Deep-Sea Research Part I 138 (2018) 22–33

Contents lists available at ScienceDirect

Deep-Sea Research Part I

journal homepage: www.elsevier.com/locate/dsri

Mapping Mediterranean tidal currents with surface drifters

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ARTICLE INFO

Keywords:
Mediterranean Sea
Drifters
Tidal currents

ABSTRACT

Velocities of surface drifters are analyzed to study tidal currents throughout the Mediterranean Sea, with main focus on the semi-diurnal tide. Harmonic analysis on 15-day long trajectory segments reveals semi-diurnal tidal amplitudes larger than 5 cm/s in the Alboran Sea, the northern Adriatic Sea, the Sicily Channel and the Gulf of Gabès. Elsewhere the tidal currents are weak (< 2 cm/s) except for a few isolated locations where the semi-diurnal currents are significant, such as in the eastern Aegean Sea. S2 is similar to M2, but the amplitudes are generally smaller. In general, the drifter-inferred results confirm previous (mostly coastal) observations and numerical simulations of the Mediterranean tidal currents. In addition, they provide novel information on the tidal currents in the open sea. It was found that substantial K1 signals prevail in the Alboran Sea and some regions of the Sicily Channel and the Adriatic Sea. However, the results for the diurnal constituents should be interpreted with caution due to the possible contamination by leakage of near-inertial energy in the tidal bands and by currents forced by the sea breeze.

1. Introduction

The tides of the Mediterranean Sea are produced by direct gravitational forcing and the boundary forcing at the Strait of Gibraltar (Pugh, 1987; Tsimplis et al., 1995). The Mediterranean Sea has a complex topography characterized by both deep (e.g. Liguro-Provençal, Tyrrhenian, Ionian, Levantine) and shallow (Adriatic and Aegean) sub-basins separated by straits, channels, sills and islands (Fig. 1). The tidal regime can be different in each sub-basin, depending on the propagation of the tidal waves through the sub-basin entrances and their interaction with the bathymetry. Even though the vertical tide is generally small in the Mediterranean (exceeding 20 cm in sea level amplitude only in a few regions such as the Alboran Sea, the northern Adriatic Sea and the Gulf of Gabès), the interaction of the different tidal regimes at the main connections between the sub-basins generates significant tidal currents (Pugh, 1987; Tsimplis et al., 1995). Hence, currents at tidal frequencies can be larger than a few cm/s in some regions of the Mediterranean Sea (see Fig. 1 for geographical references), such as the Strait of Gibraltar and the Alboran Sea (Candela et al., 1990; García Lafuente and Cano Lucaya, 1994; Albérola et al., 1995; Soto-Navarro et al., 2016), the Sicily Channel (Grancini and Michelato, 1987; Gasparini et al., 2004; Cosoli et al., 2015), the Strait of Messina (Vercelli, 1925; Hopkins et al., 1984; Bignami and Salusti, 1990) and the northern Adriatic Sea (Poulain, 2013). Tidal currents can also be substantial in coastal areas, including the continental shelf/slope off northeastern Spain (Rippeth et al., 2002) and off southern Italy in the Otranto Channel (Ursella et al., 2014).

Knowledge on the tidal currents in the Mediterranean Sea is based on direct current measurements in localized areas, from shipboard (Garcia-Gorriz et al., 2003; Gasparini et al., 2004) and moored instruments (Grancini and Michelato, 1987; García Lafuente and Cano Lucaya, 1994; Albérola et al., 1995; Ursella et al., 2014) and by means of high-frequency (HF) coastal radars (Chavanne et al., 2007; Cosoli et al., 2012, 2015; Soto-Navarro et al., 2016).

In the eastern part of the Strait of Gibraltar, near-surface currents measured by moored current meters are mostly zonal with amplitudes near 30 cm/s in both the semi-diurnal and diurnal bands (Candela et al., 1990). This was confirmed with HF radar observations in and east of the Strait of Gibraltar (Soto-Navarro et al., 2016), disclosing significant surface tidal currents with amplitudes as large as 35 cm/s and 17 cm/s for the semi-diurnal (M2) and diurnal (K1) tidal currents, respectively. Ship-board ADCP data analyzed by Garcia-Gorriz et al. (2003) showed that the largest amplitudes of the semi-diurnal currents in the Alboran Sea also occur in the vicinity of the Strait of Gibraltar, with values of 25–30 cm/s. More to the east off the Spanish coast in the Alboran Sea, harmonic analyses of current meter data revealed tidal amplitudes reaching 6–9 cm/s (García Lafuente and Cano Lucaya, 1994). In the Strait of Messina, connecting the Tyrrhenian and Ionian seas, Vercelli (1925) measured extremely large M2 tidal currents with amplitude of 2–3 m/s. A review of the tidal dynamics in the Strait of Messina can be

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https://doi.org/10.1016/j.dsr.2018.07.011
Received 4 August 2017; Received in revised form 19 June 2018; Accepted 16 July 2018
Available online 17 July 2018

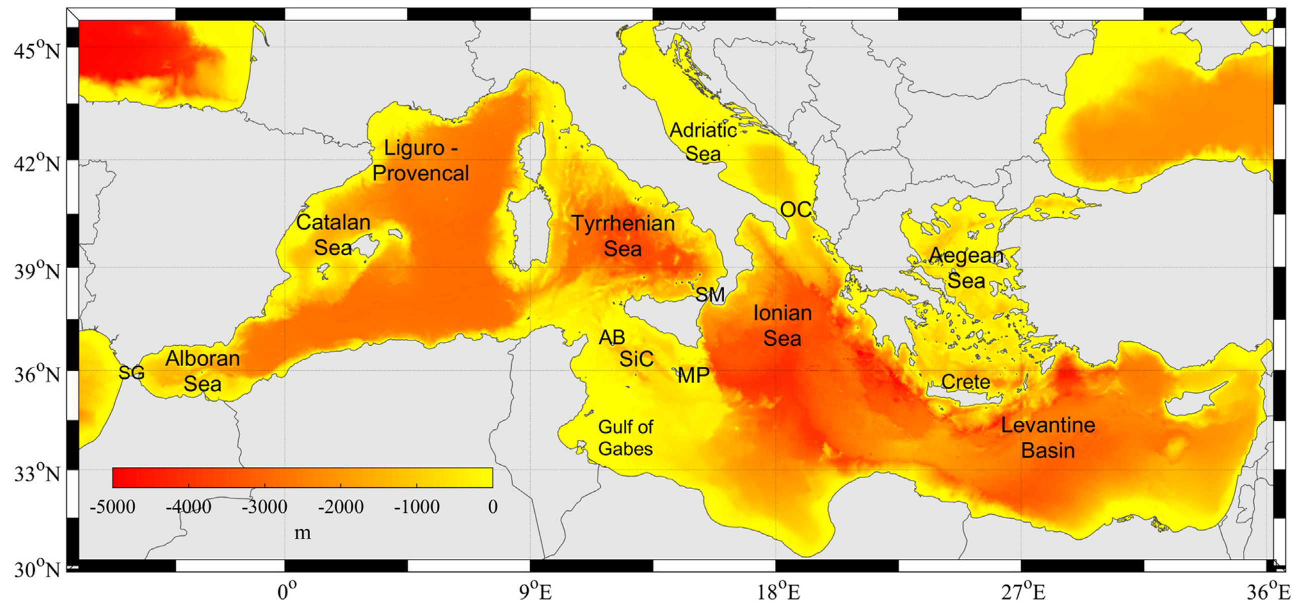

Fig. 1. Geography and bathymetry of the Mediterranean Sea: SG (Strait of Gibraltar), AB (Adventure Bank), SiC (Sicily Channel), MP (Malta Plateau), SM (Strait of Messina) and OC (Otranto Channel).

