Data monitoring and sea level forecasting in the Venice Lagoon: the ICPSM's activity

A. Massalin, L. Zampato, A. Papa and P. Canestrelli

Dipartimento di Istituzione Centro Previsioni e Segnalazioni Maree, Venezia, Italy

(Received: April 20, 2006; accepted: March 05, 2007)

ABSTRACT A complete description of the Istituzione Centro Previsioni e Segnalazioni Maree (ICPSM) of the Venice Municipality is given, together with some notions about the characteristics of the tide and the wave motion in the Venice Lagoon. The monitoring network of the ICPSM, for the observation of oceanographic and meteorological parameters in the lagoon and in the northern Adriatic Sea, is described in its different parts: the tide gauge and meteorological monitoring network, the meteorological stations at the Venice Lido Hospital, the wave gauge network and the Acoustic Doppler Current Profiler at the Chioggia inlet. The procedures adopted for the data quality control are reported. The data exploitation is displayed in all its different aspects from the sea level forecast to the daily information activities and the operative plan in case of exceptional high tide.

1. Introduction

High waters in Venice cause serious damage to the urban structure and compromise daily activities of the city. An accurate and reliable forecast of such events allows us to quickly alert the population, minimizing inconveniences due to the phenomenon.

Motor boat traffic produces strong stress to the foundations of buildings and to the natural lagoon environment. Regulation monitoring and control of the wave motion has become necessary to fight the erosion.

In 1981, the Istituzione Centro Previsioni e Segnalazioni Maree (ICPSM) was founded as an office of the Venice Municipality, to develop an operational forecasting system for the sea level in Venice. At present ICPSM's official tasks are:

- observation of the sea level and weather parameters;
- water level forecasting;
- give information to the city and alarm in case of flooding events;
- wave motion monitoring.

Sea level, waves and related meteorological parameter observation is carried out through a monitoring network, covering the city, the inner Venice Lagoon and the northern Adriatic Sea.

The water level forecast is performed by means of numerical models.

Citizens are informed about tidal phenomena and alarmed in case of an incoming high water event through a number of procedures and devices, some of which are automatic and the others are activated manually. A dedicated web site (http://www.comune.venezia.it/maree) describes the ICPSM's activity and gives access to some data of the observing stations.

The monitoring network, supplying observed data in real time, is the core of the whole of

ICPSM's activity. In fact, observed data are part of the input of operational sea level models and they have also a crucial importance for tuning and validating them. Moreover, information on observed parameters, the sea level in particular, are diffused to the population in real time. Observed data are also currently supplied to a great variety of interested users, as research institutions, public service companies and citizens.

The main purpose of this paper is to describe the ICPSM's monitoring network and explain the role played by real time observed data in the sea level forecasting and related activities. The phenomenology of high water events in Venice is summarized in Chapter 2. Chapter 3 deals with the observation of sea level, weather parameters, wave motion and currents: the monitoring network is described in detail and the adopted procedures to control and validate data are outlined. An extended archive of meteorological data, collected at the Lido di Venezia (Venetian littoral) and recently acquired by ICPSM, is also presented. The procedures adopted for the data quality control are reported. The data exploitation is the topic of Chapter 4: ICPSM operational numerical models are described and the ways to inform and alert the city are listed. Chapter 5 reports some conclusive remarks.

2. Phenomenology of sea level in Venice

The city of Venice is situated in the middle of the Venice Lagoon and communicates with the Adriatic Sea through three inlets: Lido, Malamocco and Chioggia. The tidal wave propagates from the Adriatic Sea through these inlets into the Lagoon and reaches the city of Venice.

The observed water level in Venice can be described as the sum of two terms (Goldmann *et al.*, 1975): the astronomical tide, related to the motion of astronomical bodies, principally the moon and the sun, and the meteorological contribution, or surge, due to weather conditions.

The astronomical tide is calculated as a sum of 8 components, the principal being the semidiurnal M2 (Polli, 1960). The amplitude varies following lunar phases: during full moon or new moon the water level experiences the maximum change (spring tide), typically from -35 cm to +75 cm with respect to the conventional zero of Punta Salute, currently used in Venice. The lowest change in the water level (neap tide), typically from +5 cm to +40 cm, happens during the first or the last quarter of the moon.

In the occurrence of adverse weather conditions (typically low pressures, strong winds as sirocco from SE or bora from ENE) the meteorological contribution becomes important (Polli, 1962; Tomasin and Frassetto, 1979; Tomasin and Pirazzoli, 1999): the water level in the city reaches higher values, of the order of 100 cm and more. In the historical flooding of November 4, 1966, the observed water level reached +194 cm, on the local datum of Punta Salute: the astronomical tide was +10 cm, so the surge contribution reached the value of +184 cm (Canestrelli *et al.*, 2001; De Zolt *et al.,* 2006). A more recent and less dramatic example can be seen in Fig. 1, referring to the period November 9 - 11, 2004: at the Punta Salute station, in Venice, the maximum sea level (+124 cm) occurred on November 10, with a surge of about 50 cm.

In the last 40 years, the flooding event frequency grew, because of phenomena as the eustatism that increases the sea level and the subsidence that lowers the town (Carbognin and

