JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 112, C03S04, doi:10.1029/2005JC003177, 2007

Surface drifter derived circulation in the northern and middle Adriatic Sea: Response to wind regime and season

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Received 20 July 2005; revised 17 February 2006; accepted 19 June 2006; published 15 December 2006.

[1] More than 120 satellite-tracked drifters were deployed in the northern and middle Adriatic (NMA) Sea between September 2002 and November 2003, with the purpose of studying the surface circulation at mesoscale to seasonal scale in relation to wind forcing, river runoff, and bottom topography. Pseudo-Eulerian and Lagrangian statistics were calculated from the low-pass-filtered drifter velocity data between September 2002 and December 2003. The structure of the mean circulation is determined with unprecedented high horizontal resolution by the new data. In particular, mean currents, velocity variance, and kinetic energy levels are shown to be maximal in the Western Adriatic Current (WAC). Separating data into seasons, we found that the mean kinetic energy is maximal in fall, with high values also in winter, while it is significantly weaker in summer. High-resolution Local Area Model Italy winds were used to relate the drifter velocities to the wind fields. The surface currents appear to be significantly influenced by the winds. The mean flow during the northeasterly bora regime shows an intensification of the across-basin recirculating currents. In addition, the WAC is strongly intensified both in intensity and in its offshore lateral extension. In the southeasterly sirocco regime, northward flow without recirculation dominates in the eastern half of the basin, while during northwesterly maestro the WAC is enhanced. Separating the data into low and high Po River discharge rates for low-wind conditions shows that the WAC and the velocity fluctuations in front of the Po delta are stronger for high Po River runoff. Lagrangian covariance, diffusivity, and integral time and space scales are larger in the along-basin direction and are maximal in the southern portion of the WAC.

Citation: Ursella, L., P.-M. Poulain, and R. P. Signell (2006), Surface drifter derived circulation in the northern and middle Adriatic Sea: Response to wind regime and season, *J. Geophys. Res.*, *111*, C03S04, doi:10.1029/2005JC003177. [printed *112*(C3), 2007]

1. Introduction

[2] The Adriatic Sea has been widely explored and studied since antiquity due to its central position for the ancient civilization and its economical importance. It is a complex system, being a semienclosed shallow basin, greatly influenced by seasonal and interannual climatic changes and short-term external forcing, like river runoff, wind stress and heat fluxes. These forcing mechanisms, often in the form of extreme events, produce a complex dynamical response that affects the entire local ecosystem [*Cushman-Roisin et al.*, 2001]. In addition, the highly variable (both in time and space) forcing factors combined with the relatively small baroclinic Rossby radius of deformation ($\sim$10 km) produces a highly variable circulation field with small-scale structures, that are responsible for the transport of heat, nutrients and dissolved substances of various origin.

[3] The general circulation of the Adriatic basin is cyclonic [*Orlic et al.*, 1992] and includes a rather weak and broad northwestward current (the Eastern Adriatic Current (EAC)) to the east and a fast and coastally confined southeastward current (the Western Adriatic Current (WAC)) along the Italian coast. Three major cyclonic features are embedded in this main circulation structure [*Poulain*, 2001]. The WAC is formed in the northern Adriatic Sea principally due to the Po river, which is located in the northwestern part of the basin, and whose mean discharge is 1500 m^3 s^{-1} [*Raicich*, 1994]. The EAC brings Levantine Intermediate waters and Ionian surface waters into the Adriatic Sea. Major wind events force the circulation for short periods. In particular, in the northern Adriatic, northeasterly bora wind forms two gyres, one cyclonic in the far north and another anticyclonic just to the south of the first one [*Zore-Armanda and Gacic*, 1987; *Kuzmic and Orlic*, 1987; *Orlic et al.*, 1994]. An exhaustive description of the Adriatic circulation and forcing mechanisms is given by *Cushman-Roisin et al.* [2001].

[4] As described by *Poulain* [2001], the first scientific studies of the Adriatic circulation began at the end of the 18th century, but they remained very qualitative. A crucial improvement in the measurement of surface currents was gained with the technological development of instrumenta-

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0148-0227/06/2005JC003177$09.00

tion in the 1970s, and in particular with the advent of satellite systems for tracking surface drifters. However, deployments of satellite-tracked drifters in the Adriatic Sea did not start before the early 1990s. The data of more than 200 surface drifters deployed in the Adriatic between 1990 and 1999 were analyzed by *Poulain* [2001] to study the spatial characteristics and temporal evolution of its near-surface currents at mesoscale and seasonal scales. Since most drifters were deployed near the eastern flank of the Strait of Otranto (southern opening of the Adriatic Sea to the Ionian), the observations were mostly obtained in the Southern Adriatic Sea and in the Strait of Otranto region. The mean flow map compiled by *Poulain* [2001] shows a global circulation in most of the Adriatic basin broken into three recirculation cells in the northern, middle and southern subbasins. In addition, an isolated cyclonic gyre prevails near the northern head of the Adriatic. *Poulain* [2001] also assessed the seasonal variability of the statistics of the near-surface currents (mean and variance). The gyres and coastal currents are mostly prevailing in summer and fall, whereas the velocity variance was found to be maximal in fall in the middle and southern subbasins, presenting, however high values also in winter. In the northern and middle Adriatic (NMA), the WAC reaches maximal mean velocities (~20–25 cm/s) within 5–10 km from the coast in winter and spring, while a weaker core (~15–20 cm/s) is seen more offshore (15–25 km) during the other seasons.

[5] In the framework of the Dynamics of Localized Currents and Eddy Variability in the Adriatic (DOLCEVITA) program [*Lee et al.*, 2005a, 2005b] and the NATO ADRIA02/03 Field Trials [*Signell*, 2002, 2003], more than 120 satellite-drifters were operated in the NMA between September 2002 and December 2003 to explore the variability of its near-surface currents. The main objective of this new drifter project was to quantify the mesoscale variability of the NMA, with particular attention to the structure and variability of the coastal current along the Italian Peninsula, the cold filaments extending from the Croatian coast and the instability structures of the Po River plume. A related goal was to study NMA surface circulation variability as a function of the wind and river forcing.

[6] In the present work, the subinertial variability of the NMA near-surface currents is studied in terms of Eulerian and Lagrangian statistics computed from the drifter velocities. The drifter systems and drifter data sets are first described (section 2) together with the methodology used to compute the statistics. Information about the wind products and the Po River data is also provided. Eulerian (maps of mean currents, velocity variance ellipses and kinetic energy levels) and Lagrangian (covariance, diffusivity, integral scales, mean angular momentum) statistics are presented in section 3. The Eulerian statistics are also presented after the drifter data have been separated into the four seasons of the year (section 4) and into various wind and Po River forcing regimes (section 5). The new results are discussed and summarized in section 6.

2. Data and Methods

2.1. Drifter Systems and Deployments

[7] A total of 124 surface drifters were deployed between September 2002 and November 2003 in the NMA as part of the DOLCEVITA and NATO ADRIA02/03 projects, corresponding to 188 deployments because some units were recovered and redeployed several times. They were mainly of the CODE type [*Davis*, 1985; *Poulain*, 1999, 2001]. Two versions were used: one with the standard Argos tracking and telemetry (65 units), and the other equipped with a Global Positioning System (GPS) system (43 units). The Doppler-based Argos tracking has an accuracy of 300–1000 m (Argos manual) and positions are typically available 6–12 times per day [*Ursella et al.*, 2004]. GPS locations have a higher accuracy (~10 m [*Barbanti et al.*, 2005]). CODE-GPS drifters were programmed to sample position at 1 hour intervals, together with sea surface temperature (SST). Data were kept in memory on the drifter before being transmitted to the Argos satellite system.

[8] A study on the water-following capabilities of the CODE type drifter (P.-M. Poulain and L. Ursella, Direct measurements of water-following characteristics of CODE surface drifters, manuscript in preparation, 2006) was conducted using CODE drifters equipped with Aquadopp acoustic velocimeters positioned at the top and at the bottom, i.e., about 1 m apart along the vertical. The velocimeters measured the current perpendicular to the drifter body about 1 m away from the transducers. This study has shown that the CODE drifters follow the surface current within 2 cm/s and that they move in a manner consistent with the near-surface Ekman dynamics [*Ekman*, 1905] with a velocity component perpendicular to the prevailing wind. Therefore the CODE type drifter can be considered an efficient instrument to measure surface currents in the first meter of the water column with 1–2 cm/s accuracy.

[9] Drifters of different types were also deployed during the project [*Poulain et al.*, 2003; *Poulain and Barbanti*, 2003], but they are not used to compute circulation statistics in the present study due to their different water-following characteristics and depth of current measurement.

[10] All drifters were tracked with the Argos Data Location and Collection System (DCLS) carried by NOAA polar-orbiting satellites. Between 6 May and 23 October 2003, the Argos system was also available on the Japanese satellite ADEOS II, resulting in a more uniform coverage with almost one fix per hour [*Ursella et al.*, 2004]. Transmission problems were often found, however, meaning that some of the received data were wrong or incomplete [*Poulain et al.*, 2003].

[11] Of the total number of CODE drifters (108), 38 units were deployed from the NATO R/V *Alliance* and 34 from the Woods Hole Oceanographic Institution R/V *Knorr* [*Poulain et al.*, 2003; *Poulain and Barbanti*, 2003; *Lee et al.*, 2005a], while 36 drifters were released with the help of Croatian colleagues from the R. Boskovic Institute (Rovinij) and from the Institute of Oceanography and Fisheries (Split), mostly during Eastern Adriatic Circulation Experiment (EACE) oceanographic cruises [*Orlic et al.*, 2006] and from ferries. The rest of the drifters were recovered and redeployed with other ships of opportunity. Eighteen drifters belonged and were deployed by the NATO Undersea Research Centre, La Spezia, Italy. Because of redeployments, the total number of CODE drifter tracks used in this work is 132.

[12] Drifters were deployed prevalently in triplets with locations separated by about 10 km, with the purpose of

studying their relative dispersion. Optimal deployment positions to obtain maximum data coverage were determined with a numerical simulation assuming that the Lagrangian eddy velocity satisfies a Langevin equation, i.e., the eddy velocity is modeled as a linear Markov process [*Ozgokmen et al.*, 2000; *Falco et al.*, 2000]. The aim was to have an almost homogeneous coverage in space and time in the NMA during the whole project. The results of these numerical simulations [*Ursella et al.*, 2004] were combined with the availability and logistical constraints of the various research vessels and ships of opportunity involved in order to make final decisions on the release sites. The actual deployment locations are depicted with asterisks in Figure 1a.

