MODELING THE TIDE INDUCED WATER EXCHANGES BETWEEN THE VENICE LAGOON AND THE ADRIATIC SEA

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Riassunto.

In questo lavoro un modello idrodinamico bidimensionale basato sul metodo degli elementi finiti è stato applicato per analizzare gli scambi d'acqua che avvengono attraverso le tre bocche di porto della Laguna di Venezia.

Il modello risolve le equazioni Shallow Water su un dominio spaziale che descrive l'intero mare Adriatico e la Laguna di Venezia mediante una griglia agli elementi finiti con risoluzione spaziale variabile.

Il modello è stato calibrato attraverso il confronto con i dati sperimentali di livello mareale provenienti da 20 stazioni di misura disposte internamente alla laguna di Venezia e lungo le coste del mare Adriatico.

Il modello calibrato è stato quindi utilizzato per simulare la propagazione della marea astronomica all'interno del dominio di indagine.

Quindi i flussi d'acqua attraverso le tre bocche di porto sono stati analizzati e i risultati confrontati con misurazioni effettuate mediante sonda elettroacustica ADCP posizionata all'interno delle bocche di porto.

Abstract.

A 2D hydrodynamic model of the Venice Lagoon and the Adriatic Sea has been developed. The model is based on the finite element method. It solves the shallow water equations on a spatial domain constituted by a staggered finite element grid. The grid represents the Adriatic Sea and the Venice Lagoon with different spatial resolutions varying from 30 m for the smallest channels of the lagoon to 30 km for the inner areas of the central Adriatic Sea.

Empirical measurements collected by more than twenty tide gauges displaced inside the Venice Lagoon and the Adriatic Sea have been used in the different calibration process. After the calibration, the tidal wave propagation in the North Adriatic and in the Venice Lagoon is well reproduced by the model.

The water exchanges through the three inlets of the Venice Lagoon has been analysed. To validate the model results, empirical data measured by ADCP probes installed inside the inlets of Lido and Malamocco have been considered.

1. Introduction.

The lagoon of Venice is a complex and unique environment both for the ecological aspects and for the beauty of its landscape. In the last decades due to the increased frequency of the flooding events and to the deterioration of the water quality, more research has been focused to control and preserve the hydrologic and bio-geo-chemical characteristics of the lagoon.

The city of Venice is an island situated approximately in the center of the lagoon with other important islands in the southern or in the northern part (Fig. 1) The lagoon is connected to the Adriatic Sea through inlets which guarantee the water exchange with the open sea. The southern and the central inlet (Chioggia and Malamocco, respectively) are about 500 meters wide whereas the northernmost inlet (Lido) is nearly 1000 m wide. The maximum depth is around 8 m for Chioggia and 14 meters for Malamocco and Lido.

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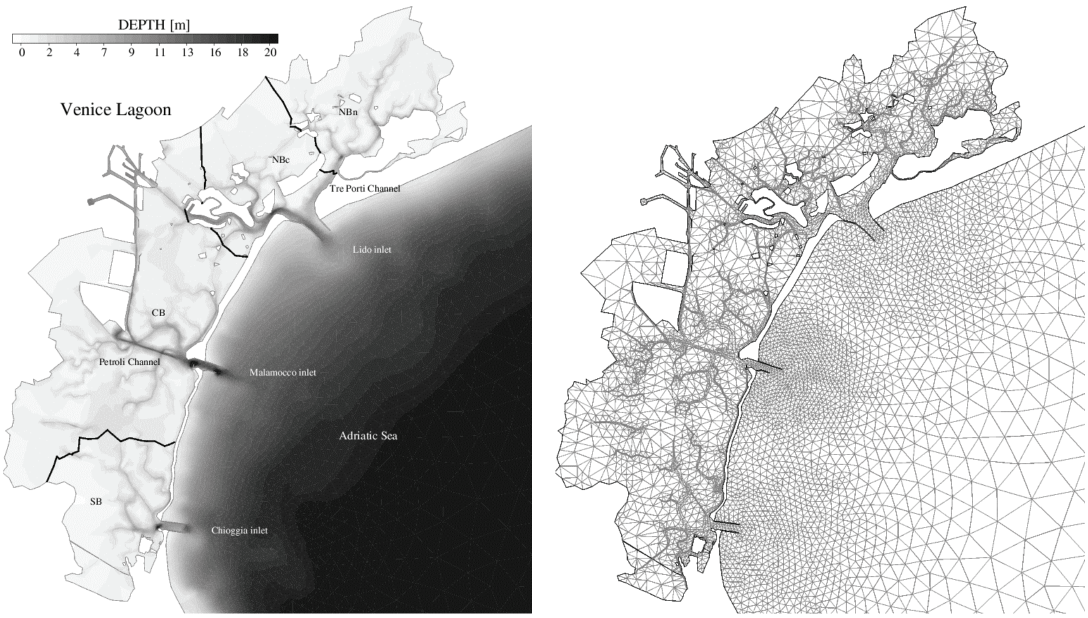

Fig. 1 – Bathymetry (left panel) and finite element grid (right panel) of the Venice Lagoon and Gulf of Venice, a subset of the numerical domain of the model.

The inlets have undergone major changes in the second part of the 19th and the first part of the 20th century. Due to silting up of the entrances only small boats could pass in this period. Therefore jetties have been constructed that reach 2-3 km into the

Adriatic Sea and that gave the inlets the shape and morphology that can nowadays be observed.

It might be surprising that, even with the importance that the inlets have to the Venice lagoon, no major studies have been carried out that try to measure or describe the exchange and its mechanisms through the inlets. Two modeling studies deal with this subject. The first one is a tentative by [Umgiesser, 2000] to understand the residual currents due to the most prominent wind regimes found in the northern Adriatic. It uses a finite element model [Umgiesser and Bergamasco, 1993; 1995] that is able to capture most of the bathymetric details inside the lagoon. This study modeled also the residual currents of a complete year [1987]. The other study [Bergamasco *et al.*, 1998] applied the POM model]Blumberg and Mellor, 1987; Mellor, 1991] to the lagoon and parts of the Adriatic Sea and used the resulting hydrodynamic current field to run a simple eutrophication model consisting in phytoplankton and macronutrients, forced also by water temperature and light intensity.

