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Circulation in the surface and intermediate layers of the Black Sea

T. OGUZ,* V. S. LATUN,† M. A. LATİF,* V. V. VLADIMIROV,† H. İ. SUR,* A. A. MARKOV,† E. ÖZSOY,* B. B. KOTOVSHCHIKOV,† V. V. EREMEEV† and Ü. ÜNLÜATA*

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Abstract—Circulation features of the Black Sea are presented based upon a basin-scale survey carried out in September–October 1990. The circulation pattern for the upper 300–400 dbar consists of a cyclonically meandering Rim Current, a series of anticyclonic eddies confined between the coast and the Rim Current, and a basin-wide, multi-centered cyclonic cell in the interior of the basin. In contrast to prior investigations, although the currents are much weaker as compared with those in the upper layer, the intermediate depth (defined here between 500 and 1000 dbar) circulations reveal considerable structural variability. This involves counter-currents, shift of eddy centers, coalescence of eddies, and associated sub-basin-scale recirculation cells separated by the meandering Mid-Basin Current system. A descriptive synthesis of the upper layer circulation, combining the present results with earlier findings, identifies the quasi-permanent and recurrent features even though the shape, position, strength of eddies and meander pattern, and the bifurcation structure of currents vary.

INTRODUCTION

THE general cyclonic character of the Black Sea circulation, resulting from the cyclonic nature of the wind field, was first described by KNIPOVICH (1932) and NEUMANN (1942; see also CASPERS, 1957). Further details of the circulation characteristics were provided later by FILIPPOV (1968), BOGUSLAVSKIY *et al.* (1976), BLATOV *et al.* (1984), STANEV *et al.* (1984), STANEV (1990) and EREMEEV *et al.* (in press), which, however, did not lead to a significant modification in Knipovich's classical circulation concept. Recently, satellite imagery and high resolution hydrographic data along the Turkish coast indicate the presence of temporally and spatially variable mesoscale features, and specific organized forms of local nonstationary currents (such as jets, filaments and dipole eddies), embedded within the basin-wide cyclonic general circulation (OGUZ *et al.*, 1992).

Lack of international cooperation, preventing basin-wide coverage of the sea was a major drawback of the earlier studies. Consequently, the circulation maps were based upon either nonsynoptic pooled data or selected individual data sets with mostly a coarse resolution network of stations (approximately more than half a degree spacing; see

*Institute of Marine Sciences, Middle East Technical University, P.O. Box 28, Erdemli 33761, Icel, Turkey.
†Marine Hydrophysical Institute, Academy of Sciences of the Ukraine, 2 Kapitanskaya Street, Sevastopol 335000, Ukraine.

Blatov et al., 1984). Considering that the first baroclinic deformation radius is of the order of 20–25 km, available maps hardly represented features smaller than sub-basin-scale and/ or the coarse mesoscale ranges. In addition, the insufficiency and unreliability of the existing data hindered a proper understanding of the circulation dynamics below the upper 200–300 m, leading often to contradictory conclusions. New observational studies with finer temporal and horizontal resolutions and with nearly full vertical coverage of the water column using highly accurate, continuously recording CTD instruments therefore should establish a better description of the hydrography and circulation of the Black Sea, allowing us to understand, quantify, and model the fundamental physical processes and their interactions with biogeochemical processes. A proper knowledge of the circulation and currents is also necessary for applications related to the very serious health and ecological problems of the Black Sea.

Recently a major cooperative research effort was undertaken by the coordinated field experiment of the R.V. *Bilim* of the Institute of Marine Sciences–Middle East Technical University (IMS–METU), Turkey, and the R.V. *Lomonosov* of the Marine Hydrophysical Institute–Ukrainian Academy of Sciences (MHI–UAS), during 15 September–14 October 1990 (hereafter referred to as SO90) in the region to the east of approximately 31°E. The SO90 survey is the first extensive, quasi-synoptic, three-dimensional coverage of most of the Black Sea. As we describe in the following sections, this unique quasi-synoptic, medium resolution hydrographic data set delineates new features and adds further details to our classical concept of the structural variability of the Black Sea circulation.

DATA ANALYSIS

One dbar bin-averaged CTD data were collected at 172 stations located on a regular grid with spacings of 1/3° latitude (~20 nm) and 1/2° longitude (~22 nm; Fig. 1). Each vessel completed its survey within 18 days (15 September–3 October for R.V. *Bilim*; 27 September–14 October for R.V. *Lomonosov*). The measurements were performed with the SeaBird Electronics Model 9 CTD system on board the R.V. *Bilim* and with the Istok-5 CTD system on board the R.V. *Lomonosov*. The combined data set was intercalibrated by comparing the potential temperature and salinity values at four common intercalibration stations (Fig. 1).

The intercalibration benefited from the vertical and temporal uniformity of water mass properties in the bottom mixed layer at depths below 1700 m (Murray et al., 1991) where the R.V. *Bilim* data show practically no variability, indicating its internal consistency. The data also agreed with those obtained by the R.V. *Knorr* in April–August 1988. The R.V. *Lomonosov* data were corrected against the R.V. *Bilim* data by applying the constant correction factors for the potential temperature and salinity for the entire water column, depending on their deviations in the bottom mixed layer. The correction factors for each station varied between −0.01 and +0.01°C, and 0.020 and 0.035 psu.

The density field of the combined and intercalibrated data set was used to compute dynamic heights based on the common reference level of 1500 dbar, which is known to have currents with negligible speeds and practically no horizontal variability (Titov, 1980). The geopotential anomaly fields were calculated at selected pressure levels at all stations and then mapped onto a regular grid with 0.15 degrees horizontal spacing by utilizing the objective analysis method described by Ozsoy et al. (1991).

