An operational forecasting system for the sea level in Venice based on a finite element hydrodynamic model

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Abstract

The center for tidal level forecast and signalling (Centro Previsioni e Segnalazioni Maree - CPSM) is an office of the Venice Municipality, founded in 1981 with the aim to study and forecast the storm surge events that recurrently cause the flooding of the historical center of Venice. In collaboration with the Sea Science Institute of the National Research Council (ISMAR-CNR) in Venice, a new operational forecasting system for the sea level in Venice has been set up. The system is based on using a deterministic numerical model instead of a statistical one, now in use at the CPSM. A 2-D hydrodynamic tide-surge model based on finite element method developed at ISMAR-CNR is used to compute the sea level elevation in the Mediterranean Sea. The model is forced with both wind and pressure fields provided by the European Centre for Medium- Range Weather Forecasts (ECMWF). To validate the model three surge events that occurred during November 1997, November 2000 and November 2001 are studied. The simulations are carried out forcing the basin with ECMWF post-processed meteorological data sets. The model results are compared with elevation data from tide gauges located outside the Venice Lagoon. The storm surge elevation computed by the model shows a similar behaviour with respect to empirical data except for the cases where the ECMWF wind field is underestimated compared to real data collected at a platform off the Coast of Venice

1 Introduction

In the last century the city of Venice has seen an increase in the frequency and intensity of the flooding events that periodically submerge parts of the old center. These floodings pose a threat not only to the artistic and cultural heritage, but also to the economic assets and the environment.
To be able to counteract these floodings the city of Venice and the Italian government have decided to invest in the safeguarding of Venice through the planning and building of flood barriers, the raising of the pavement level and the general cleaning up from pollution of the lagoon. Especially for these flood barriers, but also as a means of protection for the inhabitants the city needs a good forecasting system for the water level.

At the moment this system consists in a statistical model that has been calibrated with the historical time series of the primary tide gauge station, Punta Salute, now operating for over a century. This forecasting system is predicting the water level in the lagoon using some tide gauge and meteorological stations along the Adriatic Sea.
However, the time frame for the validity of the statistical model results is quite limited. The forecast of water levels for more than a day does not seem reliable. The municipality of Venice has therefore started some projects in order to assess the feasibility of deterministic storm surge models that will be able to produce good forecasts for more than just a day.
This work is one of these projects that have been started as a collaboration between the Venice Municipality and the Venitian institute of the National Research Council (ISMAR-CNR). In this case the model set up uses the wind fields of the European Center for Medium-Range Weather Forecasts (ECMWF) in Reading to produce its forecast of the water level in Venice.
This article describes the first results that have been achieved with this storm surge model. Three test cases are analysed and discussed and the operational model is described in detail.

2 Numerical model

To reproduce the water level set-up induced by the meteo-marine forcing in the Adriatic a 2D finite element hydrodynamic model of the whole Mediterranean Sea has been implemented. The model has been forced over the whole domain with the wind and pressure dataset provided by the ECMWF global atmospheric model.

2.1 The storm surge finite element hydrodynamic model

In this application, a 2D storm-surge hydrodynamic model of the Mediterranean sea, based on the finite element method, has been used (Umgiesser et al., 1993; Umgiesser et al., 1995; Umgiesser, 2000; Cucco et al., 2003; Umgiesser et al., 2003). The numerical computation has been carried out on a spatial domain that represents the entire Mediterranean Sea through a finite element grid. The grid contains 10495 nodes and 18626 triangular elements (figure 1). The model considers as open boundary the Gibraltar channel, elsewhere as closed boundary the whole perimeter of the basin. The model resolves the vertically integrated shallow water equations in their formulations with levels and transports:

$$\frac{\partial U}{\partial t} - fV + gH\frac{\partial \zeta}{\partial x} + RU + X = 0 \tag{1}$$

$$\frac{\partial V}{\partial t} + fU + gH\frac{\partial \zeta}{\partial y} + RV + Y = 0 \tag{2}$$

$$\frac{\partial \zeta}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 \tag{3}$$

where ζ is the water level, U and V the vertically-integrated velocities (total or barotropic transports), g is the gravitational acceleration, $H = h + \zeta$ the total water depth, h the undisturbed water depth, t the time R the friction term and f the Coriolis parameter, which is variable. The terms X and Y contain all other terms like the wind stress and the nonlinear advective terms. The wind stress is computed in the quadratic formulation:

