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Abstract: The surface circulation of the Marmara Sea was studied with satellite-tracked drifters during 2 field experiments. A total of 29 drifters were released in September 2008 and February 2009 at key locations south of the Bosphorus and in the central part of the sea. The spatial structures and temporal variability are described together with the atmospheric conditions of the Marmara Sea during the period of study. The behavior of drifters with respect to the wind was qualitatively analyzed. The pseudo-Eulerian velocity statistics were computed from the interpolated positions and maps of the mean currents were produced using the data sorted by experiment. The results are the first of their kind in the area and complement previous findings obtained by means of hydrographic and ADCP measurements. The overall surface flow is westward oriented from the Bosphorus Strait to the Dardanelles Strait. A jet-like flow that enters the Marmara Sea from the Bosphorus Strait and, meandering, crosses the sea prevailed during the entire study period. The surface circulation of the Marmara Sea is quite complex and displays very high variability. For example, the drifter data reveal that during the study period the mean flow was confined immediately north of Marmara Island in the western part of the sea. This was due to the presence of a large anticyclone in the northwestern area of the sea that had never been observed before. Additionally, sudden reversals and a complex eddy activity (mainly anticyclonic) were observed. Wind plays an important role in the surface circulation. The upper layer currents seem to respond very rapidly to the direct and indirect effect of the wind forcing.

Key words: Surface circulation, Marmara Sea, drifters, mean flow, variability

1. Introduction

The Marmara Sea is a small continental sea located between the Aegean Sea and the Black Sea, connected to these seas by the Dardanelles Strait (Çanakkale Boğazı) and the Bosphorus Strait (İstanbul Boğazı), respectively (Figure 1). The Marmara Sea together with the above-mentioned straits constitutes the Turkish straits system (TSS) that extends over a distance of approximately 300 km. The topography of the Marmara Sea is complex and characterized by 3 subbasins, oriented in the east-west direction. Each subbasin is deeper than 1000 m and is separated by deep sills (about 750 m). The Marmara Sea is connected to the straits through canyons. Both straits are narrow, long, and shallow (Dardanelles: average depth = 55 m, length = 60 km, and width = 4 km; Bosphorus: average depth = 36 m, length = 31 km, and width = 1.5 km).

The TSS flow is mainly driven by the sea level differences between the Black Sea and the Aegean (Beşiktepe et al. 1994). The Black Sea water enters the Marmara Sea through the Bosphorus Strait as an upper

flow (thickness about 25 m) and exits via the Dardanelles Strait. Likewise, the Mediterranean (Aegean) water enters through the Dardanelles Strait as a lower layer flow and exits to the Black Sea through the Bosphorus Strait.

There is a pronounced sea-level difference along the TSS. The mean sea level of the Black Sea is about 55 cm higher than the Aegean Sea, but the slope along the TSS is not linear and can display reversals associated with wind perturbations (Alpar & Yüce 1998).

Local tidal forcing has little effect on the sea level of the Marmara Sea and is masked by fluctuations caused by the wind forcing. Additionally, this sea is not affected by the tidal oscillation of the neighboring seas because of the narrowness of the straits (Yüce 1993; Alpar & Yüce 1998).

The upper layer circulation of the Marmara Sea has been poorly investigated over the years and only a few papers report information about it. The first systematic study on the surface circulation occurred during the summer of 1952 (Pektaş 1953). About 250 drift bottles were released in the vicinity of the Bosphorus and 50 were recovered. The bottles contained a postal card requesting

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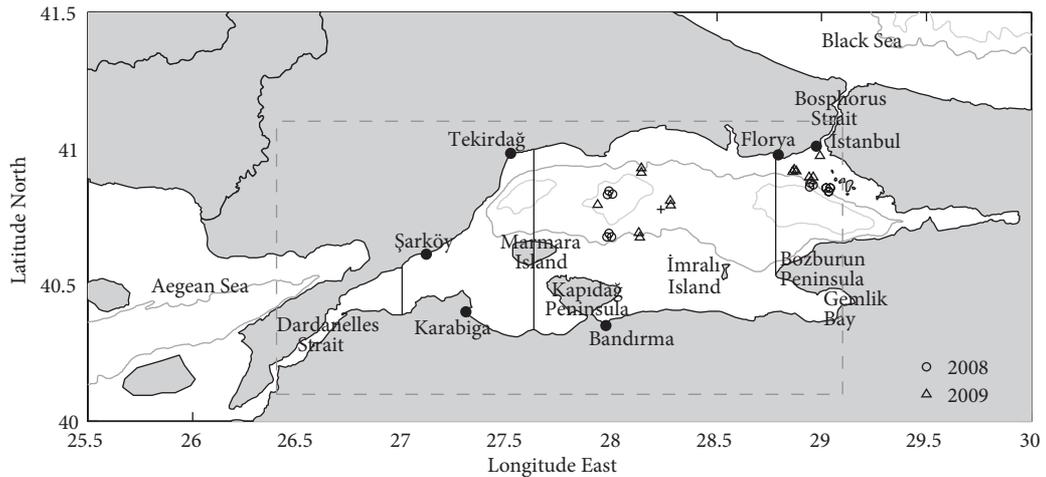
Figure 1. The Marmara Sea with geographical references and deployment locations in 2008 (open circles) and 2009 (open triangles). The 200 m and 1000 m isobaths are represented with gray curves. The dashed rectangular area corresponds to the area displayed in the other figures. The cross near the middle of the Marmara Sea indicates the grid point where the wind field was estimated during the period of study. The vertical lines indicate the limits of the areas used for the computation of the crossing times in Section 3.4.

information on the date and location of the recovery. All 50 bottles were recovered on the southern coast. It was concluded that the water entering the Marmara Sea from the Bosphorus arrives at the Dardanelles within 10 days. More recently, using hydrographic and acoustic Doppler current profiler (ADCP) measurements, Beşiktepe et al. (1994) indicated that the surface circulation is dominated by the outflow of low salinity Black Sea water. A jet-like flow enters the Marmara Sea from the Bosphorus Strait. It is southwestward oriented, and then it curves first westward and then northwestward along the southern shelf. This current then crosses the width of the Marmara Sea and finally bends southwestward towards the Dardanelles Straits, forming a large meander loop. A large anticyclone is formed in the northeastern or central area of the Marmara Sea typically under low wind conditions. During strong wind episodes, several smaller (subbasin scale) eddies are generated. These circulation features are highly variable and strongly forced by local winds in addition to the basin morphology and bathymetry.