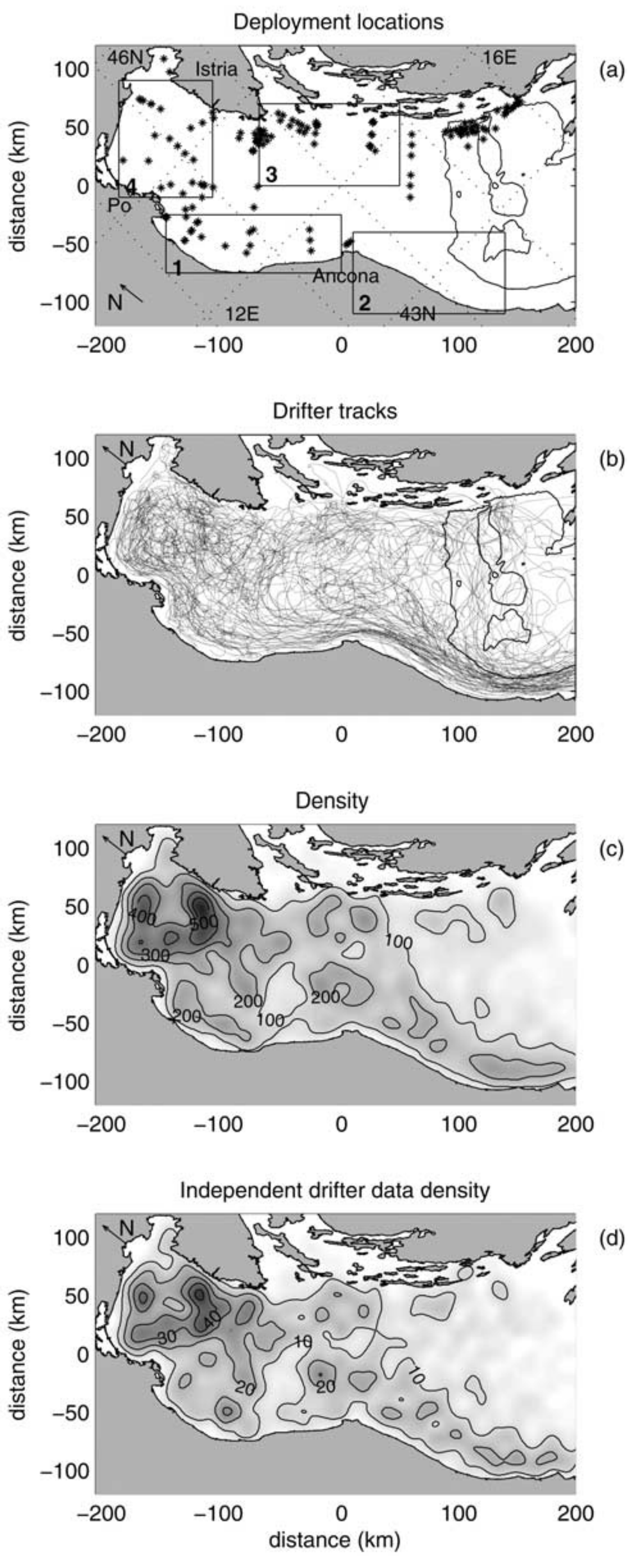

Figure 1. (a) Map of the northern and middle Adriatic with bathymetry (100 and 200 m isobaths) and drifter release sites (denoted by asterisks). Coordinates are rotated by 45° (in the counterclockwise direction) around a central location 14°E and 44°N. Selected zones with particular dynamics used for calculation of Lagrangian statistics are also indicated. (b) Low-pass drifter tracks for the period 21 September 2002 to 31 December 2003. (c) Drifter data density, i.e., the number of 6-hourly observations in each 10 km radius bins. (d) Same as Figure 1c but for the independent observations, calculated using a Lagrangian timescale of 3 days and a typical horizontal scale of 10 km.

[13] In general, whenever it was possible, the drifters that came ashore or were retrieved by fishermen were recovered and redeployed. The data of a redeployed drifter were considered to be belonging to a new track. This was done because the probability that a drifter reaches the coast in a confined basin like the NMA, is high, and the drifter lifetime may be as short as a few days. The maximum lifetime of the DOLCEVITA drifters is about 300 days, while the mean half-life, i.e., the time after deployment for which 50% of drifters is still transmitting, is 35 days. These values were obtained considering all the drifters deployed during the project, including those that reached the Ionian Sea. This mean half-life is lower that the value of 40 days, found by *Poulain* [2001], probably because the NMA is more confined and has more fishing activity than the Southern Adriatic. The temporal distribution of the number of drifters operating in the NMA over the entire period is depicted in Figure 2. It is evident that the highest number of drifters is found in September 2002, February 2003, May 2003 and June 2003, in coincidence with the four oceanographic cruises during which most of the drifters were released. Despite the high variability (or intermittency) of the temporal coverage, we can see that between 21 September 2002 and 31 December 2003, the number of active drifters is almost always above 3 units, except for a few days at the beginning of November 2003.

2.2. Drifter Data and Data Processing

[14] Both Argos and GPS data were quality controlled and interpolated at half an hour uniform intervals using a "kriging" optimal interpolation method based on a structure function whose characteristics were calculated from the data themselves [*Hansen and Poulain*, 1996; *Barbanti et al.*, 2004]. They were subsequently low-passed filtered with a hamming filter with cutoff period at 36 hours, in order to eliminate tidal and inertial variability, and then subsampled every 6 hours. In the present work, the GPS data were used when available, while the Argos data were only used for the drifters without GPS or to fill the gaps in the GPS time series [*Ursella et al.*, 2004]. Velocities were then calculated as finite differences of the subsampled positions. Latitudes and longitudes were transformed to distances using a

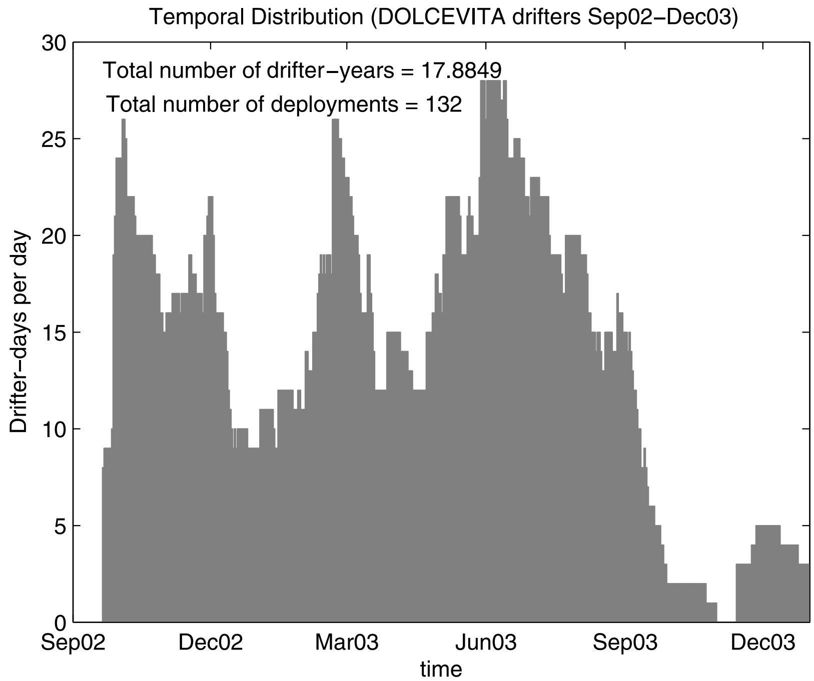

Figure 2. Temporal distribution of the number of drifters during DOLCEVITA project in the NMA. The maxima correspond to the main cruises during which most of the drifters were deployed.

coordinate system centered at 14°E and 44°N and rotated counterclockwise by 45° with respect to the zonal and meridional directions. In the processing procedure described above, the total number of drifter trajectories containing useful data was reduced from 188 to 161 (86%). The reduction is mainly due to problems with the position acquisition system, such as the blocking or malfunctioning of the GPS-Argos system, or to short data segments (less than three days) that were discarded before applying the "kriging" procedure.

2.3. Spatial Scale of Averaging

[15] In order to represent the mean surface current field in the NMA, a spatial scale of averaging must be chosen. This issue is important since, in general, the numerical values of the Eulerian statistics depend significantly on the scale of averaging. In a previous drifter study of the Adriatic Sea [*Poulain*, 2001], 20 km radius bins separated by 20 km were selected as spatial scale of averaging for the Eulerian velocity statistics. This choice was made imposing a minimum of one 6-hourly observation in each bin when considering the maximum possible speed and was also based on the variations of the kinetic energy levels as a function of scale. The selected averaging scale permitted to average out the mesoscale motions, whose dimensions in the Adriatic are about 10–20 km [*Barale et al.*, 1984; *Gacic et al.*, 1996, 1999; *Mauri and Poulain*, 2001]. In the present study, the density of drifter data is larger and the data spatial coverage is more uniform. Energy calculations with different bin sizes [*Ursella et al.*, 2004] show that the overall energy values are generally lower than those of *Poulain* [2001], but that the behavior is comparable: the kinetic energy of the mean flow (MKE) increases and the mean eddy kinetic energy (EKE) decreases with decreasing bin sizes. In the present case the energy values do not change significantly when choosing a bin size of 10 or 20 km. Therefore a size of 10 km radius was chosen for the bins. The mean values for the MKE and EKE with this scale of averaging are about 40 and 75 cm^2/s^2, respectively.

[16] The Eulerian (mean flow, velocity variance ellipses, MKE and EKE) and the Lagrangian statistics (covariance, diffusivity, angular momentum and integral space and timescales) were estimated using the definitions of *Poulain* [2001]. Some of the bins were excluded in the Eulerian fields where the number of observations is less than five to discard results with poor statistical reliability.

[17] The composite diagram of all the low-pass-filtered tracks is shown in Figure 1b together with the drifter data density (Figure 1c), that is the number of 6-hourly observations in the 10 km radius bins. The majority of the data is concentrated in the northernmost part of the basin, in particular near the Istrian Peninsula where only a few drifters were deployed. This zone is probably an accumulation point for the surface drifters [*Poulain*, 1999]. The same structure is maintained when considering only the independent data (Figure 1d). The independent density was calculated by subsampling the data every three days (twice the typical Lagrangian integral timescale, see Table 1) and counting only once the simultaneous observations separated by less than 10 km (typical Eulerian length scale) in the same bin [*Flierl and McWilliams*, 1977; *Poulain*, 2001].

2.4. Wind Products

[18] High-resolution Local Area Model Italy (LAMI) winds were used to construct maps of Eulerian statistics corresponding to the major Adriatic wind regimes, following a methodology similar to the one of M. A. Jeffries, and C. M. Lee (A mode-based climatology of the northern Adriatic Sea, submitted to *Journal of Geophysical Research*, 2006). LAMI winds were obtained for the period

Table 1. Maximum Values for Along- and Across-Basin Lagrangian Statistics Over the Time Lag Range −10 to 10 days for the Whole NMA and for Four Selected Regions[a]

	Variance, cm^2/s^2		Diffusivity, 10^7 cm^2/s		Timescale, days		Length Scale, km	
Zone Number	Along	Across	Along	Across	Along	Across	Along	Across
All	77.3	51.4	0.94–1.1	0.46–0.51	1.4–1.6	1.0–1.2	10.7–12.5	6.4–7.1
1: Northern WAC	90.2	38.0	0.83–1.83	0.49–0.5	1.1–2.3	1.48–1.5	8.8–19.2	7.9–8.1
2: Southern WAC	173.2	79.9	2.28–4.68	0.69	1.5–3.1	1.0	17.3–35.6	7.8
3: EAC	55.0	51.4	0.77–0.89	0.59–0.38	1.6–1.9	0.85–1.3	10.3–12.1	5.2–8.3
4: Northern NMA	37.3	43.5	0.33–0.37	0.38–0.50	1.0–1.1	1.0–1.3	5.5–6.1	5.8–7.6

[a]See text for definitions.

1 September 2002 to 31 December 2003 over the NMA with 3 hour time intervals. The spatial resolution of the wind field is about 6.5–7 km in the along and across basin directions, respectively. It is well known that the NMA is characterized by three major wind regimes [*Cushman-Roisin et al.*, 2001; *Yoshino*, 1976]: the northeasterly bora, the southeasterly sirocco and the northwesterly maestro. A forth wind category corresponding to winds blowing from the southwest (libeccio) is also defined. Two options were explored to separate the drifter data into these wind-forcing categories and to compute the corresponding NMA circulation statistics (based on conditional Eulerian averaging). The first one was to interpolate the wind field at the positions and times of the drifter observations and to construct the maps of Eulerian statistics sorting the drifter data using the interpolated wind values. The second method was to average the winds over the NMA geographical area at every time step and to consider this mean wind to sort the drifter data into the four wind regime categories. We ended up using the second method because the major winds have strong spatial variability. In particular, bora winds are affected by the orography east of the Adriatic Sea and are blowing over the NMA in well-known specific areas (e.g., near Trieste and near Senj) whereas other regions (off central Istria) are characterized by reduced winds during bora events. As a consequence, using the locally interpolated winds to sort the drifter data do not represent well the strong spatial variability (strong shear) of the wind forcing. In contrast, in the second method based on the spatially average winds, a unique wind category is assigned at every time step to the drifter observations, no matter where they are located.

