Storm surge modelling in Venice: two years of operational results

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ABSTRACT

Sea-level forecasting in Venice is a fundamental task for safeguarding the ancient city, its cultural heritage and natural environment. In the last 10 years the finite-element numerical Shallow Water Hydrodynamic Model (SHYFEM), developed at the Institute of Marine Sciences (ISMAR) of the National Research Council (CNR) of Venice, has been operationally implemented at the Istituzione Centro Previsioni e Segnalazioni Maree (ICPSM) forecast centre of the Venice Municipality. The model calculates sea level and currents in the whole Mediterranean Sea and the Venice Lagoon under the action of atmospheric forcing fields (pressure and winds) operationally supplied by the European Centre for Medium-Range Weather Forecasts (ECMWF). A neural-network module was implemented to correct model results with observed sea-level data in the Adriatic Sea. Every 6 h, the operational model produces a sea-level forecast for the next six days in the Northern Adriatic Sea in the Venice Lagoon. A statistical analysis was performed on the operational results for 2008–2009, to investigate the model goodness-of-fit and its reliability in the operational context. The main statistical quantities (mean error $E$, standard deviation $\sigma$, maximum overestimation $E_{\text{max}}$ and maximum underestimation $E_{\text{min}}$) were computed. The model predicts the sea level both in Venice and in the open sea with good accuracy, with $E$ and $\sigma$ of the order of 1 cm and 5 cm, respectively, in the first 24 h of anticipation during normal weather conditions. Model errors increase when only considering periods of storm surge events.

Introduction

The city of Venice, located in the centre of the Venice Lagoon, is exposed to severe storm surge events occurring in the Adriatic Sea, particularly during autumn and winter (Canestrelli et al. 2001). Low pressure and Sirocco winds, blowing from the south-east and channelled by orography along the Adriatic major axis, raise the sea level in the Northern Adriatic and cause flooding in Venice. Such events damage the unique historical and artistic heritage of the city and influence both daily life and tourism. The frequency of storm surges has increased in recent years as a consequence of sea-level rise: in the period 1990–1999, the city was subjected to high-water events on average 4 times per year, and during the period 2000–2009 an average of 5.2 times per year. Here, ‘high-water events’ are defined as a water level higher than 110 cm above datum. These events flood about 12% of the urban area (Battistin & Canestrelli 2006). This frequency decreases to twice per year for water levels above 120 cm, which flood 28% of the city area. As can be seen, a small increment in water level has a strong impact on the flooding area.

For water levels above 140 cm, 59% of the city is already flooded (ICPSM-flooding 2016).

Tides are also relatively important. The tidal excursion in Venice is about 1 m, one of the highest observed in the Mediterranean. These tides interfere with the peaks of high tide; normally a positive interference is a prerequisite for the occurrence of high tides.

In recent decades, a great effort has been made to forecast such meteorological events with increasing accuracy. Various kinds of numerical models, both statistical (Canestrelli & Moretti 2004; Tosoni & Canestrelli 2011) and hydrodynamic (Bajo et al. 2007; Bajo & Umgiesser 2010) were operationally set up at the Istituzione Centro Previsioni e Segnalazioni Maree (ICPSM), the office of the Venice Municipality in charge of sea-level forecasting and communicating with the city to alert the population in the case of upcoming predicted high-water events (Canestrelli & Zampato 2005).

Statistical models are based on an autoregressive scheme and compute the sea level in Venice on the basis of predictors (observed sea level in Venice, observed and predicted atmospheric pressure in certain
locations of the Adriatic and Tyrrenhian seas) and coefficients, derived through calibration on a 25-year database containing data for the period 1966–1990 (Tosoni & Canestrelli 2011). Such models, largely used at the ICPSM since 1990, provide accurate sea-level forecasting, especially in the short term (mean error $\bar{E} = -0.8$ cm, standard deviation $\sigma = 6.0$ cm, with 24-h anticipation, computed on the results of the operational simulations run at the ICPSM in the period 1 August 2008–31 July 2011, from the ICPSM website (ICPSM-model accuracy 2016).