Significant modifications to this circulation pattern were observed during the period 1986–1992 (Beşiktepe et al. 1994). Indeed, the jet is largely determined by the fresh water inflow into the Black Sea and, during periods of low Black Sea river discharge (from the Danube, for example), the jet becomes weaker and tends to flow along the coast. The central anticyclone can block the jet or strong winds can disintegrate it into smaller eddies. Northeasterly flow along the northern region and reversal of the normal upper layer circulation were also observed.

Northeasterly winds from the Black Sea are prevalent in the Marmara region throughout the year (frequency:

60%). When not blowing from the northeast direction, winds are most often from the southwest. Southwesterly winds are of secondary importance and their frequency is about 20% (Beşiktepe et al. 1994; Alpar & Yüce 1998).

Surface satellite-tracked drifters were launched during 2 cruises of the NATO Undersea Research Center (NURC) on board the NRV Alliance during September 2008 and February 2009. The overall objective of the NRV Alliance cruises in the TSS was to define multiscale dynamic processes during the water exchange between the Black Sea and the Aegean Sea through the collection of comprehensive data sets (Beşiktepe et al. 2010).

To accomplish the objectives of the research, a series of process-oriented field measurements were carried out in the TSS as well as in the Black and Aegean Seas covering different scales of motion. Large-scale hydrographic surveys were carried out by the R/V Alliance to provide a complete synoptic view of the hydrophysical variables in the Marmara Sea (Chiggiato et al. 2012) and in the Black Sea (Vandenbulcke et al. 2010). Currents, sea level, temperature, and salinity measurements obtained from fixed moorings and coastal observation networks were used to explain their variability over different time scales (from hourly to seasonal) (Jarosz et al. 2011a), and to estimate mean, seasonal, and synoptic exchange rates in the Bosphorus Strait (Jarosz et al. 2011b). Complementary to these measurements, drifters were launched at the beginning of each cruise to obtain a synoptic view of the circulation in the Marmara Sea and to understand the role of the Bosphorus outflow and the atmospheric forcing on the Marmara Sea circulation.

Here we focus on the surface circulation results obtained from drifter data in the Marmara Sea. The paper is organized as follows: a brief explanation of the drifter system, the deployment strategy, and the methodology used to process the drifter and wind data are given in Section 2. A detailed description of the drifter trajectories, qualitative descriptions of the drifter data in time and space, and an estimate of the wind effect on the drifters are presented in Section 3. The mean surface circulation is described by computing the pseudo-Eulerian velocity statistics for the 2 experiments separately. Finally, Section 4 contains the discussion and conclusions.

2. Data and methods

2.1. Drifter characteristics
The drifters used in this experiment are modified CODE drifters, similar to the ones used in the Coastal Ocean Dynamics Experiment in the early 1980s (Davis 1985). They consist of a negatively buoyant 1-m vertical tube from which 4 vertical cloth planes extend radially. Four foam balls provide net positive buoyancy and maintain the antenna out of the water. In addition to the standard positioning and data telemetry (SST, battery) provided by the Argos data collection and location system (DCLS) using polar-orbiting NOAA satellites (with 300–1000 m position accuracy and about every 100 min), the drifters are equipped with GPS receivers to determine their position more accurately (within 10 m) and more frequently (every 30 min). Comparisons with current meter data (Davis 1985) showed that the CODE drifters follow the current of the first meter below the surface to within 3 cm/s, even during strong wind episodes. More recently, Poulain et al. (2009) compared CODE drifter data with the European Centre for Medium-Range Weather Forecasts wind products and proved that the drag effect of the wind on the emerged part of the drifter is responsible for wind-driven velocities of about 1% of the wind speeds in the Mediterranean Sea.

2.2. Drifter deployments
A total of 29 drifters were deployed in the Marmara Sea during 2 episodes (September 2008 and February 2009; Figure 1). Due to the small dimensions of the Marmara Sea, a short drifter lifetime was expected. To maximize the geographical coverage and to study the jet-like flow south of the Bosphorus and the eddy activity in the central part of the Sea, the drifters were released at key locations. These areas were chosen after considering the mean general circulation from the bibliography (Beşiktepe et al. 1994) and were fine-tuned a few days before the deployment by using the available satellite images. To allow the calculation of dispersal statistics (not discussed here), the deployments occurred mainly in small clusters of 2–3 drifters separated about 1 nautical mile apart.

During the first experiment (TSS08), 12 drifters were deployed from the R/V Alliance. In particular, on 30 August 2008, 6 drifters were released in 2 triplets in the central open sea, and on 31 August 2008, the other 6 drifters were released in 2 triplets to the east and west of the Bosphorus jet previously identified using satellite imagery. Three drifters stranded rapidly and were recovered after a few weeks. They were redeployed in late September south of the Bosphorus. After 2 months, nearly all the drifters stopped working or were stranded, mainly on the southern coast. An expedition was organized at the beginning of November and 7 drifters were recovered.

In the second drifter experiment (TSS09), a total of 14 drifters were deployed on 20 and 21 February 2009. The open sea deployment locations were moved a bit to the east with respect to the 2008 deployments and the releases occurred in 3 clusters of 2 drifters. An additional drifter was released more to the west, with the aim of forming, along with the previous deployments, a diamond pattern around a presumed eddy feature. South of the Bosphorus, the deployment locations were moved a bit to the northwest close to the coast and one additional drifter was deployed just south of the Bosphorus Strait.

