2001

Adriatic Sea surface circulation as derived from drifter data between 1990 and 1999

Poulain, Pierre-Marie

Elsevier
Adriatic Sea surface circulation as derived from drifter data between 1990 and 1999

Pierre-Marie Poulain*

Department of Oceanography, Naval Postgraduate School, Code OC/Pn, Monterey, CA 93943-5000, USA

Received 1 December 1999; received in revised form 15 May 2000; accepted 15 November 2000

Abstract

The Adriatic Sea surface circulation for the period 1990–1999 is studied using the data of more than 200 satellite-tracked drifters. The spatial structure and the temporal variability of the surface currents, at meso- to seasonal scales, are described in terms of Eulerian and Lagrangian statistics estimated from the low-pass filtered drifter velocities.

Maps of mean currents, subtidal velocity variance and mean kinetic energies were produced using a 40-km averaging scale. The mean flow map confirms that the global cyclonic circulation in most of the Adriatic basin is broken into three re-circulation cells in the northern, central and southern sub-basins (the latter two being controlled by the bathymetry of the Jabuka and South Adriatic Pits, respectively). An isolated cyclonic gyre prevails near the head of the basin. Mean velocities in the cyclonic gyres can exceed 25 cm s⁻¹ in the coastal areas where the velocity variance is also maximum (reaching 500 cm² s⁻²).

Values near 2 × 10⁷ cm² s⁻¹, 2 days and 18 km were obtained for the diffusivity and the Lagrangian integral time and spatial scales in the along-basin direction, respectively. In the across-basin direction, the statistics are typically 50% of the above values. Geographical and seasonal variations of the Lagrangian statistics can be substantial. It was found that the fluctuating velocities (or the mesoscale eddies) have a preferential cyclonic sense of rotation.

The gyres and the coastal currents are mostly prevailing in summer and fall. In winter and spring, they are less intense but the southern one tends to re-circulate more around the South Adriatic Pit. The mean eddy kinetic energy is maximum in winter and fall throughout the central and southern sub-basins.

The drifters showed that the southeastward flow along the Italian Peninsula has a width varying between 45 and 70 km and a mean core speed of 25–35 cm s⁻¹. In the northern and central sub-basins, maximum velocities are found within 5–10 km off the coast in winter and spring, while a weaker maximum is seen more offshore (15–25 km) during the other seasons. In the southern Adriatic, the current is wider in summer, fall and winter, whereas in spring, it becomes thinner (maximum core speed near 10 km from shore and width of about 50 km). The maximum core speed is generally larger in summer than in winter. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Surface circulation; Seasonal cycle; Mesoscale eddies; Lagrangian drifters

1. Introduction

The surface circulation of the Adriatic Sea, a semi-enclosed basin in the northern Mediterranean, has been explored and studied since antiquity due to
its central geo-political location and its importance for maritime commerce. Until the mid-1950s, most of the information on the surface currents (qualitative estimates of strength and direction) was acquired through estimates of navigation times or ship drifts, through measurements of temperature and salinity (Wolf and Luksch, 1887) and through observations of bottle drifts (Mazelle, 1914; Feruglio, 1920).

During the second half of the 20th century, analysis of hydrographic data (temperature and salinity) provided estimates of the geopotential topography or the baroclinic geostrophic currents in the Adriatic Sea (Zore, 1956; Mosetti and Lavenia, 1969; Kosarev, 1977; Artegiani et al., 1997b). Global maps of the baroclinic circulation were compiled showing singular spatial features and substantial temporal variability at seasonal scales. Being indirect estimates based on the geostrophic assumption, these current maps do not include the wind-driven (Ekman type) and the barotropic (due to the sea surface slope) components. Extensive bottle (Vucak, 1965) and card (Ferencak et al., 1982; Zore-Armanda et al., 1996) experiments were also performed. Regional measurements with moored current meters and moored/shipboard Acoustic Doppler Current Profilers (ADCP) were also made to study the circulation at various depths (e.g., Zore-Armanda, 1966; Kovačević et al., 1999; Gacic et al., 1999). The properties of the Adriatic Sea circulation, along with their historical investigations, were reviewed by Orlic et al. (1992) and more recently summarized by Poulain et al. (2001a).

Ship, bottle and card drifts were the first Lagrangian observations collected in the Adriatic. Lagrangian measurements essentially consist in estimating the displacement of instruments that approximately follow the surface currents during a known time period. With bottles and cards, only the total displacements between their release sites and the coastal locations where they were recovered are known. The uncertainties on the effective time of drift, on the actual trajectories of the bottles/cards, and the obvious direct influence of the surface winds and waves, precluded a quantitative and accurate analysis of the basin-wide Adriatic surface circulation.

With the advent of satellite tracking technology in the 1970s, the trajectories of drifting instruments were determined with position accuracy of less than 1 km. Dividing the successive displacements by the respective time intervals (typically 1–2 h), velocity estimates were obtained wherever the instruments drifted between their release and their recovery/end sites. Furthermore, special buoy designs that reduce the effect of surface winds and waves were operated, with obviously better water-following capabilities than bottles and cards. Thus, localized and more accurate estimates of the velocity of the surface waters were obtained.

It is not until the early 1990s, however, that satellite-tracked drifters were operated in the Adriatic Sea. In 1990, Borzelli et al. (1992) measured the surface currents in the northern Adriatic using a limited set of five drifters. Deployments of more than 60 surface drifters started in earnest in late 1994 (Poulain, 1999), with focus on the southern Adriatic and the Strait of Otranto, connecting the Adriatic to the rest of the Mediterranean. Maps of mean surface circulation and velocity variance were created at 0.25° spatial resolution using these drifter observations between December 1994 and March 1996.

A new surface drifter program in the Adriatic was started in summer 1997 with better focus on the seasonal variability of the circulation throughout the basin. Repeated seasonal deployments at key locations provided a temporal and geographical data distribution suitable to study the seasonal variations of the Adriatic-wide circulation. The data from 201 drifters in the Adriatic Sea over a 9-year period (August 1990–July 1999) have been used to estimate subtidal velocity statistics of the Adriatic Sea surface circulation. The results are presented in this paper. This new drifter-based description of the Adriatic circulation is novel with respect to the work of Poulain (1999) because of the larger amount, the more uniform geographical distribution and the different time period of the drifter data, which in turn allowed to estimate the statistics in a more robust way.

The paper is organized as follows: Section 2 provides information on the drifting buoy systems, the drifter datasets and the methodology used to compute Eulerian and Lagrangian statistics from the drifter trajectories. The statistical results are presented in Section 3 assuming stationarity over the 9 years of observations. In Section 4, this assumption
is partially relaxed and the seasonal signal in the Eulerian velocity statistics is assessed. Section 5 contains the discussion and interpretation of the results, followed by Section 6 with conclusions and recommendations for future work.

2. Data and methods

2.1. Drifter systems and data processing

Most of the drifters used in this study (~77%, 155 units) are similar to the ones used in the Coastal Dynamics Experiment (CODE) in the early 1980s (Davis, 1985). They were manufactured by Technocean, Cape Coral, FL, USA. They consist of a slender, vertical, 1-m-long negatively buoyant tube with four drag-producing vanes extending radially from the tube over its entire length and four small spherical surface floats attached to the upper extremities of the vanes to provide buoyancy (Poulain, 1999). Comparison with current meter measurements (Davis, 1985) and studies using dye to measure relative water movements (D. Olson, personal communication) showed that the CODE drifters follow the surface currents to within 3 cm s\(^{-1}\), even during strong wind conditions.

Other buoy systems included the Compact Meteorological and Oceanographic Drifter (CMOD; Selsor, 1993) developed by Metocean, Dartmouth, Nova Scotia, Canada (~18%, 37 units). These sonobuoys consist of a 60-cm-long aluminum cylindrical hull with a floatation collar (35-cm overall diameter). They were drogued with the sonobuoy case (62-cm long and 12-cm-diameter) on a 100-m-long (4 m for a few of them) 0.5-in.-diameter tether, resulting in a wet to dry area ratio of about 5 to 1.

Four units (~2%) were of the Surface Velocity Program (SVP) or WOCE/TOGA design with a holey-sock at 15 and 300 m nominal depths (Sybrandy and Niiler, 1991). The remaining five drifters (~3%) are briefly described in Borzelli et al. (1992). Table 1 summarizes the drifter types.

