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Estimating sediment transport from acoustic measurements in the Venice Lagoon inlets

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ABSTRACT

This paper presents the results of a 3-year-long (November 2004–November 2007) study based on the use of acoustic Doppler current profilers (ADCPs) to estimate the solid transport through the three inlets of Venice lagoon. In each of the three inlets instruments were mounted both on survey boats and deployed on the channel bed. The three bottom-mounted ADCPs were positioned in the central part of the inlets, continuously monitoring vertical profiles in the water column. Periodic transects along the investigated sections were collected by the boat-mounted ADCP. Both installations measured current speed and acoustic backscatter intensity. The latter expresses the attenuation of acoustic energy due to material in the water column.

The conversion of acoustic backscatter into suspended solids concentration (SSC) was carried out by means of direct measurements of concentration; also an indirect method was used. Boat-mounted ADCP acquisitions were used to calibrate and to validate the bottom-mounted ADCP data. Hourly time series of water discharge and SSC were obtained by calculation from the current speed and acoustic backscatter data recorded by the fixed ADCPs. Hourly solid flux time series were computed.

The solid flux and SSC time series at the three inlets were analyzed in relation to the hydrodynamic and atmospheric conditions, highlighting the impact of intense meteorological events on the resuspension process. The lagoon sediment budget is estimated to be about 0.5×10^6 t/yr and shows a tendency for sediment loss.

1. Introduction

Sedimentary processes play a fundamental role in the dynamics of coastal environments (Thorne et al., 1994; Holdaway et al., 1999; Gartner, 2004), such as lagoons and estuaries. A key issue for management and safeguard of these habitats is the quantification of solid transport. Traditional techniques used in this regard are based on the acquisition of point measurements of current speed, water discharge and suspended solids concentration (SSC). The main limitation of this approach is, therefore, poor spatial and temporal resolutions, which are quite often insufficient to describe the variability associated with highly dynamic coastal environments (Gartner, 2004).

The search for alternative methodologies has increased the interest in the use of acoustic techniques, in particular acoustic Doppler current profilers (ADCPs). These instruments are used to measure current speed and water discharge in coastal–sea and river environments (Gordon, 1989, 1996; Oberg and Muller, 1994; Simpson, 2001; Simpson and Bland, 2000; Simpson and Oltmann, 1993; Yorke and Oberg, 2002; Muste et al., 2004a, 2004b). One of the main advantages of the ADCP is the capability to simultaneously acquire vertical profiles of current speed and acoustic backscatter. The acoustic backscatter is a measure of sound attenuation due to suspended particles in the water column; thus, under ideal conditions, SSC can be derived. Acoustic methods have high spatial and temporal resolutions, suited, for example, to the investigation of small scale turbulent processes (Thorne and Hanes, 2002) or mean discharge through tidal inlets.

Several studies have investigated the applicability and reliability of acoustic methods in SSC and solid transport estimates. Thorne et al. (1991, 1993, 1994) and Reichel and Nachtnebel (1994) provide a detailed description of the relevant acoustic theories, analyzing the effect of suspended solid particles on sound propagation through the water column. Various field applications both in continental waters (Holdaway et al., 1999; Kostaschuk et al., 2005), and in tidal environments, such as estuaries (Lane et al., 1997; Hill et al., 2003; Wall et al., 2006) and coastal–sea areas (Alvarez and Jones, 2002; Hill et al., 2003; Gartner, 2004; Hoitink and Hoekstra, 2005) demonstrated the potential of the acoustic approach. Moreover, acoustic techniques have been employed to monitor dredging in coastal areas due to the ease and speed of acquisition as well as their high spatial and

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temporal resolutions (Puckette, 1998; Tubman and Corson, 2000; Reine et al., 2002; HR Wallingford Ltd and Dredging Research Ltd, 2003).

Many of the cited studies were focused on the verification of the reliability of acoustic backscatter and the acoustic method. However, the datasets on which the reliability was tested are limited.

An improvement in the calibration procedure is applied in Sediview (Land and Bray, 2000; Land and Jones, 2001); this method corrects for dispersion and attenuation of an acoustic beam propagating through water. This method was preliminarily used by Zaggia and Ferla (2005), to estimate, for a relatively short period, solid transport in one of the three inlets of Venice lagoon. The results showed that the methodological approach is effective in providing interesting information on the distribution of the suspended sediment in the studied sections. Moreover, the technique was reliable for long term monitoring if supported by frequent calibration measurements.

Estimates of the sediment budget of the lagoon were previously made on the basis of modelling studies (Tambroni and Seminara, 2005, 2006) or the analysis of bathymetric differences on appropriate time intervals (Pillon et al., 2003; Magistrato alle Acque di Venezia e Technital, 2007). However, no systematic experimental observations of sediment transport have been made to support these estimates. Such an experimental data set represents a key tool for studying the recent and future morphological evolution of the lagoon and its inlets, especially if the ongoing changes for the construction of the mobile gates to protect the lagoon from storm surges are considered.

A 3-year long research and monitoring project was started to test the reliability of acoustic techniques to estimate solid transport through the three inlets of Venice lagoon. The study, carried out from November 2004 to November 2007, was focused on the use of data sets from three ADCPs, which have been deployed on the bottom of the inlets for the monitoring of tidal flows since 2001 (Gačić et al., 2004, 2005a, 2005b, this issue; Mancero Mosquera et al., 2007).

The first results of this study are presented in Defendi et al. (2007) and Kovačević et al. (2007). Two instrumental set-ups (boat- and bottom-mounted) were used to collect a large dataset, comprising both instantaneous and continuous measurements of current speed and acoustic backscatter. During the project three types of calibration surveys (monthly, seasonal, during storm events) were performed in order to investigate the effects of different experimental conditions on acoustic backscatter intensity and on suspended sediment transport. From the calibration of backscatter acquired by the boat- and bottom-mounted ADCPs, SSC estimates were computed. Time series of SSC and solid flux were derived from the bottom-mounted ADCP acquisitions. These time series were analyzed in order to evaluate their temporal variability in relation to flow patterns and meteorological conditions. The solid flux time series were also used to quantify the sediment budget of the lagoon.

2. Field methodology

Field research was carried out along cross-sections, in the middle reach of the three inlets (Lido, Malamocco and Chioggia) of Venice lagoon (Fig. 1). Most of the research was concentrated in the Lido inlet because of its greater complexity in terms of water circulation and morphology. Moreover, more than half of the water discharge and solid load from the tributaries of the drainage basin are transported through this inlet (Zonta et al., 2005). The estuaries of the northern tributaries are also sites of high primary productivity which affect the partitioning of the inorganic and organic particulates in the water column, thus complicating the calibration of ADCP backscatter.