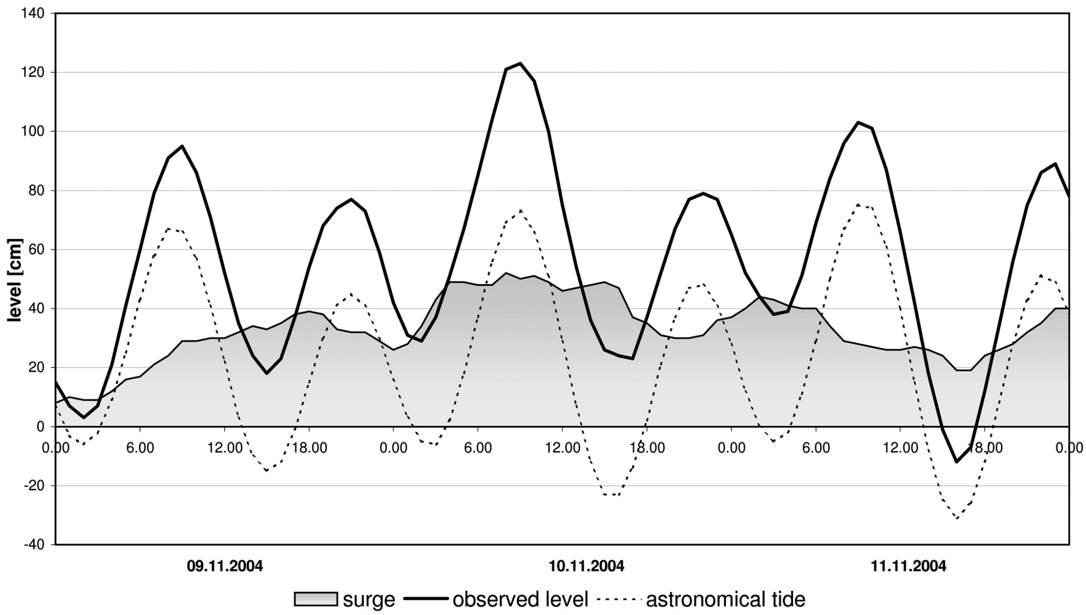

Fig. 1 - A case of "high water" in Venice: observed level, astronomical tide and surge at Punta Salute (Gran Canal).

Taroni, 1996): the height of 110 cm on the local zero, the typical level at which several activities of the city are compromised, was reached 44 times in the period 1990-99 (Battistin and Canestrelli, 2006).

Besides the worsening of the high water problem, the intensification of motor boat traffic has negative effects: the "wave motion" causes erosion of building foundations and the natural lagoon environment. A statistical analysis on wave observations in the Venice canals and in the lagoon was presented by Canestrelli and Cossutta (2001). A daily trend was pointed out in the significant wave height: high values during the day, low values during the night. The motor boat traffic is clearly the principal cause of the wave motion and wave values depend on boat types, on their charge condition and velocity. The effect of strong winds, with speed greater than 15 m/s, is important only in open areas: the bora increases the wave height in the northern lagoon and the sirocco along the southern boundary of the city. Mean values of significant wave height vary from 6 to 12 cm in all locations, while maximum values reach 30 cm in the inner canals and exceed 70 cm in the northern lagoon.

3. The monitoring network

At present the ICPSM's monitoring system includes an extended sea level and meteorological monitoring network, constituted by 14 automatic stations, located in the Venice Lagoon and northern Adriatic Sea, a wave monitoring network (10 stations in the city of

Fig. 2 - The ICPSM's monitoring network. In the little box on the right the wave gauge network is visible. The current meter at the Chioggia inlet is marked by a star.

Venice), two meteorological stations at the Venice Lido Hospital ("Ospedale al mare" stations) and a current meter at the Chioggia inlet (see Fig. 2). The position of each station and the features of recorded parameters are reported in Tables 1 to 5.

3.1. The tide gauge and meteorological monitoring network

The ICPSM has progressively developed a monitoring network from a tide gauge in the city, to what now gives a real time picture of the water level and meteorological parameters in the whole Venice Lagoon and in the part of the Adriatic Sea that faces it. The first tide gauge was placed in 1982 in the historical location of Punta Salute. Today the monitoring network is constituted by 14 measurement stations connected to a central station by radio (UHF), via an additional station operating as repeater. Fig. 2 shows the sea level monitoring network in the current configuration. The geographical coordinates of each station, a list of the recorded parameters, with the acquisition frequency and the archive start date are reported in Table 1 and Table 2. The central station is a 'Fault-Tolerant' system with software SIAP CMX5000/FT for UNIX System V: it is situated at the ICPSM's operational headquarters. Each peripheral measurement station and repeater (automatic meteorological station SIAP SM3840) are located in their own reinforced concrete housing. Some measurement stations can alternatively measure or operate as repeaters, allowing several different architectures in the network.

Peripheral stations acquire and preprocess the data measured by active sensors whose features are listed in Table 5. Automatically or on operator request, the central station collects data and

Table 1 - The tide gauge and meteorological monitoring network stations.

Station	Geographical coordinates	Observed parameters	Archive beginning	Data frequency
Punta Salute (Gran Canal)	N 45° 25' 51" E 12° 20' 13"	level (m) water temperature (°C)	Apr 1998 May 1998	5' 5'
Punta Salute (Giudecca Canal)	N 45° 25' 51" E 12° 20' 15"	level (m)	Jan 1983	5'
Palazzo Cavalli	N 45° 26' 11" E 12° 20' 01"	air temperature (°C) relative humidity (%) air pressure (hPa) precipitation (mm) solar radiation (W/m^2)	Apr 1998 Apr 1998 Nov 1998 Apr 1998 Apr 1998	5' 5' 5' 5' 5'
Misericordia	N 45° 30' 40" E 12° 04' 60"	level (m)	Jan 2002	5'
Murano	N 45° 31' 40" E 12° 05' 40"	level (m)	Jan 2003	5'
Burano	N 45° 33' 00" E 12° 08' 00"	level (m)	Jan 2002	5'
Laguna Nord (Saline)	N 45° 29' 44" E 12° 28' 19"	level (m) wind speed (m/s) wind direction (°) precipitation (mm)	Jan 2000 Jan 2000 Jan 2000 Jan 2000	5' 5' 5' 5'
Malamocco Porto	N 45° 24' 10" E 12° 04' 40"	level (m) wind speed (m/s) wind direction (°)	Sep 2003 Sep 2003 Sep 2003	5' 5' 5'
Chioggia Porto	N 45° 17' 48" E 12° 03' 00"	level (m) wind speed (m/s) wind direction (°)	Sep 2003 Sep 2003 Sep 2003	5' 5' 5'
Chioggia (Canal Vena)	N 45° 13' 12" E 12° 16' 47"	level (m)	May 1999	5'
Diga Sud Lido	N 45° 25’ 06” E 12° 25’ 36”	level (m)	Jan 1983	5’
Diga Nord Malamocco	N 45° 20' 04" E 12° 25' 30"	level (m)	Jan 1983	5'
Diga Sud Chioggia	N 45° 13' 44" E 12° 18' 33"	level (m) wind speed (m/s) wind direction (°)	Jan 1983 Jan 1983 Jan 1983	5' 5' 5'
Piattaforma CNR “Acqua Alta”	N 45° 18' 51" E 12° 30' 30"	level (m) wind speed (m/s) wind direction (°) air temperature (°C) relative humidity (%) air pressure (hPa) precipitation (mm) solar radiation (W/m^2) water temperature (°C)	Jan 1983 Jan 1983 Jan 1983 Jan 1983 Jan 1983 Jan 1983 Jan 1983 Jan 1983 Jan 1983	5' 5' 5' 5' 5' 5' 5' 5' 5'