Both approaches suffered from main deficiencies. Both models could not be validated with data because flux measurements were not available at the inlets. Moreover, the second study applied the POM model with a 1200 m grid size that is to coarse to resolve the important hydrodynamic features of the Venice lagoon. On the other side, the first study used a calibrated model for the water levels inside the lagoon with good resolution of the channel system (due to its finite element method), but failed to describe well the interface dynamics, since the model domain ended exactly at the inlets.

In the year 2000 an interdisciplinary project has been started by the Consortium for Coordination of Research Activities Concerning the Venice Lagoon System (CORILA) that aims to investigate the exchange mechanisms between the lagoon and the Adriatic Sea, both by measurements of fluxes and biochemical parameters at the inlets, and by the application of models that can be validated through these field campaigns. During this project bottom mounted Acoustic Doppler Current Profilers (ADCP) have been installed at the three inlets and the data has been analysed (Gacic *et al.*, 2002). This is the first time that good current and flux measurements are available for the Venice lagoon inlets.

This article is concerned with the modeling aspects of this project. The model used is a 2D hydrodynamic finite element model, the same as in Umgiesser [2000]. However, the model domain now comprises not only the Venice Lagoon, but also the whole Adriatic Sea, in order to move the open boundary as far away as possible from the area of interest. In this study the model is calibrated with harmonic constants of tidal data available at stations around the Adriatic Sea and just o side the Venice Lagoon. The fluxes computed at the inlets are then validated with the astronomical contribution of the measured ones.

2. Methods.

In this section the equations and the construction of the model and the numerical grid are described. After that a summary about the available data (sea surface elevation and ADCP data) is given. Finally we described the general simulation set-up and the model calibration process followed to reproduce the tides in the Adriatic Sea.

2.1. The hydrodynamic model.

For this application a finite element hydrodynamic model developed at ISMAR-CNR (Istituto di Scienze Marine) has been used [Umgiesser and Bergamasco, 1993; 1995]. This model has already been applied successfully in its 2D version to the Venice lagoon [Umgiesser, 2000; Melaku Canu *et al.*, 2001; Umgiesser *et al.*, 2004] and in its 3D version to the Adriatic Sea [Umgiesser and Bergamasco, 1998].

The finite element method is especially well suited for the application to the Venice Lagoon with its narrow channels that run between large flat shallow areas. It gives the possibility to faithfully follow these channels, reducing the grid resolution in other areas that are less important for the propagation of the tidal wave. It also gives the possibility to increase the resolution close to the inlets and move the open boundary further away, reducing numerical disturbances close to the zone that is under investigation.

The model is here applied in its 2D version. The focus of this paper is an investigation of the water exchanges between the lagoon and the Adriatic Sea. In the lagoon, due to its shallow character and the relatively high tides (50 cm during spring tide) stratification can develop only far from the inlets where the tidal energy is lowest. Inside the inlets, the water velocities are high (over 1 m/s) [Gacic *et al.*, 2002], and therefore the velocity shear creates enough turbulence to mix the water. It must be noted that the exchanges between the lagoon and the sea are mostly driven by the tide and the wind action, and are therefore essentially barotropic in nature. The baroclinic contribution is in this case a minor one.

The model uses finite elements for horizontal spatial integration and a semi-implicit algorithm for integration in time. It resolves the vertically integrated shallow water equations in their formulations with levels and transports The terms treated implicitly are the water level gradient and the Coriolis force in the momentum equation and the divergence term in the continuity equation. The friction term is treated fully implicitly for stability reasons due to the very shallow nature of the lagoon. All other terms are treated explicitly. The model is unconditionally stable what concerns the fast gravity waves, the bottom friction and the Coriolis acceleration [Umgiesser and Bergamasco, 1995].

The equations read:

$$\frac{\partial U}{\partial t} - fV + gH\frac{\partial \varsigma}{\partial x} + RU + F_x = 0 \quad (1)$$

$$\frac{\partial V}{\partial t} + fU + gH\frac{\partial \varsigma}{\partial y} + RV + F_y = 0 \quad (2)$$

$$\frac{\partial \varsigma}{\partial t} + \frac{\partial U}{\partial t} + \frac{\partial V}{\partial t} = 0 \quad (3)$$

where ζ is the water level, U and V the vertically-integrated velocities (barotropic transports) in x and y direction,

$$U = \int_{-h}^{\varsigma} v \partial z \qquad V = \int_{-h}^{\varsigma} u \partial z \quad (4)$$

g is the gravitational acceleration, H = h + ζ the total water depth, h the undisturbed water depth, t the time, f the Coriolis parameter and R the friction term. The terms X and Y contain all other terms like the wind stress, the nonlinear advective terms and those that are treated explicitly in the time discretization.

The friction term has been expressed with a standard bulk formula:

$$R = \frac{c_b}{H}\sqrt{u^2 + v^2} \tag{5}$$

with c_b the value of the bottom friction coefficient. This term can be assumed either as constant with the standard value for oceanographic applications of 2.5×10^{-3} or dependent on the depth through the Strickler formula:

$$c_b = \frac{g}{c^2} \qquad c = k_s H^{1/6} \tag{6}$$

with C the Chezy coefficient and Ks the Strickler coefficient.

At the open boundaries of the domain the water levels are prescribed while at the closed boundaries the normal velocity is set to zero and the tangential velocity is a free parameter. This correspond to a full slip condition.

The model allows also for flooding and drying of the shallow water flats. This is especially important for the Venice lagoon, since about 15% of the area is partially wet and dry during a spring tidal cycle. The flooding and drying mechanism has been implemented in a mass consistent way, and spurious oscillations that are generated by are damped out fast.

2.2. The numerical grid.

In the studies mentioned before the numerical grid consisted of either the lagoon of Venice alone [Umgiesser, 2000; Melaku Canu *et al.*, 2001; Umgiesser *et al.*, 2004] or the Adriatic grid alone [Umgiesser and Bergamasco, 1998]. The bathymetric information for the lagoon has been collected from the regional charts that have been compiled in 1970 with some interpolations in the 1990s. For the bathymetry of the Adriatic Sea the global data base of the National Ocean and Atmospheric Administration (NOAA, link to www.ngdc.noaa.gov/mgg/bathymetry/relief.html) has been used with the resolution of the gridded data of 1/12 of a degree.

These two available grids have been merged together in order to construct a unified grid of the Adriatic Sea and the Venice lagoon. The areas close to the inlets have been re-gridded, in order to guarantee a smooth transition of the two grids. The resulting grid consists of 10948 nodes and 20013 triangular elements (Fig. 1 and Fig. 2).

