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SPECIAL ISSUE ON UPPER OCEAN PROCESSES:
PETER NIILER'S CONTRIBUTIONS AND INSPIRATIONS

Mediterranean Surface Currents Measured with Drifters

From Basin to Subinertial Scales

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ABSTRACT. Drifter observations in the Mediterranean Sea between 1986 and 2012 have allowed study of important aspects of the surface dynamics in most areas of this marginal sea, including: interannual and seasonal variabilities; basin, subbasin, and mesoscale circulation features; inertial and tidal currents; coastal circulation; and relative dispersion by surface waters. This paper reviews selected important studies, carried out in the last two decades or still in progress, that used or are using Mediterranean drifter observations and ancillary remotely sensed observations (satellite altimetry and high-frequency coastal radars).

INTRODUCTION

Since the advent of satellite tracking in the 1980s, drifters have been used to observe surface currents in the Mediterranean Sea over a wide range of scales, from tidal/inertial to interannual and from a few to thousands of kilometers. Drifters move with the currents (i.e., they are Lagrangian) and can cover substantial geographical areas, providing new insights into near-surface dynamics. Hence, quantitative descriptions have been developed for circulation in several Mediterranean areas, such as the Adriatic Sea (Poulain, 1999, 2001; Ursella et al., 2006), the Sicily Channel (Poulain and Zambianchi, 2007), the Eastern (Gerin et al., 2009) and Western (Salas et al., 2001; Poulain et al., 2012a) Mediterranean basins, and also for the entire Mediterranean Sea (Mauerhan, 2000).

This article reviews selected important scientific results derived from Mediterranean drifter data. After a brief description of the drifters used and the data obtained from them, we show a Lagrangian rotary spectrum of drifter velocities to confirm that drifters can indeed effectively sample scales ranging from synoptic variations and mesoscale features to inertial and tidal motions. In addition, drifters operating in the Mediterranean Sea for more than 25 years permit study of seasonal and interannual variations. First, we concentrate on the quantitative description of surface geostrophic circulation in the Mediterranean basins as obtained from a combination of low-pass filtered drifter data and satellite observations of sea level. Second, we show how the high-frequency drifter velocities can be used to map the characteristics of surface tidal motions in the entire Mediterranean, although tidal signals are known to be relatively small in most of the basin. We then present some results of coastal applications in which drifter measurements, eventually combined with high frequency (HF) coastal radar data, can provide extremely useful information on surface currents and dispersion of passive tracers. We close this review by showing how drifter data can be used to study spreading by mixing and stirring in terms of relative dispersion.

DRIFTERS AND MEDITERRANEAN DRIFTER DATA

The majority of the drifters deployed in the Mediterranean are of three types (see photographs in Figure 1a): (1) Surface Velocity Program (SVP) drifters that are the standard design of the Global Drifter Program (Sybrandy and Niiler, 1991; Lumpkin and Pazos, 2007) with a subsurface holey-sock drogue centered at 15 m nominal depth; (2) Coastal Ocean Dynamics Experiment (CODE) drifters that were developed by Davis (1985) in the early 1980s to measure coastal currents in the first meter below the ocean surface; and (3) Compact Meteorological and Oceanographic Drifters (CMOD) or XAN-1 drifters (Selsor, 1993) that were mainly operated by the US Navy.

Surface drifters are actually quasi-Lagrangian because they can slip with respect to the near-surface water due

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to the direct effects of local wind and waves acting on their elements that protrude above the sea surface. This slip varies substantially among the different drifter designs. Direct measurements of water-following capabilities of the SVP show that when the drogue is attached, they follow the water to within 1 cm s^{-1} in 10 m s^{-1} winds (Niiler et al., 1995). Slip measurements (Poulain et al., 2002) with acoustic current meters show that the CODE drifters follow the surface currents within 2 cm s^{-1} and that they move in a manner consistent with the near-surface Ekman dynamics with a velocity component to the right of the prevailing wind. Wind-induced slips and wind-driven Ekman surface currents

