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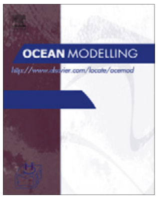

Tide-surge-wave modelling and forecasting in the Mediterranean Sea with focus on the Italian coast

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ABSTRACT

A tide-surge-wave modelling system, called Kassandra, was developed for the Mediterranean Sea. It consists of a 3-D finite element hydrodynamic model (SHYFEM), including a tidal model and a third generation finite element spectral wave model (WWMII) coupled to the hydrodynamic model. The numerical grid of the hydrodynamic and wave models covers the whole Mediterranean with variable resolution. The comparison with coastal tide gauge stations along the Italian peninsula results in a root sum square error for the main tidal components equal to 1.44 cm. The operational implementation of the Kassandra storm surge system through the use of a high resolution meteorological model chain (GFS, BOLAM, MOLOCH) allows accurate forecast of total water level and wave characteristics. The root mean square error for the first day of forecast is 5 cm for the total water level and 22 cm for the significant wave height. Simulation results indicate that the use of a 3-D approach with a depth-varying loading factor and the inclusion of the non-linear interaction between tides and surge improve significantly the model performance in the Italian coast.

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1. Introduction

Several authors (Kim et al., 2008; Brown and Wolf, 2009; Roland et al., 2009; Wolf, 2009) have shown that the coupling of wave, surge and tide is a key element to improve the accuracy of total water level coastal prediction. At the same time, accurate wave forecasting in coastal waters, where the wave field is remarkably influenced by time varying depths and currents, is only possible through a two-way coupling with a hydrodynamic model.

Simulation of storm surge and of the principal physical processes affecting coastal areas requires the use of both numerical models at high spatial and temporal resolution and downscaling techniques capable of reproducing mass exchange between the open sea and coastal waters (Xing et al., 2011). This goal can be achieved through implementation of either nested numerical models based on regular and curvilinear spatial grids (Oddo et al., 2006; Kim et al., 2008; Brown and Wolf, 2009; Debreu et al., 2012), and or numerical models based on unstructured grids Walters, 2006; Jones and Davies, 2008b; Zhang and Baptista, 2008; Roland et al., 2009; Lane et al., 2009; Xing et al., 2011.

The north Adriatic Sea is the Mediterranean sub-basin where storm surges reach higher values (Marcos et al., 2009). For this reason and also because of the presence of the city of Venice, in this area storm surges have been investigated and modelled since the 1970s (Sguazzero et al., 1972; de Vries et al., 1995). Presently, an ensemble of different statistical and deterministic models is operationally used for daily forecasts of the water level in Venice Lionello et al., 2006; Bajo et al., 2007; Bajo and Umgiesser, 2010. However, all these models do not include interactions with waves and/or tides. Climatological studies suggest that in the 21st century the storm surge frequency and magnitude in the Mediterranean Sea will progressively decrease (Marcos et al., 2011; Bellafiore et al., 2011). On the other hand the expected sea level rise will flush in the opposite direction. Exact quantifications in this aspect are not yet foreseeable. Both for this reason and because we are necessarily interested in the present times, we steadily aim at improving the accuracy of the total water level forecast.

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The tidal oscillation in the Mediterranean Sea is generally of the order of few cm, except for the north Adriatic Sea, the north Aegean Sea and the Gulf of Gabes (Tsimplis et al., 1995).

The aim of this study is to investigate and forecast tides, storm surges and waves in the Mediterranean Sea through an unstructured-grid modelling system. Tidal model performance was evaluated against a three year long observational database of water levels acquired in the Italian coast. The accuracy of the operational model was evaluated comparing the modelled water level and wave characteristics against the corresponding measurements taken along the Italian peninsula over a one-year period.

The model chain, called Kassandra, consists of a finite-element 3-D hydrodynamic model (SHYFEM), that includes an astronomical tidal model, coupled with a finite element spectral wind wave model (WWMII). The principal forcing for the wave and hydrodynamic models is the wind at the sea surface. It is well known Wakelin and Proctor, 2002; Zampato et al., 2007; Ardhuin et al., 2007; Cavaleri et al., 2010 that, due to the complicated bordering orography, high-resolution atmospheric modelling is required to properly simulate and forecast wind fields in the Adriatic Sea. To implement an accurate forecasting system, meteorological fields are supplied by the BOLAM and MOLOCH limited-area, high-resolution models, developed and implemented at ISAC-CNR (Institute of Atmospheric Sciences and Climate – National Research Council of Italy) with a daily operational chain, using GFS (NOAA/NCEP) initial analyses and forecast lateral boundary conditions.

The short term (four days) forecasts for the Mediterranean Sea of the storm surge system are available at http://www.ismar.cnr.it/kassandra. The corresponding meteorological model products used as input of the marine model component are available at http://www.isac.cnr.it/dinamica/projects/forecasts.

2. The modelling system

The system discusses here is a coupled wave, current and astronomical-tide model using the same computational grid for all the processes. Forecast 10 m wind and atmospheric pressure fields are provided by the high resolution meteorological models BOLAM and MOLOCH described in more detail in Section 2.3.

The application of triangular unstructured grids in both the hydrodynamic and wave models has the advantage of describing more accurately complicated bathymetry and irregular boundaries in shallow water areas. It can also solve the combined large-scale oceanic and small-scale coastal dynamics in the same discrete domain by subdivision of the basin in triangles varying in form and size.

The considered interactions between waves, surge and tides are: (1) the contribution of waves to the total water levels by mean of the wave set-up and wave set-down; (2) the influence of tides and storm surge on the wave propagation affecting the refraction, shoaling and breaking processes; (3) the effect of water level variation and currents on the propagation, generation and decay of the wind waves.

