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Influence of Dardanelles outflow induced thermal fronts and winds on drifter trajectories in the Aegean Sea

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Abstract

The data provided by 12 drifters deployed in the Northern Aegean Sea in the vicinity of the Dardanelles Strait in August 2008 and February 2009 are used to explore the surface circulation of the basin and the connectivity to the Black Sea. The drifters were deployed within the Dardanelles outflow of waters of Black Sea origin in the North-eastern Aegean. Thanks to the particular choice of the drifter deployment positions, the data set provides a unique opportunity to observe the branching behaviour of the surface currents around Lemnos Island. Such pathways were not possible to study with previous drifter deployments that were far from the Dardanelles Strait. In addition, the drifter tracks covered the Aegean basin quite thoroughly, mapping major circulation features and supporting the overall general circulation patterns described by previous observational and modelling studies. The collected data display cases in which drifters are driven by winds and thermal fronts. Wind products were used to estimate the influence of atmospheric forcing on drifter trajectories. Satellite sea surface temperature images were connected to the drifter tracks, demonstrating a high correlation between remote and *in situ* observations. The waters of Black Sea origin were traced all the way to the Southern Aegean, establishing a strong connectivity link between the Aegean and Black Sea basins.

Keywords: Aegean surface circulation, surface drifters, Dardanelles outflow, thermal fronts, local winds.

Introduction

The Aegean Sea is a semi-enclosed basin of the Mediterranean Sea located between the Greek peninsula on the west and Asia Minor on the east. It is connected to the Turkish Straits System (TSS: Dardanelles Strait, Sea of Marmara and Bosphorus Strait), while the island of Crete can be taken as marking its southern boundary with the rest of the Mediterranean Sea.

The Aegean Sea has an intricate topography due to the presence of thousands of islands and numerous gulfs and straits with an alternation of shelves and sills (Fig. 1). The bottom topography of the northern Aegean is characterized by a shelf area about 200 m deep that sinks into deep basins north of the Sporades Islands and north of Lemnos Island (respectively, Sporades and Lemnos Basins). The central area of the Aegean Sea has other relevant depressions such as the basin between Agios Efstratios and Skyros Islands and the Chios Basin that extends from south of Skyros Island to north of the Cyclades and touches the Turkish coast to the east. The Cycladic Islands also separate the central from the southern Aegean Sea. The area is dominated by shallow water (generally below 400 m), while more to the south the depth easily reaches 2000 m. The southern Aegean Sea is bounded by the island of Crete and is connected to the Ionian and Levantine basins through the eastern and western Straits of the Cretan Arc.

The topography has a marked effect on the main flow depicting a cyclonic general circulation with several sub-basin permanent and recurrent eddies such as the Samothraki anticyclone, the Sporades eddy and the Chios cyclone (Korres *et al*., 2002; Nittis & Perivoliotis, 2002; Kontoyiannis *et al*., 2003; Zervakis *et al*., 2004; Olson *et al*., 2007; Kalantzi *et al*., 2010), which are connected by intense jets and meandering currents (e.g. the Evoia jet, Olson *et al*., 2007). As in other marginal seas, the flow is also thermohaline and wind driven. The Dardanelles outflow (waters of Black Sea origin, BSW) plays a very important role in surface circulation. The outflow is generally cooler, fresher and with higher nutrient content with respect to the Aegean Sea and generates strong fronts with the warm, highly saline and extremely oligotrophic waters of the Aegean Sea. As a result, this outflow can be identified in ocean colour and Sea Surface Temperature (SST) satellite images (Zodiatis

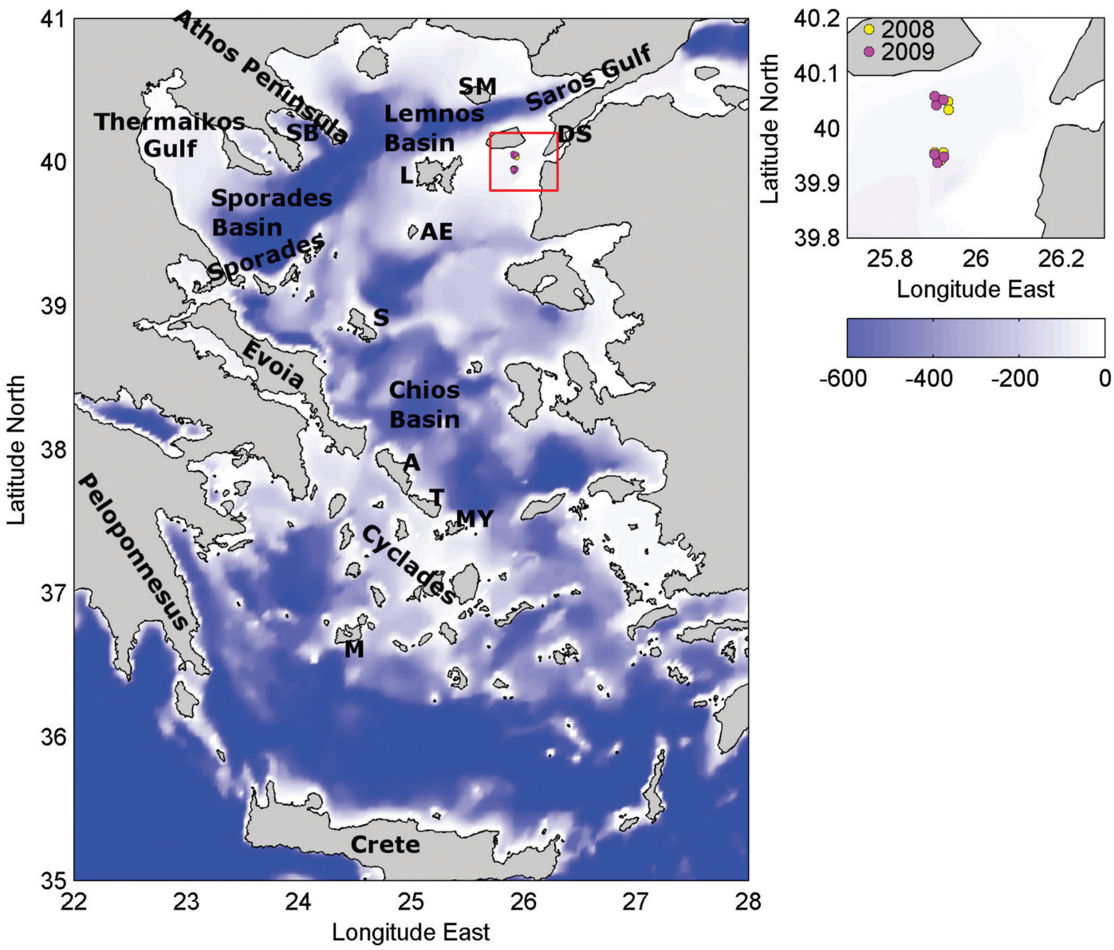

Fig. 1: Geographical references and deployment positions during 2008 (yellow dots) and 2009 (magenta dots). The bathymetry is saturated at - 600 m. SB: Singitikos Bay; SM: Samothraki Island; L: Lemnos Island; DS: Dardanelles Strait; AE: Agios Efstratios Island; S: Skyros Island; A: Andros Island; T: Tinos Island; MY: Mykonos Island; M: Milos Island.