Unfortunately, since they are based on correlation among physical variables without including any mathematical description of the physical processes, their performance is strictly dependent on the calibration database. For this reason their reliability could decrease in the future, in case of relatively rapid changes in the atmospheric circulation patterns or due to morphological modifications in the Venetian littoral, as those related to the works for the safeguarding of Venice already initiated at the inlets of the lagoon (MOSE 2016; Gentilomo & Cecconi 1997).

Hydrodynamic models integrate the primitive equations on a computational grid that represents the physical system of the Mediterranean Sea, the Adriatic Sea and the Venice Lagoon. They take into account the sea bathymetry and morphology and a great amount of atmospheric information constituted by forcing atmospheric fields over the whole geographic area, instead of the punctual pressure data required by statistical models. Hydrodynamic models seem to be a forecasting tool suitable for adapting to environmental changes (WMO 2011).

Reliable forecasts are especially important in view of the new mobile gates that are being built at the inlets of the Venice Lagoon. These barriers should protect the city from flooding above a certain water level (to date, up to 110 cm). The decision on the closure is taken several hours (around four) in advance based on the predicted water level at peak surge. Therefore, errors in forecasts could lead to false alarms, erroneous closures or missed closures in case of underestimated water levels (Umgiesser & Matticchio 2006).

This paper is focused on the quality of results of the operational Shallow Water Hydrodynamic Model (SHYFEM), developed at the Institute of Marine Sciences (ISMAR) of the National Research Council (CNR) of Venice and operationally implemented since 2002 at the ICPSM of the Venice Municipality (Umgiesser et al. 2004). Different versions of the SHYFEM have been developed, the last one running four times per day and taking into account sea-level data in the Northern Adriatic Sea available in real time at the ICPSM. Model results obtained during the operational activity for the two-year period 2008–2009 were compared with observed data in the open sea and in the inner lagoon. A statistical evaluation of the model performance is presented, supplying useful information on the model reliability and accuracy.

**Methods**

The operational model

The hydrodynamic module

The SHYFEM solves the shallow-water equations spatially by means of a finite-element discretisation technique, while the temporal integration is made with a semi-implicit algorithm that enables good computational stability with low computational cost (Umgiesser et al. 2004). The 2D equations are as follows:

\[
\begin{align*}
\frac{\partial U}{\partial t} - fV + gH \frac{\partial}{\partial x} \left( \zeta + \frac{p}{\rho_0 g} \right) & - A_H \left( \frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} \right) - \frac{1}{\rho_0} (\tau_{sx} - \tau_{sy}) = 0, \\
\frac{\partial V}{\partial t} + fU + gH \frac{\partial}{\partial y} \left( \zeta + \frac{p}{\rho_0 g} \right) & - A_H \left( \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} \right) - \frac{1}{\rho_0} (\tau_{sy} - \tau_{sx}) = 0, \\
\frac{\partial \zeta}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} & = 0,
\end{align*}
\]

where $\zeta$ is the water level, $U$ and $V$ are the vertically-integrated velocities (total or barotropic transports), $t$ is the time, $x$ and $y$ are the Cartesian coordinates, $f$ is the gravitational acceleration, $p$ is the atmospheric pressure at the mean sea level, $\rho_0$ is the reference water density, $H = h + \zeta$ is the total water depth, $h$ is the undisturbed water depth, $f$ is the variable Coriolis parameter, $\tau_x$ is the wind stress, $\tau_b$ is the bottom stress and $A_H$ is the horizontal diffusion coefficient.

The model is used in two dimensions in order to reduce the computational cost. This is a common and widely-accepted simplification used in storm-surge operational systems (WMO 2011).

The wind stress is specified with a Smith and Banke (1975) formulation and is computed from the European Centre for Medium-Range Weather Forecasts (ECMWF) wind fields. The bottom stress in $x$ is specified with the following bulk formula:

\[
\tau_{sx} = \rho_0 c_b \frac{H}{U^2} |U|
\]

where $c_b = 0.0025$ is the bottom drag coefficient and $|U|$ is the modulus of the current transport. A similar equation is valid for the $y$ direction.
A grid of the whole Mediterranean Sea and a grid of the Venice Lagoon are used (Figure 1). The boundary conditions at the Gibraltar Strait leave the normal fluxes free and set the sea level to zero. In the operational implementation the surge water levels computed by the first run of the model in the Mediterranean Sea are extracted near Venice at the CNR platform, and post-processed by the neural-network routine (described below). The corrected residual level is added to the astronomical tide, computed from the harmonic constants, and applied as a boundary condition to the Venice Lagoon inlets. A second simulation runs inside the lagoon, providing the total sea level and current forecast. Results are extracted in the main locations.

