Vorticity Patterns Offshore of the Venetian Lagoon from HF Radar Observations

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Abstract.

A network of high frequency (HF) radar systems was used to produce maps of surface velocity offshore of the Malamocco inlet during the 12-month period from November 2001 through October 2002. Inspection of the sub-tidal residual flow fields revealed frequent occurrences of small-scale (~10 km) eddy structures both north and south of the inlet. In addition, several monthly averaged velocity maps indicate the presence of a persistent meander in the mean current patterns. A more objective technique, based on vorticity, was developed to search the data set for the presence of eddies near the inlet and to separate those features from the larger-scale meander pattern. The vorticity at scales of 5-10 km was computed each hour using the low-pass-filtered data set and year-long vorticity statistics were investigated at selected locations surrounding the inlet.

The vorticity histograms and temporal variability changed significantly as a function of location relative to the Malamocco inlet. Both north and south of the inlet, the mean vorticity was weakly negative reflecting the larger-scale meander pattern whose crest is aligned, approximately, with the inlet. However, the range of vorticity north of the inlet was much greater than it was south of the inlet. A minor peak (or shoulder) in the year-long histogram of vorticity north of the inlet highlighted frequent occurrences of strong ($\sim 5 \times 10^{-5}$ s^{-1}) positive vorticity events in that area. A similar statistical behaviour was not seen south of the inlet. This observation was used to define a conditional sampling criteria that lead to a map of the typical flow field associated with strong eddy events.

The vorticity time series were also used to investigate the relationship of eddy events to external forcing parameters. Strong winds, for instance, acted to destroy vorticity in the surface current field since they lead to a strong but horizontally uniform response in the surface currents. The roles of sea level variability and offshore current velocity were also investigated.

1. Introduction.

The two antenna system of the HF radars (SeaSonde, by COS, LTD) installed on Lido and Pellestrina islands enabled monitoring of the surface currents in the zone depicted in Fig. 1. A regular grid with about 750 m of resolution, and the surface of about 145 km^2 is denoted with bold dots, while the colour scale reflects the data return during the one-year period of measurements, from November 1, 2001 through October 2002. Due to various reasons (noisy environment, for instance) there are gaps within the hourly time series over the study zone. The best covered area is in the central zone offshore the Malamocco inlet, where more than 90% of data were collected. The black bold dots denoted the grid nodes which were not considered at all. The thin dots represent the potential area to be covered in combination with the third antenna from the CNR Oceanographic Platform. The third site did not operate continuously during the study period due to the lack of a reliable power supply. Therefore data from that site was not used in the time series analysis.

All details about the installation, configuration and determination of the surface current vectors have been reported in [Kovačević et al., 2002].

The long term mean currents (Fig. 2), as well as the mean monthly current maps [Kovačević et al., 2003b] have revealed the presence of a meandering feature. Moreover, the presence of small scale eddies, north and south to the Malamocco inlet was observed on several occasions. Consequently the vorticity maps and the times series of vorticity at selected locations near the inlets were examined in more details.

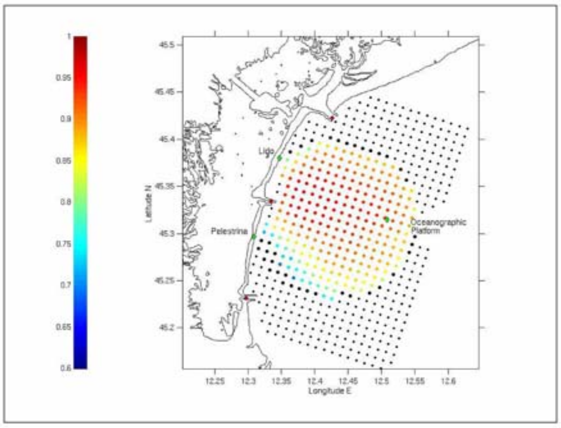


Fig. 1 - Regular spatial grid for the hourly HF radar data set. Coloured scale indicates the rate of the data return for the one year period from November 1, 2001 through October 31, 2002.

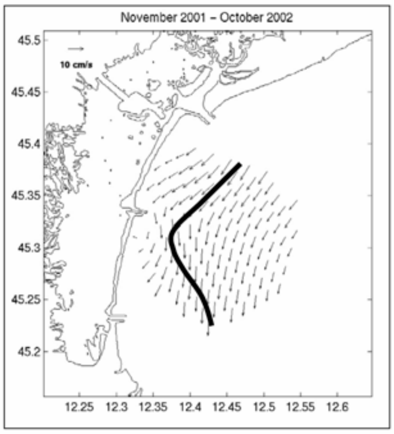


Fig. 2 - Annual mean surface velocity from the Lido and Pellestrina CODAR - SeaSonde HF radar systems.

