7</td>
<td>45</td>
<td>5.0</td>
</tr>
</tbody>
</table>

$^a$See Figures 2 and 4 for location.

are observed at the sides of the jets in both dipoles. The vorticity shown in Figure 4c is nondimensionalized by the Coriolis parameter $f = 9.92 \times 10^{-5}$ s$^{-1}$ estimated for the latitude of 43°. The ratio of vorticity to the Coriolis parameter is in fact the Rossby number $Ro = \omega f$. The fact that the values of the Rossby number are small justifies the application of the geostrophic approximation to the CTD data and makes it clear why the MCC velocities agree reasonably well with the geostrophic currents (at least in the areas where MCC procedure gives reliable results).

[15] We made an attempt to apply both MCC and variational methods to reconstruct the velocity field in the entire central part of the Black Sea. For this purpose, we used two subsequent NOAA IR images obtained on 27 September 1999, 15:59 MSK, and 28 September 1999, 04:21 MSK. The time interval between the images was more than 12 hours. The images were relatively cloud free with the exception of the region around the Crimean peninsula and the region in the southeast. Maps in Figures 5a and 5b show the velocity and vorticity fields obtained by both the MCC analysis and by further application of the variational procedure. The currents along southern coast as well as the currents in the central part of the Black Sea (including the region of the dipole) are well resolved by MCC. Interesting spatial features including the meanders of the Rim Current along the southern coast are clearly visible both in the satellite images and on the flow map obtained. Note that the flow field west of the Crimean peninsula, as well as in the south-eastern region of the sea, can hardly be reliable because of the clouds, and must be disregarded.

### 4. Discussion

[16] Relatively long life of the dipole reported in this paper can be explained on the basis of general properties of vortex dipoles. Vortex dipoles are well known dynamical entities in geophysical fluid dynamics [see, e.g., Voropayev and Afanasyev, 1994]. Dynamics of individual dipoles as well as their interactions with each other and solid boundaries have been extensively studied both in laboratory experim-
transport in southward direction, is provided by the southward propagation of the drifter 1 (Figure 1).

[17] It is interesting to note the meandering of the boundary current system along the southern coast. The flow develops strong finite amplitude meanders with longshore wavelength of 80–90 km along the smooth part of the coast (between 0 and 250 km in Figure 5). It appears that further perturbations of the boundary current system are due mostly to strong alongshore topographic irregularities in the region between 250 and 500 km in Figure 5.

[18] The first application of MCC method to the Black Sea gave very promising results as it was justified by the comparison with satellite thermal imagery, drifters data and geostrophic velocities calculated from the CTD casts of the survey performed. The dynamical structure of the pronounced mushroom-like current in the northeastern part of the sea was obtained in details and then compared with geostrophic velocities at 36 CTD stations and with trajectories of six Argos-tracked drifters deployed simultaneously during the Black Sea '99 expedition. As a further step in the complex study of variability in the Black Sea a large-scale drifter experiment is planned in the near future as a part of the Black Sea GOOS program.

Figure 5. (a) Velocity and (b) vorticity fields in the central and eastern Black Sea reconstructed by the MCC analysis of two subsequent NOAA IR images derived on 27 September 1999, 15:59 MSK, and 28 September 1999, 04:21 MSK, and superimposed on that of 27 September. Vorticity field is nondimensionalized by the Coriolis parameter $f = 9.92 \times 10^{-5}$ s$^{-1}$ estimated for the latitude of 43°. Vorticity contours are given with the interval of 0.03 starting from ±0.045. Solid and dashed lines represent cyclonic and anticyclonic vorticity, respectively. See color version of this figure at back of this issue.

ments and theoretically [e.g., Afanasyev et al., 1988; Voropayev et al., 1991; Voropayev and Afanasyev, 1992]. Since a vortex dipole can be characterized by net linear momentum it must in general perform translational motion. The particular dipole identified by MCC, would tend to move to the east in the absence of the boundaries. This primary dipole, however, does not move, which is most likely a result of the particular character of its interaction with other vortices and the coast. Note that another dipole of opposite sign can be clearly observed within the Rim Current to the east of the primary dipole (Figure 5). The northern coastline prevents the transport in this direction while motion to the south is still possible. The evidence of the southward flow can be observed in Figure 4. The anticyclonic vortex of the dipole is elongated. A strong jet to the south is clearly seen at the anticyclone in Figure 4. Further evidence of the transport in southward direction, is provided by the southward propagation of the drifter 1 (Figure 1).