The water-following capability of the drifters (mostly of the CODE and CMOD designs) was assessed by comparing, in a quantitative way (least-squares fit), their velocities with data of wind speed and direction interpolated at the their locations (Mauerhan, 2000). Orographically steered winds of the Navy Operational Regional Atmospheric Prediction System (NORAPS) 1995 nowcasts were used in the Adriatic and Ionian Seas to perform this comparison (Horton et al., 1997). Significant correlation between drifter velocities and wind was only found in limited shallow areas such as the Italian shelf on the western side of the Strait of Otranto. In general, however, the correlation is weak, and the statistical techniques adopted to study the wind effects on the different drifter types yielded inconclusive results. Hence, the drifter velocities were not corrected for the drift directly related to the wind in this work. The fact that the drogued depths vary between ~0 and 300 m (see Table 1) was not used to discriminate drifters because (1) drogued and undrogued drifters appeared to have similar drift characteristics and (2) it is generally difficult to determine when drifters lost their drogue. For example, we suppose that most of the CMOD drifters lost their 100-m line soon after release, but there was no sensor to indicate the time of rupture. The circulation statistics presented here were computed from all the data of all the drifter types, including all the drogue depths.

All drifters were tracked by the Argos Data Location and Collection System (DCLS) carried by the

<table>
<thead>
<tr>
<th>Buoy design</th>
<th>Quantity</th>
<th>Drogue type (quantity)</th>
<th>Origin (quantity)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CODE</td>
<td>155</td>
<td>None</td>
<td>NPS (91), SACLANTCEN (62), NAVOCEANO (2)</td>
</tr>
<tr>
<td>CMOD</td>
<td>37</td>
<td>Tether with sonobuoy case: 100-m long (32), 4-m long (5)</td>
<td>NAVOCEANO</td>
</tr>
<tr>
<td>SVP</td>
<td>4</td>
<td>Holeysock at: 15 m (3), 300 m (1)</td>
<td>NPS (3), SACLANTCEN (1)</td>
</tr>
<tr>
<td>Other</td>
<td>5</td>
<td>None</td>
<td>TELESPAZIO</td>
</tr>
<tr>
<td>Total</td>
<td>201</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
NOAA polar-orbiting satellites (Poulain et al., 2001b). After editing for outliers, the typical drifter position accuracy was found to be 200–300 m. For the latitude range of the Adriatic Sea (40–46°N), the typical number of satellite fixes per day was 12 using the Argos system on two satellites. The corresponding number of good locations per day was nine. In order to take advantage of a special scientific reduced tariff for the Argos tracking, the transmitters of some drifters were programmed to transmit with an intermittent duty cycle 1 day on–2 days off after 30 days of continuous operation. About 23% of the data used in this study corresponds to this intermittent mode. Note that the surface circulation statistics presented in this paper do not change significantly whether the drifter data corresponding to the intermittent transmission mode are considered or rejected.

The raw position data were edited for outliers and spikes using statistical and manual techniques (Poulain et al., 2001b) and were interpolated at 1-h uniform intervals using a “kriging” optimal interpolation scheme (Hansen and Poulain, 1996). The interpolated positions were subsequently low-pass filtered with a Hamming filter with cutoff period at 36 h to eliminate tidal and inertial currents and were sub-sampled at 6-h intervals. Velocity components were then estimated from centered finite differences of the interpolated sub-sampled latitudes and longitudes. Based on the typical Argos location accuracy and the characteristics of the above averaging, we estimated the low pass filtered velocity accuracy to be 2–3 cm s⁻¹, which is of the same order of magnitude as the error due to direct wind effects.

2.2. Drifter data

In this study, the southern limit of the Adriatic was taken as the parallel connecting the tip of the heel of the Italian Peninsula (Cape Santa Maria di Leuca) to the Greek island of Corfu at latitude 39°N48'. The deployment sites of the 198 drifters that were released in or near the Adriatic and which contributed data in the Adriatic basin are shown with star symbols in Fig. 1a. The geography and bathymetry of the basin are also introduced. Of major interest are two depressions, the Jabuka and South Adriatic Pits, which reach 260 and 1200 m in the central and southern sub-basins, respectively.

A total of 91 drifters were deployed by the Naval Postgraduate School (NPS), Monterey, CA, providing data from August 1997 to July 1999. A few of these units belonged to the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Trieste, Italy. Most of these drifters were of the CODE type. They were released with the help of Italian and Croatian colleagues, mostly during oceanographic cruises. The release sites were widely distributed throughout the Adriatic basin in an effort to increase the spatial coverage of the data. Deployments at these sites were repeated on a seasonal basis so as to maintain a minimum drifter population at all times during the 2 years of study.

Sixty-two drifters were deployed by the North Atlantic Treaty Organization SACLANT Underwater Research Centre (SACLANTCEN), La Spezia, Italy, with main focus on the eastern side of the Strait of Otranto (Poulain and Zanasca, 1998; Poulain, 1999). These drifters, mainly of CODE design, spanned the period December 1994–March 1996.

In support of military operations, the Naval Oceanographic Office (NAVOCENO), Stennis Space Center, Mississippi, has deployed surface drifters in the Mediterranean since 1989. Forty drifters were deployed in the Adriatic starting in 1992 (14 units) and continuing in 1993–1998 with three to five deployments per year. Most of these drifters were sonobuoys of the CMOD design. The

Fig. 1. (a) Bathymetry (50, 100, 200, 1000 and 1200 m isobaths) of the Adriatic Sea with the sites of drifter deployments (star symbols). The basin was rotated by 45° counterclockwise so that the north direction corresponds to the left-top corner of the panel. (b) Low-pass filtered trajectories of the 201 drifters that provided data in the Adriatic (north of 39°N48′) between 1-Aug-1990 and 31-Jul-1999. (c) Drifter data density, i.e., the number of 6-hourly observations divided by the percentage of sea area in the bin, computed in disks of 20-km radius. The values, represented with gray shades and contour lines, have been interpolated at 1-km resolution using cubic splines. Three maxima in data density are outstanding in the region north of Ancona, near the South Adriatic Pit, and in the eastern part of the Strait of Otranto. (d) Same as (c) but for the number of independent observations (see Appendix C).
five drifters that were released by Telespazio, Rome, Italy, in the northern Adriatic in 1990 were also included in the dataset (Borzelli et al., 1992).

Three drifters originally deployed in the northern Ionian and in the Strait of Sicily, and which entered the Adriatic basin through the Strait of Otranto, provided additional measurements. The 201 trajectories of the drifters in the Adriatic Sea are depicted in Fig. 1b. It can be seen that over the 9 years of observations, the drifter observations covered most of the Adriatic with the following exceptions: the regions south of the Po River delta and south of the Gargano Promontory to the west, and some of the Croatian coastal waters isolated by islands to the east.

The maximum lifetime of the drifters in the Adriatic (north of 39°N48′) is 230 days. The drifter mean half-life, i.e., the time after deployment for which 50% of the drifters still provide useful data in the Adriatic basin, is about 40 days. Although substantially less than the value obtained from drifter programs in the world oceans (more than 400 days), this number is quite satisfactory in view of the high probability of being retrieved by seafarers or being grounded ashore in the relatively small Adriatic semi-enclosed basin.

The time distribution of the number of drifter velocity observations is depicted in Fig. 2a for the entire Adriatic (north of 39°N48′). The observations span the time period between 1 August 1990 and 31 July 1999. They include a total of 27.9 drifter-years. Note the scarcity of data in 1991 and the two periods with large drifter population (peaking with 23 drifters on 23 May 1995) in 1995–1996 and 1997–1999, corresponding to the SACLANTCEN and NPS drifter programs, respectively. Over the 9 years of observations, the drifter observations are rather well distributed over the seasons (Fig. 2b), at least for the whole Adriatic basin.

Information about the origin, type and numbers of drifters used in this Adriatic circulation study is summarized in Table 1. More details about the drifter hardware, data processing techniques and the drifter dataset (individual drifter paths, velocity time series, etc.) can be found in a data report available on CD-ROM (Poulain et al., 2001b).
2.3. Spatial scale of averaging

In order to represent the Adriatic surface currents as the sum of (1) a mean flow that is constant in time and slowly varying in space, and (2) residual fluctuations that are due to temporal and small-space variabilities, a spatial scale of averaging must be chosen. In previous studies, a simple averaging or binning in domains of $0.25^\circ \times 0.25^\circ$, that is, with scales between 19 and 28 km, was used (Poulain, 1999). Falco et al. (2000) estimated the Adriatic mean flow using bicubic spline interpolation with parameters optimized to minimize the energy in the fluctuation field at low frequency. Their results are very similar to those of Poulain (1999).