$$\tau_x = \frac{\rho_a}{\rho_0} C_D |u| u_x \tag{4}$$

$$\tau_y = \frac{\rho_a}{\rho_0} C_D |u| u_y \tag{5}$$

where ρ_a, ρ_0 is the density of air and water respectively, u the modules of wind speed and u_x, u_y the components of wind speed in x and y direction. In this formula C_D is a dimensionless Drag coefficient that has to be considered constant over the whole domain:

$$C_D = 2.5 \times 10^{-3} \tag{6}$$

The wind speed is directly specified for each element of the domain as the horizontal components of the wind velocity. At the open boundary the water levels are prescribed in accordance with the Diriclet condition, while at the closed boundaries only the normal velocity is set to zero and the tangential velocity is a free parameter. This correspond to a full slip condition.

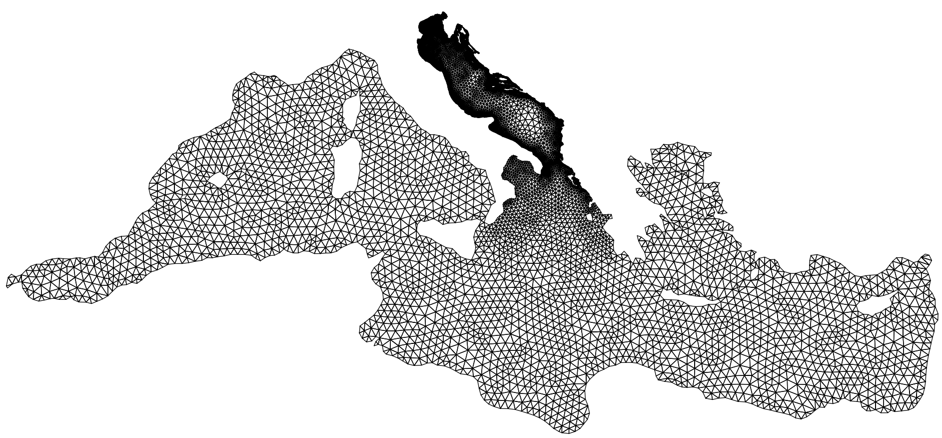

Figure 1: Grid of the hydrodynamic finite element model for the Mediterranean sea.

2.2 Meteorological forcing

The model has been forced with the wind and pressure field dataset produced by the atmospheric global model of the ECMWF. The data have been provided by the Italian Air Force. The atmospheric model is a spectral global model that is able to simulate the dynamics occurring at different atmospheric layers. The meteorological data used in this study concern the wind and pressure fields that govern atmospheric motion of the bottom layer, about 10 m above the average sea level. The dataset covers the whole investigated area, between 6° W and 37° E and between 30° N and 48° N. The wind components and the pressure value are given for each point of a 0.5° spacing regular grid. The time spacing of the meteorological data is synoptically scaled with 4 fields a day, one each 6 hours. The wind speed and the pressure values are given in m/s and $Pascal$ respectively.

3 Model results

Extremely high sea levels that occurs in the northern Adriatic coast (known as Acqua Alta) are primarily caused by four major forcing components: tides, synoptic and lower time scale meteorological

disturbances (storm surge and seiches) (Beltrami et al. 2002, Cerovêcki, et al.,1997, Tomasin et al. 1999), water level oscillations induced by planetary atmospheric waves and seasonal processes (Pasariĉ et al. 2000). In particular, the synoptic scale meteorological forcing, that generates the strong southerly wind (scirocco), and the basin free inertial oscillations (seiches), have to be considered the primary causes of the Acqua Alta phenomenon (Wakelin et al., 2002).
While the astronomical contribution (tides) is well reproducible all over the Adriatic Sea, the meteorological components and their correlation with the peak water level events (Acqua Alta phenomenon) are still not well known and easy to reproduce by numerical modeling. Therefore the model simulations have been focused to reproduce the water level setup induce by the meteorological forcing (residual water level).
To validate the model three surge events that occurred during November 1997, November 2000 and November 2001 are studied. The astronomic contribution has been neglected in the numerical simulation, no water level has been imposed to the Gibraltar open boundary. The basin have been forced with ECMWF wind and pressure data only to reproduce the residual water level in the northern Adriatic sea. 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 scheme of the finite element model. A spin up time of 10 days has been always used for the simulations. This time was enough to damp out all the noise that has been introduced through the initial conditions. The model results are compared with residual elevation data obtained from tide gauge measurements located 16 km off the Venice Lagoon coastline in the Oceanographic Platform Acqua Alta (PCNR) of the National Research Council.

