MESOSCALE VARIABILYTY

The mesoscale variability of the World Ocean have ranges of spatial scale 10^1-10^2 km, and time scale 10^0-10^2 days – (Blatov and Tuzhilkin, 1990). In the Black Sea spatial scale of mesoscale water motions are comparable with scale of its general water circulation. So in many cases it is difficult to distinguish between mesoscale and general circulation elements in the Black Sea. In particularly, the quasi-permanent near-shore anticyclonic eddies are regarded as the general circulation elements (fig. 1) and also as mesoscale eddies (Oguz et al., 1998, Ginsburg et al., 2002b).

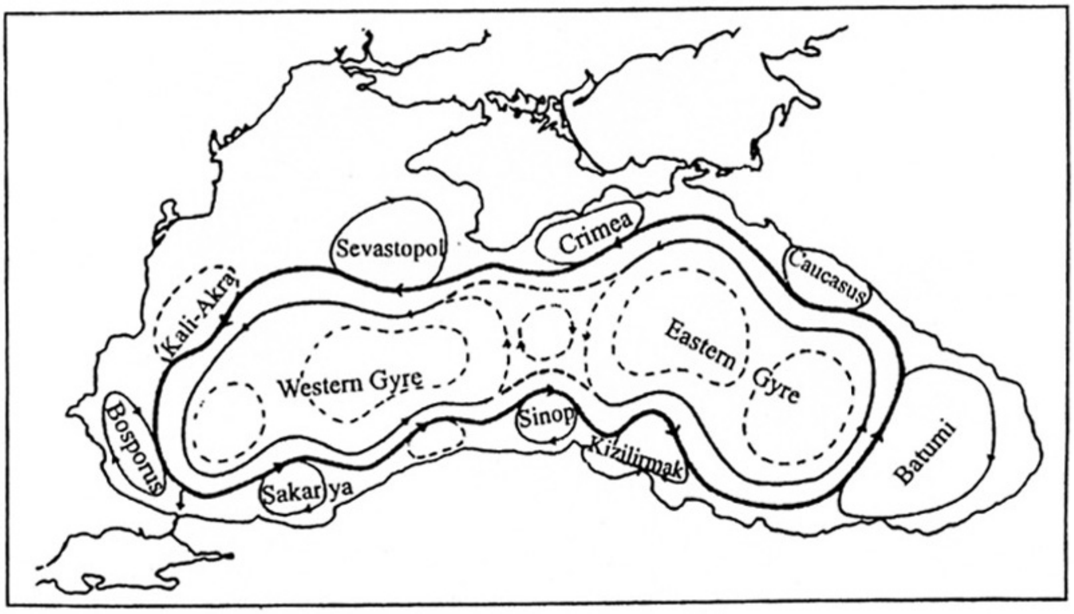


Fig. 1 –General water circulation scheme in the upper 500-m layer of the Black Sea; solid lines indicate quasi-permanent flows, dashed lines – recurrent features of general circulation. After Oguz at al. (1993).

Many quasi-synoptic surveys have revealed a strong mesoscale variability of water dynamics in the Main MRC (MRC) zone (fig. 2). It was observed that inshore of MRC jet anticyclonic meanders and so called nearshore anticyclonic eddies (NAE) are formed, and offshore cyclonic meanders and eddies are developed.