2. Data Preparation.

Times series of hourly currents were formed over the study area. The tidal signal was filtered out using harmonic properties of the most important tidal constituents [Kovačević et al., 2003a, Kovačević et al., 2003b]. Such residual time series were interpolated for gaps not greater than 6 hours, and subsequently filtered for other high frequency oscillations (of the inertial period) applying a digital symmetrical filter with 25 weights.

The time series of such residual and filtered currents over the study area were used for determining the 2-dimensional best fit for u (eastward) and v (northward) current velocity over a 5 km spatial scale. Such a fit was then used for calculating vorticity ($\partial v/\partial x - \partial u/\partial y$) in each node of the new regular grid at a time step of one hour.

3. Vorticity Analysis.

From the time series of vorticity values at established grid points, the mean annual vorticity for the period November 1, 2001 – October 31, 2002 was calculated (Fig. 3). Positive values indicate anti-clockwise motion, while the negative ones represent clock-wise rotation. The central zone of slightly positive vorticity is enclosed between the two zones of negative vorticity to the north and to the south of Malamocco inlet. Such a pattern corresponds to a meandering feature derived from the annual mean current field (Fig. 2).

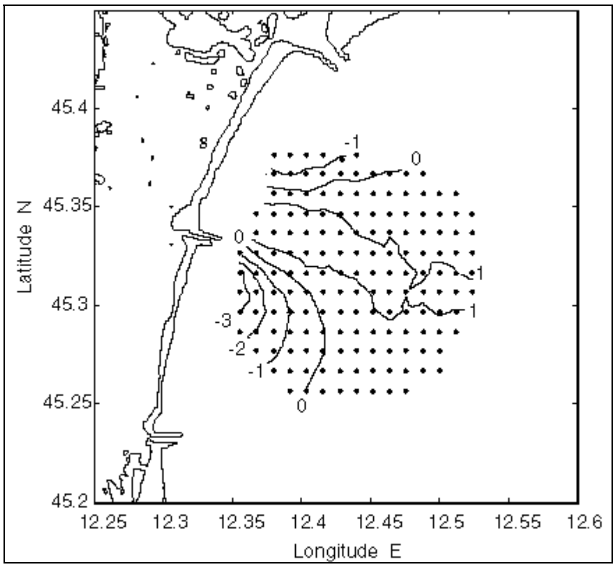


Fig. 3 - Annual mean vorticity calculated as an average from the hourly vorticity values (unit scale 1e-5 s-1) in the locations indicated by heavy dots, for the period November 2001 through October 2002.

Several examples of vorticity maps and the associated surface current field are reported in Fig 4. In some cases elevated vorticity values are associated with small scale eddies. One or two of them are seen from the HF data in the study zone. In rare cases the eddies are detached from the coast (Fig. 4f), and they mostly appear close to the northern and southern side of the Malamocco inlet, as an along-shore current became relaxed. From HF radar data sometimes only one-core eddy is observed (Fig. 4a), and sometimes it is associated with the eddies to the south. When the two-core vortex structures occur they may be rotating in the same sense (both clock-wise, like in Fig. 4h) or in an opposite sense (Fig. 4b, 4k, 4l).

In a few situations the presence of the eddies is accompanied with the southward flow further off shore (Fig. 4h, 4l), and, less frequently, with the northward flow (Fig.