3.1 November 1997

During November 1997 the Diga Sud Lido tide gauge located at the northern inlet, outside the Venice Lagoon, measured 8 high tide events higher than 100 cm, of which 2 events, occurred at November 11 and 12 reached the level of about 112 and 119 cm respectively (figure 2). The peak events are grouped in the first half of the month between the 5^{th} and the 15^{th} day. During this period an intense lowering of the atmospheric pressure associated to a planetary scale meteorological perturbation preconditioned the basin coastal floods. In the same period, the synoptic scale meteorological disturbances and the basin resonance generated the water level peak events.
In figure 3 the comparison between the residual water level model results and the experimental data is reported. While the long period residual level oscillation is well reproduced by the simulation results, the daily excursion signal, induced by the strong scirocco wind event and the seiche action are generally underestimated by the numerical results.
The statistical parameters of the two series (table 1) are in accordance with the previous consideration: a good agreement between the model and the experimental time series average value (0.24 m for the measured time series and 0.23 for the modeled one) and an underestimation of the peak events that is well evidenced by the different standard deviation (0.14 for the experimental data and 0.12 for the modeled results) and top water levels value in the two cases (0.69 for the experimental data and 0.59 for the modeled results). Considering the daily excursion (see figure 3), the underestimation of the model results with respect to the experimental data is more evident. The correlation index between the two datasets is 0.89 that indicates a low difference between the two time series phases.

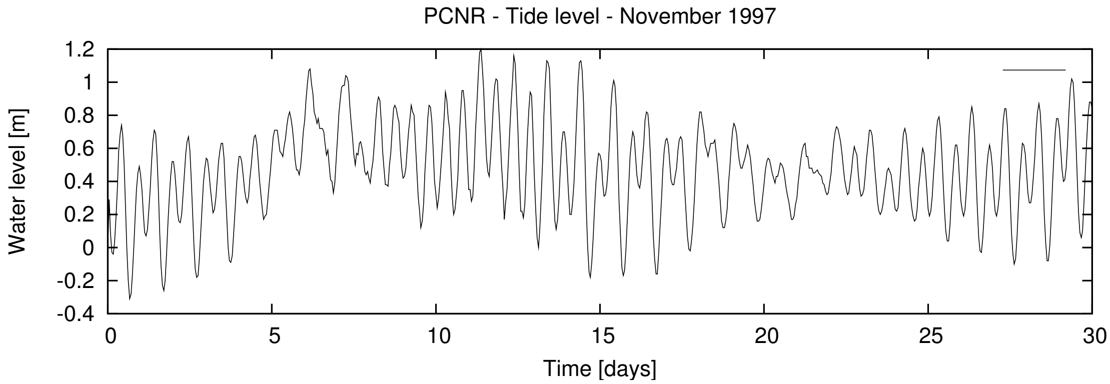

Figure 2: Tide level measured at the CNR Platform tide gauge during November 1997.