**Neural-network module**

An artificial neural network (ANN) model is used to improve the deterministic forecast at the CNR platform. The Fast Artificial Neural Network (FANN) is an open-source package, freely available online (FANN 2016). The network is fed with the residual level observed at the CNR platform one day before the operational run and with the deterministic hindcast and forecast in the same location. The network provides an improved storm-surge forecast at the CNR platform. The ANN calibration is executed using a three-year database, while the validation is made with a one-year database (Bajo & Umgiesser 2010).

**Operational implementation**

The SHYFEM has been implemented into several versions over the years, always keeping the previous versions to compare them with the new one. At present two versions are running operationally, V02 and V03. Both versions are forced with ECMWF 0.5 resolution wind and mean sea level (MSL) pressure fields every 6 h. Simulations run for two days using analysis fields and the remaining five days using forecast fields.

The main difference between the two versions is the pre-processing of the wind. In V02 the wind speed over the Adriatic Sea is multiplied by variable coefficients, obtained from a spatial comparison of modelled and scatterometer wind data. With V03, this correction depends not only on the location of the wind but also on its direction. This is a sort of bias correction, as the wind is often underestimated in the Adriatic Sea due to the poor orographic representation of this zone (Cavaleri & Bertotti 2004).

Both model versions extract the computed surge at the Acqua Alta Platform (AAPTF) near Venice (Figure 1), and add the tide, computed through a harmonic analysis. This provides the total sea-level forecast outside the Venice lagoon, which is corrected by means of a neural-network routine that uses the observed residual level of the last day as input neurons (Bajo & Umgiesser 2010). The ANN implementation differs in the two version of the model. In version V02 the post-processing is run once a day, whereas the results analysed in this work come from V03, for which the neural-network routine is executed every 6 h, using the latest available data and producing four forecasts per day.

The ultimate sea-level forecast is applied as forcing at the three lagoon inlets, for a simulation running inside the lagoon, in order to have an accurate forecast in several locations inside the lagoon.

**Statistical analysis methodology**

The accuracy of SHYFEM results was assessed comparing forecast sea levels with observed data. Two locations of interest were considered: the CNR platform in the Northern Adriatic Sea, 15 km offshore from the Lido inlet, and the Punta Salute station, in the historical city of Venice (Figure 1). The analysis of the results at the CNR platform gives an indication of the accuracy of the Mediterranean Sea model and the neural-network
module, while the Punta Salute results allow an evaluation of the
performance of the Venice Lagoon model. The study was conducted on the
predicted sea levels of the two-year period 2008–2009.

The statistical analysis was carried out following the
same approach already used to evaluate the results of
statistical models (Canestrelli & Moretti 2004), by con-
sidering the difference $z_i$ between modelled $z_{mi}$ and
observed $z_{oi}$ sea level at time $t_i$:

$$z_i = z_{mi} - z_{oi}. \quad (3)$$

The commonly-used statistical quantities were com-
pounded for each forecast lag $f$: mean $\bar{E}$, standard deviation $\sigma$, maximum overestimation $E_{\text{max},f}$ and maximum underestimation $E_{\text{min},f}$:

$$\bar{E}_f = \frac{1}{N} \sum_i z_{fi} = \frac{1}{N} \sum_i (z_{mi} - z_{oi}) = \bar{z}_m - \bar{z}_o \quad (4)$$

$$\sigma_f = \sqrt{\frac{1}{N-1} \sum_i (z_{fi} - \bar{E}_f)^2}$$

$$\sigma_f = \sqrt{\frac{1}{N-1} \sum_i [(z_{mi} - \bar{z}_m) - (z_{oi} - \bar{z}_o)]^2} \quad (5)$$

$$E_{\text{max}} = \max \{z_{fi}\} \quad (6)$$

$$E_{\text{min}} = \min \{z_{fi}\} \quad (7)$$

where $N$ is the number of data, both modelled and
observed.