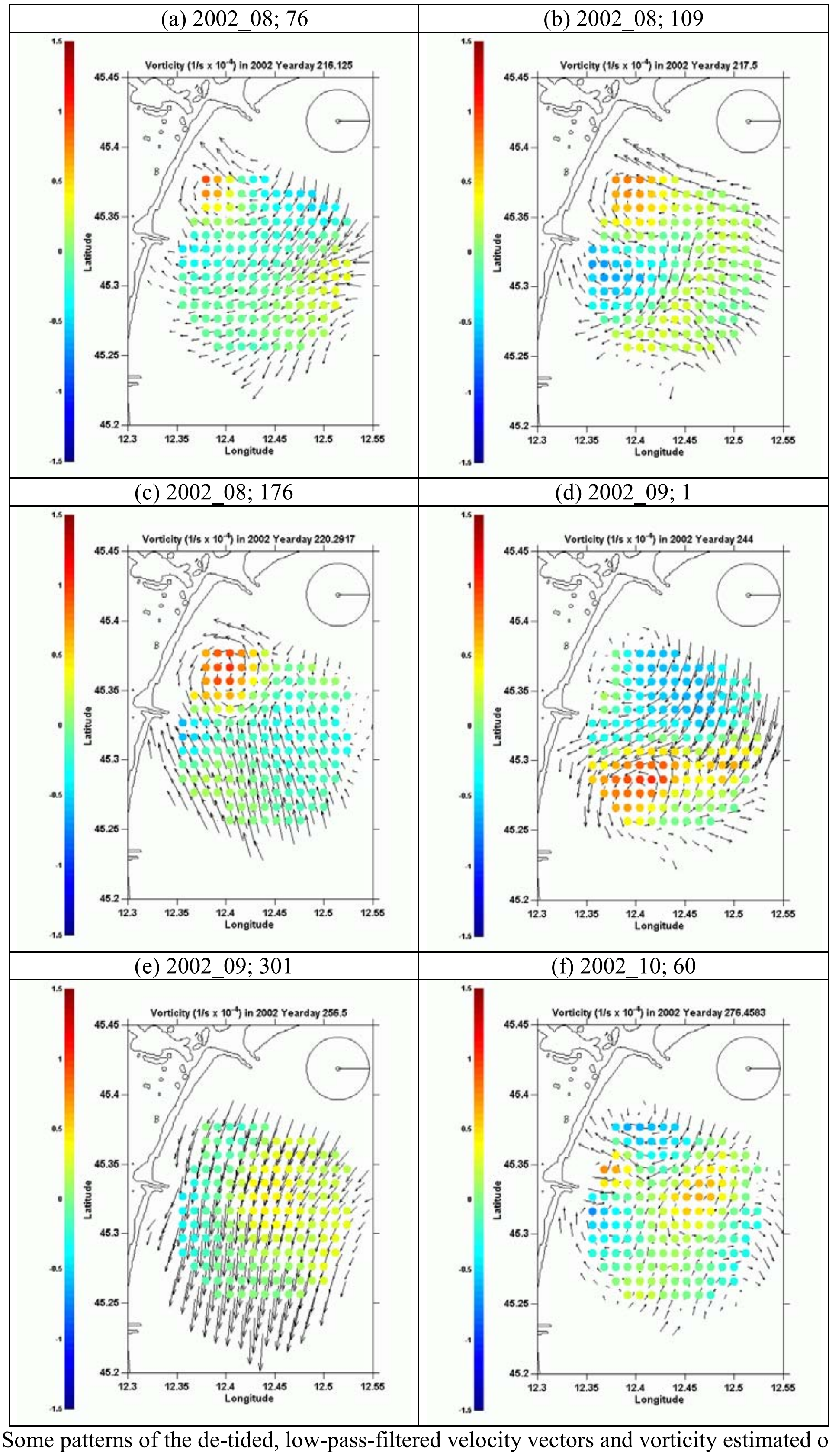
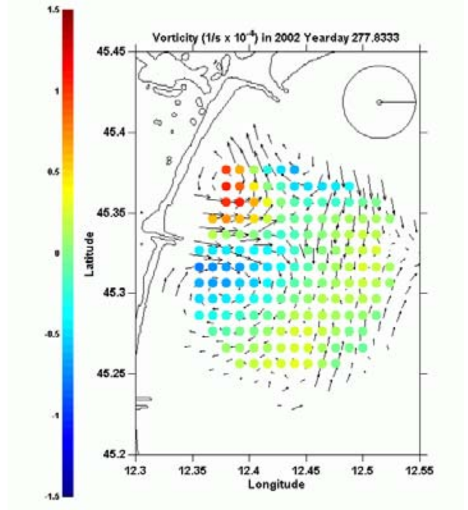
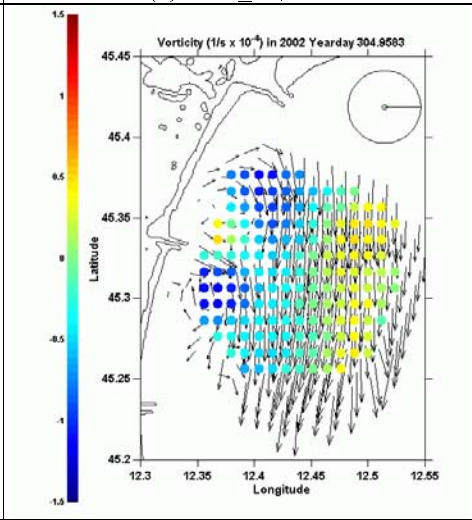


Fig. 4 - Some patterns of the de-tided, low-pass-filtered velocity vectors and vorticity estimated over 5-10 km horizontal scales (reference circle). The time is indicated as the year_ month and a sequential hour of the month

