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OPERATIONAL FORECAST SYSTEM OF STORM TIDES IN THE AEGEAN SEA (GREECE)

Yannis Krestenitis[1,*], Yannis Androulidakis[1], Katerina Kombiadou[1], Christos Makris[1], Vassilis Baltikas[1]

1 Laboratory of Maritime Engineering and Maritime Works, School of Civil Engineering, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece

* Corresponding author; e-mail: ynkrest@civil.auth.gr, tel.: +30 2310995654, fax: +30 2310995649

Abstract

WaveForUs is a high-resolution forecasting system for public and emergency use that delivers 3-day sea-state prognoses. In this framework, a prognostic tool for total coastal surges (storm surge, tidal extremes and wave-induced setup) was implemented, aiming at the notification of the authorities and the public in cases of high coastal inundation risk; more specifically, the results of a 2D hydrodynamic model (HRSS) that simulates the free surface elevation due to the combined effect of atmospheric forcing (pressure and wind) and tides and the results of a spectral wave model (WaveWatch-III) are used to estimate the total setup along the coasts, combining storm surge maxima, tidal constituents and near-shore irregular wave breaking. The model is applied in the North Aegean Sea and in the nested domain of Thermaikos Gulf. Both areas are of high environmental and socioeconomic value, with extensive low-elevation planes, protected (Natura 2000 and Ramsar) sites and a broad spectrum of sea-based activities. The validation and calibration of the modelling platform was based on hindcasting simulations; the numerical results are satisfactory and correlate well with in-situ and satellite/modelling data.

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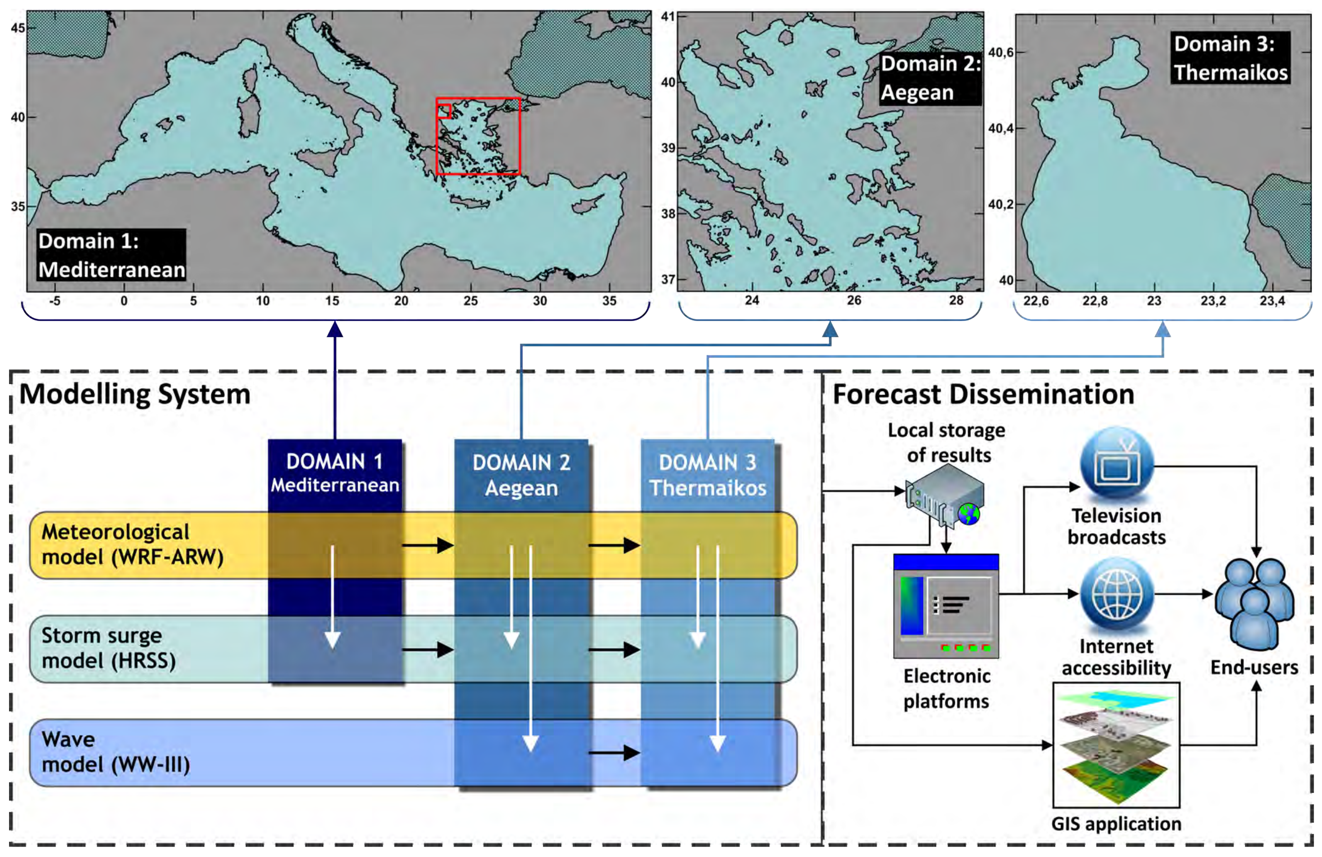
1. General Information