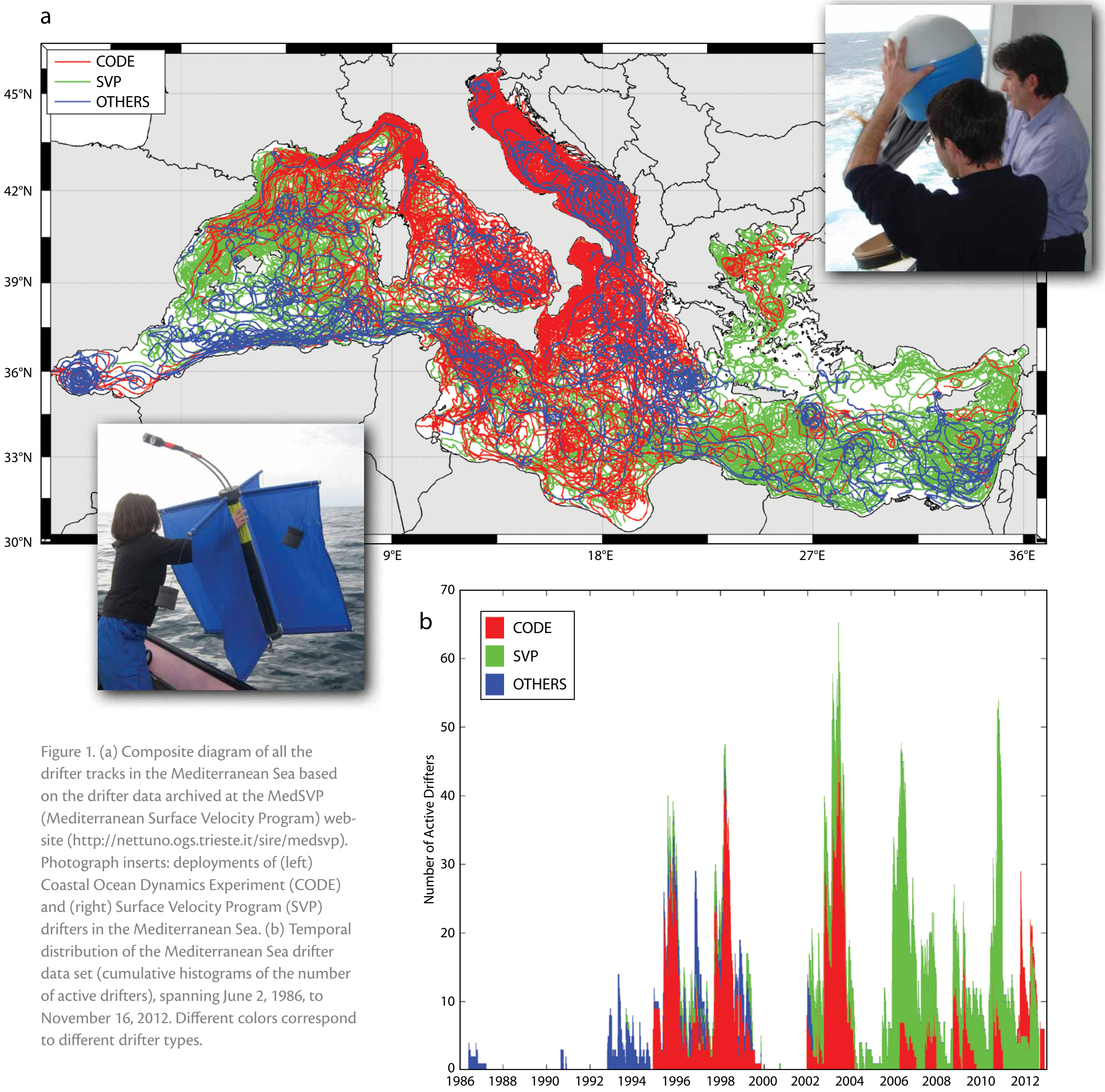

Figure 1. (a) Composite diagram of all the drifter tracks in the Mediterranean Sea based on the drifter data archived at the MedSVP (Mediterranean Surface Velocity Program) website (http://nettuno.ogs.trieste.it/sire/medsvp). Photograph inserts: deployments of (left) Coastal Ocean Dynamics Experiment (CODE) and (right) Surface Velocity Program (SVP) drifters in the Mediterranean Sea. (b) Temporal distribution of the Mediterranean Sea drifter data set (cumulative histograms of the number of active drifters), spanning June 2, 1986, to November 16, 2012. Different colors correspond to different drifter types.

can also be estimated from drifter data using simple regression models that include complex drifter velocities and surface wind products (Ralph and Niiler, 1999; Rio and Hernandez, 2003; Centurioni et al., 2009; Poulain et al., 2009, 2012b). In the Mediterranean, the drogued SVP drifters were shown to measure the smallest wind-driven currents, less than 1% of the wind speed, to the right of the wind (~30°) (Poulain et al., 2009, 2012b). These currents represent only 1–3% of the total velocity variance. The undrogued SVP and CODE drifters moved with wind-driven currents of 1–2% of the wind speed, at an angle of 20–30° to the right of the wind. The corresponding explained variance is about 10–20%. Given their worst water-following capabilities, the CMOD drifters move more downwind (~ 20° to the right of the wind, 27% explained variance) with wind-driven currents amounting to 2% of the wind speed.

