HiReSS: Storm surge simulation model for the operational forecasting of sea level elevation and currents in marine areas with harbor works

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Abstract

In this paper we present recent evolvements of a robust numerical model for the simulation of storm surges in gulfs and coastal areas, inside which large harbors and significant urban port facilities exist. HiReSS (High-Resolution Storm Surge) is a 2-DH barotropic model for the simulation of hydrodynamic circulation and sea level variations, based on the depth-averaged shallow water equations. It is applied in large enclosed water bodies or semi-enclosed marginal seas, gulfs, bays and shallow coastal areas over the continental shelf. HiReSS takes into account several processes, such as the inverse barometer effect, shear stresses of wind on the sea surface, Coriolis effects, astronomical tides, ocean bottom friction, turbulence of horizontal eddies, and impact of wave-driven circulation in open seas and nearshore zones. It is implemented in large computational fields, covering e.g. the entire Mediterranean Sea, led to dynamically downscaled simulations in nested high-resolution domains, e.g. Thermaikos Gulf in northern Greece. HiReSS model results refer to sea surface elevation and depth-averaged currents, used as input in irregular wave simulations with a spectral wave model at 3-hour time intervals for 3-day forecasts, producing 24 representations of storm surge impacts per daily prognostic model implementation. The model will be applied in 25 regions worldwide with complex bathymetries and diverse coastlines that contain in total 50 port facilities with high traffic load and commercial interest (project Accu-Waves). The produced data sets support mooring, navigation and towage procedures of vessels in commercial ports and harbors, reducing risk of vessel impact at the bottom.

Keywords Sea surface height, Ocean circulation, Ports, Navigation safety.

1 INTRODUCTION

1.1 Theme of research

In this paper we present recent evolvements of a robust numerical model for the simulation of storm surges (De Vries et al. 1995) in gulfs and coastal areas, inside which large harbors and urban port facilities exist. The model is named HiReSS (High-Resolution Storm Surge) and it is based on 2-DH formulations of the depth-integrated Navier-Stokes equations for the simulation of the barotropic mode of hydrodynamic circulation (Krestenitis et al. 2016). It can simulate the free surface elevation and the depth-integrated sea currents due to meteorological forcing (mostly severe weather conditions) combined with astronomical tide effects (Krestenitis et al. 2015a). Its newest version under development is intended to be part of a software suite for an operational tool that will provide reliable 3-hourly forecasts for 3 upcoming days about sea state conditions in coastal areas near ports and inside harbor basins (Memos et al. 2019; project Accu-Waves, http://accuwaves.eu/).

1.2 Scope of research

Main goal of this study is to develop new features of the HiReSS model in order to render it fully operational for robust forecasts of sea level and currents in engineered coastal regions. A second goal is to validate HiReSS against available sea level data from in situ observations by tide gauges of national hydrographic services (e.g. HNHS; https://www.hnhs.gr/). Moreover, the Fortran code of the storm surge model will be fitted in an integrated modeling system suite for automated operational forecasting of both surge-induced and tidal sea levels in the framework of high-resolution spectral wave modeling in and around fifty significant ports globally (Memos et al. 2019; project Accu-Waves, http://accuwaves.eu/). Conclusively, the produced data sets of HiReSS results will support mooring, navigation and towage procedures of ships and boats in commercial ports and harbors, mostly reducing risk of vessel impact at the bottom.

2 METHODOLOGY

2.1 Numerical model

2.1.1 Basic attributes

HiReSS is a new version of the HRSS model (Krestenitis et al. 2015b); it is based on the depth-averaged shallow water equations of hydrodynamic circulation, and it is capable to simulate the response of the sea surface and consequent barotropic sea currents to atmospheric weather conditions (wind and pressure) in large regions of either enclosed water bodies or semi-enclosed marginal seas, gulfs and bays over the continental shelf (Krestenitis et al. 2015a).