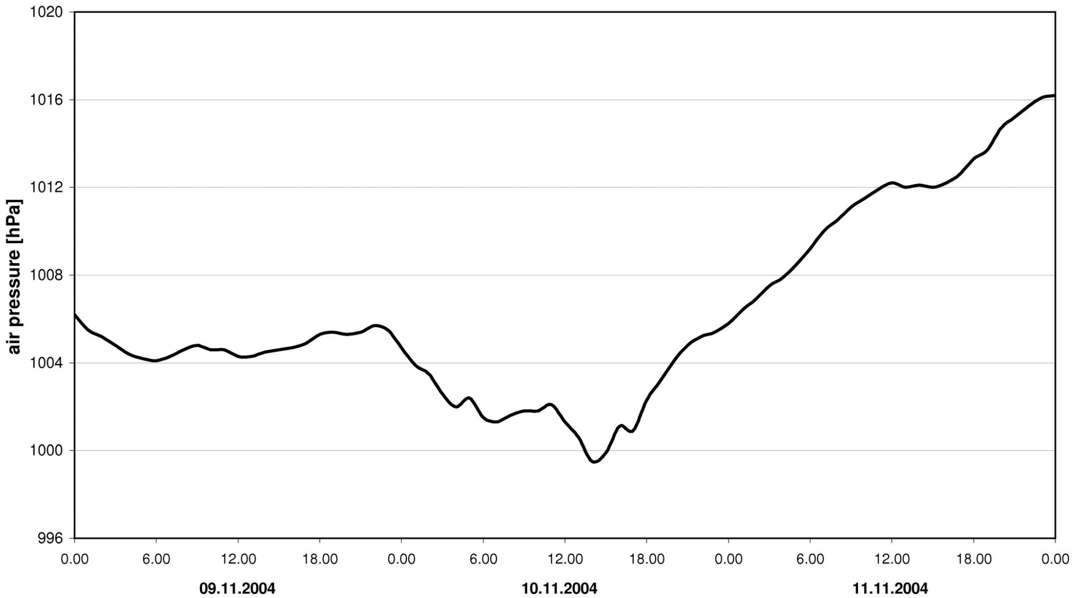

Fig. 3 - The observed pressure at Palazzo Cavalli on November 9 – 11, 2004.

stores them in a database based on SQL language. A graphical interface, installed at the operational headquarters, permits ICPSM operators to immediately control the network situation, giving a synoptic image of the sea level and weather parameters in the whole lagoon. To assure the continuity of the data reception and the database completeness, the ICPSM staff takes care of the monitoring network maintenance, periodically inspecting the instruments and the buildings.

The situation of a storm surge event that occurred in Venice, in the period November 9 - 11, 2004, is shown as an example in Figs. 3 to 5.

The storm surge event was characterized by a marked lowering of the atmospheric pressure (see Fig. 3) and a strong bora wind, with speed higher than 20 m/s, in the northern Adriatic (see Fig. 4). Sirocco winds, not shown in this paper, were observed at some southern Adriatic SYNOP stations. The observed sea levels in different sites of the Venice Lagoon are shown in Fig. 5. It evidences the propagation of the tide from the open sea to the inner lagoon, with a delay of about 1 hour between Piattaforma CNR and Punta Salute stations. In the same figure, the effect of the bora wind is well visible: this northeasterly wind pushes the water toward the southern lagoon (Chioggia station) that experiments a higher sea level value than the northern lagoon (Saline station). At the moment of the maximum surge, the level gap between Chioggia and Saline stations was about 45 cm.

3.2. The meteorological stations at the Venice Lido Hospital

From 1940 to 2003 at the Venice Lido hospital a meteorological station observed and archived climatic data. The ICPSM has been administering the observing site since February 2004. ICPSM operators have collected and digitalized the 64-year archived data listed in Table 2. Old

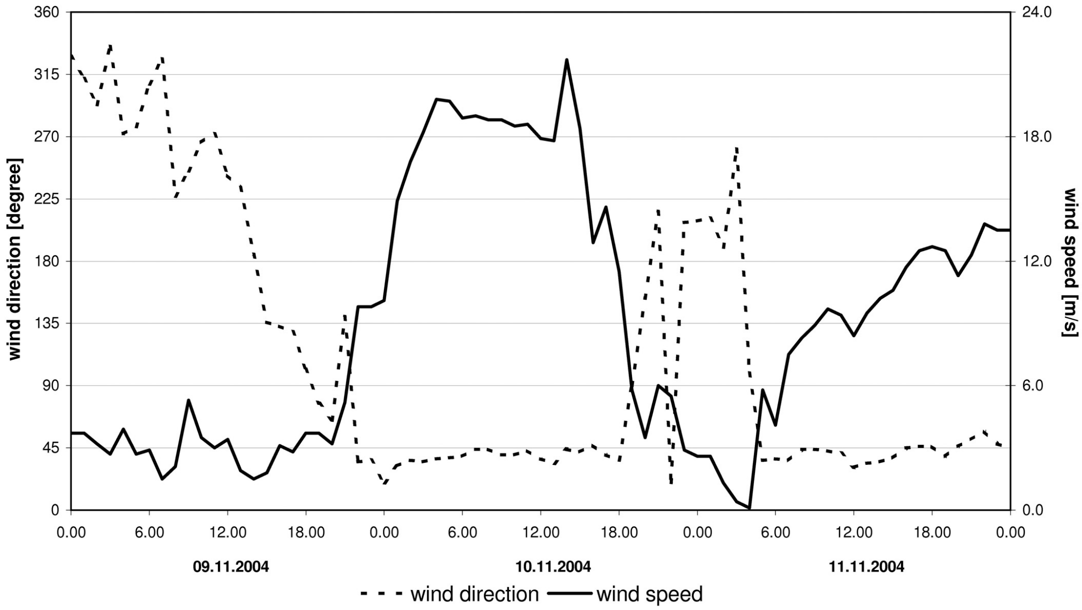

Fig. 4 - The observed wind at Piattaforma CNR on November 9 – 11, 2004.

instruments were placed in two different locations: over a terrace of the hospital (at a 14 m height) and in an open air area, at sea level, between the hospital and the sea. In November 2004, two new automatic meteorological stations SIAP SM3840 were installed to guarantee historical

Table 2 - The Venice Lido Hospital monitoring network stations.