For the bathymetry of the inlets and the areas around it new data collected by the Consorzio Venezia Nuova (CVN) in the 1992 during the project VENICE and provided by CORILA has been used. These data consist of depth values on a regular grid with a resolution of 50 m inside the inlets and of 300 m just outside the inlets in the Adriatic Sea. The data has been interpolated together with the old data in a transition zone in order to not create sharp gradients with the older grids.

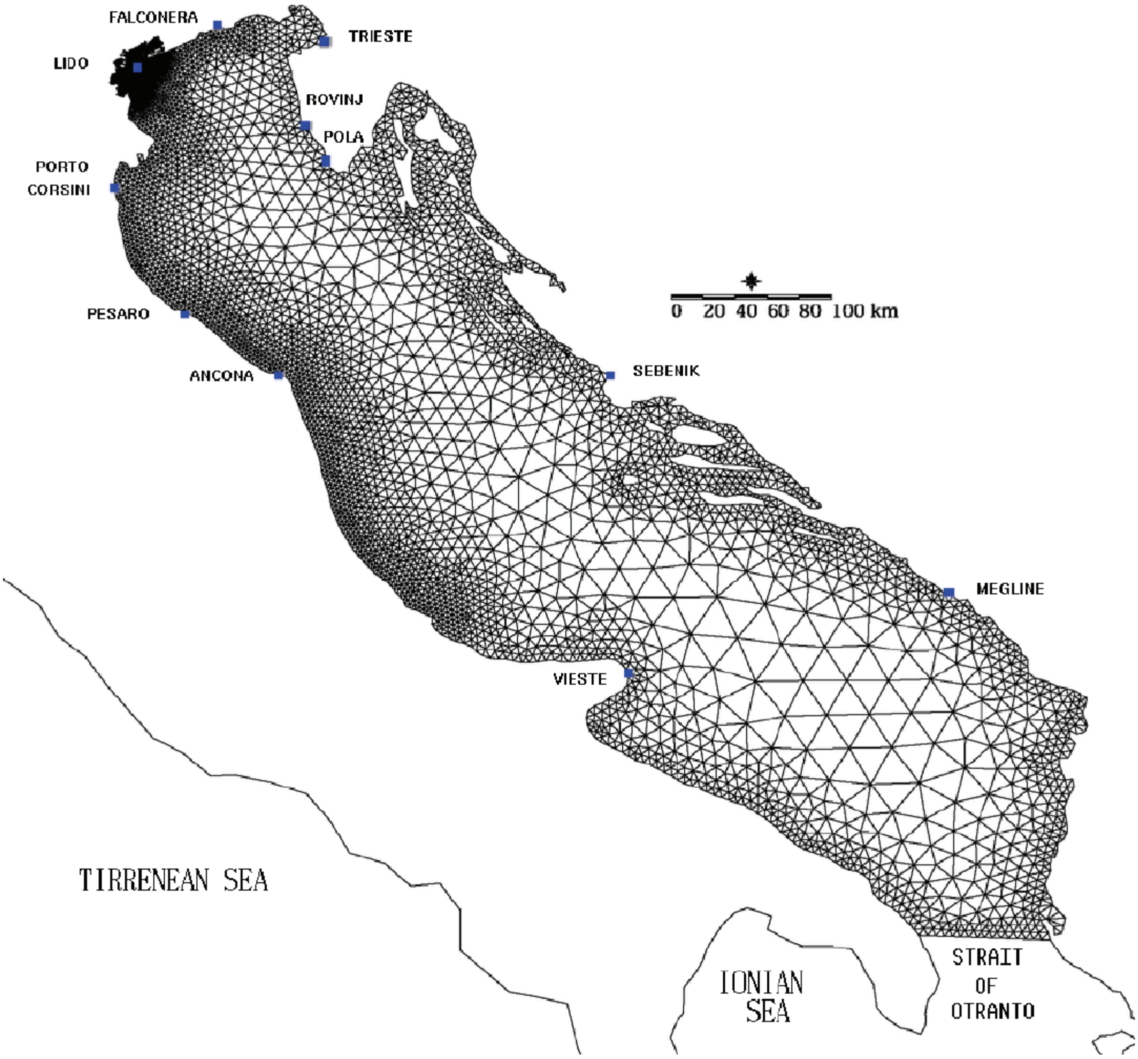

Fig. 2 – The numerical domain of the Adriatic Sea and the location of the tide gauges considered during the calibration process.

The open boundary has been chosen as a straight line across the strait of Otranto (Fig. 2). This seems a logical choice for the Adriatic Sea, because on one side the boundary is far away from the investigated area of the inlets and on the other side the strait of Otranto is the narrowest part of the whole Adriatic Sea. This parametrization was suggested by the results obtained in a previous work by Malacic *et al.* [2000]. In that case the open boundary was chosen between Pesaro and Kamenjak in the Northern part of the basin close to the Venice Gulf. From the model calibration the worst results were obtained just for the stations located in the western part of the basin close to the Venice Lagoon (Venezia-Lido, Malamocco and Porto Corsini), which is the studied area of the present work. Therefore the location of the open boundary conditions far away from the investigated area was considered. Moreover the adopted parametrization is the same followed by Cushmain-Roisin and Naimie [2002] even if, in that case, the model, based also on the finite element method, was used in the 3D version with a horizontal resolution varying from 16 to 2 km. Since the description of the vertical stratification of the water column is not the aim of the present work, the use of a two-dimensional model is considered as suitable [Malacic *et al.*, 2000].

2.3. The available data.

In this work two different sets of measured data have been considered both to calibrate the model and to corroborate the simulation results. The first dataset concerns the amplitude and the phase of the main tides that dominate the sea surface elevation (SSE) of the Adriatic Sea. The second one contains the discharge data through the three lagoon inlets measured by ADCP probes.

23.1. Water level data.

The Adriatic sea is a basin characterized by moderate tides. The highest amplitudes are found in the Northern sub-basin (extending from the line connecting Pesaro to Kamenjak to the northern coast) where the amplitude of the M2 frequency reaches 0.266 m.