2.3. Data and processing
The combined raw Argos and GPS drifter positions were edited for outliers and spikes using statistical and manual techniques with criteria based on maximum distance, maximum speed, and maximum angle between 2 consecutive points (Poulain et al. 2004). Edited positions were merged and interpolated at regular 2-h intervals with a kriging optimal interpolation schema (Hansen & Poulain 1996). Surface velocities were then calculated by central finite differencing of the interpolated positions.

As stated by Alpar and Yüce (1998), spectral analysis confirms that tidal currents are weak and negligible compared to the fluctuations forced by the winds. As a result, no low-pass filter was used to eliminate high frequency current components.

To describe the surface circulation of the Marmara Sea, pseudo-Eulerian statistics were calculated (Poulain 2001; Emery & Thomson 2004) by grouping drifter data in $0.1° \times 0.1°$ bins with 50% overlap and organized on a grid with a $0.05° \times 0.05°$ mesh size. Bins with less than 5 observations were rejected for the computation of the statistics. The pseudo-Eulerian statistics were computed separately for the 2 deployment episodes.

Kinetic energy per unit of mass was considered as the sum of 2 terms: the mean kinetic energy of the mean flow per unit of mass (MKE) and the mean kinetic energy of the fluctuations per unit of mass, also called eddy kinetic energy (EKE). Definitions can be found in the work of Poulain (2001).

2.4. Wind products

The wind products of the high-resolution model of the Consortium for Small-Scale Modeling – Mediterranean (COSMO–ME; http://www.cosmo-model.org/) provided by the national meteorological service of the Italian Air Force were used to relate the Marmara Sea surface circulation to wind forcing. In particular, we obtained a succession of daily analysis and forecasts on a 7-km grid, covering the Marmara Sea and spanning the period of the 2 experiments with a temporal resolution of 3 h. The wind computed near the middle of the Marmara Sea (40.7780°N, 28.2348°E; cross symbol in Figure 1) was used as a representative of the Marmara Sea atmospheric conditions during the study period. This selection was made by assessing the differences in terms of mean and standard deviation between this location and all the other grid points. The mean difference did not exceed 1 m/s in speed and ±10° in direction in the open sea. Wind products were also interpolated at the drifter positions every 2 h so as to relate the drifter velocities to the local wind speed.

3. Results

3.1. Drifter data

The Marmara Sea was sampled quite differently by the drifters in the 2 experiments (Figure 2). The southern part was covered mainly during the first experiment (from 30 August to 23 October 2008), while the northern part was covered mainly during the second one (from 21 February to 23 April 2009).

The trajectories of the drifters deployed during the TSS08 experiment (Figure 2a and movie at http://nettuno. ogs.trieste.it/sire/drifter/tss/database/video/TSS08.avi) show that the drifters deployed south of the Bosphorus (31 August 2008) moved coherently southwestward for a few days and then southward, approaching the southern coast where the majority of the units stranded. Only 2 drifters survived. One continued westward until stranding near Bandırma and the other one recirculated southeast of İmralı Island in a small cyclonic loop and then stranded in Gemlik Bay (see Figure 1 for all geographical references). Another drifter separated from the other drifters west
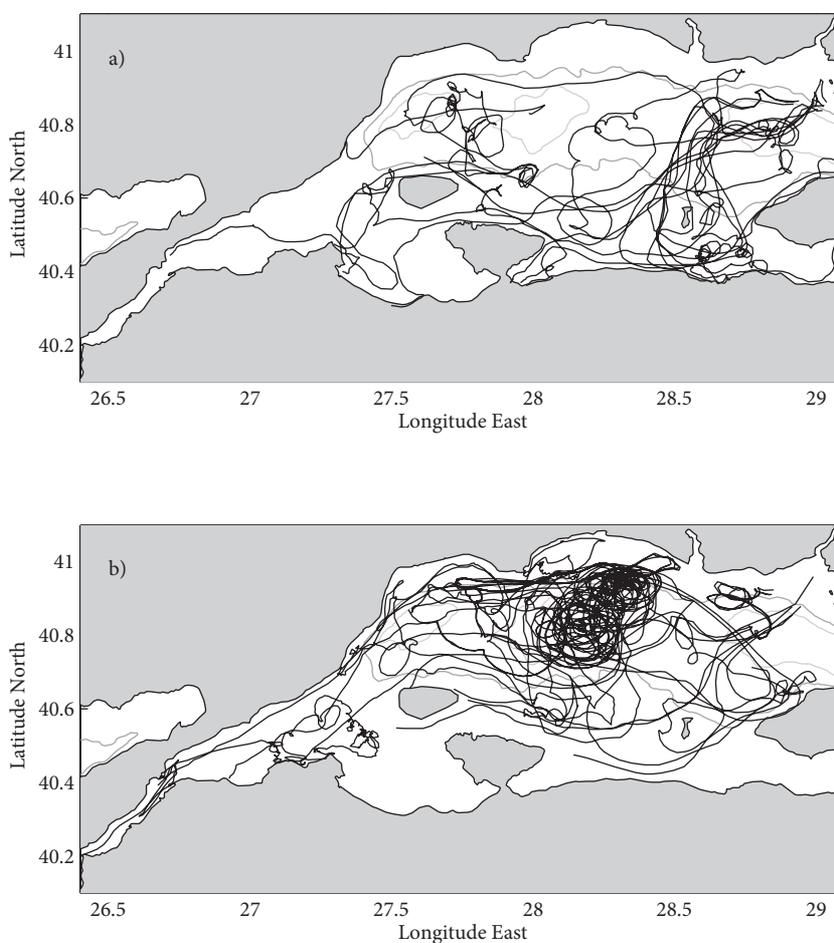
Figure 2. Edited and 2-h interpolated drifter trajectories of the (a) first and (b) second experiment. The 200-m and 1000-m isobaths are represented with gray curves.

of İmralı Island and survived longer. It first explored the central part of the Marmara Sea anticyclonically, reaching the northern coast near Florya, and then crossed the Marmara Sea passing between the southern continental land and Marmara Island and stranding on the coast close to Karabiga.