Station	Geographical coordinates	Observed parameters	Archive beginning	Data frequency
Lido Hospital (meadow)	N 45° 24' 30" E 12° 05' 50"	air pressure (hPa) air temperature (°C) relative humidity (%)	Nov 2004 Nov 2004 Nov 2004	5' 5' 5'
Lido Hospital (terrace)	N 45° 24' 30" E 12° 05' 50"	wind speed (m/s) wind direction (°) precipitation (mm) solar radiation (W/m^2)	Nov 2004 Nov 2004 Nov 2004 Nov 2004	5' 5' 5' 5v
Lido Hospital ARCHIVE 1940-2003	N 45° 24' 30" E 12° 05' 50"	air pressure (hPa) wind speed (km/h) wind direction (°) precipitation (mm) air temperature (°C) relative humidity (%) insolation (h) nebulosity (tenth) water temperature (°C) sand temperature (°C)	1940-2003 1940-2003 1940-2003 1940-2003 1940-2003 1940-2003 1940-2003 1940-2002 1940-1961 1940-1991	1h (2h until 1963) 1h 1h 1h 1h (2h until 1963) 1h (2h until 1963) 1h not regular 3h (9 a.m. to 3 p.m.) 3h (9 a.m. to 3 p.m.)

Table 3 - The wave monitoring network stations.

Station	Geographical coordinates	Observed parameters	Archive beginning	Data frequency
Piattaforma CNR "Acqua Alta"	N 45° 18' 51" E 12° 30' 50"	level (m)	Jul 1998	15'
GRAN CANAL				
Palazzo Cavalli (Venice)	N 45° 26' 11" E 12° 20' 01"	level (m)	Apr 2003	15'
S. Geremia (Venice)	N 45° 34' 00" E 12° 11' 00"	level (m)	Feb 2003	15'
Punta Salute (Gran Canal)	N 45° 25' 51" E 12° 20' 13"	level (m)	Jul 1998	15'
INNER CANALS				
Rio di Noale (Venice)	N 45° 31' 40" E 12° 13' 25"	level (m)	Feb 2003	15'
Rio Novo (Venice)	N 45° 30' 25" E 12° 13' 25"	level (m)	Feb 2003	15'
NORTHERN LAGOON				
Burano	N 45° 33' 00" E 12° 08' 00"	level (m)	Feb-Dec 2003	15'
Murano	N 45° 31' 40" E 12° 05' 40"	level (m)	Feb 2003	15'
Celestia (Venice)	N 45° 35' 00" E 12° 11' 25"	level (m)	Feb 2003	15'
Misericordia (Venice)	N 45° 30' 40" E 12° 04' 60"	level (m)	Feb 2003	15'
GIUDECCA CANAL				
Punta Salute (Giudecca Canal)	N 45° 25' 51" E 12° 20' 15"	level (m)	Jul 2003	15'

continuity for the registrations. The two stations, working in the same way as all the other peripheral stations, have been integrated into the meteorological monitoring network, described in the previous section.

3.3. The wave gauge network

The ICPSM's wave monitoring network (see Table 3) today is composed of 11 Siap ID0810B ultrasound ceramic temperature compensated sensors (see Table 5). They are placed at 2.5 m on the mean sea level. The zero crossing method with a period of 15' is used to get the wave profile. The data are transmitted once a day via GSM. The Piattaforma CNR sensor is the only exception: it is placed at 10

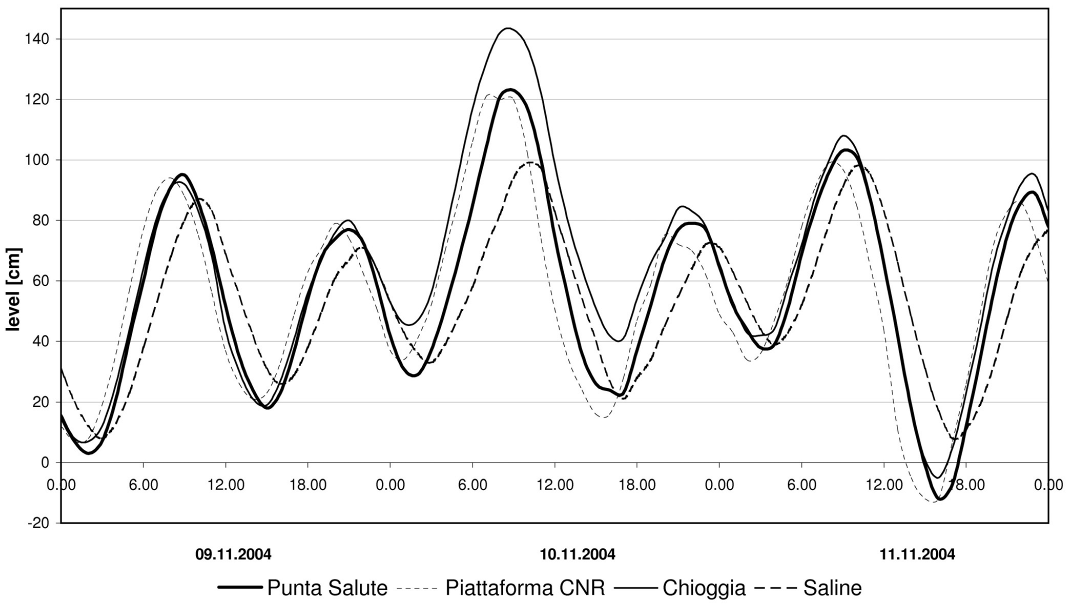

Fig. 5 - The sea level in different stations of the Venice Lagoon on November 9 – 11, 2004.

m on the mean sea level and transmits via radio, every 15', data averaged on the previous 3'.

The network is operative from July 2003. The data archive includes some observations collected at Palazzo Cavalli and Punta Salute stations since 1996.

To describe the wave motion phenomenon in the Venice lagoon, four characteristic zones can be distinguished: the northern lagoon, the inner canals of Venice, the Gran Canal and the Giudecca Canal. Similar behavior of the maximum wave height (H_m) and the significant wave height (H_s), can be observed in all of them: lower values in the night, higher values during the day, when commercial activities and citizens transport are at their highest. In addition, the wave motion is influenced by meteorological factors, in particular the wind, depending on the geographical position. As an example, Fig. 6 shows the observed waves at the Misericordia station, located at the northern boundary of the city, during a bora event: the strong influence of this northeasterly wind is evident on February 20 and 21, 2005 when the wind speed reached 20.9 m/s.