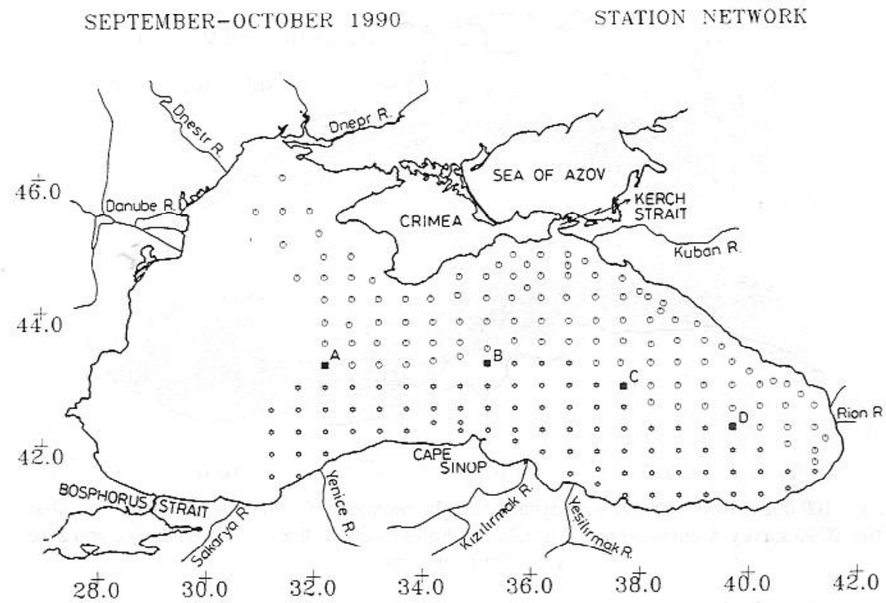

Fig. 1. Station network for the September–October 1990 joint Soviet–Turkish Black Sea survey. The circles are the R.V. *Lomonosov* and the stars are the R.V. *Bilim* stations. The four intercalibration stations are shown by A, B, C and D.

RESULTS

The upper layer circulation above the permanent pycnocline, shown by the surface (5 dbar) and 100 dbar dynamic topography maps (Figs 2 and 3), consists of a well-defined cyclonically meandering peripherial current system (hereafter referred to as the Rim

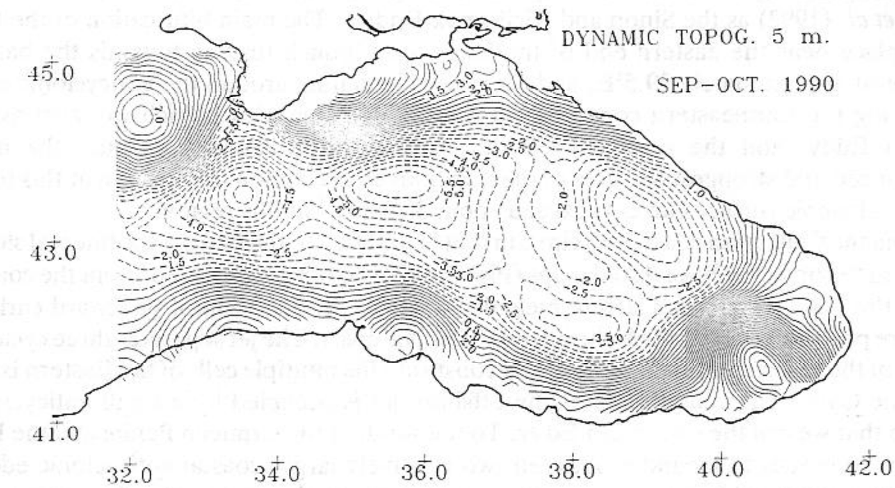

Fig. 2. 5 dbar objectively mapped dynamic height anomaly field (in cm) relative to 1500 dbar for the SO90 survey. Contour interval is 0.5 cm. Solid (dashed) lines indicate positive and zero (negative) contours.

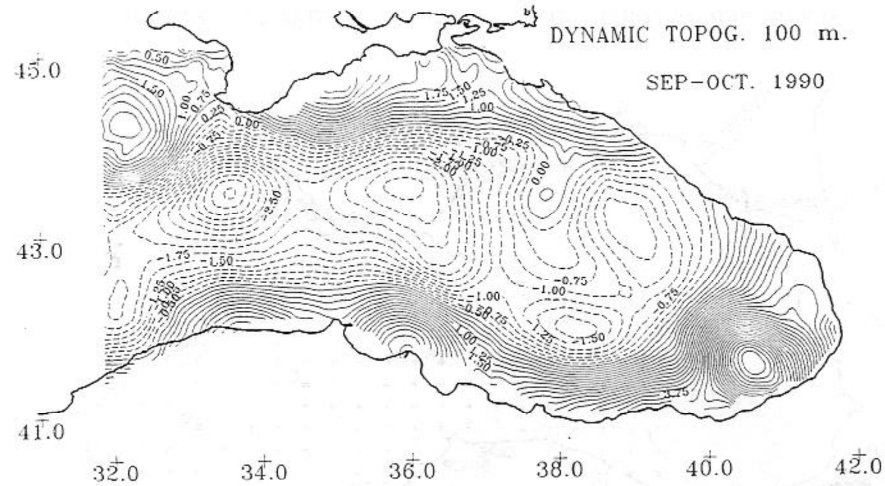

Fig. 3. 100 dbar objectively mapped dynamic height anomaly field (in cm) relative to 1500 dbar for the SO90 survey. Contour interval is 0.25 cm. Solid (dashed) lines indicate positive and zero (negative) contours.

Current; also referred to as the Main Black Sea Current System in the Russian literature) and a series of mesoscale eddies distributed over the basin. The Rim Current, <75 km wide, and with an average speed of 20 cm s^{-1} at the surface, separates the cyclonically dominated interior of the basin from anticyclonically dominated narrow coastal zone. While the main part of this current system meanders eastward along the Anotolian coast, it forms two anticyclonic coastal eddies and supports the two cyclonic eddies within the interior of the basin; the centers of cyclone–anticyclone pairs situated approximately along 33.5 and 36°E longitudes. These anticyclonic eddies were identified and labeled earlier by Oguz *et al.* (1992) as the Sinop and Kizilirmak Eddies. The main bifurcation of the flow takes place near the eastern end of the basin, one branch turning towards the basin's interior at approximately 39.5°E, and the other circulating around the anticyclonic eddy occupying the southeastern corner of the Black Sea. This eddy, which we label as the Batumi Eddy, and the northerly current around its periphery constitute the most pronounced and strongest features of the upper layer circulation in the basin at this time. The geostrophic surface currents exceed about 30 cm s^{-1} in this region.