Tidal observations in the Northern sub-basin have been collected from the middle of the 18th century. For some stations the length of the water level records is more than 100 years (Trieste, Venezia-Lido, Rovinj). The most important tidal constituents are M2, S2, K1, N2, K2, O1 and P1 [Polli, 1960]. For these tidal constituents amplitude and phase values have been derived from the tide gauge measurements in stations along both the western and eastern coast [Polli, 1960; 1961; Mosetti, 1987].

In Tab. 1 the harmonic constants of the most energetic semidiurnal and diurnal tides (M2, S2 and K1) are reported for the stations chosen as calibration points for the tidal simulations of the Adriatic sea (Fig. 2).

For what concerns the tides in the Venice lagoon, measured data of amplification and delay of the main diurnal and semidiurnal constituents with respect to the Diga Sud Lido tide gauge are reported for many stations inside the lagoon by Goldmann *et al.* [1975]. This dataset has been considered for the calibration of the model to reproduce the tidal propagation in the Venice lagoon [Umgiesser *et al.*, 2004].

2.3.2. The flow rate ADCP data.

The ADCP data at the inlets were collected in the framework of the CORILA project that started in January 2001. The program includes 2 years of simultaneous current measurements in all three lagoon inlets. The aim of these measurements is to study the time-dependent variability of the inlet currents as well as of water exchange rates.

The current data have been collected using bottom-mounted ADCP installed in each inlet. Current speed and direction along the water column are recorded every 10 minutes with a vertical resolution of 1 meter in selected locations inside the inlets.

Tab. 1 – Comparison between model results (m) and observations (o) of the amplitude H and phase g of the most energetic tidal constituents (M2, S2 and K1) at the eleven tidal stations in the Adriatic Sea.

Site	Constituent	H_m [cm]	H_o [cm]	H_m - H_o [cm]	$(H_m - H_o)/H_o$ [%]	g_m [deg]	g_o [deg]	g_m - g_o [deg]
Lido	M2	23,4	23,4	0	0	295	291	3
	S2	14	14	0	0	303	298	5
	K1	17,6	17,6	0	0	84	77	7
Falconera	M2	23,1	24	-0,9	-6	289	289	0
	S2	13,9	14	-0,1	-1	290	297	-7
	K1	18,3	18,3	0	0	82	79	3
Trieste	M2	28,2	26,6	1,6	7	289	276	13
	S2	17,3	16	1,3	9	292	284	8
	K1	19,3	18,6	0,7	4	83	70	13
Porto Corsini	M2	14,3	15,6	-1,3	-5	305	303	2
	S2	8,2	9,2	-1	-6	307	310	-3
	K1	16,5	15,9	0,6	-3	89	81	8
Rovinj	M2	16,9	19,3	-2,4	-12	273	270	3
	S2	10	11,2	-1,2	-11	273	277	-4
	K1	16,9	16,1	0,8	-5	76	71	5
Pula	M2	12,9	15,1	-2,2	-14	261	265	-4
	S2	7,5	8,7	-1,2	-13	259	273	-14
	K1	15,9	15,5	0,4	2	82	69	13
Pesaro	M2	9,7	12,8	-3,1	-24	316	311	5
	S2	5,4	6,8	-1,4	-20	318	313	5
	K1	15,3	15,4	-0,1	-1	92	84	8
Ancona	M2	3,7	6,6	-2,9	-43	9	332	37
	S2	2,1	3,5	-1,4	-40	27	347	40
	K1	12,7	13,2	-0,5	-4	104	88	16
Sebenik	M2	11,3	6,3	5	80	121	135	-14
	S2	7,5	4,4	3,1	70	120	132	-12
	K1	8,99	9,3	-0,4	-3	69	57	12
Vieste	M2	11,2	9,4	1,8	20	104	105	-1
	S2	6,9	6	0,9	15	105	115	-10
	K1	4	5,1	-1,1	21	99	91	8
Megline	M2	11,3	9,1	2,23	24	100	99	1
	S2	6,8	5,9	0,9	16	99	103	-4
	K1	4,3	5	-0,7	-14	67	52	15

During a preliminary phase, measurement campaigns have been carried out to estimate the relationship between the vertically-averaged water velocity collected by the fixed ADCP and the inlet flow rate. About 100 ship-borne ADCP surveys were conducted to estimate the water inflow and outflow through each inlet both during spring and neap tide. Comparing the discharge results with the average vertically velocity collected by the bottom mounted ADCP for the same period, the parameters of a linear correlation function has been calculated [Arena and Arcari, 2001]. Therefore, the flow rate is available every 10 minutes applying the calculated linear regression formula to the vertically integrated measured current values [Gacic *et al.*, 2002].

On June 17, 2001 the continuous current record started inside Lido and Malamocco inlet. At Chioggia the measurements started only one year later, on May 8, 2002.

2.3.3. ADCP data processing and usage.

From the harmonic analysis of the ADCP discharge time series collected at the Malamocco inlet during the period between June 17, 2001 and July 29, 2001 it was found that the signal is mainly due to the principal tidal components less than a residual of about 4% of total amplitude due to meteorological forcing (wind and pressure). This result is expected, since the ADCP data refers to the summer season. In fact, during this period, intense meteorological events generally do not occur and the wind variation is characterized mainly by a sea breeze diurnal cycle which contribution to the total flow is extremely difficult to separate from the tidal one [Gacic *et al.,* 2002].

A different situation is the winter period, in particular those months characterized by the acqua alta (high tide) events. An example is given by the November 2001 discharge time series (Fig. 3). This data set, being collected during a period of exceptional high tides, contains a strong signal caused by wind and pressure forcing. Therefore the average contribution of the residual components, during the whole month, is very high with a top value of residual flow measured in the Malamocco inlet of about 5300 m^3/s (the astronomical contribution to the flow rate can reach up to 10000 m^3/s inside this inlet).