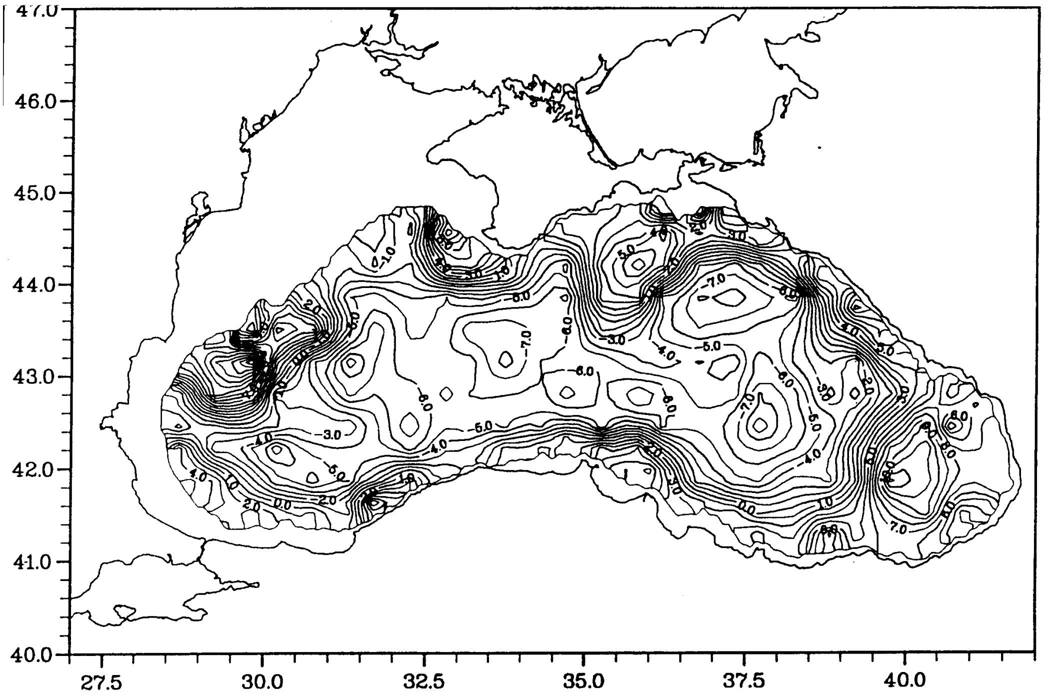
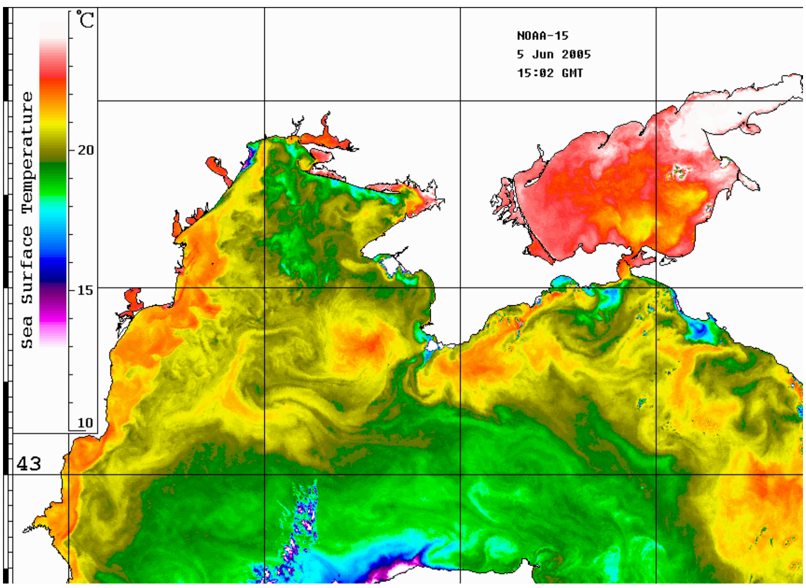


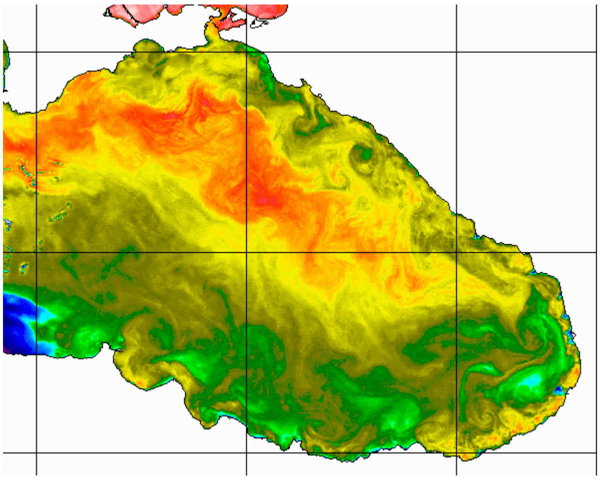
Fig. 2 – Dynamic topography of 25 dbar level relative 900 dbar during September 1991. After Oguz et al., 1994.

The mesoscale water dynamics in the sea surface layer is well represented by satellite infrared and color images of the Black Sea surface (fig. 3). These images often demonstrate the high mesoscale eddy variability in the whole Black Sea area, including the MRC that is probably the most energetic source of the variability. Satellite data show that circulation in the Black Sea surface layer and associated physical, chemical, and biological processes are considerably more complicated than might be expected from the traditional hydrographic data sets.

a)



b)



c)