Along the Caucasian coast, the Rim Current is confined to the narrow continental slope, although the objectively analyzed maps (Figs 2 and 3) do not properly represent the coastal jet. In this region the Rim Current meanders intensely in the form of backward curling, offshore protruding jet towards the interior from the coast. The jet separates three cyclonic eddies of the eastern basin that effectively constitute the multiple cells of the Eastern Basin Cyclonic Gyre. The coastal side of the offshore jet is occupied by a small anticyclonic feature that we call the Caucasian Eddy. To the south of the Crimean Peninsula, the Rim Current continues to meander between two relatively larger coastal anticyclonic eddies and two cyclonic eddies occupying the central parts of the basin. The flow eventually proceeds southwest towards the Bosphorus region to complete its basin-wide cyclonic circulation. The anticyclonic eddies attached to the northern coast are centered along approximately 35 and 32°E longitudes and will be referred as the Crimean Eddy and Sevastopol Eddy, respectively.

The 5 dbar circulation field is accompanied by a significant basin-wide variability in the water mass properties. The most striking feature of the 5 dbar temperature distribution (Fig. 4) is the south-to-north gradient across the study area. The temperature along the southern coast exceeds 19.5°C. The higher temperatures are observed within the anticyclonic eddies, reaching 23.0°C in the Batumi Eddy region. The temperature in the cyclonic features of the basin's interior is about 18.0°C. In the southeastern part of the basin, the relatively colder interior waters are separated from warmer waters of the Batumi Eddy by a sharp temperature front.

Satellite imagery from the survey period (see Fig. 5a,b for the 21 and 30 September 1990 AVHRR pictures) also indicates temperature variability along the center of the basin. In particular, two cold anomalies situated to the southeast and southwest of the tip of the Crimean peninsula and the one situated within the central part of the eastern basin (between 37 and 38°E) emerge as well-pronounced features of the satellite image. The three relatively warm spots in the southeastern basin, west of Cape Sinop and along the Caucasian coast, are also well-defined (Fig. 5a,b). These features of the satellite imagery appear to be consistent with the surface dynamic topography map in which colder (warmer) spots correspond to the regions of cyclonic (anticyclonic) eddies.

The salinity at 5 dbar pressure level along the periphery of the basin is typically lower than $S < 18.15$ psu. The lowest values (about $S \sim 17.0$ psu) occur in the Sevastopol Anticyclonic Eddy, which is influenced by the relatively fresh waters of the northwestern shelf. As with the temperature distribution, the anticyclonic eddies are separated by sharp

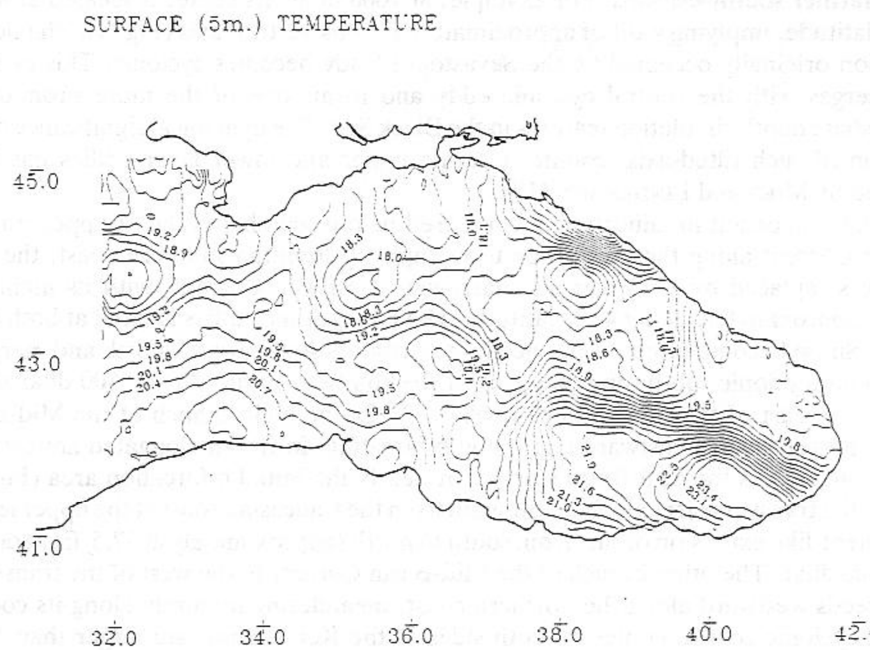

Fig. 4. 5 dbar objectively mapped horizontal distribution of the potential temperature (°C) for the SO90 survey. Contour interval is 0.5°C.

frontal zones along the periphery of the basin from the more saline (>18.20 psu) interior waters.

Compared with those at the 5 dbar level, the temperature and salinity at the 100 dbar level agree better with the circulation pattern inferred from dynamic topography. The most pronounced changes in the water mass properties take place along the offshore part of the Rim Current, which forms the frontal zone separating the cyclonic interior from the anticyclonic coastal belt. The frontal zone, identified by $T \cong 8.10$–8.20°C, $S \cong 20.2$–20.4 psu ($\sigma_\theta \cong 15.7$–$15.9\ \mathrm{kg\,m^{-3}}$), has an approximate width of 30–40 km along the periphery of the basin. These values decrease down to $T < 8.0$°C, $S < 20.1$ psu ($\sigma_\theta < 15.6\ \mathrm{kg\,m^{-3}}$) in the anticyclonic eddies, whereas they increase up to $T > 8.2$°C, $S > 20.5$ psu ($\sigma_\theta > 15.9\ \mathrm{kg\,m^{-3}}$) within the cyclonic eddies of the interior waters. As discussed below, the cooler temperatures along the coast are associated with the deeper penetration of the Cold Intermediate Layer (CIL).

Below the permanent pycnocline located at approximately 150 m depth, major features of the circulation begin to change. At 250 dbar, the center of the Sevastopol Eddy situated to the west of the Crimean peninsula at the upper levels is shifted south (Fig. 6). In its northern part, the flow reverses and becomes a cyclonic eddy at lower levels. Whereas the Rim Current weakens at this level, the anticyclonic eddies along the Anatolian coast and at the two sides of the Kerch Strait become more pronounced. The transverse jet is nearly perpendicular to the Caucasian coast and no longer divides the two cyclonic eddies of the eastern basin. These eddies, in fact, coalesce and constitute two cells of a larger sub-basin-scale cyclonic gyre. The transverse jet appears to be thinner compared with upper levels.