The Argos Data Collection and Location Systems onboard polar-orbiting satellites provide locations for most drifters and transmit their data (e.g., sea surface temperature, voltage, drogue presence indicator) to shore. The Doppler-based Argos tracking has an accuracy of 300–1,000 m; positions are typically available six to 12 times per day, with the most frequent sampling period lasting about 100 minutes, corresponding to the period of the orbiting satellites. Some units (mostly CODE drifters) are also equipped with GPS receivers to obtain more accurate (~ 10 m) and more frequent (hourly) positions. A small number of drifters equipped with GPS use terrestrial cellular phone networks (for coastal operations) or satellite global phone systems (e.g., Iridium and Globalstar-SPOT) for data telemetry.

Drifter positions were edited for outliers and spikes (Poulain et al., 2004; Gerin and Bussani, 2011). Edited positions were interpolated at regular 0.5 h intervals with a kriging optimal interpolation technique (Hansen and Poulain, 1996). Velocities were estimated by central finite differencing the interpolated positions. For some applications, positions and velocities were also low-pass filtered to remove high-frequency motions, and subsampled every 6 h. The data were finally archived in several databases (organized by subbasins or projects) accessible through the MedSVP website (http://nettuno.ogs.trieste.it/sire/medsvp) maintained at the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale in Trieste, Italy.

In total, for the time period June 1986 to November 2012, more than 233 years of drifter data were obtained in most areas of the Mediterranean Sea, corresponding to 1,369 individual tracks (see Figure 1a). The temporal distribution of the drifter data (Figure 1b) is very intermittent due to the relative short lifetime of the drifters. The longest drifter track corresponds to an operational lifetime of 575 days. The mean half-lives vary between 39 days (CMOD) and 94 days (SVP).

> “DRIFTER OBSERVATIONS IN THE MEDITERRANEAN SEA BETWEEN 1986 AND 2012 HAVE ALLOWED STUDY OF IMPORTANT ASPECTS OF THE SURFACE DYNAMICS IN MOST AREAS OF THIS MARGINAL SEA...”

LAGRANGIAN SPECTRUM

The interpolated velocity time series corresponding to all the drifters in the Mediterranean were separated in 30-day-long segments, overlapping by 50% for each drifter, in order to analyze the spectral distribution of energy for periods ranging between a few hours and a few weeks. Hence, a rotary power spectrum was calculated from all the Mediterranean drifter data (Figure 2). The spectrum is typically “red,” with maximal energy at low frequencies corresponding to motions at periods from a few days to a few weeks. Tidal motions at diurnal (K1) and semidiurnal (M2 and S2) frequencies correspond to significant peaks in the spectrum. Inertial oscillations dominate the clockwise component of the spectrum in the range of inertial periods (from 16.75 h to 1 day). It is remarkable that clockwise (CW) motions dominate at all frequencies, including tidal and synoptic/mesoscale motions. The CW dominance at larger scales can be explained by the preponderance of anticyclonic circulation features in the Mediterranean observed by drifters. These features might be a sampling artifact because it is believed that anticyclonic CW-rotating eddies are generally convergent and downwelling at their centers, thus trapping surface drifters for longer times. So far, studies based on satellite altimeter data have not revealed the dominance of a specific sense of rotation for the vortices in the Mediterranean (e.g., see Isern-Fontanet et al., 2006).