et al., 1996; Jönnson, 2003; Tsiaras *et al*., 2012). The low salinity signal dominates, so the plume is characterized by low density waters and the related buoyancy-driven circulation: an anticyclonic bulge near the Dardanelles (generally over the Lemnos plateau) and a cyclonic rim current around the North Aegean shelf break (Olson *et al*., 2007; Androulidakis & Kourafalou, 2011). This circulation is influenced by topography and modified by the wind field.

There is a well defined seasonal variability in the meteorological conditions in the Aegean Sea. Northerly winds, locally known as Etesians, prevail from June to October. During the period of November-May, the Aegean is under the influence of extratropical cyclones, which result in strong southerly winds (Nittis *et al*., 2002). This strong variability in wind regime in the area has an influence on the route of the Dardanelles outflow and on basin scale circulation (Zervakis & Georgopoulos, 2002; Tzali *et al*., 2010; Androulidakis & Kourafalou, 2011; Androulidakis *et al*., 2012a, b). The tides of the Aegean basin are generally weak. They barely exceed 10 cm (Tsimplis, 1994; Poulain, 2013) and, therefore, contribute very little to the general circulation of the Aegean Sea. A remarkable exception is the strait of Euripus (lying between continental Greece and Evoia Island), which is subject to strong tidal currents.

The first effort to study the surface circulation of the Aegean Sea by means of drifters took place in a one year period, between March 2002 and February 2003, as described by Olson *et al*. (2007). They used a total of 45 drifters over four deployments and concluded that surface circulation associated with the dynamics of the Dardanelles outflow was a major factor controlling drifter pathways. The drifters were deployed relatively far from the Dardanelles Strait, but within the influence of the Dardanelles plume. This study confirms these results and extends the findings by examining the relative role of winds and thermal fronts on drifter pathways. The study data are based on a total of 12 surface CODE drifters that were deployed in 2 clusters immediately west of the Dardanelles Strait and well embedded in the Dardanelles plume in 2008 and 2009 (Besiktepe *et al*., 2010), in the framework of an experiment focussing on the dynamics of the flow and the water mass characteristics of the TSS. This is an unprecedented data set which allows better study of the influence of buoyant waters of Black Sea origin on the surface circulation of the Aegean Sea. A novel aspect of this study is the focus on the thermal contrast between Aegean and Black Sea waters and the related near surface circulation, in the context of wind influence. After a brief explanation of the characteristics of the drifters, the wind and SST products, a detailed description of the drifter trajectories is given. The effect of the wind and the role of the thermal fronts were estimated considering a linear complex regression model.

Data and Methods

Twelve drifters were deployed in the framework of the TSS experiment in the Aegean Sea during two periods (launches on 28 August 2008 and 1 February 2009, Table 1). They were released just west of the Dardanelles Strait in two clusters, one north and one south with respect to the Strait entrance (see Fig. 1 and Table 1). The instruments are modified CODE drifters, similar to the ones used in the Coastal Dynamics Experiment (CODE) in the early 1980's (Davis, 1985). They consist of a 1-m vertical structure with four vertical sails that extend radially. The entire structure is immersed in the first meter of water with the transmission antenna out of the water. 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, as recently shown by Poulain *et al*. (2009) comparing CODE drifter data with the wind products of the European Centre for Medium-Range Weather Forecasts (ECMWF).

In addition to the standard positioning and data telemetry (SST, battery) provided by the Argos Data Collection and Location System (DCLS), the drifters are equipped with GPS receivers for more frequent (every hour) and more accurate determination of their position (about 10 m). Drifter data were first edited for outliers (following Poulain *et al*., 2004) and then interpolated at regular 6-h intervals with an optimal interpolation scheme (Hansen & Poulain, 1996).

Considering the complex morphology of the Aegean Sea with a large number of islands and narrow passages (Fig. 1), a short drifter lifetime was expected. However, most drifters provided several weeks of data, with the exception of two units deployed in 2009 that stopped working after a few hours and do not contribute to the statistics (Table 1). Over the entire data set, the maximum number of days at sea is about 115 days and the mean lifetime is about 39 days.

The Cross-Calibrated Multi-Platform (CCMP) wind products provided by the Physical Oceanographic Distributed Active Archive Center (PO.DAAC) of NASA (Atlas *et al*., 2011) were used to determine the meteorological conditions over the Aegean Sea during the period of study. These data are provided over a 0.25° x 0.25° spatial grid and every 6 h. The wind at 39.125°N, 24.125°E was chosen as reference for the Aegean Sea (Fig. 2A). Although spatial variability in the wind field over the Aegean at large exists (Kourafalou & Tsiaras, 2007), the chosen central grid point (Fig. 2A) is quite representative of the atmospheric conditions of most of the Aegean basin (excluding the Thermaikos Gulf interior, where winds can be different, but this is an area that remained mostly clear of drifter pathways). The wind data were also interpolated at the 6-h drifter positions in order to relate the drifter velocities to local wind speed.

Remotely sensed SST data were used to examine the influence of fronts on drifter pathways, focusing on the thermal differences due to the outflow at Dardanelles and the overall heat exchanges in the Aegean. In particular, we collected the data from the Advanced Very High Resolution Radiometer (AVHRR) onboard the NOAA polar-orbiting environmental satellite. These data were processed with the TeraScan software (http://www.seaspace.com/software.php) and SST images of the Mediterranean Sea were produced.

Table 1. Drifter attributes. The reference letters indicate the cluster: a and c (b and d) represent the southern (northern) clusters during the 2008 and 2009 deployment episodes, respectively.