The analysis of inner canals data, also showed the dependence of the wave regime on the boat traffic during particular days of the year, as can be New Year's Day and Regata Storica day. In these special situations the usual daily wave behavior disappeared.

3.4. The acoustic Doppler current profiler at the Chioggia inlet

The ICPSM participates in the current meter network of the Venice Lagoon, realized in collaboration with the National Institute of Oceanography and Experimental Geophysics (OGS) of Trieste (Gacic *et al.,* 2004), with its own Acoustic Doppler Current Profiler (ADCP) installed at the Chioggia inlet. The data archive began at the end of 2002. The acoustic current meter works at 600 Hz and has been placed at a depth of 9 m. The recording frequency is 10 Hz, the vertical

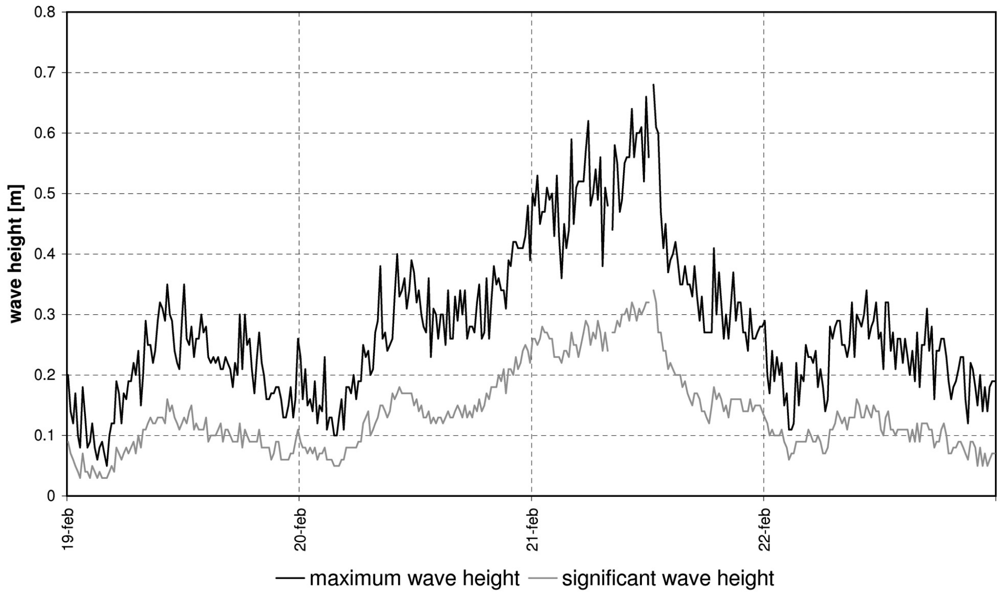

Fig. 6 - The waves in the northern boundary of Venice (Misericordia station) during a bora wind event in February 2005.

resolution is 1 m and the data are averaged over a 10' period. The data transmission is activated once a day by GSM connection. The location of the ADCP is visible in Fig. 2 and its geographical coordinates are reported in Table 4.

3.5. The data quality control

After the acquisition, all data are automatically validated by the system, rejecting values that are out of range according to the World Meteorological Organization (WMO, 1997).

Date and time are assigned to each measurement by a data logger in the station. ICPSM technicians control and synchronize the data logger with a GPS satellite clock on a weekly basis.

The data are subjected to a visual control daily: anomalous data behaviors are identified.

Each month all data are archived: data received at the central station are integrated by station memory card data and submitted to a visual control. Out of range data and spikes are detected and eventually eliminated. If some data are still missing, a linear interpolation is applied to fill a maximum gap of 15 minutes.

Due to their importance, sea level data undergo further controls. The relationship between the recorded sea level and the benchmark level on land is periodically checked. In neap tide conditions a comparison between neighbou≠ring stations helps to detect and correct inconsistent measurements. Daily maximum and minimum sea level values are calculated for principal stations. This procedure is useful to identify suspicious periods when there is no change in the magnitude of the sea level after several time steps (stability test).

ICPSM sea level data follow the standard quality level control LC1 defined by European SEA level Service (ESEAS) described in Garcia *et al*. (2005).

Table 4 - The acoustic Doppler current profiler at the Chioggia inlet.

Station	Geographical coordinates	Observed parameters	Archive beginning	Data frequency
Diga Sud Chioggia (ADCP)	N 45° 13' 32" E 12° 17' 36"	current velocity (cm/s) flow rate (m^3/s)	Nov 2002 Nov 2002	5′ 5′

Table 5 - The characteristics of the ICPSM monitoring network sensors.
The sensors are operative at temperature higher than –30 °C and lower than +50 °C with the exception of the precipitation sensor that does not work below 0 °C. Most of them can work also at a temperature higher than +50 °C, as the solar radiation sensor (maximum temperature +80 °C) and all kinds of sea-level sensors (maximum temperature +70 °C).

Observed parameter	Sensor	Range	Sensibility	Precision	Resolution	Measure frequency
air pressure	SIAP PA9880B	(500÷1100) hPa	-	± 0.3 hPa	0.01 hPa	-
air temperature	SIAP UM9830B	(-50÷50) °C	< 0.1 °C	± 0.3 °C	0.1 °C	-
sea level (ultrasonic hydrometer)	SIAP ID0810B	(0÷15) m	-	± 1 cm	0.3 cm	-
precipitation	SIAP UM7525	(0÷300) mm/h	0.2 mm	± 0.1 mm (pg < 5 mm/h) ± 2 % (pg > 5 mm/h)	0.2 mm	-
relative humidity	SIAP UM9830B	(0÷100) %	$4 \frac{\mu V}{W/m^2}$	± 3 %	1 %	-
solar radiation	SIAP SO9856B	(0÷1300) W/m (0.3÷3.5) Ìm		1.5 % f.s.	0.1 % f.s.	-
water temperature	SIAP TM9856B	(-50÷50) °C	0.1 °C	± 0.3 °C	0.1 °C	-
wind direction	SIAP VT0805B	(0÷360) °	0.25 m/s	± 3 °	2 °	2 Hz
wind speed	SIAP VT0805B	(0.25÷50) m/s	0.25 m/s	± 0.5 m/s (v < 10 m/s) ± 5 % (v > 10 m/s)	0.1 m/s	2 Hz
sea level (mechanic hydrometer)	SIAP ID7877	(0÷40) m	-	± 1 cm	1 cm	-
wave sea level (ultrasonic hydrometer)	SIAP ID0810B/W	(0÷15) m	-	± 1 cm	0.3 cm	4 Hz

4. Data exploitation

Observed data allow ICPSM to accomplish all its tasks: forecasting the sea level, supplying information about tidal phenomena and alert the population in case of flooding events.

