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Long-term changes in the kinematics of inlets of the Venetian Lagoon (NE Italy)

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Summary. — Long-term variations of the water flow through three Venice lagoon inlets are analysed seeking for the possible impact of structures under construction for the mobile gates for defending Venice against flooding. Time-series of monthly mean flow and standard deviations show long-term variations, mainly on the seasonal time-scale. An important increase in the water flow variance due to an increase in amplitudes of major tidal constituents in the Chioggia inlet can probably be explained as a consequence of the structures constructed recently that narrowed the channel.

PACS 92.10.A- – Circulation and currents.
PACS 91.50.Cw – Beach and coastal processes.
PACS 92.10.Sx – Coastal, estuarine, and near shore processes.

1. – Introduction

Since February 2001 bottom-mounted Acoustic Doppler Current Profiler (ADCP) measurements have been carried out continuously in the three inlets of the Lagoon of Venice (Lido, Malamocco and Chioggia; see fig. 1). The long-term records have revealed spatial and temporal characteristics of the flow field and water exchange between the lagoon and the open sea, which have been presented in a series of papers published recently [1-3]. One of the prominent features of inlet flows is a very high contribution of tidal currents to the total flow variance that in average reaches even more than 95%. Another important property of the water flow is a strong polarization approximately along the geometrical axis of inlets due to the channel walls constraint. Cross-inlet current components are negligible. In fact, more than 99% of the flow variance is associated with the variability along axes of maximum variance that on its turn coincide with the inlet axes. The long-term current records enable us to evidence weekly time-scale, seasonal or even year-to-year variations of the inlets' flow properties [3].

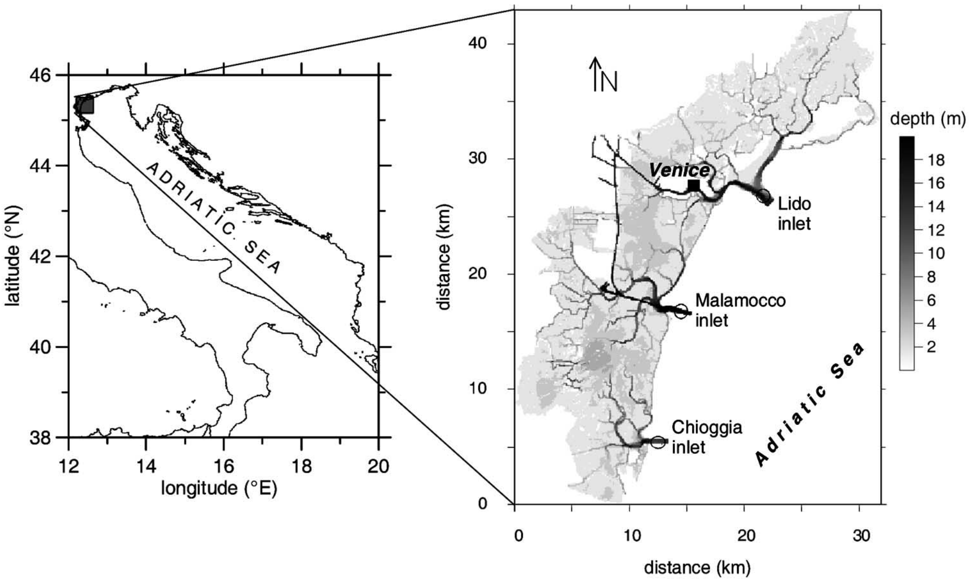

Fig. 1. – Bathymetric map of the Venice Lagoon.

2. – Brief description of carried out civil works

External wave-breaking barriers have been completed in front of Malamocco (June, 2003-November 2004) and Chioggia (April 2004-April 2005) inlets within the framework of a project for the Venice lagoon defense against the "acqua alta" events. In addition, the width of the Chioggia inlet was, in one part of the channel, reduced within the framework of building of the haven for fishery vessels (see fig. 2 showing aerial photographs of the Chioggia inlet before and during the civil works on the haven for fishery vessels). Presumably the width of the Malamocco inlet has not been changed. The width of the

Fig. 2. – Aerial photograph of Chioggia inlet before (left) and during the construction works (right). Note different horizontal scales. The construction of fishery vessels' haven is evident along the northern shore of the inlet in a more recent photograph. The position of the ADCP is presented by a dot.