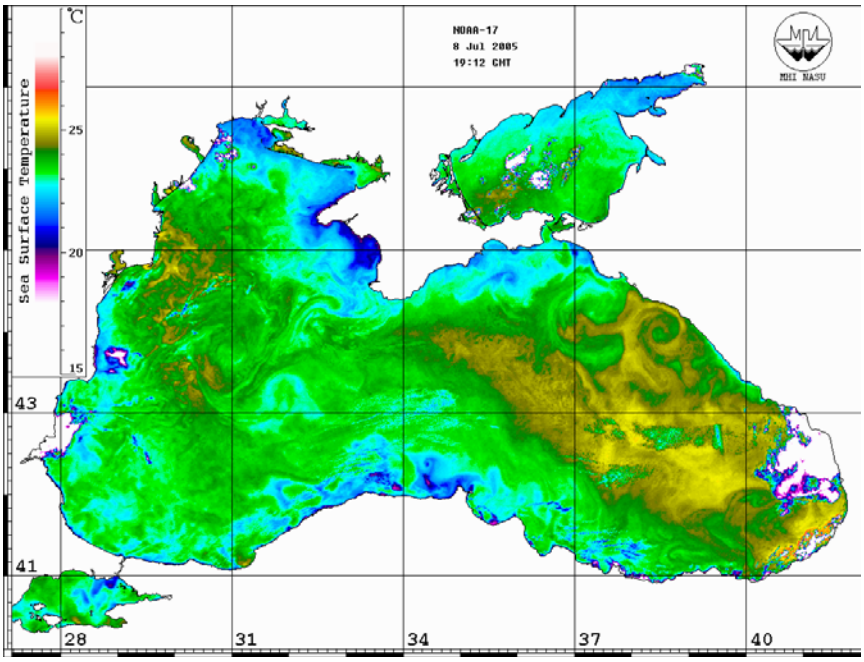


Fig. 3 – Cloud-free fragments of satellite infrared sea surface temperature images (AVHRR NOAA-17) of mesoscale features in the Black Sea: (a) 5 June 2005, (b) 8 June 2005, (c) 8 July 2005. From Internet data of Remote Sensing Dept. MHI NASU: http://dvs.net.ua/data/index.shtml

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 Black Sea.

Among the quasi-permanent mesoscale anticyclonic eddies the largest and most long-living are the Batumi eddy in SE corner of the Sea, the Sevastopol eddy situated to the SW off Crimea and the Sinop eddy, situated off the Anatolian coast to the west of Sinop cape (Fig. 1).

The Batumi eddy practically does not migrate, while the two others are migrating with a speed of 0.015-0.02 m s^{-1} (1-2 km per day) along the MRC general direction (Oguz et al., 1993). The mean diameter of these large anticyclonic eddies are 75-150 km and their depth - 700 to 1000 m. The current velocity in the young anticyclonic eddies is 0.30-0.40 m s^{-1} in their periphery and 0.10-0.20 m s^{-1} in the centers The life span of these mesoscale anticyclonic eddies is about 3 to 6 months. Thus they are relatively long-living mesoscale features, which drastically influence the whole system o surface currents. They are characterized by a descending upper water layer together with specific features of temperature, salinity, density and chemicals. This can be traced at sections across the anticyclonic eddies (Fig. 4). In the centers of large mesoscale anticyclonic eddies the upper limit of H_2S-zone usually descends to 50-100 m.

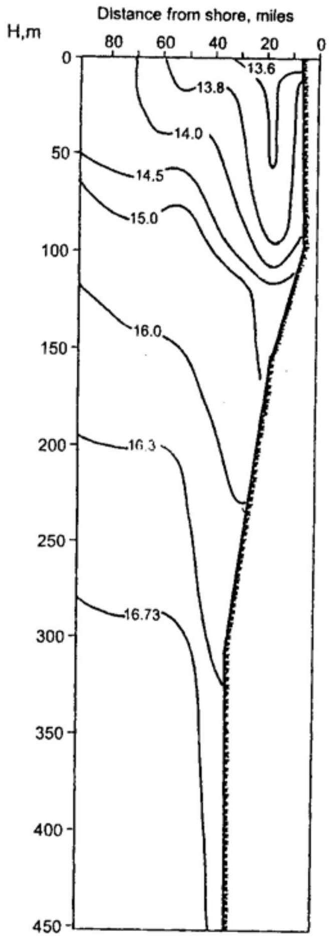


Fig. 4 – Water density (kg m^{-3}) section across the hear-shore anticyclonic eddy to the south of Crimea in March.

In the central Black Sea both anticyclonic and cyclonic mesoscale eddies, long-lived (about 3-8 months) and relatively short-lived (less than a month), were observed. 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 (Blatov et al., 1984, Golubev and Tuzhilkin, 1990, 1992, Kryvosheya et al., 1998, Zatsepin at al., 2003) and satellite information (Ginsburg at al, 2002a,b).