As seen in the track diagram (Fig. 1b), in satellite imagery (Barale et al., 1984; Gacic et al., 1996; Mauri and Poulain, 2001) and in in-situ measurements (Gacic et al., 1999), the size of the mesoscale eddies (small loop and meander features) is about 10–20 km. This scale is of the same order of magnitude as the first internal Rossby radius of deformation (4–9 km) calculated by Grilli and Pinardi (1998). Therefore, a distance of 40 km appears adequate for averaging out the mesoscale motions.

Two other concerns have to be considered when selecting the averaging scale. The first involves the time interval between consecutive observations and imposes a lower limit on the averaging scale so that sub-sampling every 6 h provides at least one observation in each bin crossed by a drifter. With a maximum speed of about 100 cm s$^{-1}$, the maximum displacement that an Adriatic surface drifter moves in 6 h is: $0.001 \times 6 \times 3600 = 21.6$ km. Choosing a bin size of 40 km guarantees that a fast drifter crossing the bin contributes to 1–2 observations in that bin.

The second is a sensitivity criterion. We would like to assess the sensitivity of the velocity statistics with respect to the averaging scale selected. To illustrate the scale dependence, we have computed the kinetic energy of the mean flow per unit mass (MKE) and the mean eddy kinetic energy per unit mass (EKE) in bins of increasing size (see definitions in Appendix B), from one single disk including the entire Adriatic (radius = 400 km) down to disks with 12.5 km radius, staggered in a grid with 12.5 km mesh size. As expected, the MKE (EKE) averaged over all the bins increases (decreases) with decreasing bin size (Fig. 3). The EKE does not become inferior to the MKE, and does not reach small values because it corresponds to temporal variability which is not resolved deterministically by increasing the spatial resolution.

We have chosen to compute the Eulerian velocity statistics in 20-km-radius circular bins separated by 20 km on a grid oriented along the axes of the Adriatic basin (see details in Appendix A). For 20-km radius bins, the mean energy levels are about 80 and 100 cm$^2$ s$^{-2}$ for the MKE and EKE, respectively. It is obvious that increasing/decreasing the averaging scale has a significant effect on the energy levels. The numerical values of the Eulerian statistics presented in this paper are therefore specific to the specific averaging scale chosen, that is, 40 km (the diameter of the bins).

Once the scale of averaging has been chosen, some of the bins have to be rejected in order to obtain robust Eulerian statistics, that is, to limit sampling and bias errors to reasonable levels. As discussed in Appendix A, bins were only considered if they passed the following tests: (1) the number of independent observations is larger or equal to 5; (2) at the most, 75% of the bin area corresponds to land; and (3) each of the four seasons are represented by at least 5% of the total numbers of observations.

2.4. Geographical data distribution

The drifter data density, that is the number of 6-hourly observations in the 20-km-radius bins, divided by the percentage of sea water in the bins (see Appendix A), is shown in Fig. 1c. In spite of our efforts to maximize the geographical coverage of the data, the drifter data density shows three maxima in the region north of Ancona, near the South Adriatic Pit and in the eastern part of the Strait of Otranto. Note that drifters were not necessarily deployed in these regions (Fig. 1a) and that some maxima in drifter population correspond to the “natural” accumulation or convergence of the drifters. The drifter density related to the number of independent observations (Fig. 1d) was also estimated (see Appendix C for details). Its spatial distribution is similar to the one of the 6-hourly observations, except in the east-
ern Strait of Otranto and off the Albanian coast where it is reduced due to the fact that many simultaneous 6-hourly observations are statistically dependent of each other following the drifter release in large clusters (Poulain, 1999).

It is important to note that the non-uniform Lagrangian sampling depicted in Figs. 1c,d and 2a can introduce significant aliasing between the spatial and temporal scales, and as a consequence, the space and time variabilities generally cannot be separated. For example, the velocity variance within the bins represents both spatial variability at scales smaller than 40 km and temporal sub-tidal variations with timescales longer than a few days, including the seasonal signal if it is not considered separately like in Section 4. In addition, the velocity statistics calculated from a non-uniformly distributed dataset are generally specific to the particular data distribution available and may be different from ideal statistics computed from uniformly distributed data, especially in bins with few observations. The use of stringent rejection criteria based on the number of independent observations, and on their temporal distribution, alleviates somewhat this problem.

2.5. Eulerian and Lagrangian statistics

Theoretically, Eulerian velocity statistics should be computed over an ensemble of many realizations of the Adriatic flow field. In practice, however, this ensemble averaging is substituted by an averaging over time and in spatial bins, assuming stationary and uniform statistics within the bins. Maps of mean flow, subtidal velocity variance, and the related MKE and EKE, called hereafter Eulerian velocity statistics, were computed by averaging all the six hourly low-pass filtered drifter velocity observations within the 20-km-radius circular bins. The definitions of the Eulerian statistics are included in Appendix B. A discussion of the random and bias errors associated with them can be found in Appendix C.

By definition Lagrangian velocity statistics are computed over an ensemble of selected particles. Again, this is not practically feasible using real drifters and the assumptions of stationarity and uniformity (at least locally) are invoked to estimate statistics that characterize the displacement and absolute dispersion of selected drifters over time. Let us consider all the drifters that occupy a given spatial
domain, which can be the entire Adriatic or a small 20-km-radius circular bin. Each observation in the domain can be considered as a “deployment” position from which the drifter is tracked with positive time lags (arriving at that position) and with negative time lags (going away from that position). Likewise, Lagrangian statistics are estimated for particles reaching (positive time lags) and leaving (negative time lags) the spatial domain considered (Davis, 1991; Poulain et al., 1996). They are defined in Appendix D.

Lagrangian statistics depend not only upon the domain selected (in space and eventually in time) but also on the time lag. For turbulent motions, however, they plateau after time lags of the order of the integral time scale, for both positive and negative time lags; the covariances approach zero and the diffusivities diagonal elements and scales asymptote to maximum constant values (Taylor, 1921). Lagrangian statistics are intrinsically non-local as particles spread over a finite-size domain which can be, in our case, a substantial portion of the entire Adriatic basin. They can consequently include dispersion effects by the mean flow shear. Furthermore, when the particles approach the boundaries of the basin, asymptotic quantities such as the diffusivity are affected. A way of handling this problem could be to use more appropriate descriptions of dispersion, e.g., using scale-dependent Lyapunov exponents (Artale et al., 1997; Lacorata et al., 2001). This is beyond the scope of this paper. We have chosen to account for the effects of shear dispersion (at least partially), which become important when particles spread over distance larger than 40 km, by subtracting the deterministic Eulerian mean flow from the individual drifter velocities before computing the Lagrangian statistics. The mean Eulerian velocity field was interpolated at the drifter locations using cubic splines.

3. Mean circulation, velocity variance and diffusivity

3.1. Eulerian statistics

Assuming that the Adriatic surface velocity statistics are stationary over the 9 years of interest, Eulerian statistics were computed for the entire Adriatic basin using 20-km-radius bins. Considering only the bins that passed the rejection criteria (Appendix A), it was found that the velocity observations within each good bin spanned a minimum of 3.2 years and a maximum of 8.7 years.

The map of mean surface circulation in the entire Adriatic Sea (Fig. 4a) reveals and quantifies the main characteristics of the surface circulation throughout the Adriatic basin and confirms most of the results previously obtained from hydrographic data, current meter observations and other drifter studies. A global basin-wide cyclonic circulation is striking with fast northward currents along the eastern side, referred to as the East Adriatic Current (EAC), and a swift return flow along the Italian Peninsula on the western side, called the West Adriatic Current (WAC). This pattern is composed of major sub-basin re-circulation cells in the central and southern Adriatic where the circulation is controlled by the bathymetry of the Jabuka and South Adriatic Pits, respectively. Further to the north, northward currents eventually reach the southern tip of the Istrian Peninsula, turn westward and join the southward return flow forming a third cyclonic re-circulation with the northern limb following approximately the 40–50 m isobath. At the north end of the Adriatic, the surface circulation is in the form of a fourth isolated cyclonic gyre. Maximum mean speeds exceeding 25 cm s\(^{-1}\) are found in both the WAC and EAC in the southern sub-basin.

It is important to note that the mean circulation map (Fig. 4a) represents a robust statistical estimate of the mean Adriatic surface circulation. Indeed, due to the strict criteria adopted for choosing the bins, the confidence intervals around the mean vectors are generally relatively small (see Appendix C and Fig. 13a). As discussed in Appendix C, the “array” bias (Fig. 13b) can be significant in some areas (as large as 5 cm s\(^{-1}\)) but it stays bounded by the 95% confidence intervals. As a result, the “array” bias does not affect significantly the mean circulation map presented in Fig. 4a and a correction was judged unnecessary.