Below 400 dbar, the data reveal significant modification in the flow structure (Figs 7–9). Towards deeper levels, the Sevastopol Eddy appears to weaken, becoming smaller and shifted farther southwestward. For example, at 1000 dbar, its center is located at about 43.5°N latitude, implying a tilt of approximately 1° in its vertical axis (Fig. 9). The flow in the region originally occupied by the Sevastopol Eddy becomes cyclonic. This cyclonic eddy merges with the central cyclonic eddy and forms one of the more pronounced intermediate depth circulation features in the Black Sea. The dynamical significance of the evolution of such tilted-axis, counter-rotating upper and lower layer eddies has been discussed by Mied and Lindemann (1982).

Another important modification encountered below 400 dbar is the disappearance of the Rim Current along the shelf/slope topography. Along the southern coast, the Rim Current is replaced by a weaker and narrower Mid-Basin Current, with its main axis situated approximately along 43°N latitude. The anticyclonic eddies located at both sides of Cape Sinop become more pronounced, their centers shift towards north and merge to form an anticyclonic sub-basin-scale gyre of the southern basin. At the 500 dbar depth level, to the east of the Cape Sinop, at about 37°E, the main branch of the Mid-Basin Current proceeds northeastward and, upon bifurcating, forms an elongated anticyclonic feature and rejoins the Mid-Basin Current at nearly the initial bifurcation area (Fig. 7). Thus, as the transverse jet extends southward from the Caucasian coast at the upper levels, the filament-like extension occurs from south to north (approximately at 37.5°E) at depths below 500 dbar. The other branch of the Mid-Basin Current to the west of the transverse jet proceeds westward along the northern coast, meandering intensely along its course. The anticyclonic coastal eddies on both sides of the Kerch Strait are larger than those observed in the upper levels. This pattern of circulation remains essentially constant at the 750 and 1000 dbar levels. The northern part of the basin becomes cyclonic whereas the

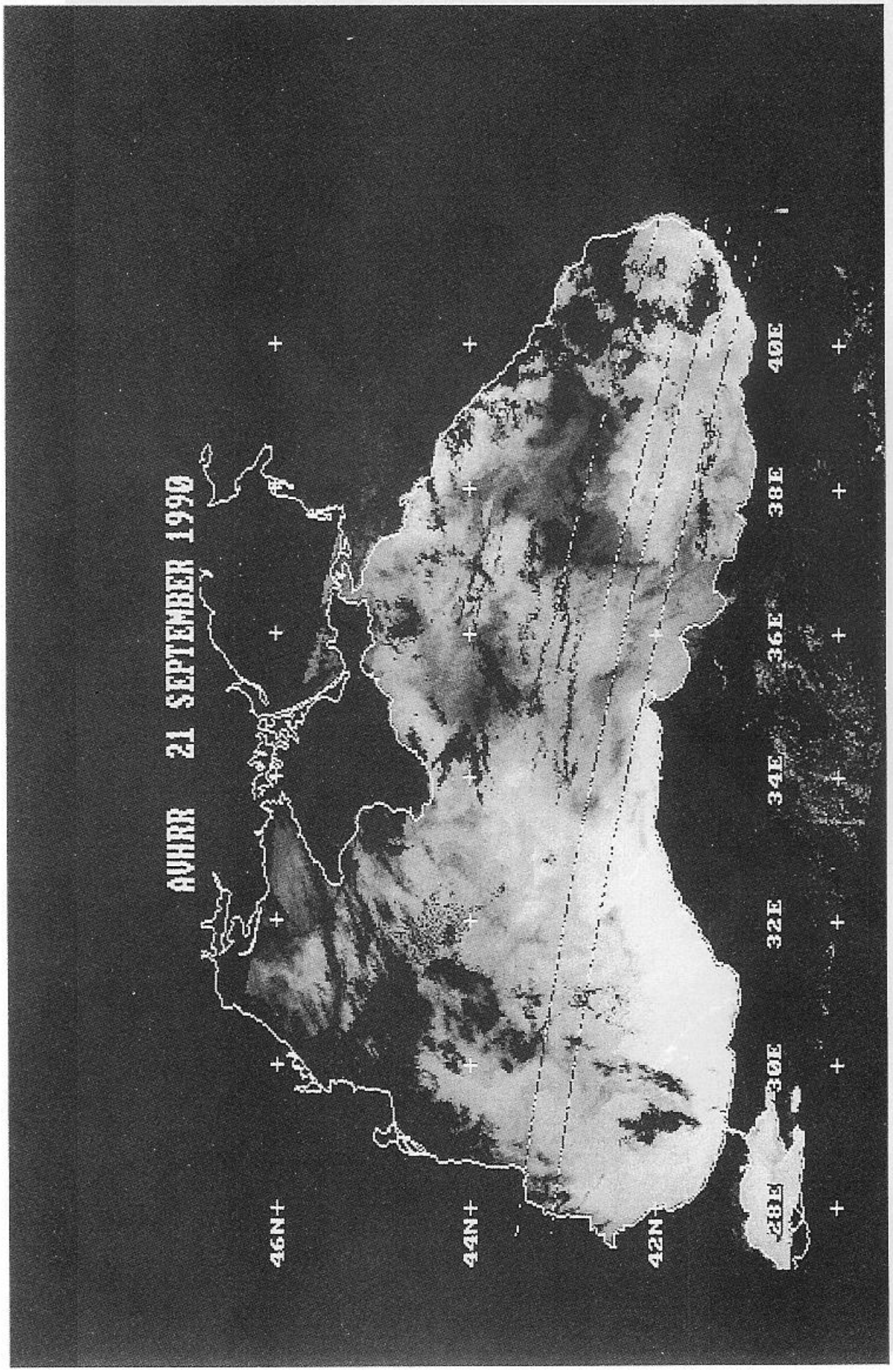

Fig. 5. (a) NOAA-10 AVHRR-IR satellite image for 21 September 1990. In the image, darker (lighter) tones indicate colder (warmer) waters. No cloud masking has been performed. Areas that are completely black represent clouds.