found in Bignami and Salusti (1990). These tidal currents can generate internal waves or solitons at semi-diurnal frequency which propagate into the deep basins. They can be detected as they modulate the surface reflection of satellite radar signals (Brandt et al., 1997). Similar internal waves or solitons radiating from the Strait of Gibraltar can be routinely observed in the Alboran Sea (Brandt et al., 1996). In the Sicily Channel, large diurnal tidal currents of about 10 cm/s were measured on the Sicilian shelf (and Adventure Bank) by Grancini and Michelato (1987). This amplification of the tidal currents on Adventure Bank was confirmed by the ship-board ADCP data collected by Gasparini et al. (2004), with a maximum of 20–25 cm/s for M2 and 5–10 cm/s for K1. Large diurnal currents were also shown (~ 5 cm/s) over the Malta Plateau. They were also recently measured by HF coastal radars (Cosoli et al., 2015). Tidal currents in the Adriatic Sea were studied by means of HF radars (Chavanne et al., 2007) and surface drifters (Poulain, 2013). The M2 currents reach 7 cm/s in the northern Adriatic whereas the K1 currents have speed larger than 5 cm/s in areas of the northern and central Adriatic. In the southern Adriatic and Otranto Channel, tidal current amplitudes are reduced to 1–2 cm/s, as also confirmed by the current meter data analyzed by Ursella et al. (2014). However, on the western flank of the Otranto Channel, over the continental shelf, Ursella et al. (2014) reported diurnal tidal currents reaching 10 cm/s.

Tidal sea level variations and currents are also derived from numerical models. Molines (1991) used a numerical barotropic model to study the tide in the Sicily Channel and adjacent areas. He found that the M2 tidal currents are maxima in two areas: in the Gulf of Gabès, due to M2 resonance (Sammari et al., 2006), with speeds reaching 30 cm/s, and on Adventure Bank (reaching about 15 cm/s). Tsimplis et al. (1995) developed a Mediterranean barotropic tidal model forced by the equilibrium tide (direct gravitational forcing) and by the tide in the Strait of Gibraltar. Their M2 tidal currents are weak (< 1 cm/s) in most areas except near the Strait of Gibraltar, in the northern Adriatic, the Sicily Channel, the Gulf of Gabès, and parts of the Aegean and the Egyptian coastal waters, where their amplitude can exceed 10 cm/s. S2 currents have similar spatial patterns but with reduced amplitudes. Diurnal (K1) currents exceed 5 cm/s in the Strait of Gibraltar, the Sicily Channel and the Adriatic Sea. Arabelos et al. (2011) operated a high-resolution barotropic tidal model that assimilates satellite altimeter data and coastal tide-gauge stations. Their simulated semi-diurnal currents are large in the Strait of Gibraltar, the Sicily Channel and southwest of Crete, in some contradiction with Tsimplis et al. (1995)'s results. Abdennadher and Boukthir (2006, 2016) studied the M2 tide in the Sicily Channel with barotropic and baroclinic models. They found that semi-diurnal currents are maximum in the Gulf of Gabès whereas diurnal components dominate on Adventure Bank. Three sites of internal tide generation were found, where the barotropic M2 tidal flow interacts with the sloping topography to generate internal tidal waves which propagate mostly to the north (towards the Tyrrhenian Sea) and to the southwest (towards the Tunisian shelf). Most of the above-mentioned models also provide information on the inclination and sense of rotation of the tidal current ellipses.

This work represents the first attempt to estimate the tidal currents in the entire Mediterranean Sea using surface drifter data. The method, adapted from Poulain and Centurioni (2015), allows to describe the mean general features of the surface tidal currents using four principal tidal constituents (M2, S2, K1 and O1) at scale of about 100 km. The paper focuses mainly on the semi-diurnal tide (M2 and S2) due to complexities involved with the interpretation of the diurnal results. The Strait of Messina is not considered given its small width and the scarce drifter sampling in its vicinity. The paper is organized as follow: the drifter dataset and the methodology used to process the data are described in Section 2 and the main results of the spectral and harmonic analysis are presented in Section 3. Discussions and conclusions are in Section 4.

2. Data and methods

2.1. Mediterranean Sea drifter dataset

The Mediterranean Sea drifter dataset used in this work is named MedSVP_db24 (Menna et al., 2017, 2018a, b). It includes data come from a variety of drifter designs, but only the data of Coastal Ocean Dynamic Experiment (CODE) and Surface Velocity Program (SVP) drifters with known drogue status were considered here. A total of 931 drifter trajectories longer than 15 days were used (526 CODE and 405 SVP), covering the period from June 1986 to December 2017 (http://nettuno.ogs.trieste.it/sire/medsvp/). Technical details about the different drifter designs and their slip with respect to the surface currents can be found in Poulain et al., (2012, 2013) and Menna et al. (2017) and references therein. The CODE drifters measure the currents in the first meter below the surface with an accuracy of less than 2 cm/s (Poulain et al., 2002). The SVP drifters are fitted with a holey-sock drogue at a nominal depth of 15 m and measure the mixed layer currents. The drogue presence status was estimated using the data of the drogue presence sensor (strain gauge) and the correlation with the local winds (see Menna et al., 2018a, b). In this work, the data of 21 SVP drifters with drogue at 10, 12 and 12.5 m were also included in the database even though they do not correspond to the SVP standards. Measurements of the water-following capabilities of the SVP have shown that, when the drogue is attached, they follow the water to within 1 cm/s in 10 m/s winds (Niiler et al., 1995). Poulain et al. (2009) have shown that the low-frequency drifter currents are correlated with the local wind: they are 1% of the wind speed for the CODE and drogued SVP designs and 2% of the wind speed for the undrogued SVP drifters. In this work, the drifter velocities were not corrected for possible slippage due to winds and waves, and the wind-related components were not removed, because this complicated endeavor is beyond the scope of this paper.

Although we are well aware that the currents measured by the drifters can vary due to their different water-following characteristics and the different depths at which the currents are measured, all the CODE and drogued SVP drifters have been combined in this work in order to maximize the density and the geographical coverage of the observations in the entire Mediterranean Sea. We have attempted to divide the drifter dataset and compute the tidal statistics only for CODE, drogued and undrogued SVP drifters separately. Unfortunately by doing so, the spatial coverage is only partial and different for all the drifter types. Hence, the comparison is difficult. We have only noticed that for undrogued SVP drifters the diurnal (K1) tidal currents are generally larger in the northwestern Mediterranean and central Ionian, when compared with the results for the drogued SVP and CODE drifters. As a result, we have decided to exclude the data of SVP drifters with unknown drogue presence status and corresponding to known drogue loss for the analysis of tidal currents.