SURFACE CIRCULATION IN MEDITERRANEAN SUBBASINS

When calculating pseudo-Eulerian velocity statistics from drifter data, the robustness and accuracy of the statistics is questionable due to data scarcity and temporally and spatially nonuniform data distribution over the study area. This problem can be partially alleviated by combining drifter data and satellite observations of sea level to compute statistics on geostrophic surface currents. On the one hand, if wind-driven velocities can be removed using a good regression model and wind products, drifters provide direct estimates of surface geostrophic currents. On the other hand, satellite altimeters sample sea level uniformly in space and time, and geostrophic currents can be calculated using the geostrophic assumption. Thus, after adequate filtering, both data sets can be combined in a regression model to produce the best unbiased statistics on surface geostrophic circulation at scales larger than 25–100 km and longer than 1 week (see Niiler et al., 2003, and Centurioni et al., 2008, for more details on this combination method and Poulain et al., 2012b, and Menna et al., 2012, for its application to the Mediterranean Sea). This method is similar to the one used by Rio et al. (2007) to compute the Mediterranean synthetic mean dynamic topography. Figure 3 shows the mean surface geostrophic circulation using spatial bins of 0.5° × 0.5° for the period October 14, 1992, to December 31, 2011. Both drifter and satellite data were binned in 0.5° × 0.5° × 1 week. The top panel shows the map obtained using the drifter data only (after removal of wind-driven currents), whereas the middle panel displays the unbiased mean circulation obtained by combining drifter and altimeter data (for details, see Poulain et al., 2012b). At first glance, the two maps appear quite similar, which means that the mean circulation obtained by averaging the drifter data is actually not a bad estimate despite the fact that the data are scarce and nonuniformly distributed in space and time. A closer look reveals that differences can be substantial in areas of strong currents and of strong variability, such as the Alboran and Algerian subbasins, the northern Tyrrhenian and northern Ionian Seas, and the Levantine subbasin. In particular, the mean southward Mid-Ionian Jet is significantly overestimated by the drifters in the central Ionian Sea.

Drifter data, combined or not with altimeter observations, revealed the following circulation features in the Mediterranean Sea (see bottom panel of Figure 3). In the western basin, the main surface waters generally flow eastward from the Strait of Gibraltar to the Strait of Sicily (the Algerian Current), and the Northern Current transports waters back westward along the Italian, French, and Spanish coasts. Intermittent and long-lived subbasin-scale eddies and gyres

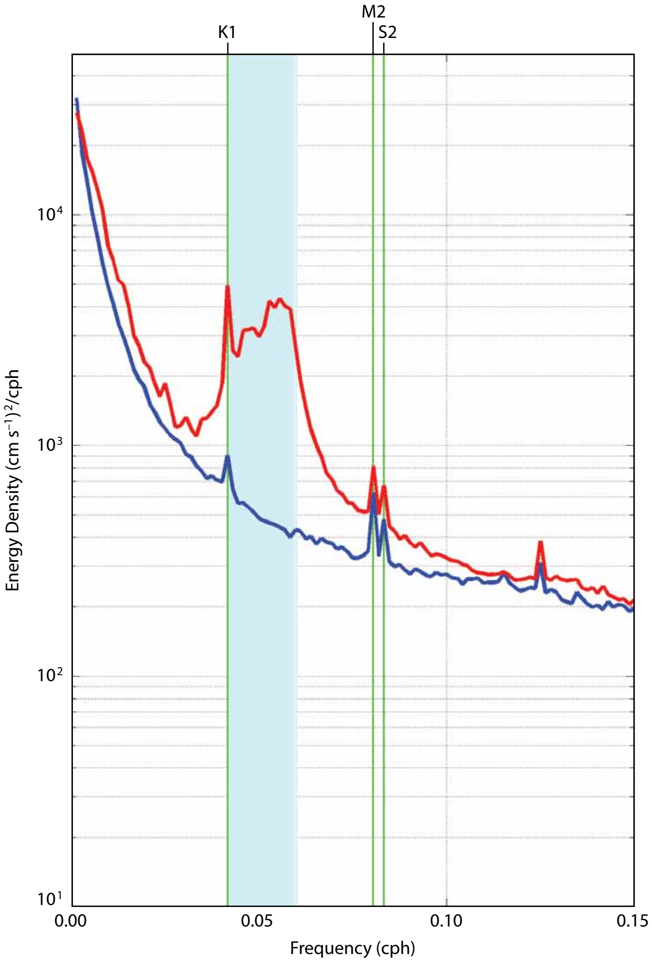

Figure 2. Rotary power spectrum computed from all the drifter velocities in the Mediterranean Sea, using trajectory segments that overlap by 50%. The clockwise and counterclockwise components are shown with red and blue curves, respectively. Diurnal and semidiurnal tidal frequencies are depicted with green lines, and the inertial frequency range is shown in cyan.

abound in the Tyrrhenian and Algerian Seas. In the eastern basin, several currents transport surface waters eastward, including the Mid-Ionian and Mid-Mediterranean Jets, but recirculate in numerous eddies and gyres (e.g., Pelops, West Cretan, Ierapetra, Mersa-Matruh) before reaching the northward coastal current off Israel, Lebanon, and Syria and veering westward off Turkey as the Asia Minor Current. The latter current is the northern limb of an extended cyclonic Rhodes Gyre.

In the Ionian Sea, Poulain et al. (2012b) also produced mean geostrophic velocity maps separately for the two extended seasons and for multiyear periods. Significant variations are confirmed, with seasonal reversals of the currents in the south off Libya, and changes in the circulation from anticyclonic prior to July 1, 2007, to cyclonic, and back to anticyclonic after December 31, 2005, possibly associated with the Eastern Mediterranean Transient (Borzelli et al., 2009; Gačić et al., 2011).