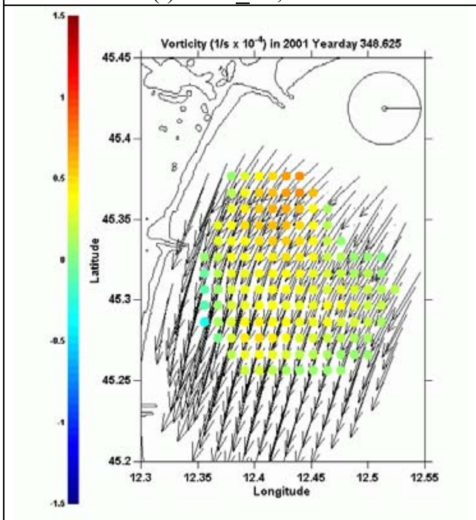
(g) 2002_10; 93



(h) 2002_10; 744



(i) 2001_12; 328



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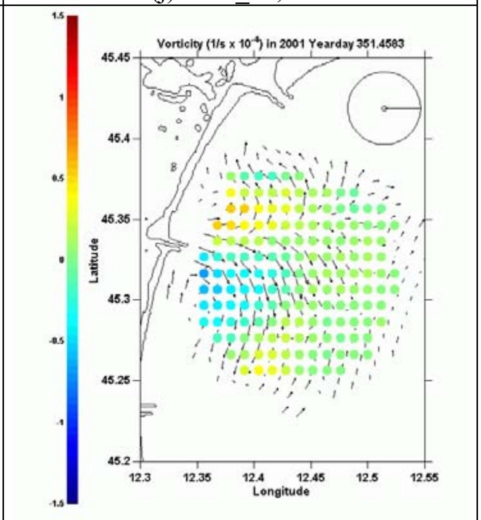
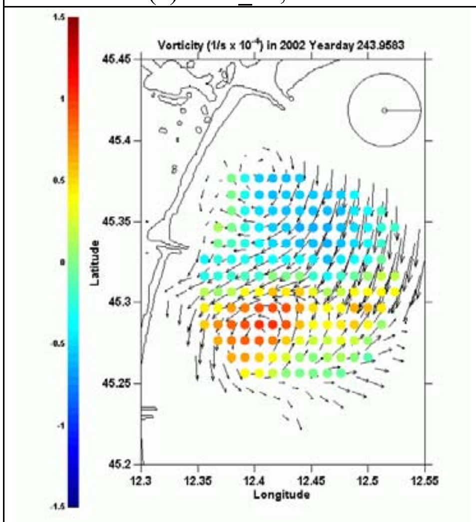


(k) 2002_08; 744



(l) 2002_01; 676

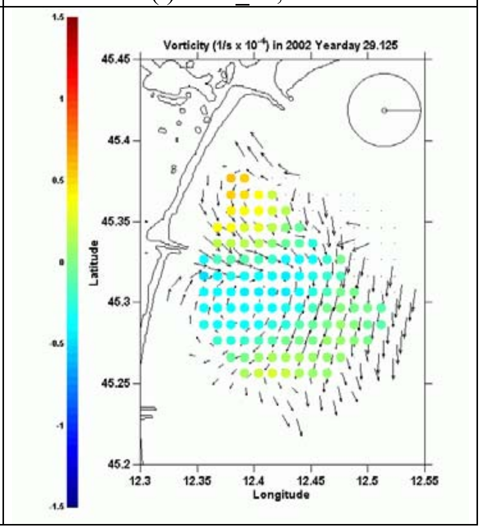


Fig. 4 - cont.

4c, 4g). The southward flow is a signature of the prevalent general circulation pattern in the Northern Adriatic, while the northward one is associated with the reversal, probably related to a mesoscale variability. The speeds associated with the eddies are about 5cm/s, and duration are of the order of a day.

In particular, one of the events with vorticity values higher than 5×10^{-5} s^{-1} observed north and south of the Malamocco inlet, occurred at the beginning of October (Fig. 4f, 4g). The vorticity field evolved from a multi-core eddy field into a two counter-rotating eddies. The event is associated with a current reversal to the south of the study zone, possibly due to mesoscale variability within the study area.

There are two examples showing relatively strong, coherent southward flow and no eddies present near the inlet (Fig. 4e, 4i).

The histograms representing the vorticity distribution over a one year period at three selected locations surrounding the Malamocco inlet (Fig. 5) are depicted in Fig. 6.

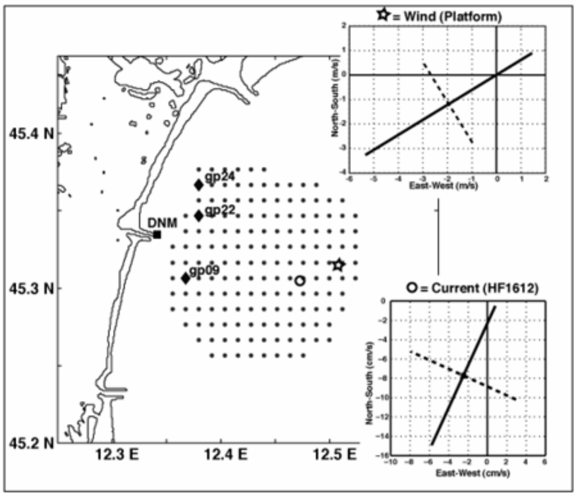


Fig. 5 - Vorticity analysis grid with locations selected for statistical analyses (gpxx) along with location of tidal height station (DNM), representative offshore current (HF1612) and research platform. The annual mean speeds, together with major (solid) and minor (dashed) principal axis components of the current and wind, are also shown.