Some drifters were localized by, and transmitted data to, the Argos system on-board polar-orbiting satellites with a position accuracy of 300–1000 m and a most frequent sampling period (mode) of about 100 min. Others used Iridium for data telemetry and the Global Positioning System (GPS) to obtain more accurate (about 10 m) and more frequent positions (hourly).

2.2. Drifter data processing

Argos and GPS data were quality controlled and interpolated at half-an-hour uniform intervals using a kriging technique based on a structure function whose characteristics were calculated from the data themselves (Hansen and Poulain, 1996; Poulain, 2001; Menna et al., 2017). Velocities were then calculated as finite central differences of the interpolated positions with an hourly time interval.

The drifter position and velocity data were split in 15-day long segments overlapping by 50% along the individual trajectories. For SVP drifters, data corresponding to drifter with drogue attached were only considered. Segments containing interpolated values over data gaps longer than 6 h were discarded. In total, 2254 drifter trajectory segments were available in the Mediterranean Sea for the period 1986–2017, including 315 (~ 14%) segments of Argos-tracked drifters and 1939 (~ 86%) of GPS-tracked drifters. A period of 15 days allows separating the M2 and S2 tidal constituents as it is larger than the corresponding Rayleigh period of 14.77 days. The t_tide MATLAB package (Pawlowicz and Lentz, 2002) was applied to all the segments using the following diurnal and semi-diurnal tidal constituents: K1 (lunar diurnal, period = 23.93 h), O1 (lunar diurnal, period = 25.82 h), M2 (principal lunar semi-diurnal, period = 12.42 h) and S2 (principal solar semi-diurnal, period = 12 h). These constituents were chosen as the most important ones characterizing tidal currents in the World Ocean (Poulain and Centurioni, 2015). As shown in Poulain and Centurioni (2015) additional constituents can be determined using inference but for the Mediterranean Sea the difference is negligible and inference is not necessary. Confidence limits on the t_tide output parameters (amplitude of semi-major and semi-minor axes, inclination, Greenwich phase), and corresponding signal-to-noise ratios, were estimated using a linearized error analysis that assumes an uncorrelated bivariate colored noise model (Pawlowicz and Lentz, 2002). In the rest of the paper, the results of the t_tide package were only considered if the signal-to-noise ratio (SNR) for the semi-major amplitude is larger or equal to 1. This restriction reduced drastically the number of available segments from 2254 to 1313 and 1221 for M2 and S2, respectively. The results were assigned at the mean location of each segment. Tidal ellipse inclination and Greenwich phases are given in degrees counted counterclockwise (CCW) from east. The rotary coefficient was calculated following Book et al. (2009).

The main advantage of Lagrangian drifter data is their broad coverage of the entire Mediterranean Sea, including deep open sea areas not easily monitored with other instruments. However, there are several drawbacks which need to be considered when using drifter data. First, drifters are moving with the currents and 15-day trajectory segments can cover geographical areas with scale as large as 100 km. Thus, over 15 days drifters can possibly sample zones characterized by different tidal regimes. Second, erroneous or missing positions during long temporal gaps can degrade our ability to extract the high-frequency drifter motions. As mentioned before, to be conservative, we have excluded segments with data gaps larger than 6 h (the Nyquist period of semi-diurnal motions). Although the majority of the raw data are sampled hourly, temporal gaps between 1 and 6 h can occur (mostly for Argos drifters).

Another important problem is the separation of diurnal tidal motions from near-inertial currents and from currents induced by sea breezes in the coastal areas. Indeed, the harmonic analysis results of the diurnal tidal currents can be contaminated by possible leakage of inertial or near-inertial energy into the K1 and O1 spectral bands near the critical (turning) latitudes. These latitudes are 30.0018°N and 27.6148°N for K1 and O1, respectively, so diurnal tidal and near-inertial signals are difficult to separate in the southern areas of the Mediterranean, especially for K1. Furthermore, because of the possible shift of the effective inertial energy by the background vorticity (Perkins, 1976; Kunze, 1985) the diurnal tidal constituents can be potentially contaminated by inertial energy as far north as 35°N. The sea and land breezes can contaminate the harmonic analysis results in the K1 band, especially for the CODE drifters because they are more sensitive to the local wind forcing. Given the above-mentioned problems to extract diurnal tidal constituents from the drifter data in the entire Mediterranean Sea, we have decided to focus mainly on the results obtained in the M2 and S2 tidal bands.

3. Results

After the presentation of an example of harmonic analysis results, we hereafter present the semi-diurnal tide results for the whole Mediterranean basin, followed by specific discussions on the tidal currents in the northern Adriatic, the Sicily Channel and Gulf of Gabès and the Alboran Sea, where the tidal signal is stronger.

3.1. Example of harmonic analysis for a specific drifter trajectory segment

Fig. 2 shows the trajectory of drifter a47835, a SVP drifter with drogue centered at 12 m and with Argos positioning and telemetry system, between 25 December 2010 and 9 January 2011, on Adventure Bank off the western corner of Sicily. This example was taken because it corresponds to the strongest tidal signal measured by the drifters. Note, however, that the tidal currents are not striking at first glance in Fig. 2.

The results of the harmonic analysis applied to this trajectory segment are listed in Table 1 and illustrated in Fig. 3. When adding the

Table 1
Tidal harmonic analysis results for drifter a47835 between 25 December 2010 and 9 January 2011.

Tide	Major (cm/s)	Error major (cm/s)	Minor (cm/s)	Error minor (cm/s)	Inclination (degree)	Error inclination (degree)	Phase (degree)	Error phase (degree)	SNR
O1	5.9	4.1	− 3.4	6.0	66	93	132	78	2.1
K1	18.9	3.4	− 11.5	6.4	87	32	116	24	30
M2	10.2	2.4	− 3.00	2.4	120	15	172	16	17
S2	4.1	2.4	− 1.7	2.4	142	45	196	44	3

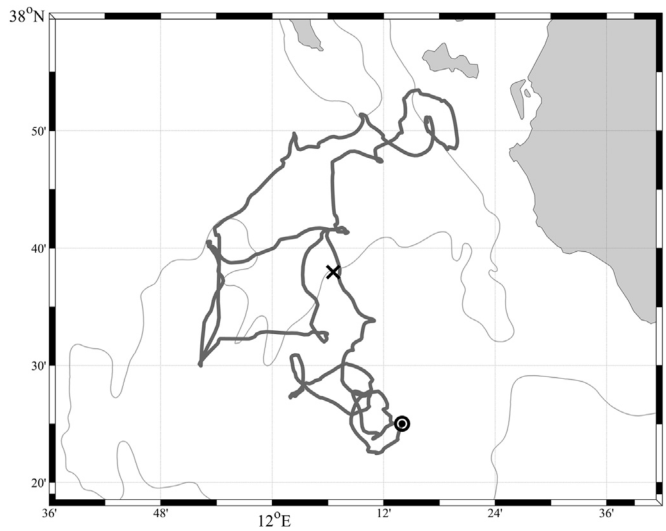

Fig. 2. Fifteen-day trajectory segment (dark curve) and initial position (circle symbol) of drifter a47835 on 25 December 2010 at 18:30 UT. The drifter mean position is shown with a cross symbol. The 100-m isobath is shown with a light gray curve.

four constituents, maximum tidal currents reach 35 cm/s, explaining 33% of the total velocity variance. The M2 and K1 constituents dominate with semi-major axis amplitudes in excess of 10 and 18 cm/s, respectively. The S2 and O1 tides are smaller (< 6 cm/s) and less significant as the signal to noise ratio less than 3. All tidal currents rotate in the clockwise (CW) sense of rotation.