The sub-tidal velocity variance (Fig. 4c), which in this case includes the variability due to small scale eddies, to wind-driven current events and also to the seasonal modulation of the surface circulation, is generally large in regions of strong currents, where it
can reach values above 500 cm$^2$ s$^{-2}$ corresponding to a r.m.s. speed of $\sim 22$ cm s$^{-1}$ (in the western Strait of Otranto). Thus, the standard deviation of the velocity fluctuations can be as large as the mean. The velocity variance is typically oriented in the direction of the mean currents (see ellipse orientation in Fig. 4c) as most of the velocity variations are related to changes in amplitude, and eventually reversals, of the prevailing currents over time. The orientation of both the mean current vectors and the principal axes of velocity variance follow generally the coast or the bathymetric contour lines due to topographic constraint. The eccentricity of the velocity variance ellipse range from 0.25–0.8 in the open sea to values $> 0.95$ in the coastal areas.

As expected, the MKE is maximum in the coastal areas (Fig. 4b), especially off Dubrovnik on the eastern side, and off the Gargano Promontory and southern Italy to the west. Mean currents are also more intense on the Albanian shelf break and along the northern slope of the Jabuka Pit. The maximum MKE in the 20-km radius circular bins is over 400 cm$^2$ s$^{-2}$ (off southern Italy). MKE is minimum (inferior to 10 cm$^2$ s$^{-2}$) in most of the open sea and in the center of the Strait of Otranto.

The mean kinetic energy of the fluctuating velocities, also called EKE, has weaker gradients compared to the MKE (Fig. 4d). It is maximum (reaching over 300 cm$^2$ s$^{-2}$) in the western side of the Strait of Otranto. It exceeds 150 cm$^2$ s$^{-2}$ in localized zones of the WAC (off the Po River delta, south of Ancona and around the Gargano Promontory). Substantial EKE levels are also found on the Albanian shelf and south of Dubrovnik.

As already found by Poulin (1999), the drifter data indicates three major regions in the open sea with quiescent mean circulation (speed < 5 cm s$^{-1}$ or MKE < 10 cm$^2$ s$^{-2}$; see Fig. 4b) and reduced velocity variance (EKE less than 50 cm$^2$ s$^{-2}$; see Fig. 4d). They are located near the center of the three cyclonic gyres in the southern, central and lower northern Adriatic. In addition, the zone between the two gyres in the northern Adriatic, extending toward the coastal waters off the Istrian Peninsula, is characterized by weak mean and fluctuating currents.

It is interesting to examine the ratio of MKE to EKE (not shown) which provides information on the division of energy between mean constant and fluctuating currents. The coastal regions with large mean currents discussed above are characterized by a high ratio, as the MKE can be three times as large as the EKE. Everywhere else, the ratio is less than one, and the fluctuating velocities dominate the energy of the surface currents. The ratio is minimum (less than 0.1) in most of the open Adriatic Sea and the central Strait of Otranto where the velocity fluctuations are at least 10 times more energetic than the mean flow. Exceptions include areas northwest of the Jabuka Pit and northwest of the South Adriatic Pit where the mean recirculating flow is important.

To conclude this presentation of the Eulerian velocity statistics in the Adriatic, we would like to discuss briefly the results of vorticity and divergence. The mean surface circulation depicted in Fig. 4a was interpolated on a 1-km resolution grid using bicubic splines, and the velocity gradients were estimated. These gradients were combined to estimate the vertical component of relative vorticity and the horizontal divergence. The former gave robust and interesting results, whereas the latter turned out to be below the noise level (difference of comparable quantities). The vorticity of the mean surface flow in the Adriatic ranges between $-0.65$ and 0.85 in units of $10^{-5}$ s$^{-1}$. Compared to the planetary vorticity at the mid-latitude (43$^\circ$N) of the Adriatic basin (about $9.9 \times 10^{-5}$ s$^{-1}$), the vorticity values obtained are less than 10%, meaning that the mean flow is approximately in geostrophic balance. As expected, the vorticity is negative to the right of the fast currents (e.g., on the Albanian Shelf, north of the Jabuka Pit) and positive to the left of strong currents (e.g., east of the WAC).

Fig. 4. Maps of surface mean flow (a), kinetic energy of the mean flow (b), subtidal velocity variance ellipses (c) and mean eddy kinetic energy (d) calculated in circular bins (20 km radius) on a grid (20 km resolution) covering the entire Adriatic basin. The mean flow arrows and the variance ellipses are centered at the center of mass of the observations in each bin. The 200- and 1000-m isobaths are shown in panels (a) and (c). The mean kinetic energy levels are represented with gray shades and contour lines after interpolation (using cubic splines) at 1-km resolution. The contour interval is 50 cm$^2$ s$^{-2}$ (above 50 cm$^2$ s$^{-2}$). Bins with less than five independent observations, with less than 25% sea area and for which any season is represented by less than 5% of the data have been omitted.
An attempt was made to estimate surface transports, especially in the along-basin direction. Globally, the along-basin NW surface flux on the eastern side of the basin compensates rather well the SE transport along the Italian coast. Calculations of along and across-basin transports at specific locations (e.g., Strait of Otranto, Palagruza Sill, northern wall of Jabuka Pit) revealed that the surface water mass is not conserved, probably due to the particular sampling of the drifters (non-uniform in space and

![Fig. 5. Lagrangian statistics calculated for the entire Adriatic basin after removal of the mean Eulerian circulation. All statistics are shown versus time lag between ~10 and 10 days. (a) Mean angular momentum, (b) Lagrangian integral time scale, (c) diffusivity and (d) Lagrangian velocity covariance. See Appendix D for definitions.](image-url)
time and spanning 9 years). Hence, the circulation map based on the drifter data (Fig. 4a) should not be used to search for specific areas of divergence/convergence, nor to investigate transports and identify zones where the surface waters sink to deeper levels (deep water formation).

### 3.2. Lagrangian statistics

The Lagrangian statistics computed for the entire Adriatic basin, after the Eulerian mean flow has been subtracted from the drifter velocities, are presented in Fig. 5 for time lags ranging from $-10$ to $10$ days. They are also summarized in Table 2. Asymptotic values (independent of time lag) were taken as the maximum values over the range $0$ to $10$ days. Energy levels (Fig. 5d), diffusivities (Fig. 5c) and integral time scales (Fig. 5b) are larger in the along-basin direction. In agreement with the results depicted in Fig. 3, the variance at zero time lag reaches over $100 \text{ cm}^2 \text{ s}^{-2}$ in the along- and across-basin directions, respectively. The off-diagonal elements of the covariance matrix are significantly negative ($\sim -15 \text{ cm}^2 \text{ s}^{-2}$) indicating that the residual velocities as a whole vary along a major principal axis oriented by about $20^\circ$ with respect to the along-basin axis. The along-basin diffusivity reaches extremum values (near $2 \times 10^7 \text{ cm}^2 \text{ s}^{-1}$) after about 10 days. In the across-basin direction, values are much smaller (maximum diffusivity less than $1 \times 10^7 \text{ cm}^2 \text{ s}^{-1}$ after 2–3 days). For larger time lags, the lateral boundaries of the Adriatic Sea constrain across-basin dispersion and, as a consequence, diffusivity decreases versus time lag. Note that, at least in the along-basin direction, the decrease of diffusivity, and associated scales for time lags larger than 5–10 days, can also be due to the removal of a non-adequate overestimated mean velocity shear. The Lagrangian statistics estimated without subtracting the Eulerian mean flow from the drifter velocities (not shown) have the opposite trend, with increasing and non-saturating diffusivities versus increasing time lags, caused by mean flow shear dispersion.

Maximum Lagrangian integral time scales are about 2 (1) days for the along- (across-) basin direction. The distance over which particles diffuse away with the fluctuating velocities (excluding the mean Eulerian flow) during the Lagrangian integral time scale is the Lagrangian integral length scale (see Appendix D). It is equal to about 18 and 8 km, for the along- and across-basin directions, respectively. The difference between the two off-diagonal elements of diffusivity (Fig. 5a), i.e., the mean angular momentum of the velocity fluctuations, is positive for all time lags, corresponding to predominant cyclonic polarization of the mesoscale field.