HiReSS can take into account the combinatory effects of several processes, such as the inverse barometer (response of sea level to atmospheric pressure gradient of large barometric systems); shear stresses of wind applied on the air-water interface; geostrophic Coriolis forces on large water masses; astronomical tides; ocean bottom friction; turbulence of horizontal vortices through the eddy viscosity concept; impacts of the wave-induced mean flows (Stokes drift) on the wind-driven currents in open seas and nearshore coastal zones. It can predict the mean free surface elevation (termed herein as sea surface height) and the depth-integrated sea currents due to surges induced by wind-storms combined with the effect of low/high barometric systems and astronomical tides.

2.1.2 Main equations and assumptions

The extended continuity and momentum equations, in order to account for storm surge-driven and tidally affected circulation can be written as (Krestenitis et al. 2016):

$$\frac{\partial \zeta}{\partial t} + \frac{\partial}{\partial x} UH + \frac{\partial}{\partial y} VH = 0 \qquad (1)$$

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} - fV + Z_x = -\frac{1}{\rho_o}\frac{\partial P_A}{\partial x} + E_h\left(\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2}\right) + \frac{C_s}{\rho_o}\frac{W_x\sqrt{W_x^2+W_y^2}}{(h+\zeta)} - C_b\frac{U\sqrt{U^2+V^2}}{\rho_o(h+\zeta)} \qquad (2)$$

$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} + fU + Z_y = -\frac{1}{\rho_o}\frac{\partial P_A}{\partial y} + E_h\left(\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2}\right) + \frac{C_s}{\rho_o}\frac{W_y\sqrt{W_x^2+W_y^2}}{(h+\zeta)} - C_b\frac{V\sqrt{U^2+V^2}}{\rho_o(h+\zeta)} \qquad (3)$$

$$Z_x = 0.9g\frac{\partial \zeta}{\partial x} - 0.7g\frac{\partial \zeta_{tide}}{\partial x}, \quad Z_y = 0.9g\frac{\partial \zeta}{\partial y} - 0.7g\frac{\partial \zeta_{tide}}{\partial y} \qquad (4)$$

where ζ is the free surface elevation, $H=h+\zeta$ is the total water depth of the sea, h is the local still water depth, U and V are the depth-integrated horizontal velocity components along the x and y axes of an ortho-regular staggered Cartesian grid of the Arakawa-C type for the finite difference method, t is the time, f is the Coriolis coefficient, g is the acceleration of gravity, P_A is the atmospheric sea level pressure (*SLP*), ρ_o is the water density, C_b is the bottom friction Manning-type coefficient, C_s is the air-water drag coefficient (Smith and Banke 1975), W_x and W_y are the wind velocity components at 10m above mean sea level, and E_h is the horizontal eddy viscosity coefficient.

HiReSS also takes into account the effects of astronomical tides on barotropic circulation through the static model parameterization by Schhwiderski (1980), by initiating Z_x and Z_y terms (Eq. 4) in the momentum equations (Eqs. 2, 3). Tide forecasts are based on the solution of harmonic equation ζ_{tide} in all georeferenced grid cells with discrete longitudes and latitudes, concerning both semi-diurnal and diurnal tidal range signals (Krestenitis et al. 2015a). HiReSS model is implemented in the framework of dynamically downscaled simulations initiating from computational fields covering e.g. the entire Mediterranean Sea (discretization step of $\Delta x \approx 1/25^\circ$ or ~4Km) and led to nested domains of high spatial resolution ($\Delta x \approx 1/200^\circ$ or ~500m). These results are also used as input in TOMAWAC model runs.

2.2 Application study

General application of HiReSS model is intended for 25 coastal regions globally, indicatively covering among others the Red, Caribbean, Java, Yellow, Mediterranean and Black Seas, and Persian, Tokyo and Halifax Gulfs. These areas have rather complex bathymetries with diverse coastlines and contain in total 50 port facilities with high traffic load and commercial interest. Herein we present specific implementations of HiReSS in the Mediterranean Sea with a special focus on the Thermaikos Gulf (northeastern Aegean Sea) and the port of Thessaloniki (Figure 1); ports of Patra and Piraeus in Greece are also checked together with the harbors in Barcelona, Algeciras, Haifa and Genova).