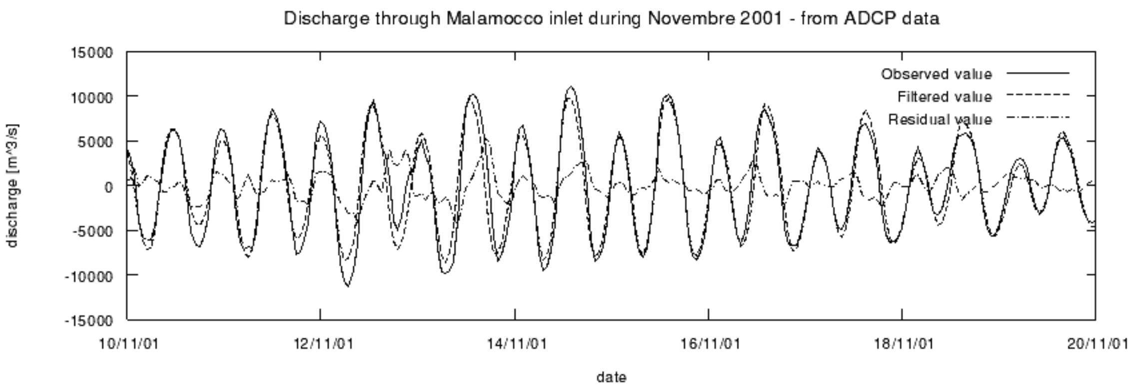

Fig. 3 – Discharge time-series through the Malamocco inlet, derived from ADCP data, for a 10 days period during November 2001. Observed, tidal signal and residual values.

Even if the meteorological contribution can affect strongly the dynamics of the water exchanges, it has not been considered in this work. In fact, the residual water level in the Adriatic sea and the related residual flow through the lagoon inlets are generated by the intense meteorological phenomena that occur in this area. To reproduce their effect on the water circulation, hydrodynamic models are forced with wind and pressure data that covers the whole Adriatic Sea. These data are the result of atmospheric numerical models (i.e., ECMWF global meteorological model) and generally strongly underestimate the real meteorological status [Cavaleri and Bertotti, 1996], especially in the Venice Gulf, where the meteorological phenomena are more intense at the synoptic scale. This can be considered the main cause of error for the storm surge models used to forecast the exceptional high tide in the Venice Lagoon that carries a strong contribution to the residual water circulation.

A storm surge finite element model has been set up and made operative at the Venice Municipality [Canestrelli *et al.*, 2003] with the aim of forecasting the water level elevation generated by the meteorological action (the residual water level). The results obtained by forcing the model with the ECMWF meteorological data set (wind direction and intensity and pressure values every 6 hours over the whole Mediterranean sea with a spatial resolution of half a degree) are in good agreement with other forecast models of the area, but are still not good enough for a reliable water level forecast and for a computation of the exchange rate through the inlets in extreme meteorological situations.

Therefore in this work only the contribution of the tide to the flow rate through the inlets has been considered. The model has been set up and calibrated to simulate the tidal wave propagation in the Adriatic Sea and in the Venice lagoon. To validate the model results, only the tidal signal of the measured discharge data has been considered.

Harmonic analysis is therefore applied to the ADCP data collected at Lido and Malamocco inlet during the period between September 1st, 2001 and December 31st, 2001. The contribution of the seven major tidal components to the total flow rate -M2, S2, K2, N2, O1, P1, K1- was obtained and the parameters related to these constituents are presented in Tab. 4.

2.4. The general simulation set-up.

All simulations presented in this work have been carried out using a time step of 300 seconds. This time step could be achieved due to the unconditionally stable time integration scheme of the finite element model.

As forcing the SSE is prescribed at the open boundary of Otranto. In this work tidal constituents M2, S2, K1, N2, K2, O1 and P1 are imposed. During the calibration, the empirical amplitudes and phases of the single tidal constituents at Otranto were modified. No variations of these values across the open boundary line was considered.

A spin up time of 30 days has been used for the model runs. This value has been found by numerical simulations carried out to test the sensitivity of the model to different forcing conditions. A simulation has been run for two months with only the M2 tide as forcing at the open boundary. From the water level results, the spin up time is calculated. It is the time over which the difference between consecutive water level maxima is less than 1% with respect to the tidal excursion. This time is enough to damp out basically all the noise that has been introduced through the initial conditions.

No meteorological forcings, such as wind pressure and heat fluxes are considered. The baroclinic contribution of the fresh water input released inside the basin by the main Italian rivers is also not taken into account. All of these processes are neglected because the focus of this work is to reproduce the barotropic tidal contribution to the Lagoon-Sea water exchange only.

As mentioned in section 2.1, the bottom boundary condition enforces quadratic friction based on barotropic (depth-averaged) velocity according to the classical quadratic drag law. In this application two formulations for the bottom friction coefficient C_b have been considered. For the deeper areas of the domain (Adriatic Sea) the coefficient it is imposed to be constant with value of 2.5x10^3. However, in the shallow parts (Venice Lagoon) it has been set up as dependent on the depth through the Strickler formula. In particular, inside the lagoon, different areas have been distinguished, such as channels, tidal flats, inlets etc., and different values of C_b have been computed in these areas by varying the Strikler coefficient in the Chezy formula (6) [Umgiesser *et al.*, 2004].

2.5. Model calibration.

The model has been calibrated to reproduce the harmonic constants in the Adriatic Sea and, more specifically, in the gulf of Venice. The first step in this model calibration is to seek a match between the model results and the sea level data measured by the 11 stations chosen along the coast-line of the Adriatic Sea (Fig. 2).

Starting from the harmonic constants (amplitude and phase) of the main semidiurnal constituent (M2) given for the Otranto station by Polli [1960], we prescribed pre-calculated SSE values as open boundary condition in the model. A first set of calibration runs is then carried out. The duration of these simulations is 120 hours after the spin-up time. The calculated SSE values for all the 11 stations are then compared to the observations and the differences with the real data are minimized by varying the tidal constants at Otranto.

Once an accordance between the model results and observations at Diga Sud Lido station has been found, the other semidiurnal and diurnal main constituents have been considered separately, and further calibration runs have been carried out.

Finally, a complete SSE with all the 7 main tidal frequencies has been prescribed at the open boundary of Otranto and the harmonic constants have been varied until the gaps with the real data at Diga Sud Lido station were close to zero. These calibration runs have been extended to 8760 hours (1 year), a time that is sufficient to separate the K2 and S2 frequencies in the harmonic analysis [Foreman, 1996]. The coupling of all the main tidal constituents is necessary because of the non linear e ect of the bottom friction that links the components between both in terms of retarding e ects and amplification.