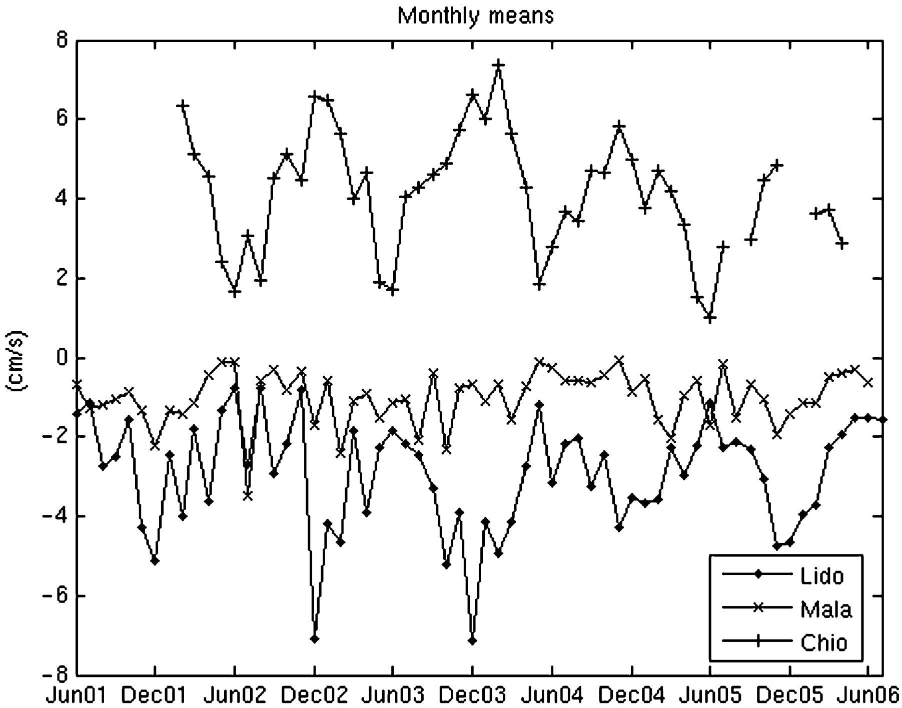

Fig. 3. – Time-series of the monthly mean vertically averaged inflowing current component in the three lagoon inlets. Negative values stay for the inflow.

inlet of Lido was not changed either and the wave-breaking barrier has not yet been built there. All these construction works may have changed characteristics of the flow in inlets. As an example, local fishermen have claimed that an increase in the velocity of currents in Chioggia channel have taken place recently.

A detailed study was carried out in order to seek for possible changes in the kinematics of the inlets. Moreover, the aim of this paper is to investigate long-term variations in the flow characteristics and to assess whether some changes that took place can be associated with the construction works.

3. – Analysis of the long-term flow variations

Detailed description of the experimental set-up of current measurements in the lagoon inlets and ADCP data available were presented in [2]. In order to analyze long-term variability, a number of parameters describing the flow characteristics were estimated on a monthly basis for each inlet. Following the principal component decomposition [4], time-series of the first two statistical moments of the flow (figs. 3 and 4) have been computed for the along-axes vertically averaged current component. Results have shown that prominent long-term variations in time-series of both average flow and its standard deviation are present. There is a good agreement with previous studies that indicated a prevalent long-term mean inflow in Lido and an outflow in Chioggia [3]. Also, a rather prominent seasonal variability in the water exchange is evident in Lido and Chioggia with