Two of the locations are from the zone of prevalent negative vorticity (gp24 and gp09) and one is from the zone of prevalent positive vorticity (gp22; see Fig. 2). At locationgp24 (Fig. 6a) negative vorticity (clock-wise sense of rotation) prevails over the zero values, but the secondary peak indicates occurrences of relatively strong positive vorticity events. At location gp22 (Fig. 6b) the vorticity is prevalently zero, but then events of positive vorticity (anti-clockwise rotation) prevail. At location gp09 (Fig. 6c) south of Malamocco inlet, negative vorticity is dominant.

Some mechanisms possibly responsible for the generation of vorticity were taken into consideration for the same time interval as vorticity data (Fig. 5), such as the tidal regime near the inlet. This was determined from the hourly sea level data available from the Northern dyke of the Malamocco inlet (DNM), and smoothed by a moving average with a window length of 51 hours). The wind data time series from the CNR Oceanographic Platform was decomposed into two orthogonal principal components, which resolve very well the two principal wind directions, namely that of the bora (blowing from the ENE direction) and of the sirocco (blowing from the SE direction). The hourly mean wind data were treated with the same kind of digital filter as currents with the scope to eliminate high frequency variability.

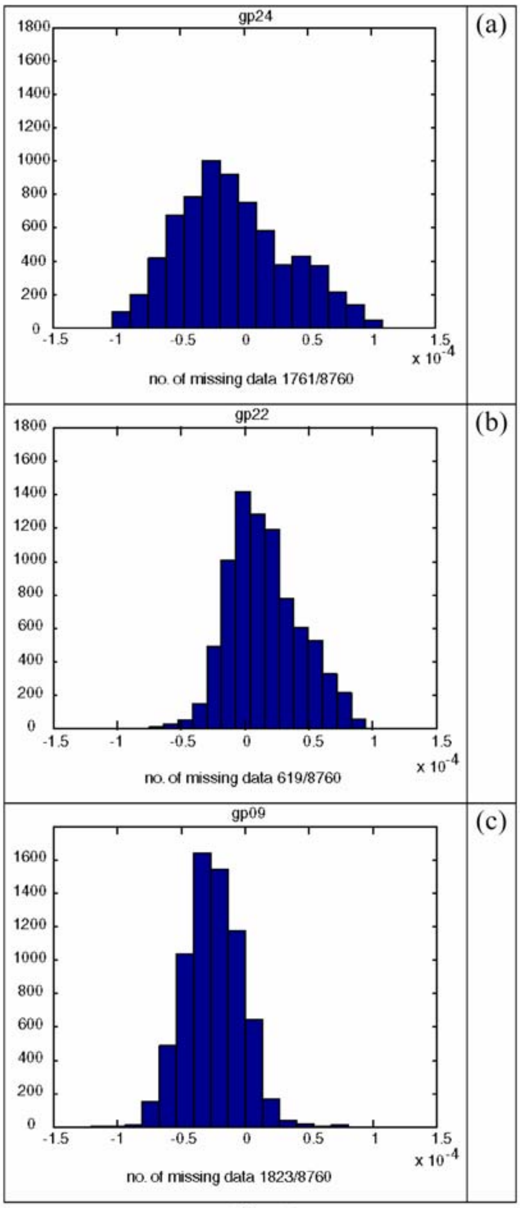


Fig. 6 - Histograms of the vorticity distribution for a period November 1, 2001 through October 31, 2002 at three selected locations near the Malamocco inlet.

The current time series near the platform at location HF1612 (Fig. 5) was taken as representative of the current regime off shore. The current data were decomposed into major and minor principal components, which highly correspond to the along-shore and across-shore current orientation.

In Fig. 7 the time series of vorticity at two locations, gp24 and gp09, together with all other investigated data are presented: shaded areas denote absolute vorticity values higher than $5 \times 10^{-5}\ s^{-1}$. It has been observed on several occasions that values higher than this threshold correspond to the presence of eddies while values lower than this indicate usually only a meandering of the along-shore current in the vicinity of the inlet.

Both by visual inspection of the time series, and by scatter plotting of the vorticity as a function of other external parameters, it seems that there is no straight-forward cause-effect relationship that would indicate the forcing for the eddies to occur. No relationship with the tidal regime may indicate that there is no influence of the ‘tidal pumping’ from the lagoon on the formation of these vortex structures. The only reasonable relationship, in a very wide sense of the meaning, is the fact that during low wind conditions, the vorticity tends to develop more than during strong wind conditions. This is most evident from the scatter plot between the vorticity and the major principal wind component (representing the bora wind) in Fig. 8. This is coherent with the current structure observed in some occasions during the strong bora episodes, when the surface current field in front of the lagoon is relatively homogeneous, and parallel to the shore, while during calm the current filed near shore is weaker and small eddies of about 5 km in diameter develop and persist off-shore the lagoon islands.

