Ocean Modelling 113 (2017) 85–94

Contents lists available at ScienceDirect

Ocean Modelling

journal homepage: www.elsevier.com/locate/ocemod

Impact of using scatterometer and altimeter data on storm surge forecasting

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ARTICLE INFO

Article history:
Received 26 May 2016
Revised 22 March 2017
Accepted 30 March 2017
Available online 5 April 2017

Keywords:
Storm surge
Data assimilation
Satellite observations
Mediterranean Sea
Numerical modelling

ABSTRACT

Satellite data are rarely used in storm surge models because of the lack of established methodologies. Nevertheless, they can provide useful information on surface wind and sea level, which can potentially improve the forecast. In this paper satellite wind data are used to correct the bias of wind originating from a global atmospheric model, while satellite sea level data are used to improve the initial conditions of the model simulations. In a first step, the capability of global winds (biased and unbiased) to adequately force a storm surge model are assessed against that of a high resolution local wind. Then, the added value of direct assimilation of satellite altimeter data in the storm surge model is tested. Eleven storm surge events, recorded in Venice from 2008 to 2012, are simulated using different configurations of wind forcing and altimeter data assimilation. Focusing on the maximum surge peak, results show that the relative error, averaged over the eleven cases considered, decreases from 13% to 7%, using both the unbiased wind and assimilating the altimeter data, while, if the high resolution local wind is used to force the hydrodynamic model, the altimeter data assimilation reduces the error from 9% to 6%. Yet, the overall capabilities in reproducing the surge in the first day of forecast, measured by the correlation and by the rms error, improve only with the use of the unbiased global wind and not with the use of high resolution local wind and altimeter data assimilation.

1. Introduction

Storm surges are among the most dangerous natural phenomena affecting human settlements in coastal areas. In Europe, 40% of the population of coastal countries lives within 50 km of the sea and 40% of the Europe's gross domestic product is made in these regions (EEA, 2013). Therefore, a good forecast of these events can avoid big economic losses and, sometimes, fatalities (Chaumillon et al., 2017).

Due to these motivations and to the small usage of satellite data in this field, in 2012 the European Space Agency (ESA) decided to fund two projects, eSurge (CGI-group, 2012) and eSurge-Venice (ISMAR, 2012). While eSurge considered storm surge cases in different areas in the world, most of them located in Europe, the eSurge-Venice project was dedicated only to Venice and the Adriatic Sea. The aim of the projects was to collect data of past events and to set-up a web-system able to automatically collect data of future events. Moreover, several experiments have been carried out to investigate the impact of the use of satellite data in storm surge forecasting. Different methodologies have been developed and some results have been shown in Madsen et al. (2015) for eSurge and in De Biasio et al. (2016) for eSurge-Venice.

The main satellite quantities that can be related to storm surge are altimeter sea level and ocean surface wind, derived from scatterometer data. The former provides a quantity directly comparable with the output of storm surge models, while the latter can be compared with the 10-m wind over the sea computed by atmospheric models and used as forcing in the storm surge models.

Altimeter data have been used in Han et al. (2012), with tide gauge data, to study the cross-shelf features of a past storm surge event, while in Antony et al. (2014) a 15 year dataset of storm surges in the Bay of Bengal, obtained by altimeter data, has been analysed. However, possible applications of altimeter data, in an operational context, have been investigated only recently (Etala et al., 2015).

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http://dx.doi.org/10.1016/j.ocemod.2017.03.014

The most straightforward method to use scatterometer data to improve a model wind is through data assimilation. At the moment, scatterometer data are assimilated by both global atmospheric models (Hersbach, 2010) and limited area models (De Haan et al., 2013). Usually these models cannot exploit the full information of such data and data thinning is needed before assimilation, see Section 3.2. Due to their higher resolution, limited area models potentially require less thinning in the assimilation, but they are not operational everywhere and not always well calibrated. Therefore, scatterometer data can contain information on the wind not assimilated, which can be used to support the model wind (Zampato et al., 2006).

The methodology followed in this paper is to produce new wind fields, from those of a global atmospheric model, through tuning with scatterometer data. This tuned wind has been tested against the original one, by forcing a finite element hydrodynamic model for the reproduction of eleven storm surge cases, observed in Venice from 2008 to 2012. Finally, also the wind of a high resolution local atmospheric model has been tested. Altimeter data are assimilated directly into the hydrodynamic model, using a variational method. The results presented here extend and refine those obtained in the eSurge-Venice project. The modelling chain has been improved by using a more refined computational grid and a different prescription of the error covariances in the altimeter data assimilation. Moreover, the results obtained using a high resolution local wind have been added.

The sections of this paper include the description of the study area and of its storminess features, of the hydrodynamic model, of the different forcing fields, of the methodology to tune the wind and of the altimeter data assimilation. Then, results are divided in a statistical analysis of the eleven cases simulated and in the exposition of a particular case, the most extreme one. Discussion and the conclusions are set out at the end.