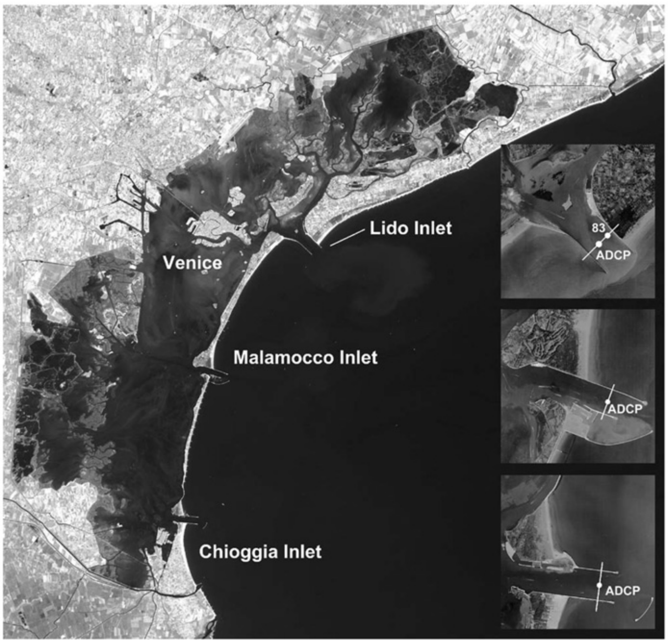

Fig. 1. Satellite image of the three inlets (Lido, Malamocco and Chioggia) of the Venice lagoon (*Source*: http://spg.ucsd.edu/Satellite_Data/Venice/2006.06.14). Positions of the three investigated sections and three bottom-mounted ADCPs are indicated.

Since April 2007, the survey activity has been concentrated in the Chioggia inlet, as there have been significant morphological modifications associated with the works for protection against storm surges. In particular, the inlet channel was considerably narrowed (Fig. 1).

Two different types of ADCP set-up were used in this study. (1) An ADCP was mounted on a moving boat, which carried out transects across the inlets. The instrument used was a 600 kHz RDI Workhorse Rio Grande (Teledyne RD Instruments, 2007a), operated with a 0.5 m vertical cell size and (2) three 600 kHz ADCPs, which were positioned on the inlets bed near the centre of the sections. RDI Workhorse Sentinels (Teledyne RD Instruments, 2007b) were employed in the Lido and Malamocco inlets, while an RDI Workhorse Monitor (Teledyne RD Instruments, 2007b) was used in the Chioggia inlet. For all the three bottom-mounted ADCPs, the size of the depth cells was set to 1.0 m. The positions of the stations are shown in Fig. 1.

Integration of acquisitions of the two instrumental set-ups was undertaken to better investigate the variability of hydrodynamics and solid flux through the inlets. For this purpose different spatial and temporal resolutions were selected for the two installations. The three bottom-mounted ADCPs acquired, with a 10-min sampling interval, time series of current velocity and acoustic backscatter through the vertical profile. The vessel-mounted ADCP performed periodic instantaneous measurements of the same variables along transects perpendicular to the inlet channels in the sections of the fixed instruments. The data set from the mobile ADCP was used to calibrate the fixed ADCP data and to estimate their representativity compared to the behavior of the studied sections.

The experimental plan was chosen in order to obtain spatial and temporal resolutions suited for a highly dynamic environment such as Venice lagoon. During the whole duration of the project, 71 measurement sessions were performed by means of the boat-mounted ADCP according to different schedules:

monthly, seasonal and during storm events. The monthly surveys covered a half tidal cycle, while the seasonal surveys monitored whole tidal cycles. Durations of the storm surveys were variable, being determined by meteorological conditions. For each measurement session, sets of 2–4 repeated transects, depending on flow conditions, were acquired at 1-h intervals for a total number of 2083 ADCP transects. Pairs of transects were sufficient to minimize any directional bias under relatively steady flow conditions (Yorke and Oberg, 2002).

After each set of transects, one or two calibration acquisitions were taken with the boat moored on a fixed position. Simultaneously, vertical profiles were acquired by means of a multiparameter probe (Ocean Seven 316 CTD; Idronaut, 2002) and water samples were collected at different depths with a Rosette sampler, equipped with 0.5 l Niskin bottles. Temperature, conductivity, dissolved oxygen, pH and turbidity were acquired throughout the water column. The water samples were used for subsequent laboratory determination of the SSC by filtration. The number of the calibration stations was chosen according to the section morphology: two stations were selected in the Lido inlet (bottom-mounted ADCP and point 83, Fig. 1), because of the asymmetry of the section; while one station (bottom-mounted ADCP, Fig. 1) was selected in the Malamocco and Chioggia inlets. Three water samples were collected at the bottom-mounted ADCP station (sampling depth: 2, 6 and 12 m), while only two samples were collected (sampling depth: 2 and 4 m) at point 83.

Discharge was derived from the boat-mounted ADCP, which acquired transects perpendicular to the flow. Linear regression between the total water discharge, measured by the mobile instrument, and the vertically averaged current velocity, acquired by the bottom-mounted ADCPs, was used for the computation of the time series of discharge (index velocity method, Simpson and Bland, 2000).

The ADCP transects were also useful for a detailed investigation of distribution of acoustic backscatter intensity and flow characteristics. The calibration procedure for the conversion of acoustic backscatter into SSC is described in the following section.

3. Data processing

The calibration procedure of acoustic backscatter data from the ADCP is based on the Sediview method (Dredging Research Ltd., 2003; Land and Bray, 2000; Puckette, 1998; Land and Jones, 2001; Reine et al., 2002), which uses a simplified version of the acoustic theory discussed in Thorne et al. (1994). The first phase took place in the field, and included simultaneous acquisition of an ADCP calibration transect, vertical profiles of temperature and salinity, and water samples for SSC determination. SSC concentrations in the water samples, temperature and salinity were correlated with the corresponding vertical profile of acoustic backscatter in depth and time. The first part of the calibration included estimation of water density and kinematic viscosity from temperature and salinity. The water density and kinematic viscosity were essential in the determination of the water absorption coefficient, which is the acoustic energy attenuation due to sound propagation through the water column. The sediment attenuation coefficient was determined from measurements of suspended solids and is the attenuation of sound caused by scattering due to suspended particles.

The instruments used are relatively insensitive to particle scattering up to 200 μm particle diameter. As with water absorption, attenuating effects of the sediment are greatest in the case of high frequency instruments, such as the 2400 kHz ADCP (Dredging Research Ltd., 2003). However, the procedure for calibration also uses a representative grain size, which is here assumed to be equal to the median diameter of the typical distribution of solids transported in suspension (25–30 μm)—this is derived with laser in situ scattering and transmissometry (LISST-100X; Sequoia Scientific Inc., 2004) deployed in the three sections. These observations showed that, in normal conditions, the grain size distribution of suspended materials is rather uniform (predominantly silt). A variable percentage of sand is found in the near-bed region, when the tidal currents are intense or even in the upper water column during storm events. The clay fraction is almost always absent.