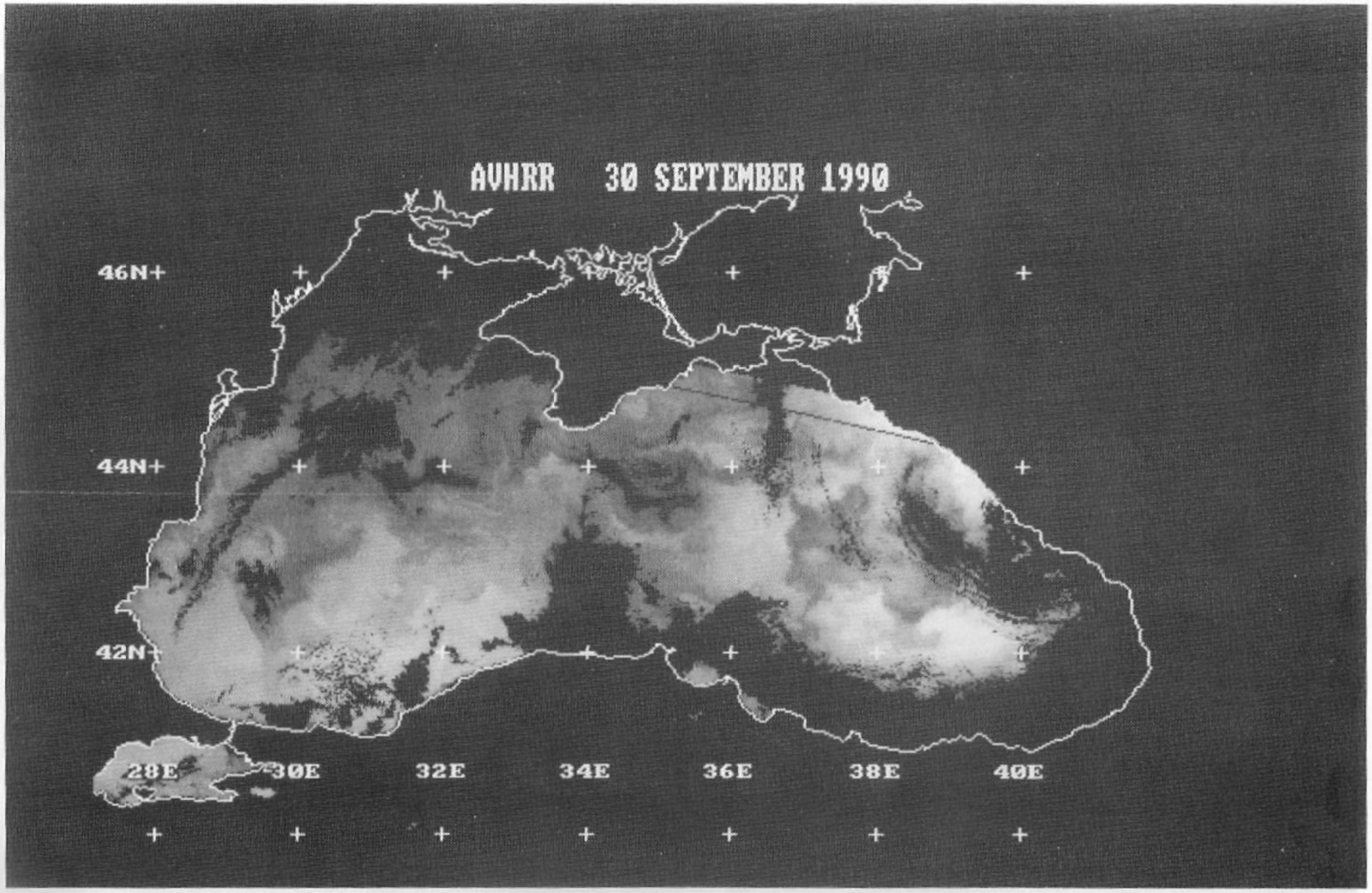

Fig. 5. (b) NOAA-10 AVHRR-IR satellite image for 30 September 1990. In the image, darker (lighter) tones indicate colder (warmer) waters. No cloud masking has been performed. Areas that are completely black represent clouds.

southern part becomes anticyclonic, excluding the filament-like anticyclonic extension region from the south to the north. The cyclonic and anticyclonic regions are separated by an approximately east–west flow at the middle of the basin.

The individual geopotential anomaly fields produced separately from both the R.V. *Bilim* and the R.V. *Lomonosov* data sets support the existence of this zonal Mid-Basin Current. These maps present a consistent picture in terms of the sign and the orientation of the streamlines along the common boundary of the data sets, and thus provide an additional check on the validity of the combined analysis of the two calibrated data sets.

Distribution of the Cold Intermediate Layer (CIL)

The Cold Intermediate Layer (CIL), marked by temperatures lower than 8°C, is a unique water mass of the upper layer thermohaline structure. It is formed by the convective processes associated with the winter cooling of surface waters (Filippov, 1965; Tolmazin, 1985; Ovchinnikov and Popov, 1987). Formation is limited to the upper layer since the intensity of the vertical convection is normally not sufficient to overcome the stability of the pycnocline dome (the Brunt–Vaisala frequency, N^2, ranges from 50 to >200 h^{-2} in the upper 200 m; see Murray *et al.*, 1991). Once it is formed, the CIL is advected and maintained within the coastal waters, where it is entrapped by the coastally-attached anticyclonic eddies and continuously modified throughout the year. It often interacts with the basin's interior through transverse jets extending from the shelf–slope region to offshore waters (Oguz *et al.*, 1991).

Understanding the basin-wide distribution of the oxygen-carrying CIL waters has important implications on the health and ecology of the Black Sea. For example, fishery studies suggest a correlation between the upper boundary of anchovy aggregations and the upper boundary of the CIL situated immediately below the seasonal thermocline in summer months (Panov and Chashchin, 1990). The lower boundary of the CIL has been