Drifter	Deployment date	Last date	Lifetime (day)	Travelled distance (km)	Mean speed (cm/s)	Max speed (cm/s)
a1	28 Aug 2008	25 Oct 2008	58.7	1111	22.0	59.5
a2	28 Aug 2008	10 Sep 2008	13.6	344	29.5	73.3
a3	28 Aug 2008	26 Oct 2008	59.4	1283	25.2	67.6
b1	28 Aug 2008	21 Dec 2008	115.2	2018	20.3	60.8
b2	28 Aug 2008	7 Sep 2008	10.5	211	23.9	41.5
b3	28 Aug 2008	6 Oct 2008	44.7	812	21.1	55.5
c1	1 Feb 2009	25 Feb 2009	24.4	273	13.0	39.3
c2	1 Feb 2009	19 Feb 2009	18.1	244	15.7	28.4
c3	1 Feb 2009	1 Feb 2009	0	-	-	-
d1	1 Feb 2009	29 Mar 2009	55.9	611	12.7	51.2
d2	1 Feb 2009	2 Feb 2009	0.7	-	-	-
d3	1 Feb 2009	6 Mar 2009	33.3	472.9	16.6	56.2

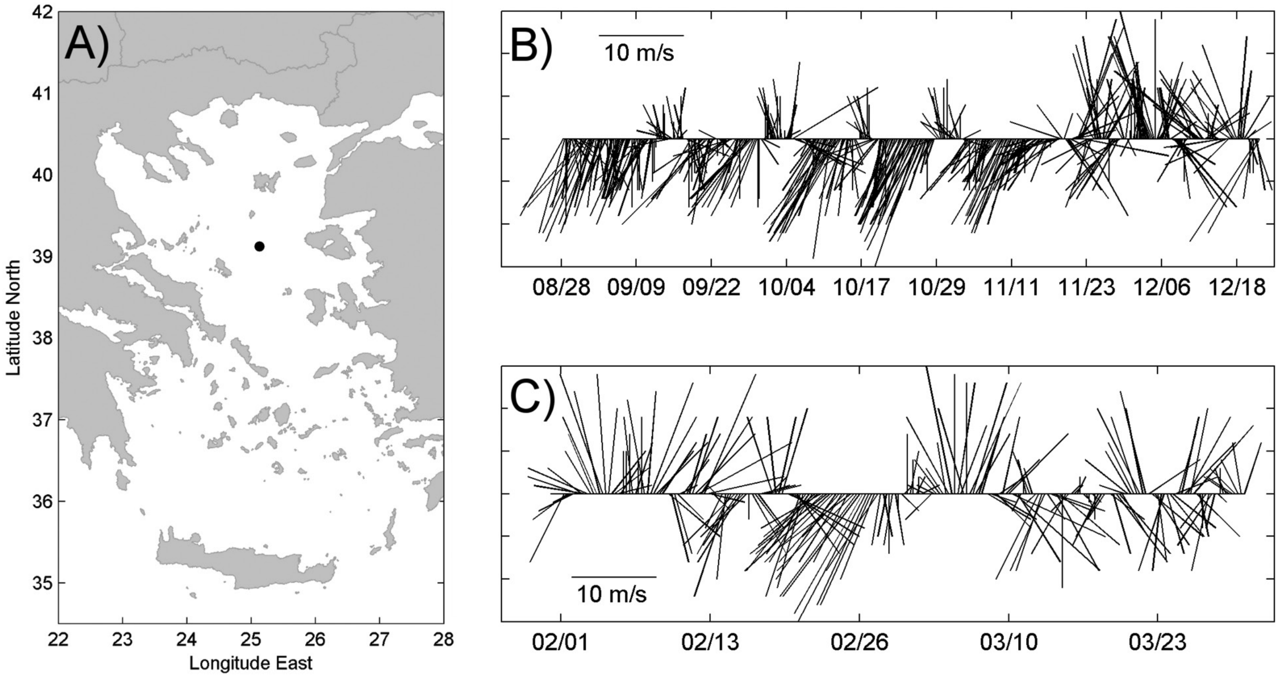

Fig. 2: (A) Central points chosen as reference for the meteorological conditions of the Aegean Sea (black dot in the middle of the basin). Wind time series during the 2008 (B) and 2009 (C) experiments.

Description of the drifter trajectories

2008 experiment

The 6-h interpolated trajectories of the 2008 drifters show that the three units released in the northern cluster (magenta curves in Fig. 3A and Figs. 4A and 4B) initially slowly moved coherently north of Lemnos Island along 40°N until reaching 24°E. The cyclonic pattern of the basin scale circulation was obvious during this experiment. It is evident that the basin scale circulation was intensified on the western boundary of the basin, as evidenced by the increased spacing between consecutive drifter positions. There, one drifter displayed cyclonic activity and then was trapped in a sub-basin scale cyclone (the so-called Sporades Eddy) centred at 39.5°N, 23.75°E (Fig. 4B). Another drifter slowed down south of the Athos Peninsula,

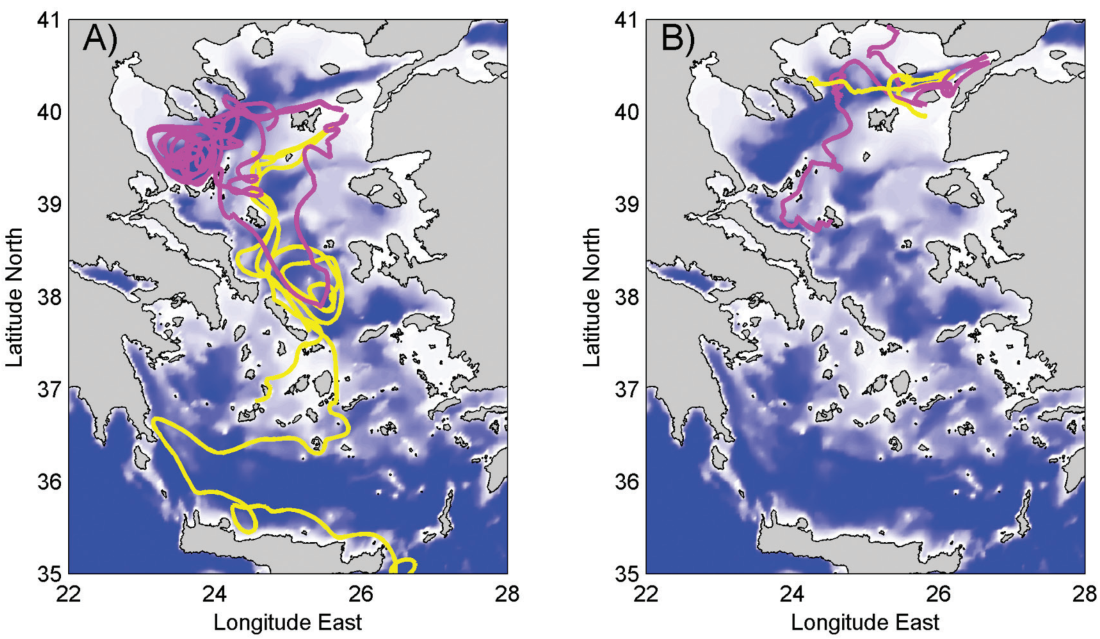

Fig. 3: Drifter trajectories during the 2008 (A) and 2009 (B) experiments. The drifters of the northern triplets are indicated in magenta colour, while the drifters of the southern triplets are depicted in yellow colour. Depth colourbar is the same as in Figure 1.