These anticyclones usually have diameter of about 80-100 km (fig. 5) and they penetrate deeply into the pycnocline (at least down to 300-400 m, fig. 6). 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 MRC jet.

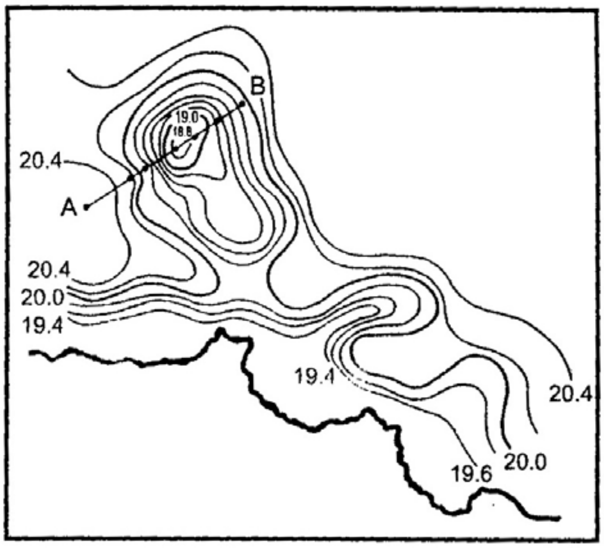


Fig. 5 - Sinop cape anticyclonic eddy at the Anatolian coast in July 1976, evidenced by the salinity field at 100 m depth; isohaline 20‰ corresponds to the core of MRC. After Blatov et al. (1984).

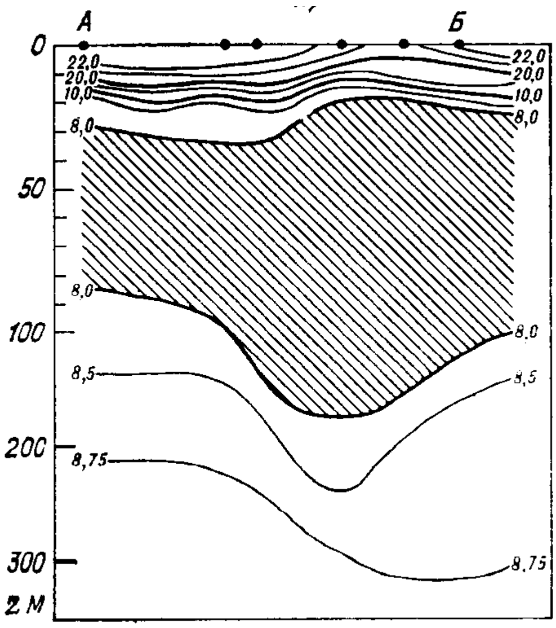


Fig. 6 – Vertical structure of water temperature (ºC) at a cross-section through the anticyclonic eddy along line AB on fig. 5. Hatched area – the cold intermediate layer. After Blatov et al. (1984).

They open sea eddies play an important role in horizontal mixing of the Black Sea upper layer waters providing their advection and entrainment (detrainment) into the orbital motion. The most intensive advection and mixing occur when a vortex pair (cyclone and anticyclone) is formed, or when the anticyclonic eddy interacts with the MRC. In the last case the MRC may be deflected far from the coast and decomposed into several jets. Two of the examples of such interaction shows (fig. 7) that the deflection of the MRC into the central region of the sea may produce water transport that is comparable with that produced by the detachment of a NAE from the shore (see below).

