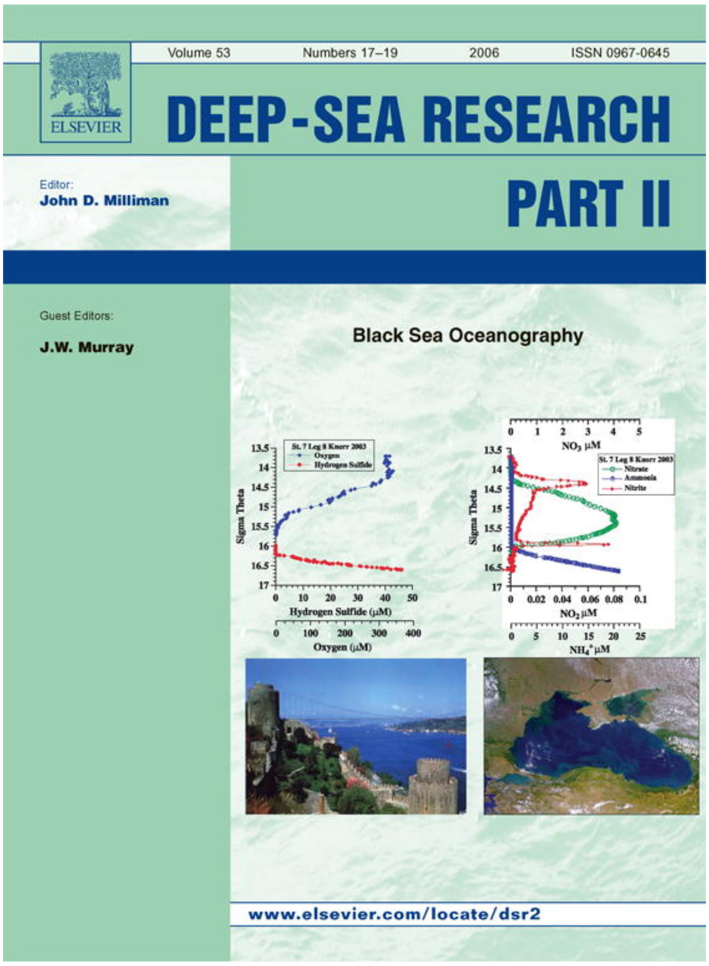
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Intermediate and deep currents of the Black Sea obtained from autonomous profiling floats

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Abstract

Float trajectories observed at three depths (200, 750 and 1550 m) in the Black Sea during a 1.5-yr period offer new insights on the circulation below the permanent pycnocline. The float observations for the first time provided direct, quantitative evidence for strong currents and a well-organized flow structure at intermediate and deep layers, in contrast to prior ideas of a rather sluggish deep circulation of the Black Sea. The magnitudes of intermediate and deep currents are typically about 5–10% of the surface currents, reaching as much as 5 cm s^{-1} at 1550 m, adjacent to the steep topographic slope on the periphery. The combination of float and sea-level height altimeter data suggests that a well-defined cyclonic circulation extends from the surface to the bottom, without reversal in its direction. Deep currents are steered by the steep topographic slope, and well correlated with surface currents at seasonal and longer time scales.

Keywords: Black sea; Profiling floats; Deep currents; Mesoscale activity; Topographic control

1. Introduction

Albeit the physical structure of the Black Sea has been intensively observed for the last two decades, an overwhelming majority of hydrographic measurements have been conducted within the uppermost 500 m due to the weak stratification in the lower ~1500 m of the water column. Geostrophic current estimates, together with the satellite data, suggested a highly dynamic upper layer circulation structure prevailing throughout the year above the permanent pycnocline located around 100–200 m depth (Oguz et al., 1992, 1993, 1994, 1998; Sur et al., 1994, 1996; Sur and Ilyin, 1997; Oguz and Besiktepe, 1999; Gawarkiewicz et al., 1999; Ginsburg et al., 2000, 2002a, b; Sokolova et al., 2001; Afanasyev et al., 2002; Korotaev et al., 2001, 2003; Zatsepin et al., 2003). The building block of this circulation system involves a basin-wide cyclonic circulation cell, encircled by the Rim Current jet stream, and a wealth of anticyclonic and cyclonic eddies located on its coastal and interior sides, respectively. The cyclonic circulation is primarily driven by the quasi-permanent positive wind-stress curl field intensifying in winter and weakening in summer months, and is further supported by the

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buoyancy contrast between the fresh-water inflow from rivers around the basin and the salt-water supply through the Bosphorus Strait (Whitehead 1998; Korotaev et al., 2001). The entire system further evolves continuously at shorter, daily-to-seasonal time scales under high-frequency component of external forcing and internal dynamics. Direct observations based on surface buoys (Eremeev et al., 2003; Zhurbas et al., 2004; Poulain et al., 2005) and ADCP measurements (Oguz and Besiktepe, 1999) within the upper 100 m have indicated current speeds of about 40–50 cm s^{-1}, occasionally increasing up to 100 cm s^{-1} along the main axis of the Rim Current jet.