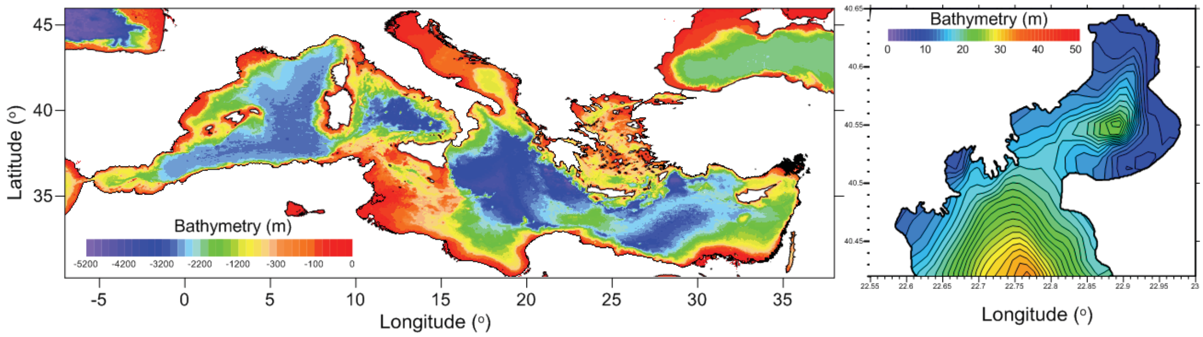

Figure 1 Bathymetry charts of Mediterranean Sea (left graph) and Thermaikos Gulf with the Thessaloniki Port basin (right graph); contours and color bars refer to depth *d* (m)

3 RESULTS

The results of pilot simulations with HiReSS concern maps of meteorologically induced sea surface heights (*SSH*) and current velocities (by zonal and meridional components, *U* and *V*) at 3-hourly time intervals for 3-day forecasts; 24 representations of storm surge impacts per day are produced. Preliminary results concern the entire Mediterranean basin with a focus on the Thermaikos, Patraikos and Saronikos Gulfs in Greece and other four Spanish, Italian and Israeli commercial ports.

3.1 Model validation

The model has been applied on a number of sites in the past, comprising large regions in open seas and coastal areas. It was calibrated and thoroughly validated via comparisons of hindcast modeling results against in situ observations for either short periods with intense weather events (Krestenitis et al. 2017) or large periods (>15yrs; for extreme events of annual maxima *SSH*) in the Mediterranean, Aegean and Ionian Seas, i.e. MeCSS (Androulidakis et al. 2015) and GreCSS (Makris et al. 2015, 2016) model versions. In Figure 2 characteristic comparisons of HiReSS hindcasting model results against tide-gauge measurements of *SSH* during 2012 in Thessaloniki and Genova ports are provided. Satisfactory accuracy of prediction is achieved with quite high Pearson product-moment correlations (*r*>0.7) and acceptable errors reaching down to 15%. It is noted that the forecast skill of the storm surge model highly depends on the quality and resolution of the atmospheric weather input data, rather than its own parameterizations.