4.1. Sea level forecast

After the disastrous flooding of 1966, a great effort was made to predict similar events and possibly mitigate their effects. Many numerical models were developed [see for example: Accerboni and Manca (1973), Robinson *et al.* (1973), Chignoli and Rabagliati (1975), Goldmann *et al.* (1975), Tomasin and Frassetto (1979), Lionello *et al.* (1998), Zaldivar *et al.* (2000)]. Today the sea level forecast for the city of Venice is performed by ICPSM through a set of numerical models (Canestrelli and Zampato, 2005), some of which are based on statistical methods, others follow a deterministic approach. All models calculate the sea level component due to atmospheric conditions: the meteorological residual or surge. After the computation, the astronomical tide is added to give the total sea level. Model results are controlled and interpreted by the ICPSM's technical staff, who compares them to observed data and formulates the official sea level forecast for the next two days.

4.1.1 Statistical models

Statistical models are based on a linear autoregressive model (Tomasin and Frassetto, 1979) computing the sea level h in Venice at time $t+\tau$ as linear combination of predictors and coefficients:

$$h_{t+\tau} = \sum_i (a_i^\tau h_{t-i} + b_i^\tau p_{t-i}) \tag{1}$$

The forecast is realized at time t with forecast lag τ. The predictors are the values of sea level h_{t-i} and pressure p_{t-i} observed in the previous hours t-1, t-2, …, in Venice and in a set of SYNOP stations located in the Adriatic and Tyrrhenian Seas. The coefficients a_i^τ , b_i^τ were estimated by means of statistical methods based on the least squares theory: this calibration procedure has been realized by means of a twenty five-year (1966 - 1990) database. The sea level data were recorded by the ICPSM monitoring network and by the Italian Hydrographic Service of Venice (at present Agenzia per la Protezione dell'Ambiente e i Servizi Tecnici - APAT), and the pressure data have been supplied by the Italian Air Force Meteorological Service.

Since 1981, different statistical models, of increasing complexity and characterized by different predictor choices, were operationally set up. As predictor, the ESTESO model, official model of the ICPSM, which has been operational since 1996, also uses forecasted pressures in the same set of stations, calculated by the atmospheric model of the European Centre for Medium-range Weather Forecasts (ECMWF) of Reading (UK) and distributed in real time by the Centro Nazionale di Meteorologia e Climatologia Aeronautica (CNMCA) of the Italian Air Force.

An estimation of the model's reliability was obtained in terms of accuracy index (AI), defined as the average error ± 2 times the standard deviation: this corresponds to an interval in which 95% of the data are included. The ESTESO model accuracy index, at different forecast lags, computed on the operational runs of the period 1997-2001, are reported in the Table 6.

Table 6 - ESTESO model accuracy index of the period 1997-2001 (after Canestrelli and Moretti, 2004).

	AI (cm)	AI (cm)	AI (cm)	AI (cm)	AI (cm)	AI (cm)
	1 hour	**3 hours**	**6 hours**	**12 hours**	**24 hours**	**48 hours**
ESTESO model	-0.2 ± 4.0	-0.7 ± 9.5	-1.2 ± 12.8	-1.3 ± 13.3	-2.2 ± 14.0	-4.0 ± 18.5

New statistical models, based on artificial intelligence methods, able to decide which set of coefficients to use, depending on observed meteorological conditions, have been recently developed and are in phase of study.

4.1.2. Deterministic models

Two deterministic models for the sea level forecast in Venice are operative at the ICPSM: the hydrodynamic model SHYFEM (Shallow water HYdrodynamic Finite Element Model) developed at the ISMAR-CNR Institute of Venice (Umgiesser, 1986; Umgiesser and Bergamasco, 1993; Umgiesser *et al.,* 2004) and the hydrodynamic model HYPSE (HYdrostatic Padua Sea Elevation model) developed at Padua University (Lionello *et al.,* 1998; Lionello, 2002).

Both hydrodynamic models solve the primitive equations in the shallow water approximation. In their operative implementation, they are driven by the meteorological fields, pressure and wind, computed by the ECMWF atmospheric model and supply a daily automatic sea level forecast at the CNR oceanographic platform location, for the next six days.

The SHYFEM model is based on the finite element approach and uses a grid of the whole Mediterranean Sea: the grid is finer (Δx ~ 1.5 km) in the region of interest, i.e. the northern Adriatic coasts and coarser (Δx ~ 30÷40 km) in the other regions. A wind speed correction, obtained from the comparison between ECMWF winds and satellite observed QuikSCAT winds, is applied to meteorological fields imposed as input (model version v2). Moreover, only for sea level results at the CNR platform, a post-processing is activated (model version v3): after the end of the daily run, the modeled sea level in that location is corrected through a linear regression that uses previous day observed and modeled values. The regression coefficients were calculated from the analysis of observed data and model results, during the whole year 2003, through a least mean square procedure. Details on the SHYFEM model new version and on this post processing are given in Bajo *et al.* (2007).

In Table 7, the SHYFEM model accuracy index computed on the operational simulations of the year 2003, are shown (Bajo *et al.*, 2006): the SHYFEM model results, for version v2 and version v3, are reported.

Table 7 - SHYFEM model accuracy index in the year 2003.