[19] The two-dimensional histogram of the spatially averaged wind is shown in Figure 3, along with the practical separation into the four wind regimes for wind speed exceeding 2 m/s: Bora corresponds to wind direction in the third trigonometric quadrant, sirocco corresponds to wind direction in the second trigonometric quadrant, maestro corresponds to wind direction in the forth trigonometric quadrant, and libeccio corresponds to wind direction in the first trigonometric quadrant. The "no-wind" regime corresponds to all averaged winds with magnitude less than 2 m/s.

[20] It is important to note that the bora, sirocco, maestro, and libeccio are usually defined on the basis of well defined directions or restricted sectors [*Yoshino*, 1976]. Given the distribution shown in Figure 3 and in order to include more points in the different wind regimes, we have chosen to widen the sectors corresponding to the major winds to entire quadrants in order to obtain more robust statistics. Doing so, we obtain the following partition of the spatially averaged Adriatic winds: 26% corresponds to the no-wind region, 35% to bora, 21% sirocco, 10% maestro, and 8% to libeccio.

[21] In order to quantify the relation between surface currents and winds, complex correlation coefficients have been calculated without separating different wind regimes and following the definition of *Kundu* [1976]. They have been evaluated considering different time lags between currents and winds, i.e., 0, 6 and 12 hours, and also different minimum thresholds for wind speed. The magnitude of the complex coefficient gives a measure of the correlation, while the phase gives the averaged angle between winds and drifter velocities [*Kundu*, 1976].

2.5. Po River Discharge

[22] The daily Po River discharges (Figure 4) were used to construct Eulerian maps in different Po River discharge situations. The discharge data were collected at the Pontelagoscuro station upstream of the Po River delta, and are daily averaged values measured in m^3/s. It is well known that Po River discharge is one of the main driving forces of the Adriatic circulation [*Cushman-Roisin et al.*, 2001]. We

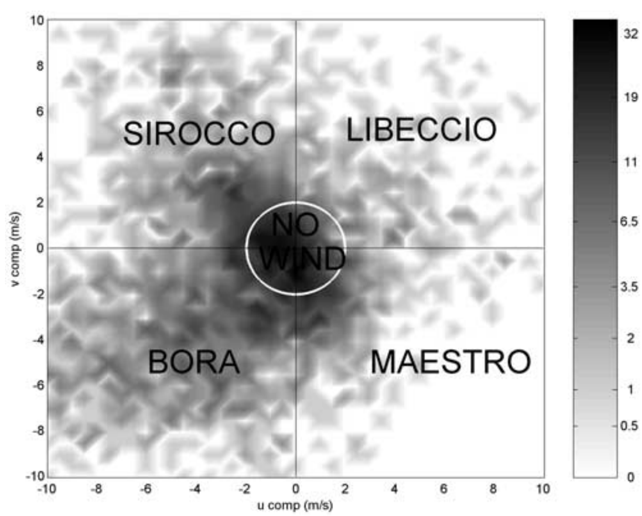

Figure 3. Two-dimensional histogram of the LAMI winds averaged over the domain with a resolution of 0.1 m/s for both zonal and meridional components. The white circle indicates the no-wind region (speed <2 m/s). The quadrants relative to bora, sirocco, maestro, and libeccio are indicated and correspond to vectorial definition of winds instead of meteorological convention.

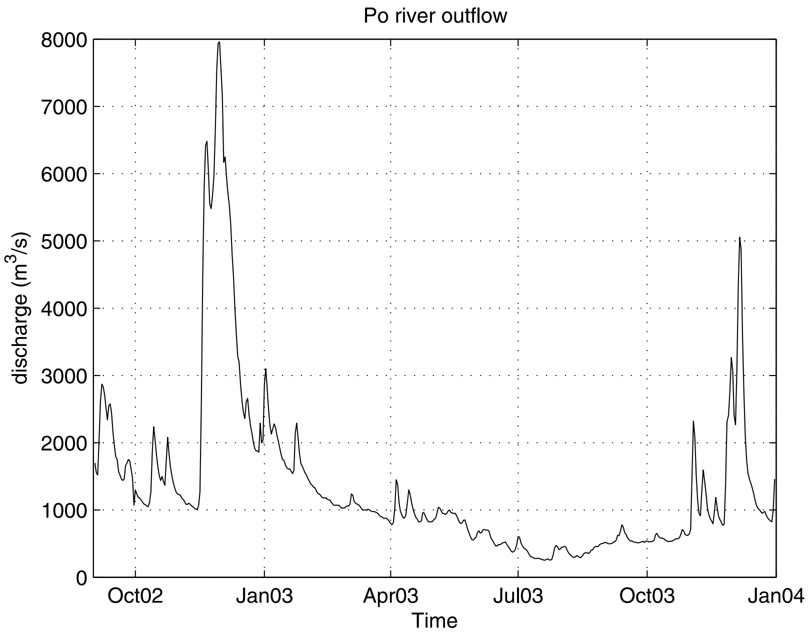

Figure 4. Daily Po River discharge rates at Pontelagosocuro between September 2002 and December 2003.

have chosen the value 1500 m^3/s, the annual average of the Po river discharge rate [*Raicich*, 1994], to separate low and high runoff regimes. The drifter data under low-wind (speed <2 m/s) conditions were therefore separated according to this criteria. Drifter data corresponding to the days for which Po River discharge was lower (higher) than 1500 m^3/s were used for low (high) Po River regime statistics.

[23] The conditional averaging based on the winds and Po River discharge assumes that the NMA currents respond rapidly (within a few hours) to changes in wind forcing and buoyancy input. The almost instantaneous response of the currents with respect to local wind forcing was confirmed by *Book et al.* [2005]. The detailed analysis of the delayed time response of the circulation to wind and river forcing is beyond the scope of this paper.

3. Mean Circulation, Velocity Variance, and Diffusivity

[24] Assuming that the surface currents are stationary over the considered period, Eulerian statistics were calculated over the NMA, using low-pass-filtered data binned in circles of 10 km of radius, separated by 10 km (with roughly 50% overlap, providing some smoothing). Only bins with more than 5 velocity observations were considered to compute the statistics.

[25] The mean surface flow is depicted in Figure 5a. It reveals the well-known persistent features of the Adriatic surface circulation, such as the WAC along the Italian coast and the EAC along the Croatian coast, that recirculates partially around the Middle Adriatic Pit (MAP) and partially near the tip of the Istrian Peninsula, and finally the northernmost cyclonic gyre [*Poulain*, 2001; *Cushman-Roisin et al.*, 2001]. A weak anticyclonic circulation feature can be seen off Istria, wedged between the strong cyclone to the north, and the EAC recirculation branch to the south.

[26] Velocity variance (Figure 5b) is largest in the WAC and strongly oriented parallel to the coast. It is also substantial and more isotropic near the branching of the EAC on the northern side of the MAP. This means that the major currents mentioned above are highly variable over the period considered, in particular they can reverse direction (see *Poulain et al.* [2004] for a case of WAC reversal in summer 2003). A zone of almost no mean flow and weak velocity variance is evident in front of the tip of Istria (where the data density is maximal).

[27] The MKE and EKE were calculated from the mean currents and the velocity variance. They are depicted in Figures 5c and 5d, respectively. The highest values for MKE are found in three zones: (1) in front of the Po River delta, (2) along the Italian coast south of the Po delta, and (3) over the MAP. The maximum value, reaching 394 cm^2/s^2, is located in front of Ancona, where the EKE has a value of about 82 cm^2/s^2, indicating a partition of energy in favor of the mean flow. In contrast, the zone south of Ancona is characterized by a local maximum in EKE (about 260 cm^2/s^2), corresponding to a highly variable WAC and including current reversals. The zone in front of the tip of Istria is characterized by very low values of MKE (<5 cm^2/s^2) and slightly higher values for EKE (about 30 cm^2/s^2).

[28] The ratio EKE/MKE (Figure 6) provides a description of the partition of energy between the mean stationary flow and the fluctuating currents. The lowest values (between 0.2 and 0.7) are found principally in the zones of recirculation of the EAC and along the Italian coast near Ancona, indicating that the fluctuations are less energetic than the mean flow. In contrast, areas corresponding to weak current regimes, such as the one in front of the tip of Istria or the one to the north of the MAP, are characterized by a ratio of the order of 10, showing that energy corresponds prevalently to the fluctuating currents.

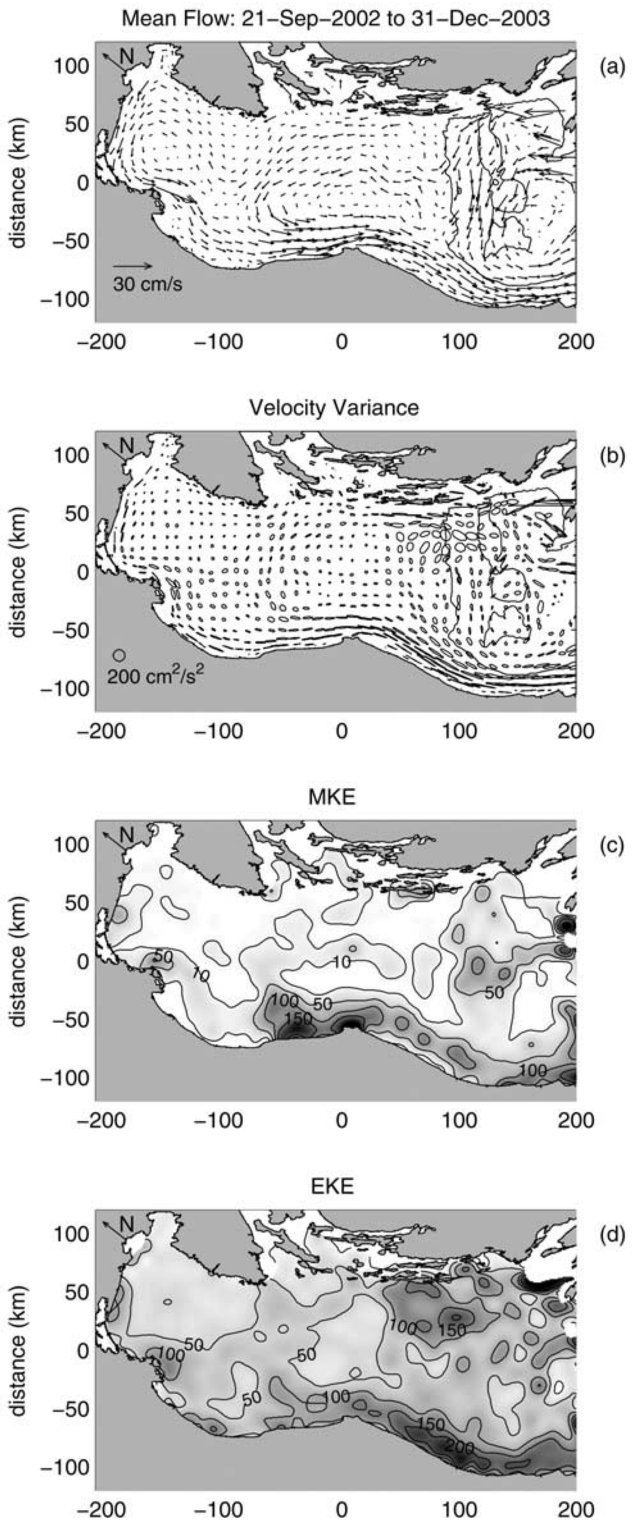

Figure 5. Eulerian statistics for the whole data set, computed in 10 km radius bins separated by 10 km and only shown in bins with more than five observations: (a) Mean flow, (b) velocity variance ellipses, (c) mean kinetic energy of the mean flow (MKE), and (d) eddy kinetic energy (EKE).