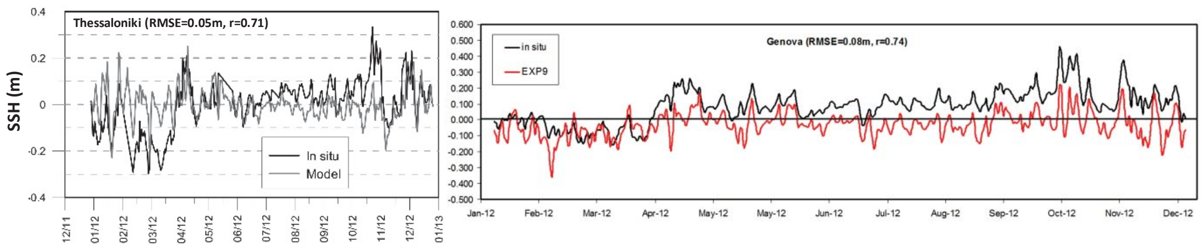

Figure 2 Comparisons of HiReSS hindcasting model results against in situ observations of *SSH* (m) by tide gauges during 2012 in Thessaloniki and Genova ports; *RMSE*: root-mean-square error; *r*: Pearson correlation

3.2 Case study

Figure 3 presents plots of HiReSS model forecast results concerning simulated fields of *SSH* and ocean current velocities in the entire Mediterranean Sea basin in conjunction with an atmospheric weather conditions field (*SLP* and wind vectors; upper graph). Negative *SSH* (sea surface below mean sea level) are observed in the Adriatic and Aegean Seas naturally due to the presence of a large atmospheric high-pressure barometric system ("good weather") and northerly winds (even if faint). On the contrary, large values of positive *SSH* are shown in the Gulf of Gabes (northcentral African coast) and near the Gibraltar straits, which are influenced by the low-pressure barometric system that prevailed south of the Iberian Peninsula on the northwestern African region. Strong easterly winds occurred between the two systems. It is concluded that HiReSS model may efficiently reproduce the inverse barometer effect together with wind-driven circulation.

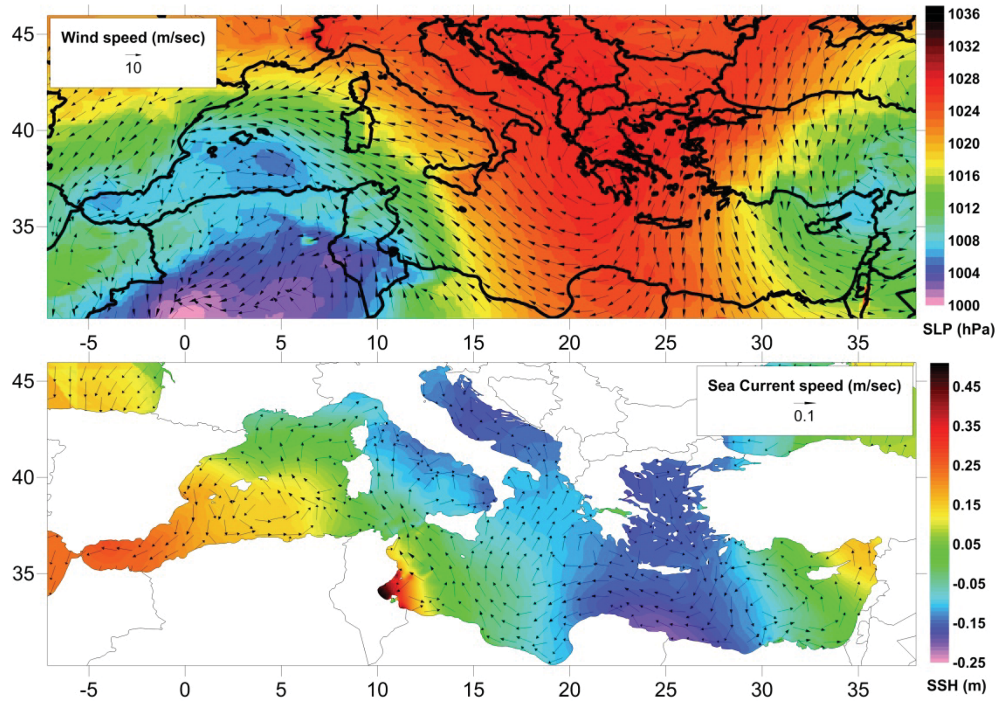

Figure 3 Upper graph: Atmospheric weather conditions (*SLP* in hPa and wind vectors in m/sec) chart over the Mediterranean Sea; Lower graph: HiReSS forecast results (*SSH* in m and current vectors in m/sec) chart of the Mediterranean basin on April 21st 2019, UTC 00:00.