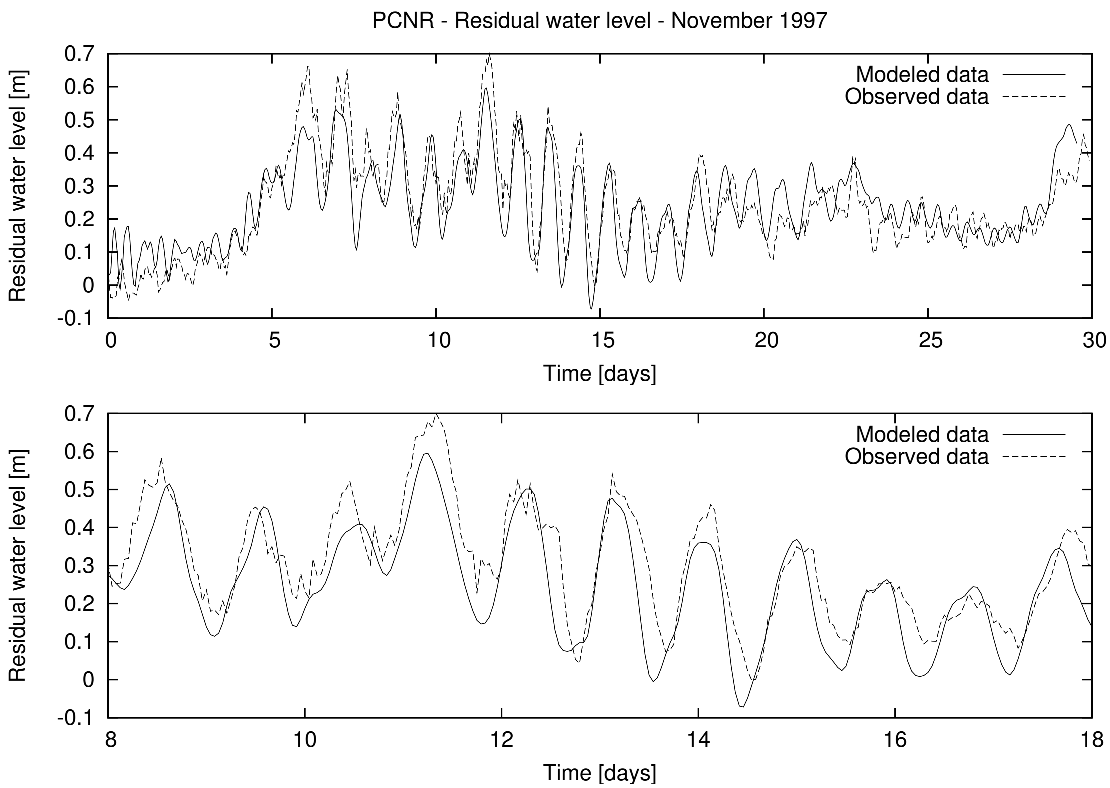

Figure 3: Time series of the residual sea surface elevation at CNR Platform, November 1997: modeled values and observed values.

3.2 November 2000

Four high tide events have been observed in the northern Adriatic sea during November 2000 (figure 4). The events, all higher than 100 cm, occurred at November 6, 12, 13 and 20. In two cases the water level reached 120 cm at Diga Sud Lido. In figure 5 the residual water level measured at the PCNR tide gauge and the model results are plotted. As can be seen, from the experimental time series, two peak values of 100 cm and 73 cm have been measured during the first and the last

Acqua Alta event. During the 5^{th} November the water level reached the 123 cm with a residual contribution of about 100 cm. The 20^{th} November the event of high tide reached 120 cm and the residual contribution has been about 73 cm. In the two cases the causes of the high tide are different. While in the first event the high water level absolute value is mostly generated by the meteorological forcing, in the second one the Acqua Alta event is the result of both meteorological and astronomical constituents. The modeled and the experimental time series comparison shows that the model reproduces with good accuracy the long period evolution of the residual water level signal. For what concerns the diurnal and semidiurnal water level fluctuation the simulation results underestimate the real data.

The statistics of the two time series (table 1) confirm these considerations. The average residual level is well reproduced by the model (0.24 m in the two cases), but both the peak value (1.04 m measured and 0.65 m resulted by the model) and the standard deviation (0.16 m in the real data case and 0.13 in the model results) are lower in the simulation results with respect to the real data. The two time series correlation index is lower than the previous case, about 0.63, which indicates a low degree of similarity between the two time series. The main differences between the two sets of data concern the first part of the month when the meteorological forcing are more intense. In figure 5 the residual water level evolution modeled and measured during the last days of November 2000 is shown. For high water level values (the first part of the considered period) the two time series are not well correlated. When the meteorological forcing is lower and consequently the residual water level too (the second part of the considered period), the two time series are in good agreement.

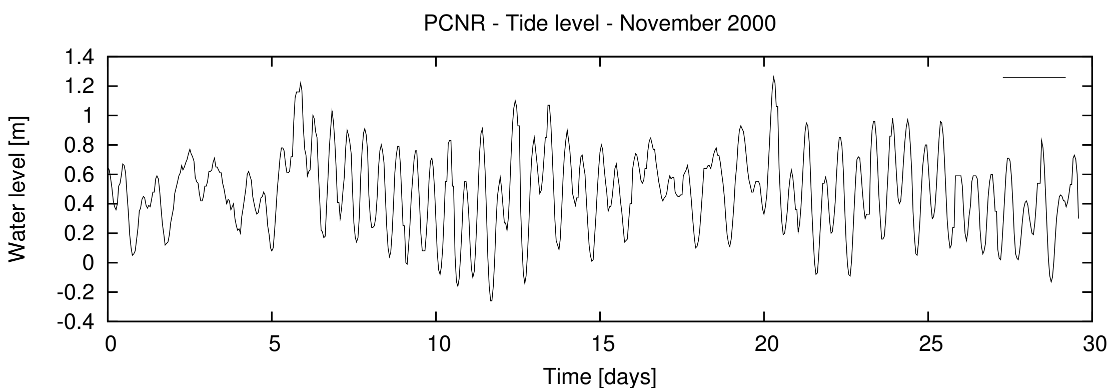

Figure 4: Tide level measured at the CNR Platform tide gauge during November 2000.