An attempt was made to estimate the Lagrangian statistics in the individual 20-km-radius bins (not shown). Despite the large uncertainties due to the reduced number of observations and because shear dispersion is not always well accounted for by removing the mean Eulerian field of Fig. 4a, some interesting qualitative results arose from this exercise. It was found that diffusivities vary from $1 \times 10^5$ to $5 \times 10^5 \text{ cm}^2 \text{ s}^{-1}$ with higher values obtained in the coastal areas in the along-shore direction. Open sea areas are characterized by low ($0.5–1 \times 10^5$ cm$^2$ s$^{-1}$) and approximately isotropic diffusivities. Lagrangian length scales follow the same trends ranging from values inferior to 5 km in the open sea to 40 km near the coast (in the direction parallel to the coast). Lagrangian time scales were seen to vary between 0.5 and 5 days. In summary, the coastal and open areas of the Adriatic appear to have significantly different Lagrangian statistics. Thus, the results presented in Fig. 5 represent averaged statistics.

### Table 2

<table>
<thead>
<tr>
<th>Direction</th>
<th>Variance ($\text{cm}^2 \text{ s}^{-2}$)</th>
<th>Diffusivity ($10^7 \text{ cm}^2 \text{ s}^{-1}$)</th>
<th>$T_1$ (days)</th>
<th>$L_1$ (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Along</td>
<td>Across</td>
<td>Along</td>
<td>Across</td>
</tr>
<tr>
<td>All</td>
<td>106.3</td>
<td>70.3</td>
<td>1.9</td>
<td>0.7</td>
</tr>
<tr>
<td>Winter</td>
<td>76.3</td>
<td>59.3</td>
<td>1.1</td>
<td>0.5</td>
</tr>
<tr>
<td>Summer</td>
<td>101.5</td>
<td>65.7</td>
<td>2.7</td>
<td>0.7</td>
</tr>
</tbody>
</table>

that should be interpreted and used with caution. In particular, the marked difference between the results in the along- and across-basin directions shown in Fig. 5 is merely the effect of the coastal areas and is not representative of the open sea.

4. Seasonal cycle

Being a land-locked basin of the northern Mediterranean where atmospheric conditions vary considerably with the seasons, the Adriatic Sea circulation is expected to contain a significant seasonal signal. The quantity and the geographic and temporal distribution of the drifter data are adequate to estimate Eulerian velocity statistics for each season of the year in order to assess the Adriatic circulation seasonal variability.

4.1. Definition of seasons

In order to obtain some guidance to define the four seasons over which the statistics are computed, we first explored the month-to-month variations of the surface kinetic energy level in the Adriatic. The mean kinetic energy (MKE + EKE) computed over the whole Adriatic basin is shown for the 12 months of the year in Fig. 6. According to the drifter data, low energy levels are observed between February and July with values ranging between 100 and 130 cm$^2$ s$^{-2}$. There is a sharp increase of energy from July to August which represents the beginning of a 6-month period of high energy (August to January, with values exceeding 150 cm$^2$ s$^{-2}$).

Based on the above results, the Adriatic seasons were chosen according to the standard separation, namely: winter (Jan–Feb–Mar), spring (Apr–May–Jun), summer (Jul–Aug–Sep) and fall (Oct–Nov–Dec). We did not adopt the seasons based on the Adriatic Sea heat storage (Artegiani et al., 1997a) for three reasons. First, these seasons Jan–Apr, May–Jun, Jul–Oct, and Nov–Dec are not efficient at separating high from low energy conditions (see Fig. 6). Second, we believe that the seasonality of the forcing parameters (surface wind stress, river runoffs) should be considered when defining the circulation seasons, rather than the heat storage alone. And third, the short transition seasons May–Jun and Nov–Dec have significantly less drifter observations than the other two extended seasons, resulting in poorer estimates of the statistics.

Fig. 6. Mean kinetic energy (MKE + EKE) for the entire Adriatic Sea computed for the individual months of the year.
4.2. Basin-wide Eulerian statistics

The low-pass filtered trajectories are depicted for each season in Fig. 7. The entire Adriatic basin is rather well covered except in the northern sub-basin where the drifter trajectories are scarce in fall and winter. As a whole, the drifter population is almost equally distributed over the seasons, with a slightly more abundant population in fall (reaching 30% of the global drifter dataset).

The circulation seasonal signal was first investigated in terms of basin-wide Eulerian statistics, for which the same threshold as in Section 3 was applied (five independent observations in 20-km-radius bins with at least 25% of sea area). The binning method is the same as before, but the data were now separated out per seasons. The maps of mean flow (Fig. 8) show the persistence of the cyclonic cells in the central and southern basins, and in the lower northern Adriatic. The strength and spatial structure of these circulation features, however, vary from one season to the other. Statistical tests (see Appendix C) revealed that the seasonal variations of the mean surface flow estimates are significant for most of the bins considered. Note that to the north, the cyclonic gyre near the head of the Adriatic appears to be maximum in summer, but poor coverage during the other seasons prevent a quantitative assessment of the full seasonal cycle.

Although the maximum mean speed does not vary significantly with the seasons (from 28 to 33 cm s\(^{-1}\)), the geographical distribution of the fast currents changes substantially. The speed of the mean currents (Fig. 8) and the MKE (Fig. 9) show extended areas of high values in summer and fall (and also in winter for the southern sub-basin), especially in the coastal currents of the southern Adriatic. Spring has weaker mean currents in most of the Adriatic. In fall, the MKE of the two coastal currents and the re-circulation northwest of the Jabuka Pit are enhanced in the central basin. Re-circulation around the South Adriatic Pit tends to be more important in winter and spring. In winter a larger portion of the EAC re-circulates into the WAC at the northern escarpment of the Jabuka Pit. In fall, the cyclonic gyres in the central and southern sub-basins are somewhat combined, but the recirculation near the Jabuka Pit does not preclude flow from continuing along the Croatian coast. It is during this season that exchange between the three basins are enhanced (see also Falco et al., 2000).

Focussing our attention to the two extreme seasons (winter and summer) in the southern basin (Fig. 8a,c), it can be seen that the EAC is generally weaker in summer than in winter. In contrast, the WAC appears slightly stronger in summer with respect to the winter situation. More details about the statistical significance of these variations can be found in Appendix C and Fig. 13c.

Velocity variance ellipses (not shown) and EKE (Fig. 10) are larger in fall throughout the Adriatic (mostly above 100 cm\(^2\) s\(^{-2}\)). In winter, they are also substantial in the central and southern sub-basins. In spring and summer, the WAC fluctuations are the most energetic. Elsewhere and particularly near the center of the cyclonic gyres, the EKE stays low.

4.3. Eulerian statistics in the Western Adriatic Current (WAC)

We now focus on the WAC, one of the most striking and important currents of the Adriatic Sea, which is defined here as the entire current flowing southeastward along the Italian Peninsula and includes the western limbs of the re-circulation cyclonic gyres. This definition differs from the one used in Artegiani et al. (1999) and Hopkins et al. (1999) where it corresponds to the coastal amplification of the southeastward current on the mini-shelf (depth < 20 m). In order to increase resolution in the off-shore direction, the drifter velocities were averaged as follows. First two regions were defined: the northern WAC extending between the Po River delta and the Gargano Promontory (from \(x_1 = -380\) to 0 km in Fig. 1a), and the southern WAC from the Gargano to the Strait of Otranto (\(x_1 = 80\) to 340 km) in which along-basin homogeneity was assumed. Second, the across-basin coordinate was replaced by the distance from the Italian coast in the across-basin direction. Third, this distance was used to average the along-basin drifter velocities in 8-km wide bins separated by 4 km. The latter scales of averaging represent a good compromise between spatial resolution and accuracy of the results. The drifter data were also separated into the four seasons of the year.
Fig. 7. Maps of the low-pass filtered drifter trajectories for the four seasons of the year. The number of drifter-days and the corresponding percentage are posted near the top-right corner of each panel: (a) Winter (Jan–Feb–Mar), (b) spring (Apr–May–Jun), (c) summer (Jul–Aug–Sep) and (d) fall (Oct–Nov–Dec).
Fig. 8. Seasonal maps of surface mean flow calculated in circular bins (20 km radius) on a grid (20 km resolution) covering the entire Adriatic basin. The mean flow arrows are centered at the center of mass of the observations in each bin. The 200- and 1000-m isobaths are also shown. Bins with less than five independent observations and with less than 25% sea area have been omitted.
Fig. 9. Same as in Fig. 8 but with seasonal maps of the kinetic energy of the mean flow (MKE). The values, represented with gray shades and contour lines, have been interpolated at 1-km resolution using cubic splines. Bins with less than five independent observations and with less than 25% sea area are masked with white areas. The contour interval is 50 cm$^2$ s$^{-2}$ (above 50 cm$^2$ s$^{-2}$).
Fig. 10. Same as in Fig. 9 but with seasonal maps of the mean eddy kinetic energy (EKE).
The results are depicted in Figs. 11 and 12. The number of independent observations, $N^*$, in the elongated bins (obtained using a typical Lagrangian integral time scale of 1.5 days, see Appendix D) does not exceed 30, with the larger values generally obtained in winter and fall (Figs. 11d and 12d). Because of the substantial r.m.s. velocity of the fluctuations, spanning 5 to 25 cm s$^{-1}$ (Figs. 11b and 12b) and because $N^*$ is limited to 30, the 95% confidence intervals around the mean velocity estimates can be quite large. For clarity purposes, the error bars are not displayed in Figs. 11 and 12. They range from 2–3 to $\sim$ 15 cm s$^{-1}$, meaning that they can be as large as the mean estimates themselves, and that they are generally larger than the differences in the mean values between the different seasons.