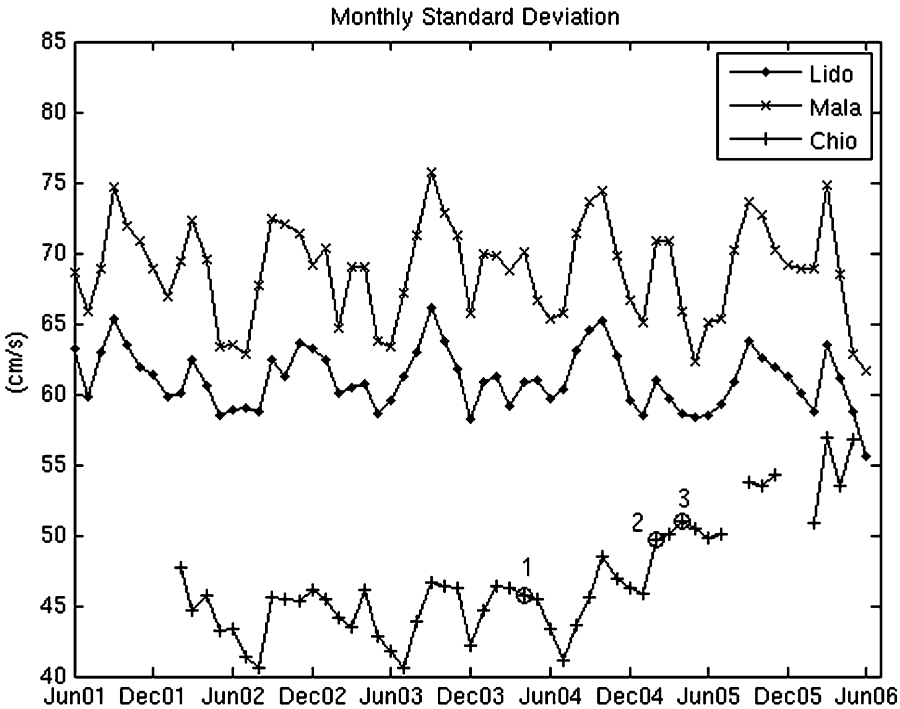

Fig. 4. – Time-series of monthly standard deviations of the inflowing vertically averaged current component. Numbers denote different phases of the completed construction works in the area of the Chioggia inlet (1—External breakwater completed, 2—Southern wharf of the refuge haven completed, 3—Lock and navigation chambers done).

a maximum inflow and outflow, respectively, in late autumn/early winter. Conversely, monthly mean water flow in the inlet of Malamocco is rather weak and does not show any significant seasonal signal. On the other hand, time-series of the flow standard deviations show in Malamocco the maximum value of all three inlets with the most prominent seasonal signal. Lido shows slightly weaker seasonal signal in the standard deviations and the values smaller than in Malamocco. In Chioggia the seasonal signal can hardly be distinguished from the background noise and the flow standard deviations are the smallest of all three inlets. The flow kinetic energy (variance time-series) shows obviously the same features as standard deviations. In addition, time-series of either variance or standard deviations show coherent temporal variations in Malamocco and Lido, while Chioggia appears uncorrelated with other two inlets.

Landmarks of the works carried out in the inlets and surroundings are shown in fig. 4. Standard deviations and variance show a clear trend of increase in Chioggia starting from the last quarter of the year 2004 that continues until the end of the time-series. The point of change in the variance was found to be significant applying the cumulative sum of square statistic test [5, 6]. Other tests aimed to find changes in the mean yielded no change detected.

The trend in the current field in Chioggia inlet was sought also in the time-series of maximums of the inflow (negative current values) and the outflow (positive current