Two triplets were released in the central part of the Marmara Sea (30 August 2008). Two drifters of the northern triplet immediately stopped working and the remaining drifter moved westward and stranded east of Şarköy after 5 days. In contrast, 2 drifters of the southern triplet encircled the eastern side of Marmara Island and approached the coast near Karabiga. One stranded and the other continued westward, nearly reaching the Dardanelles strait and stranding west of Şarköy. The third drifter was trapped into a large anticyclone (about 90 km × 30 km) located in the northern half of the Marmara Sea. It completed the loop in about 7–8 days, after which it indicated some small-mesoscale features near 40.8°N and 27.8°E and finally reached the southern coast near Bandırma, moving close around the eastern coast of the Kapıdağ Peninsula.

Three drifters were recovered and redeployed after about 1 month (27 September 2008) south of the Bosphorus. Their trajectories revealed a cyclonic eddy southeast of İmralı Island. From there, they headed towards the north, returning approximately to the deployment positions, or in the vicinity of the northern coast of the Bozburun Peninsula, and then they collectively moved westward about 15 km apart from each other. Two of them stranded on Marmara Island and near Bandırma, while the northern unit slowed down in a meandering pattern in the central part of the Marmara Sea and then passed between Marmara Island and the Kapıdağ Peninsula, ultimately stranding east of Karabiga.

The trajectories of the drifters released in February (TSS09 experiment, Figure 2b and movie at http://nettuno. ogs.trieste.it/sire/drifter/tss/database/video/TSS09.avi) pointed out that all the drifters deployed in the open sea moved straight towards the Dardanelles for about 1 week up to longitude 27.5°E. One of them reached the Dardanelles Strait 12 days after deployment. Two drifters stranded on Marmara Island and 3 drifters suddenly reversed and came back eastward, bordering the northern coast up to 28°E, where they finally veered to the south. One of them was trapped inside a large cyclonic feature located in the northern half of the Marmara Sea, where it looped several times.

Some drifters released south of the Bosphorus revealed 2 separate small anticyclonic loops (diameter of about 5 km) centered at 40.9°N, 28.7°E and 40.8°N, 28.3°E and then together approached the Bozburun Peninsula. Some units proceeded first southwestward, eventually encircling

İmralı Island, and then westward, stranding after less than 1 week on Marmara Island or near Bandırma. Additionally, some drifters evidenced a cyclonic submesoscale eddy off the Bozburun Peninsula.

Two drifters crossed the Marmara Sea from the Bozburun Peninsula to the northern coast at longitude 28°E and then looped in the large cyclonic eddy mentioned before. One unit slowed down around İmralı Island and in front of the Bozburun Peninsula and then crossed the sea as far as south of Tekirdağ. It then moved to the southern coast, where it slowed down again, moving slightly eastward and revealing a small submesoscale cyclonic feature centered at 40.5°N, 27.4°E, before finally heading towards the Dardanelles Strait, where it stranded.

The mean half-life of the drifters in the Marmara Sea (Figure 3) was very low (12.6 days) compared to drifters deployed in the world oceans (300–500 days, Lumpkin & Pazos 2009) and the number of days at sea spans from only 2 days to a maximum of 51 days. Not all the drifter deaths were caused by stranding. A significant percentage (about 34%) of the drifter mortality was due to human interference or technical problems.
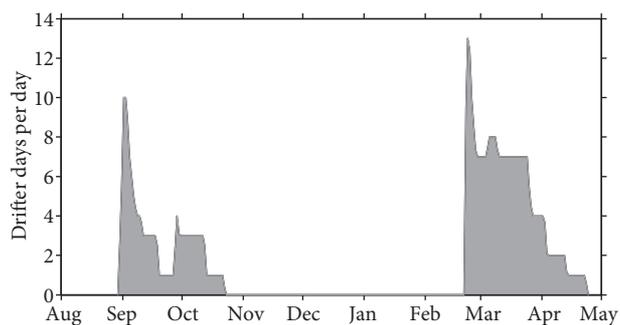
The temporal distribution of the drifter data (Figure 4) shows a clear separation between the 2 experiments.

Drifters provided useful data for only a maximum of 2 months, between 30 August and 23 October 2008 and between 21 February to 23 April 2009, hence covering the late summer–early fall and the late winter–early spring periods. The maximum drifter days per day occurred on 1 September 2008 and on 22 February 2009 with 10 and 13 drifters working simultaneously, respectively.