TIDAL CURRENTS

Mediterranean drifter tracks show ubiquitous small-scale looping motions that correspond to inertial or tidal velocity oscillations (see peaks of enhanced energy for periods smaller than one day in the rotary spectrum of Figure 2). Even though Argos sampling is not regular, with positions available six to 12 times per day (but with most frequent sampling periods of about 100 minutes), the looping in the tracks and the rotary spectrum reveal that high-frequency currents can indeed be studied for periods as small as a few hours. In particular, harmonic analysis can be applied to the drifter velocity time series to

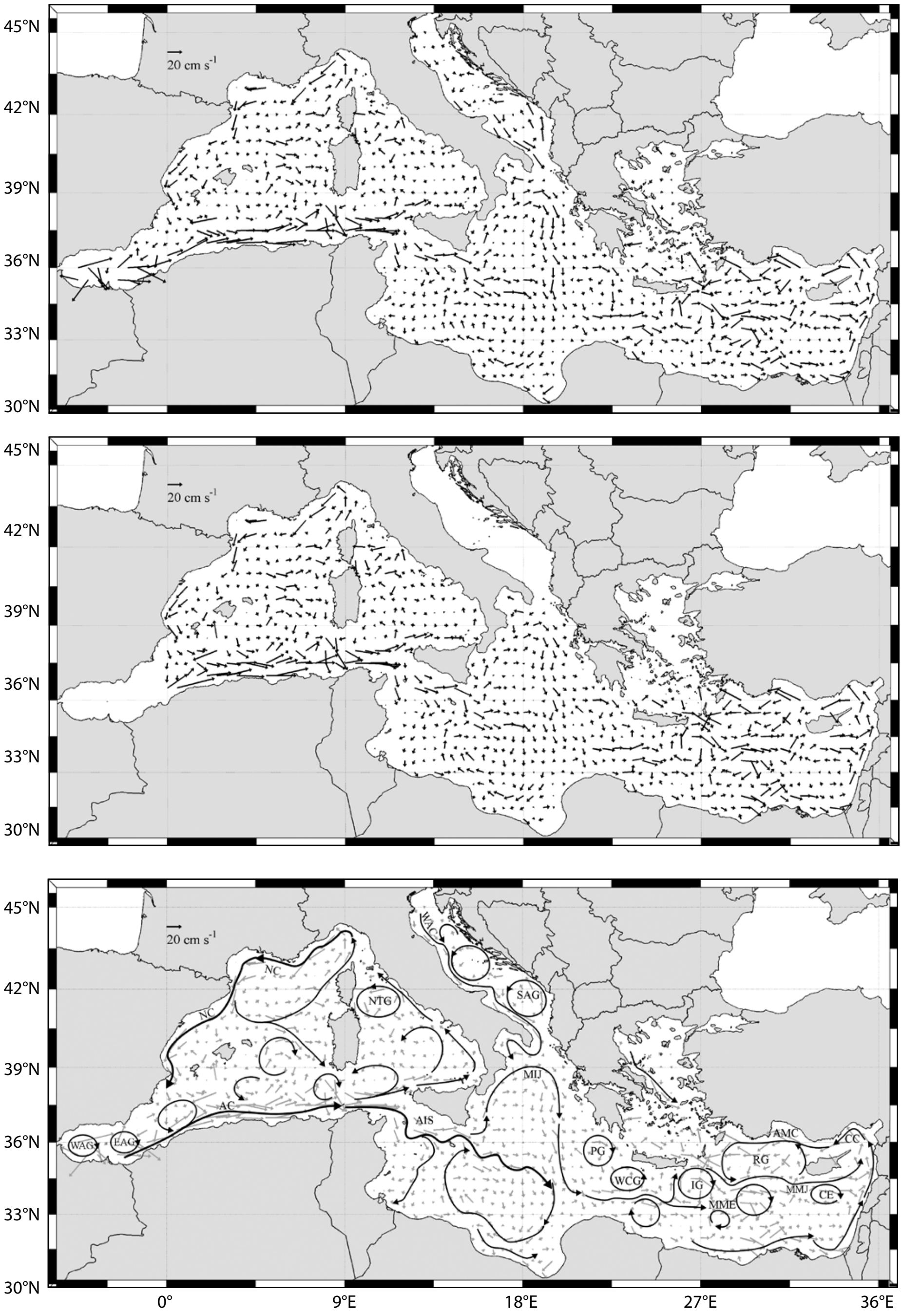

Figure 3. Mean surface geostrophic circulation in the Mediterranean Sea for the period 1992–2011 based on drifter observations (top) and the combination of drifter and satellite altimetry data (middle). Mean currents in bins of 0.5° x 0.5° are shown with gray arrows, and the major circulation features are overlaid in the bottom panel.