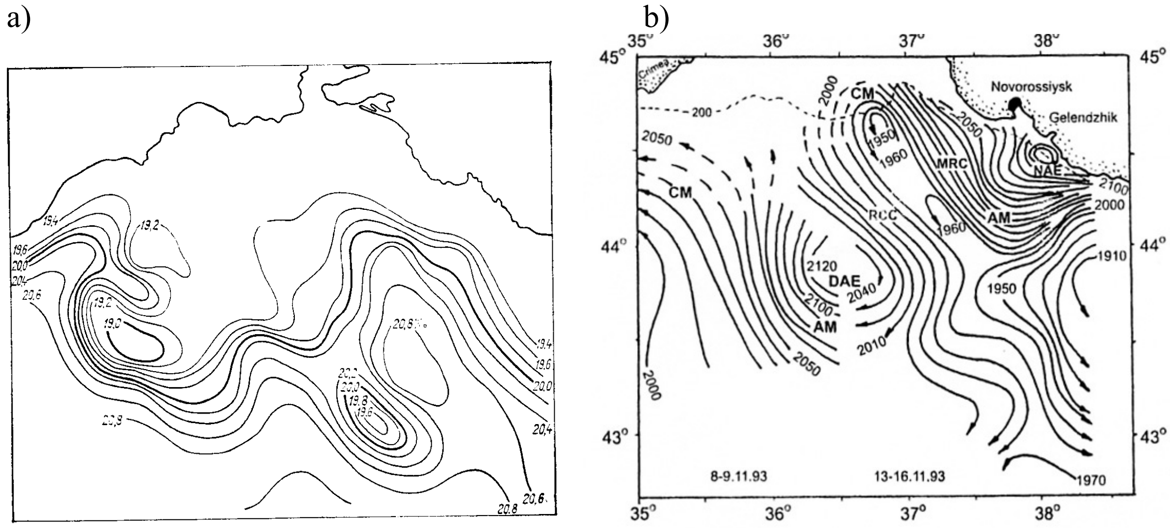


Fig. 7 – (a) Salinity (ppt) field at 100 m depth in the north-eastern area of the Black Sea in August 1951 (after Blatov et al., 1984) and (b) dynamic topography of the sea surface relative 500 dbar in the same region during November 1993 (after Kryvosheya et al., 1998).

The several cases of a long lived evolution of open sea anticyclonic eddies in the Black Sea are described below in brief.

A large (80-90 km in diameter) anticyclonic eddy centered at 43°N, 37-38°E has been the subject of complex investigation in the summer-autumn of 1999 based on measurements carried out during the "Black Sea'99" expedition (CTD surveys, deployment of Argos-tracked drifters), analysis of satellite imagery, and using altimetric sea level anomaly maps from merged TOPEX/POSEIDON and ERS-2 satellite data) (Zatsepin at al., 2003). The eddy was formed as a NAE in the Sochi-Sukhumi region, separated from the coast on 6-9 April 1999, stayed at the center of the eastern basin, which is usually characterized by cyclonic circulation, during about 8 months and decayed near the Turkish coast in December 1999. A similar offshore trajectories of two another anticyclonic eddies (in 1993 and 1997) are shown on fig. 8.

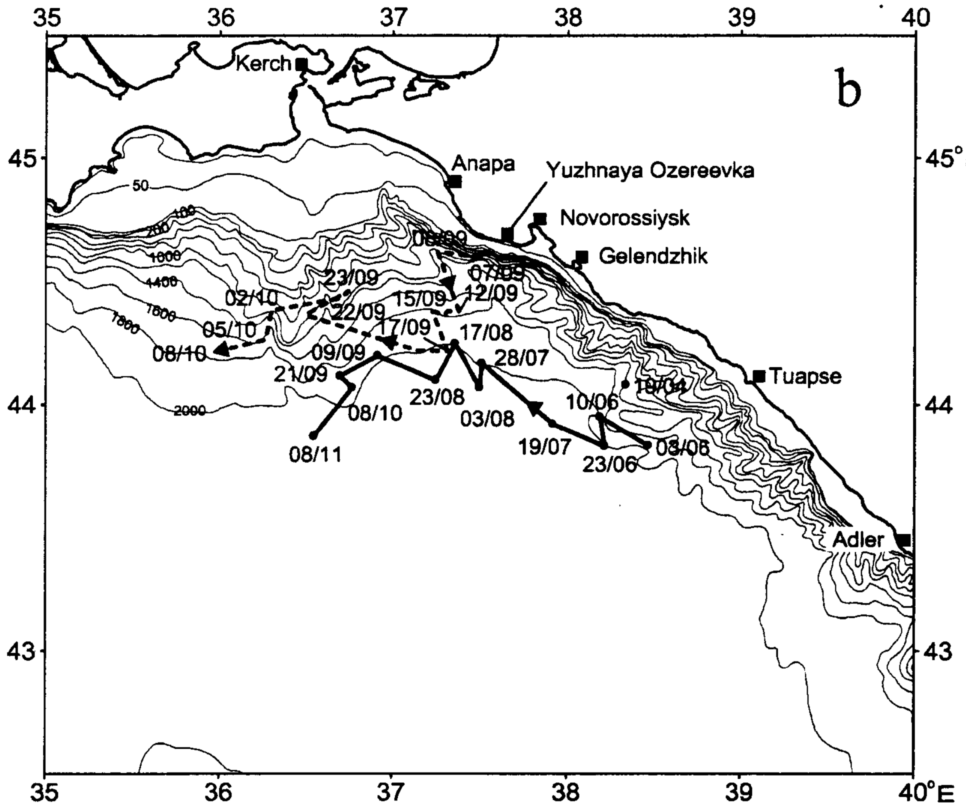


Fig. 8 - Trajectories of offshore movements of two anticyclonic eddies in north-eastern area of Black Sea: form 3 June to 8 November 1993 (thick line) and from 7 September to 8 October 1997 (dashed line). The arrows indicate the direction of the movements of eddies, the numerals mean corresponding dates. After Ginsburg et al., 2002a.