The statistics obtained by grouping drifter data in bins (Figures 5a and 5b) show that during the first experiment the larger number of observations was recorded north of Kapıdağ Peninsula and close to Bandırma (where some drifters stranded) and between the Bosphorus and the southern coast southeast of İmralı Island, where the maximum (80 bihourly observations per bin) was located. The maximum number of drifter observations per bin
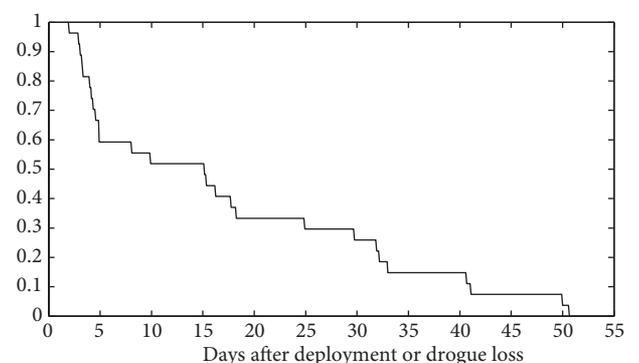
Figure 3. Mean half-life of the drifters in the Marmara Sea computed using all the interpolated data.
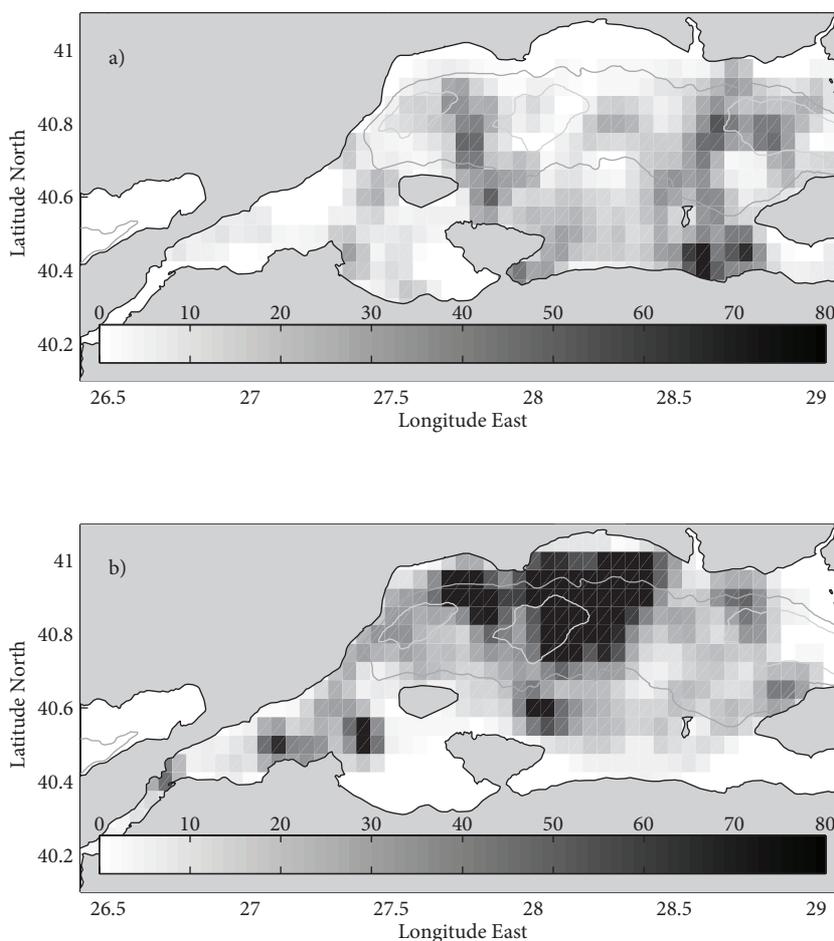
Figure 4. Temporal distribution of drifter data in the Marmara Sea. Number of drifter days per day from 30 August 2008 to 23 April 2009.

3.2. Wind effect

Winds (Figure 6) recorded in the middle of the Marmara Sea (40.7780°N, 28.2348°E) during the 2 experiments are in agreement with the known climatology. They were mainly from the northeast sector (75% and 64% during TSS08 and TSS09, respectively) and quite strong during both experiments. Wind speeds exceeding 5 m/s were registered for about 57% (41%) of the duration of the first (second) experiment and exceeding 10 m/s for about 14% (10%). Southwest winds were also present, especially during TSS09. They were not constant and mainly related to a rotation of the wind direction.

During the first 3 weeks of the TSS08 experiment, the wind blew mainly from the northeast with a nearly constant speed of about 10 m/s (Figure 6a). Variations of this predominant wind consisted of several quick rotating winds, 2 sudden direction changes, and 1 reversal. The first direction change occurred after about 5 days; the wind speed diminished and the wind started to blow from the north. Nearly all the drifters deployed south

was larger (up to 390 in the northeastern part) during the second experiment due to the permanence of the drifters in the northern half of the Marmara Sea, where they recirculated several times. Data in those areas were provided by up to 9 different units.

Figure 5. Spatial distribution of drifter data in the Marmara Sea. Number of observations per bin saturated at 80 units for the (a) first and (b) second experiment. The maximum number of observations is about 80 and exceeds 390 during TSS08 and TSS09, respectively. The 200-m and 1000-m isobaths are represented with gray curves.

of the Bosphorus were close to the southern coast south of İmralı Island and veered mainly eastward (see also the movie at http://nettuno.ogs.trieste.it/sire/drifter/tss/database/video/TSS08.avi). Other drifters in the open sea responded by describing small-scale loops. Unfortunately, stranding occurred very soon and only 3 drifters continued to provide useful data after the first week. They described other small-scale loops in the area between İmralı Island and Gemlik Bay, north of Marmara Island and in the open sea south of Florya. These loops are associated with quick rotating winds. The wind reversal caused reversal of the drifter trajectories in the open sea close to the area of the central deployments and west of Marmara Island. Finally, the effect of the second abrupt change in wind direction was evidenced only on the trajectory of the last surviving drifter and of the 3 drifters redeployed in late September. It generated small-scale loops northeast of Kapıdağ Peninsula and south of the Bosphorus. The redeployed drifters worked for about 20–30 days, during which time the predominant wind was from the northeast for about 1 week, then completely reversed for about 1 more week before returning to blowing from the northeast. Each wind reversal was associated with sudden drifter reversal or mesoscale eddies followed by changes of drifter direction. The 1-week periods of wind blowing from the first/third quadrants were characterized by some variability associated with decreasing wind speed and abrupt changes

of wind direction, rapid wind rotations, and reversals that generated small-scale loops and reversals in the drifter trajectories.

The wind during the TSS09 experiment was more irregular in intensity and direction. Long periods of cyclonic and anticyclonic patterns alternated. Nearly all the drifters were in the open sea and their trajectories displayed large loops mainly in the northern central part of the Marmara Sea. These loops seem to have originated from the abrupt inversion of the wind rotation and lasted until the next inversion (see gray boxes in Figure 6b and the movie at http://nettuno.ogs.trieste.it/sire/drifter/tss/database/video/TSS09.avi). Some wind reversals were also evidenced and induced net drifter reversals in the northern half of the Marmara Sea (3 drifters involved) and between Tekirdağ and Şarköy (1 drifter involved).

In order to further estimate the effect of the wind on the circulation, we also computed the daily wind stress curl on the 7-km grid over the Marmara Sea. The curl was very variable over this area and no particular agreement with the drifter trajectories was found, not even during the period of the reversals.