AC = Algerian Current
AIS = Atlantic-Ionian Stream
AMC = Asia Minor Current
CC = Cilician Current
CE = Cyprus Eddy
EAG = Eastern Alboran Gyre
IG = Ierapetra Gyre
MIJ = Mid-Ionian Jet
MME = Mersa-Matruh Eddy
MMJ = Mid-Mediterranean Jet
NC = Northern Current
NTG = Northern Tyrrhenian Gyre
PG = Pelops Gyre
RG = Rhodes Gyre
SAG = Southern Adriatic Gyre
WAC = Western Adriatic Current
WAG = Western Alboran Gyre
WCG = Western Cretan Gyre

describe the geographical distribution of the surface motions at diurnal and semidiurnal tidal frequencies. Assuming that tidal forcing and tidal characteristics are constant for the time period sampled by the drifters (~ 25 years), gappy pseudo-Eulerian time series are constructed from data collected by drifters passing in geographical areas (or bins), and harmonic analysis is also performed (see details in Poulain, 2013). Although this technique provides spatially smoothed and somewhat underestimated results with respect to the results obtained from moored current meter data (Poulain, 2013), it has the advantage of providing maps of tidal velocity characteristics, such as amplitude, phase, inclination, and eccentricity of the tidal ellipse as well as sense of rotation over an extended sea area, even over the entire Mediterranean basin if sufficiently sampled by the drifters. Poulain (2013) applied this method to the large drifter data set of the Adriatic Sea and confirmed that tidal currents are large (maximum amplitude of ~ 7 cm s^{-1}) near its northern tip at semidiurnal frequencies (periods of 12.421 and 12 h for M2 and S2 constituents, respectively). The diurnal tidal currents (K1, 23.934 h) dominate across the Adriatic basin near specific capes with speed larger than 5 cm s^{-1}.

If harmonic analysis is applied to the full Mediterranean drifter data (spanning 1986 to 2012) using 1° × 1° bins, that is, with about 100 km horizontal resolution, we can obtain a novel description of the tidal currents in the Mediterranean. The spatial distribution of the amplitude of the M2 tidal currents is contoured in Figure 4. It represents the first experimental evidence that these currents are mostly negligible throughout the basin, except in specific regions (Alboran Sea, Tunisian Shelf and Gulf of Gabes, Sicily Channel, northern Adriatic) where they can be substantial. The amplitude of the M2 currents reaches ~ 6 cm s^{-1} in the Gulf of Gabes. For diurnal currents (K1), amplitudes are significant in the Sicily Channel and the Adriatic Sea (not shown). These experimental results are in good agreement with the numerical simulations of Tsimplis et al. (1995). The study of surface tidal currents using drifter data at the level of the entire Mediterranean basin is still in progress, and further results will be published in the near future.

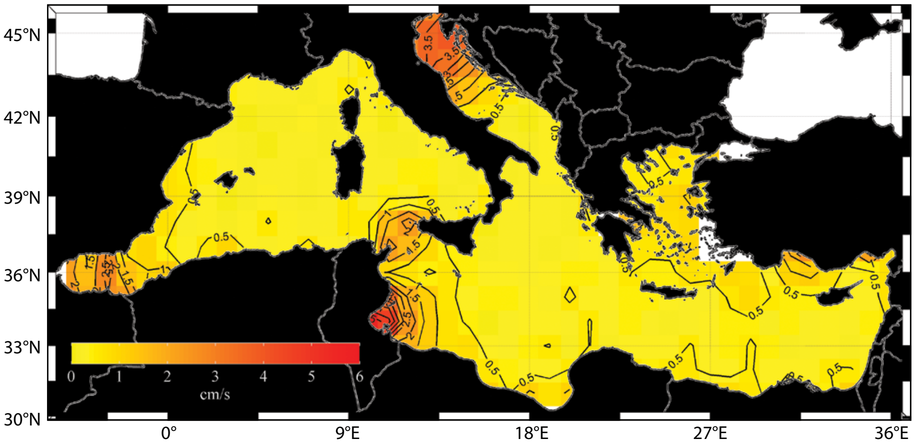

Figure 4. Amplitude of semidiurnal tidal currents (M2) in the entire Mediterranean Sea as computed with harmonic analysis applied to the drifter data in bins of 1° x 1° for the period 1986–2012.