Note that $\bar{E}_f$ is the bias of the two time series of mod-
elled $x_{mi}$ and observed $x_{oi}$ data at forecast lag $f$, which
gives indications about amplitude and signs of systematic
errors of the model, if present. A positive value of $\bar{E}_f$ indi-
cates that the model systematically overestimates sea
levels.

The standard deviation $\sigma_f$ relates to the difference in
the dispersion of data around their average in the two
time series. If the time series of modelled and observed
data were translated to the same mean, the standard
deviation $\sigma$ would be equal to the route mean square
(RMS) error.

The maximum overestimation $E_{\text{max},f}$ and the max-
imum underestimation $E_{\text{min},f}$ are of great importance in
the operational context, indicating respectively the
occurrence of false alarms and missing alarms.

At first all model results were considered. In a second
phase, only data with observed surges (residual level)
exceeding some fixed thresholds were taken into
account.

### Results and discussion

#### Statistical analysis

Figure 2 and Table 1 display the results of the statistical
analysis carried out on forecasted sea levels by SHYFEM
V03 at different forecast lags for the CNR platform and
Punta Salute, considering all model results. The errors of
the model are very similar for the CNR platform in the
open sea and for Punta Salute in the historical centre of Venice.

For the CNR platform, the mean error is very small,
lower than 1 cm in the first 48 h, but always negative,
indicating a good sea-level forecast on average, with a
light tendency to underestimation. For Punta Salute, $\bar{E}$
is of the order of 1 cm, positive in the first 60 h of antici-
pation and negative afterwards. For the CNR platform,
the standard deviation is of 5.2 cm at 24-h forecast lag,
6.9 cm at 48 h and 8.4 cm at 72 h. It is lower than 5
cm during the first hours of anticipation (3–18 h).
Slightly worse values were obtained for Punta Salute.
Such values of $\sigma$ witness a very good performance of
the SHYFEM in the open sea and the lagoon, both at
short forecast lags, necessary for the nowcasting in an
operational forecasting centre, and at higher antici-
pations (one or two days) at which the operational
activity is planned.

The behaviour of maximum overestimation and
maximum underestimation is not symmetrical; Figure 2
reveals the occurrence of cases of severe sea-level
underestimation by the SHYFEM; about 80 cm at great
forecast lags. At 24-h forecast lags the maximum under-
estimation observed during the two-year period of 2008–
2009 was 47 cm. The maximum overestimation was less
severe, with values of the order of 30 cm at high forecast
lags (from 72–120 h). This asymmetry can be explained
by the features of the physical system; maximum errors
are related to the occurrence of extreme sea-level events
in the Northern Adriatic, both high and low water.
Nevertheless, cases of strong underestimation happen
with severe storm surges, when the sea level reaches
very high values that the model cannot reproduce. On
the contrary, cases of very low sea level are rarely
observed. As a consequence, it is more probable that a
forecast model of any type will underestimate than
overestimate.

It has to be noted that analysis data, represented in
Figure 2 and Table 1 as data at forecast lag 0, show higher
errors than the forecast data from the CNR platform.
This is due to the structure of the SHYFEM; analysis
data are computed by the base version of the model with-
out taking into account observed sea-level data and only
factoring in meteorological forcing, while forecast data
benefit from the neural-network procedure which greatly improves the model’s performance. This feature is not observed at Punta Salute, because in that location the sea level is computed by the Venice Lagoon model, where the boundary conditions at the inlets are observed sea levels when available (that is in the ‘past’) or forecasted sea levels after neural-network post-processing.

The performance of the SHYFEM should also be evaluated with regard to specific situations in which severe weather conditions cause the occurrence of a storm surge.

Figure 2. Mean error $\bar{E}$, standard deviation $\sigma$, maximum overestimation $E_{\text{max}}$ and maximum underestimation $E_{\text{min}}$ of the SHYFEM V03 results for 2008–2009 with respect to the observed sea levels at the CNR platform (top) and the Punta Salute station (bottom).