[29] The horizontal gradients were calculated from the mean flow field, and horizontal divergence and relative vorticity were estimated (not shown). The divergence field has no significant structure indicating that it is probably below the noise level. The values for relative vorticity, however, are significant and are mostly bounded by 1×10^{-5} s^{-1}, in absolute value, that is $\sim$10% of the planetary vorticity (which is about 1×10^{-4} s^{-1} at the midlatitude (44°N) of the considered area). This means that the mean surface flow might be in geostrophic balance, in agreement with the results of *Poulain* [2001].

3.1. Lagrangian Statistics

[30] In order to compute Lagrangian statistics each drifter observation in a selected area was considered as a deployment and the points belonging to its track were considered to have negative time lags before reaching that position and positive time lag when leaving [*Davis*, 1991]. The statistics depend on the time lag and on the dynamics of the different regions.

[31] Lagrangian statistics were first calculated over the whole NMA after removing the Eulerian mean flow (depicted in Figure 5a) interpolated at the drifter positions from the drifter velocities. The results are shown in Figure 7 for time lags ranging from -10 to 10 days. Along-basin values for covariance, diffusivity and integral timescale are larger than the corresponding values in the across-basin direction, as already pointed out by *Poulain* [2001]. This is probably related to the elongated shape of the Adriatic and to its narrow across-basin dimension. The values for variance at zero time lag correspond to the EKE and amount to 50 and 80 cm^2/s^2 for the across and along-basin components, respectively. These values have the same order of magnitude as those presented in Figure 5d. The off-diagonal elements of covariance are negative and equal to -10 cm^2/s^2 at zero time lag. This means that the residual velocities vary along a principal axis oriented by about 15° with respect to the along-basin axis. The along-basin diffusivity reaches its maximum values (about 1×10^7 cm^2/s) at ±10 days. The across-basin values are about half the along-basin ones due to the geographical lateral boundaries of the basin, that limit dispersion at large time lags. This agrees with the results of *Poulain* [2001] and *Falco et al.* [2000]. The angular momentum, the difference between the off-diagonal elements of the diffusivity matrix, is

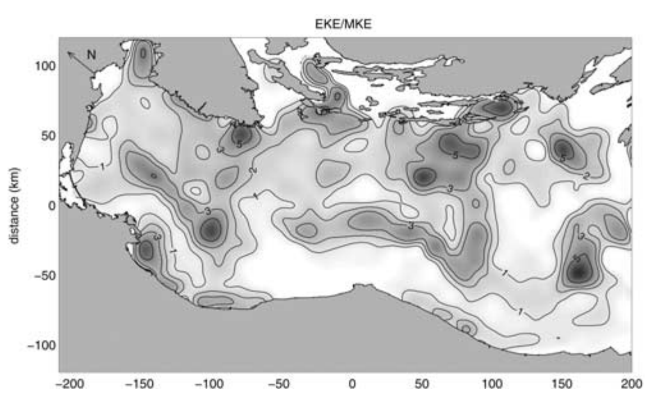

Figure 6. Ratio EKE/MKE calculated from EKE and MKE depicted in Figures 5c and 5d.

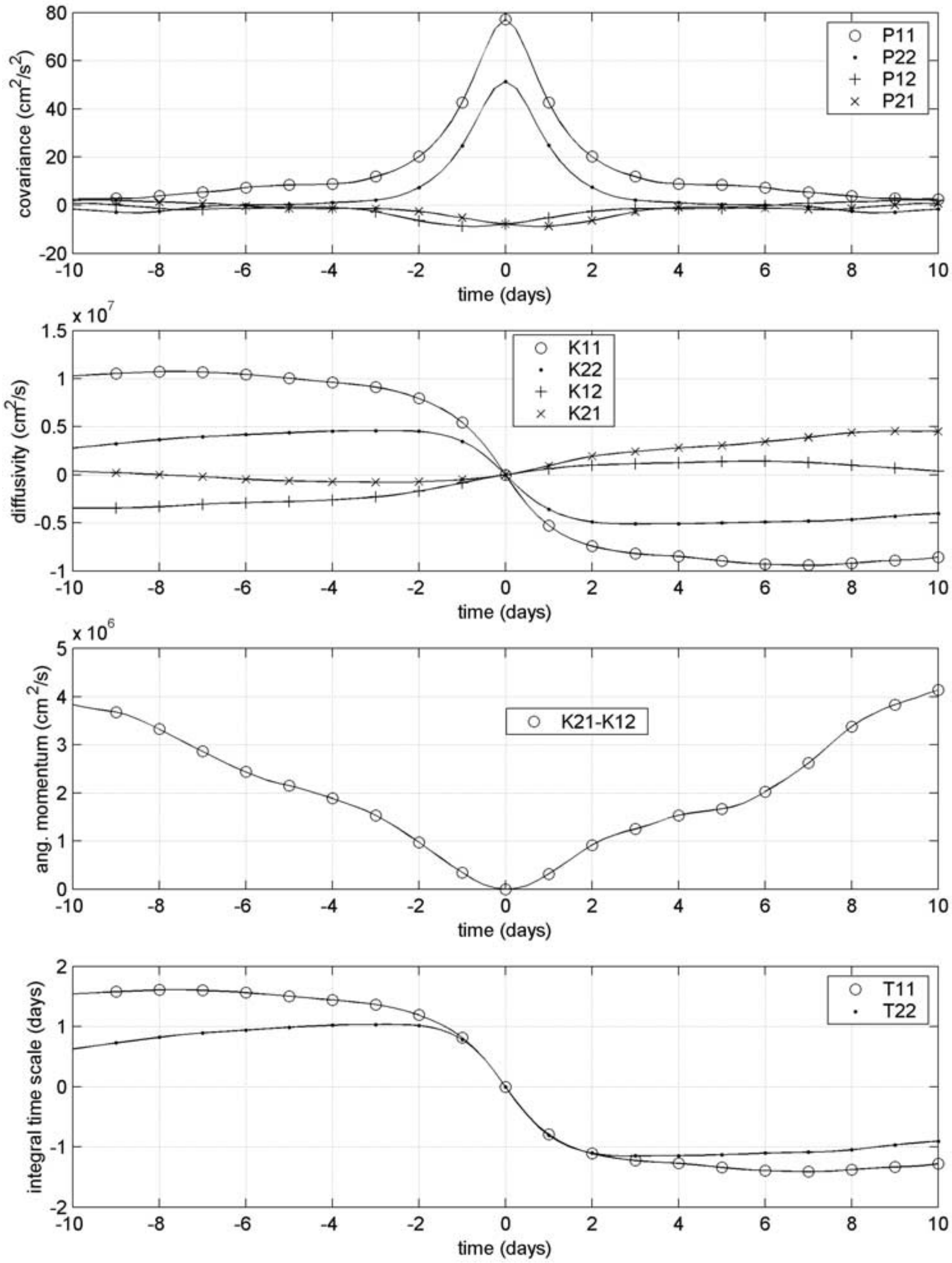

Figure 7. Lagrangian statistics calculated after removal of the mean Eulerian field interpolated at the drifter positions. All quantities are plotted as a function of time lag from −10 to 10 days: (a) Lagrangian covariance, (b) diffusivity, (c) angular momentum, and (d) integral timescale. Along (across) basin quantities are plotted with circles (dots). Off-diagonal elements of the covariance and diffusivity matrices are plotted with stars and crosses.

always positive, indicating a prevailing cyclonic tendency of the velocity fluctuations. Finally, the calculation for the integral timescale gave a value of 1.5 days for the along-basin direction and a value less than one in the across-basin direction. The corresponding integral space scales are about 13 km and 6 km, respectively. This is the scale for which the drifters maintain a memory of the processes and therefore the data within these scales are not independent. The calculations of the Eulerian statistics were repeated after subsampling the data every 3 days, i.e., twice the integral timescale, and excluding data separated by less than 10 km within the same bin (see data density in Figure 1d). We found that the patterns for the mean flow, variance, MKE and EKE (not shown) are comparable to those obtained with the original 6-hourly data.

[32] It is interesting to note that higher values for covariance and diffusivity were found calculating Lagrangian statistics without removing the mean Eulerian field, in particular in the along-basin direction. A value of 113.4 cm^2/s^2 (62.6 cm^2/s^2) for variance, and a value of 3.5×10^7 cm^2/s (0.5×10^7 cm^2/s) for diffusivity at 10 days time lag, were found in the along (across) basin direction.

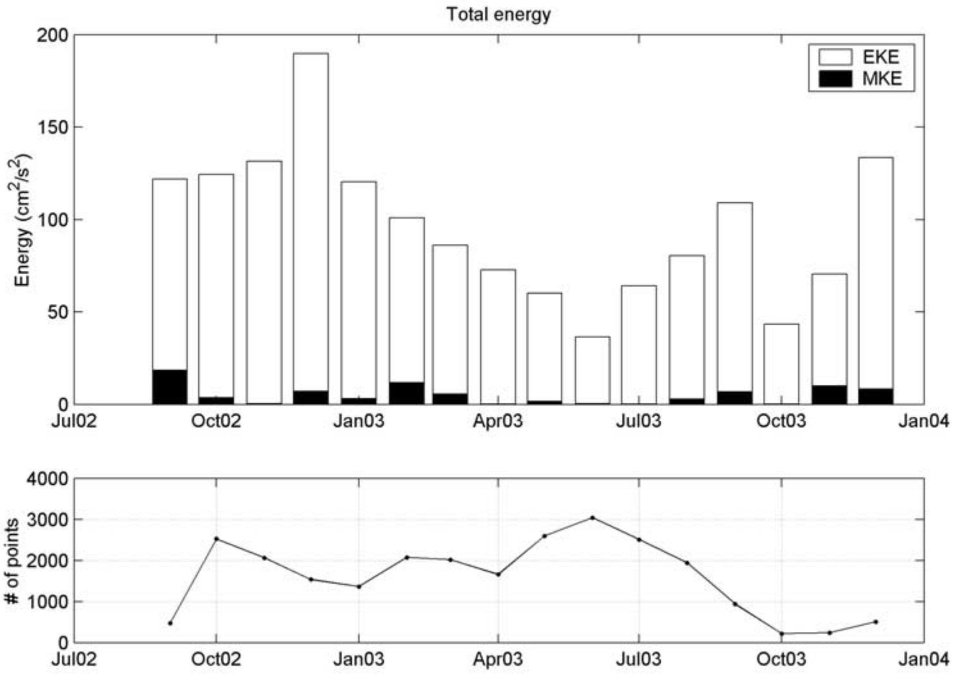

Figure 8. (top) Total kinetic energy (MKE+EKE) for the NMA as function of time in months. In the histogram, MKE (black) and EKE (white) are also evidenced. (bottom) Number of data used in the calculation of the total energy for each month.

The larger along-basin diffusivity includes the contribution of the shear of the mean circulation, especially near the WAC edge, that can efficiently disperse particles.

[33] Lagrangian statistics were also calculated for selected zones characterized by particular dynamics, such as the area along the Italian coast, the area along the Croatian coast and the northernmost part of the studied area. In particular, four zones were defined (depicted with rectangles in Figure 1a): zones 1 and 2 include the WAC north and south of Ancona, respectively; zone 3 corresponds to the EAC south of the Istria Peninsula and zone 4 is the northern part of the MNA. The results are shown in *Ursella et al.* [2004] and are summarized in Table 1. The maximum values for the parameters over the time range −10 to 10 days are indicated. It must be pointed out that for these areas the parameters can have an asymmetric behavior with respect to the zero time lag. For this reason two values, one for positive and the other for negative lags, are reported in Table 1 for each parameter. Covariance and diffusivity have the highest values in the southern WAC (in zone 2) where the along-basin length scale assumes its maximum value, ranging from about 17 to 36 km. The along-basin values are larger than those in the across basin direction in all the selected zones except in the northern one, probably due to the constraint of the northern boundary.