3.3. Overall mean flow and crossing time

The overall mean flow computed using all the bihourly interpolated drifter data is cross-basin oriented (westward) from the Bosphorus to the Dardanelles with a mean speed of about 4 cm/s and a standard deviation of 20 cm/s.
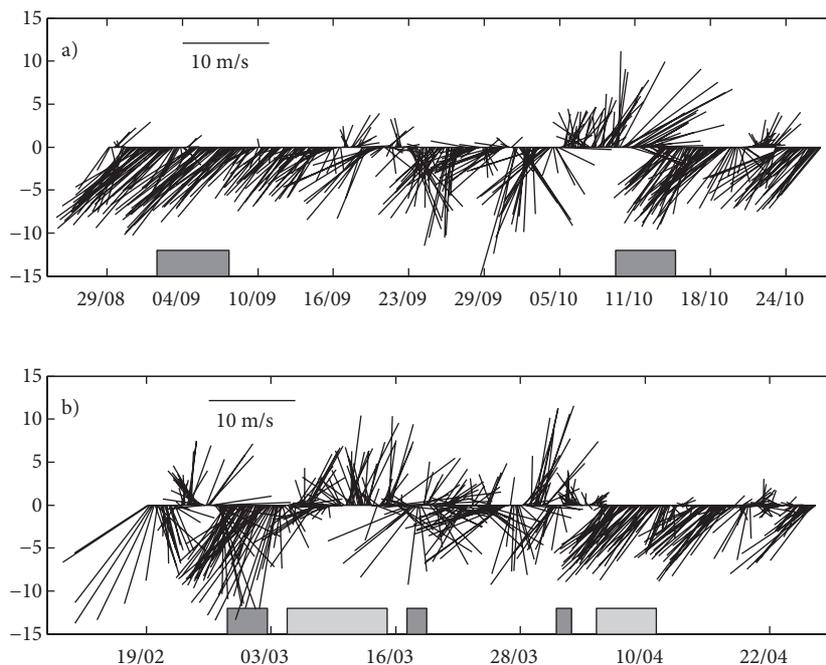
Figure 6. Wind time series in the center of the Marmara Sea (see cross symbol in Figure 1) concurrent with the (a) first and (b) second drifter experiments. Dark and light gray boxes represent the periods of anticyclonic and cyclonic rotation of the large eddy in the central basin, respectively.

The time required for a drifter to cross the Marmara Sea was also calculated. Since all the drifters deployed south of the Bosphorus stranded before reaching the Dardanelles, 2 areas were considered (delimited by the vertical lines in Figure 1): an area between the western part of the Bozburun Peninsula and the longitude dividing the Marmara Island in half, and another more to the west, as far as 27°E. Only a few drifters crossed these areas (Table; Figure 7). Four drifters spanned the eastern area and the

other 4 spanned the western area. The minimum time to cross these areas was 3.4 days and 1.8 days, respectively. Therefore, ideally, drifters can cross the Marmara Sea in about 5 days.

### 3.4. Pseudo-Eulerian velocity statistics

The mean surface circulation pattern was investigated by computing pseudo-Eulerian velocity statistics for the 2 experiments. In both cases (Figures 8a and 8b), the mean flow south of the Bosphorus is southwestward oriented,

Table. Crossing times for the eastern and western areas evidenced in Figure 7.

	Eastern area	Western area
Number of drifters	4	4
Min time (days)	3.4	1.8
Max time (days)	13.9	25.3
Mean time and standard deviation (days)	8.5 ± 4.8	9.5 ± 10.7
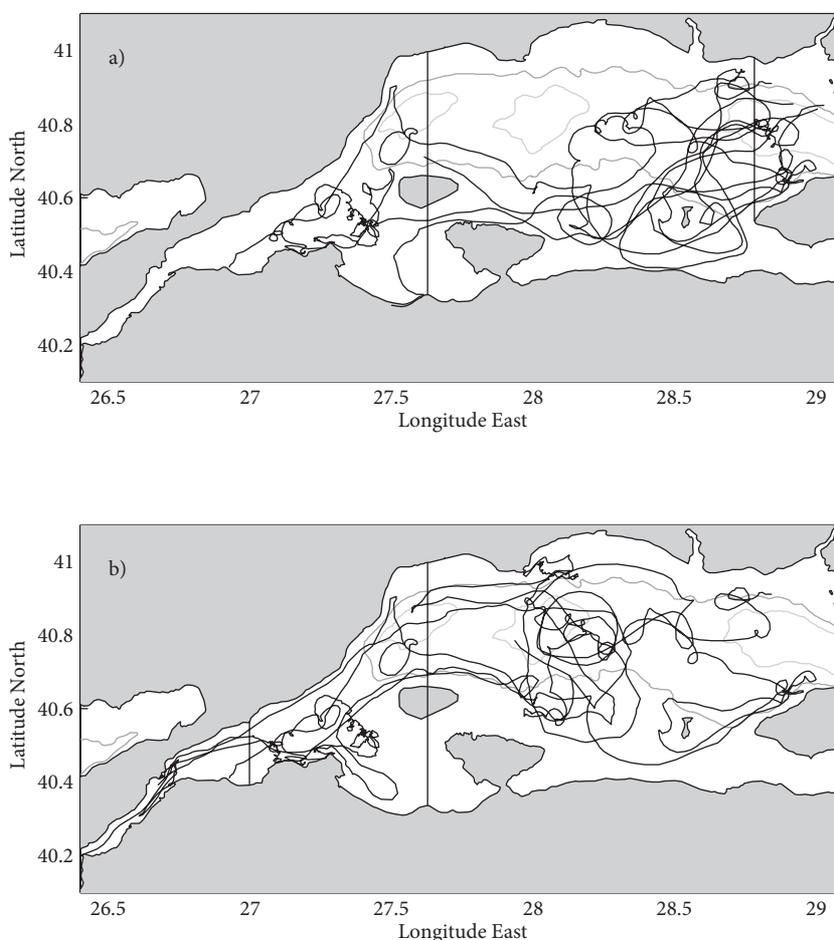
Figure 7. Trajectories of the drifters that crossed the (a) eastern and (b) western areas. The vertical lines indicate the limits of the areas. The 200-m and 1000-m isobaths are represented with gray curves.
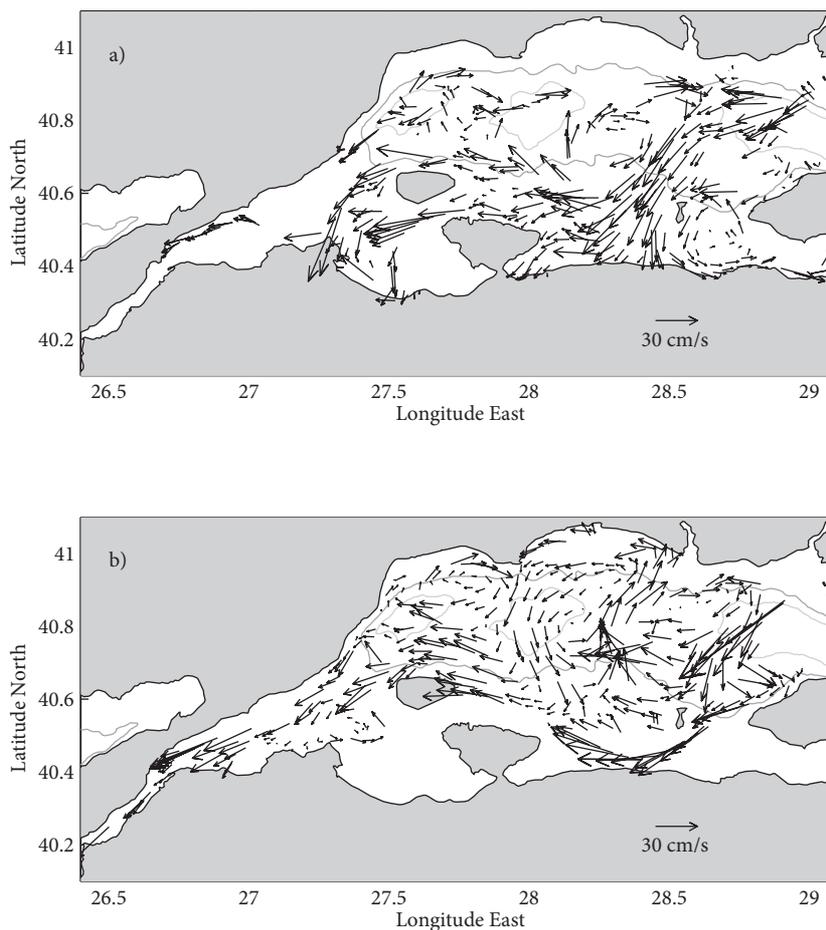
Figure 8. Mean flow maps for the (a) TSS08 and (b) TSS09 drifter experiments. The mean flow arrows are centered at the center of mass of the observations in each bin. Data are grouped into 0.1° × 0.1° bins overlapped by 50%. Bins containing fewer than 5 observations were rejected for statistical computation. The 200-m and 1000-m isobaths are represented with gray curves.