The deep-layer circulation and thermohaline structure have been traditionally accepted to be sluggish and rather invariant at seasonal-to-interannual scales. The R/V *Knorr* 1988 Expedition and the multi-ship hydrographic surveys carried out within the framework of the HydroBlack and ComsBlack Programs during the early 1990s constituted the first reliable data sets for exploring deep-water physical characteristics of the Black Sea (Murray et al., 1991; Oguz et al., 1993, 1994, 1998). One of the most important findings of these studies was an indication of horizontally as well as vertically highly structured flow systems formed by a series of large mesoscale eddies (with typical size of about 100 km) and sub-basin-scale gyres (with typical size of several hundreds of km's) within the intermediate layer between 300 and 1000 m. These observations provided only the baroclinic component of the circulation, however, they underestimated the intensity and additional contribution of the barotropic structure of the flow field, particularly along the strong topographic slope zone around the periphery of the basin. While valuable for describing in a qualitative sense large-scale basinwide circulation of the intermediate and deep layers, the geostrophic method applied to hydrographic observations was often unsatisfactory because of the questionable "level of no motion" assumption. The strength of the intermediate layer flow was partly elucidated by the ADCP absolute current velocity measurements carried out during April 1993 in the western Black Sea. These measurements reported for the first time relatively strong sub-pycnocline currents up to 10–20 cm s^{-1} within the 200–350 m layer (Oguz and Besiktepe, 1999), the latter depth being the approximate limit of the ADCP measurements.

Following the pioneering development by John Swallow in the 1950s, neutrally buoyant floats have been a central element of global ocean circulation observations with highly temporal and spatial resolution (Gould, 2005). By late 2004, over 1500 neutrally buoyant floats were drifting at depth throughout the global ocean, and this number is expected to double by 2007. They already have provided valuable contributions to our understanding of deep ocean's mesoscale structure and variability, such as in the California Current system (Kelly et al., 1998), the Japan Sea (Yanagimoto and Taira, 2003), the North Atlantic Ocean (Zhang et al., 2001; Bower et al., 2002; Lavender et al., 2005), the Brazil Basin of the South Atlantic Ocean (Hogg and Owens, 1999), the Labrador Sea (Steffen and D'asaro, 2002), the tropical and South Pacific (Davis, 1998). Neutrally buoyant floats are also considered an important element of operational oceanography for making more realistic and improved predictions of ocean currents and thermohaline properties, when their products are combined with remote sensing and other in situ data sets (Global Ocean Data Assimilation Experiment Strategic Plan, 2001; Guinehut et al., 2004).

As a pilot project of the Black Sea GOOS Program, a total of 55 satellite-tracked drifters were deployed at 15 m depth in the Black Sea at different periods of the program during 1999–2003 (Eremeev et al., 2003; Zhurbas et al., 2004; Poulain et al., 2005). The drifter trajectories confirmed the prevalence of the Rim Current trapped along the periphery of the basin, where sub-inertial speeds can reach 1 m s^{-1}. Meanders and loops in the tracks proved the existence of mostly anticyclonic features inshore of the Rim Current. They also revealed the presence of cyclonic and anticyclonic currents in most areas of the Black Sea. Pseudo-Eulerian statistics (mean currents and velocity variances) showed a strong and highly fluctuating signature of the Rim Current, and the enhanced variability associated with the Batumi and Sevastopol eddies. The Rim Current tended to form a stronger single loop trapped on the continental slope in winter/spring, whereas in summer/fall the mean circulation was more meandering and recirculation cells appeared in the central areas. In the Batumi eddy region, the currents changed from mainly anticyclonic in summer/fall to cyclonic in winter/spring. These surface drifter observations were in close agreement with those deduced from the satellite altimeter data (Korotaev et al., 2001, 2003).

The recent US–Turkish–Ukranian collaboration between the US Office of Naval Research, School of

Oceanography—University of Washington, Institute of Marine Sciences—Middle East Technical University, and Marine Hydrophysical Institute—Ukranian Academy of Sciences has led to a new opportunity to explore further the sub-pycnocline characteristics of the flow field by means of three autonomous profiling floats. In contribution to our ongoing efforts towards the development of an operational oceanographic system within the framework of the Black Sea GOOS Program, the primary goals of this project are to enhance the capability for near-real-time temperature and salinity measurements within the entire water column, and to promote a better understanding of the intermediate and deep circulation and water mass characteristics at seasonal and longer time scales.