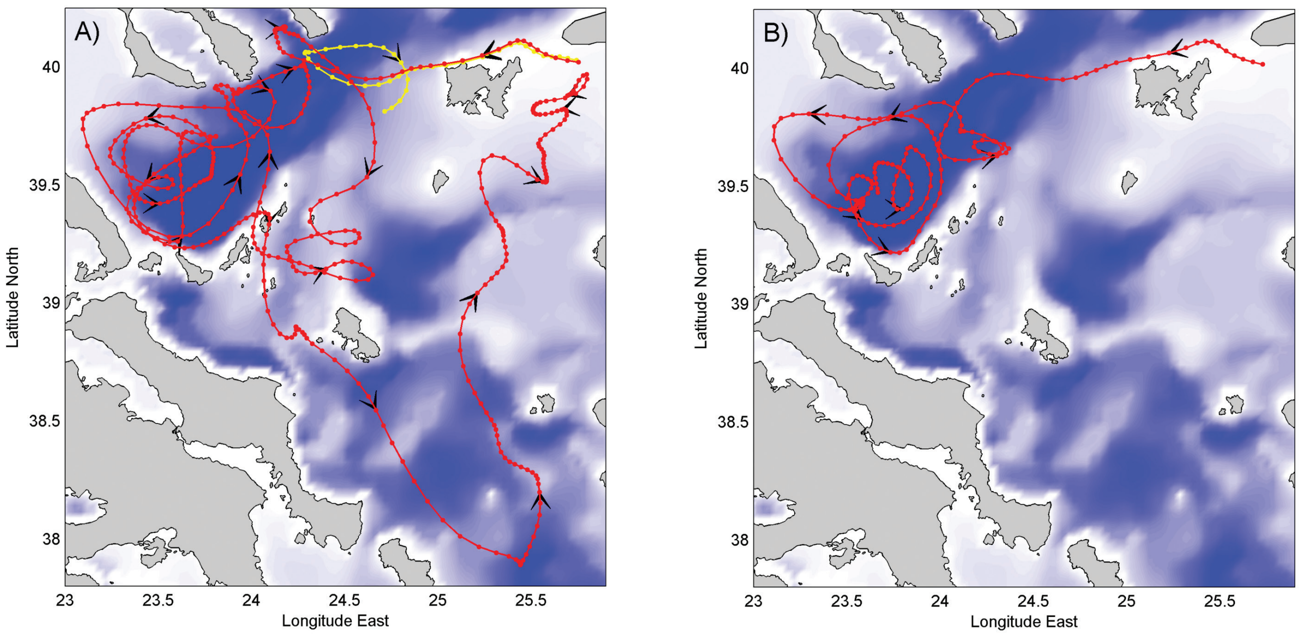

Fig. 4: Six-hourly interpolated trajectories of the northern triplet drifters during the 2008 experiment superimposed on the bathymetry: A) drifter b1 (red curve) and drifter b2 (yellow curve) and B) drifter b3. The dots show the drifter position every 6 hours and the black arrows, indicating the direction of the drifters, are depicted every 5 days. See Table 1 for drifter attributes. Depth colourbar is the same as in Figure 1.

completed an anticyclonic loop in 5 days and then stopped functioning (yellow curve in Fig. 4A). The third drifter slowed down even more (the points representing the drifter positions every 6 hours get very close) and remained inside Singitikos Bay for about 5 days and then headed to the south. It displayed two loops (one anticyclonic and one cyclonic; extension of about 15 km and periods of 2-3 days) east of the Sporades Islands before veering to the north (passing between the Sporades Islands) and joining the drifter that was entrained in the cyclonic Sporades Eddy. This cyclone did not appear very strong during this period. Indeed, drifters inside it slowed down, depicted some smaller scale features (extension of about 10-15 km and period of 2-4 days) and even reversed for a short period of time or jumped in and out from a contiguous anticyclone (displayed also by Zervakis & Georgopoulos, 2002) located south of Singitikos Bay. One drifter stopped functioning while depicting the cyclonic feature (Fig. 4B), whereas the other one (red curve in Fig. 4A) escaped from the eddy passing again between the Sporades Islands and heading southward along the Evoia coast until 38°N. Then it veered to the north and reached the deployment area in a meandering path.

Drifters deployed in the southern triplet on 28 August 2008 (yellow curves in Fig. 3A and Figs. 5A, 5B and 5C) headed straight towards Agios Efstratios Island where they slowed down, then proceeded further westward and, at about 24.5°E, they veered southward bordering the eastern coast of Skyros Island. All three drifters moved southward as far as southern Evoia Island and then depicted a strong flow along the northern Cycladic Islands (drifter speed up to 73 cm/s; Table 1). East of Andros Island, one drifter completed 3 loops in about one month marking the presence of the Chios cyclonic gyre (Fig. 5A). Two drifters crossed the Cycladic Islands, one passed between Tinos and Mykonos and then was stranded at Milos Island (Fig. 5A) and one slowly encircled the entire plateau marked by the Cycladic Islands and then headed westward along about 36.5°N, as far as the Peloponnesus (Fig. 5C). Upon reaching Crete Island, the drifter was entrained in an anticyclonic feature centred at 35.7°N, 24.3°E and exited the Aegean Sea east of Crete Island.