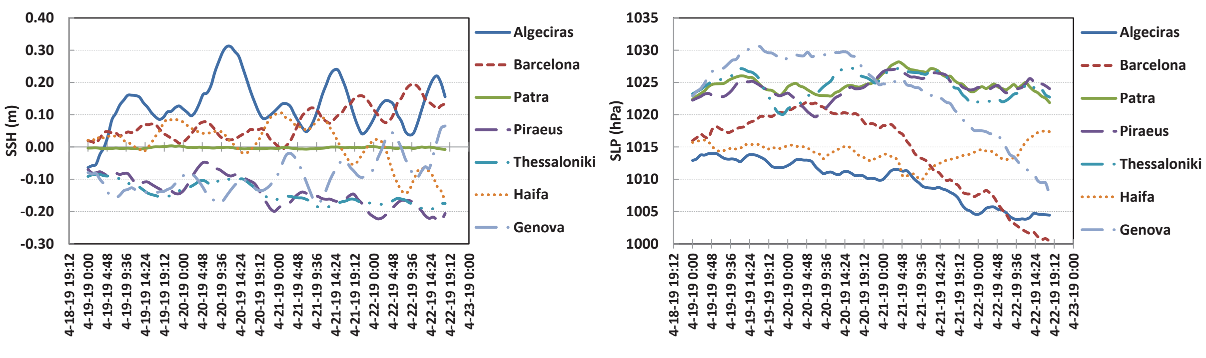

Figure 4 Graphs of HiReSS model results about surge- and tide-induced *SSH* (m) [left graph] and *SLP* (hPa) [right graph] in seven characteristic ports of the Mediterranean basin (Algeciras, Barcelona, Genova, Haifa, Patra, Piraeus, Thessaloniki ports); Forecasts refer to a 3-day period of April 19th-22nd 2019

Figure 4 presents characteristic *SSH* time-series (left panel) produced by HiReSS forecasts in seven ports of the Mediterranean basin. Sea levels in Greek ports and Genova are shown to range from zero ("dead calm" sea state in Patra port) to -20cm, whereas storm-induced sea surface elevation is evident in Algeciras and Barcelona up to 30cm. Reversed patterns are shown in *SLP* graph (right panel), corroborating the influence of the inverse barometer effect in these areas. Semi-diurnal undulating configurations are also clearly seen in the surge- and tide-driven *SSH* time-series, revealing the characteristic tidal patterns in the Mediterranean Sea; tidal effects are obvious even if astronomic tidal ranges are not significant in the specific region.

4 CONCLUSIONS

A robust operational forecast model for storm surges is built in the framework of an integrated tool for short-term marine weather and sea-state prognoses in broader areas around and inside port facilities with global commercial interest and high transportation loads. HiReSS has been validated by comparisons of model output against sea level observations from tide gauges in ports by official navy hydrographic services in southern Europe. It is proved to satisfactorily simulate the sea level variations inside harbor areas, providing also rough estimates of mean sea currents there. HiReSS results will hopefully address significant needs of port authorities, ship pilots and navigators towards battling problems of vessel impact on the harbor bed during mooring, towage and berth operations, according to reliable short-term sea-state forecasting. Presented cases in Mediterranean ports support that inference. Results are also judged to be crucial as input (local bathymetric changes) in irregular wave simulations with the TOMAWAC spectral wave model in the Accu-Waves modeling system.

Acknowledgements

This research is part of the Accu-Waves project (http://accuwaves.eu) co-financed by the European Union and Greek national funds through the Operational Program Competitiveness, Entrepreneurship and Innovation, under the call RESEARCH – CREATE – INNOVATE (project code: T1EDK-05111).

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