2. Methodology

Three profiling floats, assembled by the School of Oceanography—University of Washington, were deployed from the R.V Bilim on 2 September 2002 in the southwestern Black Sea, approximately 180 km offshore of the Bosphorus Strait. Two of the floats were released at parking depths of 1550 and 200 m at the 42.25°N and 30.34°E position, which lies roughly inside the cyclonic gyre of the western basin as inferred by the altimeter sea-level data. The third float was deployed at a parking depth of 750 m at the 41.83°N and 29.83°E position, which is slightly closer to the coast along the main axis of the Rim Current system. The floats were programmed to drift for a week at the parking depth and to continue to measure temperature and salinity at 58 vertical levels as they rose from 1550 m to the sea surface. The floats parked at the shallower depth of 200 m first descend to a sampling depth of 1550 m before rising to the surface. Upon reaching the sea surface the floats transmit the data to orbiting satellites via the ARGOS system within a period of 8–12 h. The floats then repeat the same observation cycle. The accuracy of the temperature, salinity and pressure sensors is typically better than 0.005 °C, 0.01, and 5 m (The ARGO Science Team, 2000). The temperature and salinity profiles together with float trajectories are documented in near-real time mode at the URL site http://flux.ocean.washington.edu/metu. The currents were estimated by dividing float displacement by the time elapsed between their movement after they sink to their parking depth and their next surfacing. Float trajectories (Figs. 1–3) are possibly subject to some estimation errors as they are periodically modified by the surface transport during their 8–12-h surface periods once every week.

The interpretation of float trajectories is further complemented by the horizontal circulation maps derived from the analysis of altimeter data provided at the URL site http://las.aviso.oceanobs.com/las/servlets/dataset. The original data set comprises weekly global merged products of several satellites such as GFO, Topex/Poseidon (or Jason-1), and ERS-2 (or Envisat) at 1/3° resolution. The data ware first extracted for the Black Sea region, then optimally interpolated to 0.1° square grid, and then superimposed on the mean sea-level height field

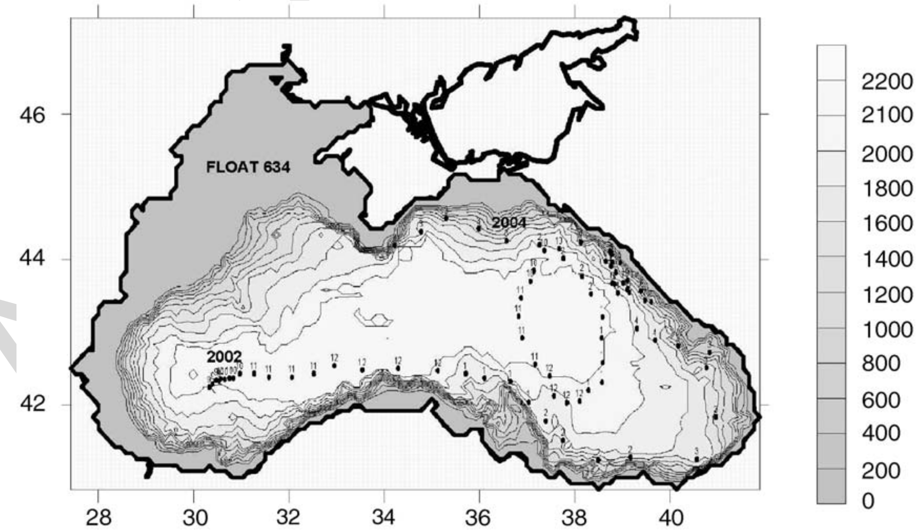

Fig. 1. Trajectory of the profiling float BS634 at 200 m parking depth. The dots and numbers represent the position of the float during a particular month.

deduced from the climatological hydrographic data (Korotaev et al., 2003) to produce a series of weekly average sea-level height maps at selected times of the observation period (Fig. 4A–H).

3. Float trajectories and variations of current velocity

3.1. Trajectories at 200 m depth

Soon after deployment, all three floats drifted eastward almost parallel to the coast by the peripheral current system (Figs. 1–3). During the first 2 months, the float BS634 at 200 m first moved very slowly eastward (~1 cm s^{-1}), suggesting entrapment at the center of the western cyclonic gyre. Upon approaching the Anatolian coast and encountering the Rim Current by mid-November the speed of translation of the float first increased to about 5 cm s^{-1} (Fig. 5A), then to 10 cm s^{-1} during December–January and to 15 cm s^{-1} during February–March. As drifting eastward from its initial position of deployment, the float BS634 gradually approached the southern coast and finally resided on the topographic slope zone where the main jet axis of the Rim Current is situated. A coherent Rim Current system, known to be a robust feature of the Black Sea upper-layer circulation in winter (Figs. 4A, B), is therefore confirmed at a depth of 200 m.

The float BS634 continued to drift along the topographic slope zone around the southeastern corner of the basin during the latter part of winter, suggesting the absence of the Batumi gyre during the winter months of the observation period. The absence of the Batumi gyre during the winter 2003 period is also noted in the sea-level height maps shown in Figs. 4A, and B. Its formation in spring, development to a mature state later in summer months, and finally disintegration and disappearance in autumn and winter, respectively, have been reported by Korotaev et al. (2003) using approximately 7 years of altimeter data (1993–1999) assimilated into a circulation model. A further confirmation on similar evolutionary characteristics of the Batumi eddy is provided by the surface float observations performed during the 1999–2003 period (Poulain et al., 2005).