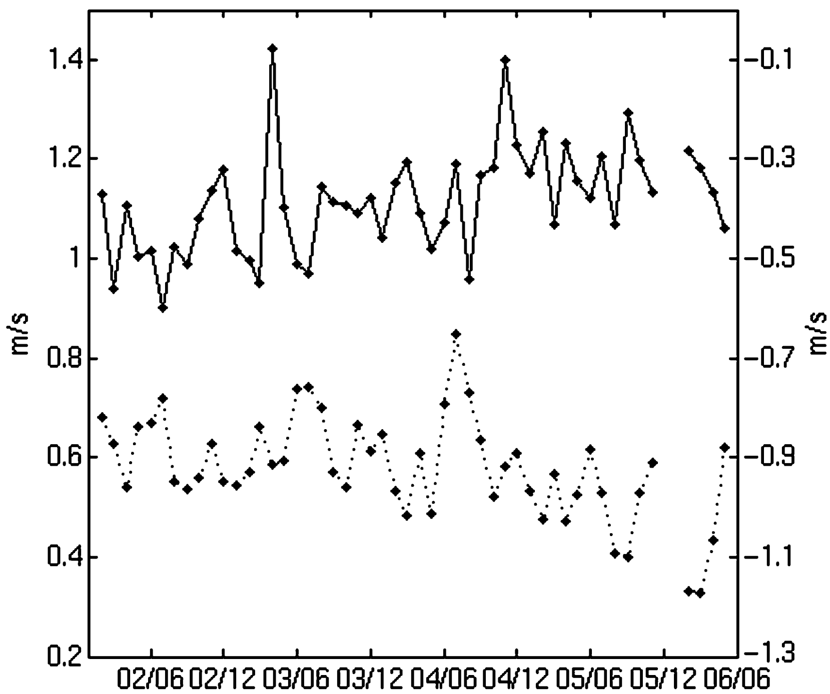

Fig. 5. – Time-series of maximum monthly inflows, dotted curve (negative values) and outflows, continuous line (positive values) for the Chioggia inlet.

values). Maximums were extracted from the monthly sub-sets and their time-series for the entire study period are presented in fig. 5. Both inflow and outflow show clear increasing trend as observed in the average current and the flow kinetic energy. The maximum values of outflow are generally larger than inflow as they are superimposed on the long-term average outflow in the Chioggia inlet. Moreover, the outflow shows larger temporal variations than the inflow. This can be explained in terms of the influence of bora episodes that reinforce the outflow as shown in previous studies [2]. Extremely large outflows that occurred in March 2003 and in November 2004 coincide in fact with strong bora events with the wind speed of about 20 m/s taking place immediately prior and during the maximum tidal outflow occurrence. In addition, the two strong bora episodes were taking place in concomitance with the spring tide.

Harmonic analysis [7] was applied in order to determine whether any variability in tidal parameters occurred as a consequence of construction works. This technique allows extracting variability due to astronomical forcing by fitting currents time-series by a sum of well-known constituents via the least-square method. Explained variance associated with the tidal oscillations in the Venice lagoon inlets reaches about 95% of total variability as already reported in previous papers (see, *e.g.* [1]). The most important group of constituents is the semidiurnal one with M2 and S2 as the most energetic ones. For current vector time-series from harmonic analysis, the following estimates of ellipse parameters can be obtained: major-axis amplitude, minor-axis amplitude, phase, orientation angle, and errors of each one.

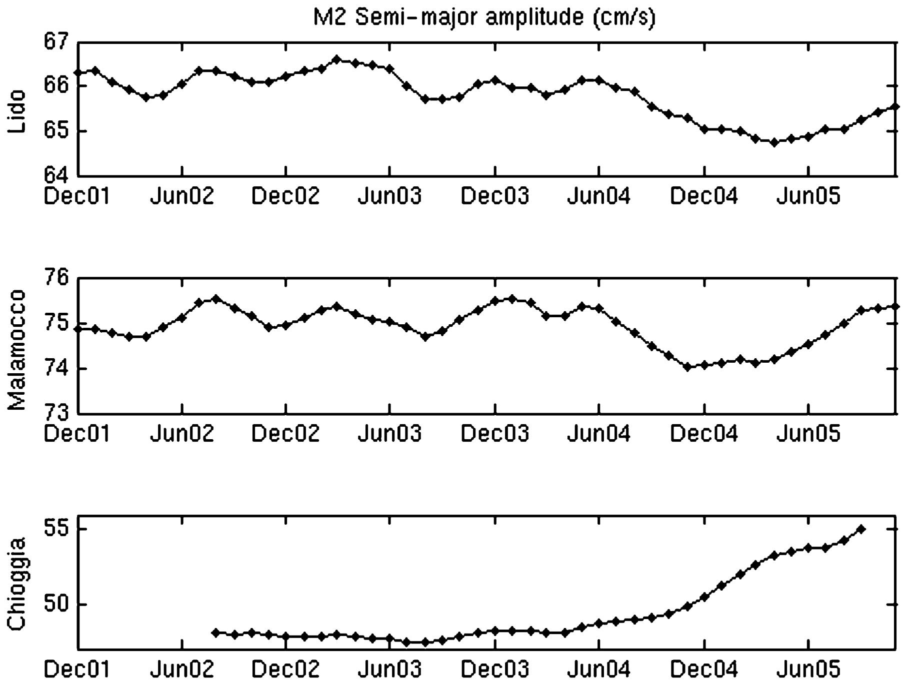

Fig. 6. – M2 semi-major tidal constituent as a function of time calculated from the 13-month moving time series of the vertically averaged currents.