We assume that the calibrated harmonic constants at Otranto are representative for the SSE along the whole open boundary line of the strait of Otranto. This is because we do not have any exact information about the tides on the Eastern side of the strait and the variation of the SSE along the boundary is unknown. This shortcoming could in principal overcome by using larger models, that include the Ionian Sea and are able to reproduce the SSE along the strait of Otranto [Cushmain-Roisin and Naimie, 2002]. Otherwise in the previous work of Malacic *et al.* [2000] the harmonic constant of the main tidal components were known both on the western and eastern side of the boundary line in the northern Adriatic. These informations allowed the use of parametric polinomial functions to reproduce the SSE along the boundary line. In this case the calibration process was based on the varying of the SSE polynomial function parameters. Due to these shortcomings we expect the results for the Southern Adriatic to be less satisfactory, which could be combined also by the results.

The second step in the model calibration is to reproduce the propagation of the tide inside the Venice lagoon. This step can be tackled separately from in the Adriatic Sea, since tidal level in the lagoon does not really influenced the one in the open sea. For the explanation of the method we refer to Umgiesser *et al.* [2004] and to Solidoro *et al.* [2004].

3. Results.

In this section the model results are presented. In the first part, the model calibration results are compared with the available harmonic data. In the second part, the fluxes through the lagoon inlets are computed and compared with the ADCP data.

3.1. Tidal simulations.

In this simulation the propagation of the main tides in the Adriatic sea is reproduced. The calibrated model is forced with SSE values at the open boundary of Otranto and then the results are compared with the real data from stations along the Adriatic sea and inside the Venice lagoon.

In Tab. 2 the set of harmonic constants obtained from the model calibration and the discrepancies with the initial values given by Polli [1960], are shown. For what concerns the amplitude of the main frequencies (M2, S2 and K1), the tides imposed as forcing at the open boundary of Otranto overestimates the empirical data by values always lower than 24%. Moreover an average difference of about 20 degrees is detected for what concerns the phase. From these harmonic constants the SSE values to be imposed as open boundary conditions at Otranto have been constructed.

Tab. 2 – Open boundary condition. Comparison between the amplitude H and phase g of the main tidal constituents of the SSE imposed as forcing along the open boundary of Otranto (m) and the observed values (o) at this stations.

Constituent	H_m [cm]	H_o [cm]	$H_m - H_o$ [cm]	g_m [deg]	g_o [deg]	$g_m - g_o$ [deg]
M2	8.1	6.5	1.6	103	110	-7
S2	4.4	4	0.4	104	116	-12
N2	1.4	1.2	0.2	103	104	-1
K2	1.4	1.7	-0.3	80	118	-38
K1	2.6	2.5	0.1	42	83	-41
O1	1.2	0.7	0.5	51	58	-7
P1	1	0.8	0.2	33	72	-39

In Tab. 1 the amplitudes and the phase lags of the main semidiurnal and diurnal tides (M2, S2 and K1) are compared to the observations along the coast of the Adriatic sea (for locations see Fig. 2).

As we could expect the calibrated model reproduces the SSE at Diga Sud Lido station with high accuracy. In Tab. 3 the harmonic constants of the whole set of tides are reported for this station. For what concerns the elevations, no discrepancies with real data can be noted.

The phase differences of the most energetic constituents (M2, S2 and K1) are always less then 7 degrees. The highest phase lag of 10 degrees has been found for the N2 frequency, which contribution to the total tide is the weakest of all the constituents considered. What concerns the rest of the domain, we can assume that the area of interest, far away from the open boundary, is the Northern Adriatic Sea which is limited in the South by the line connecting Pesaro to Pula. The stations located in this area are Falconera, Porto Corsini, Trieste, Rovinj, Pesaro and Pula.

Tab. 3 – Comparison between model results (m) and observations (o) of the amplitude H and phase g of the whole set of tide at Diga Sud Lido stations.

Constituent	H_m [cm]	H_o [cm]	g_m [deg]	g_o [deg]
M2	23,4	23,4	295	291
S2	14	14	303	298
N2	3,9	3,9	298	288
K2	4,2	4,2	289	294
K1	17,6	17,6	84	77
O1	5,4	5,4	64	64
P1	6	6	72	72

The results obtained for the stations close to the Venice Gulf, Falconera and Porto Corsini are in good agreement with the empirical data. The SSE o shore the Venice lagoon is in fact reproduced with an error always lower than 6% for the amplitude of the main tides and with a phase difference not higher than 8 degrees. These results are in accordance with the main task of this work which is the reproduction of the fluxes through the three lagoon inlets.

A first look at the other stations inside the Northern sub-basin, (Trieste, Rovinj, Pesaro and Pula) reveals that the phase discrepancies are always lower than 14 degrees. For what concerns the amplitudes, the worst results are obtained for Pesaro with an underestimation of the M2 and S2 tides of about 24% and 20% respectively. For the same station and frequencies, Cushmain- Roisin and Naimie [2002] underestimates the real data by 16% and 12%. The last three stations (Trieste, Rovinj and Pula) present differences in the amplitude with respect to the real data always lower than 15%. In particular in all the cases the results show an underestimation of the semidiurnal components and an overestimation of the diurnal ones. An exception is given by the Trieste station which values overestimate the real data both at the semidiurnal and diurnal frequencies. In particular slightly better results than in Cushmain-Roisin and Naimie [2002] have been found for this station especially for the amplitude of the most energetic tides (an underestimation of 8% both for M2 and K1 in Cushmain-Roisin and Naimie [2002] against 7% and 4% respectively in this work). As we can see in Fig. 4 the differences of the semidiurnal amplitudes (M2 and S2) present a similar trend which tends to zero approaching to the Diga Sud Lido station. Better results can be found in the diurnal frequency band where the amplitude for the stations of the Northern sub-basin is reproduced by the model with an error always lower than 10%.

The southern part of the domain, that comprises the Central and the Southern Adriatic sea, is strongly affected by the imposed boundary condition and in this work is not taken into account. Nevertheless a brief digression can be done about the results obtained for the stations of Ancona and Sebenik. Even if not located closed to the open boundary, the results for these stations show strong discrepancies with respect to the real data, especially for what concerns the semidiurnal tides. This can be partially explained by the vicinity to the semidiurnal amphidromic point [Polli, 1961]. In fact the tidal excursion in this area is very weak especially at the semidiurnal frequencies and this gives rise to higher relative errors both for the water level computation and for the harmonic analysis.

What concerns the model results about the propagation of the tide inside the Venice lagoon we always refer to Umgiesser *et al.* [2004] for a more accurate description.