In April–May 2003, as the float moved along the northeastern (Caucasian) coast, it was trapped within an anticyclonic eddy for almost 3 months until the end of July, possibly the same one confirmed by altimetry (Fig. 4C), known to be the quasi-persistent Caucasian eddy of the circulation system during spring and summer months (Korotaev et al., 2002, 2003). The anticyclonic rotation of the float within the Caucasian eddy is further supported by the changes in both magnitude and direction of the current components in the later part of Fig. 5A. Following disintegration of the Caucasian eddy, the float continued drifting northwestward along the coast in August 2003. It was once again entrapped by the weak anticyclonic Kerch eddy (Fig. 4D), and then proceeded its movement along the Rim Current jet of the northeastern coast in September 2003.

The float BS634 was eventually diverted south in October 2003 to move along the western flank of a

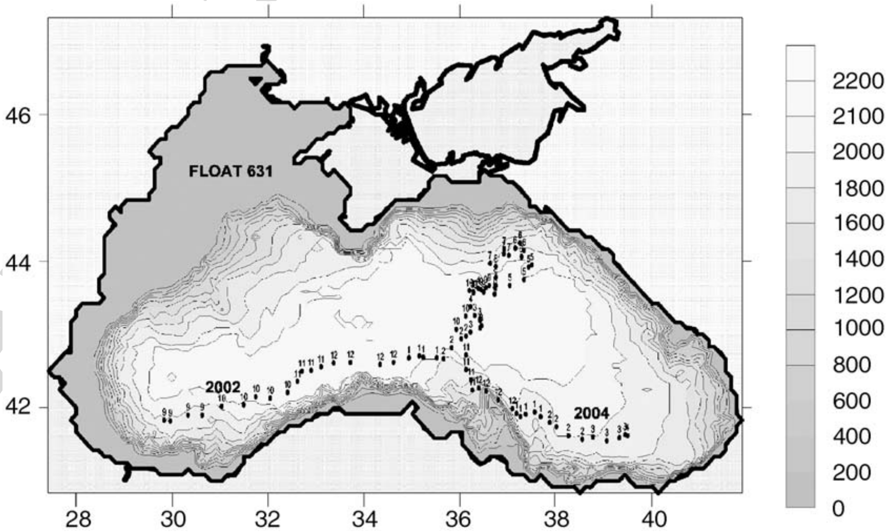

Fig. 2. Trajectory of the profiling float BS631 at 750 m parking depth. The dots and numbers represent the position of the float during a particular month.

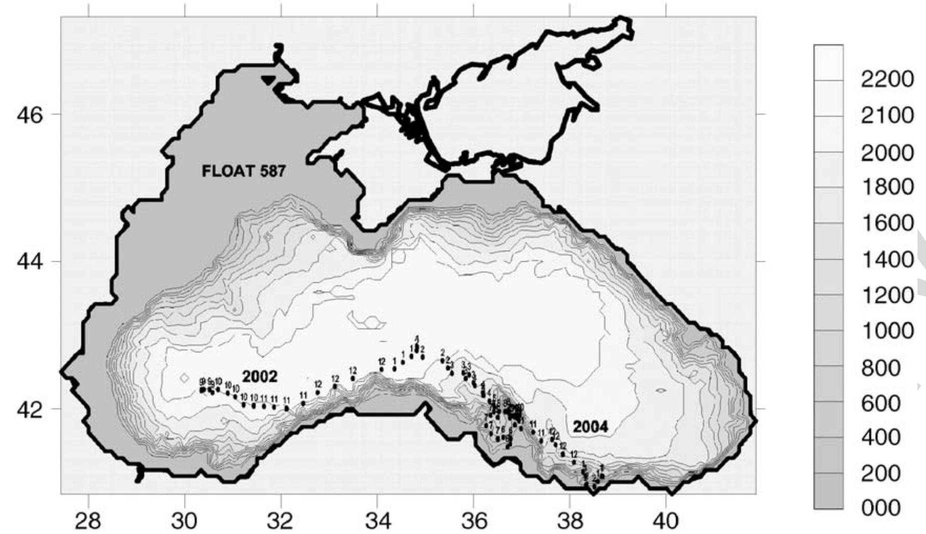

Fig. 3. Trajectory of the profiling float BS587 at 1550 m parking depth. The dots and numbers represent the position of the float during a particular month.