approaches the southern coast, and then heads toward the Dardanelles. In the first experiment, this flow was well defined and continuously sampled from south of the Bosphorus as far as east of Kapıdağ Peninsula, at which point it bifurcated and surrounded Marmara Island, and sampling became discontinuous near 27°E. In the second experiment, the jet (stronger than during TSS08) was depicted south of the Bosphorus. The flow gently curved before approaching the southern coast, where it then passed north of Marmara Island and proceeded westward to reach the Dardanelles. Several looping features can be found in the mean flow maps. In particular, during TSS08, 2 anticyclonic eddies (diameter of about 20–25 km) were located in the northern half of the basin, centered at about 27.6°E and 28.4°E. The eastern one was not closed to the south and joined the stronger flow from the Bosphorus. In the central part of the Marmara Sea, a larger anticyclonic feature was visible. It was centered at 40.75°N, 28.25°E.

It included the smaller eddy described above and its southeastern part coincided with the main flow crossing the Sea. Only 1 cyclonic eddy (diameter of about 25 km) appeared close to the southern coast, southeast of İmralı Island. The 2 anticyclonic eddies located in the northern half of the basin could be recognized again during TSS09 (centered at 27.7°E and 28.6°E, respectively), with a 10–15 km displacement to the east compared to TSS08. In Figure 8b, the large eddy located in the central area is cyclonic and typical of the periods characterized by winds not blowing from northeast, as evidenced by the pseudo-Eulerian velocity statistics computed under different wind regimes (not shown). The area southeast of İmralı Island was not covered by drifters, so there was no evidence of the cyclone there.

The principal axes of the velocity variance ellipses (not shown) are generally oriented with the mean flow, indicating that the velocity variations were due to changes

of the amplitude of the mean current and possible reversal. The ellipses are more isotropic and indicate a strong variability in the areas characterized by eddy activities north of Marmara Island (especially during the first experiment) and in the whole central part of the sea during the second experiment.

Concerning the energy level, large MKE values are related to strong mean flows. The MKE maxima exceeded 1000 cm²/s² in the central area and around Marmara Island (central area, southern coast, and close the Dardanelles) during the first (second) experiment and reached 4000 cm²/s² south of the Bosphorus during the TSS09 experiment.

The EKE presented large values corresponding to the eddy features mentioned above. Maxima were about 1000 cm²/s² during both experiments. The ratio of EKE/MKE was also computed to understand the importance of the mean flow with respect to the fluctuating currents. During both experiments, the areas south of the Bosphorus, in the central part of the eastern half of the Marmara Sea, and between 27°E and the Dardanelles are characterized by a MKE larger than the EKE, while the MKE is lower than the EKE in the areas south of Tekirdağ, south of Florya, east of Kapıdağ Peninsula, and west of Bozburun Peninsula.

North and east of Marmara Island there is a kind of inversion: during TSS08 the variability was more important than the mean flow, while during TSS09 the MKE prevailed.

4. Discussion and conclusions

Surface CODE drifters were deployed at key locations in the Marmara Sea during 2 experiments (September 2008 and February 2009) in the framework of the TSS project. Drifter observations were the first of that kind in that region and allowed us to confirm and improve the knowledge of the surface circulation of the TSS, previously deducted from hydrographic and ADCP measurements.