The spatial variation of the wave action spectra causes a net momentum flux known as radiation stress (Longuet-Higgins and Steward, 1964). The onshore component of this momentum flux is balanced by a pressure gradient in the opposite direction. The physical manifestation of this pressure gradient is the rise or fall of the mean sea level, known as wave set-up and wave set-down respectively. Especially during storm conditions, the radiation stress can be an important terms in storm surge applications as wave set-up increases the water level close to the coast causing widespread damages associated with flooding of the coastal areas (Brown et al., 2011).

The influence of the wave dependent ocean surface roughness on the wind stress parameterization Øyvind et al., 2007; Moon et al., 2009; Olabarrieta et al., 2012; Bertin et al., 2012; Bolaños et al., 2011 and the increase of the bottom friction due to the presence of a wave boundary layer (e.g.Grant and Madsen, 1979) are not considered in this study and will be investigated in a future version of the modelling system.

2.1. The hydrodynamic model

The 3-D hydrodynamic model SHYFEM here applied uses finite elements for horizontal spatial integration and a semi-implicit algorithm for integration in time (Umgiesser and Bergamasco, 1995; Umgiesser et al., 2004).

The primitive equations, vertically integrated over each layer, are:

$$\begin{aligned}
&\frac{\partial U_l}{\partial t}+u_l\frac{\partial U_l}{\partial x}+v_l\frac{\partial U_l}{\partial y}-fV_l\\
&\quad=-gh_l\frac{\partial\zeta}{\partial x}-\frac{gh_l}{\rho_0}\frac{\partial}{\partial x}\int_{-H_l}^{\zeta}\rho' dz-\frac{h_l}{\rho_0}\frac{\partial p_a}{\partial x}+\frac{1}{\rho_0}\left(\tau_x^{top(l)}-\tau_x^{bottom(l)}\right)\\
&\qquad+\frac{\partial}{\partial x}\left(A_H\frac{\partial U_l}{\partial x}\right)+\frac{\partial}{\partial y}\left(A_H\frac{\partial U_l}{\partial y}\right)+\frac{F_l^x}{\rho h_l}+gh_l\frac{\partial\eta}{\partial x}-gh_l\beta\frac{\partial\zeta}{\partial x}
\end{aligned}\tag{1a}$$

$$\begin{aligned}
&\frac{\partial V_l}{\partial t}+u_l\frac{\partial V_l}{\partial x}+v_l\frac{\partial V_l}{\partial y}+fU_l\\
&\quad=-gh_l\frac{\partial\zeta}{\partial y}-\frac{gh_l}{\rho_0}\frac{\partial}{\partial y}\int_{-H_l}^{\zeta}\rho' dz-\frac{h_l}{\rho_0}\frac{\partial p_a}{\partial y}\\
&\qquad+\frac{1}{\rho_0}\left(\tau_y^{top(l)}-\tau_y^{bottom(l)}\right)+\frac{\partial}{\partial x}\left(A_H\frac{\partial V_l}{\partial x}\right)+\frac{\partial}{\partial y}\left(A_H\frac{\partial V_l}{\partial y}\right)\\
&\qquad+\frac{F_l^y}{\rho h_l}+gh_l\frac{\partial\eta}{\partial y}-gh_l\beta\frac{\partial\zeta}{\partial y}
\end{aligned}\tag{1b}$$

$$\frac{\partial\zeta}{\partial t}+\sum_l\frac{\partial U_l}{\partial x}+\sum\nolimits_l\frac{\partial V_l}{\partial y}=0\tag{1c}$$

with l indicating the vertical layer, (U_l,V_l) the horizontal transport at each layer (integrated velocities), f the Coriolis parameter, p_a the atmospheric pressure, g the gravitational acceleration, ζ the sea level, ρ_0 the average density of sea water, $\rho=\rho_0+\rho'$ the water density, τ the internal stress term at the top and bottom of each layer, h_l the layer thickness, H_l the depth at the bottom of layer l. Smagorinsky's formulation (Smagorinsky, 1963; Blumberg and Mellor, 1987) is used to parameterize the horizontal eddy viscosity (A_h). For the computation of the vertical viscosities a turbulence closure scheme was used. This scheme is an adaptation of the k-ϵ module of GOTM (General Ocean Turbulence Model) described in Burchard and Petersen, 1999.

The coupling of wave and current models was achieved through the gradients of the radiation stress induced by waves (F_l^x and F_l^y) computed using the theory of Longuet-Higgins and Steward (1964). The vertical variation of the radiation stress was accounted following the theory of Xia et al. (2004). The shear component of this momentum flux along with the pressure gradient creates second-order currents.

The model calculates equilibrium tidal potential (η) and load tides and uses these to force the free surface (Kantha, 1995). The term η in Eqs. 1a and 1b, is calculated as a sum of the tidal potential of each tidal constituents multiplied by the frequency-dependent elasticity factor (Kantha and Clayson, 2000). The factor β accounts for the effect of the load tides, assuming that loading tides are in-phase with the oceanic tide (Kantha, 1995). Four semi-diurnal (M2, S2, N2, K2), four diurnal (K1, O1, P1, Q1) and four long-term constituents (Mf, Mm, Ssa, MSm) are considered by the model.

Velocities are computed in the center of the grid element, whereas scalars are computed at the nodes. Vertically the model applies Z layers with varying thickness. Most variables are computed in the center of each layer, whereas stress terms and vertical velocities are solved at the interfaces between layers. The

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