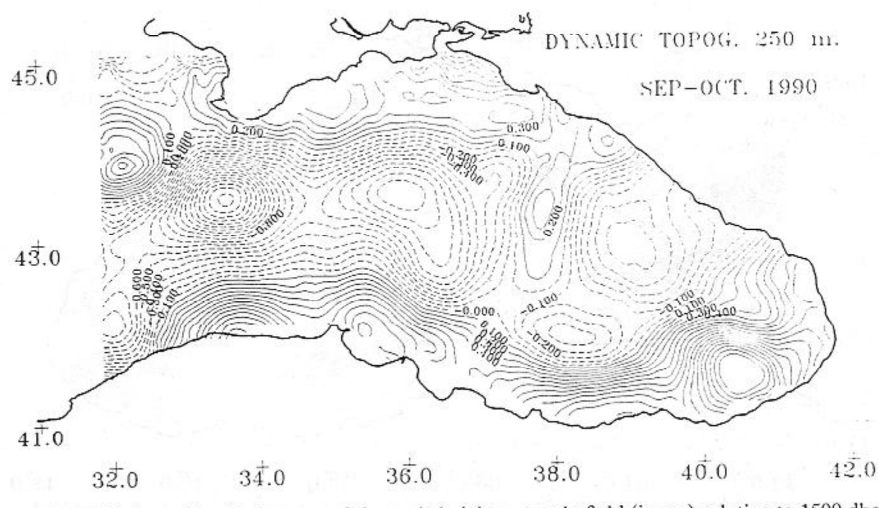

Fig. 6. 250 dbar objectively mapped dynamic height anomaly field (in cm) relative to 1500 dbar for the SO90 survey. Contour interval is 0.1 cm. Solid (dashed) lines indicate positive (zero and negative) contours.

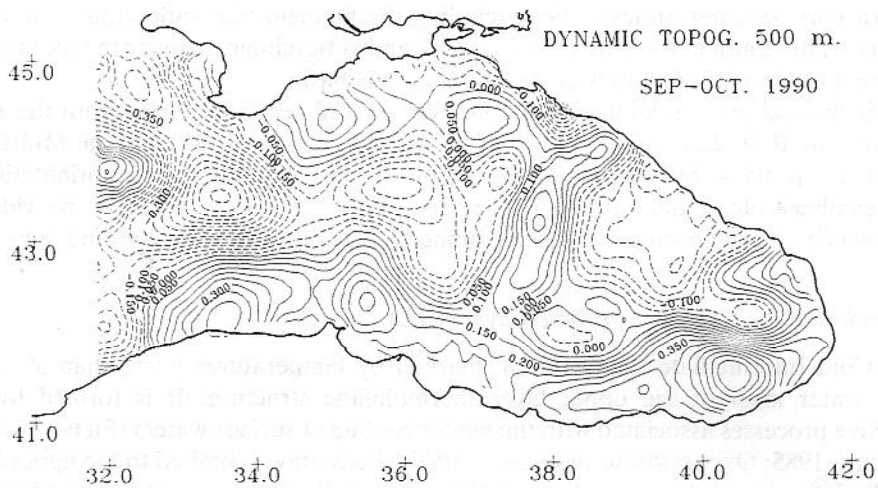

Fig. 7. 500 dbar objectively mapped dynamic height anomaly field (in cm) relative to 1500 dbar for the SO90 survey. Contour interval is 0.05 cm. Solid (dashed) lines indicate positive (zero and negative) contours.

used as an indirect estimation of the oxic/anoxic interface position in response to circulation dynamics of the basin (BRYANTSEV *et al.*, 1988).

SO90 data reveal significant horizontal variability of the CIL properties in the basin. Within the interior of the cyclonic eddies, the CIL is situated at shallower depths with an approximate thickness of 50 m, its base being elevated to depths of 75–80 m (Figs 10 and 11), reflecting the doming structure of the circulation. The base of the CIL deepens towards the periphery of the basin to depths >100–110 m, and the layer itself thickens to

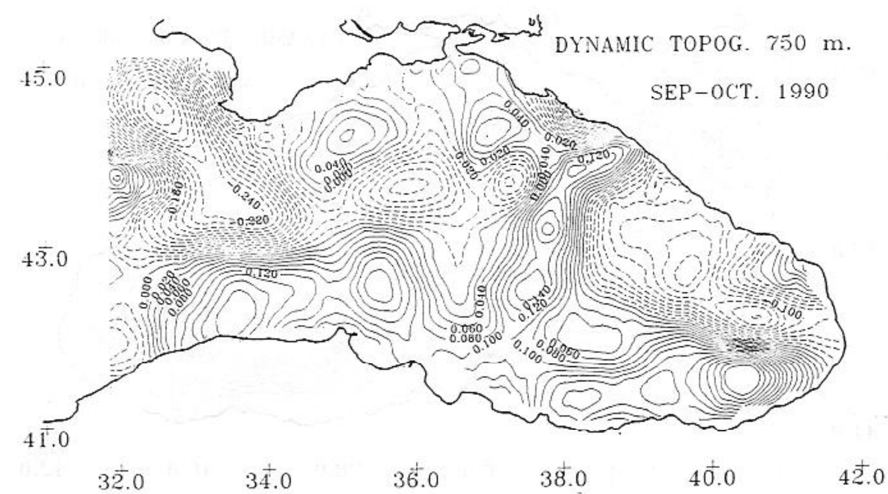

Fig. 8. 750 dbar objectively mapped dynamic height anomaly field (in cm) relative to 1500 dbar for the SO90 survey. Contour interval is 0.02 cm. Solid (dashed) lines indicate positive (zero and negative) contours.

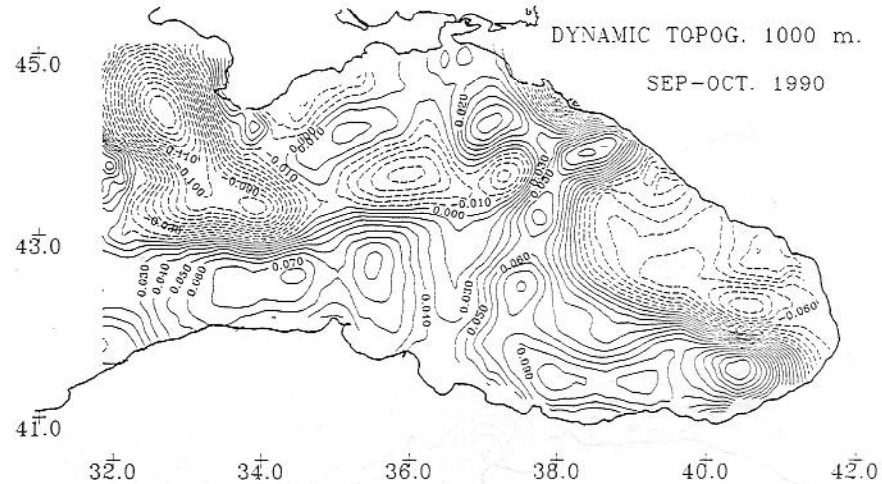

Fig. 9. 1000 dbar objectively mapped dynamic height anomaly field (in cm) relative to 1500 dbar for the SO90 survey. Contour interval is 0.001 cm. Solid (dashed) lines indicate positive (zero and negative) contours.