	AI (cm)	AI (cm)	AI (cm)	AI (cm)
	6 hour	**12 hours**	**24 hours**	**48 hours**
SHYFEM v2	0.7 ± 19.2	-2.4 ± 17.9	2.1 ± 18.6	2.2 ± 19.5
SHYFEM v3	0.7 ± 13.5	-1.1 ± 12.7	2.3 ± 14.7	2.4 ± 16.5

The HYPSE model solves the hydrodynamic equations on a finite difference C-Arakawa curvilinear grid of the Adriatic Sea. The grid step assumes the minimum value (Δx ~ 2.4 km) in the northern Adriatic and the maximum value (Δx ~ 9.3 km) at the Otranto Strait. An important and useful feature of the HYPSE model is the coupling with an adjoint model that allows the assimilation of available observations to improve the initial condition for HYPSE (Lionello *et al.,* 2006). By the conjugate gradient method, the adjoint model computes the minimum of a cost function related to the difference between modeled and observed sea level at the CNR oceanographic platform (ICPSM's monitoring network data) and in Ancona (APAT daily supplied data). A new system has been recently implemented to obtain a probabilistic forecast for the sea level in Venice: an *ensemble* of simulations is performed, with slightly different meteorological forcings, allowing us to assign a probability to overcome some fixed thresholds in some future temporal windows.

The analysis of the results obtained in November 2006 runs, reported in Table 8, supplies an order of magnitude of HYPSE model errors. The accuracy index of the basic version and of the version with data assimilation through the adjoint model are shown.

Table 8 - Results analysis obtained in November 2006 runs.

	AI (cm)	AI (cm)	AI (cm)
	24 hours	**48 hours**	**72 hours**
HYPSE base	-6.7 ± 19.5	-5.2 ± 20.5	-3.8 ± 19.6
HYPSE adjoint	+0.8 ± 14.2	+1.5 ± 19.2	+0.5 ± 21.3

4.1.3. Comparison between different models

The statistical models have been operative for many years. They have been tested and verified for a long time, being particularly reliable at short forecast lags, up to 24 hours. This is principally due to their dependence and sensitivity to the sea level values in the immediate previous hours. For this reason, up to now, the statistic ESTESO model is the official model of the ICPSM: it constitutes the basis on which the sea level forecast is formulated in the city for the next two days.

The deterministic models, operationally set up after 2002, have been placed next to the statistic ones and their accuracy is presently under study. A proper comparison between the results of different models is not possible here, because the tables of sections 4.1.2 and 4.1.1 do not refer to the same period. However, the deterministic model performance appears to be improved in the more recent versions. In particular, the SHYFEM version v3 shows a reduction of the AI interval, related to the quadratic error, while for the HYPSE adjoint, a strong improvement of the average error can be noted. The accuracy of both deterministic models is similar to that of the ESTESO model at a forecast lag of +24 hours.

The experience gained by ICPSM technicians, working daily on operational forecasting, indicates that hydrodynamic models are particularly sensitive in predicting a high water at forecast lags of the order of two or three days. This suggests that deterministic and statistical models are very efficient if used together.

In the operational activity, the models outputs are not immediately transmitted to the city. On the contrary, they are controlled and interpreted by the ICPSM's technical staff, who compares them to observed data from the monitoring network and other sources (SYNOP data, Meteosat images, different meteorological data also available on the web) and, on the basis of the experience and the personal knowledge of the phenomenon, formulates the official sea level forecast for the next two days. This procedure, based on numerical models results, but essentially subjective, has turned out to be the most effective in the operational forecast of the high water events occurring during the years 1997-1998, as documented in Canestrelli (1999).

4.2. Information for the city

Observed data and general informations about the tide are diffused to the city by means of:

- a web site (http://www.comune.venezia.it/maree) supplying the sea level forecast and allowing users to download real time and archived data from the monitoring network;
- a set of analogic digital displays, located at some strategic points around the city, communicating in real time the observed tide level and its next maximum or minimum value;
- several touch screen monitors, showing the sea level forecast for the next 48 hours.

In addition the principal venetian newspaper supplies a graph of the forecasted sea level in the city every day. The informations can also be requested directly from the ICPSM's technical staff. An automatic answering device gives the daily forecast for high and low tide values, for the coming two days.

Another of ICPSM's task is the set up of an emergency plan to realize alternative pedestrian routes, through raised mobile walkways. A map of such alternative routes, ensuring the mobility in the dry during high tide events, is distributed to the citizens.

4.3. Alert in case of high water events

If the forecasted sea level is greater than 110 cm on the local datum of Punta Salute, the ICPSM is the official authority delegated to carry out the alerting scheme. It informs the institutions, the public service companies, the public transport service companies, the police, the public security and the population.

A call manager system automatically warns some particular users, as ground floor residents or economic activities by telephone. In addition, interested users, previously registered in a suitable database, are alerted through an automatic SMS.

A siren network, constituted by 16 sirens located in the historical center of Venice and in the principal islands of the lagoon, warns the population 3 or 4 hours before the tide maximum. During 2007, a new sound alarm system will be realized: electronic devices, with sound depending on the forecasted level, will substitute the sirens and the system will be able to spread vocal messages. Warning messages are displayed on big panels along the road and the bridge leading to Venice.

5. Conclusions

The activities of the ICPSM are the object of this paper. The core of the whole ICPSM is the monitoring network: it is essential to the sea level forecasting, carried out through numerical models, and to alert and inform the city.

The number of sea level and meteorological stations recently reached 16 units, considering the two observing sites at the Venice Lido Hospital. A wave gauge network, constituted by 11 stations located in the historical center of Venice, has been operational since 2003. Moreover the ICPSM participates in the current meter network of the Venice Lagoon with its own ADCP, installed at the Chioggia inlet.

The peculiarity of this observing system and its particular value consist in the operational character: observed data are available in real time at the ICPSM central office and allow a continuous monitoring of the sea level and the weather situation in the lagoon and in the northern Adriatic. This tool is of utmost importance, in particular during extreme storm surge events, when the city of Venice is going to be flooded and a prompt alarm, based on an accurate evaluation of the sea level height, must be supplied to the population.

This data richness is necessary for a better knowledge of the particular natural environment of the Venice Lagoon. A complete and continuous data archive will be a great support for any future research project and operational activity concerning the safeguard of the city and of the lagoon.

Acknowledgements. The contents of this paper was presented at the ARCHIMEDE project workshop held in Rome (Italy) on November 29 - 30, 2005.

REFERENCES

Accerboni E. and Manca B.; 1973: *Storm surges forecasting in the Adriatic Sea by means of a two-dimensional hydrodynamical numerical model.* Boll. Ocean. Teor. Appl., **55**, 3-22.

Bajo M., Umgiesser G., Zampato L. and Cucco A.; 2006: *Modello deterministico agli elementi finiti per la previsione del livello del mare a Venezia.* Final report ICPSM, Venice Municipality, Venice, Italy, 85 pp.