4. Seasonal Statistics

[34] The data set was divided into the different seasons of the year in order to assess the seasonal variability of the surface currents. As already shown by different authors [*Zore*, 1956; *Zore-Armanda*, 1969; *Metallo*, 1965; *Mosetti and Lavenia*, 1969; *Artegiani et al.*, 1997; *Hopkins et al.*, 1999] the dynamics in the Adriatic is strongly influenced by wind conditions, Po River discharge and weather conditions in general. Therefore a strong dependence of current patterns on seasons is expected. The temporal definition of the seasons, according to *Artegiani et al.* [1997] and *Poulain* [2001], is as follows: spring (April-May-June), summer (July-August-September), fall (October-November-December) and winter (January-February-March). The majority of the drifters were deployed in winter and spring (February and June 2003), but the temporal coverage also depends on the dynamics and the time of residence of the drifters in the considered zone. In general, there is a relatively good coverage for all the seasons. It must be pointed out that the fall data set used in this study is the combination of two years, 2002 and 2003, even if the amount of data for fall 2003 is less than one fourth compared to fall 2002.

4.1. Eulerian Statistics

[35] The temporal distribution of the kinetic energy levels (Figure 8) was calculated on a monthly basis by averaging the drifter velocities over the whole NMA basin. The values for MKE are very low and they are approximately zero, as it should be, in periods when the data coverage is almost uniform over the semienclosed basin. The total mean energy presents a maximum in December 2002 and a minimum in June 2003, and in general fall and winter are the more energetic seasons. Another way of studying the energetics in the area, is to spatially average the MKE and EKE calculated in bins of 10 km radius (see Figures 9 –12). Therefore considering only bins with more than 10 observations, the mean of the MKE over the whole area of study is in fall 95.8 cm^2/s^2, in winter is 56.5 cm^2/s^2, while in spring it is 29.7 cm^2/s^2, and in summer it reaches the minimum value

equal to 26.6 cm^2/s^2. The average of the EKE has values slightly lower than MKE for fall and winter: 93.3 cm^2/s^2 in fall, 54.2 cm^2/s^2 in winter, 44.0 cm^2/s^2 in spring and 65.0 cm^2/s^2 in summer. The ratios of these averaged quantities (EKE/MKE), show an almost equipartition of

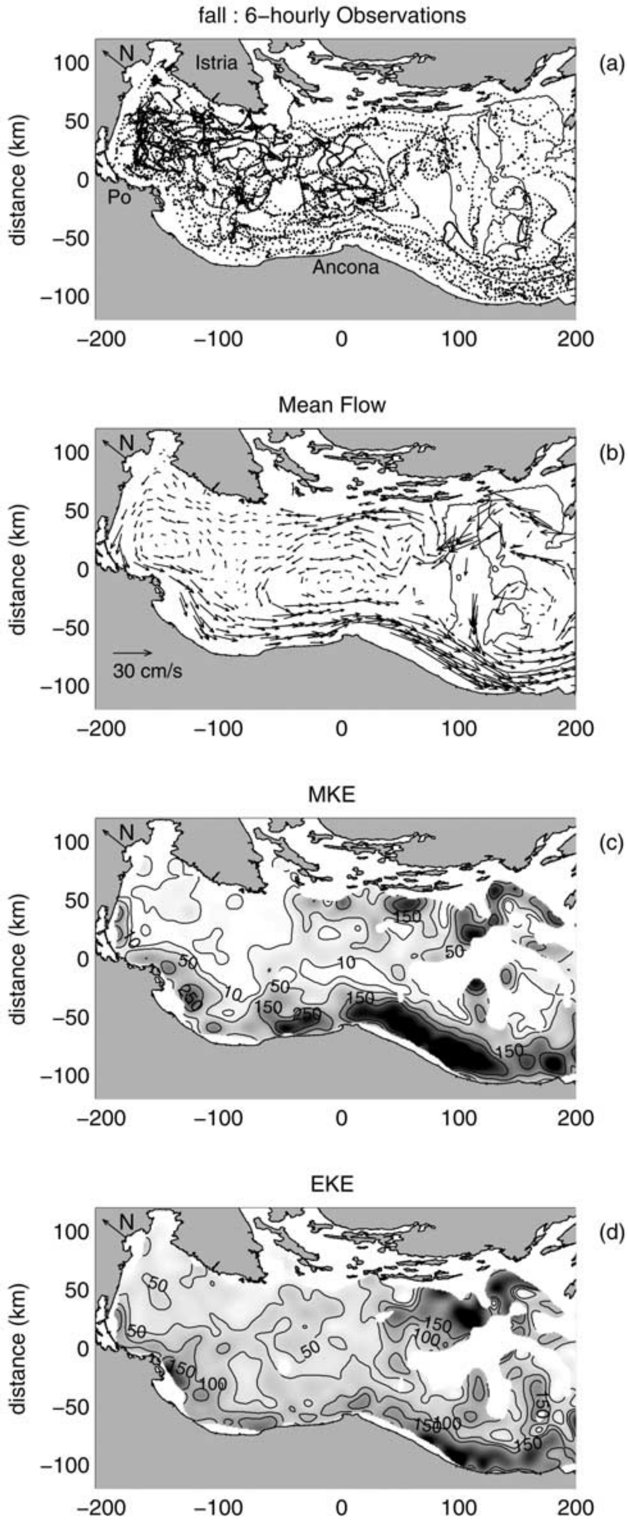

Figure 9. Eulerian statistics computed from the fall drifter data in 10 km radius bins separated by 10 km (results are only shown for bins with more than 10 observations): (a) 6-hourly observations, (b) mean flow, (c) MKE (isolines at 10, 50, 150, and 250 cm^2/s^2), and (d) EKE (contour lines at 50, 100, and 150 cm^2/s^2).

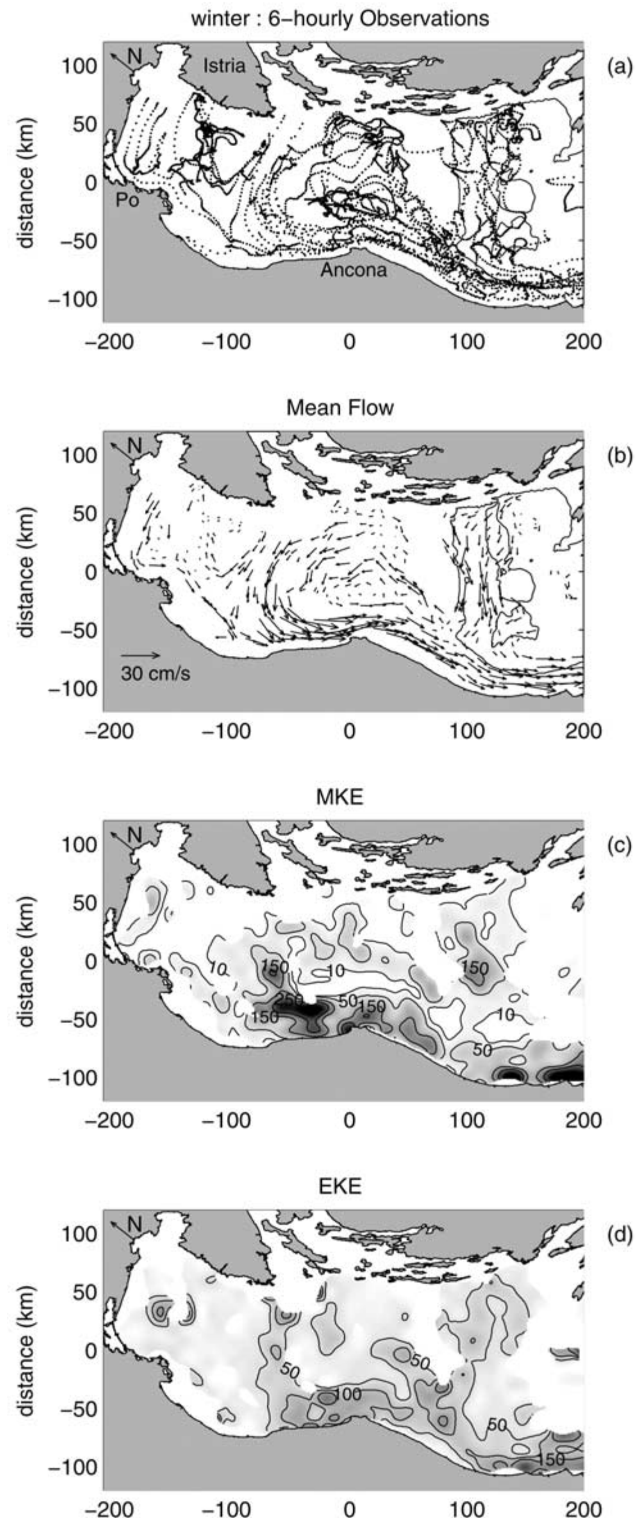

Figure 10. Same as in Figure 9 but for winter.

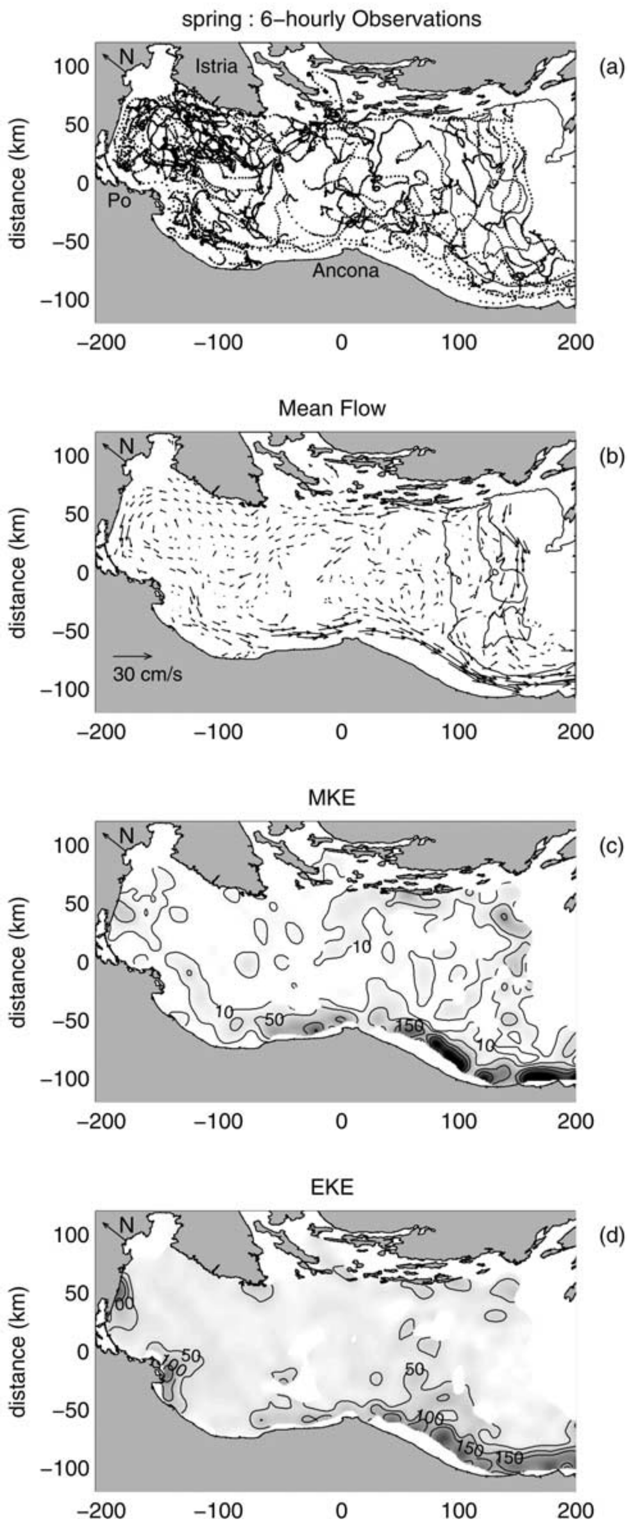

Figure 11. Same as in Figure 9 but for spring.

energy between mean and fluctuations in fall, winter and spring, whereas in summer the kinetic energy corresponds mainly to the fluctuations.