WaveForUs is a high-resolution forecasting system for public and emergency use that delivers 3-day sea-state prognoses. In this framework, a prognostic tool for total coastal surges (storm surge, tidal extremes and wave-induced setup) was implemented, aiming at the notification of the authorities and the public in cases of high coastal inundation risk; more specifically, the results of a 2D hydrodynamic model (HRSS) that simulates the free surface elevation due to the combined effect of atmospheric forcing (pressure and wind) and tides and the results of a spectral wave model (WaveWatch-III) are used to estimate the total setup along the coasts, combining storm surge maxima, tidal constituents and near-shore irregular wave breaking. The model is applied in the North Aegean Sea and in the nested domain of Thermaikos Gulf. Both areas are of high environmental and socioeconomic value, with extensive low-elevation planes, protected (Natura 2000 and Ramsar) sites and a broad spectrum of sea-based activities. The validation and calibration of the modelling platform was based on hindcasting simulations; the numerical results are satisfactory and correlate well with in-situ (tide gauges) and modeling (MyOcean system) data.



System Description

- 3-day prognoses of total Sea Level Heights that are updated daily at 08:30 UTC. Dissemination of forecast products
- 3 domains of atmospheric (WRF-ARW; Pytharoulis et al., 2014) and storm surge (HRSS) forecast fields (Mediterranean Sea, Aegean Sea, Thermaikos Gulf)
- Computation of the Total Surge based on the storm surge and wave set-up computation
- Alert system for strong surges that reach coastal waters
- Hindcasting calibration period 2012

Fig. 1: Schematic representation of the WaveForUs forecasting system: The lower panel (left part) shows the numerical models used in each application domain and the transfer of data within the system (black arrows denote transfer of initial and boundary conditions, white ones introduction of input data) and the dissemination of forecast products (right part), while the upper panel shows the location of the three application domains (hatched areas aren't included in the calculations)

2. Models' Description

HRSS Model

- 2-dimensional hydordynamic model (Krestenitis et al. 2010)
- Implementation in 3 domains
- Shallow water equations:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}-fu+g\frac{\partial z}{\partial x}=-\frac{1}{\rho_o}\frac{\partial P}{\partial x}+\frac{1}{\rho_o}\frac{\tau_\chi}{(h+z)}-k\frac{u\sqrt{u^2+v^2}}{\rho_o(h+z)}-\frac{g}{\rho_o}\frac{0.9\partial z-0.7\partial z_o}{\partial x}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+fu+g\frac{\partial z}{\partial y}=-\frac{1}{\rho_o}\frac{\partial P}{\partial y}+\frac{1}{\rho_o}\frac{\tau_y}{(h+z)}-k\frac{u\sqrt{u^2+v^2}}{\rho_o(h+z)}-\frac{g}{\rho_o}\frac{0.9\partial z-0.7\partial z_o}{\partial y}$$

$$\frac{\partial z}{\partial t}+\frac{\partial (h+z)u}{\partial x}+\frac{\partial (h+z)v}{\partial y}=0$$

- Tidal Parameterization included in the momentum equations
- Validation of different surface drag coefficients (C_D) $\tau=\rho_A C_D|W|W$

WaveWatch-III Model

- Implementation of WaveWatch-II model in Domains 1 & 2
- The model is run on a spherical grid
- The governing equation is the balance equation of the wave action density spectrum:

$$\frac{\partial N}{\partial t}+\frac{1}{\cos\varphi}\frac{\partial}{\partial\varphi}\left(\dot{\phi}\cdot N\cdot\cos\theta\right)+\frac{\partial}{\partial\lambda}\left(\dot{\lambda}\cdot N\right)+\frac{\partial}{\partial k}\left(\dot{k}\cdot N\right)+\frac{\partial}{\partial\theta}\left(\dot{\theta}_g\cdot N\right)=\frac{S}{\sigma}$$

$$\text{and}\left\{\begin{array}{ll}\dot{k}=-\dfrac{\partial\sigma}{\partial d}\dfrac{\partial d}{\partial\sigma}-\mathbf{k}\dfrac{\partial\mathbf{U}}{\partial s} & \dot{\phi}=\left(c_g\cdot\cos\theta+U_\varphi\right)/R \\ \dot{\theta}=-\dfrac{1}{k}\left[\dfrac{\partial\sigma}{\partial d}\dfrac{\partial d}{\partial m}-\mathbf{k}\dfrac{\partial U}{\partial m}\right] & \dot{\lambda}=\left(c_g\cdot\cos\theta+U_\lambda\right)/R\cdot\cos\varphi \\ & \dot{\theta}_g=\dot{\theta}-c_g\cdot\tan\varphi\cdot\cos\theta/R\end{array}\right\}$$