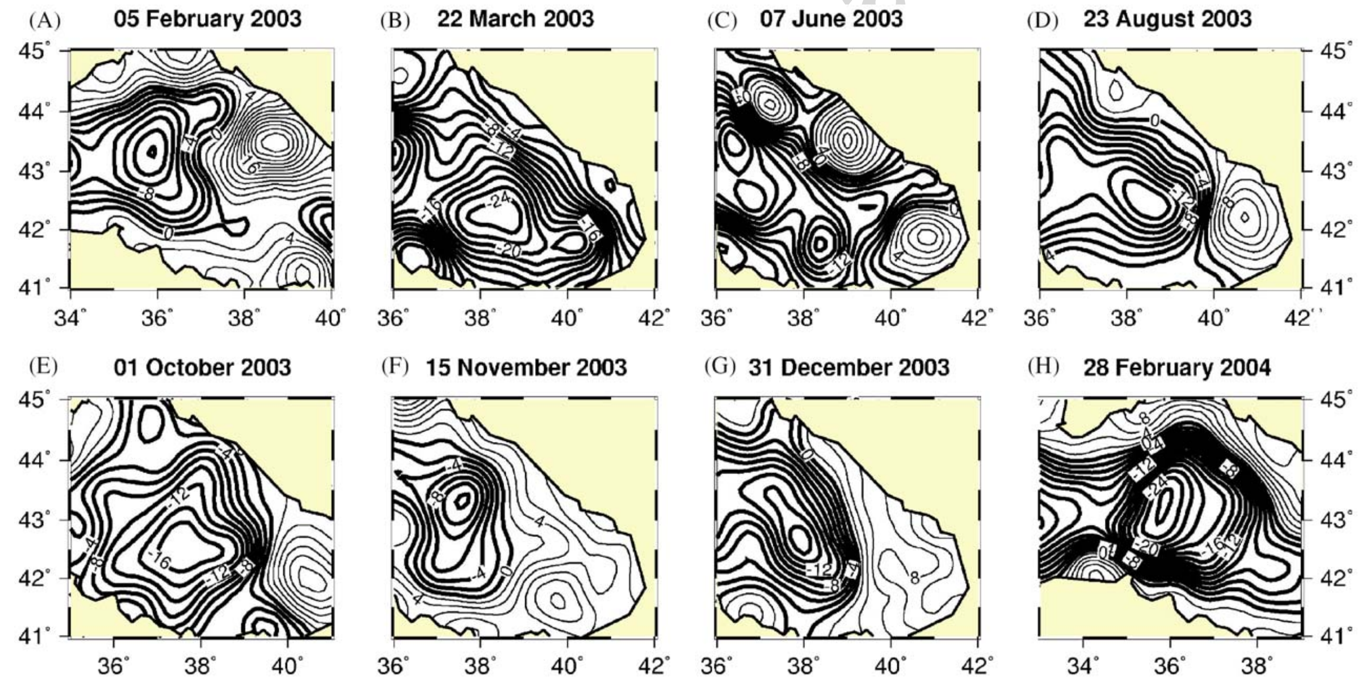

Fig. 4. Sea-level anomaly maps obtained by merging of various altimeter data during (A) 05 February 2003, (B) 22 March 2003, (C) 07 June 2003, (D) 23 August 2003, (E) 01 October 2003, (F) 15 November 2003, (G) 31 December 2003 and (H) 28 February 2004. Negative contours are shown by thick lines and represent cyclonic circulation and positive contours by thin lines representing anticyclonic features.

cyclonic eddy of the eastern interior basin (Fig. 4E). The float continued to move first southward along the periphery of the gyre in November and December 2003 (Fig. 4F, G), and then turned northward along its eastern flank during January-February 2004 (Fig. 4H). Upon reaching the northern coast, it continued to travel west along the periphery of the cyclonic gyre towards the Crimean coast (Fig. 4H). Excluding approximately 5 months of entrapment in the Caucasian and Kerch anticyclones and the eastern basin interior cyclone, the float accomplished its approximately 2000-km route along the periphery of the basin from its deployment site near the Bosphorus Strait to the tip