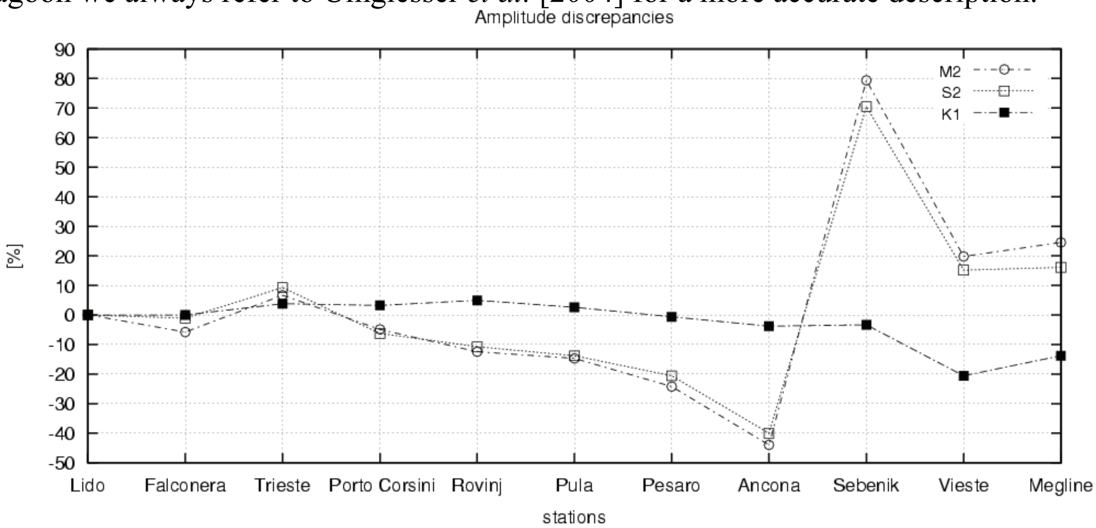

Fig. 4 – Relative difference between model and observed values of the amplitude of M2, S2 and k1 tidal constituents at the eleven stations in the Adriatic Sea.

3.2. Flux data validation.

Once the model has been calibrated with the water levels, it has been used to estimate the water exchange through the three inlets when only the tide drives the circulation between the two basins. A tidal simulation of 152 days long has been carried out. The open boundary condition was derived by the calibration process as explained above (see section 2.5). The SSE values are imposed at the open boundary of Otranto to reproduce the expected tides in the Adriatic sea in the period between September and December 2001. Computed fluxes have been compared with ADCP data measured inside the Lido and Malamocco inlet. In the following the results of the comparison are given.

The duration of the simulation and the period investigated is the same that is covered by the ADCP data. The harmonic analysis is applied both to the measured flux data and to the Malamocco and Lido inlet discharge time series obtained by the model. In Tab. 4 the amplitudes and the phases of the most energetic frequencies (M2 and K1) are given and compared with ones derived from the real data. As we can see in all cases the model overestimates the real data. At Lido inlet the differences in the phase are about 7% for the M2 and 6% for K1. The results for Malamocco inlet are lightly worse at the diurnal frequency K1 (9%) while quite similar to the previous case at the semidiurnal frequency M2 (7%). What concerns the phases, the model results show a general delay with respect to the real data. At Lido, the M2 frequency shows a time delay of about 16 minutes while, for the diurnal frequency K1, the time delay is about 11 minutes. At Malamocco the discrepancies are more marked than at the Lido particularly for the diurnal component which shows a delay of about 40 minutes, whereas the M2 component shows a delay of about 30 minutes.

Tab. 4 – Water discharge of the Lido and Malamocco inlet. Comparison between empirical data (o) (derived from ADCP measurements) and model results (m) of the amplitude H and phase g of the most energetic diurnal and semidiurnal frequencies (M2, and K1).

Inlet	Constituent	H_m [cm]	H_o [cm]	$H_m - H_o$ [cm]	$(H_m - H_o)/H_o$ [%]	g_m [deg]	g_o [deg]	$g_m - g_o$ [deg]
Lido	**M2**	5209	4813	396	7	219	227	-8
	K1	2508	2347	161	6	272	275	-3
Malamocco	**M2**	4830	4509	321	6	251	266	-15
	K1	2180	1973	207	9	288	301	-13

At the most energetic frequencies, M2 and K1, the model reproduces the variability of the water exchange through the two inlets with an accuracy of what concerns the amplitude values better than 90% and with a phase error always lower than 15 degrees.

To investigate the contribution to the sea-lagoon water exchange of the complete tide, the computed discharge time series has been compared with the real data. In Fig. 5 the empirical and the modeled fluxes due to the tide trough Lido and Malamocco inlet are plotted. The time series shows only the month of November 2001, a sub-sample of the whole data set used for the analysis.