The organic component in suspension (phyto- and zooplankton) is also expected to have an effect on the backscatter calibration. Our procedure considers the total solids content, which includes the inorganic and organic components. According to Bianchi et al. (2004), who studied the composition of suspended particulate in the inlets throughout a year, the organic component is generally a limited percentage of the total. However to minimize uncertainties, our calibrations make use of the measurements at appropriate time intervals to ensure uniformity of the experimental parameters. Moreover, as the composition of the suspended particulate matter, in general, changes considerably during storms, specific calibrations were made for any significant event.

The calibration was made in successive iterations by means of an optimization procedure that minimizes the differences between measured and estimated concentrations. For each step, the two attenuation coefficients are refined and the acoustic backscatter intensities are compensated for dispersion of the acoustic beam during its propagation in the water column. Every adjustment is propagated to the successive depth cell and the process stops at the last valid cell. Finally, the site-specific relationship between the acoustic backscatter intensity (I) and concentration (C) is computed: $\mathrm{I(dB)}=S\ \log \mathrm{C\ (mg/l)}+K$. The two calibration constants, the backscatter coefficient (S) and the calibration constant (K), represent, respectively, the slope and the offset of the line.

The adopted procedure for the conversion of acoustic backscatter into SSC followed two approaches: one direct, with water sample concentrations; the other indirect, from SSC profiles obtained from the calibration of the boat-mounted ADCP transects. The direct calibration was used with the backscatter data acquired by the boat-mounted ADCP, while the indirect approach was employed for the bottom-mounted ADCP. The direct calibration was also applied to a limited portion of the dataset recorded by the bottom-mounted ADCP in the Lido inlet. This investigation was performed as a test to determine how representative are estimates for the fixed station with respect to those obtained in the entire section as the known asymmetry in the morphology, hydrodynamics and sediment transport of the Lido inlet (Zaggia and Ferla, 2005) was expected to affect the estimates.

A set of instantaneous measurements of the total solid flux was obtained from the direct calibration of acoustic backscatter from the boat-mounted ADCP. Hourly time series of solid flux were computed combining the hourly water discharge (Gačić et al., this issue) and the vertically averaged concentration from the three bottom-mounted ADCPs. It is stressed that estimates from the bottom-mounted ADCPs are limited to the water column directly above the instrument and do not include the surface (about 1.0 m) and the near-bed zone (about 2.0 m). The ADCP is unable to detect the water surface because of the draft of the four transducers and the blanking distance (Yorke and Oberg, 2002; Simpson, 2001). Side-lobe interference also prevents measurement of the layer close to the bed. This occurs when the side lobes of the acoustic beams strike the bottom before the main beams (Simpson, 2001), causing the instrument to record echoes from the bottom instead of those from the suspended particles in the water column. The boat-mounted ADCP transects have other unmeasured zones near the edges of the section, which were inaccessible due to the depth limitation. A detailed description of the algorithms used for the estimation of contribution from unmeasured zones is reported in Dredging Research Ltd. (2006).

The suspended solid transport (SST) derived from the solid flux time series was corrected for contributions of the unmeasured ADCP zones. This correction was computed for a test period by the SEDTRANS96 model (Li and Amos, 1997, 2001), coupled to the SHYFEM hydrodynamical model (Umgiesser et al., 2004, 2006). From the adjusted time series, the solid flux sedimentary budget was estimated for each inlet as well as the whole lagoon.

4. Results

The trend of the vertically averaged SSC concentration during the longest period of coincident acquisition by the three bottom-mounted ADCPs (February–April 2006) is represented in Fig. 2. This figure also shows, for each inlet, the vertically averaged axial current speed as well as wind components (u-eastward, v-northward). Wind speed and direction were recorded at the “Acqua Alta” oceanographic tower, situated about 8 nautical miles offshore from the Malamocco inlet.

The trends of SSC in the three inlets are very similar and are modulated by the semi-diurnal tide excursion and the spring–neap tidal cycle. The amplitude of SSC variations is, generally,