3.2. Semi-diurnal tidal currents in the entire Mediterranean Sea

The semi-diurnal tidal amplitudes are displayed in Fig. 4. The amplitude of the M2 semi-major axes is maximum in the Gulf of Gabès (~ 13 cm/s). It exceeds 5 cm/s in the Alboran Sea, the Sicily Channel, the Gulf of Gabès, and the northern Adriatic Sea. Significant M2 amplitudes are also found in the Catalan Sea (near 39.5°N, 1°E), in the eastern Aegean Sea (near 37°N, 26°E) and in southeastern Levantine Basin (near 32.5°N, 33.5°E). More details on these specific results can be found in Appendix A. The geographical distribution of the S2 amplitudes is similar to M2, although the amplitudes are significantly smaller. The maximum S2 is found again in the Gulf of Gabès (~ 11 cm/s).

3.3. Tidal currents in the northern Adriatic Sea, Sicily Channel, Gulf of Gabès and Alboran Sea

In the northern Adriatic Sea, the M2 currents reach 9 cm/s, the tidal ellipse inclination is 109–155° (more or less parallel to the main axis of the Adriatic basin) and the Greenwich phase is 160–180° with some decreasing tendency going from west to east (Fig. 5). For S2 (not shown), the maximum semi-major axis is 6.4 cm/s, the inclination ranges between 75° and 169° and the Greenwich phases is 151–207°. The rotary coefficient is near zero (almost rectilinear motion) for both semi-diurnal constituents.

Semi-diurnal tidal currents are large (> 7 cm/s) in the western side of the Sicily Channel, in particular on Adventure Bank (Fig. 6). As

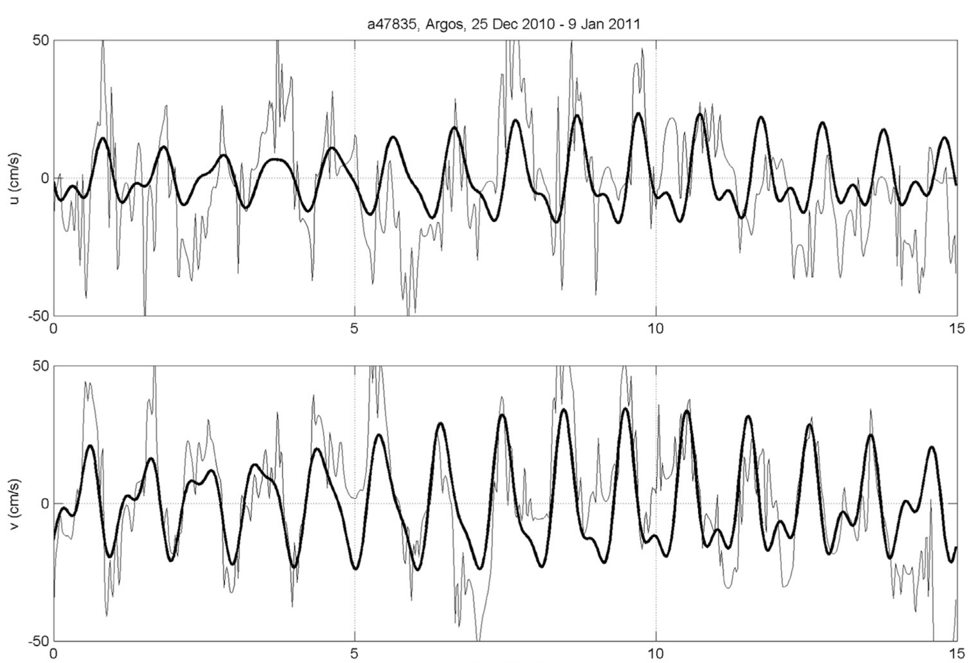

Fig. 3. Time series of zonal (top) and meridional (bottom) velocities of drifter a47835 between 25 December 2010 and 9 January 2011 (thin curves) and corresponding tidal currents (thick curves) calculated by t_tide.