2009 experiment

During the 2009 experiment (Fig. 3B and Figs 6A and 6B), only 4 drifters out of the 6 drifters released roughly at the same positions as those of the 2008 deployments, provided useful information. All drifters initially moved north-westward as a result of the southerly winds which were advecting surface waters to the north. Two of them (yellow and magenta curves in Fig. 6B) explored back and forth the Saros Gulf and the others crossed the deep Lemnos Basin (Fig. 6A and red curve in Fig. 6B). Only one drifter exited the Lemnos Basin and provided additional information east of the Sporades Islands (Fig. 6A). It displayed several cyclonic loops with an extension of about 5-15 km east of the Athos Peninsula and then headed southward and south-westward in a meandering path as far as Evoia Island, surrounding the eastern coasts of the Sporades Islands. This drifter then veered eastward and continued to meander slowly until it reached Skyros Island.

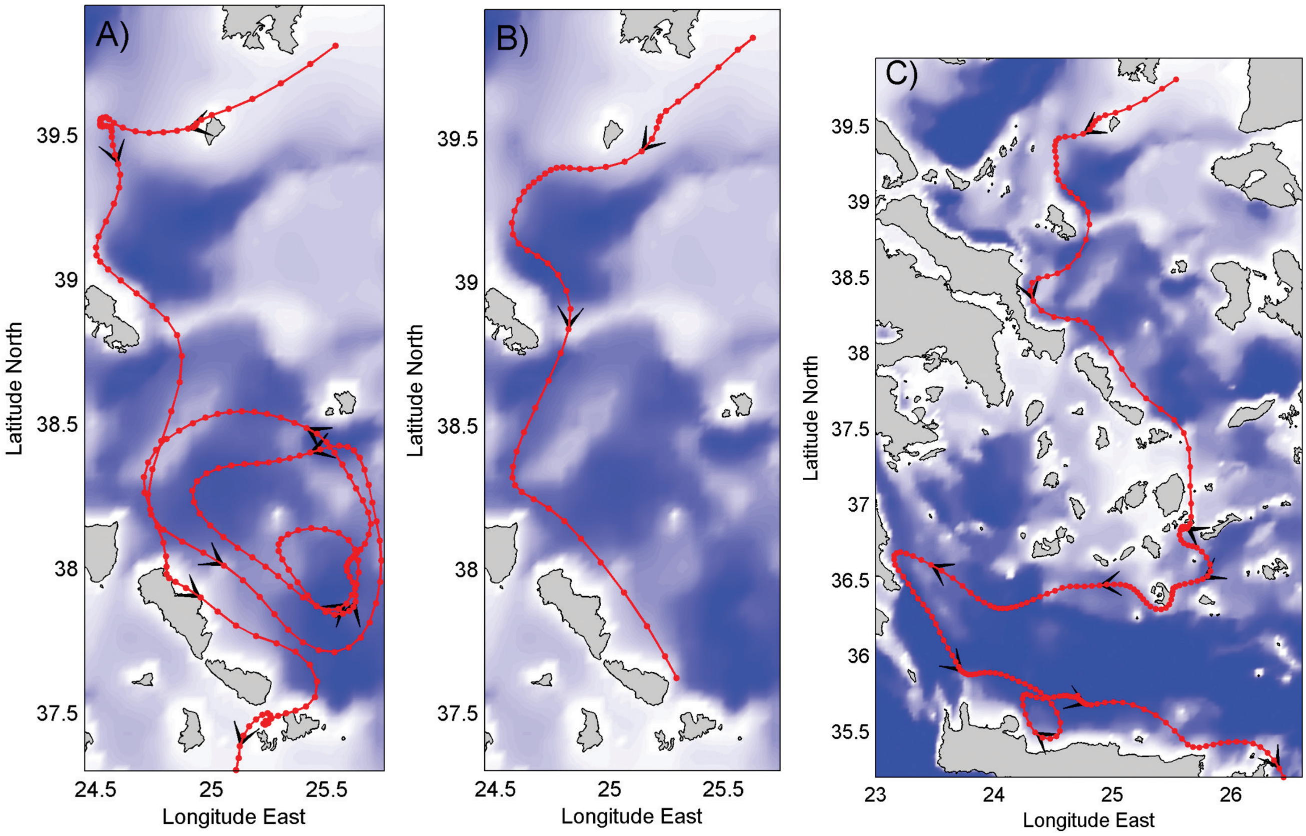

Fig. 5: Same as Figure 4, but of the southern triplet drifters during the 2008 experiment: A) drifter a1; B) drifter a2 and C) drifter a3.

Discussion

Wind influence

During the first experiment (2008 late summer launches) wind blew mainly from the northeast with some short episodes of southerly winds and a strong reversal to southerlies at the end of the experiment (Fig. 2B). The prolonged winds from the north to northeast are typical during the summer to early autumn months in the Aegean and, therefore, the conditions in 2008 were quite normal. The second experiment (2009 winter launches) was short in time and characterized by two wind reversals (Fig. 2C). This was also a seasonally typical pattern, as winter months are characterized by frequent reversals, due to the passage of cold fronts.

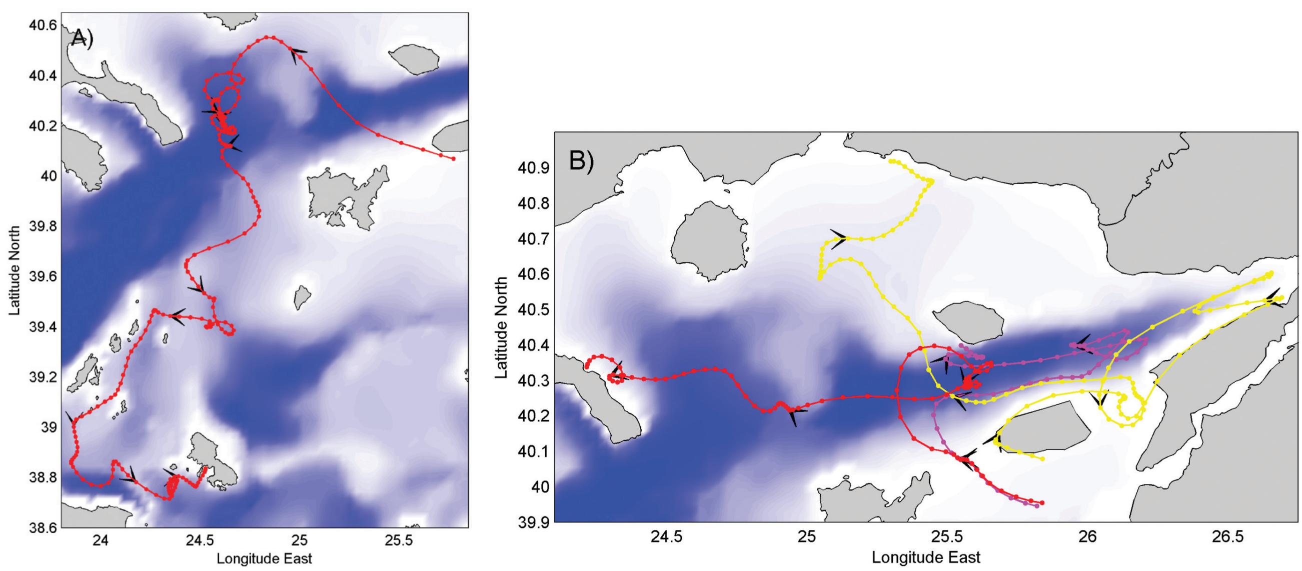

Fig. 6: Same as Figure 4, but of the drifters during the 2009 experiment: A) drifter d1 and B) drifter c1 (red), drifter c2 (magenta) and drifter d3 (yellow).