Table 1. Mean error $\bar{E}$, standard deviation $\sigma$, maximum overestimation $E_{\text{max}}$ and maximum underestimation $E_{\text{min}}$ plus total number of data for the SHYFEM V03 results for 2008–2009 with neural-network correction with respect to the observed sea levels at the CNR platform and the Punta Salute station. Labels f003, f006, …, f120 refer to model results at forecast lags 3, 6, …, 120 hours.

| Site          | $\bar{E}$ | $\sigma$ | $E_{\text{min}}$ | $E_{\text{max}}$ | n       |
|---------------|-----------|----------|------------------|------------------|---------|
| CNR platform  | -4.7      | 8.3      | -47.0            | 29.0             | 59,452  |
| Punta Salute  | 1.4       | 2.5      | -20.0            | 12.0             | 55,336  |
| f003          | -0.1      | 4.1      | -32.0            | 22.0             | 2308    |
| f006          | -0.3      | 4.8      | -40.0            | 26.0             | 2308    |
| f012          | -0.3      | 4.8      | -40.0            | 25.0             | 2308    |
| f018          | -0.4      | 4.9      | -42.0            | 25.0             | 2308    |
| f024          | -0.4      | 5.2      | -47.0            | 27.0             | 2308    |
| f048          | -1.0      | 5.2      | -56.0            | 30.0             | 2308    |
| f072          | -1.6      | 6.9      | -55.0            | 30.0             | 2308    |
| f096          | -2.1      | 8.4      | -69.0            | 30.0             | 2308    |
| f120          | -2.5      | 9.9      | -75.0            | 30.0             | 2308    |

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| f120          | -2.5      | 9.9      | -75.0            | 30.0             | 2308    |
Figure 3 shows the behaviour of mean error $\bar{E}$ and standard deviation $\sigma$ for CNR platform, at different forecast lags, considering only cases in which the observed surge was higher than some fixed thresholds: 20, 30, 40 and 50 cm. The accuracy of the forecast drastically decreases as the surge threshold increases; this effect concerns in particular the mean error, while $\sigma$ seems less sensitive, suggesting that in the case of severe storm surges the model underestimates the sea level globally, on the whole sea-level time series rather than only on sea-level peaks. The errors increase at high forecast hours: for surges $>40$ cm, at 24-h forecast lag, $\bar{E} = -8.6$ cm and $\sigma = 9.3$ cm; at 72 h, $\bar{E} = -20.9$ cm and $\sigma = 13.0$ cm.

Figure 4 and Table 2 report the complete statistical analysis results obtained considering only forecast sea levels when the observed surge was higher than 40 cm. They highlight the capability of the SHYFEM to predict sea levels in storm surge conditions, in comparison with the normal weather and tide conditions of Figure 2. The model accuracy is obviously worse, as already shown in Figure 3. Maximum underestimation does not change with respect to Figure 2, because the maximum values that emerge considering all cases are just those obtained in storm surge events. Maximum overestimation is lower than in the normal case: in case of storm surges it is very rare that the sea level is overestimated, which results in a false alarm.

In Figure 5, a comparison between SHYFEM V02 and V03 is presented, giving the mean error $\bar{E}$ and standard deviation $\sigma$ for the CNR platform at different hours of the day. In V03 the model runs four times every day, at 00:00, 06:00, 12:00 and 18:00 Coordinated Universal Time (UTC), while in V02 it runs once a day at 00:00 UTC. The mean error $\bar{E}$ shows similar values in both versions. The improvement in V03 is evident in the plot of the standard deviation $\sigma$: every 6 h the model assimilates the observed sea level.
through the neural-network module and consequently reduces the error in the prediction. In V02, on the contrary, $\sigma$ increases slowly during the day and decreases abruptly with the new simulation at 00:00 UTC of the day after.

**Analysis of two severe storms: 1 December 2008 and 27 April 2009**

In this section, the SHYFEM results for two high-water cases which occurred in Venice during the period 2008–2009 are presented.

**The high-tide event of 1 December 2008**

The event of 1 December 2008 was of exceptional intensity; the water reached a level of 156 cm at 10:45 am (local time), the fourth-highest level registered in Venice since the beginning of regular observations. Figure 6 reports the pressure field over Europe on 1 December at 00:00 UTC.