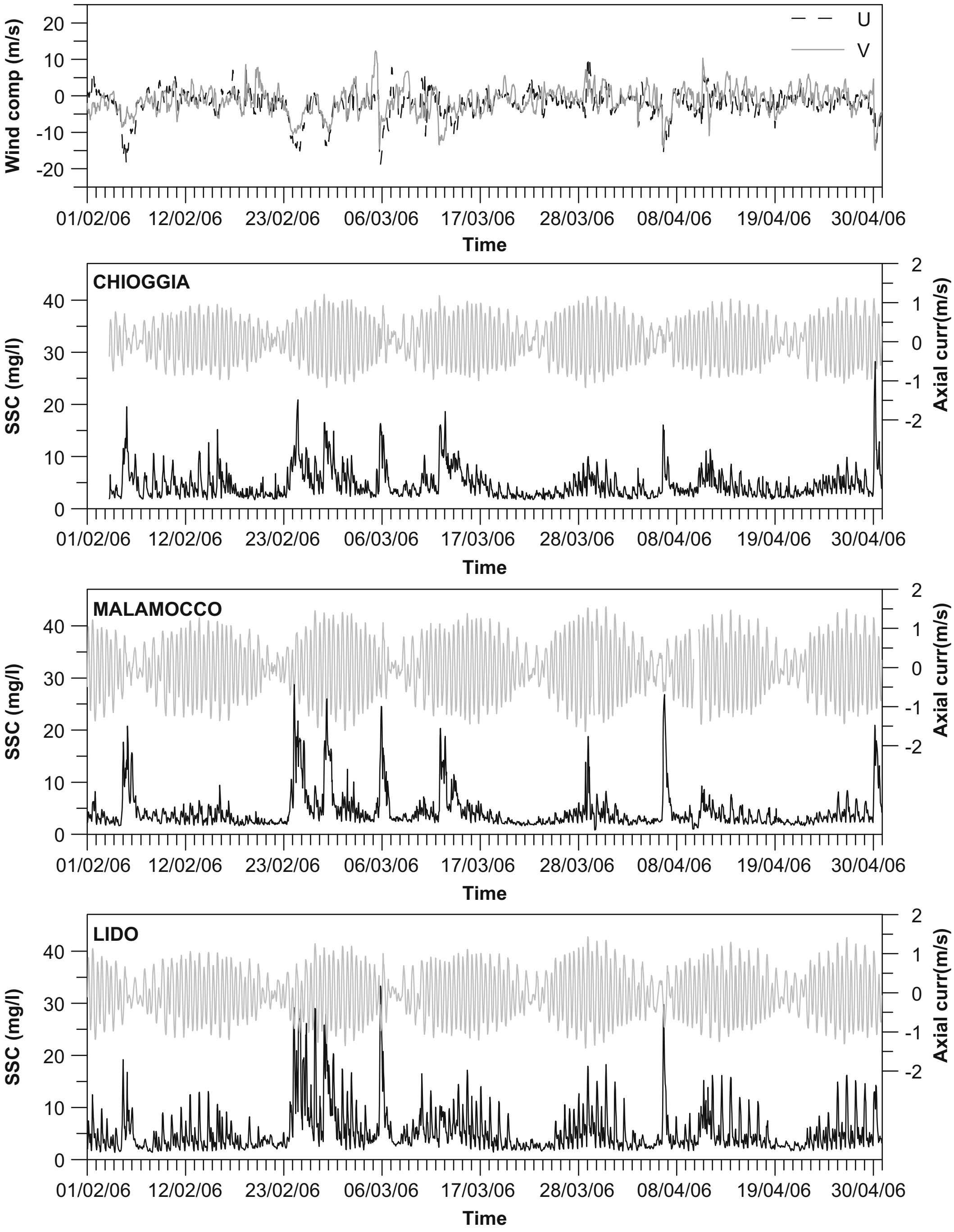

Fig. 2. February–April 2006: hourly time series of the vertically averaged suspended solids concentration (SSC) and axial current in the three inlets of the Venice lagoon. Wind components (u-east, v-north), measured at the “Acqua Alta” oceanographic tower, are also shown.

higher during spring tides and lower during neap tides. The most pronounced SSC peaks, particularly in the Lido inlet, correspond to meteorological events characterized by *bora* (north-easterly) winds. *Bora* storms are identified by a negative sign for both wind components and by wind intensities higher than 9 m/s. The time interval in Fig. 2 does not comprise particularly strong meteorological events. Three *bora* events in February (4–5 February 2006, maximum wind speed: 19 m/s; 23–25 February 2006, maximum wind speed: 17 m/s; 27–28 February 2006, maximum wind speed: 16 m/s), one in March (5–6 March 2006, maximum wind speed: 21 m/s) and one in April (6–7 April 2006, maximum wind speed: 21 m/s) can be distinguished. During these *bora* events similar concentration peaks were found in the Lido (min. SSC: 19 mg/l, 5 February 2006; max. SSC: 33 mg/l, 5 March 2006) and Malamocco inlets (min. SSC: 21 mg/l, 5 February 2006; max. SSC: 29 mg/l, 24 February 2006), while slightly lower concentrations were measured in the Chioggia inlet (min. SSC: 16 mg/l, 6 April 2006; max. SSC: 21 mg/l, 24 February 2006). None of these events had particularly important consequences for net (long-term) transport.

Frequency and duration of extreme meteorological events characterized the measurement period of November 2005–January 2006, shown in Fig. 3. This interval, for which only SSC time series of the Lido inlet is available, can be considered as an anomaly. The frequent *bora* events in December 2005 and January 2006 caused significant variations in the SSC. Both the average concentration for December (34 mg/l) and January (30 mg/l) are markedly higher than the average concentration on the whole measurement period (8 mg/l). Moreover, the peak values recorded during these 2 months are the highest found during the entire study. The two maxima are, respectively, 338 mg/l (11 December 2005) and 392 mg/l (23 January 2006). Both were measured during events characterized by persistence of intense *bora* winds (9–14 December 2005 and 23–28 January 2006).

Bora storms strongly influence the Lido inlet, accentuating the asymmetric spatial distribution of the solid load along the section. This feature is evident in Fig. 4, where a boat-mounted ADCP transect acquired on 13 December 2005 is shown. The experimental conditions were characterized by a spring flood tide (average axial current: −0.65 m/s) and intense *bora* winds with a maximum speed of 15 m/s. The solid load was mainly concentrated along the northern side of the section and peak concentrations were as high as 100 mg/l.

For the bottom-mounted ADCP of the Lido inlet, which has the most complete SSC time series, it is possible to analyze the trend of the differences between the SSC estimates derived from indirect and direct calibration of the acoustic backscatter, here indicated as CT and CC, respectively. This test was performed to evaluate the reliability of the CT indirect SSC estimates. Fig. 5 shows, as an example, the differences between the two estimates for December 2005. The trends of axial current and *bora* events with intensity higher than 9 m/s are also shown in the figure. The most significant differences between the two concentration estimates are, generally, found during the strongest *bora* events and spring tide conditions, during which the axial current is the highest. The highest peak (11 December 2005) is about 150 mg/l. A statistical analysis of the differences was carried out on some test periods. The results show that the two estimates are in good agreement beneath a threshold of 50 mg/l (unpublished technical report). This threshold was seldom exceeded (2.4% of the time). An analogous test was performed on the suspended solid flux estimates. Fig. 6 shows the comparison between the two solid flux estimates, obtained, from the boat- and bottom-mounted ADCPs for the entire monitoring period (November 2004–November 2007) in the Lido inlet. The two flux estimates are in good agreement ($R^2=0.93$). The best linear fit, reported in Fig. 6, diverges only slightly from the 1:1 line ($y=x$). The slope indicates a