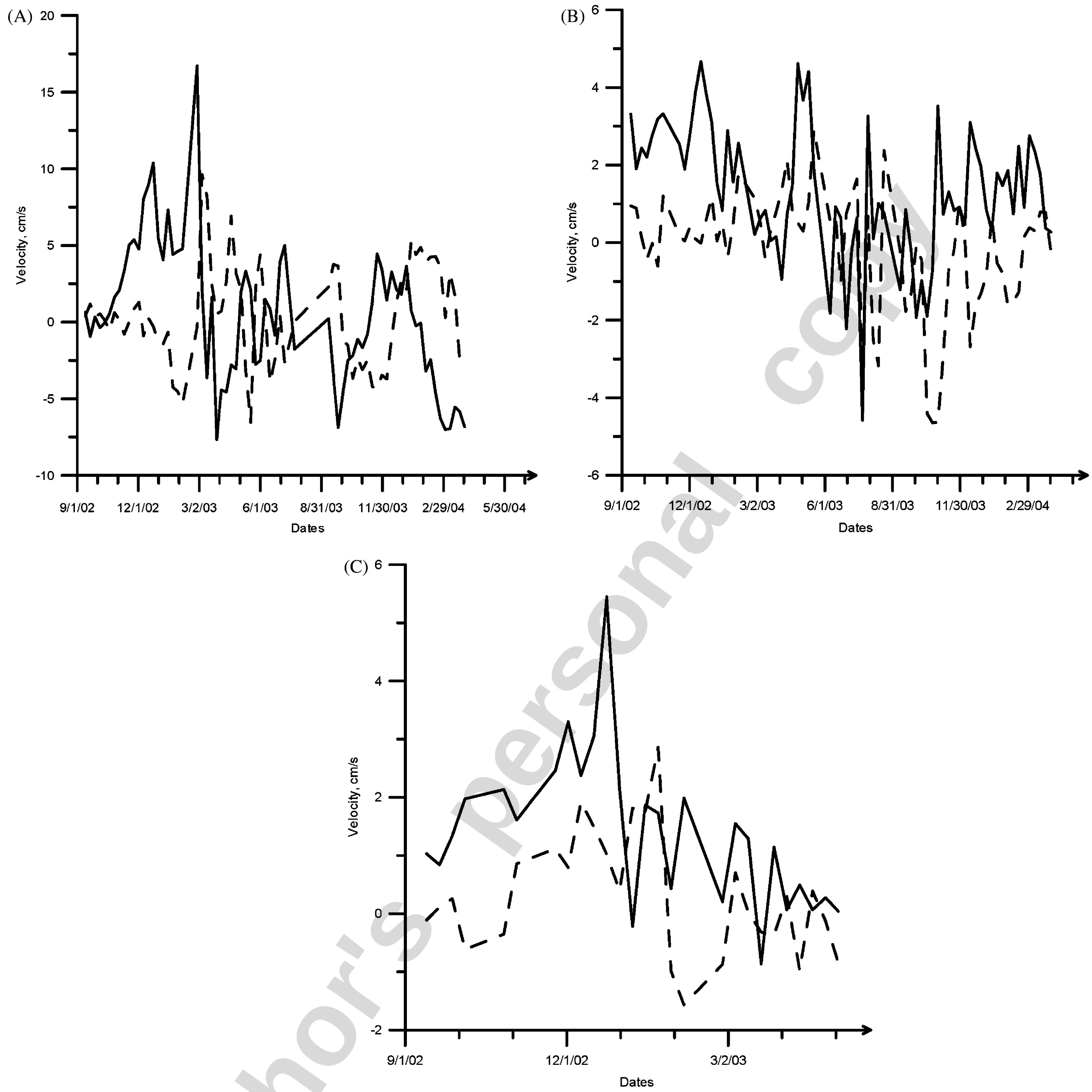

Fig. 5. Temporal evolution of the velocity components at the depth (A) 200 m, (B) 750 m and (C) 1550 m. Solid line represents the zonal component, and the dash line represents the meridional component.

of the Crimean Peninsula within about 300 days. This implies an average speed of the Rim Current about 7 cm s^{-1} at 200 m.

3.2. Trajectories at 750 m depth

The float BS631, drifting at 750 m, followed a very similar route along the southern coast (Fig. 2), and reached the vicinity of Cape Sinop in January 2003 with 1-month delay with respect to float BS634. The average speed of its translation was around 2–4 cm s^{-1} with a maximum value of about 4.5 cm s^{-1} during December 2002 (Fig. 5B). Afterwards, it experienced a different route, and instead of continuing to move along the southern coast of the eastern basin it was deflected towards north into the basin's interior during February 2003. As suggested by the altimeter data (Fig. 4A), the deflection seems to be caused by the local current system comprising the western flank of the anticyclonic eddy in the north and eastern flank of the cyclonic eddy in the south. This system apparently blocked eastward penetration of the intermediate depth currents along the southern coast between 36° and 37°E longitudes. Once the float entered into the interior, it moved slowly to the northeast over the next 3 months. The slow movement on the order of $1\,cm\,s^{-1}$ (Fig. 5B) was caused primarily due to frequent diversions of its excursion by eddy activity in the region, rather than weakness of the currents. Towards the end of May 2003, the float reached the northeastern coast, and was entrained into the Kerch anticyclonic eddy for the next 2 months (Fig. 4C). By the end of August, as the Kerch eddy was disintegrated and the region was replaced by a system of cyclonic eddies (Fig. 4D), the float started drifting southwest into the interior basin once again at a maximum speed of $5\,cm\,s^{-1}$ (Fig. 4E, F), and in mid-November 2003 returned almost to the same position it held previously in February 2003. At the end of November 2003, the float was re-captured by the Rim Current system (Fig. 4H), and it started to move eastward along the Turkish coast at an approximate speed of $3–5\,cm\,s^{-1}$ (Fig. 5B). The float took about 310 days to reach its last position at 39.5° E in April 2004, excluding time spent for its northeast and southwest excursions within the interior of the basin. We recall that the float BS634 at the parking depth of 200 m required only 170 days to travel the same distance, or to cover a distance almost twice as long during the same time period. The average speed of the Rim Current at 750 m is then estimated as $\sim 4.0\,cm\,s^{-1}$, which roughly corresponds to about half the speed at 200 m.

3.3. Trajectories at 1550 m depth

Float BS587, launched at the parking depth of 1550 m at the same site with float BS634, first drifted towards the coast at a rate of $2\,cm\,s^{-1}$ (Fig. 5C) during its first 2 months. Later it moved eastward along the coast by the Rim Current, gradually increasing its speed to $5\,cm\,s^{-1}$, and reaching Cape Sinop in mid-February 2003 (Fig. 3). The time elapsed to reach Cape Sinop from the deployment site is almost the same as float BS631 at 750 m, indicating similar current speeds of the boundary flow system at intermediate and deep layers. On the eastern side of Cape Sinop, the float translation speed gradually decreased to $1\,cm\,s^{-1}$ during the subsequent 3 months, prior to entrapment by the quasi-permanent Kizilirmak anticyclonic eddy, which is a coastal feature situated over a complicated small canyon and ridge-type topographic features along the Turkish coast between 36°E and 37°E longitudes (Fig. 3). Starting in June 2003, it underwent an anticyclonic loop within the eddy until the end of September 2003. When the float approached the coast at depths shallower than 1550 m, it resided on the bottom and was able to move only once a week when it came to the surface. Leaving the Kizilirmak eddy by November 2003, the float continued to move along the coast further eastward and was captured by another small-scale coastal anticyclone between roughly 38°E and 39°E longitudes in winter 2004.