As expected, tidal variability is strongly polarized along channel axes, hence only estimates of major-axis amplitudes were considered. The three most prominent constituents, namely M2, S2 and K1, have been analyzed, and they account for about 87% of total currents variability. In order to analyze continuous temporal variations in amplitudes of the three most important tidal constituents, harmonic analysis was applied to a 13-month moving period with one-month time-step for the entire time-series, and major ellipse axes are presented in figs. 6, 7 and 8 as a function of time. Low-frequency variability is the most prominent in the M2 constituent and occurs on the six-month time-scale. S2 shows the most important variability on a biennial time-scale. However, the length of the time-series does not allow us to give a definite answer on the time-scale of the variability of that constituent. The diurnal K1 tidal constituent changes rather weakly in time. Also, temporal variations of major ellipse axis values for inlets of Lido and Malamocco result rather highly correlated for all three tidal constituents as it was shown for the mean flow and its standard deviation. On the other hand, major ellipse axes for all three constituents in the Chioggia inlet show an increase starting from the second half of 2004 suggesting that the noticed trend in the flow variance is connected to the augmentation in the tidal currents magnitudes.

This increase in the flow intensity can possibly be associated with the reduction of the inlet cross-section after it has been narrowed down as evident from the chronology of the construction works carried out.

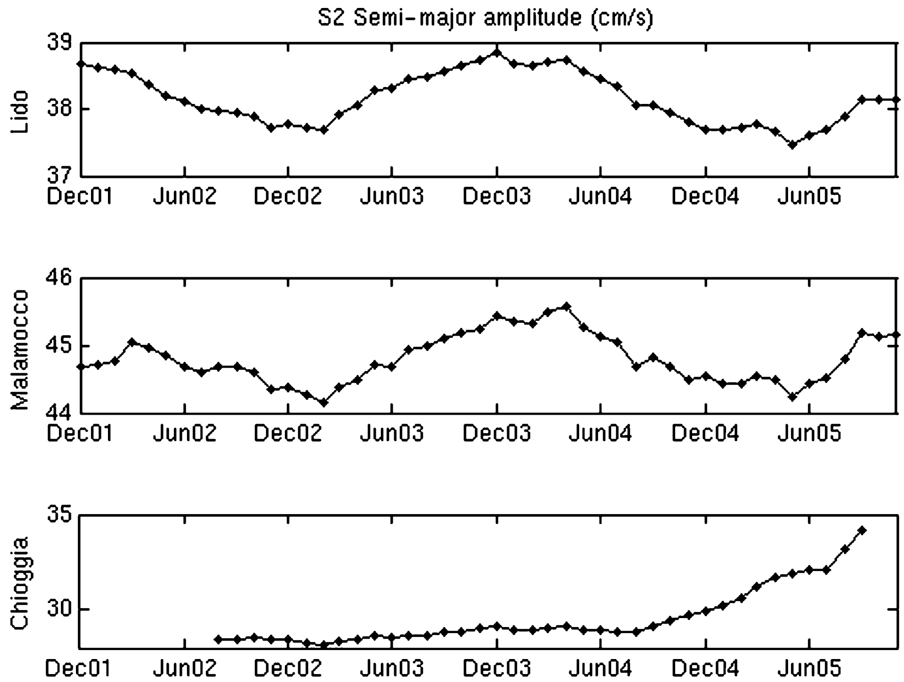

Fig. 7. – The same as in fig. 5 except for the S2 semi-major tidal constituent.