The variability of the Dardanelles outflow was coherent with the along-strait wind stress and the bottom pressure anomaly gradient (Jarosz *et al*., 2012). Obviously, strong north-easterly winds during September 2008 were in favour of initially westward pathways for the Dardanelles outflow and resulting in outflow intensification. During this period we observed southward movement of the drifters further offshore. On the other hand, drifters were moving towards the north during the winter, indicating the role of the prevailing southerlies.

The wind progressive vector diagrams (Fig. 7) were considered to explore the motion of a water particle moving under wind forcing only. To draw the path of such a particle, its speed was considered to be 1% of the wind speed (according to Poulain *et al*., 2009). During the 2008 experiment, the effect of the predominant northerly winds is clearly evident. The theoretical particle moved in a south-southwest direction almost continuously for about 2.5 months displaying only a few short reversals. This wind regime is common to almost all drifters of the 2008 experiment. When wind changed to southerlies in November (Fig. 2B and as evidenced by the change of trajectory of the theoretical particle, Fig. 7A) only one drifter was still providing useful data (drifter b1 of Fig. 4A). This significant reversal of the wind corresponds to an abrupt change of the trajectory of this drifter on 23 November at about 38.0°N - 25.5°E (Fig. 4A). The wind progressive vector diagram during the 2009 experiment (Fig. 7B) shows a theoretical particle that first moves towards the north and then oscillates along the north-northeast – south-southwest direction under the effect of two wind reversals, before it veers to the south in

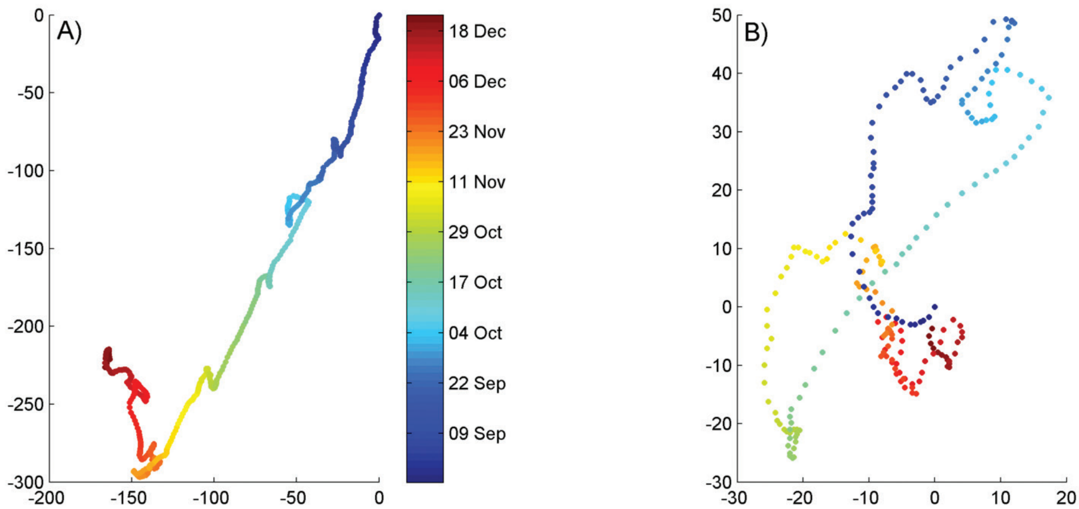

Fig. 7: Wind progressive vector diagrams for the 2008 (A) and 2009 (B) experiments colour coded with the time. The axis represents the displacements in km of a pure wind-driven particle having a speed equal to 1% of wind speed.

Table 2. Results of the wind linear regression model $D=a+bW$ ($D=u_{drifter}+iv_{drifter}$; $W=u_{wind}+iv_{wind}$; speeds in cm/s; angles in degrees counter clockwise from east; R^2 is the determination coefficient and N the number of 6-h observations).

Drifter	*a*	*b*	*R2* (%)	*N*
all	0.6*exp(-93*i)	0.014*exp(-14*i)	13	1727
Exp 1	1.1*exp(-29*i)	0.016*exp(-11*i)	12	1203
Exp 2	2.3*exp(171*i)	0.011*exp(-31*i)	16	524
a1	0.3*exp(89*i)	0.016*exp(-6*i)	17	234
a2	7.1*exp(-54*i)	0.026*exp(-10*i)	11	54
a3	5.0*exp(-133*i)	0.018*exp(23*i)	14	236
b1	2.3*exp(2*i)	0.013*exp(-27*i)	8	460
b2	3.4*exp(16*i)	0.027*exp(-39*i)	16	41
b3	2.2*exp(-152*i)	0.011*exp(-49*i)	3	178
c1	6.5*exp(165*i)	0.008*exp(-44*i)	12	97
c2	3.3*exp(168*i)	0.017*exp(-37*i)	38	72
d1	3.1*exp(-134*i)	0.007*exp(1*i)	7	223
d3	2.0*exp(90*i)	0.018*exp(-42*i)	31	132

mid-March. The wind reversals clearly influenced the trajectories of the drifters located in the north-eastern part of the Aegean Sea. For example, a portion of the paths of the two drifters deployed during 2009 that explored the Saros Gulf (drifters c2 and d3, yellow and magenta curves in Fig. 6B, respectively) can be recognized in Fig. 7B.