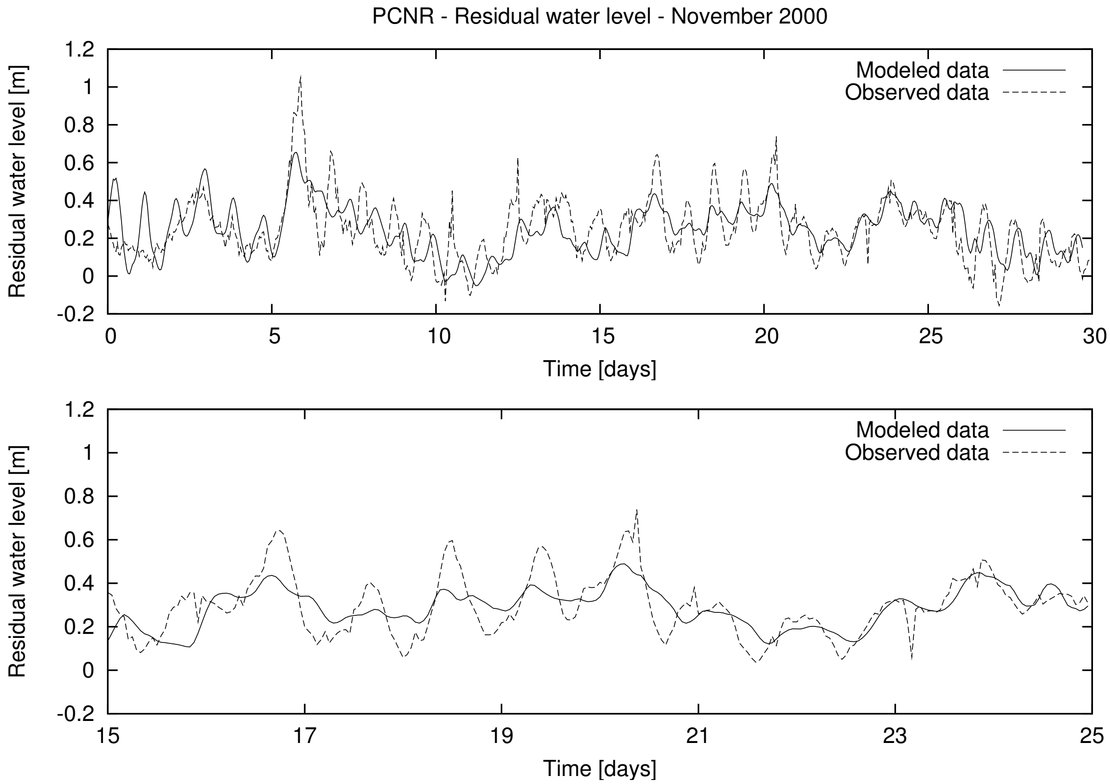

Figure 5: Time series of the residual sea surface elevation at CNR Platform, November 2000: modeled values and observed values.

3.3 November 2001

During November 2001 three high tide events followed one another in the northern Adriatic sea. The events occurred in the 12^{nd}, 13^{rd} and 14^{th} of the month with water level measured at PCNR tide gauge higher than 100 cm in the three cases. The peak value measured was 118 cm and occurred during the 14^{th} (figure 6).

Observing the residual water level time series obtained by the measured data (figure 7), an increase of the average water level is evident starting from the 4th of the month. This phenomenon lasts until the half of the month and is related to the lowering of the atmospheric pressure over the central Mediterranean Sea induced by the passage of a cyclonic perturbation. The three peak events measured during the second half of the month are generated by an intense scirocco wind blowing over the Adriatic Sea.

The model results reproduce with good accuracy the low range variations of the residual signal (figure 7). Even in this case the modeled results underestimate the peak values of the diurnal oscillations. Higher differences between real data and modeled ones are related to the events of high tide when the measured residual signal is higher the 50 cm. In this cases the underestimation of the model results is also greater than 50 cm.