Fig. 11. Along-shore or along-basin velocity statistics for the northern WAC ($x_1$ between −380 and 0 km, see Fig. 1a). The drifter velocities were averaged in overlapping 8-km wide bins using the distance from the Italian coast. The results, that is, the mean (a) and r.m.s. (b) speeds, the number of six hourly observations (c) and the number of independent observations (d), are shown for the four seasons of the year.
For example, using James’ test (at the 5% significance level; see Appendix C) we cannot reject the hypothesis that the four mean speeds are equal to the same value.

Despite the relatively large errors, some seasonal variations in the WAC strength and structures are evident. Between the Po River delta and the Gargano Promontory (Fig. 11), the WAC width (distance at which the mean speed approaches zero) varies between 45 km (in winter, spring and summer) and 60 km (in fall). In winter and spring, maximum speeds reaching 20–35 cm s\(^{-1}\) are concentrated near the coast (\(\sim 5\) km offshore), while in summer and fall, the core of the WAC is weaker (\(\sim 15\) cm s\(^{-1}\)) and is located more offshore (15–25 km).

In the southern WAC, between Gargano and the Strait of Otranto, the WAC velocity statistics are slightly different (Fig. 12). Speeds are generally larger (up to 30–35 cm s\(^{-1}\)). Summer, fall and winter have similar characteristics, with a current width near 60–70 km and maximum speeds located between 10 and 15 km from shore. Spring is diverse
with respect to the other seasons. It is characterized by a rather thin (about 50 km from the coast) and swift (maximum mean speed exceeding 30 cm \( s^{-1} \)) current system. A decrease in speed is generally seen in both the northern and southern WAC for distances less than 5 km.

It is interesting to calculate the typical maximum time that a water parcel discharged by the Po River takes to exit the Adriatic basin on the western flank of the Strait of Otranto. Taking a maximum mean speed of 30 cm \( s^{-1} \) (the average of the maximum spring values for the north and south parts of the WAC) and a distance of about 750 km, we end up with about a month.

In general, for both the northern and the southern parts of the WAC, the magnitude of the fluctuating currents (r.m.s. speed) is maximum in the mean current core and decreases seaward of it (Figs. 11b and 12b). There is a reduction of r.m.s. speed very near the coast in the north. In contrast, the maximum fluctuations appear in the first bin (0–8 km) in the southern WAC.

### 4.4. Lagrangian statistics

In order to explore the potential seasonal signal in the Lagrangian statistics, the drifter observations were separated out into the four seasons of the year and the statistics were computed for the entire Adriatic considering the data of each season separately. The seasonal Eulerian mean flow (Fig. 8) was subtracted from the drifter velocities before computing the Lagrangian statistics. Only the results of the two extreme seasons, winter and summer, are discussed here. The velocity variances (Lagrangian covariances at zero time lag), the diffusivities (maximum values for time lags between 0 and 10 days), and the corresponding integral time and length scales are listed in Table 2.

In winter, fluctuations are generally weaker and more isotropic. The diffusivities and scales, however, are larger in the along-basin direction (about twice the values in the across-basin direction). As expected, the fluctuating currents are stronger and more polarized in the along-basin direction in summer. The summer across-basin statistics are similar to those of winter. In the along-basin direction, the values are quite large: diffusivity approaches \( 3 \times 10^7 \) cm\(^2\) \( s^{-1} \) and the scales are roughly 3 days and 30 km. Note that these estimates of seasonal variations in the Lagrangian statistics are inferior to (or at least of the same order of magnitude as) the geographical variations discussed in Section 3.2.

### 5. Interpretation and discussion

Our map of mean surface circulation (Fig. 4a) discloses in a quantitative fashion, significant circulation patterns with details and accuracy never obtained in previous studies. In particular, the results presented here are much improved, in terms of spatial resolution and statistical reliability, with respect to previous drifter studies (Borzelli et al., 1992; Poulain, 1999).

The Adriatic Sea mean surface flow is globally cyclonic due to its mixed positive–negative estuarine circulation (Hopkins et al., 1999) forced by buoyancy input from the rivers (mainly the Po River) and by strong air–sea fluxes resulting in loss of buoyancy and dense water formation. The EAC flows along the eastern side from the eastern Strait of Otranto to as far north as the Istrian Peninsula. A return flow (the WAC) is seen flowing to the southeast along the Italian coast. Re-circulation cells embedded in the global cyclonic pattern are found in the lower northern, the central and the southern sub-basins, the latter two being controlled by the topography of the Jabuka and South Adriatic Pits, respectively. The bifurcation of the coastal flow at the northern steep wall of the Jabuka Pit is striking in the mean flow (Figs. 4a and 8) and the mean kinetic energy (Figs. 4b and 9) maps. This particular flow pattern has been studied analytically and numerically by Carnevale et al. (1999). It essentially results from potential vorticity conservation. Borzelli et al. (1999) have used satellite thermal images to describe the off-shore flowing filament associated with the bifurcation. They also argue that the filament formation can be ascribed to the interaction of the EAC with bathymetry.

The drifters delineate clearly the re-circulation cell in the northern basin (Fig. 4a) which appears to persist all year (Fig. 8). This feature is not easily seen in Artegiani et al.’s (1997b) maps but it was confirmed by hydrographic (Malanotte-Rizzoli and...
Bergamasco, 1983; Manca et al., 2001) and satellite (Borrelli et al., 1999) observations. This cell is not controlled by bathymetry as the bottom is gently sloping in the area. The existence and the variations of the re-circulation cell are related to the northern Adriatic dynamics. According to Malanotte-Rizzoli and Bergamasco (1983), the northern Adriatic circulation is primarily of thermohaline origin with major contributions coming from the Po River (buoyancy gain) and from winter heat loss (buoyancy loss and deep water formation). The wind-driven circulation is secondary and is only important during transient strong wind events. The thermohaline conditions generally favor a stronger re-circulation of the EAC in summer due to enhanced opposing density gradients. Unfortunately, our drifter data are too scarce to study the seasonal variations of the northern Adriatic circulation.

An isolated cyclonic gyre is evident in the northern part of the northern sub-basin (Fig. 4a). This feature was well sampled by the drifters in summer (Fig. 8c) when it appeared to be maximum (with speeds exceeding 10 cm s\(^{-1}\)). There is also some signature of it in spring and fall, and some evidence of its disappearance or reversal in winter (Fig. 8a), but these results must be interpreted with caution because they are based on the data of few drifters. The cyclonic gyre is in good agreement with the hydrographic observations of Mosetti and Lavenia (1969).

Under the influence of extremely variable surface and lateral fluxes, including bora wind events (Zore-Armanda and Gacic, 1987) and strong buoyancy inputs from the Po River (Barale et al., 1986), the northern Adriatic basin has complex dynamics (Malanotte-Rizzoli and Bergamasco, 1983) and its circulation varies substantially at relatively short scales (a few days and 5–10 km). The variability of the circulation was qualitatively described by Mauri and Poulain (2001) using drifter and satellite-derived sea surface temperature and chlorophyll concentration images in fall 1997. As a consequence of this large variability, our statistical results based on limited Lagrangian observations should be interpreted with great caution in the northern basin.