Bajo M., Zampato L., Umgiesser G., Cucco A. and Canestrelli P.; 2007: *A finite element operational model for the storm surge prediction in Venice.* Estuarine Coastal and Shelf Science, doi:10.1016/j.ecss.2007.02.025.

Battistin D. and Canestrelli, P.; 2006: *La serie storica delle maree a Venezia 1872-2004.* ICPSM, Venice Municipality, Venice, Italy, 208 pp.

Canestrelli P.; 1999: *Il sistema statistico del Comune di Venezia per la previsione del livello di marea in cittá. Risultati teorici e in fase di operativitá.* Tech. rep., CPSM, Venice Municipality - ISDGM-CNR, Venice, Italy, 27pp.

Canestrelli P. and Cossutta L.; 2001: *Moto ondoso in Canal Grande - Punta della Salute anno 2000.* Tech. rep., Centro Previsioni e Segnalazioni Maree - Comune di Venezia, Venice, Italy, 179 pp.

Canestrelli P. and Moretti F.; 2004: *I modelli statistici del Comune di Venezia per la previsione della marea: valutazioni e confronti nel quinquennio 1997-2001.* Atti dell'Istituto Veneto di Scienze Lettere ed Arti, **162**, 479-516.

Canestrelli P. and Zampato L.; 2005: *Sea level forecasting at the Centro Previsioni e Segnalazioni Maree of the Venice Municipality.* In: Fletcher C. and Spencer T. (eds), Flooding and environmental challenges for Venice and its Lagoon: state of knowledge, Cambridge University Press, Cambridge, UK, pp. 85-97.

Canestrelli P., Mandich M. Pirazzoli P. and Tomasin A.; 2001: *Venti, depressioni e sesse: perturbazioni delle maree a Venezia (1951-2000).* Tech. rep., CPSM-Centro Previsioni e Segnalazioni Maree, Comune di Venezia, Venice, Italy, 105 pp.

Carbognin L. and Taroni, G.; 1996: *Eustatismo a Venezia e Trieste nell'ultimo secolo.* Atti dell'Istituto Veneto di

Scienze Lettere ed Arti, **154**, 281-298.

Chignoli C. and Rabagliati R.; 1975: *Un modello dell'idrodinamica lagunare.* In: Venezia e i problemi dell'ambiente. Il Mulino, Bologna, pp. 225-297.

De Zolt S., Lionello P., Nuhu A. and Tomasin A.; 2006: *The disastrous storm of 4 November 1966 on Italy*. Natural Hazards and Earth System Science, **6**, 861-879.

Gacic M., Mosquera I., Kovacevic V., Mazzoldi A., Cardin V., Arena F. and Gelsi G.; 2004: *Temporal variations of water flow between the Venetian lagoon and the open sea.* Journal of Marine Systems, **51**, 33-47.

Garcia M. J., Gomez B. P., Raicich F., Rickards L. and Bradshaw E.; 2005: *Quality control of sea level observations.* Version 1.0. Eseas work package 1, deliverable 1.2, task 1.2, European Sea Level Service - Research Infrastructure, N-3511 Honefoss, Norway.

Goldmann A., Sguazzero P. and Giommoni A.; 1975: *La previsione dell'acqua alta.* In: Venezia e i problemi dell'ambiente, Il Mulino, Bologna, pp. 63-224.

Lionello P.; 2002: *Studio: sistema operativo di previsione del livello del mare Adriatico basato su un modello numerico di tipo deterministico della circolazione marina.* Report (phase I and II), CPSM, Venice Municipality, Venice, Italy, pp. 18-20.

Lionello P., Zampato L., Malguzzi P., Tomasin A. and Bergamasco A.; 1998: *On the correct surface stress for the prediction of the wind wave field and the storm surge in the northern Adriatic Sea.* Il Nuovo Cimento, **22**, 515-532.

Lionello P., Sanna A., Elvini E. and Mufato R.; 2006: *A data assimilation procedure for operational prediction of storm surge in the northern Adriatic Sea.* Continental Shelf Research, **26**, 539-553.

Polli S.; 1960: *La propagazione delle maree nell'Adriatico.* Technical Report 370, Istituto Sperimentale Talassografico, Trieste, 11 pp.

Polli S.; 1962: *Effetti meteorici, statici e dinamici, sul livello dell'Adriatico settentrionale.* In: Atti del simposio internazionale: Influenze meteorologiche e oceanografiche sulle variazioni del livello marino LXXVIII/1963, 18 pp.

Robinson A., Tomasin A. and Artegiani A.; 1973: *Flooding of Venice: phenomenology and prediction of the Adriatic storm surge.* Quart. J. Roy. Meteorol. Soc., **99**, 688-692.

Tomasin A. and Frassetto R.; 1979: *Cyclogenesis and forecast of dramatic water elevations in Venice.* In: Nihoul J. (ed), Marine Forecasting, Elsevier, Amsterdam, pp. 427-437.

Tomasin A. and Pirazzoli P. A.; 1999: *The seiches in the Adriatic Sea.* Atti dell'Istituto Veneto di Scienze Lettere ed Arti, **157**, 299-316.

Umgiesser G.; 1986: *A model for the Venice Lagoon.* Master's thesis, University of Hamburg, Hamburg, Germany, 64 pp.

Umgiesser G. and Bergamasco A.; 1993: *A staggered grid finite element model of the Venice Lagoon.* In: Periaux J., Morgan K., Ofiate E. and Zienkiewicz O. (eds), Finite Element in Fluids. Pineridge Press, Swansea, pp. 659-668.

Umgiesser G., Melaku Canu D., Cucco A. and Solidoro C.; 2004: *A finite element model for the Venice Lagoon. Development, set up, calibration and validation.* Journal of Marine Systems, **51**, 123-145.

WMO; 1997: *Guide to meteorological instruments and methods of observation.* WMO-No.8. World Meteorological Organization, Geneva, Sixth edition, 416 pp.

Zaldivar J., Gutierres E., Galvan I., Strozzi F and Tomasin A.; 2000: *Forecasting high waters at Venice Lagoon using chaotic time series analysis and nonlinear neural networks.* Journal of Hydroinformatics, **02.1**, 61-84.

Corresponding author: Annamaria Massalin
Dipartimento - Istituzione Centro Previsioni e Segnalazioni Maree,
Comune di Venezia, 30100 Venezia, Italy
phone: +39 041 2748564; fax +39 041 5210378; e-mail: annamaria.massalin@comune.venezia.it