[36] Let us now discuss the seasonal variability in terms of spatial structure of the mean flow and the energy levels. It is important to note that now the EKE mostly corresponds to scales smaller than months (the seasonal signal is removed) and principally to mesoscale and synoptic fluctuations.

[37] In fall (Figure 9), the coverage is almost uniform over the NMA, apart from two zones in which drifters do not seem to move in, i.e., two areas in the center of the

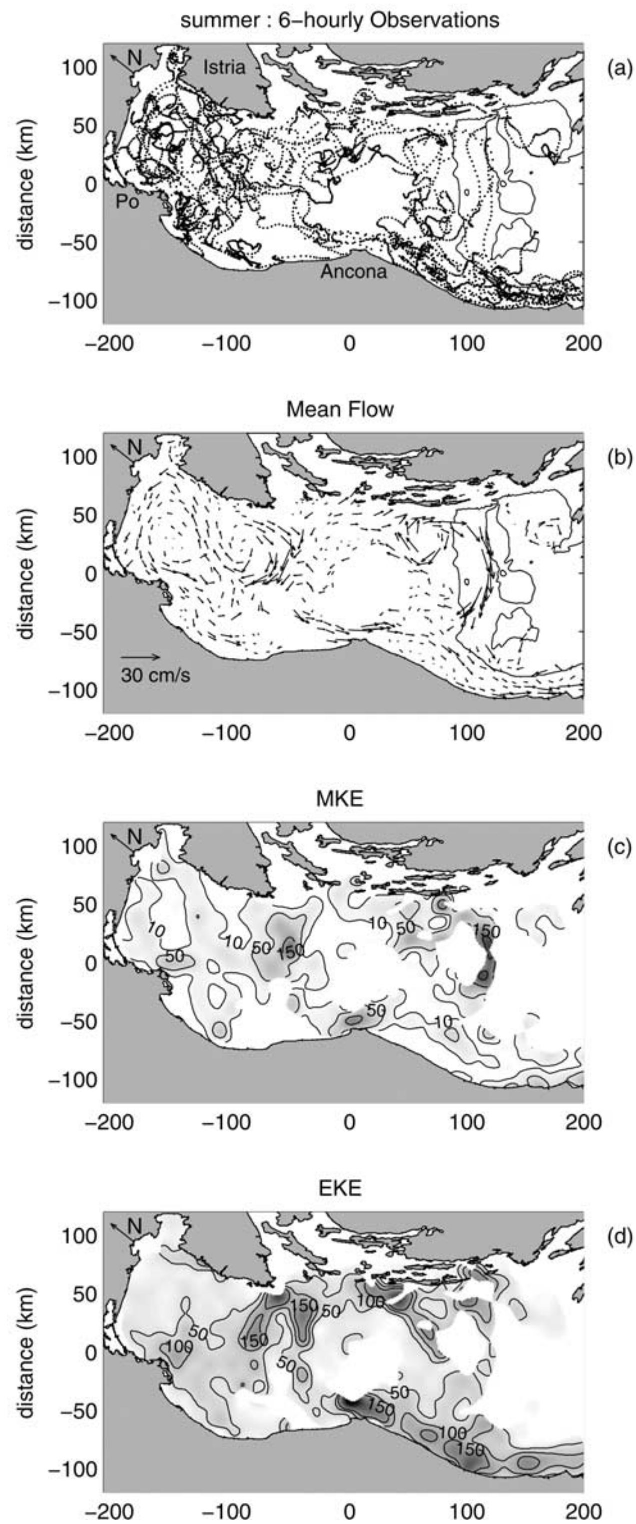

Figure 12. Same as in Figure 9 but for summer.

basin, just to the north and to the south of Ancona. The principal characteristics of the mean flow are a very strong and horizontally extended WAC and an evident recirculation around the MAP and in front of the tip of Istria. Moreover, a cyclonic gyre is positioned to the north of the Po River delta. The MKE (Figure 9c) is substantial in two zones: (1) in the WAC with a maximum value of 880 cm^2/s^2 south of Ancona, probably due to the strong Po River discharge during the second half of November and December 2002 (up to 8000 m^3/s) and in early December 2004 ($\sim$5000 m^3/s) (see Figure 4) and (2) around the MAP. High values for EKE (Figure 9d) are found in front of the Po River, in the WAC south of Ancona and in the EAC east of the MAP, indicating high variability of the fluctuating currents.

[38] In winter (Figure 10), the coverage is good in the central area, while only a few observations are available south of the tip of Istria, even though some drifters were deployed there. This is due to the dynamics of the basin, which includes (1) a vigorous cyclonic gyre in the northernmost NMA, (2) a strong WAC along the Italian coast, even if horizontally reduced with respect to fall and weaker just in front of the Po River delta, and (3) a reinforced current between the tip of Istria and the Italian coast (recirculation of the EAC) related to the strong bora wind activity mostly in February 2003 (P.-M. Poulain et al., Circulation and temperature-salinity-pigment fields in the northern Adriatic Sea in winter 2003, manuscript in preparation, 2006). The MKE (Figure 10c) reflects this behavior, with large values in the recirculation cell south of Istria and its continuation into the WAC. A maximum of about 563 cm^2/s^2 is found south of Ancona. The regions characterized by high MKE also show enhanced values of EKE (Figure 10d).

[39] In spring (Figure 11) the mean currents and corresponding velocity variance are generally low. The EAC is weak and there is no evidence of recirculation off the tip of the Istrian Peninsula. The WAC is thin but relatively fast corresponding to large values for the MKE (maximum 572 cm^2/s^2). The EKE is only substantial south of Ancona.

[40] Finally, in summer (Figure 12) the mean circulation is relatively weak and the mean EAC and mean WAC are almost absent. There is a signature of a double vortex circulation in front of the Po River delta, with a well developed anticyclone prevailing south of Istria whose eastern branch corresponds to the Istrian coastal countercurrent [*Supic et al.*, 2003]. The MKE is weak all over the basin with a maximum value of only 255 cm^2/s^2, and the EKE is strong only along the Italian coast south of Ancona.

5. Circulation Variability Related to Wind and Po River Forcing

[41] In order to better understand the variability of surface currents, and their response to the wind forcing, maps of Eulerian statistics were constructed for different wind regimes. Only bins with more than 5 observations were considered. Figure 13a and 13b show the mean wind field and variance ellipses obtained averaging the LAMI data for times corresponding to the bora regime. The regions of strong bora winds are evident north and south of the Istrian Peninsula (larger mean vectors and larger variability) whereas off central Istria the bora winds are weaker. The drifter data density (Figure 13c) during bora forcing shows a good coverage all over the basin. The WAC and the recirculating current going from the tip of the Istrian Peninsula to the Italian coast are strongly enforced (Figure 13d) as well as the cyclonic circulation around the MAP and the northernmost cyclonic gyre. In contrast, a pool of almost steady water is found just in front of the southern part of Istria. The zones with strong currents are also characterized by high values of surface velocity variance (Figure 13e). The MKE field reflects the structure of the mean flow field, with a maximum value (about 500 cm^2/s^2) in the WAC.

[42] The wind and circulation statistics for the sirocco wind regime are depicted in Figure 14. The mean sirocco winds are slightly enhanced on the eastern part of the NMA, but in general they have little spatial variability (Figure 14a). The EAC is enhanced, its lateral extension is greater and no recirculation near the tip of the Istrian Peninsula is evident (Figure 14d). The EAC continues northward as far as the northern part of the NMA and forms the eastern limb of the cyclonic gyre still present north of the Po River delta. The water flows back south along the Italian coast in the WAC that is reduced both in intensity and lateral extension. The steady pool encountered off Istria in the bora regime has disappeared. The MKE is maximal (340 cm^2/s^2) in the EAC in the vicinity of the MAP (Figure 14f). The variance of the surface currents is larger along the WAC and around the MAP (Figure 14e), even though the variance of the wind field is minimal in those zones. Therefore the variability of the flow field around the mean is probably not due to wind variability.

[43] In the maestro regime (Figure 15) the number of drifter observations is even lower but some circulation features are still statistically significant. The EAC is essentially absent and a strengthening of the WAC can be seen both in speed and dimension. The other circulation features are based on limited drifter observations and, as a result, are not statistically significant. The MKE is maximal in the WAC (269 cm^2/s^2) where the surface currents are also very variable.

[44] The Eulerian circulation maps corresponding to the libeccio wind regime are not discussed since the drifter observations are scarce and the results are not statistically significant.

[45] The complex correlation coefficient between currents and winds was estimated for different local wind intensities and time lags, and the results are reported in Table 2. The square of the magnitude of the correlation coefficient (R^2), i.e., the explained variance, for the same wind intensity condition, decreases as time lag increases. For example, choosing 2 m/s as threshold in wind speed, the coefficient decreases from 8% to 4%, with time lag from 0 to 12 h, while the angle decreases, departing always more from the theoretical Ekman transport direction [*Ekman*, 1905]. This confirms that the effect of the local wind forcing on the near-surface currents is instantaneous [see also *Book et al.*, 2005]. Moreover, for a fixed time lag, the correlation and veering angle increase with increasing threshold, meaning that the higher the wind speed is, the greater the influence of winds on near-surface currents.

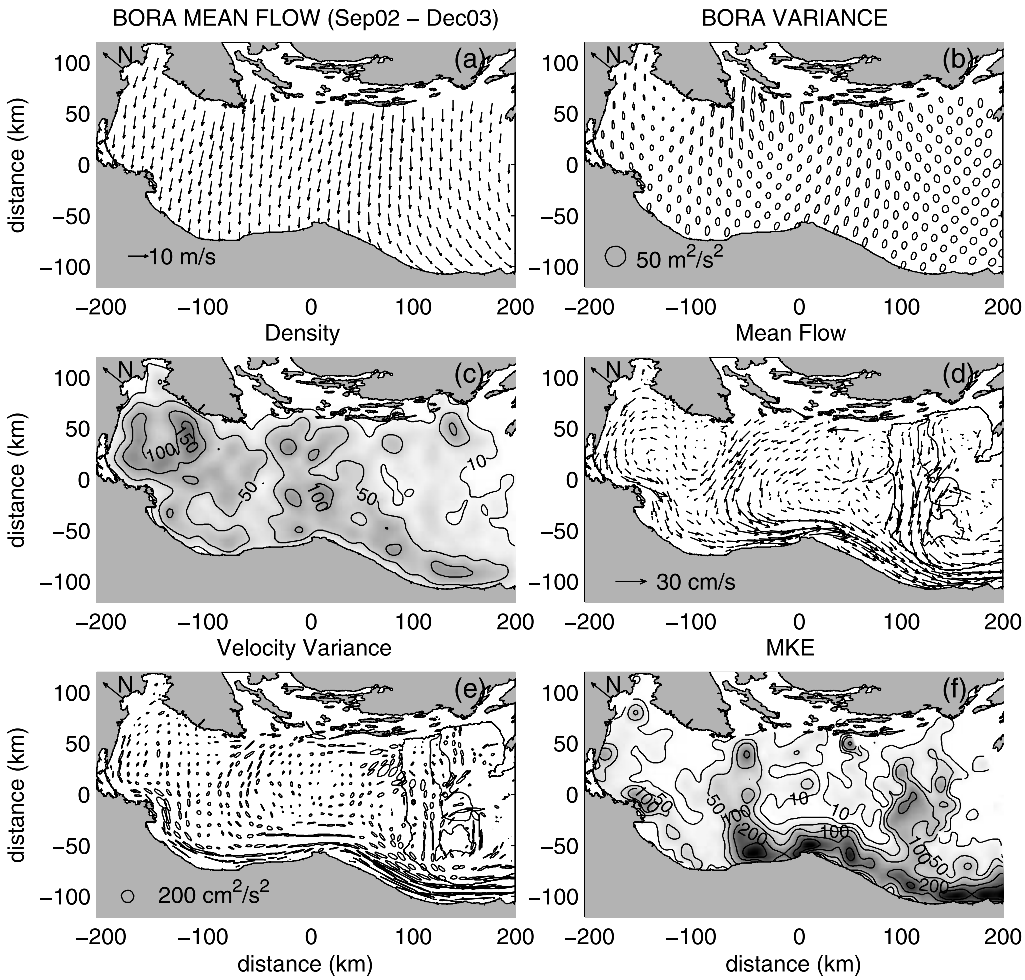

Figure 13. (a) Mean flow and (b) variance ellipses of the LAMI winds corresponding to the bora wind regime (see Figure 3). Eulerian statistics obtained averaging the drifter data for the bora wind regime: (c) Data density (contour lines at 10, 50, 100, and 200), (d) mean flow, (e) velocity variance, and (f) MKE (contour lines at 50, 100, and 150 cm^2/s^2).