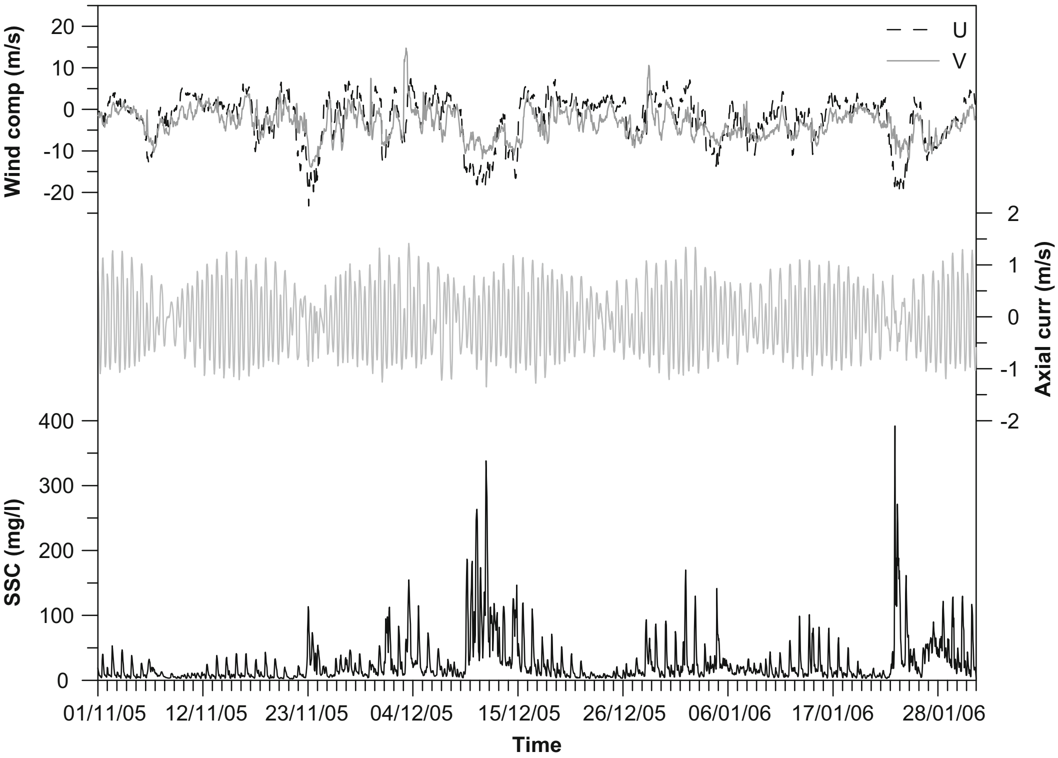

Fig. 3. November 2005–January 2006: hourly time series of the vertically averaged suspended solids concentration (SSC) and axial current in Lido inlet. Wind components (u-east, v-north), measured at the "Acqua Alta" oceanographic tower, are also shown.

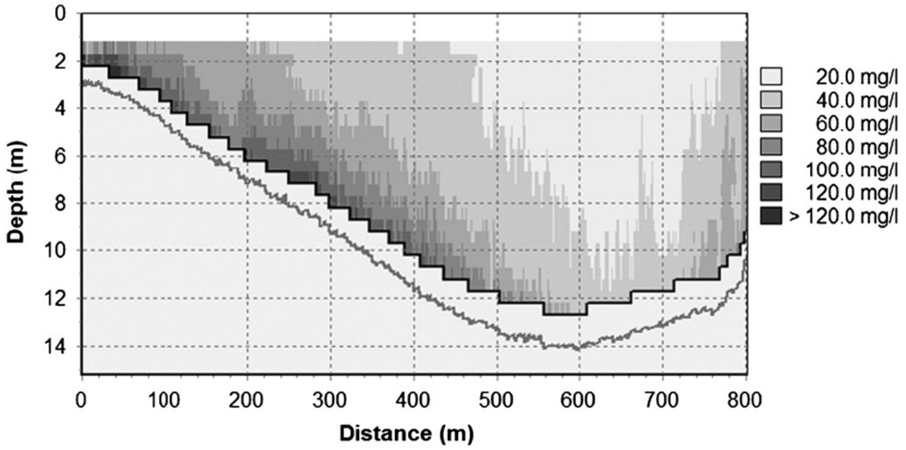

Fig. 4. Lido inlet, 13th December 2005, 18.29–18.35 UT: spatial distribution of the suspended solid concentration along the bottom-mounted ADCP section. The unmeasured layer near the water surface is indicated in light grey, that at the bottom is bounded by the side-lobe interference line (in black) and the bottom track (in grey). Experimental conditions: spring tide, inflowing current (average value: −0.65 m/s), *bora* wind (maximum speed: 15 m/s).

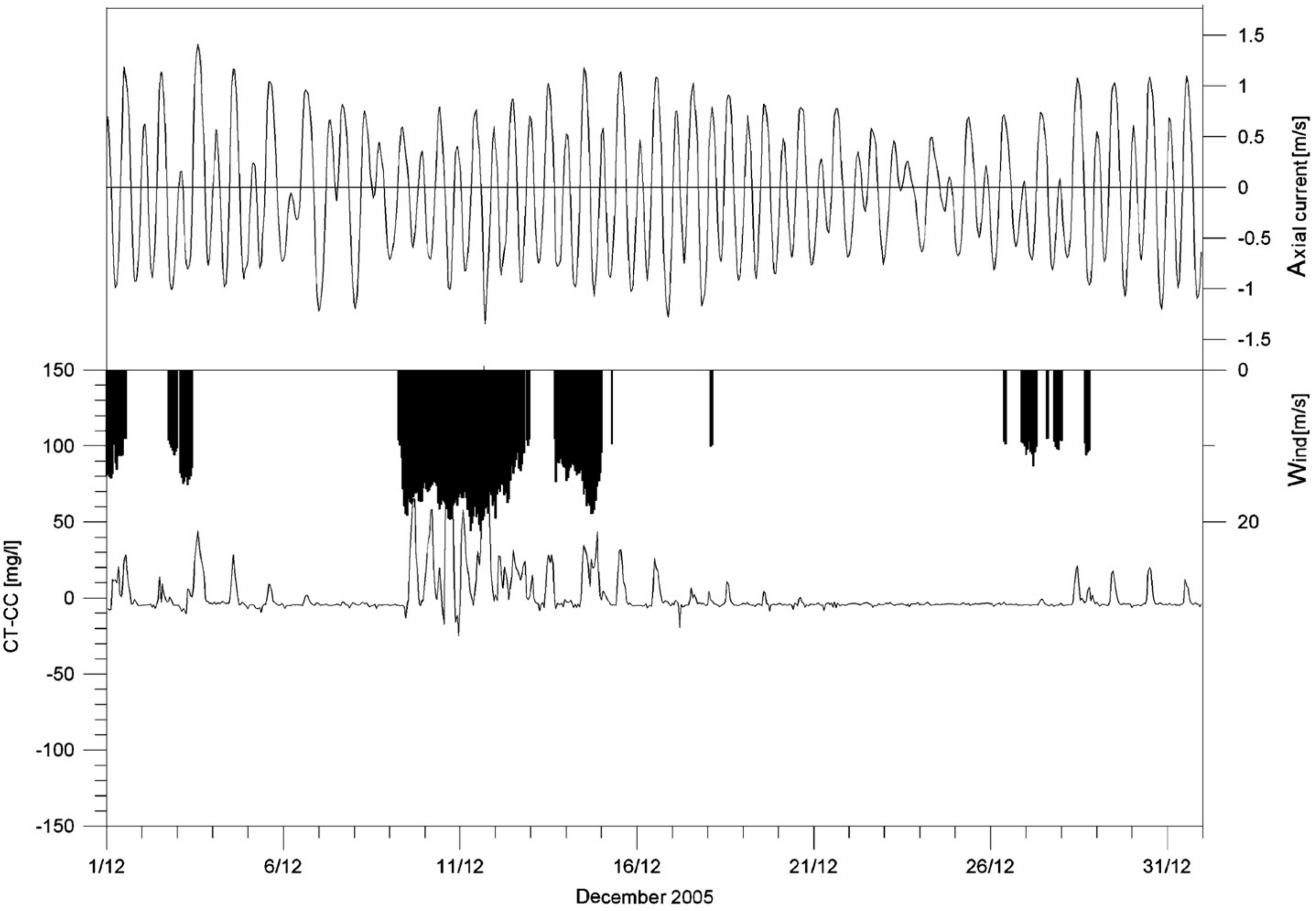

Fig. 5. Lido inlet, December 2005: trends of the differences between the two concentration estimates, CT and CC (lower panel, grey continuous line), *bora* wind events with wind speed higher than 9 m/s (lower panel, black histogram) and axial current (upper panel).