A linear complex regression model $D=a+bW$ was employed for all drifters (and also divided by experiments and for each individual drifter), to assess the direct effect of the wind on the drifters ($D=u_{drifter}+iv_{drifter}$; $W=u_{wind}+iv_{wind}$). The regression model explains about 13% of the overall drifter velocity variance in terms of linear wind dependence (12% and 16% for the first and second experiment, respectively). The highest correlations occur for the drifters in the north-eastern part of the Aegean Sea with an explained variance higher than 30% (drifters c2 and d3, see Table 2). The complex coefficient *b* indicates that the wind-driven current measured by the drifters is between 0.7% and 2.7% of the wind speed. In particular, the wind-driven current for the two drifters that appear qualitatively to be largely influenced by the wind (c2 and d3) is 1.7%. This value is larger than the value (1%) found by Poulain *et al*. (2009) for the Mediterranean Sea and is consistent with the shorter length of the oscillations depicted by the theoretical particle (Fig. 7B, about 20 km) during the 2009 experiment with respect to the real drifter displacements (Fig. 6B, about 40-45 km). Additionally, the exponent of the *b* coefficients ($b = |b|\ e^{i\varphi}$) is nearly always negative, meaning that drifters move to the right of the wind vector (between 6° and 49°) in qualitative agreement with the Ekman dynamics.

The influence of the Dardanelles outflow induced thermal fronts

The initial drifter positions were well into the general area of influence of the Dardanelles plume, as detected from ship-borne CTD data (E. Jarosz, personal communication). The Dardanelles plume is the result of the BSW outflow through the TSS to the Aegean Sea. Therefore, it has a signature in both the near surface salinity and temperature fields, and appears fresher and cooler than the surrounding Aegean waters.

Hundreds of SST satellite images from the AVHRR data were considered in order to quantify the correlation between the drifter tracks and the thermal fronts. Such satellite data are usually very noisy and incomplete mainly because of cloud coverage. Therefore, in order to reduce the noise and qualitatively evaluate the influence of the thermal front with respect to the drifter motion, the 3-day composites of the SST satellite images were elaborated and the 3-day long drifter trajectories were superimposed on them. Unfortunately, the SST images during the 2009 experiment are very scarce and, therefore, it was not possible to obtain good composite pictures for this second experiment. Nevertheless, the correspondence between the orientation of the thermal front and drifter trajectories in some cases is remarkable as for the periods 28-30 August 2008 and 5-7 September 2008 (Fig. 8).

These images give only a qualitative idea of the relation between a thermal front and drifter motion. To evaluate quantitatively the importance of the thermal front, the SST image much closer in time (within 1 h) to each drifter observation was selected, the SST data were spatially averaged and the thermal gradient was

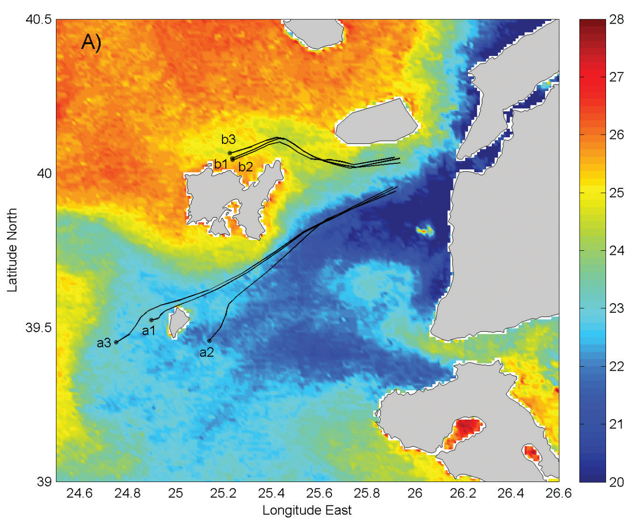

Fig. 8A: Three-day drifter trajectories superimposed on the SST composite of the period 28-30 August 2008. The dot symbols correspond to the end of the 3-day trajectories.

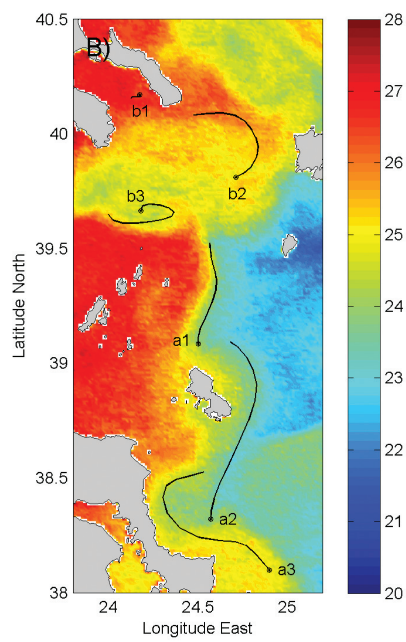

Fig. 8B: Same as Figure 8A but for the period 5-7 September 2008.

computed on a 3 km x 3 km grid; the grid point closest to the drifter position was then chosen. The bin size was conveniently selected so as to smooth the SST noise, while capturing the important front patterns and in order to have, on average, two consecutive drifter observations in different but adjacent SST bins. In case of missed values, the selection was repeated considering the SST images within a time window of ± 3 hours from the drifter observation.

The complex regression model already used to evaluate the wind influence was applied, considering the contributions of the wind and the thermal gradient both together and separately (whenever the SST gradient observations were available). These statistics are conditioned by the limited number of SST satellite images. For example, the wind-only statistics for 2008 are quite similar to the ones computed by using all available wind data. However, the results for the 2009 experiment (when very few good SST images are available) are inadequate and, therefore, not shown. For the 2008 experiment, the thermal gradient contribution seems to be quite important for some drifters for which the explained variance exceeds 10-15% and is larger than the one due to the wind-only contribution (statistical results are not shown).

The selected time periods, shown in Figure 8, were further investigated. The paths of the drifters during three days after deployment (28-30 August 2008, Fig. 8A) reveal that drifters separated in two branches north and south of Lemnos, in agreement with the drifter-derived schema of Olson *et al*. (2007) and with the simulations of Kourafalou & Barbopoulos (2003). The southern branch seems to follow the 23-24°C front at least for the first 1.5-2 days; then drifters separated, crossed the front and moved into the cooler waters around Agios Efstratios Island. The northern drifters remained together for the entire 3-day period, apparently unaffected by any thermal front.

The explained variance of the overall model (wind and SST gradient contributions) for this period is around 22% (Table 3). Calculations for each forcing suggest that the front is of similar importance as the wind (determination coefficient for front-only is R^2 = 9%; for wind-only R^2 = 14%). Additionally, the drifters move to the right of the wind, keeping the colder water to the left. The drifters of the southern branch display the highest overall (wind and front) R^2 values, especially drifters a1 and a3 with R^2 close to 100%. These two drifters also have the highest front-only R^2 (89% and 44%, respectively), while the northern branch drifters have R^2 values around 9% (statistical results of each drifter are not shown).