The operating life of the drifters in the Marmara Sea was very short due to the small size of the sea and the extremely high probability of stranding (mean half-life of 12.5 days and maximum of 51 days). Moreover, Lagrangian data, by nature, are gappy in space and time. The lack of data over time was compensated for by interpolating the data, but the study area was not covered uniformly and therefore caution must be taken when interpreting the results. Despite this fact, the statistical methodology applied to the data revealed quantitatively significant features of the surface circulation in the areas with higher density of drifter observations (Figure 5) during the study period.

The overall mean flow (4 cm/s) is cross-basin oriented (westward) in good agreement with the theoretical current triggered by the sea-level differences along the TSS and with the findings of Beşiktepe et al. (1994). The standard deviation related to this mean flow is high (20

cm/s) because of the variability induced by the numerous time-dependent eddies. However, the principal axis of the velocity variance ellipse is not isotropic and is significantly oriented from the Bosphorus to the Dardanelles.

The Marmara Sea surface circulation is rather complex and highly conditioned by the Bosphorus outflow and the action of wind stress. The general circulation pattern is a basin scale anticyclonic gyre formed by the Bosphorus outflow, further modified by the wind. Drifter experiments were carried out during autumn and winter months, which corresponds to the low mean Bosphorus outflows. However, short-term transient responses to meteorological events were frequently observed (Jarosz et al. 2011a). While the wind was blowing from the northeast during the autumn period, the winter was characterized by a combination of northeasterlies and southwesterlies. Northeasterly winds have a tendency to increase the Bosphorus outflow (Jarosz et al. 2011a). On the other hand, the winter circulation is more complicated, probably due to the larger variability of the wind direction.

The mean flow maps display a jet-like flow entering the Marmara Sea from the Bosphorus Strait. It is south-southwestward oriented as far as the southern coast and then, meandering, extends into the western part of the sea, eventually heading towards the Dardanelles. This general pathway was already displayed in previous studies, but the drifters revealed that, during the study period, in the western part of the sea the flow is confined immediately north of Marmara Island and not south of Tekirdağ as shown by Beşiktepe et al. (1994) (compare Figure 8 with Beşiktepe et al. 1994, p. 331, figure 34). In both drifter experiments, an anticyclone is evident north of Marmara Island, while in previous schema there was a cyclone there. Clearly, the presence of the anticyclone precludes the westward transport close to the northern coast shown by Beşiktepe et al. (1994).

During the first experiment (Figure 8a), the mean flow in the eastern basin of the Marmara Sea was depicted closer to the southern coast with respect to the mean current computed during the second experiment. This is primarily due to the northeasterly winds permanently blowing during most of this period (see Figure 6a) that reinforced the flow of the Black Sea waters (Beşiktepe et al. 1994; Jarosz et al. 2011a) and directly acted on the surface waters.

It is important to mention that speed estimates can be overestimated under strong wind episodes, since the drag effect of the wind on the emerged part of the drifter with winds of about 10 m/s can be responsible for wind-driven velocities up to 10 cm/s.

The trajectories of each drifter were carefully examined together with the time series of wind direction and intensity. The trajectories are in alignment with the abrupt

changes of wind direction within limited time intervals during both experiments. For example, the sudden surface circulation reversal observed in the northern part of the Marmara Sea and involving 3 drifters perfectly matches a reversal of wind and suggests that the response to the wind forcing is nearly immediate, as was also stated by Chiggiato *et al.* (2012), for the first week of the TSS09 experiment by comparing the same drifter data with numerical modeling solutions from the Regional Ocean Modeling System (ROMS). Additionally, the reversals of the drifter trajectories occurred simultaneously in different parts of the Marmara Sea (at least 3 pairs of drifters separated by about 50 km and at 2 different times), indicating that the entire sea moved coherently.

Reversals of the surface circulation were also reported by Alpar and Yüce (1998), who observed that the reversals can typically be maintained for a couple of days and finish when winds weaken and the slope returns to its normal position.

Complex eddy activity is evidenced during both experiments. Cyclonic and anticyclonic mesoscale features prevail nearly everywhere in the Marmara Sea (south of Florya, off the Bozburun Peninsula, off Karabiga, and in the open sea). A prevalence of anticyclones is shown in this drifter study. They are located in the northern half of the basin, south of Tekirdağ and Florya, during both experiments. A large anticyclonic eddy is located in the middle of the sea. It is a well-known and recurrent structure that is generated by the Bosphorus outflow and the sea level differences between the Black and the Aegean seas (Beşiktepe *et al.* 1994). These structures seems to persist even when the contribution of the Bosphorus flow decreases (typical of the autumn months), but can be destroyed and even reversed by strong winds in winter. The general anticyclonic circulation is restored as soon as the influence of the strong winds disappears.

The pseudo-Eulerian statistics of the drifter velocities show that the central eddy was anticyclonic during TSS08, while it was cyclonic during TSS09. However, care must be taken when interpreting the mean flow plots. Indeed, the large eddy is anticyclonic also during limited periods of the TSS09, but the cyclonic rotation dominates on average. Two reversal events from anticyclone to cyclone were noticed during the TSS09 experiment (see Figure 6b). One occurred during the period spanning 5–15 March 2009. Five drifters were involved and the wind initially rotated clockwise before blowing from the south during the remaining period. During the period of 5–11 April 2009, the cyclonic eddy was larger and was not associated with a wind blowing from the south sectors, but its origin coincided with an unexpected change of the wind direction.

The local wind stress curl appears to have had limited effect on the eddy variability and reversal, and so we can speculate that the wind acted on the circulation through different direct and indirect mechanisms.

Other complex mechanisms like baroclinic instabilities and buoyancy induced by the Bosphorus flow could also play an important role, but their effects on the surface circulation are less rapid than the ones caused by wind stress.

Energy levels were also computed to find out the most energetic circulation features and the areas associated with high variability. The main flow that meanders across the Marmara Sea is associated with the maximum MKE, while the EKE is larger than the MKE in areas where eddy activity prevails (mainly during TSS09), confirming the extremely high variability of the eddies.

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