A compilation of hydrodynamic situations of different years (1993, 1997-1999) suggests that similar open sea anticyclonic eddies are frequently the elements of the circulation in the eastern Black Sea in the warm season (April-December). A positive correlation appears to be between eddies formation and weak macroscale circulation associated with low atmospheric wind forcing. Long lifetime of open sea anticyclones is likely determined by their by their large store of potential energy (Blatov et al., Golubev and Tuzhilkin, 1992), and interaction with neighboring eddies and MRC.

Important reason may be related to the replenishment of eddies by energy and vorticity from the surrounding fluid. At least two physical mechanisms of the replenishment was supposed (Zatsepin at al., 2003). One of them is merging two adjacent anticyclones. After merging a single eddy, more energetic than each of them is formed. It is known from the laboratory experiments that two quasi-equal baroclinic eddies with the radius comparable with the baroclinic Rossby radius should coalesce if the distance between their centers is within three radius of the eddy. This condition was apparently fulfilled for neighboring eddies in the

Black Sea. Another mechanism is the transfer of energy and momentum from the MRC by means of the coherent eddy structures. Such self-sustaining system of the dynamical structures may really occur because of a moderate size of the Black Sea compared to the size of mesoscale eddies: only a few of such eddies may be located in the central parts of eastern or western gyres. In that case the long life of the mesoscale eddies should be determined basically by the stability and permanent character of energy and vorticity fluxes through this dynamical system (Zatsepin at al., 2003).

The recent studies suggests (Zatsepin at 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 1992-1993 and warm winter of 1998-1999. The observations during the summer-autumn of 1993 and 1999 suggest that there can be a positive correlation between the intensive mesoscale eddies formation and low atmospheric wind forcing.

A modern and very important information on the mesoscale and macroscale circulation peculiarities was obtained from the Black Sea'99 Lagrangian drifter experiment (Zhurbas et al., 2004). The analysis of the displacements of the drifter trapped by the above mentioned long-lived open sea anticyclonic eddy (Figure 9) revealed that the period of orbital rotation of this eddy was about 5-15 days. It was also seen that drifters may be considered as good indicators of inertial oscillations.