small tendency of the boat-mounted ADCP to overestimate relative to the fixed ADCP. There are, however, some cases in which the differences are larger. A statistical analysis of the relative differences between the two solid flux estimates was performed in order to investigate the occurrence of large deviations in the two estimates (unpublished technical report). The cases in which the solid flux by the bottom-mounted ADCP underestimated (negative sign) the boat-mounted ADCP fluxes are about 70% of the total number (356 data). One half of the underestimations are between 16% and 43%. The number of overestimations is lower (101 data) and half of them are between 8% and the 35%.

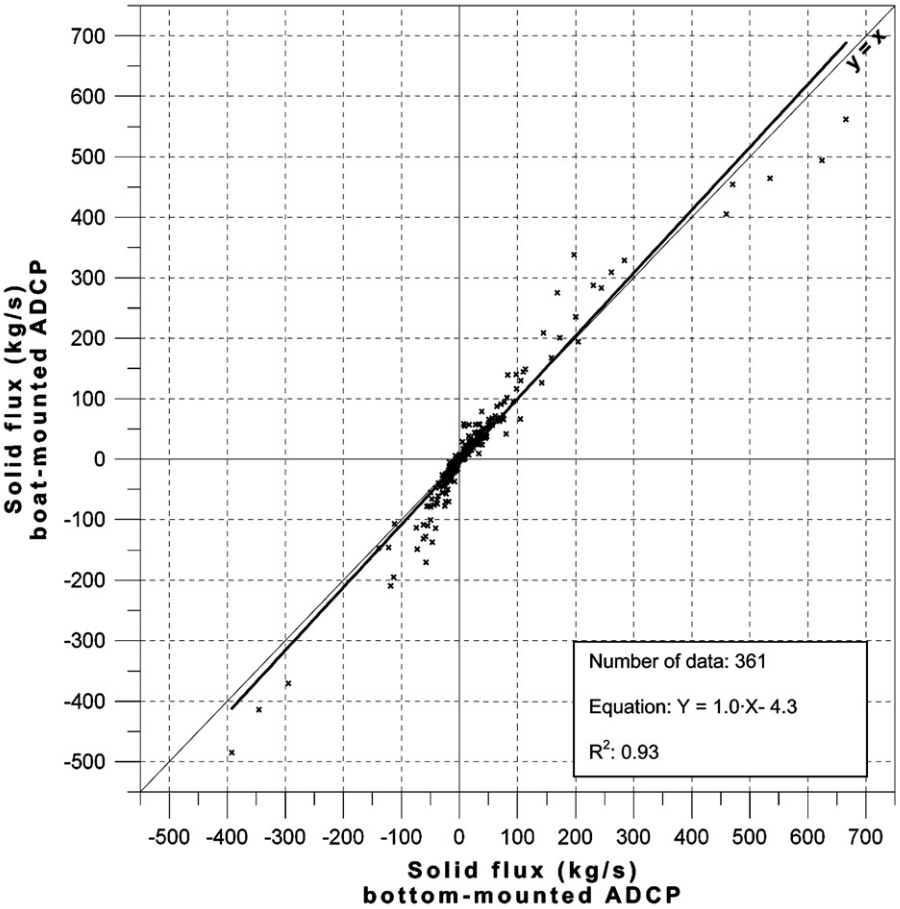

Fig. 6. Lido inlet: dispersion diagram between the two solid flux estimates obtained from the acquisition of the bottom- and boat-mounted ADCPs for the overall investigation period (November 2004–November 2007). The line of the best linear fit is depicted in black, while the theoretical 1:1 line is in grey.

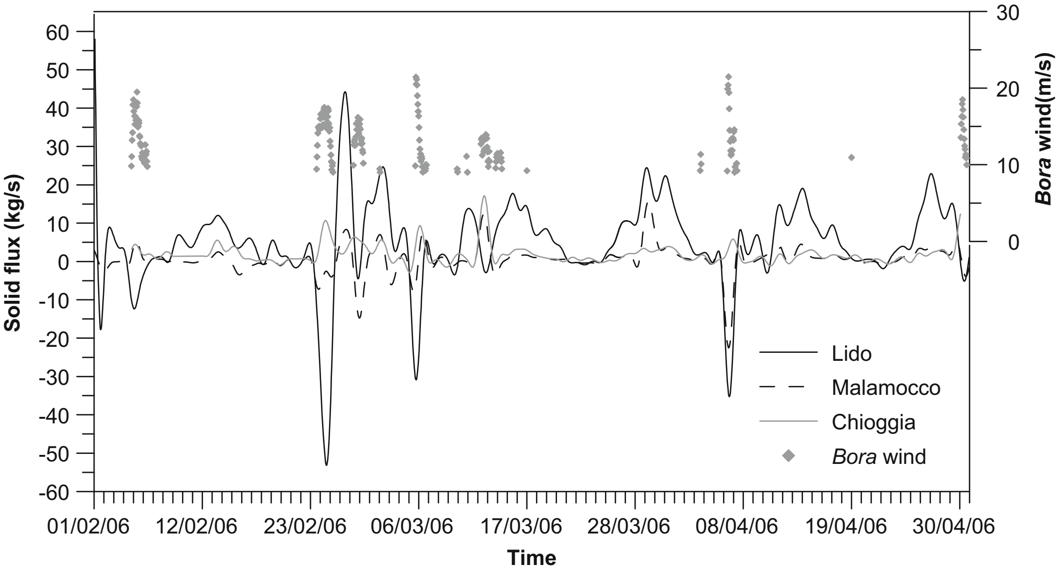

Fig. 7. February–April 2006: filtered hourly time series of the solid flux at the three inlets of Venice lagoon and *bora* wind events with speeds higher than 9 m/s.

The long-period trends, derived from the application of a low-pass filter (PL33; Flagg et al., 1976) to the solid flux time series, are presented in Fig. 7. The considered time interval is the longest period of simultaneous operation of the three fixed ADCPs (February–April 2006).