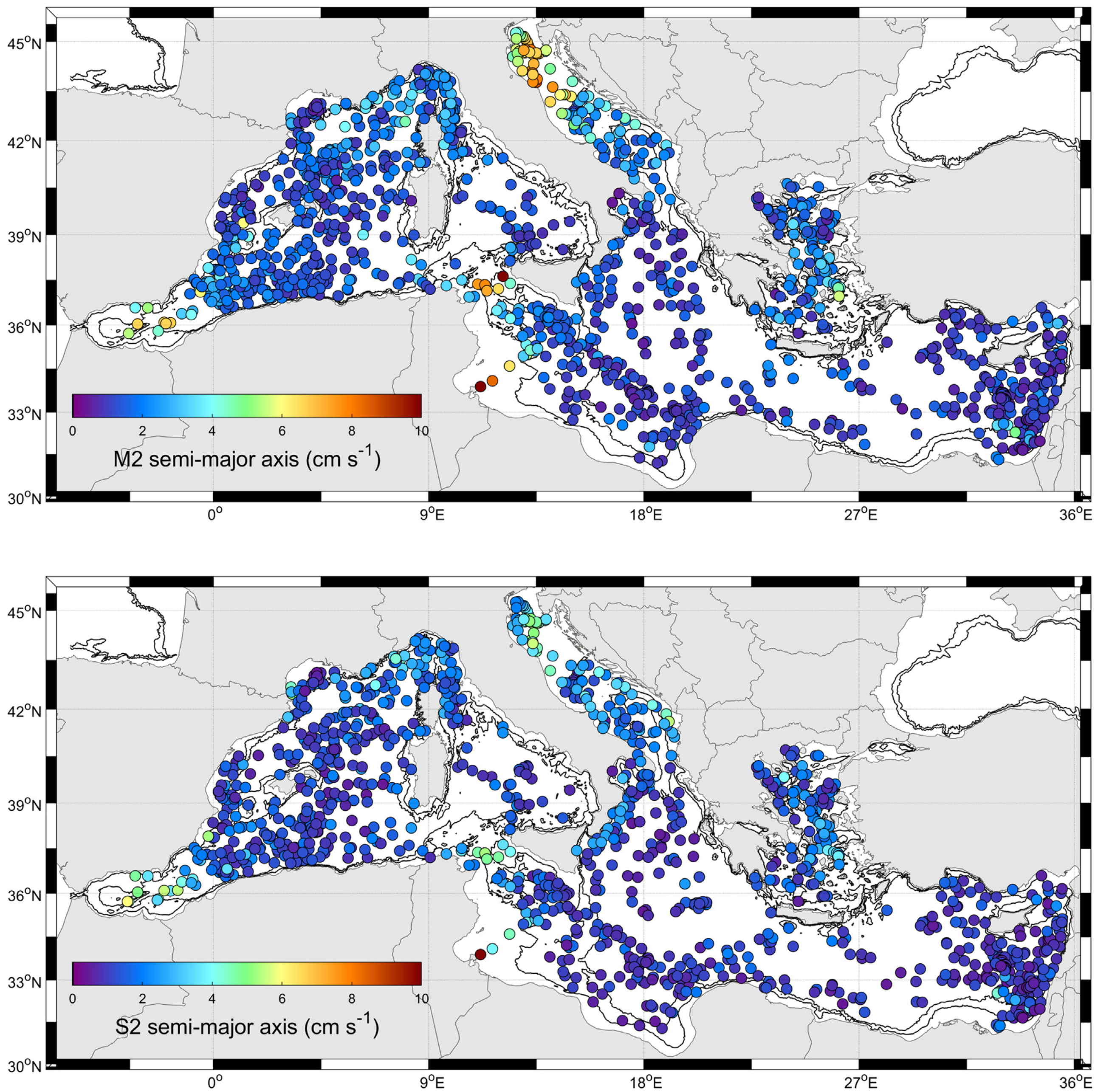

Fig. 4. Amplitude of the M2 (top) and S2 (bottom) semi-major axis derived by applying t_tide on 1313 (1221) overlapping (50%) 15-day long drifter segments. For each drifter segment, the amplitude is shown as a colored dot plotted at the mean position of the segment. Results are excluded if the SNR is smaller than 1. The 200 and 1000 m isobaths are shown with gray curves.

mentioned before, they are also enhanced in the Gulf of Gabès. The rotary coefficient is positive near 0.5 corresponding to CW rotation of the currents. In the Sicily Channel, the ellipse inclination is 100–140°, i.e., the tidal is primarily in the direction of the Channel (NW-SE direction). In the Gulf of Gabès, the inclination is almost zonal. Greenwich phases are 120–170° in the Sicily Channel whereas it is near 340° in the Gulf of Gabès. Results are similar for S2 (not shown) except that the rotation in the Gulf of Gabès is CCW and that the amplitudes are reduced (maximum near 6 cm/s on Adventure Bank).

In the Alboran Sea (Fig. 7), M2 currents reach 7 cm/s, the rotary coefficient is positive near 1 (almost circular CW rotation) and the tidal ellipse is slightly more elongated in the zonal direction. The Greenwich phase is mostly in 100–180°. S2 amplitudes are similar to the M2 ones (not shown).

4. Discussion and conclusions

More than thirty years (1986–2017) of drifter data in the Mediterranean were exploited to study the characteristics of the surface tidal currents. Harmonic analysis on 15-day trajectory segments revealed maximum amplitudes of the tidal currents reaching 35 cm/s on Adventure Bank off western Sicily (see Table 1 and Fig. 2) with strong semi-diurnal and diurnal components. The semi-diurnal tidal currents are large (> 5 cm/s) in the Alboran Sea, the northern Adriatic, the Sicily Channel and the Gulf of Gabès. Elsewhere, they are weak (< 2 cm/s) except for a few special cases presented in Appendix A.

The geographical distribution of the mean M2 currents (Fig. 4) resembles Tsimplis et al. (1995)'s map of M2 simulated barotropic currents. Differences can be due to model and measurement errors, but they can also be ascribed to the existence of freely-propagating internal

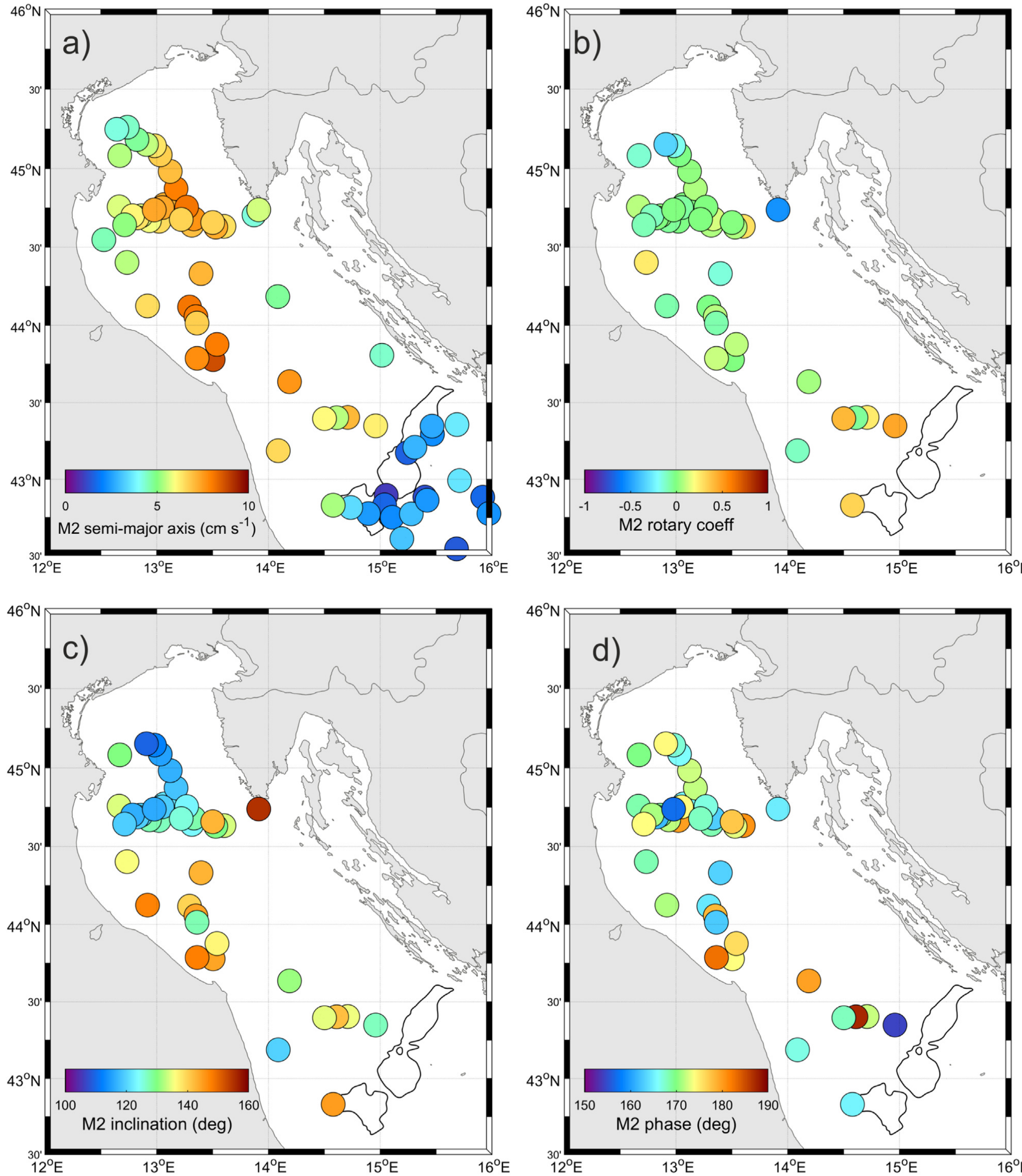

Fig. 5. Amplitude of the M2 semi-major axis (a), rotary coefficient (b), ellipse inclination (c) and Greenwich phase (d) in the northern Adriatic. Rotary coefficient, inclination and phase are plotted only if the amplitude of the semi-major axis is larger or equal to 5 cm/s. The 200 m isobaths is indicated.

tides not simulated by the barotropic model. However, our drifter dataset is not adequate to study internal tidal currents given the poor spatial resolution of the harmonic analysis results. The large M2 currents modelled by Arabelos et al. (2011) southwest of Crete are not confirmed by the drifter observations. For the S2 tide, the surface currents estimated with the drifter data have a similar geographical distribution, but with smaller amplitudes, with respect to the M2 results.