On 29 November, the Icelandic low made a deep trough west of Spain, merging with a low centred in the Western Mediterranean Sea. On 30 November there was a complex low system over the whole European region and the Mediterranean Sea, centred over France. The low system moved further east the day after, with the formation of a low-pressure centre on the Ligurian Sea, characterised by a cold front over the Tyrrhenian Sea (Figure 6). On the Adriatic Sea, strong Sirocco winds arose, with a maximum intensity reaching 20.3 m/s at the AAPTF, located near Venice.

On 30 November the water level at the Punta Salute station in Venice reached 100 cm on the local data, exceeding the astronomical tide of about 40 cm due to
the pressure minimum, a quite normal situation during autumn in the Northern Adriatic Sea. In the first hours of 1 December, because of the strong Sirocco wind, the level increased dramatically and reached the exceptional value of 156 cm at 10:45 am. The event was characterised by a sharp sea-level peak occurring in the morning, with the level resting at levels higher than 110 cm for about 7 h. The sea level rapidly decreased during the afternoon.

**Table 2.** Mean error $\bar{E}$, standard deviation $\sigma$, maximum overestimation $E_{\text{max}}$ and maximum underestimation $E_{\text{min}}$ plus total number of data for the SHYFEM V03 results for 2008–2009 with neural-network correction with respect to the observed sea levels at the CNR platform and the Punta Salute station for surges higher than 40 cm. Labels f003, f006, …, f120 refer to model results at forecast lags 3, 6, …, 120 hours.

| Site         | Analysis | f003 | f006 | f012 | f018 | f024 | f048 | f072 | f096 | f120 |
|--------------|----------|------|------|------|------|------|------|------|------|------|
| CNR platform |          |      |      |      |      |      |      |      |      |      |
| $E$          | $-16.5$  | $-8.3$ | $-7.8$ | $-7.7$ | $-8.6$ | $-14.4$ | $-20.9$ | $-26.4$ | $-27.7$ |      |
| $\sigma$     | $11.9$   | $7.4$ | $8.3$ | $8.3$ | $8.3$ | $9.3$ | $11.4$ | $13.0$ | $14.0$ | $15.0$ |
| $E_{\text{min}}$ | $-47.0$ | $-40.0$ | $-40.0$ | $-42.0$ | $-47.0$ | $-56.0$ | $-55.0$ | $-69.0$ | $-75.0$ |      |
| $E_{\text{max}}$ | $20.0$ | $11.0$ | $11.0$ | $13.0$ | $14.0$ | $10.0$ | $10.0$ | $0.0$ | $13.0$ |      |
| n            | $2735$   | $112$ | $110$ | $112$ | $111$ | $111$ | $110$ | $107$ | $117$ | $86$  |
| Punta Salute |          |      |      |      |      |      |      |      |      |      |
| $E$          | $0.1$    | $-2.4$ | $-6.9$ | $-6.5$ | $-6.7$ | $-6.9$ | $-12.5$ | $-19.7$ | $-26.3$ | $-27.6$ |
| $\sigma$     | $3.0$    | $5.2$ | $9.0$ | $9.1$ | $9.2$ | $10.2$ | $11.4$ | $13.8$ | $14.4$ | $15.9$ |
| $E_{\text{min}}$ | $-11.0$ | $-39.0$ | $-40.0$ | $-42.0$ | $-46.0$ | $-51.0$ | $-66.0$ | $-77.0$ | $-77.0$ |      |
| $E_{\text{max}}$ | $10.0$ | $16.0$ | $12.0$ | $12.0$ | $20.0$ | $13.0$ | $13.0$ | $10.0$ | $23.0$ |      |
| n            | $2718$   | $113$ | $114$ | $114$ | $113$ | $114$ | $113$ | $109$ | $117$ | $89$  |

**Figure 5.** Mean error $\bar{E}$ (top) and standard deviation $\sigma$ (bottom) of the results for SHYFEM V02 and SHYFEM V03 for 2008–2009 at different hours in a day with respect to the observed sea levels at the CNR platform.
and the day after reached a maximum of only 102 cm. At the CNR platform, in the open sea, the sea level reached a maximum of 154 cm on 1 December at 9:55 am. The model results are shown for the CNR platform, where both results of the SHYFEM without and with neural-network correction are available.