The solid flux is largely positive (outflow), with the highest values in the Lido inlet. There are also some negative peaks (inflow), which in some cases are larger than the maximum positive peaks. The most significant negative peaks were recorded on 24 February 2006 (Lido: −53.2 kg/s, Malamocco: −2.5 kg/s),

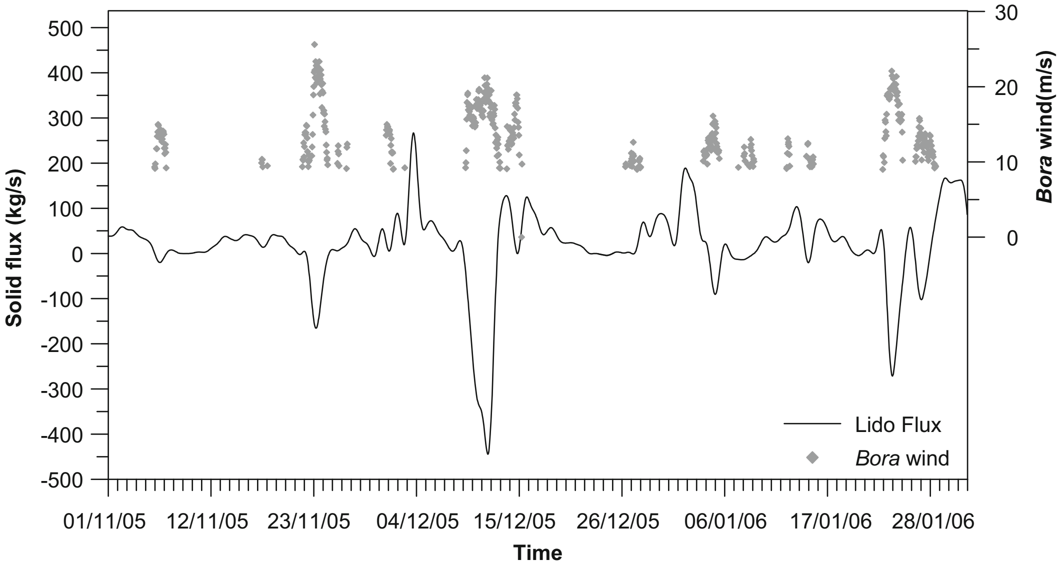

Fig. 8. November 2005–January 2006: Filtered hourly time series of solid flux at the Lido inlet and *bora* wind events with speed higher than 9 m/s.

5 March 2006 (Lido: -30.9 kg/s, Malamocco: -5.3 kg/s, Chioggia: -5.4 kg/s) and 6 April 2006 (Lido: -35.3 kg/s, Malamocco: -22.2 kg/s). The trends of the solid fluxes do vary between the three inlets.

Fig. 8 shows the filtered trend of solid flux in the Lido inlet, for the period of extreme meteorological conditions (November 2005–January 2006), previously presented in Fig. 3. Some very pronounced negative peaks (23 November 2005: -166 kg/s, 11 December 2005: -444 kg/s, 23 January 2006: -272 kg/s) are present in this interval. The December and January negative peaks occurred during periods characterized by several successive *bora* events with strong winds, often faster than 20 m/s (9–14 December 2005 and 23–28 January 2006). The highest positive peak, 267 kg/s, was recorded on 3 December 2005. The general trend of the solid flux for the entire period is positive, indicating outflow.

Yearly estimates of the lagoon sedimentary budget, obtained by the filtered time series of solid flux, are summarized in Table 1. The suspended solid transport (SST in Table 1), for the Lido inlet, was derived from the average of the filtered time series of solid flux in the period 2005–2006, which was the longest and most complete time interval of continuous measurement. The longest interval of simultaneous acquisition for the Malamocco and Chioggia inlets is the period February–April 2006. The ratio of the 2005–2006 and the February–April 2006 SST values was applied to adjust the Malamocco and Chioggia estimates, accounting for different extensions of the monitoring periods.

This operation compensated for the lower magnitudes of the Malamocco and Chioggia values, which were mainly caused by the relatively low frequency of storms during the February–April 2006 period. To evaluate the total suspended solid transport (SST* in Table 1), data were further adjusted. The total solid flux through the Lido inlet was derived by coupling the transport model SEDTRANS96 (Li and Amos, 1997, 2001) to the SHYFEM hydrodynamic model (Umgiesser et al., 2004, 2006). Then, the ratio of the simulated flux to the solid flux from the Lido Inlet time series was applied to the data. The simulation was limited to the period 19–21 September 2006. The estimate of the contribution of the bottom transport (BT in Table 1) was obtained, for the same test period, by the above mentioned models, using experimental data for the calibration. The yearly bedload component was then computed by applying the ratio of the integral of the suspended solid transport time series to the integral of the bedload transport time series, generated by the model. The uncertainty in the total solid transport was computed by means of a propagation of error, adding the products of the total error (sum of random error and bias) with correction factors for, respectively, SST* and BT.

Table 1
Yearly estimates of the sediment transport for each inlet (L: Lido, M: Malamocco, C: Chioggia) and for the lagoon (total): (a) tons and (b) cubic meters. The computation is based on a 2-year period (2005–2006, 739 days) for the Lido inlet, while the longest time interval (February–April 2006, 85 days) of simultaneous acquisition of the three bottom-mounted ADCPs is used for Malamocco and Chioggia.

(a)					
t/yr	SST	SST*	BT	TT	Error
L	283,543	340,252	44,233	384,485	12,968
M	35,131	42,157	5480	47,637	14,411
C	103,209	123,851	16,101	139,952	8632
Total	421,883	506,260	65,814	572,074	36,010
(b)					
m^3/yr	SST	SST*	BT	TT	Error
L	189,029	226,834	29,488	256,322	8645
M	23,420	28,104	3654	31,758	9607
C	68,806	82,567	10,734	93,301	5754
Total	281,255	337,506	43,876	381,381	24,007

SST: suspended sediment transport, SST*: suspended sediment transport corrected for the ADCP unmeasured zones, BT: bed-load transport, TT: total transport.

The results in Table 1 show that the total solid transport of Malamocco (48×10^3 t/yr) and Chioggia (140×10^3 t/yr) inlets corresponds, respectively, to about 12% and 36% of that of Lido (384×10^3 t/yr). The balance is equal to a total sediment loss of 5.72×10^5 t/yr (3.81×10^5 m^3/yr).