In table 1 the two time series statistical analysis are reported. While, the average water level value is the same, both the standard deviation (0.15 for the real data and 0.11 for the modeled results) and the top water level value (0.85 for the real data and 0.32 for the modeled results) differs. The correlation index between the time series is 0.81, higher than in the other two periods.

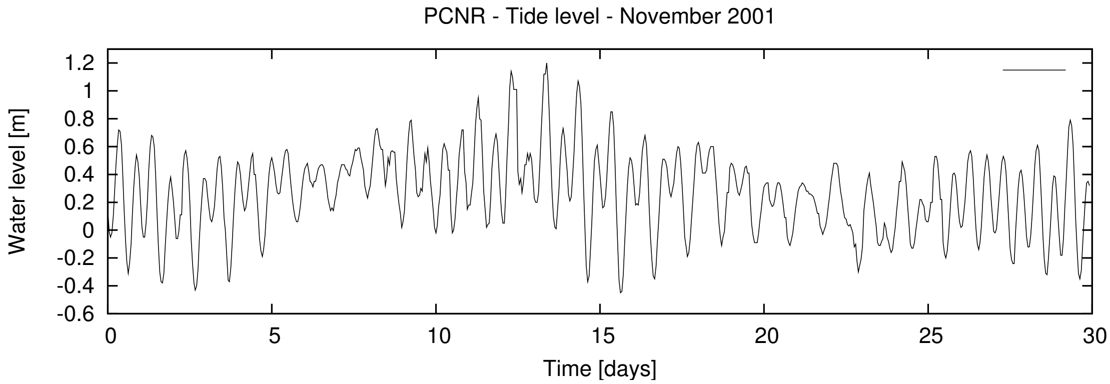

Figure 6: Tide level measured at the CNR Platform tide gauge during November 2001.

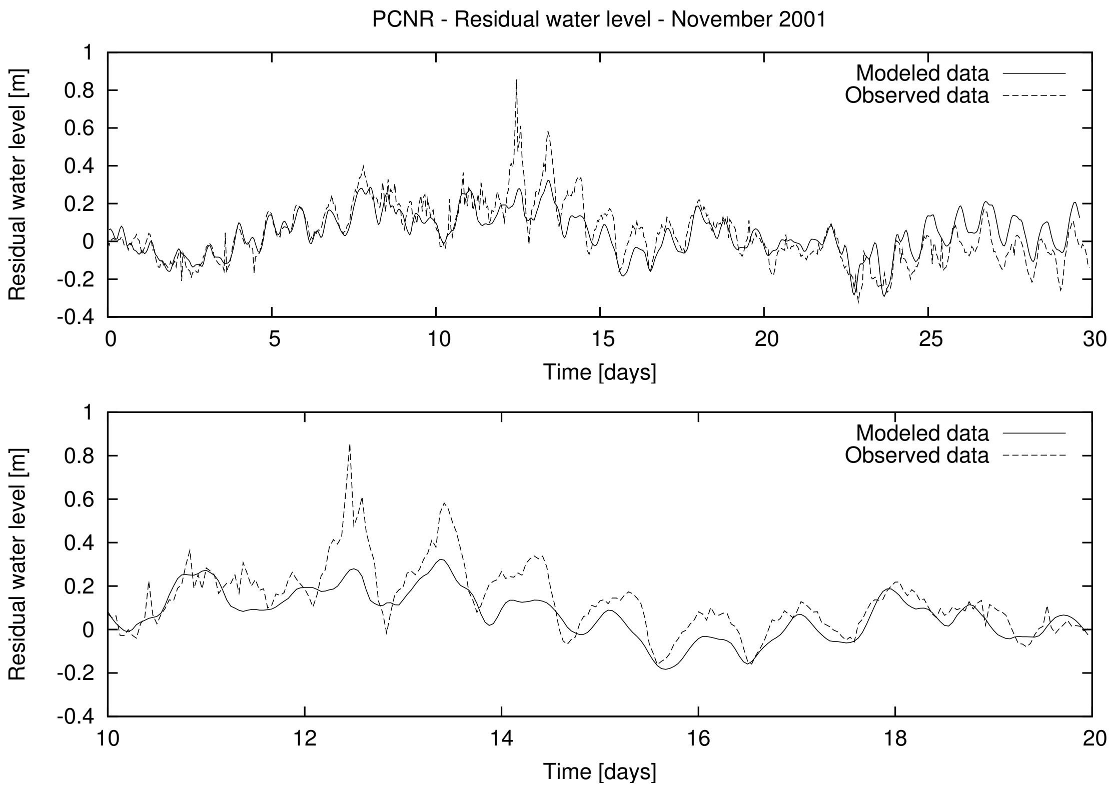

Figure 7: Time series of the residual sea surface elevation at CNR Platform, November 2001: modeled values and observed values.