A new and interesting result obtained from this drifter study is the near-shore intensification (10–20 km from shore) of the coastal currents along the Italian and Croatian coasts and the concentration of the EAC above the Albanian shelf break. For example, the core of the WAC can be located within 10 km of the Italian coastline (Figs. 11 and 12). These features are not well evident in the dynamic height maps of Zore (1956) and Artegiani et al. (1997b) due to the coarse sampling of the hydrographic arrays. The near-shore intensification of the long-shore currents is in good agreement with the simple dynamical model of Orfì (1996) that predicts the cyclonic surface circulation related to the quasigeostrophic rectification of the surface offshore flow, in a land-locked sea for which the surface buoyancy loss in locally balanced by the river buoyancy gain.

Using 40-km size bins (20 km radius), the mean kinetic energy of the surface circulation was separated into the contribution of the mean flow and of the fluctuating velocities, with typical levels near 100 cm\(^2\) s\(^{-2}\). Localized maximum values take place in the coastal currents with MKE and EKE levels reaching 400 and 300 cm\(^2\) s\(^{-2}\), respectively. The above energy levels are comparable to those obtained from current meter measurements near 50 m depth in the southern basin and in the Strait of Otranto (Gacic et al., 1996; Kovacevic et al., 1999).

How particles disperse away due to the fluctuating velocities and how long the “memory” of the particles is were quantified by calculating absolute eddy diffusivities and Lagrangian integral scales (Fig. 5 and Table 2). To study the surface transports in the Adriatic, one can use a simple advection–diffusion model (Falco et al., 2000) or the elaborated model of Davis (1994) in which tracers are advected by a constant deterministic field (e.g., the mean flow depicted in Fig. 4a or in Fig. 8) and diffused according to a Fickian-type law based on Lagrangian properties of the fluctuating velocities (diffusivities and Lagrangian scales).

We found that the dispersion properties are typically twice as large in the along-basin direction than in the across-basin axis. Diffusivities in the range 1–3 \(\times\) \(10^7\) cm\(^2\) s\(^{-1}\) agree well with the previous estimates of Falco et al. (2000). They are inferior to the values \(1–13 \times 10^7\) cm\(^2\) s\(^{-1}\) generally obtained in other coastal areas and in the open ocean, e.g., in the California Current System (Poulain and Niiler, 1989), in the Nordic Seas (Poulain et al., 1996) and in the Algerian Current (Salas et al., 2001). Adriatic diffusivities are smaller because the Lagrangian
scales are shorter (1–3 days versus 1–10 days) and/or the energy levels are lower with respect to the ones in the above-mentioned regions. The Lagrangian integral time scales estimated from the Adriatic drifter data (1–3 days) are slightly smaller than the Eulerian scales deduced from moored current meter data (Kovacevic et al., 1999). This means that drifters generally move between mesoscale features faster than the advection rate of the eddies. In the open sea, the Lagrangian integral length scales of 5–10 km are comparable to the typical size of the mesoscale eddies and to the internal Rossby radius of deformation (Grilli and Pinardi, 1998). In the coastal currents, the scales are increased in the along-basin direction, reaching values near 27 km. The Lagrangian scales were seen to be slightly larger in summer than in winter (Table 2) in some contradiction with the fact that the stratification is supposed to shorten the horizontal scales of variability (Borzelli et al., 1999).

The fact that the angular momentum of the residual Lagrangian velocities is positive for short time lags (Fig. 5a) indicates that the mesoscale fluctuations tend to be polarized in the cyclonic direction. This corresponds to the predominance of cyclonic mesoscale eddies in the Adriatic basin. Satellite images (Barale et al., 1984; Mauri and Poulain, 2001) confirm the cyclonic rotation of the mesoscale structures, especially in the WAC instabilities.

The classical seasonality of the circulation in the southern Adriatic basin revealed by the hydrographic measurements of Zore (1956), that is, a wider and stronger WAC (EAC) in summer (winter), is only partially confirmed by our drifter-based statistics. The WAC is slightly stronger is summer (maximum speed approaching 30 cm s⁻¹, see Fig. 12) but its width remains practically the same for the two seasons (~60 km). There is only a slim evidence (Fig. 13c) that the EAC is more intense in winter, but the strong currents tend to be localized closer to shore. Considering the four seasons in the southern basin, the WAC and EAC are generally stronger in summer/fall, which is in partial agreement with the results of Arregiani et al. (1997b). The re-circulation cell in the central Adriatic is maximum in winter, is still substantial in summer and spring and is minimum in winter, again in good agreement with the maps of Arregiani et al. (1997b). Contrary to the findings of Gacic et al. (1997) and the results of Arregiani et al. (1997b), the re-circulation around the Southern Adriatic Pit is more intense in winter and spring. During the other two seasons, the circulation is more in the form of a unique cyclonic gyre covering the central and southern sub-basins.

Near the Island of Vis (most offshore island off Split), the EAC does not show major seasonal variability, in contradiction with the results of Zore-Armanda (1966) whose current meter observations indicated prevailing NW currents in winter, reversing to SE in summer. Again, this discrepancy can result from the different sampling adopted, especially the limited number of drifter observations adopted.

The WAC between the Po River delta and the Gargano Promontory is more concentrated near the Italian coast in winter and spring, while during the other seasons its core is found farther offshore (about 20–30 km from the coast in fall). These variations in the northern WAC structure have been confirmed by recent hydrographic observations (Arregiani et al., 1999) and by numerical simulations of the Adriatic circulation (Zavatarelli et al., 2001). They also agree with satellite observations of seasonal changes in the width of the nutrient-rich western Adriatic layer, related to the variability of the Po discharge (Barale et al., 1984). Our results on the variability of the northern and southern parts of the WAC do not contradict those obtained from current meter mooring measurements (Kovacevic et al., 1999) and shipboard ADCP data (Gacic et al., 1999). Differences are essentially due to the different sampling adopted.
6. Conclusions

Most of the statistical properties of the Adriatic surface circulation presented in this paper, based on the data of more than 200 drifters covering a period of about 9 years, are robust quantitative estimates of results that were qualitatively known before. The originality of this work comprises the method adopted (direct velocity measurements with numerous Lagrangian drifters), the relatively high horizontal resolution chosen (40 km) and the discovery of novel results, such as the near-shore intensification of the coastal currents, a different seasonality of the mean circulation and the dispersion properties and prevailing polarization (cyclonic) of the mesoscale eddies.

The drifter-based velocity statistics presented in this paper are in some contradiction with previous studies of the Adriatic circulation which used hydrographic data and current meter measurements. We believe that this discrepancy originates more from the different sampling adopted and the different period studied than from an essential phenomenological difference in the Adriatic circulation. It is encouraging that the basic features of the Adriatic circulation were confirmed by the drifters. The fact that some differences and/or contradictions were obtained is a challenge for future studies in the Adriatic Sea. The combination of in-situ (Lagrangian and Eulerian) observations with remotely sensed data (passive and active techniques) is essential to be able to describe quantitatively, understand and forecast the functioning of the Adriatic or any other semi-enclosed seas. Monitoring systems including a variety of these observations are presently planned for the Adriatic, and for the Mediterranean Sea in general, in order to achieve the above scientific goals.

Acknowledgements

I would like to thank the various institutions and individuals who generously provided logistic help for the deployment of the NPS drifters. These included M. Gacic, P. Scarazzato and G. Gelsi (OGS, Trieste, Italy), S. Rabitti (IBM-CNR, Venezia, Italy), A. Artegiani and E. Paschini (IRPEM-CNR, Ancona, Italy), V. Dadic and M. Morovic (IFO, Split, Croatia) and J. Tamul (NAVOCEANO, Stennis Space Center, Mississippi, USA). A few of the NPS drifters belonged to OGS. E. Horton and D. Bird (NAVOCEANO) and G. Borzelli (Telespazio, Rome, Italy) are acknowledged for sharing their drifter data. Special thanks go to D. Burych, C. Fayos, P. Green, E. Mauri, L. Ursella, B. Schniling and P. Zanasca for their help with the drifter data processing. The author was funded by the Office of Naval Research under grants NW0001499WR30015 and NW00014-00WR20193. The comments of two of the anonymous reviewers contributed significantly to improve the first version of the manuscript.

Appendix A. Eulerian averaging

Once a spatial scale of averaging is chosen to estimate Eulerian statistics, the number and the distribution of the data in each bin has to be examined. If the number of independent observations is small, the error bars on the velocity statistics can exceed the estimates. In addition, given the possible existence of a significant seasonal signal, a non-uniform data distribution over the seasons can introduce a bias error.