SURFACE CURRENTS IN COASTAL AREAS

The monitoring and prediction of coastal circulation and associated transports are crucial for a variety of applications, including coastal ecological management, search-and-rescue operations, and the mitigation of accidental discharges of pollutants. In the Mediterranean, drifters have also been used to measure circulation features in local coastal areas such as off the Italian coast in the middle and southern Adriatic (Haza et al., 2007) and in the Gulf of La Spezia (Molcard et al., 2009; Haza et al., 2010). Extensive drifter experiments have recently been carried out in the Gulfs of Naples and Trieste in Italy, and in other Mediterranean areas (northern Aegean, off Toulon in France, and in the vicinity of the Balearic Islands off Spain) as part of an ongoing project funded by the European Commission (Tracking Oil Spills & Coastal Awareness network [TOSCA], http://www.tosca-med.eu). One goal is to measure coastal circulation with high geographical resolution using an array of drifters that is deployed and recovered several times during the study period. These drifter measurements are often collected in conjunction with the operation of HF coastal radars (see Molcard et al., 2009). Drifter data permit calibration and validation of the radar measurements, and the combination of both types of data (in practice, the radar data corrected by the drifters) represents the best description of the spatial structure and temporal evolution of the coastal circulation. Figure 5 shows a snapshot of the circulation in the Gulf of Trieste as measured by HF radars along with drifter trajectory segments. The agreement between the radar-derived velocities and the drifter motions is remarkably good. A second goal is to study dispersion by surface currents. In particular, drifters released in clusters (such as closely separated pairs or triplets) allow investigation of relative dispersion and the corresponding mixing and stirring properties of the surface flow field. A third objective is to assess the water-following capabilities of the surface drifters and to measure the relative shear of currents near or below them using acoustic current meters and profilers. All of these studies are in progress, and more will be reported in the coming years.

RELATIVE DISPERSION

Relative dispersion plays an important role in spreading biological constituents and marine pollutants. It is commonly calculated as the mean squared separation of particle pairs. Turbulence theory (Bennet, 1984) says that this quantity's rate of change, in other words the pair spreading, is a function of separation scale and is sensitive to the distribution of energy as a function of length scale in the turbulent flow. Pair spreading can be driven by eddies that are at the same scale as the separation distance, a condition known as "local dispersion." Or, if the kinetic energy wave number spectrum is steeper than k^{-3}, where k is the wavenumber, pair spreading can be dominated by eddies larger than the separation scale (the mean squared separation grows exponentially and the spreading is called "nonlocal"). The study and prediction of relative dispersion, mixing, and stirring, and more generally of transport properties at the ocean surface, can be conducted in the context of dynamical system theory and with assimilation of Lagrangian drifter data (for a review, see Griffa et al., 2013).

The relative dispersion of drifter pairs was studied in the Adriatic Sea (Lacorata, 2001; Haza et al., 2010) and in the Liguro-Provençal Basin (Schroeder et al., 2011, 2012). The full drifter data set spanning 1990–2007 was also recently used to estimate relative dispersion in the Adriatic Sea (Figure 6). An exponential regime (nonlocal dispersion) occurs for less than about one day when considering pairs with an initial