During some of the episodes of high vorticity presence near the inlet, such as the event that occurred at the beginning of October 2002 (see Fig. 4g, 4h), while the winds were low, strong positive vorticity to the north is coupled with a strong negative vorticity to the south of the inlet. At the same time, the current reversal off shore is observed. However the matching of the latter is not always the case. There is a hypothesis that the prevalent along shore, southward flow as a branch of the general circulation of the Northern Adriatic sea, encounters morphological “obstacles” in the vicinity of the inlet, caused by the dykes, which extend to few km off shore. Therefore the flow is in some way constrained to meander around them.

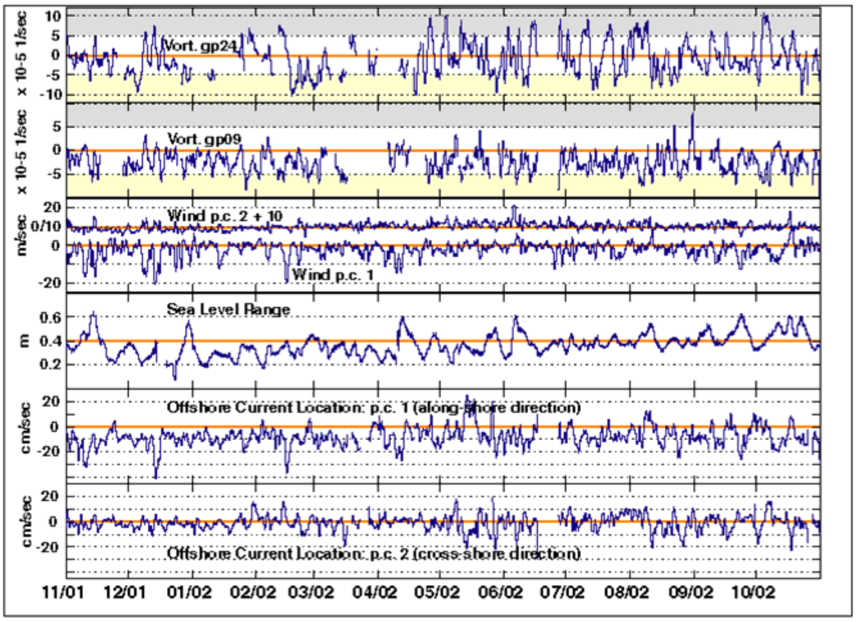


Fig. 7 - Time series of the hourly values of the vorticity at the two selected locations (24 and 9), the tidal sea level regime, the principal wind components and principal off-shore current components for the period November 1, 2001 through October 31, 2002.

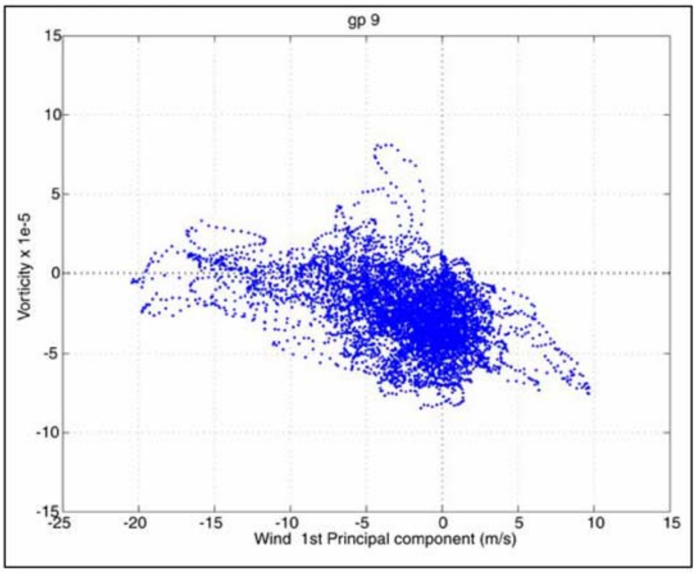


Fig. 8 - Scatter plot of the vorticity at the location 9 as a function of the major principal wind component.

4. Conditional Average Currents.

The mean flow structures over the study area have been determined according to three different conditions, namely, for very large negative vorticity values, for very large positive vorticity values, and for very low vorticity values. The thresholds have been determined such that large vorticity corresponds to the values with magnitudes greater than 5×10^{-5} s^{-1}. These are emphasized in Fig. 7 as gray and yellow bands, for positive and negative sense of rotation, respectively. Each criterion has been considered separately or simultaneously for the two locations, gp09 and gp24, as stated in Table 1.