So, a minimum number of independent observations should be used as threshold to discard bins with few observations. This number was set to five independent observations as a practical tradeoff between accuracy and geographical coverage, so that a robust statistical description of the circulation is provided with good spatial resolution. For example, most of the bins contain more observations than the threshold for the Eulerian mean flow map (Fig. 4), permitting a good spatial description of the mean circulation and the velocity variance. Furthermore, in order to exclude the bins that include significant land areas, a threshold on the percentage of sea versus land areas was adopted. A minimum of 25% of sea area in each bin is required for considering the statistical results. In other to reduce the biases due to the fact that the drifters might not sample the seasons equally in each bin, an additional constraint was applied when constructing the Eulerian maps from all the data (see Section 3); bins for which each season was not represented by at least 5% of the data were rejected.

The grid for Eulerian averaging was created as follows. First, the Adriatic basin was rotated by 45° in the counter-clockwise sense and was remapped.
using distances calculated from a center point at 16°E 15° and 42°N 45°. This very simple mapping does not introduce significant distortions given the limited size (200 by 800 km) of the basin, as shown by the rectilinear parallels and meridians in Fig. 1a. In the rotated coordinates, \( x_1 \) corresponds to distance in the main axis of the basin, and \( x_2 \) to the across-basin distance. Second, circular bins of 20-km radius with centers regularly distributed throughout the basin with 20-km interval distance in both \( x_1 \) and \( x_2 \) directions, were adopted. In this configuration, adjacent bins are overlapping and can contain common drifter observations. As a result, the maps of the statistical properties contain some spatial smoothing.

The drifter density was estimated by counting the number of six hourly observations in the bin and by dividing it by the geographical sea area in the bin. For bins including major islands and fractions of continental land, the sea area was determined manually using interactive MATLAB programs. The advantage of the density computed in this way is that it does not artificially decrease for bin including land masses i.e., near the coastline, contrary to the number of observations which can be smaller simply because the sea area available is reduced. This subtle difference in density definition is important to estimate the \( A \) bias see Appendix C.

### Appendix B. Eulerian statistics

Let us use the symbol \( \langle \cdot \rangle_E \) for the average in a geographical area and over a given time period. The following statistics are defined:

**Mean flow:**
\[
\langle u_i \rangle_E, \quad (B1)
\]

**Velocity covariance matrix:**
\[
\langle u_i u_j \rangle_E, \quad (B2)
\]

**Kinetic energy (per unit mass) of the mean flow:**
\[
\text{MKE} = 1/2 (\langle u_1^2 \rangle_E + \langle u_2^2 \rangle_E), \quad (B3)
\]

**Mean kinetic energy (per unit mass) of the fluctuating flow, also called mean eddy kinetic energy:**
\[
\text{EKE} = 1/2 (\langle u'_1 u'_1 \rangle_E + \langle u'_2 u'_2 \rangle_E), \quad (B4)
\]

where \( u_i \) are the two components of the drifter velocity and \( u'_i = u_i - \langle u_i \rangle_E \) are the residual velocity components. The indexes \( i \) and \( j \) can take the value 1 or 2, for the along- and across-basin directions, respectively. The principal axes of variances or the variance ellipses are computed from the eigenvalues and eigenvectors of the velocity covariance matrix (Emery and Thomson, 1998).

### Appendix C. Errors on the Eulerian mean flow

The mean flow estimated by averaging drifter velocities in a geographical area and over a given time period is expected to be affected by sampling errors due to the finite number of observations and due to subscale variability. The sampling error is generally represented by displaying a 95% confidence ellipse around the mean flow vector. This ellipse has the same orientation as the velocity variance ellipse. Its semi-minor and semi-major axes are approximately equal to twice the principal standard errors, namely:

\[
\text{Semi-major (minor) axis} = 2 \sqrt{\frac{\lambda_i}{N^*}}, \quad (C1)
\]

where \( \lambda_i \) are the two eigenvalues of the velocity covariance matrix and \( N^* \) is the number of degrees of freedom or the number of independent observations (Emery and Thomson, 1998).

For a time series of length \( T \), Flierl and McWilliams (1977) have shown that the number of independent observations can be approximated by:

\[
N^* = \frac{T}{2T_l}, \quad (C2)
\]

where \( T_l \) is the Lagrangian integral time scale (see definition in Appendix D). In order to estimate \( N^* \) for Lagrangian observations in a given space/time domain, both temporal and spatial decorrelation scales have to be taken into account. We have adopted the following procedure: The trajectories were first sub-sampled every 3 days, that is at twice the typical value for \( T_l \). Every 3 days, observations within the same bin were then counted, excluding simultaneous data points separated by less than 10 km (typical Eulerian decorrelation scale).

The 95% confidence ellipses are drawn at the tips of the mean flow vectors in Fig. 13a. Despite the fact that the principal standard errors can be quite large
surrounding bins did not contain data. If at least one of the four bins were not considered, the bias was not estimated. For the bin near the coast, the bias appears relatively small because drifters tend to “diffuse” away from regions of high concentration.

For bin sizes small compared to the scales of variability of the drifter concentration, the mean flow, and of the diffusivity, and assuming stationary statistics, the “array” bias can be expressed as:

\[
\text{Array Bias} = -K_{ij}^E \delta_j C / C,
\]

where the eddy diffusivity \( K_{ij}^E \) is the asymptotic value of the lag-dependent diffusivity \( K_{ij}(\tau) \):

\[
K_{ij}^E = \lim_{\tau \to \infty} K_{ij}(\tau),
\]

and \( C \) is the drifter data concentration. The actual mean flow \( U \) is related to the Eulerian estimate of \( \langle u_i \rangle_E \) through:

\[
U = \langle u_i \rangle_E + K_{ij}^E \delta_j C / C.
\]

The “array” bias was estimated as follows. First, the gradient of drifter concentration was computed by finite central differences of the concentrations in the four (overlapping) neighboring bins adjacent to the bin of interest. The drifter concentration was defined as the number of six hourly observations in the circular bins (20 km radius) divided by the corresponding sea area. Second, this gradient was scaled by the concentration in the bin considered. Third, this ratio was multiplied by the magnitude of the global diffusivity estimated in the along- and across-basin directions, \( \sim 2 \times 10^7 \text{ cm}^2 \text{ s}^{-1} \), respectively. The off-diagonal elements of the diffusivities were not considered. For the bin near the coast, the bias was not estimated if at least one of the four surrounding bins did not contain data.

Our estimates of the “array” bias are depicted in Fig. 13b. As expected, the bias points away from concentration maxima like a divergent flow controlled by downgradient diffusion (Fig. 1c). It can be substantial (as large as 5 cm s\(^{-1}\)) where the concentration varies significantly spatially. Compared to the sampling error, however, the “array” bias appears relatively small (it does not exceed the 95% confidence ellipse).

When comparing the seasonal mean velocity fields (Fig. 8) or the seasonal mean speeds for the northern and southern parts of the WAC (Figs. 11 and 12), one might ask whether the differences between seasons are statistically significant or just a sampling artifact. A way to address this question is to apply James’ test for the null hypothesis that the means are equal (Seber, 1984; Garaffo et al., 2001). This test compares the means of populations (scalars or vectors) when the variances are not equal. An example is illustrated in Fig. 13c for the comparison between the summer and winter circulations in the southern Adriatic basin. The mean estimates are only depicted for the common good bins. For the bins shaded in gray, James’ test for the null hypothesis of equal means was rejected at the 5% confidence level (probability of 5% of being wrong). As can be seen in Fig. 13c, the majority of bins show statistically different mean estimates, especially north of the South Adriatic Pit. Currents in the outer rim of the cyclonic gyre are generally faster in winter than in summer. In the WAC, this tendency is reversed (summer currents tend to be stronger) although the difference is not significant in some bins.

### Appendix D. Lagrangian statistics

The symbol \( \langle \cdot \rangle_L \) is used for the average over time and space computed at time lag \( \tau \) before/after the particles are located in a given domain. The following statistics are defined:

- Lagrangian mean velocity: \( \langle u_i \rangle_L(\tau) \).

- Lagrangian velocity covariance matrix:

\[
P_{ij}(\tau) = \langle u_i'(0)u_j'(\tau) \rangle_L,
\]

where \( x(\tau) \) and \( u_i' = u_i - \langle u_i \rangle_L \) (\( i = 1 \) and 2) are the particle position and residual Lagrangian velocity components, respectively. Note that the mean Lagrangian velocity and the Lagrangian velocity co-
Lagrangian integral time scale: following scales. Specifically, we can define the transport properties in the Adriatic Sea as deduced from drifter data. J. Phys. Oceanogr. 30, 2055–2071.