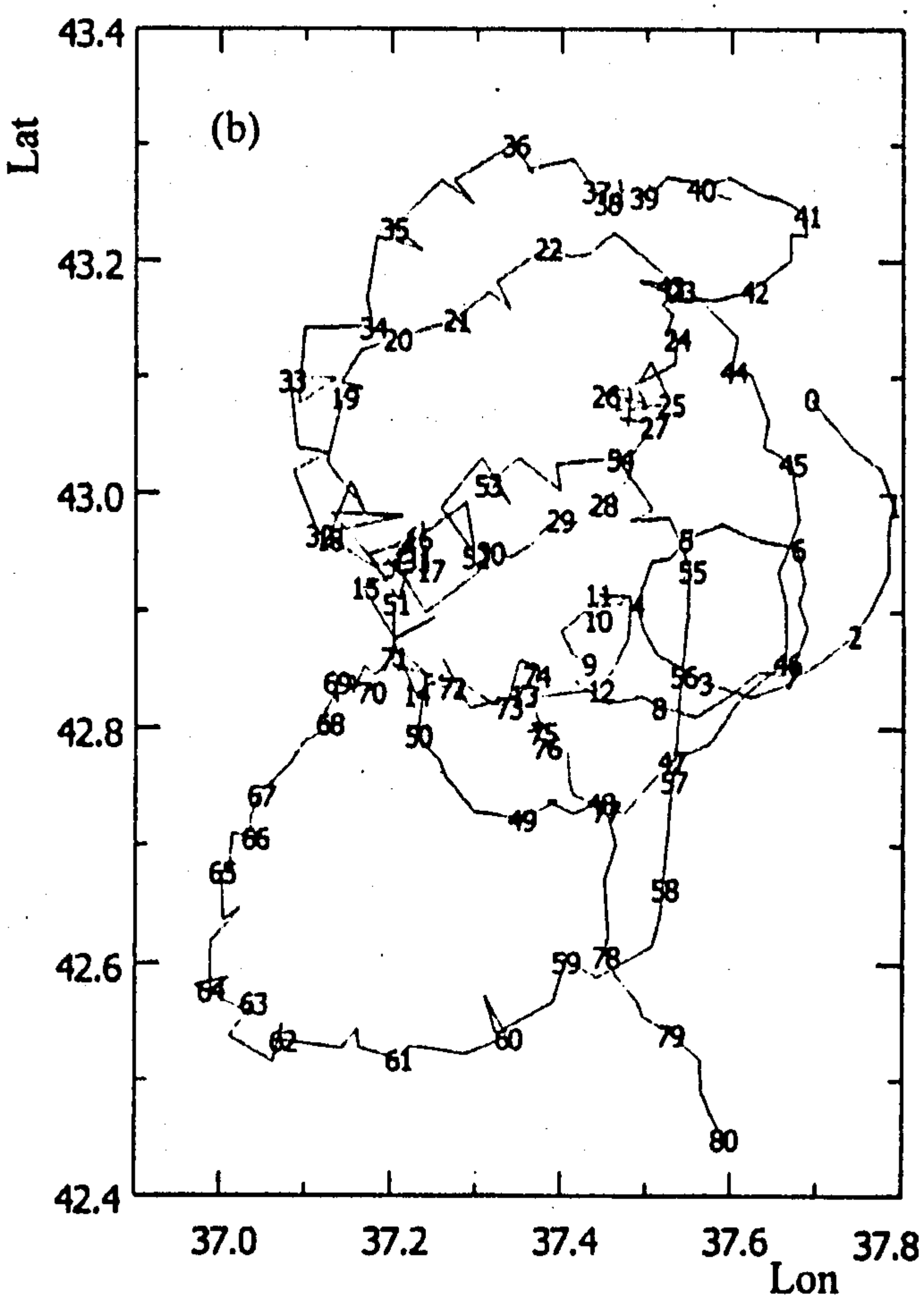


Fig. 9 – A fragment of the track of ARGOS drifter in the eastern central area of the Black Sea inside the open sea anticyclonic eddy. The numerals mean days numbers from the 29 September 1999. After Zatsepin at al., 2003.

An another example of long-lived evolution of open sea anticyclonic eddies along the Northwestern Black Sea continental slope is presented by Ginburg et al. (2002b). National Oceanic and Atmospheric Administration (NOAA) Advanced Very-High Resolution

Radiometer (AVHRR) imagery (1993, 1998) was used to investigate the structure and evolution of mesoscale anticyclonic eddies, and their role in shelf/deep basin water exchange. In the summer of 1993, two anticyclonic eddies with diameters of 90 and 55 km coexisted without coalescence for 1.5 months over a wide and relatively .gentle part of the northwestern continental slope. The directions of the eddies' movements inside this zone (speed of movement up to 0.16 m s^{-1}) were likely determined by the interaction between eddies themselves, and by the MRC meandering and forcing.

For June-August of 1998, three such eddies have been traced in the sea surface temperature (SST, AVHRR) and chlorophyll a (SeaWiFS) fields. The largest anticyclone with a diameter of 90 km moved during 3 months southwestward from the wide slope region west of Sevastopol to the area of narrower slope southeast of Cape Kaliakra with a mean speed of about 3 cm/s (fig 10). Together with nonstationary associated elements (cyclones at the eddies' peripheries, entrained and ejected jets), anticyclonic eddies determine water exchange processes in a large area of the western Black Sea between 43-45°N and 29-33°E. They transport chlorophyll-rich coastal waters to the deep basin, westerly winds being favorable to the process.