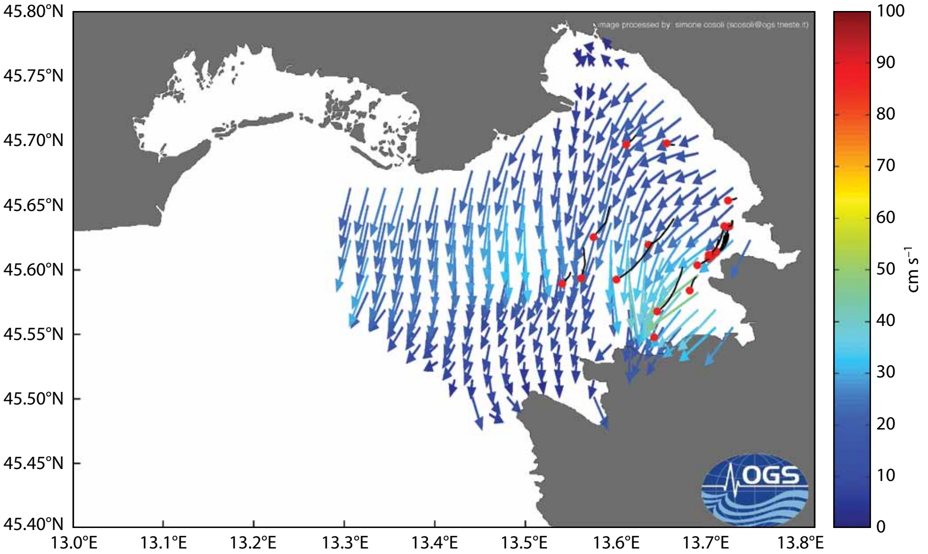

Figure 5. Surface circulation in the Gulf of Trieste as measured by the radars on April 23, 2012, at 20.00 UTC (arrows color-coded with speeds) superimposed with drifter trajectory segments. The red dots denote drifter positions on April 23, 2012, at 18.30 UTC, and the black lines trace their tracks over the previous 3 h.

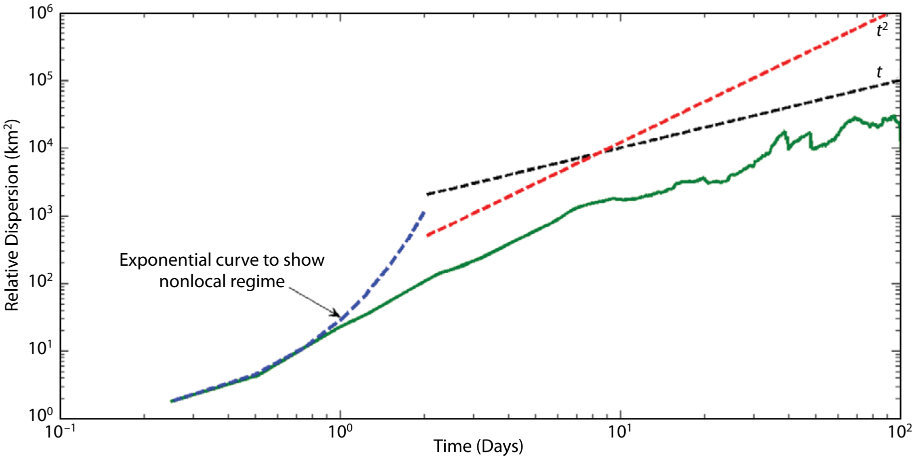

Figure 6. Relative dispersion in the Adriatic (mean squared separation distance of drifter pairs) versus time, considering initial pairs with a separation of less than 1 km. The exponential, ballistic (t^2), and diffusive (t) regimes are also shown. Results are based on drifter data spanning the time period 1990–2007.

distance of less than 1 km. For time periods ranging from two to 10 days (and a separation scale of 10–30 km), the growth of relative dispersion scales approximately like t^2 (ballistic, t is time). Finally, for time periods longer than ~ 10 days (a separation in excess of about 30 km), relative dispersion slows down considerably to a diffusive regime (linear growth rate). In contrast, in the Liguro-Provençal Basin, Shroeder et al. (2011) show the initial exponential phase to extend up to four to seven days and to be separated by between 1 and 10–20 km. Hence, mesoscale dynamics controls nonlocal relative dispersion. In addition, the shear of significant basin-scale circulation features such as the Northern Current is much more dominant than in the Adriatic Sea. Spreading of drifter pairs can alternatively be assessed using finite-scale Lyapunov exponents (Lacorata, 2001; Haza et al., 2010; Schroeder et al., 2011) but these details are beyond the scope of this paper.

> “THE RAPID PROGRESS OF NEW TECHNOLOGIES… REPRESENTS A NEW FRONTIER THAT WILL ALLOW THE OCEANOGRAPHIC COMMUNITY TO EXPLORE MORE COMPREHENSIVELY AND ACCURATELY THE MEDITERRANEAN SEA, AND THE WORLD OCEAN IN GENERAL, IN THE NEAR FUTURE.”

CONCLUSIONS

Lagrangian data provided by surface drifters over the last 25 years or so have been exploited to study Mediterranean Sea dynamics at scales ranging from a few hours (subinertial) to several years (basin scale). Despite their scarce and nonuniform data distribution, drifter data have allowed us to gain several new insights into Mediterranean surface currents, used alone or in concert with remotely sensed observations (satellite altimetry, HF coastal radars). It is hoped that a minimum population of Mediterranean drifters will be maintained in the future to monitor the temporal evolution of Mediterranean circulation. The rapid progress of new technologies such as microsensors (not only to measure physical marine properties but also biochemical and optical ones) and data telemetry and positioning (GPS, Galileo, Iridium, Globalstar-SPOT) represents a new frontier that will allow the oceanographic community to explore more comprehensively and accurately the Mediterranean Sea, and the world ocean in general, in the near future.

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