[46] Under no-wind conditions (wind speed <2 m/s), the Eulerian statistics were computed by splitting the drifter data into low and high Po River discharge rate categories. The results, considering only bins with more than 3 observations, are depicted in Figure 16. Data density is lower for high discharge rates (Figure 16b) than for low rates (Figure 16a) because periods of high Po runoff are less frequent and mostly occur in late fall and winter when winds are often strong, hence not providing data in the no-wind category. In low discharge rates, the mean flow (Figure 16c) is very weak with only a few defined features, such as the northernmost cyclonic gyre, the WAC and the recirculation around the MAP. Many weak gyres and meanders are present over the rest of the basin. The MKE (Figure 16g) also presents low values, while the EKE is slightly stronger, in particular along the southern part of the WAC and along the EAC. In the case of Po River rates higher than 1500 m^3/s, the WAC is greatly enhanced in intensity and also, to a certain extent, in lateral extension (Figure 16d), south of the Po River delta. Mean currents in the WAC reach peak values of about 44 cm/s, and the MKE is as large as 970 cm^2/s^2. The variance (Figure 16f) is high in the vicinity of the Po River delta, of the southernmost portion of the WAC and around the MAP near the Croatian coast, while over the remaining parts of the basin it is lower than for the low discharge rate situation (Figure 16e). A comparable structure is also seen in the EKE (Figure 16i).

6. Discussion and Conclusions

[47] The data of 108 CODE satellite-tracked surface drifters were used to study the dynamics of the northern and middle Adriatic (NMA) Sea at mesoscale to seasonal scales between September 2002 and December 2003. In addition, the surface circulation variability derived from the drifters was described in terms of the major wind and river discharge regimes prevailing in the area of study. Despite the relatively short operating lives of the drifters (their mean half-life is only 35 days) the NMA was sampled continuously over the whole time period by 3 drifters or more, except for a few days at the beginning of November 2003. The finite length of the drifter time series and their intrinsic Lagrangian nature, or in other words, the fact that the data are not uniformly distributed in the spatiotemporal domain, may bias significantly some of the Eulerian statistical results

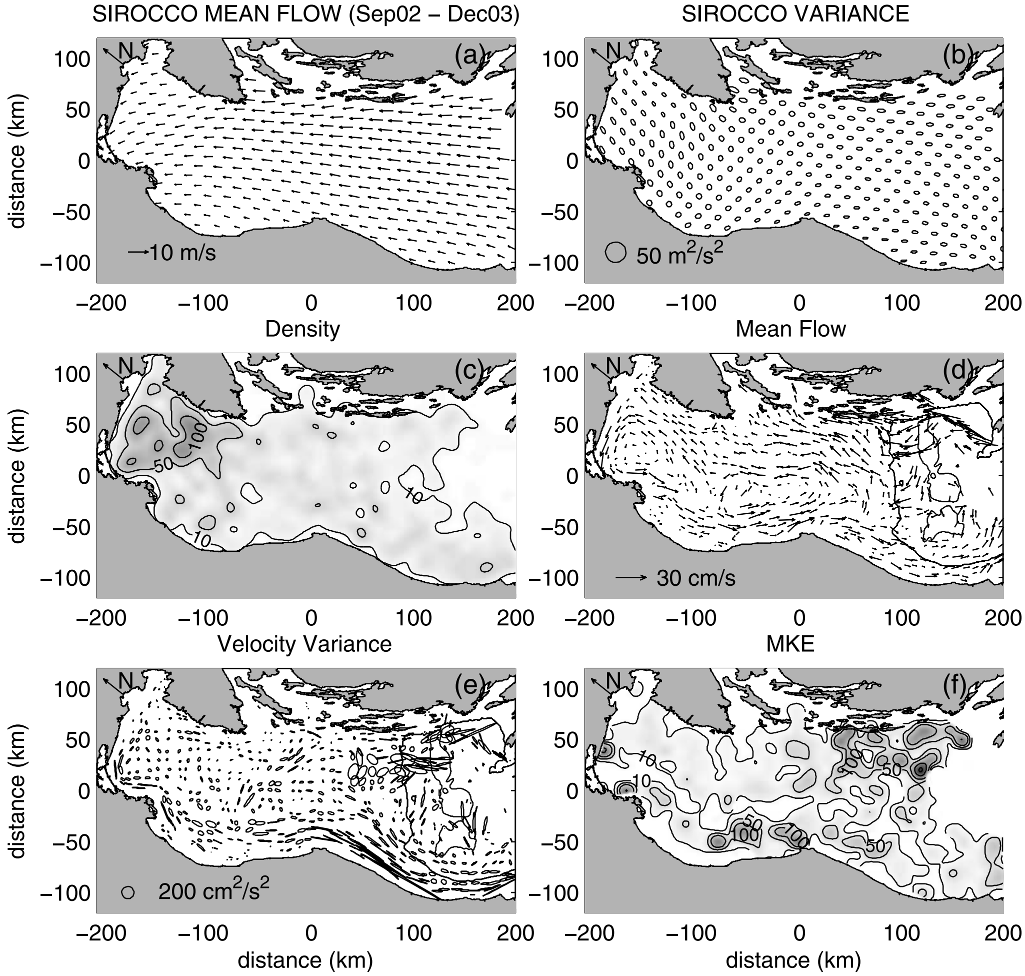

Figure 14. Same as in Figure 13 but for the sirocco wind regime.

computed from the drifter data. In order to minimize this problem, statistics were only presented if they were calculated on a large enough number of observations (i.e., 5 observations in the 10 km radius bins).

[48] Lagrangian and Eulerian statistics were computed from the edited, interpolated and low-passed-filtered 6-hourly drifter position and velocity data. In general, the results obtained from this new data set not only confirmed the well-known persistent Adriatic circulation structures discussed in the literature [*Artegiani et al.*, 1997; *Poulain*, 2001] but they provided a more quantitative and higher-resolution description of the NMA circulation features due to the high density of drifter observations in this area. In particular, the recirculation cells of the EAC at the levels of the MAP (northern wall) and of the tip of the Istrian Peninsula with strong cross-basin currents joining the WAC on the Italian side, were described in detail for the first time. A strong cyclonic gyre in the northernmost part of the basin prevails in the mean flow map (Figure 5a) whereas there is little evidence of a related anticyclonic vortex to the south of it. Indeed, off southern Istria, the mean flow and corresponding velocity fluctuations are weak, confirming the previous results of *Poulain* [2001]. In addition, high values in the velocity variance south of Ancona reveal a high variability in the WAC and in some case current reversals.

[49] The energy levels obtained with the DOLCEVITA drifter data are compared to those computed from the drifters in the 1990s [*Poulain*, 2001]. It is first important to note that the spatial resolution (10 km in our case compared to 20 km) and the geographical domain (NMA versus whole Adriatic Sea) are different. The difference in domain area precludes comparing spatially averaged values, so we only contrast maximal values that occurred in the WAC. The decrease in averaging scale to compute the Eulerian statistics generally corresponds to an increase in MKE and an decrease in EKE [*Poulain*, 2001; *Ursella et al.*, 2004]. Because of the increased resolution and better sampling of the WAC near the Italian coast, the maximum MKE is indeed 394 cm^2/s^2, which is much higher than the value reported by *Poulain* [2001] ($\sim$150 cm^2/s^2). In contrast to the general rule stated above, the velocity fluctuations are also more energetic (the maximum EKE is 260 cm^2/s^2 compared to $\sim$150 cm^2/s^2) mostly because it includes variability at the seasonal and synoptic timescales well sampled by the drifters. In brief, the NMA surface currents appear more energetic in 2002–2003 compared to the 1990s, but this is probably because of the better (both in time and space) sampling using numerous drifters in the latter period.

[50] The values for the Lagrangian statistics are in general slightly lower in absolute value than those found by *Poulain*

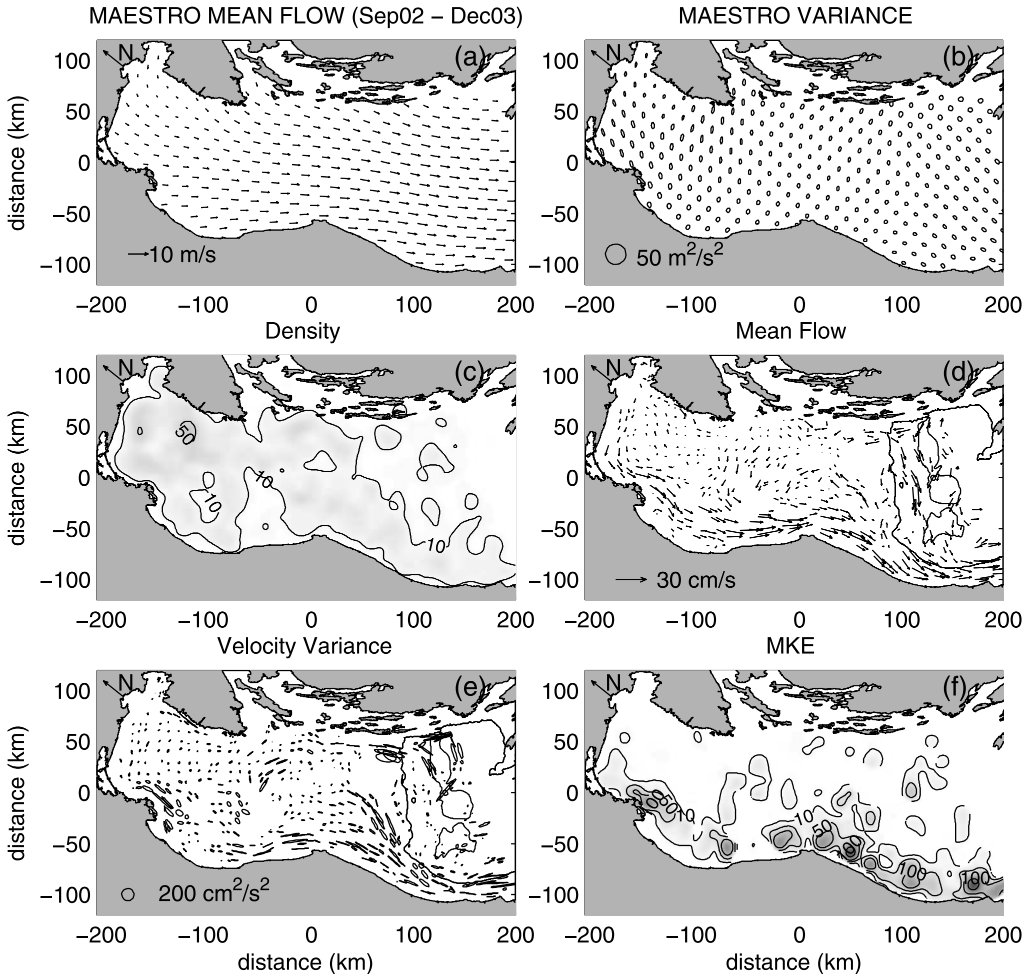

Figure 15. Same as in Figure 13 but for the maestro wind regime.