The topographic control of deep currents is shown remarkably well by the float trajectories in Fig. 3. The float, which was deployed at a site having a total depth of 2200 m, immediately started to move along this isobath up to 34°E longitude, and was then deflected offshore by the cyclonic motion at the mid-basin section. The float was then subject to cross-isobath flow after its brief excursion into the interior of the basin. Once it arrived at the Kizilirmak anticyclonic eddy, strong topographical control became effective as noted by the anticyclonic loop within the canyon structure and strong currents further downstream along the eastern side of the ridge. The strong deep current has been explained by Korotaev (2005) to be a result of the resonant intensification of deep currents due to closed potential vorticity contours, as noted by the topographic structure in Fig. 3.

3.4. Estimation of surface current speed by floats

Since the floats spent 8–12 h on the surface once per week, it is possible to infer temporal evolution of surface currents with respect to those at deeper levels. The scatter plots (Fig. 6A, B) suggest strong correlation between zonal and meridional components of currents at the surface and 200 m depth. The former is roughly eight times more intense than that on 200 m, and reach occasionally up to $40\,cm\,s^{-1}$. Time evolution of the current components (Fig. 7A, B) indicates high correlations for all resolved time scales (i.e., greater than a week), therefore suggesting vertically uniform current

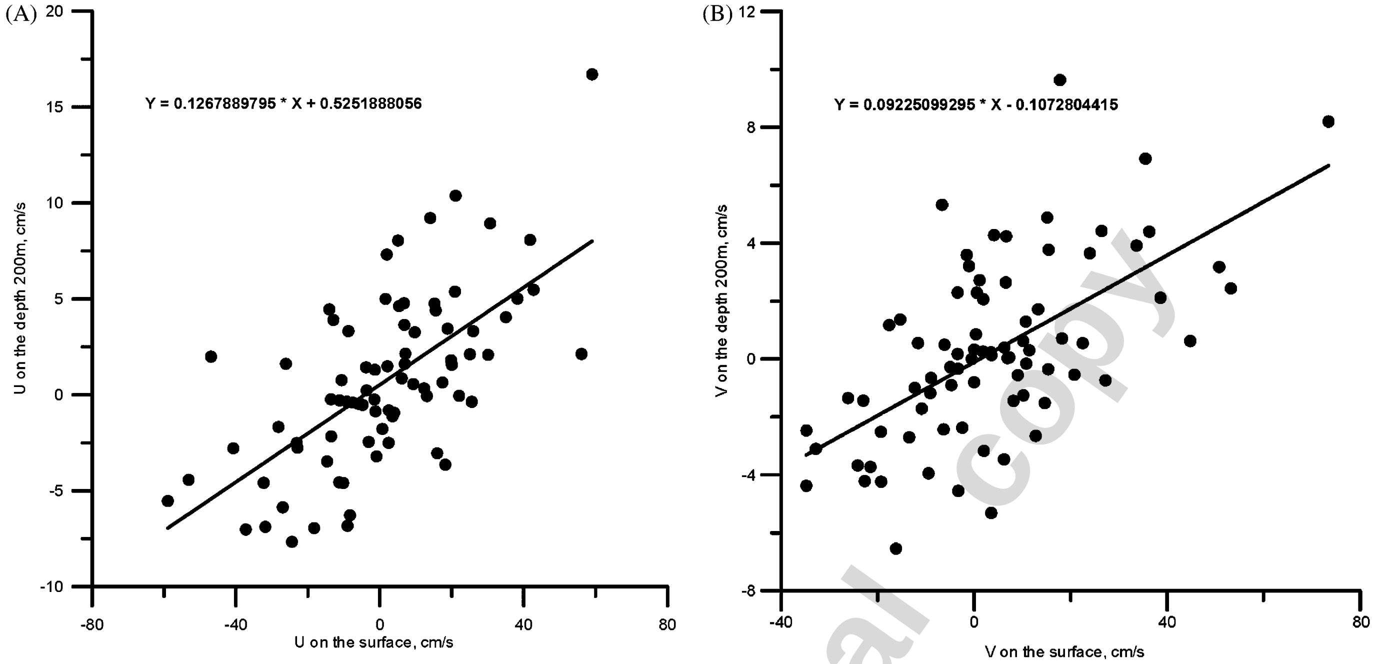

Fig. 6. The scatter plot of the surface velocity and the velocity on the depth 200 m for the (A) zonal component and (B) meridional component.