about 75 m within the anticyclonic coastal eddies. In particular, the CIL penetrates to a depth of 150 m with a thickness of 90 m in the Batumi Eddy region. The mean temperature of this layer is slightly cooler (7.50 vs 7.55 to 7.60°C) within the anticyclonic eddies, indicating that anticyclonic features are the pools of CIL. These results suggest that the

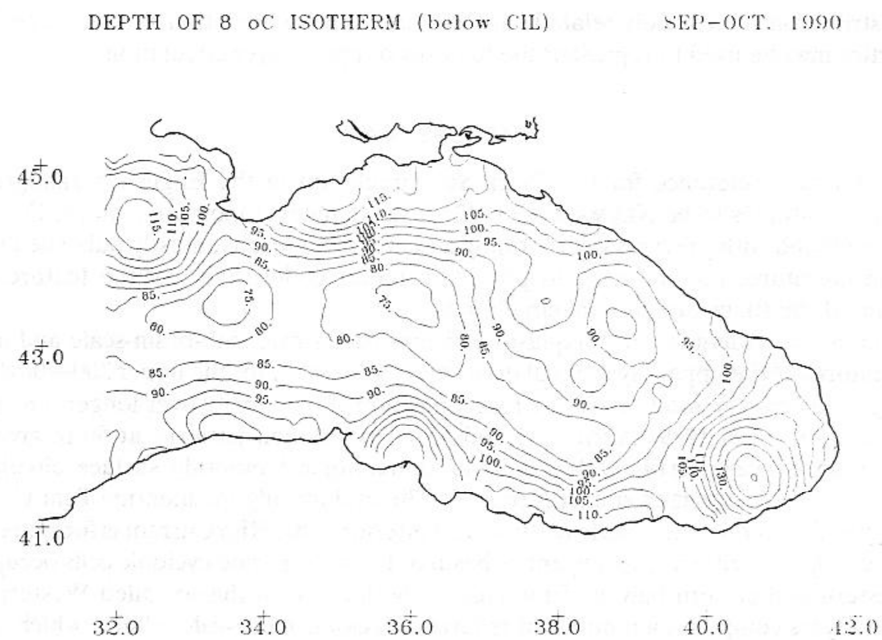

Fig. 10. Horizontal distribution of objectively mapped 8°C isotherm depth (below CIL) for the SO90 survey. Contour interval is 5 m.

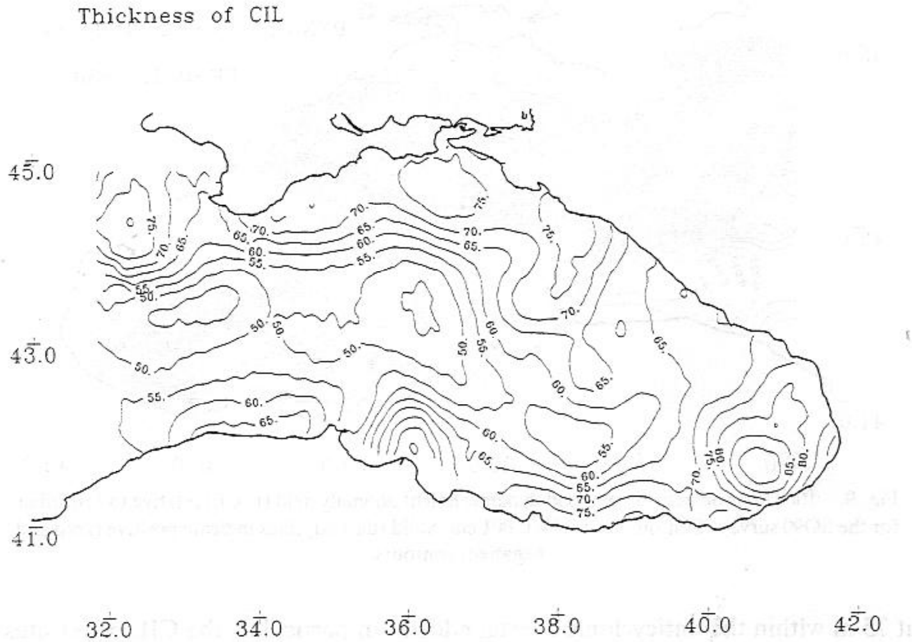

Fig. 11. Horizontal distribution of objectively mapped CIL thickness for the SO90 survey. Contour interval is 5 m.

CIL distribution is intimately related with the upper layer circulation dynamics, and CIL properties may be used to represent the features of upper layer circulation.

DISCUSSION

The standard reference for the Black Sea circulation in the English oceanographic literature continues to be Neumann's (1942, 1943) dynamic topography maps. Our data when combined with previous hydrography and modeling results, mostly published in the Russian literature, may be used to provide a more modern view of the features and structure of the Black Sea general circulation.

Available data identify certain quasi-persistent basin-scale, sub-basin-scale and meso-scale features of the upper layer circulation (more generally, for the upper 300–400 dbar), although they may be modified in their size, position and intensity over longer timescales [e.g. compare April 1979, April 1981, July 1983 circulation patterns at 50 m given by Faschuk and Ayzatullin (1986) and the climatological monthly surface circulation patterns given by Eremeev *et al.* (in press)]. The cyclonically meandering Rim Current constitutes the unique basin-scale feature. The interior of the Rim Current is formed either by one elongated cell covering the entire basin or by two separate cyclonic cells occupying the western and eastern halves of the basin. The interior of the so-called Western and Eastern Gyres comprises a number of recurrent cyclonic mesoscale eddies, which are in contact with each other by a recurrent anticyclonic mesoscale eddy, called here Central Basin Eddy. While the classical surface dynamic topography map provided by Neumann

(1942) is an example for the dual dome circulation, our present data provide an example of single cell circulation embodying a number of mesoscale cyclonic cells.