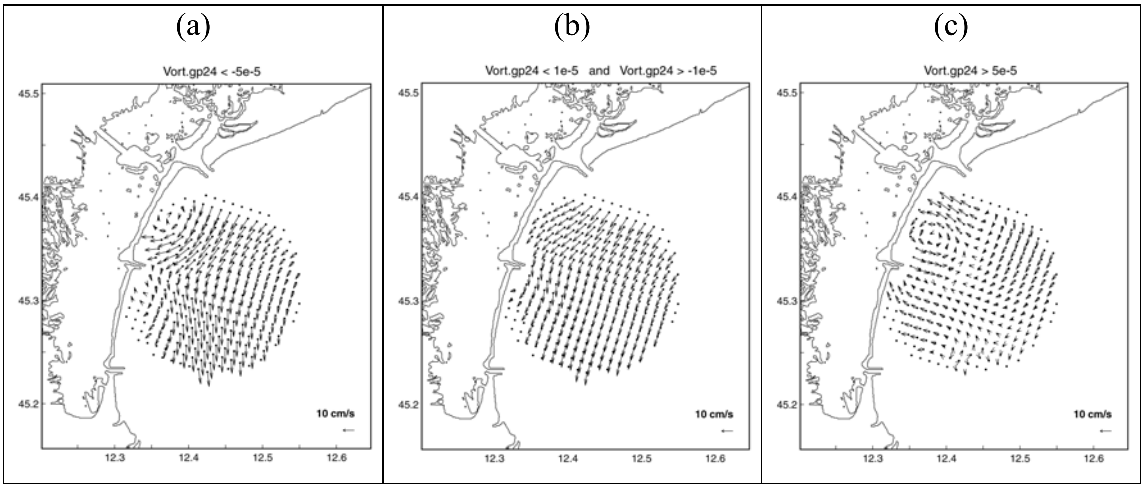


Fig. 9 - Maps of the mean flow structure corresponding to the cases 1, 2, and 3 from Table 1.

The mean flow patterns considering only gp24 to the north of the inlet, are illustrated in Fig. 9. Very large negative vorticity at gp24 seems to be associated with a prominent meandering of the residual southward flow (Fig. 9a), with current intensities within the meander larger than offshore. On the contrary, large positive vorticity at gp24 seem to be associated with a weak and non uniform southward flow (Fig. 9c). Small vorticity values at gp24 reveal relatively uniform and homogenous southward flow, with not much meandering. The patterns considering only gp09 to the south of the inlet (Fig. 10) show that large negative vorticity at this location is associated with a residual southward flow detached from the coast, and relatively weak. Low vorticity seems to be associated with the presence of non uniform southward flow (Fig. 10b), while large positive vorticity is probably associated with a mesoscale feature further offshore, lasting about a day (23 cases). This shows that large positive vorticity is not very common to the south of the inlet, as it is to the north of it. In Fig. 11, the criteria for very large negative vorticity applied simultaneously at both locations reveal a meandering flow intensified in the south-eastward portion of the study area (Fig. 11a), while a dipole-like structure, with large positive vorticity to the north, and large negative vorticity to the south seems to be associated with a blocking of the southward flow in the southernmost portion of the study area, which perhaps may be induced by temporary reversals. However, in this preliminary analysis of these phenomena we are not able to give the final answers yet.

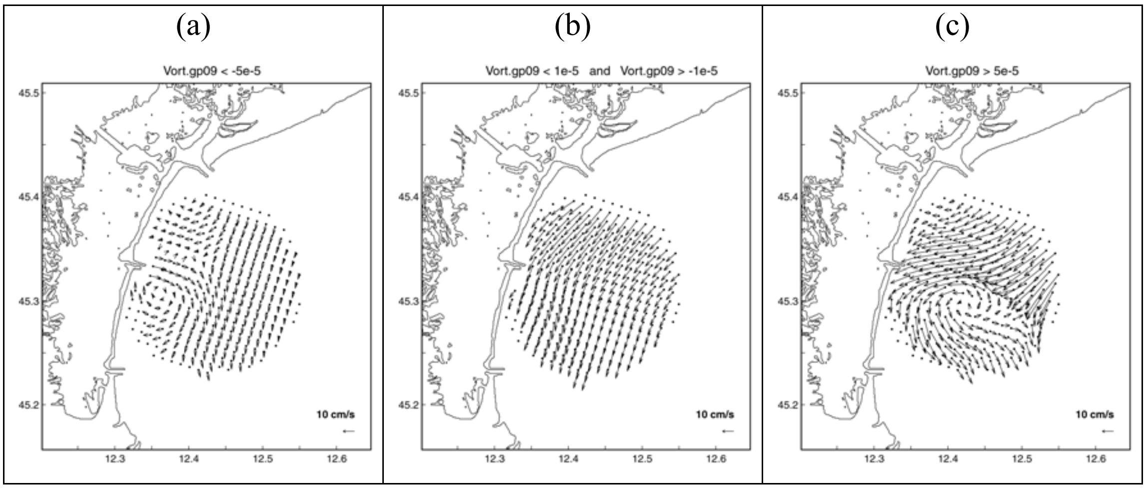


Fig. 10 - Maps of the mean flow structure corresponding to the cases 4, 5, and 6 from Table 1.