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ments and theoretically [e.g., Afanasyev et al., 1988; Voropayev et al., 1991; Voropayev and Afanasyev, 1992]. Since a vortex dipole can be characterized by net linear momentum it must in general perform translational motion. The particular dipole identified by MCC, would tend to move to the east in the absence of the boundaries. This primary dipole, however, does not move, which is most likely a result of the particular character of its interaction with other vortices and the coast. Note that another dipole of opposite sign can be clearly observed within the Rim Current to the east of the primary dipole (Figure 5). The northern coastline prevents the transport in this direction while motion to the south is still possible. The evidence of the southward flow can be observed in Figure 4. The anticyclonic vortex of the dipole is elongated. A strong jet to the south is clearly seen at the anticyclone in Figure 4. Further evidence of the transport in southward direction, is provided by the southward propagation of the drifter 1 (Figure 1).

[17] It is interesting to note the meandering of the boundary current system along the southern coast. The flow develops strong finite amplitude meanders with longshore wavelength of 80–90 km along the smooth part of the coast (between 0 and 250 km in Figure 5). It appears that further perturbations of the boundary current system are due mostly to strong alongshore topographic irregularities in the region between 250 and 500 km in Figure 5.

[18] The first application of MCC method to the Black Sea gave very promising results as it was justified by the comparison with satellite thermal imagery, drifters data and geostrophic velocities calculated from the CTD casts of the survey performed. The dynamical structure of the pronounced mushroom-like current in the northeastern part of the sea was obtained in details and then compared with geostrophic velocities at 36 CTD stations and with trajectories of six Argos-tracked drifters deployed simultaneously during the Black Sea '99 expedition. As a further step in the complex study of variability in the Black Sea a large-scale drifter experiment is planned in the near future as a part of the Black Sea GOOS program.

Figure 5. (a) Velocity and (b) vorticity fields in the central and eastern Black Sea reconstructed by the MCC analysis of two subsequent NOAA IR images derived on 27 September 1999, 15:59 MSK, and 28 September 1999, 04:21 MSK, and superimposed on that of 27 September. Vorticity field is nondimensionalized by the Coriolis parameter $f = 9.92 \times 10^{-5}$ s$^{-1}$ estimated for the latitude of 43°. Vorticity contours are given with the interval of 0.03 starting from ±0.045. Solid and dashed lines represent cyclonic and anticyclonic vorticity, respectively. See color version of this figure at back of this issue.

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Figure 3. Dynamic heights in cm (solid lines) and geostrophic velocities in cm s$^{-1}$ (arrows) at the sea surface calculated relatively to 500 dbar basing on the CTD survey (36 stations) made by R/V Akvanavt on 25–30 September 1999. Arrow in the upper left corner of the image shows the velocity scale 50 cm s$^{-1}$. 
Figure 5. (a) Velocity and (b) vorticity fields in the central and eastern Black Sea reconstructed by the MCC analysis of two subsequent NOAA IR images derived on 27 September 1999, 15:59 MSK, and 28 September 1999, 04:21 MSK, and superimposed on that of 27 September. Vorticity field is nondimensionalized by the Coriolis parameter $f = 9.92 \times 10^{-5}$ s$^{-1}$ estimated for the latitude of 43°. Vorticity contours are given with the interval of 0.03 starting from ±0.045. Solid and dashed lines represent cyclonic and anticyclonic vorticity, respectively.