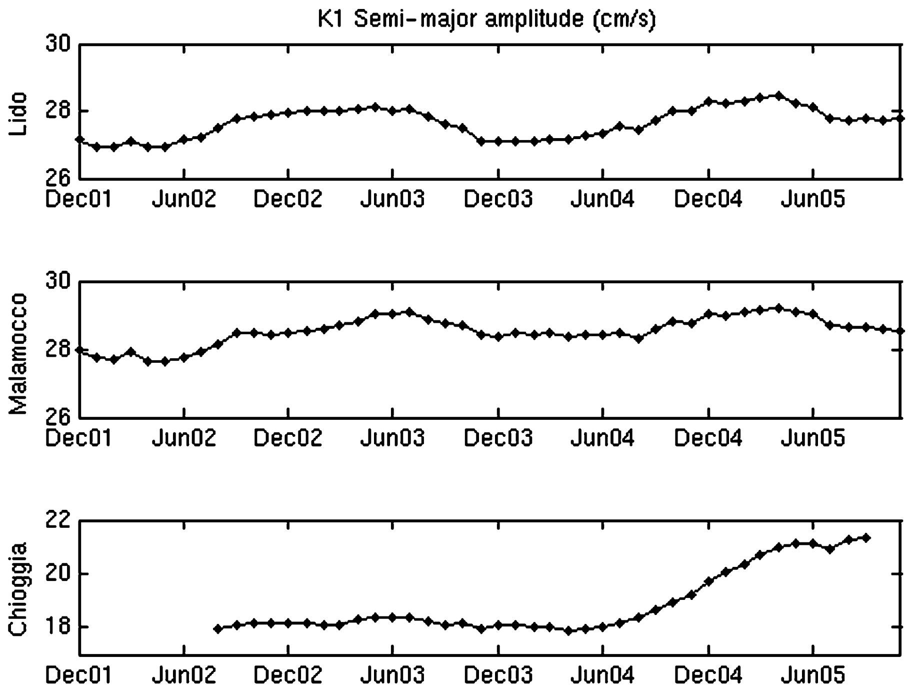

Fig. 8. – The same as in fig. 5 except for the K1 semi-major tidal constituent.

4. – Conclusions

Long-term variability of the water flow characteristics in the three inlets of the Lagoon of Venice is analyzed. Time-series of the monthly mean flow and its standard deviation show prominent seasonal signal as well as the overall mean flow compensation between Lido and Chioggia. Long-term temporal variations in amplitudes of the three most important tidal constituents (M2, S2 and K1) are analyzed from time-series obtained by harmonic analysis applied to a 13-month moving period. In Lido and Malamocco inlets semi-diurnal M2 constituent shows coherent six-month temporal variations, while the S2 is mainly varying on the biennial time-scale. The diurnal K1 constituent in the two inlets shows very weak but coherent temporal low-frequency variability. On the other hand, the three tidal constituents in Chioggia inlet display a trend of increase in amplitude starting from the second half of the year 2004, feature that may suggest a possible impact of the inlet narrowing down on the water flow. Thus, the long-term kinetic energy increase of the flow through the Chioggia inlet is mainly due to the increase in tidal energy. Also from the available time-series it can be observed that the steady state has not yet been reached.

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REFERENCES

[1] Gačić M., Kovačević V., Mazzoldi A., Paduan J., Arena F., Mancero Mosquera I., Gelsi G. and Arcari G., *Eos, Trans. Am. Geophys. Union*, **83** (2002) 217.
[2] Gačić M., Mancero Mosquera I., Kovačević V., Mazzoldi A., Cardin V., Arena F. and Gelsi G., *J. Mar. Syst.*, **51** (2004) 33.
[3] Gačić M., Kovačević V., Mancero Mosquera I., Mazzoldi A. and Cosoli S., in *Flooding and Environmental Problems of Venice and Venice Lagoon: State of Knowledge* (Cambridge University Press, London) 2005.
[4] Preisendorfer R. W., *Principal Component Analysis in Meteorology and Oceanography*, edited by Mobley C. D. (Elsevier Science Publisher, Amsterdam, Oxford, New York, Tokyo) 1988.
[5] Tanizaki H., *Commun. Stat., B*, **24** (1995) 1019.
[6] Inclan C. and Tiao G. C., *J. Am. Stat. Assoc.*, **427** (1994) 913.
[7] Foreman M. G. G., *Manual for tidal currents analysis and prediction* (revised edition). Pacific Marine Science Report 78-6, Institute of Ocean Sciences, Patricia Bay, Sidney, British Columbia (1996).