During the period between 5 to 7 September 2008 (Fig. 8B), the overall R^2 computed considering all the available observations is 22% again, but the contribution of the SST gradient is slightly reduced with respect to the other selected period (7%, Table 4). The movement of the drifter to the right of the wind and to the left of the colder waters is confirmed. The northern drifters remained confined in the northern Aegean Sea. In particular, drifter b1 remained entrapped inside Singitikos Bay. The other two units evidenced the eddy activity in the Sporades Basin. The R^2 derived from the front-only model for these drifters is between 21% and 34% and is higher than the one obtained from the wind-only model in two out of three cases. All the southern drifter motions were southward oriented and very fast. Their trajectory matched the fronts quite well, especially the a2 drifter, where the front-only R^2 reaches 70%.

Conclusions

Observations from drifters released in the north-eastern Aegean Sea have revealed new aspects of the influence of waters of Black Sea origin (BSW) on the circulation of the Aegean Sea. In particular, the

Table 3. Results of the different linear regression models for the period 28-31 August 2008 computed using all the available drifter data; first line: overall model (wind and SST gradient contributions); second line: front-only model; last line: wind-only model; $D=u_{drifter}+iv_{drifter}$; $W=u_{wind}+iv_{wind}$; $F = \partial SST / \partial x + i\, \partial SST / \partial y$; angles in degrees counter clockwise from east; R^2 is the determination coefficient and N the number of 6-h observations.

	a	***b***	***c***	***R2* (%)**	***N***
D=a+bW+cF	14.4*exp(-170*i)	0.019*exp(-44*i)	8.85*exp(111*i)	22	46
D=a+cF	21.3*exp(-162*i)		8.78*exp(107*i)	9	46
D=a+bW	15.5*exp(-171*i)	0.019*exp(-42*i)		14	46

Table 4. Same as Table 3 but for the period 5-7 September 2008.

	a	***b***	***c***	***R2* (%)**	***N***
D=a+bW+cF	13.8*exp(14*i)	0.041*exp(-9*i)	8.90*exp(75*i)	22	55
D=a+cF	12.1*exp(-69*i)		11.08*exp(94*i)	6	55
D=a+bW	15.3*exp(9*i)	0.043*exp(-14*i)		19	55

influence of thermal fronts (due to the cooler BSW) is elaborated for the first time. Although the TSS drifter data set is much smaller with respect to the one of Olson *et al*. (2007) (10 drifters VS 45 drifters), it covers the Aegean basin quite well, capable of underlining the main features of surface circulation. The data set presented herein supports previous findings on the circulation characteristics of the Aegean basin, but also provides new insights. The drifter trajectories reveal quite complex surface circulation, as already described by Olson *et al*. (2007). The basin-scale cyclonic circulation (due to the rim current along the North Aegean shelf break resulting from the Dardanelles buoyant plume) is evident from the TSS drifter trajectories. This is clearly visible in the 2008 experiment. In contrast, we were not able to identify basin-scale cyclonic circulation during winter 2009, not because of the limited number of drifters, but because of the more complex circulation pattern due to the strong southerly winds.

The unprecedented deployment of the drifters very close to the exit of the flow from the Dardanelles allowed further establishment of the relative role of the Dardanelles outflow and the wind forcing on the circulation characteristics of the northern Aegean and to characterize pathways of BSW immediately after their entry into the Aegean. With launch positions very close to the Dardanelles Strait, our study depicts the branching behaviour schematized in other works (Zodiatis *et al*., 1996; Olson *et al*., 2007; Kalantzi *et al*., 2010), but never previously verified by *in situ* measurements.

The wind strongly influences the surface current, as already pointed out in previous studies (Zervakis & Georgopoulos, 2002; Tzali *et al*., 2010; Androulidakis & Kourafalou, 2011; Androulidakis *et al*., 2012a, b). The strong southerlies recorded during the 2009 experiment confined the Dardanelles outflow to the north and worked against the buoyancy-driven, cyclonic rim current. These findings support the process-oriented numerical experiments of Androulidakis & Kourafalou (2011). During the Etesian regime in 2008, the surface current separated into two distinct branches around Lemnos Island, in agreement with modelling studies (Zodiatis *et al*., 1996; Androulidakis & Kourafalou, 2011) and previous observational findings by Olson *et al*. (2007). Water passing north of Lemnos Island flowed into the Sporades Basin, where it was trapped in the Sporades eddy and then moved southward along the Evoia and Cycladic Islands in a strong jet, finally completing the basin-scale cyclonic gyre. The southern flow crossed the basin, joined the strong jet offshore the Evoia Island and evidenced by the Chios cyclone. Finally, the path of one drifter suggests that the BSW can reach Crete Island flowing all along the western Aegean coast and eventually enter the deeper Eastern Mediterranean basin.

The wind influence explains part of the drifter velocity variance. Specific drifters are well correlated with the wind. In particular, the drifters deployed in 2009 (winter season), and especially the drifters that explored the north easternmost area of the basin, appear to be more affected by the winds. Data provided by drifter c2 support this finding, during a period when the SST satellite images indicate weak temperature variations in the area, while the Dardanelles outflow is at a seasonal low (Kourafalou & Barbopoulos, 2003). The drifter was thus highly driven by the wind, exhibiting the highest correlation (38%, see Table 2). Additionally, the drifter trajectory is very similar to the wind progressive vector diagram of the second experiment (compare Fig. 6B with Fig. 7B). This pathway was also partially followed by another drifter launched in winter (for more than half of its life), which presents a correlation with the wind exceeding 30%. Furthermore, the wind-driven current measured by the drifters in the Aegean Sea can be larger than the value found by Poulain *et al.* (2009) for the Mediterranean Sea.

The role of the thermal fronts (induced by the outflow of cooler BSW at Dardanelles) was also investigated by computing the gradient of the SST satellite images and considering a linear complex regression model. A limitation of this analysis is the lack of continuous satellite coverage, due to intermittent cloud coverage. However, the analysis provided important insights on the role of thermal fronts on the drifter tracks. The contribution of these gradients is generally of secondary importance with respect to the influence of the wind, except for some drifters, which demonstrate that the front is of the same importance as the wind during the 2008 experiment. The contribution of circulation connected to the Dardanelles outflow is even larger than the wind for some drifters during the selected periods, in agreement with the findings of Olson *et al*. (2007).

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