The results in the northern Adriatic are similar to those of Poulain (2013) who performed harmonic analysis on long and gappy time series of Adriatic drifter data in bins of 0.25° x 0.25°. In the present study, the harmonic analysis on 15-day segments ensures that all the diurnal and semi-diurnal energy is always represented by the same four constituents, and allows the phase to vary from one segment to another in the same geographical area. Thus, the method allows to extract tidal currents not phase-locked with the forcing or with the barotropic tides. The similarity between Poulain (2013)'s results and those presented here, and the narrow range of Greenwich phases depicted in Fig. 5 confirms that the M2 tidal

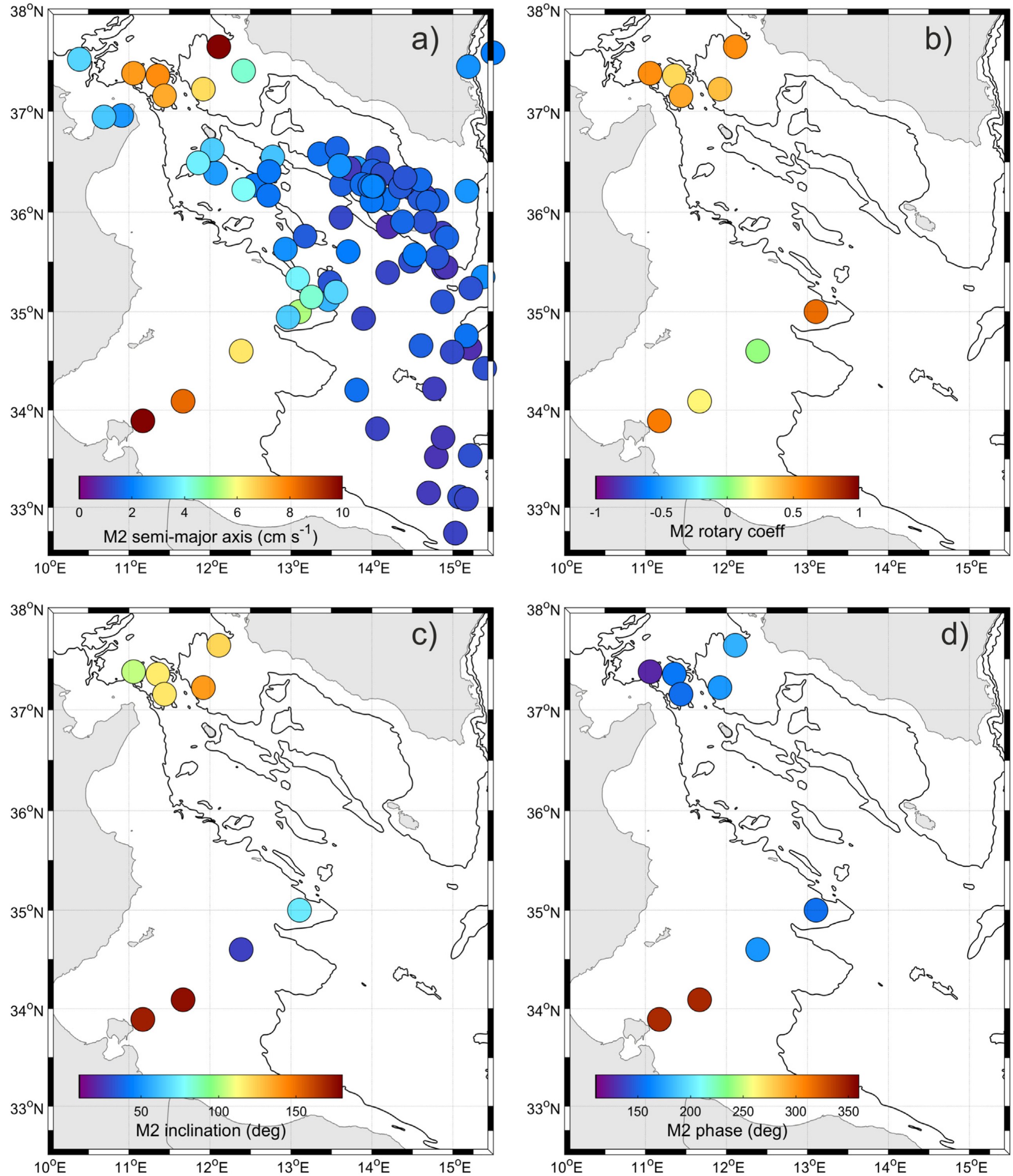

Fig. 6. Same as Fig. 5 but for the Sicily Channel and Gulf of Gabès. The 200 m and 1000 m isobaths are indicated.

currents are mainly barotropic in the northern Adriatic. It is well known (Cushman-Roisin et al., 2001) that the M2 tide in the Adriatic corresponds to two coastal Kelvin waves propagating northwestward along the Croatian coast and returning back to the southeast along the Italian Peninsula. The typical wavelength of this signal is O(1000 km). The increase of phase in the northern Adriatic of about 20° (from 160° to the east to 180° to the west), the inclination (NW-SE) and the eccentricity (∼ 1) of the tidal current ellipses are compatible with the observations and simulations of Book et al. (2009).

In the Sicily Channel and in the Gulf of Gabès our results for M2 compare favorably with the barotropic numerical simulations of Abdennadher and Boukthir (2016), with amplitudes of the semi-major axes differing by only a few cm/s. Furthermore, on the western shelf of the Sicily Channel (including Adventure Bank) our estimates for ellipse inclination and Greenwich phase are very close to their values (see their Table 6). Indeed, if we add 180° to their values for inclination (-75° or −63° becomes 105° or 117°) and phase (-39° becomes 141°) we obtain values very close to those displayed in Fig. 6 (near 114° for inclination