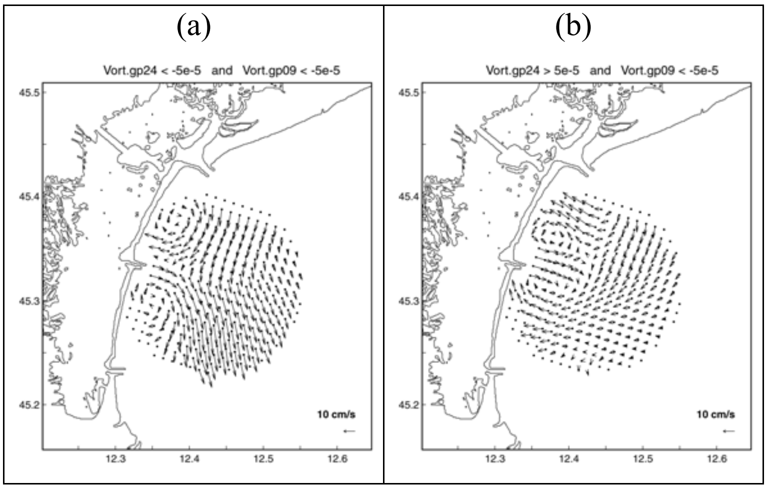


Fig.11 - Maps of the mean flow structure corresponding to the cases 7, 8 from Table 1.

Table 1. - The number of cases for each of the following eight criteria defined with respect to the vort. (vorticity): 1) vort. at gp24 < -5e-5; 2) –1e-5 < vort. at gp24 < 1e-5; 3) vort. at gp24 > 5e-5; 4) vort. at gp09 < -5e-5; 5) –1e-5 < vort. at gp09 < 1e-5; 6) vort. at gp09 > 5e-5;7) vort. at both gp24 and gp09 < -5e-5; 8) vort. at gp24 > 5e-5 and gp09 < -5e-5. The criterion vort. at gp24 < -5e-5 and vort. at gp09 > 5e-5 does not yield any solutions. Vorticity units: s-1. For the locations of the grid points gp09 and gp24, see Fig. 5.

Criterion	1	2	3	4	5	6	7	8
No. of cases	1223	1114	828	855	1404	23	126	188

6. Conclusions.

The present work is focused on describing the small scale structures in the current filed, as observed from the HF radar data. Near the Malamocco inlet their presence is quite frequent, in particular during calm wind conditions. During strong bora or sirocco winds, the current field tends to be spatially coherent and parallel to the shore over the investigated region. The phenomenology of these structures is described, confirming that the shore morphology (as inlet dykes) influences the along shore flow causing it to deviate and meander, as already stated by Gatto [Gatto, 1984]. In some dynamically favoured conditions the small scale eddies then develop. The available spatial coverage made it possible to observe them only in the vicinity of the Malamocco inlet, but there are hints of their presence in the vicinity of the other two inlets: Lido and Chioggia. We suppose that they may influence the along-shore sediment transport from north to the south and possibly have some influence also on the sediment transport between the lagoon and the adjacent sea. We argue that they may take part, together with the wave motion and a non-tidal coastal circulation, in a complex dynamical mechanism that plays a significant role in the processes of erosion and sand deposition, which are observed along the littoral of the lagoon and qualitatively synthesized by Gatto [Gatto, 1984]. He derived qualitative characteristics of the near shore circulation on a basis of geological observations of the littoral band of the Venetian lagoon. He showed the scheme in which the most important property of this circulation consists of the southward residual current, which is deviated offshore due to the inlet dykes causing a complex pattern within which vortices of small scale, not quantitatively determined, develop. Having for the first time the possibility to measure a surface circulation on the portion of the sea surrounding the lagoon, these structures may be quantified in terms of velocity and duration, as preliminary illustrated here. The argument, however, needs more in depth analysis.

Acknowledgements.

Jeffrey Paduan was partially supported in this work by the Naval Postgraduate School, Monterey, California, while Isaac Mancero Mosquera received financial support of the "ICTP Programme for Training and Research in Italian Laboratories, Trieste, Italy". Antonio Gaspari and Leonardo Pilan (CNR-ISMAR) have provided for the maintenance and the recall data from the remote sites. Michael Cook from Naval Postgraduate School, Monterey, California provided for a number of routine in MatLab for data processing and graphical representation.

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