3.4 Discussion

In the three cases, the statistical analysis results show that the numerical model is able to reproduce the long term water level oscillations. These low frequency excursions are mainly induced by the planetary scale atmospheric disturbances that determine the barometric gradient over the Mediterranean area, primary forcing for the water level set up.

The diurnal oscillations, generated by the combined action of the low range weather variations and the basin resonance, are always underestimated by the model with respect to the real data. The wind speed time series collected by the PCNR tide gauge for the three periods considered and provided by the ECMWF for the same area are reported in figure 8. The ECMWF wind data values are always lower with respect to the real data, with higher differences detected during the periods of intense activities (intense bora or scirocco wind). On the other hand, for the same periods, the atmospheric pressure evolution is well reproduced by the ECMWF data set. Therefore, the reasons for the non satisfactory model results in the three cases can be reasonably related to the low accuracy, with respect to the real data, detected in the meteorological data set.

	AVG	MIN	MAX	STD
1997 OBSERVED	0.24	-0.04	0.69	0.14
1997 MODELED	0.23	-0.07	0.59	0.12
2000 OBSERVED	0.24	-0.15	1.04	0.16
2000 MODELED	0.24	-0.05	0.65	0.13
2001 OBSERVED	0.04	-0.32	0.85	0.15
2001 MODELED	0.04	-0.29	0.32	0.11

Table 1: Average, minimum, maximum and standard deviation value of the observed and modeled residual sea surface elevation time series. The results for November 1997, November 2000 and November 2001 periods are reported