[2001] for the whole Adriatic Sea, indicating that the dynamics in the NMA are, as a whole, less energetic. Absolute diffusivities are about 0.5 and 1×10^7 cm^2/s in the across and along-basin directions, respectively. The integral timescales amount to about 1–1.5 days and are slightly larger in the along-basin direction. Correspondingly, the integral space scales vary in the range 6–13 km. These values are about 50% of those computed by *Poulain* [2001] for the along-basin direction, whereas in the across direction, they are about the same. This means that along-basin diffusive transports are weaker in the NMA with respect to the values for the whole Adriatic (actually, with respect to the southern Adriatic as *Poulain*'s [2001] data are mainly concentrated in the south). The along-basin blocking by the across-basin recirculation cyclonic currents, the northern cyclonic gyre and the northernmost Adriatic coast probably contribute to the reduced dispersion. Angular momentum values are about one third of those found by *Poulain* [2001] indicating that the velocity fluctuations have a weaker cyclonic prevalence than in the whole Adriatic basin. If

Table 2. Complex Correlation Between Local Wind and Time-Lagged Drifter Velocities[a]

Time Lag, hours	Wind Intensity	R	R^2	Angle, deg	Points
0	>2 m/s	0.2654+i*0.0718	0.076	15.1	20389
0	>5 m/s	0.3025+i*0.0871	0.099	16.1	10333
0	>10 m/s	0.3564+i*0.1104	0.139	17.2	2264
0	>2 m/s	0.2403+i*0.0591	0.061	13.8	20370
6	>5 m/s	0.2733+i*0.0781	0.081	15.9	10313
6	>10 m/s	0.3260+i*0.1002	0.116	17.1	2677
6	>2 m/s	0.2047+i*0.0337	0.043	9.3	20354
12	>5 m/s	0.2349+i*0.0548	0.058	13.1	10348
12	>10 m/s	0.2768+i*0.0677	0.081	13.7	2670

[a]R is the complex correlation coefficient, and R^2 is the square of its absolute value. Positive angle represents clockwise rotation of time-lagged velocity with respect to wind direction. For each time lag, coefficients calculated with different wind intensity threshold are shown.

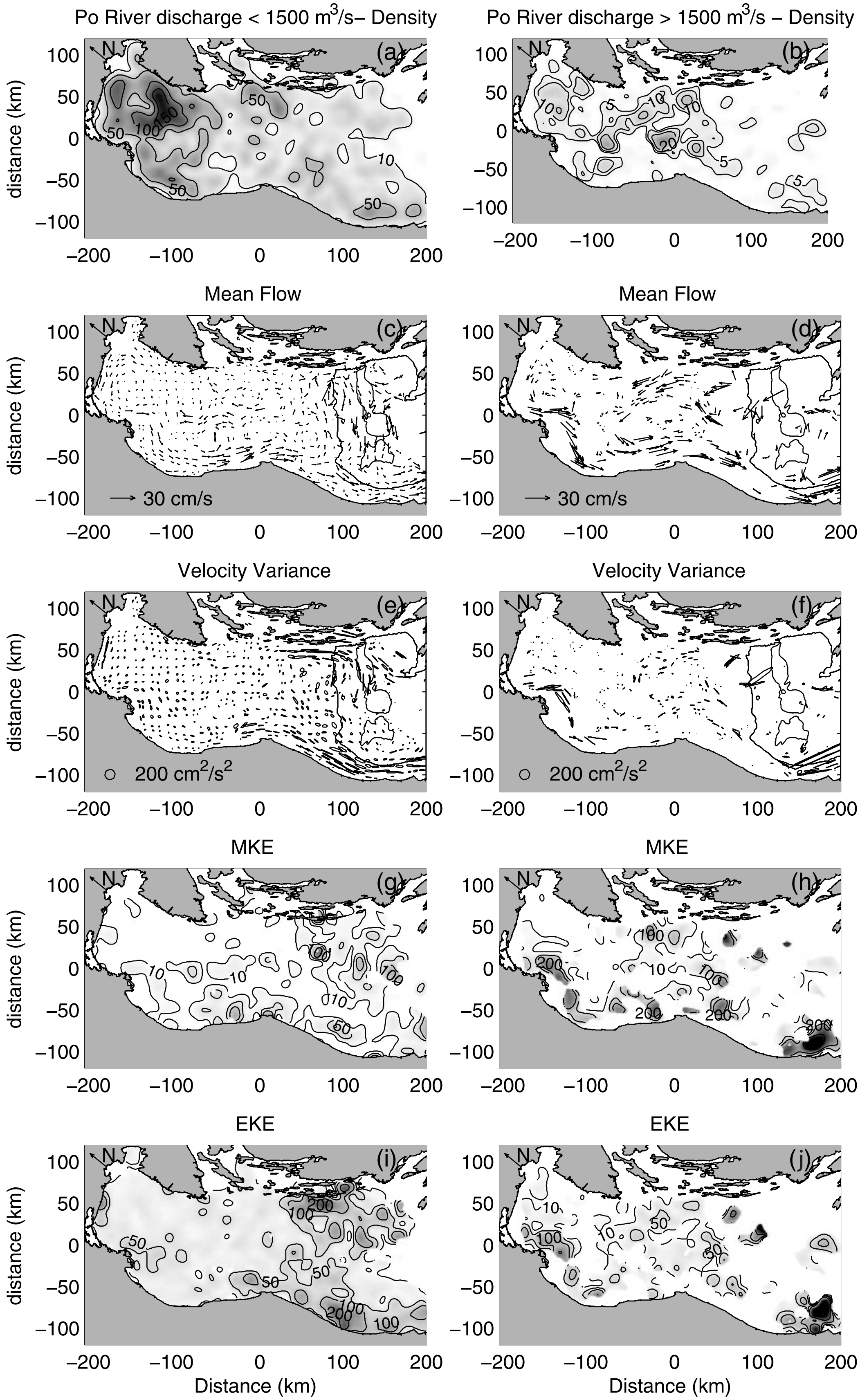

Figure 16. Eulerian statistics calculated in different Po River discharge regimes under low-wind (<2 m/s) conditions: (a, c, e, g, and i) Low (<1500 m^3/s) discharge rates and (b, d, f, h, and j) high (>1500 m^3/s) rates (right).

Lagrangian statistics are calculated over local areas where specific dynamics prevail, it was found that in the WAC south of Ancona, the values are highly nonisotropic with diffusivites and integral scales ranging from about 4×10^7 cm^2/s, 3 days, 36 km in the along-basin direction, to 0.7×10^7 cm^2/s, 1 day, 8 km in the other direction. In contrast, the results in the northernmost domain (in the vicinity of the cyclonic gyre) are more isotropic ($\sim$0.5 $\times$ 10^7 cm^2/s, $\sim$1 day, $\sim$6 km).

[51] A strong seasonal signal in the circulation is revealed by the drifter observations in terms of the magnitude and spatial structure of the mean flow and velocity fluctuations. Fall is the most energetic season, with a mean MKE of 95.8 cm^2/s^2 and a maximum in the WAC south of Ancona (883 cm^2/s^2), while summer is characterized by weak subinertial variability, with a mean MKE value of 26.6 cm^2/s^2 and a maximum of 255 cm^2/s^2. The maximum in WAC MKE during fall is related to Po River discharge maxima that occurred in November–December 2002 and 2003. It was not attempted to compare these seasonal results with those obtained previously by *Poulain* [2001] because of the poor NMA drifter data coverage in the 1990s.

[52] The relation between local winds and drifter-derived surface currents was explored for the first time using high-resolution LAMI simulated winds. A strong dependence of the mean current field on the wind regime was evidenced. Maps of circulation statistics were created for the NE bora, the SE sirocco, the NW maestro and the no-wind regimes. For the bora wind regime, an intensification of the across-basin recirculating currents (near the tip of Istria and north of the MAP) is striking, with mean speeds reaching 20–25 cm/s. The WAC is also strongly reinforced, reaching mean flow peak values of about 30–40 cm/s. The pattern of the mean flow in the bora regime is very similar to the fall/winter situation, probably because strong bora events occur prevalently in fall and winter. The sirocco wind regime corresponds to an almost uniform and weak (up to 15 cm/s) northward flow (the EAC) all over the eastern half of the Adriatic and to a reduction of the WAC intensity. The cyclonic recirculation currents are weak around the MAP and practically absent near the tip of the Istrian Peninsula. Despite the relatively low number of observations (10% of all the drifter data), the results indicate that in the maestro wind regime the WAC is enhanced and the EAC is not present.

[53] The complex correlation between currents and local LAMI winds shows a significant (R^2 about 8%) and instantaneous effect of wind forcing on near-surface velocities. This was already shown by *Book et al.* [2005], who correlated ADCP current measurements with local winds. Moreover, the explained variance R^2 increases to 10% and 14% when considering winds with intensity higher than 5 m/s and 10 m/s, respectively. The corresponding veering angles of the drifter velocities range between 15° and 17°, clockwise with respect to the winds, and agree qualitatively with Ekman theory.

[54] The relation between Po River discharge and currents under no-wind (<2 m/s) conditions was also studied, and strong dependence of the WAC on the Po River discharge rates was found. In particular, the almost absent current along the Italian coast in low Po River regime, is greatly enhanced during the high Po River discharge regime (>1500 m^3/s), with mean surface currents up to 44 cm/s. Moreover, the velocity fluctuations near the Po delta are also enforced in high Po River discharge. The characteristics of the mean flow and variance in the no wind situation, as described above, are therefore strictly related to the Po river discharge.

[55] In conclusion, we have shown that the surface circulation is significantly affected by the local wind: (1) Sirocco winds enhance the EAC and weakens the WAC, (2) bora winds create strong recirculation cross-basin flows (near the MAP and near the tip of Istria) and a sustained northern cyclonic gyre, and (3) maestro winds slightly reinforce the WAC and reduce the EAC. Most of these results are in good agreement with numerical simulations [e.g., *Orlic et al.*, 1994; *Beg Paklar et al.*, 2005]. The Po River discharge was shown to affect significantly the circulation in the vicinity of the Po delta and the WAC south of it. The bifurcation of the EAC at the northern wall of the MAP persists in no-wind conditions, indicating that the related dynamics are also controlled by the bottom topography escarpment [*Carnevale et al.*, 1999].

[56] **Acknowledgments.** This work was sponsored by the Office of Naval Research (ONR) under grant N000140310291 and by the NATO Undersea Research Centre. The LAMI winds were obtained from the "Aeronautica Militare Italiana – UGM, ARPA Emilia-Romagna and ARPA Piemonte". The mean daily Po River discharge rates were kindly provided by the "Autorità di Bacino del Fiume Po". The authors are grateful to all the people from the oceanographic institutions listed below for their help with the drifter deployment and recovery operations: Croatian Hydrographic Institute (Split, Croatia); Institute of Oceanography and Fisheries (Split, Croatia); ISMAR/CNR (Ancona, Venice, and Lesina, Italy); Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (Trieste, Italy); National Institute of Biology Marine (Piran, Slovenia); Naval Postgraduate School (Monterey, California); Rudjer Boskovic Institute Center for Marine Research (Rovinj, Croatia); University of Hawaii (Honolulu, Hawaii); University of Washington (Seattle, Washington); University of Zagreb (Zagreb, Croatia). Thanks to the two anonymous reviewers for providing helpful comments to improve the original manuscript.

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