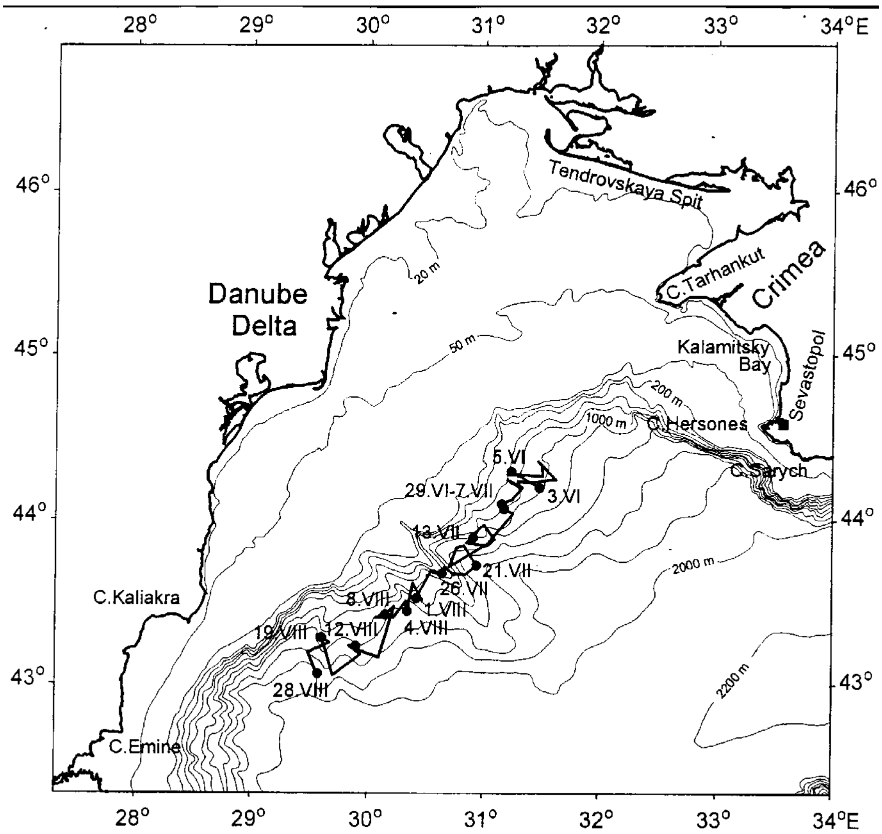


Fig. 10 - Trajectory of anticyclonic eddy in northwestern area of Black Sea form 3 June to 28 August 1998 (thick line). The numerals mean corresponding dates. After Ginsburg et al., 2002b.

According to Ginsburg et al. (2002b), when an eddy moves southwestward, its place is occupied, as a rule, by a newly formed one, so that one to three anticyclones can exist at the same time over the continental slope between the Sevastopol region and Cape Kaliakra. Therefore, the so-called "Sevastopol eddy" (fig. 1) is not a quasi-permanent structure and it is inappropriate to name the observed eddies like this. The name "Sevastopol" is in fact only representative of a geographic position of increased mesoscale activity associated with anticyclonic eddies repeatedly forming and moving southwestward. Moreover, it follows from the present study that the "Kaliakra eddy" and "Sevastopol eddy" on the scheme of the Black Sea surface circulation (fig. 1) by Oguz et al. (1993) can be the same structure registered at different times.

Besides the long-lived eddies, most eddy- or jet-like structures that are quite detectable in satellite images (fig. 2) seem to have a short life period, from a few days to 1 week usually. The description and classification of these nonstationary structures based on the analysis of IR satellite images is presented by Ginburg (1994). The short-lived eddies and jets often belong to the upper mixed layer only; they do not penetrate deeper than seasonal thermocline. So it is reasonable to suppose that the fast degradation of such structures is due to the high dissipation level typical for the Black Sea upper layer (Blatov et al., 1984, Zatsepin at al., 2003).

NAE separation from the coast and their transformation into open sea eddies provide horizontal mixing of the upper layer waters and results in deflection of the MRC offshore, formation of large meanders of the current around the eddies, and its branching when rounding such features. It is pointed out that an estimation of the shelf/open sea water exchange based on the box balance model does not contradict the assumption that such exchange is considerably determined by NAE separation from the coast (Zatsepin at al., 2003).

The continuous recording of current vectors at the stabilized buoy opposite Gelendzhik demonstrated that the time intervals between periods with inverse current direction in autumn-winter was 20-22 days per month, while in spring-summer they decreased to 12-15 days (Titov, 2002). Correspondingly, in autumn-winter along the Caucasus coast, 1-2 NAE, pass per month, while during spring-summer this number increases to 2-4. Their rate of travel along the shore is between 3-7 km per day (0.04-0.08 m s^{-1}) (Krivosheya et al., 1998).

The main factor inducing periodical formation of NAE is a large shift in current velocity between the MRC core and the coast. This shift attains its maximal gradient, 0.03-0.05 m s^{-1} per kme al a distance of 10-20 km from the shore.

The system of anticyclonic eddies play a key role in redistribution of solid (floating) and dissolved contaminants in the coastal waters. In particular, various contaminants are concentrating in the convergence zones created by the anticyclonic eddies, and result in local accumulation of nutrients and suspended particulates.

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