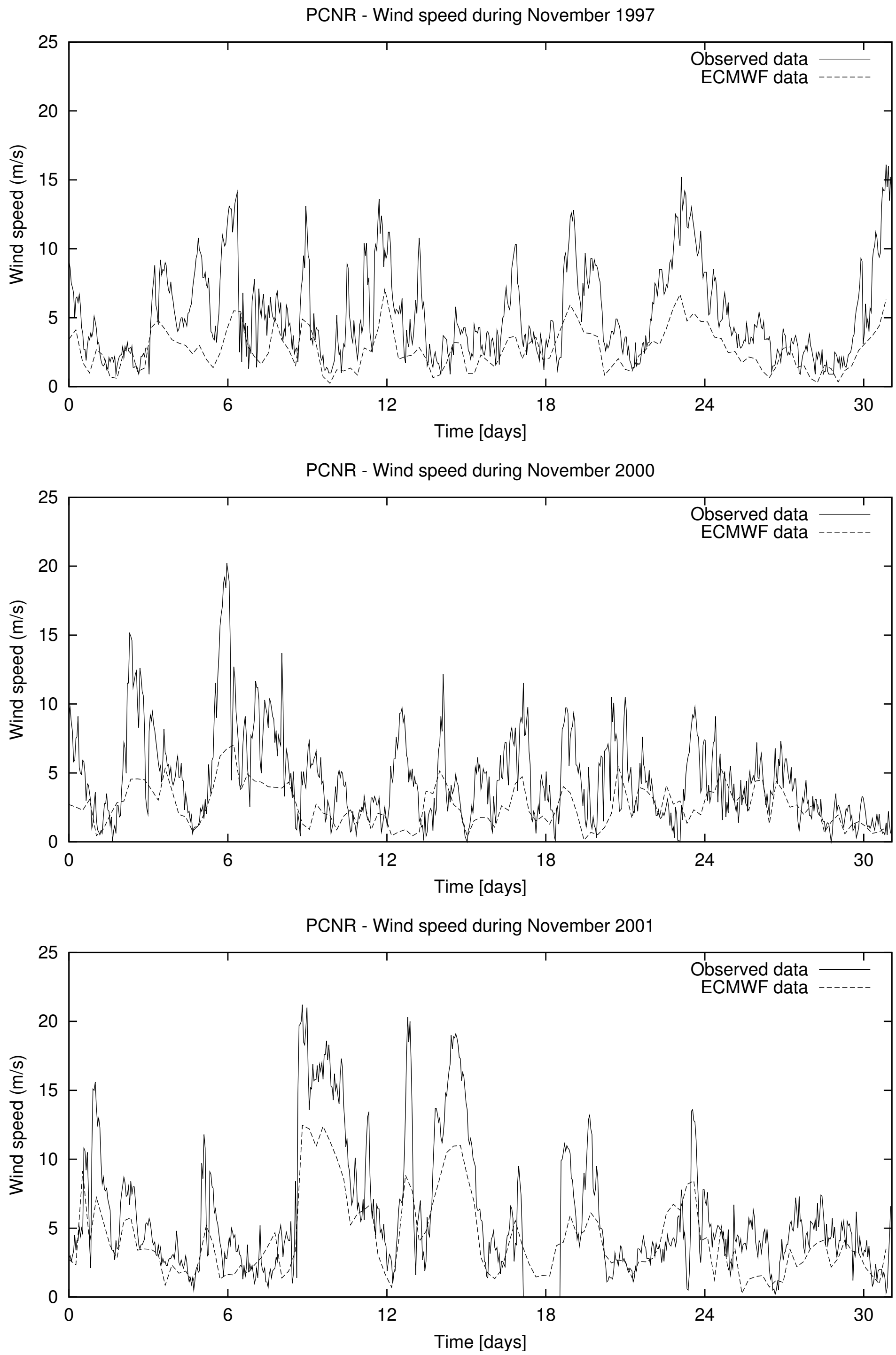

Figure 8: Time series of the wind speed at CNR Platform during November 1997, November 2000 and November 2001: ECMWF data and observed data

4 The operational forecasting system

After the numerical model has been validated through the three test simulations, the operational forecasting system has been build up and installed in the CPSM workstation terminals at the Venice Municipality. The system, daily and automatically, without any operator intervention, produces the evolution of the residual water level at the PCNR for the subsequent 6 days. The operational forecasting software package is made out of three different modules: the ECMWF data set provider, the deterministic forecast and the visualisation module.
The first group of programs is need to provide the forcing input to the model. Every day at 01:00 a.m. the system obtains the ECMWF meteorological data set from the database of the Italian Air Force through FTP connection. For the simulation runs the forecasting system needs both analysed and forecasting wind and pressure data. For each simulation the model is forced with analysed meteorological data of the past 7 days and with the meteorological data forecasted for the 6 days in the future. If the input data are not sufficient to guarantee at least a 3 days forecasting simulation, the system postpones the procedure to one hour later and continues until the minimum amount of input data is satisfied.
The second group of programs constitutes the numerical model and it can be considered as the core of the whole system. It receives the meteorological data and converts them to a format suitable for the model input. Then, the run is set up and the simulation starts. The simulation lasts about one hour, depending on the extension of the forecasting period.
Finally, after the simulation is concluded, the third group of programs extracts the residual water level time series computed by the model and converts it to the absolute water level time series considering the pre-computed astronomical contribution. The time series is plotted on a graphical standard output where is also reported the measured water level at PCNR tide gauge.

5 Conclusion

A new operational forecasting system for the water level in Venice has been set up at the ISMAR-CNR and installed in the CPSM terminal of the Venice Municipality. The system is based on a numerical deterministic model that through the use of the finite element method simulates the water level evolution in the whole Mediterranean sea. The model is forced with wind and pressure data resulted from the ECMWF atmospheric global model.
The model has been tested with several forcing to verify its sensitivity to the different forcing conditions. Three test cases have been considered: November 1997, 2000 and 2001. The results show the difficulty to reproduce the intense scirocco wind effects on the sea level surge in the Adriatic Sea using ECMWF meteorological data as model forcing. While the low range variations of the residual water level are well reproduced by the model results, the high frequency oscillations induced by the intense scirocco and bora wind events are not. The causes are to be related to the low accuracy of the meteorological data input that, being the results of a global atmospheric model are not suitable to reproduce the dynamic occurring at the local scale, such as the influence of the orography on the wind fields structure.
Future interventions are aimed mainly to improve the accuracy of the input data forcing through: reducing the ECMWF data error by applying to the wind speed suitable correction coefficient (Cavaleri et al. 1996), forcing the model with wind data provided by satellite scatterometer and by north Adriatic local atmospheric model and finally assimilating real water level data provided by tide gauges located along the Adriatic sea. The forecasting system is operative from the 1^{st} November 2002. Daily, without any operator intervention, produces the evolution of the residual water level at the PCNR for the subsequent 6 days.

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