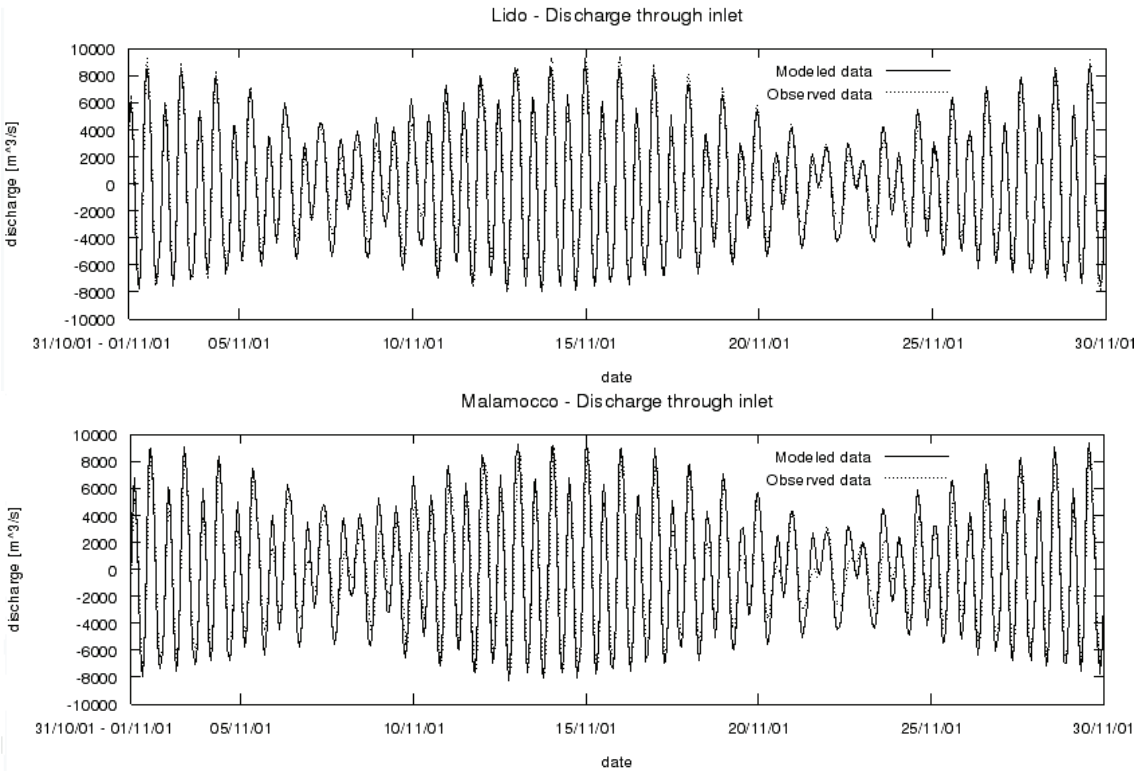

Fig. 5 – This plot shows the time-series of the fluxes through the Lido and Malamocco inlet derived from ADCP data and obtained by the model simulation for the period of November 2001.

Both for Lido and Malamocco, the correlation index with the real data is high: 0.98 and 0.94 respectively. The computed values present a delay with respect to the empirical ones in both cases. At Lido a time lag of about 20 minutes has been estimated. At Malamocco, the derived time lag is a little larger (about 30 minutes). As we expected by the previous results, the worst case has been found for Malamocco. Moreover, for Lido, the combined effect of the whole set of tides has increased the phase-displacement initially detected for the M2 and K1 constituents only, from 10 minutes to 20 minutes.

The intensity of the discharge rates is generally overestimated by the model both for Malamocco and Lido inlet. If the time series is adjusted with respect to the phase lag, the model results show an overestimation of 13% at Malamocco and 8% at Lido.

To explain the differences with the empirical data we can distinguish two different groups: one related to the measured data and one related to the numerical model.

The empirical discharge data, as explained in section 2.3, have been obtained from the vertically averaged water velocity value measured by ADCP probe for a fixed location inside each inlet. From the velocity value the discharge rate through each inlet has been extrapolated. The described method is suitable especially to measure tidal only flow. When the discharge rate is affected by high residual flow generated by intense meteorological events, such as during the period that we consider, the measurements are subjected to an adjoin uncertainty which is not known.

Further source of error for the empirical data, is related to the harmonic analysis. In fact, due to the high residual signal that affects the discharge rate data, the amplitude and the phase values obtained for each main tidal constituents from the harmonic analysis, are subjected to high relative errors.

What concerns the model, a source of error can be related to the reproduction of the SSE outside and inside the inlets. The discharge rate through the inlet is dependent on the SSE gradient along the inlet channel and therefore the accuracy of the SSE inside and outside the Lagoon strongly affects the model results. This error can not be easily assessed but the high sensitivity of the accuracy of the computed discharge values with respect to the SSE values can be realistically be assumed.

Finally, the use of recent bathymetric data to reproduce the morphology of the Venice Lagoon and the inlets could reduce the error of the model what concerns the reproduction of the SSE inside the lagoon basin and consequently of the discharge rate through the inlets.

Conclusions.

Before this study, no major studies have been carried out that try to measure or model the exchange and its mechanisms through the Venice Lagoon inlets. The object of the present work is to reproduce by numerical modeling the water exchange dynamic through the three lagoon inlets. Before this study, no major studies have been carried out that try to measure or model the exchange and its mechanisms through the Venice Lagoon inlets. The object of the present work is to reproduce by numerical modeling the water exchange dynamic through the three lagoon inlets.

With this aim we implemented a 2D hydrodynamic model of the Adriatic Sea and the Venice Lagoon based on the finite element method. The spatial resolution of the model varies from 50 meters inside the Venice Lagoon inlets to 20 km in the middle of the Adriatic Sea, with a transition zone between the open sea and the lagoon characterised by a 300 meters resolution. The open boundary has been chosen as a straight line across the strait of Otranto.

In this application the model was used in the barotropic mode to reproduce the discharge rate through the lagoon inlets driven by the action of the tide only. Along the open boundary line the tidal SSE is imposed. No other forcings such as wind and pressure have been considered, only the tide drives the water circulation inside the two basins.

The model has been calibrated to reproduce the tidal propagation in the Adriatic Sea and in the Venice Lagoon. The parameter to be varied during this process was the SSE along the open boundary line of Otranto and the bottom friction coefficient inside the Venice Lagoon basin. For the validation the model results have been compared to empirical data of harmonic constants collected in 24 stations located along both the west and the east coast of the Adriatic Sea and inside the Venice Lagoon. In this article only the results referred to the tidal propagation in the Adriatic Sea are reported. The tidal dynamic inside the Venice Lagoon and the results of the related calibration process is treated Umgiesser *et al.* [2004].

What concerns the tide, the model reproduces the set of harmonic constants for the Diga Sud Lido station, with an error always less than 1% for what concerns the amplitude and with a maximum phase lag of 7 degrees for the most energetic tidal constituents (M2, S2 and K1). The results obtained for the other stations close to the Venice Gulf, are also in good agreement with the empirical data. The SSE o shore the Venice lagoon is in fact reproduced with an error always lower than 6% for the amplitude of the main tides and with a phase difference not higher than 8 degrees. These results are in accordance with the task of this work which is the reproduction of the tidal flow through the three lagoon inlets.

Finally the water fluxes through the inlets have been computed by the model when only tide is forcing the basin. The results have been compared with empirical data of water discharge derived from ADCP measurements collected inside each inlet. The model reproduces the fluxes through the inlets with an average overestimation of about 10% with a time delay of about 25 minutes.

The success of these simulations on the reproduction both of the SSE inside and outside the Venice Lagoon and of the tidal flow through the lagoon inlets indicates that the finite element model is performing adequately on the barotropic mode. Therefore this model can be realistically considered as a fundamental support for studies that aim to investigate the nutrients, salinity or pollutants budgets of the lagoon and their exchange with the open sea. In the future it is desirable to integrate also the meteorological component in the forcings in order to describe the residual flow through the inlets adequately.

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