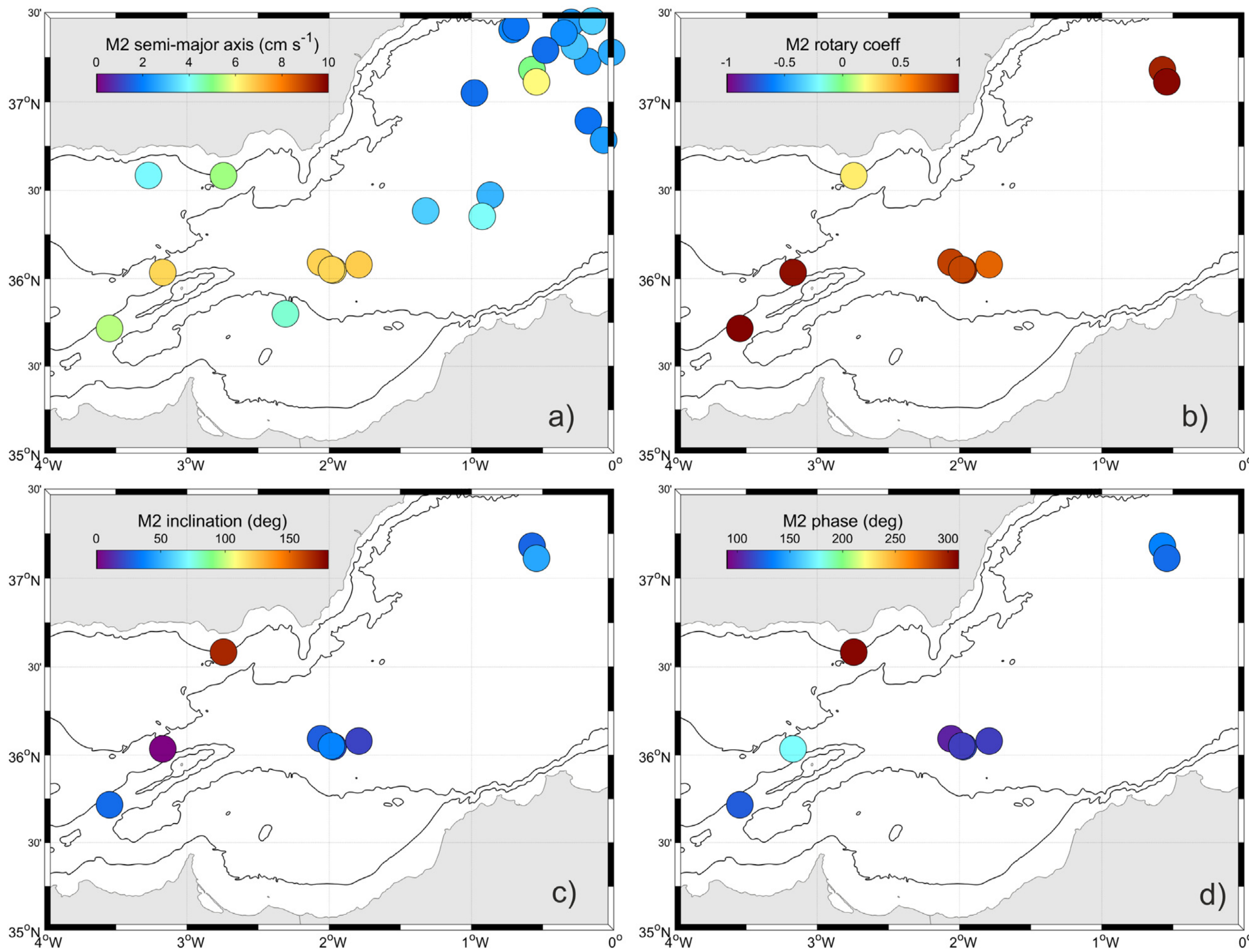

Fig. 7. Same as Fig. 5 but for the Alboran Sea. The 200 m and 1000 m isobaths are indicated.

and near 140° for phase). This indicates that the M2 tidal currents on the shelf are mainly barotropic.

Although the drifter data are rather limited in the Alboran Sea, they show that M2 currents can be significant, reaching 7 cm/s (Fig. 7). Obviously more data are needed to map the tidal currents in the whole Alboran Sea.

Large tidal currents were found in individual drifter tracks in the Catalan Sea, eastern Aegean Sea and eastern Levantine Basin (see Appendix A). The intricate morphology and bathymetry of the Aegean can possibly cause significant tidal currents and the results we obtained (M2 and S2 amplitudes in excess of 4 cm/s) are partially compatible with Tsimplis et al. (1995)'s barotropic simulations. The other two cases in the Catalan and eastern Levantine Basin, however, occur in deep (mostly open) sea. They are statistically significant but their interpretation is difficult.

Qualitative comparisons of our results with those obtained from localized observations with moored current meters, ship-board ADCP, HF radars are generally satisfactory, except inside the straits of Gibraltar and Messina, where the drifter observations are scarce and which are much smaller than the horizontal resolution of this work. In particular, the amplitudes of the M2 and S2 tidal currents in eastern Alboran Sea, the Sicily Channel and the northern Adriatic Sea compare well with the HF radar data of Cosoli et al., (2012, 2015) and Chavanne et al. (2007), the ship-board ADCP observations of Garcia-Gorriz et al. (2003) and Gasparini et al. (2004).

As discussed above, the results for the diurnal tidal constituents are mostly noisy and are therefore not illustrated in this paper. However, significant amplitudes of the K1 (and O1) currents were found in the Alboran Sea, on the western shelf of the Sicily Channel, in the eastern Malta Channel and in the Adriatic Sea, where other observations have confirmed these strong diurnal tidal currents (see Soto-Navarro et al., 2016; Cosoli et al., 2015; Gasparini et al., 2004).

This study is a first effort to estimate tidal current characteristics using Lagrangian drifter data throughout the Mediterranean Sea, a marginal sea where tidal currents are generally weak. It suffers from the fact that drifter sampling in space and time is barely sufficient for obtaining robust estimates of the tidal current characteristics in most areas due to the scarcity of observations and the rather low frequency and poor accuracy of Argos positions for some drifters in the historical database. It is therefore strongly recommended to operate GPS drifters with Iridium telemetry and at least hourly sampling period in the future and to encourage the Mediterranean Sea oceanographic community to maintain an adequate fleet of drifters, integrated in the future observing system of systems, in order to monitor the Mediterranean dynamics from inertial/tidal frequencies to basin scales.

Acknowledgements

We thank all the people who have deployed drifters, and made their data available, in the Mediterranean Sea between 1986 and 2017. Mediterranean drifters have been mainly funded by the Office of Naval Research (ONR) as part of several projects. The efforts and dedication of A. Bussani is acknowledged for the production of the Mediterranean drifter database on which this study is based. The comments of the anonymous reviewers have been extremely important to improve the first versions of this paper. The reviewers are therefore deeply acknowledged.

Appendix A. Special cases of significant semi-diurnal currents

We hereafter focus on special cases of significant semi-diurnal currents found in drifter track segments located outside the northern Adriatic, Sicily Channel, Gulf of Gabès and the Alboran Sea.

Significant M2 amplitudes (~ 6 cm/s) were found in the Catalan Sea (near 39.5°N, 1°E; see Table A1 and Fig. A1) for an SVP drifter with GPS hourly positioning. The tidal currents rotate almost circularly in the CCW direction. The SNR for the S2 and diurnal constituents is below 1.

In the eastern Aegean Sea one SVP drifter with Argos positioning revealed substantial tidal currents near 37°N, 26°E (Fig. A2). The harmonic analysis results (Table A2) disclosed CW almost circular semi-diurnal tidal motions with maximum amplitude of 4.7 cm/s.

In the southeastern Levantine Basin (near 32.5°N, 33.5°E, see Fig. A3) one SVP drifter with hourly GPS positioning sampled CCW semi-diurnal motions with maximum amplitude of 5 cm/s for M2 (Table A3).