5. Discussion

The analysis of the time series, obtained from the evaluation of the fixed ADCP acquisitions, shows SSC and the solid flux to be controlled by two main forcings: hydrodynamics and meteo-marine conditions. The SSC and solid flux trends are clearly modulated by the tidal signal, in particular by the semi-diurnal tide and also by the spring–neap tidal cycle. The peak values of

SSC, generally, correspond to low water on spring tides. The effects of meteorological forcing, in particular *bora* winds, are noticeable. *Bora* can significantly affect resuspension along shores of the Northern Adriatic as well as shallow-water areas within the lagoon. It has, therefore, a strong influence on solid transport through the inlets. Both the time series of SSC and solid flux, particularly those of the Lido inlet, show marked peaks corresponding to the strongest *bora* events, as these occurred in the November 2005–January 2006 period. These events were defined by wind speeds higher than 9 m/s. Lido inlet is the one most affected by *bora* storms. The northern lagoon basin, which is drained by the Treporti Channel, the northeastern tributary of the Lido inlet, has the largest extension of mud-flats and marshes and is, therefore, more susceptible to resuspension by wind waves than other parts of the lagoon. The northern lagoon basin has also larger terrestrial inputs, which are discharged by the Dese River and the Silone Channel—the two main freshwater tributaries of the drainage basin (Zonta et al., 2005). A further significant source of suspended particles for the Lido inlet is the adjacent littoral. The construction of long jetties in the last century resulted in a progressive accretion of the beaches north of the Lido inlet (Cavallino and Punta Sabbioni), so the present coastline is now quite close to the head of the northern jetty (Helsby, 2008). The longshore transport of sand during *bora* storms can thus bypass the inlet and be transferred into the lagoon by flood tidal currents. Considerable amounts of fine sand and silt are thus transported along the northern side of the channel. They can eventually be deposited in the flood tidal delta or even in the channel, giving rise to the asymmetrical morphology observed in Fig. 4 (Helsby, 2008). This process is less evident in the other two inlets. The direction of net transport, in the case of intense storm events, is controlled by the tidal phase and wind direction. In the long term, the average solid flux is positive, indicating a tendency for loss of sediments from the lagoon. This trend is confirmed by an estimate of the lagoon sedimentary budget, computed after the validation of the SSC and solid flux time series. However, in some cases, influx can be dominant. Strong inflowing episodes are present only on the short time scale: (e.g. single events), as in the case of the transect shown in Fig. 4, where the flux of materials, coming from the shore north of the Lido inlet, tends to be concentrated along the northern breakwater.

The statistical analysis described in the results section showed that the uncertainty of the hourly Lido concentrations is about ± 3 mg/l. This value corresponds to the median of the standard deviations of each test period considered. Its magnitude reflects the peculiar morphology and behavior of the Lido inlet and should be lesser in the other two inlets. However, we assumed the other two inlets to have the same maximum uncertainty.

The tendency of the bottom-mounted ADCP is to underestimate the total solid flux. As in the case of the SSC estimates, the highest discrepancies between the two solid flux estimates occurred under extreme meteorological conditions.

The application of the PL33 low-pass filter (Flagg et al., 1976) to the solid flux time series eliminated variability at a temporal scale of less than 2 days (which is largely due to periodic oscillations of the diurnal and semi-diurnal tides, inertial oscillations and the seiches). The filtered time series confirm that the Lido inlet is mainly affected by *bora* winds. During the interval shown in Fig. 8 this wind caused a particularly high inflow. The flux at the Malamocco inlet displayed a similar behavior; however its magnitude was lower than that of Lido inlet. The solid flux for Chioggia inlet was mainly positive (outflow) and the direction did not, generally, correspond with that of the other two inlets.

Lido inlet has the highest residual transport. The lower values of the Malamocco and Chioggia basins are, probably, due to the differences in their present day morphology. Extensive erosion and loss of marsh habitats have occurred in the last few decades and a general deepening of the corresponding areas has resulted (Molinaroli et al., 2009; Sarretta et al., this issue). A significant amount of sediments, resuspended by wind waves and conveyed by tidal currents, can be transported into the artificial shipping channel, connecting the Malamocco inlet to the port and industrial area of Marghera. According to Molinaroli et al. (2009), the greatest changes in the morphology of the central lagoon (up to about 1 m deepening) occurred after the construction of this channel. These findings are confirmed by the large efforts of the local authorities in charge of dredging interventions to maintain the draft of the navigation channel. Dredging volumes are of the order of $10^6\,m^3$, thus comparable to the estimated yearly budget. Also the present large extension of sea grass meadows (mainly *Zostera* sp.) in the central and southern lagoon may inhibit further loss of sediments.

The sediment budget of the Venice lagoon, calculated on the basis of direct measurements of sediment transport, is comparable to the estimate obtained from the results of modelling studies. Tambroni and Seminara (2005, 2006), by applying a transport model based on the Engelund and Hansen (1967) relationship, estimated a total sand transport of about 1.6×10^5 t/yr ($0.8\times10^5\,m^3$/yr). Modelling and direct measurements give consistently lower estimates than the approaches based on the analysis of bathymetric differences (Pillon et al., 2003; Magistrato alle Acque di Venezia e Technital, 2007; Sarretta et al., this issue). The estimate proposed here considers the very recent past (2004–2007), while bathymetric studies account for the 1970–2002 period and thus cannot resolve any eventual recent reductions in the effects of erosion and transport processes.

6. Conclusions

The described research was focused on the reliability of ADCPs to monitor suspended sediment concentration (SSC) and solid flux and to estimate a sediment budget for the inlets of Venetian lagoon. Acoustic techniques have proven to be satisfactory as long-term monitoring tools of the sediment transport. Because of the availability of a large calibration data set, it was possible to calculate, for the first time, an extensive time series of SSC and solid flux.

The uncertainty in the SSC estimates is quite low (± 3 mg/l) confirming the efficacy of the tested approach. The statistical analysis of differences between the two solid flux estimates highlights a general tendency of the bottom-mounted ADCP to underestimate. This seems to be related to the peculiar morphology and hydrodynamics of the test section rather than to instrumental factors. The most significant deviations correspond to extreme meteorological conditions, characterized by *bora* winds. Although these events are relatively infrequent, they can strongly influence resuspension and transport processes, particularly in the Lido inlet.

The lagoon sediment budget, obtained by the integration of the solid flux time series, indicates a general tendency of sediment loss—an overall value of 5.7×10^5 t/yr (or $3.8\times10^5\,m^3$/yr). A comparison of the results between inlets shows that the net sediment transport for the Malamocco and Chioggia inlets is considerably lower than that of Lido.

The discrepancies between the estimates of the lagoon sediment budget based on direct measurements and those based on the analysis of the bathymetric changes seem to be related to the different time scales considered by the two methodologies. Since the approach presented herein considers the recent past (2004–2007), it is possible that the present trend is characterized by a reduction of sediment loss. This could be related to the relatively low sediment yields from the central and southern basins of the lagoon, as a result of the past morphological changes.

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