In Figure 7(top), the forecasted values of V03 are shown, with neural-network correction, computed by four different runs: the run of 28 November at 00:00, 83 h before the event, the run of 29 November at 00:00, 59 h before the event, the run of 30 November at 00:00, 35 h before the event and the run of 1 December at 00:00, 11 h before the event. The forecast was not successful: the sea-level maximum on 30 November was already underestimated by more than 20 cm by the runs of 29 and 30 November. The underestimation was also greater for the peak on 1 December: the error was $-43$ cm 35 h before the event and $-24$ cm 11 h before the event. The results of V03 without neural-network correction, presented in Figure 7(bottom) for comparison, show a greater error in the prediction of peaks, indicating that the use of an ANN gives an improvement in the model performance.

The event of 1 December 2008 was very difficult to forecast for all operational models of the ICPSM: the official water-level forecast of the centre, formulated by ICPSM technical personal merging model results, observed data and subjective evaluations, was 110 cm at 10:00 am on 30 November, i.e. an underestimation of 46 cm 24 h before the event. At 00:00 on 1 December, the forecast level was 120 cm, with an underestimation of 36 cm 11 h before the maximum.

The high-tide event of 27 April 2009

Another event occurred on 27 April 2009. The event was less important in terms of the water level, which in Venice at the Punta Salute station reached 117 cm at 11:25 pm local time. However, it was predicted with greater accuracy than the 1 December 2008 event. The SHYFEM results are reported in Figure 8, where it can be seen that the model was able to forecast the event with an overestimation of 14 cm 23 h before the maximum. Actually, the timing of the maximum peak was nearly perfect, even with a forecast executed four days earlier, and the difference of the forecast level to the observed one was always less than 15 cm. However, what changed was the reproduction of the through just after the maximum of the event. The forecasts carried out three or four days before the through were heavily underestimated by over 20 cm. From two days earlier, the through was nearly perfectly reproduced. In this case the neural-network adjustment was able to successfully adapt the forecast to the observations.

Figure 6. Analysis of the mean sea-level pressure field over Europe on 1 December 2008 at 00 UTC.
Conclusions

The results of the SHYFEM for operational sea-level forecasts in Venice during the two-year period 2008–2009 have been presented. The model is capable of very accurately predicting the sea level under normal weather conditions, with $\bar{E} = 1.1$ cm and $\sigma = 5.5$ cm at Punta Salute, at 24-h forecast lag. The quality of the results decreases in case of severe storm surges. The sea level is affected in such cases by an overall underestimation, revealed by the marked worsening of the mean error; considering only cases with surges higher than 40 cm, $\bar{E} = -6.9$ cm and $\sigma = 10.2$ cm at Punta Salute, at 24-h forecast lag.

Multiple runs, four every day at synoptic hours, result in an improvement of model results in the most recent model version (V03) due to the frequent assimilation of observed data through the neural-network module.

The analysis of two storm-surge events demonstrates that severe storms are still far from being predicted reliably. The neural-network method helps to improve the difference between the predicted and observed

![Figure 7. Observed values at the CNR platform and SHYFEM V03 forecast values with neural-network correction (top) and without neural-network correction (bottom) for 1 December 2008.](image-url)
A quite anomalous event is the case of 1 December 2008, where the forecast error is quite high. However, in the case of 27 April 2009 the forecast model did a good job in describing the water level.

It must be clear that more robust results can be achieved if the data taken into account cover a longer period. Importantly, the tides have been excluded from this analysis; only the surge has been modelled. If both the surge and tides are being modelled then error estimates will go up, because tidal modelling still shows inaccuracies, especially along the coast. Much higher resolution would be needed for the Adriatic Sea, which would in turn slow down the surge forecast.

Further improvements could be implemented into the operational model by using winds with a higher resolution, even if in this case the model will have to be recalibrated. Other very promising possibilities are the application of assimilation techniques in the Adriatic Sea. These might be achieved by using tide gauge data along the Italian coast, and can also be experimentally achieved through the use of remote sensed data (winds from scatterometers or water levels from altimeters).

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