Table A1
Tidal harmonic analysis results for drifter adep0002_drifter-svp053_ime-svp018_LO_2015_11_05 between 20 November and 5 December 2015.

Tide	Major (cm/s)	Error major (cm/s)	Minor (cm/s)	Error minor (cm/s)	Inclination (degree)	Error inclination (degree)	Phase (degree)	Error phase (degree)	SNR
O1	2.1	2.8	− 0.3	3.3	55	114	40	96	0.58
K1	3.6	3.7	1.0	2.2	10	47	278	72	0.99
M2	6.2	5.3	4.6	4.7	8	121	151	125	1.4
S2	5.1	5.3	5.0	4.7	9	1291	115	1295	0.95

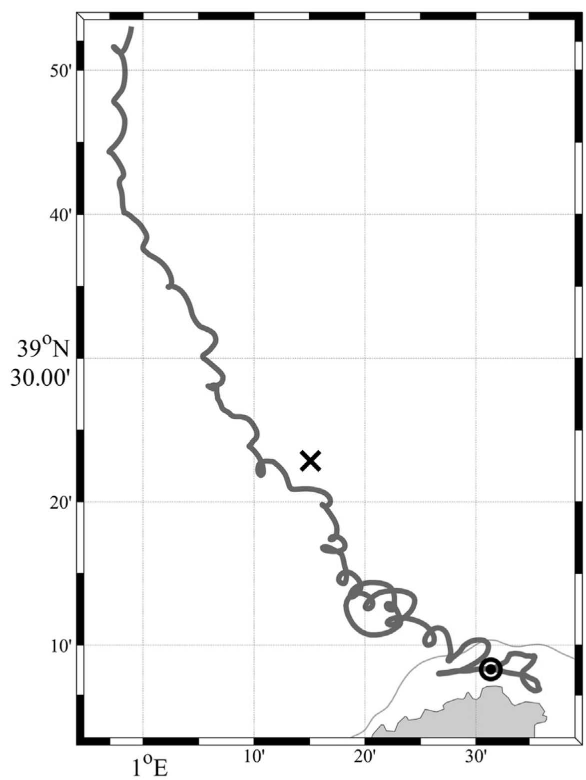

Fig. A1. Fifteen-day trajectory segment (dark curve) and initial position (circle symbol) of drifter adep0002_drifter-svp053_ime-svp018_LO_2015_11_05 starting on 20 November 2015 at 12:00 UT. The drifter mean position is shown with a cross symbol. The 100-m isobath is shown with a light gray curve.

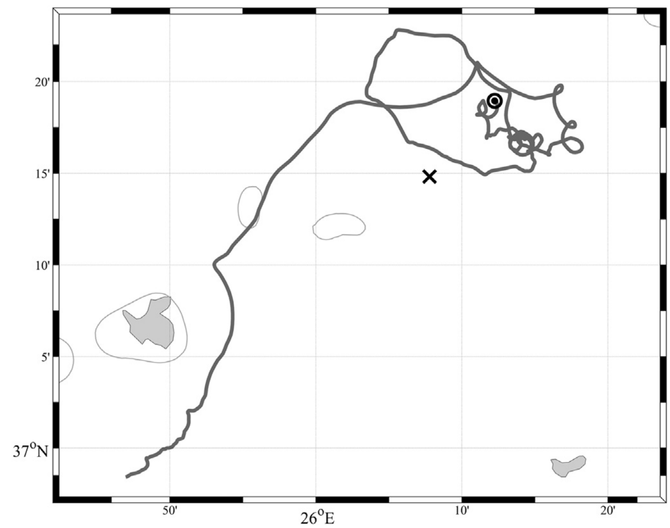

Fig. A2. Fifteen-day trajectory segment (dark curve) and initial position (circle symbol) of drifter bbb34430 starting on 27 May 2003 at 16:30 UT. The drifter mean position is shown with a cross symbol. The 100-m isobath is shown with a light gray curve.

Table A2
Tidal harmonic analysis results for drifter bbb34430 between 19 May and 3 June 2003.

Tide	major (cm/s)	Error major (cm/s)	Minor (cm/s)	Error minor (cm/s)	Inclination (degree)	Error inclination (degree)	Phase (degree)	Error phase (degree)	SNR
O1	1.5	1.0	− 0.1	1.2	55	39	183	35	2.2
K1	1.5	1.0	− 0.8	1.2	64	64	206	56	2.4
M2	4.7	1.6	− 3.7	1.8	152	66	358	64	8.8
S2	4.3	1.6	− 3.5	1.8	157	97	339	95	7.3

Table A3
Tidal harmonic analysis results for drifter a300234063569320 between 11 and 26 January 2017.

Tide	Major (cm/s)	Error major (cm/s)	Minor (cm/s)	Error minor (cm/s)	Inclination (degree)	Error inclination (degree)	Phase (degree)	Error phase (degree)	SNR
O1	1.3	4.1	0.8	5.3	150	552	91	497	0.1
K1	3.2	5.8	− 0.2	3.2	85	67	125	119	0.3
M2	5.0	1.8	4.5	2.8	81	196	99	188	7.8
S2	3.1	2.8	1.8	1.8	177	69	31	86	1.2

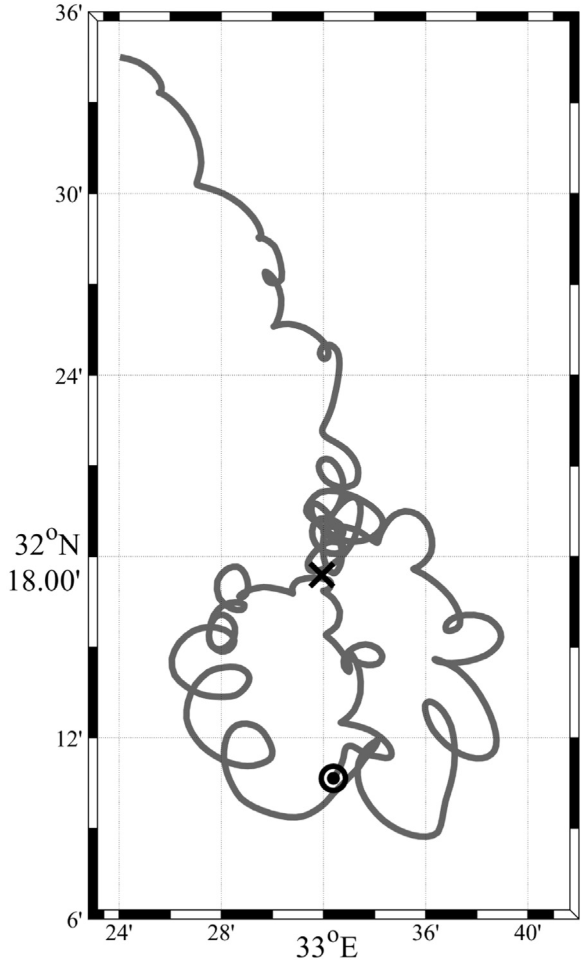

Fig. A3. Fifteen-day trajectory segment (dark curve) and initial position (circle symbol) of drifter a300234063569320 starting on 11 January 2017 at 13:00 UT. The drifter mean position is shown with a cross symbol.

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