2. Study area

In autumn and winter storm surges are frequent in the northern Adriatic Sea. They are forced partly by the inverse barometric effect but mainly by the wind, which, especially in autumn, is blowing from south-east (*Sirocco*), with a direction near to the main axis of the basin (Fig. 1). The elongated shape of the basin and the shallowness of the northern part make this region one of the most exposed to storm surges in the whole Mediterranean Sea. The Sirocco wind is warm and wet, often associated with a low pressure centred in the Tyrrhenian Sea or in the Gulf of Genoa, and in the northern Adriatic can reach a speed of 20 m/s. There is a second frequent wind coming from north-east, named *Bora*, which can be even stronger. Its fetch over the Adriatic Sea is much smaller than for Sirocco, thus generating smaller surges near Venice. If this wind is associated with the presence of a strong Russian thermal anti-cyclone, it is cold and dry and is named *Bora chiara* (clear). If otherwise, the Sirocco wind is blowing in the southern Adriatic and, driven by the mountains, turns north-easterly in the northern part, it is surnamed *Bora scura* (dark) and can bring extreme storm surges.

Although flooding events affect several sites in the northern Adriatic Sea (Pasarić and Orlić, 2001), the city of Venice is the most relevant case, due to the severity of the events and to the historical and artistic heritage of the city. Venice is located in the north-eastern Italian coast (Fig. 1), inside its lagoon, which is connected to the sea by three inlets. This position ensures a natural protection against the direct action of wind waves, but not against storm surges, which propagate inside the lagoon with delays of up to one hour and a half with respect to the open sea, depending on the distance from the inlets and on the complex shape of the lagoon bottom. The pavement of Venice is barely 80 cm above the mean sea level and, during spring tides, even moderate surges can cause floods. Considering that, at present, there are more than ten flood events per year and that this number should grow, according to the latest estimation on the mean sea level change (Tsimplis et al., 2012), the government decided to build flood barriers at the three lagoon inlets (Nosengo, 2003). These barriers should block water from entering the lagoon during storm surges. However, since the closing procedure will depend on the forecasted water level, a good forecast will be crucial for the correct operation of these barriers.

One of the main factor affecting the accuracy of storm surge forecasts is certainly the quality of the wind forcing (Zecchetto and Accadia, 2014). In the Adriatic region, southerly winds are subject to tunnelling effects at the Otranto strait, while easterly winds are often katabatic, blowing down after crossing the Dinaric Alps. These local effects are badly reproduced by global atmospheric models, thus causing an underestimation of the surge level as well (Bajo et al., 2007; Bajo and Umgiesser, 2010).

The Adriatic Sea is also subject to seiche oscillations, which must be reproduced correctly in order to have a good forecast of the sea level. These oscillations follows an initial sea level perturbation, like a storm surge, and are gradually damped by the bottom friction and by the partially open Adriatic boundary at the south. There are two important modes of oscillation, the main one has a period of about 22 h, while the second of 11 h. The first mode shows the highest amplitude in the northern Adriatic Sea, just in front of the Venice lagoon (Vilibić, 2006). Ongoing seiches can overlap with a new storm surge, further increasing the total sea level.

Other important components of the sea level are the seasonal mean sea level (Bergant et al., 2005) and the astronomical tide (Ferrarin et al., 2015). However they are well predictable, at least for some days in advance, and are not discussed further in this paper.

3. Methods

3.1. The hydrodynamic model

The hydrodynamic model used in this work is named SHYFEM (Shallow water HYdrodynamic Finite Element Model) and, as suggested by the name, solves the shallow water equations using a finite element numerical method. This technique allows an excellent reproduction of the coastal and bathymetric features and is, therefore, used also by other storm surge models (Dietrich et al., 2011; Bertin et al., 2012).

The model is written in FORTRAN 90, covered by the GNU General Public License and freely available on the Web (ISMAR, 2016). The model can be used for different applications both in deep and shallow areas (e.g., Bajo et al., 2014; Ferrarin et al., 2015) and can be coupled to ecological, sediment, Lagrangian and wave models (Ferrarin et al., 2014; 2013).

The time discretisation uses a semi-implicit scheme, in order to obtain an unconditional stability in the reproduction of gravity waves. The water levels are solved semi-implicitly, while the transports can be computed afterwards explicitly, thus obtaining a much smaller linear system than in the case of a fully implicit scheme. In order to avoid mass loss with this scheme, the variables are prescribed in a staggered grid, with water level in the nodes and water transport in the elements.

The model has different vertical discretisation schemes, but in the present case it is used in two dimensions. Furthermore, the baroclinic terms, the advection of momentum and the tides are not considered. This formulation has proved to reproduce storm surges adequately (Verlaan et al., 2005) and is computationally cost-effective, which is important for operational models using