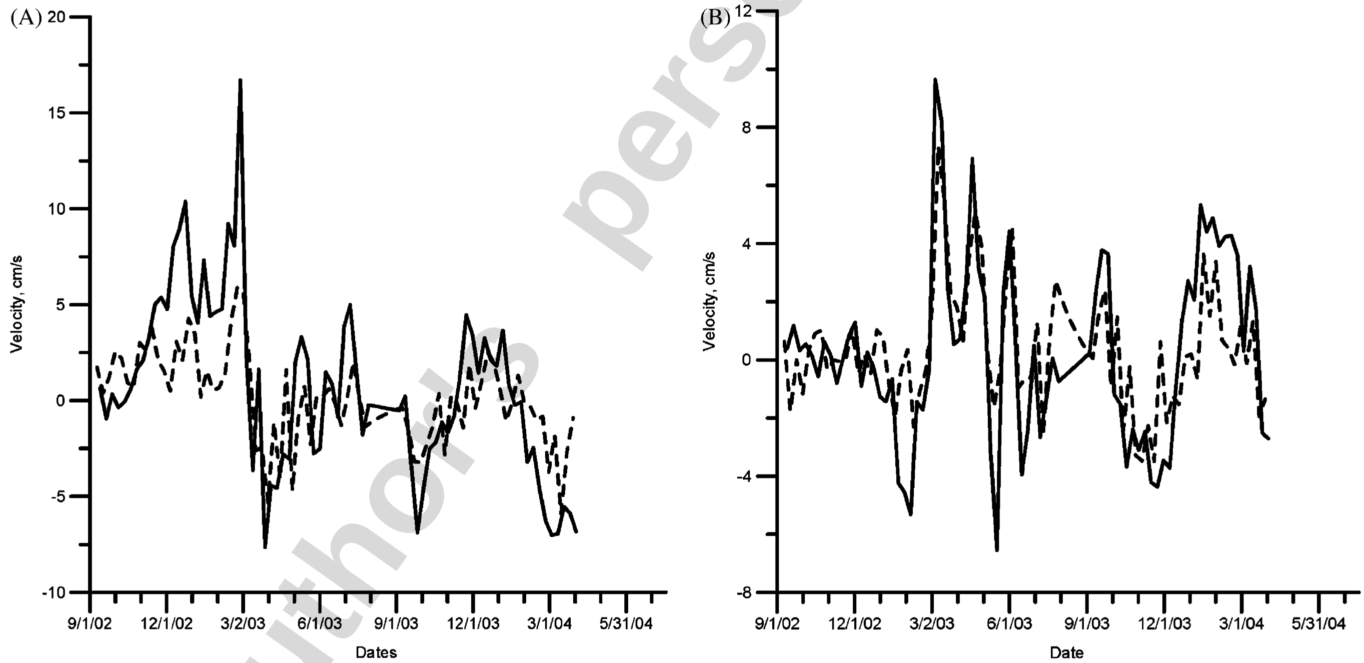

Fig. 7. Temporal evolution of the currents at the surface (dash line) and at the depth of 200 m (solid line) along the trajectory of the float number 634 for the (A) zonal component and (B) meridional component. The surface velocity is divided by a factor of 10.

structure within the upper 200 m. In other words, the current structure at 200 m depth reflects main characteristics of the upper-layer circulation system. However, good correlation between currents at the surface and deeper levels holds only at low frequencies (at seasonal and longer time scales). The scaling coefficients between the surface and intermediate (750 m) and deep (1550 m) layers are, respectively, 0.06 for the zonal flow and 0.045 for the meridional flow.

4. Conclusions

Three autonomous profiling floats deployed into the pycnocline layer at 200 m, intermediate layer at 750 m and deep layer at 1550 m provide new information about the strength and variability of the flow field during an 18 month period. The data suggested the active role of mesoscale features on the basin-wide circulation system at 200 m, similar to the case observed in the upper layer (<100 m) circulation system. The currents reach a maximum intensity of 15 cm s^{-1} along the Rim Current jet around the basin, which is consistent with the findings of ADCP measurements. The floats at the intermediate (750 m) and deep (1550 m) layers also reflect the role of mesoscale eddies on the flow field, with maximum currents of about 5 cm s^{-1}. The deep layer currents are found to flow along the strong topographic slope following constant potential vorticity isolines, and points to the importance of topographic β-effect on the Black Sea circulation system. The orientation of the currents is cyclonic at all depths, and no flow reversals and circulation cells in the opposite directions are noted in the data. The vertical uniformity of the flow direction throughout the basin further demonstrates the minor role of the Bosphorus underflow in driving anticyclonic basinwide circulation system (i.e. in opposite direction to the surface circulation) in the deep layer as suggested by laboratory experiments on buoyant plumes (Whitehead et al., 1998). The main driving force is the wind stress, which can introduce a barotropic flow on the order of 5 cm s^{-1}, as also suggested by numerical modeling studies (Stanev, 1990; Oguz et al., 1995; Stanev and Beckers, 1999). These findings allow a new perception of highly dynamic intermediate-deep layer circulation, contrary to the traditional belief of an almost inert circulation system.

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