A mechanism for the formation of the Central Basin Anticyclonic Eddy was described by LATUN (1990) and GOBULEV and TUZHILKIN (1990). Monthly hydrographic observations in June–September 1984 indicated that this eddy evolved by the merging of two anticyclonic eddies pinched off from the baroclinically unstable meandering Rim Current southeast of Crimea and off Cape Sinop. After the eddy formed in early August 1984, it was trapped between the Eastern and Western Gyres and persisted throughout the period of observation. This feature evidently is a recurrent one, as it was also noted during the subsequent survey in March 1985. Recurrency of this eddy was further apparent from the climatological monthly average surface circulation maps provided by EREMEEV *et al.* (1991).

In addition to these features, the upper layer flow field consists of mesoscale eddies distributed along the periphery of the basin. Two most pronounced and persistent eddies are the Batumi Eddy in the southeastern corner of the basin and the Sevastopol Eddy in the relatively smooth continental slope topography of the Danube Fan, west of the Crimean Peninsula. These relatively larger features were reported by numerous hydrographic observations (e.g. NEUMANN, 1942; SOROKIN, 1983; FASCHUK and AYZATULLIN, 1986; NOVSELOV, 1976; ZATS and FINENKO, 1988; LATUN, 1990; EREMEEV *et al.*, 1991) and reproduced in the numerical modeling studies by MOSKALENKO (1976), GAMSAKHURDIYA and SARKISYAN (1976), STANEV (1989, 1990) and BULGAKOV and KOROTAEV (1987). PANOV and CHASHCHIN (1990) noted the persistency of the Batumi Eddy in monthly surveys during the second half of 1985. The coastal anticyclonic feature, identified as the Trabzon Eddy in OGUZ *et al.* (1992), was apparently a part of the Batumi Eddy.

Along the Anatolian (Turkish) coastal belt, two other quasi-permanent anticyclonic eddies are situated off the Sakarya and Kizilirmak Rivers. These eddies, first identified by the fine-resolution hydrographic observations from the R.V. *Bilim* (OGUZ *et al.*, 1991, 1992), are related to the regional topography. Another apparently quasi-permanent, coastally-attached anticyclonic eddy is situated northwest of the Bosphorus–Black Sea junction (OGUZ *et al.*, 1991, 1992; OGUZ and ROZMAN, 1991; TRUKHCHEV *et al.*, 1985). Existing data indicate one or two more recurrent coastal anticyclonic eddies in the region between Sakarya Canyon and Cape Sinop (e.g. OGUZ *et al.*, 1992). Anticyclonic eddies along the Anatolian coast also were reproduced in diagnostic numerical modeling studies (e.g. BULGAKOV and KOROTAEV, 1987).

Along the northern coast of the Black Sea, the so-called Crimean and Caucasian Eddies emerge as the most pronounced quasi-permanent features of the upper layer Black Sea circulation. The offshore protrusion of the meandering Rim Current along the Caucasian coast (Figs 2, 3 and 6) appears to be a common feature of the region and is seen in some monthly climatological circulation maps (e.g. EREMEEV *et al.*, in press) and AVHRR satellite imagery. Another apparently recurrent anticyclonic feature is situated adjacent to the western coast of the basin, to the north of the Bosphorous Eddy. Observed frequently by Bulgarian oceanographers (e.g. STANEV *et al.*, 1984), we call it the Kali-Akra Eddy. These quasi-permanent and/or recurrent features of the upper layer circulation are schematically shown in Fig. 12.

The knowledge of the flow field at deeper levels (below 300–400 dbar), on the other hand, is extremely limited and generally unreliable (cf. STANEV, 1989). Basic circulation patterns have been reported to remain cyclonic at deeper levels except locally where deep counter-currents might be developed near the bottom (see e.g. BOGUSLAVSKIY *et al.*, 1976;

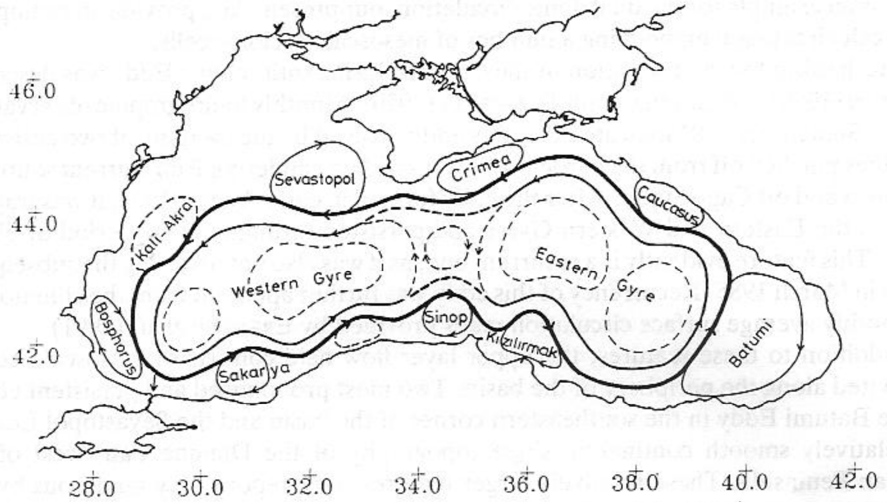

Fig. 12. Schematic of the main features of the upper layer general circulation emerging from synthesis of past studies and the SO90 survey. Solid (dashed) lines indicate quasi-permanent (recurrent) features of the general circulation.

GAMSAKHURDIYA and SARKISYAN, 1976; BLATOV *et al.*, 1984). Contrary to these earlier findings, the SO90 shows that the position and structure of the eddies and currents change towards deeper levels, although the currents are very weak, with an average speed of about 2 cm s^{-1} between 500 and 1000 dbar. The intermediate depth circulation (shown here by the 500, 750 and 1000 dbar dynamic topography maps) are characterized by disappearance of the Rim Current, shift of eddy centers, coalescence of eddies, persistence of some features for the whole water column but changes with depth in the structure for others, and more organized and larger sub-basin features. Further details of the intermediate depth circulations awaits additional collaborative field surveys similar to the SO90.

The features discussed above reflect the effect of multiple and variable forcings and modifications introduced by internal dynamic processes on the basin circulation. The high resolution of the SO90 data should provide a unique opportunity to initiate extensive dynamic studies to assess the relative contributions of the forcing fields and to carry out dynamic process and data assimilation studies.

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