- Implementation of WaveWatch-II model in Domains 1 & 2

Astronomical Tide Parameterisation

- Schwiderski (1980) parameterization
- Solution of harmonic equation at all grid longitudes and latitudes
- Semi-diurnal signal $n=k_o\sin^2(\phi)\cos(\sigma t+x+2\lambda)$
- Diurnal signal $n=k_o\sin(2\phi)\cos(\sigma t+x+2\lambda)$
- Mean distance of sun $h_o=279.69668+36000.768930485T_d+3.03\cdot10^{-4}T_d^{\,2}$
- Mean distance of moon $s_o=270.434358+481267.88314137T_d-0.001133T_d^{\,2}+1.9\cdot10^{-6}T_d^{\,3}$
- where: $\begin{cases}T_d=(27392.500528+1.0000000356D)/36525\\ D=day+365\cdot(yr-1975)+int[(yr-1973)/4]\end{cases}$

- Harmonic equation is also applied for Gibraltar open boundary.

3. HRSS Calibration Experiments

Table: List of main parameterisations in each calibration experiment

EXP#	Atmosphperic Forcing	Tide Schwiderski (1980)	Gibraltar Boundary	Other Parameterisations	Maximum Depth H
1	YES	NO	NO	C_D (Smith and Banke, 1975)	Realistic
2	YES	NO	YES	C_D (Smith and Banke, 1975)	Realistic
3	YES	YES	NO	C_D (Smith and Banke, 1975)	Realistic
4	YES	YES	YES	C_D (Smith and Banke, 1975)	Realistic
5	YES	NO	NO	$C_D = 10^{-5}$	Realistic
6	YES	NO	NO	$C_D = 10^{-6}$	Realistic
7	YES	NO	NO	C_D (Smith and Banke, 1975)	100
8	YES	NO	NO	$C_D = 10^{-5}$	100
9	YES	YES	YES	$C_D = 10^{-5}$	Realistic
10	YES	YES	YES	$C_D = 10^{-6}$	Realistic
11	YES	NO	NO	C_D (Smith and Banke, 1975) Eddy Viscosity (CCC=0.24)	Realistic
12	YES	YES	YES	$C_D = 10^{-5}$	Realistic

Willmott Skill (WS) score between observed (SLH_o) and modeled (SLH_m) SLH:

$$WS=1-\frac{\sum\left|SLH_m-SLH_o\right|^2}{\sum\left(\left|SLH_m-\overline{SLH_o}\right|+\left|SLH_o-\overline{SLH_o}\right|\right)^2}$$

Table: WS score values at selected stations for the 2012 period

Station / Experiment	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Exp11	Exp12
Thessaloniki	0.48	0.59	0.53	0.57	0.62	0.53	0.59	0.56	0.68	0.55	0.51	0.65
Genova	0.72	0.76	0.76	0.77	0.71	0.73	0.77	0.77	0.79	0.76	0.72	0.61
Ancona	0.61	0.68	0.68	0.69	0.67	0.63	0.73	0.70	0.72	0.67	0.64	0.69
Napoli	0.56	0.62	0.59	0.61	0.59	0.56	0.68	0.66	0.69	0.61	0.56	0.58
Marseille	0.50	0.51	0.55	0.52	0.42	0.51	0.39	0.43	0.46	0.52	0.81	0.46
Venice	0.61	0.71	0.71	0.72	0.80	0.66	0.75	0.71	0.82	0.69	0.68	0.68
Catania	0.40	0.47	0.36	0.43	0.40	0.38	0.45	0.44	0.51	0.43	0.36	0.46
Hadera	0.50	0.54	0.54	0.55	0.62	0.50	0.62	0.65	0.66	0.53	0.51	0.45
Cagliari	0.45	0.54	0.47	0.51	0.54	0.48	0.50	0.49	0.60	0.50	0.46	0.43
Otranto	0.44	0.53	0.46	0.51	0.52	0.45	0.54	0.51	0.62	0.50	0.43	0.39
Alexandroupolis	0.34	0.64	0.63	0.64	0.73	0.59	0.68	0.64	0.77	0.61	0.60	0.76
All Stations	0.51	0.60	0.57	0.59	0.60	0.55	0.61	0.60	0.67	0.58	0.57	0.56

4. Calculation of Total Surge (wave and storm-induced)

The total surge near the coasts (SLH_{tot}) equals the summation of the storm-induced SLH (SLH_{SS}, output of HRSS) and the irregular wave setup (n_s) and surf beat (ζ_{rms}): $SLH_{tot}=SLH_{SS}+\eta_s+\zeta_{rms}$

Wave setup and surf beat for irregular breaking waves are calculated explicitly from the outputs of WW-III, using the expressions (Dean and Dalrymple, 2002; Goda, 1985):

$$\eta_s=\frac{3\gamma^2/8}{1+3\gamma^2/8}\cdot d_b-\frac{\gamma^2\cdot d_b}{16}\quad\text{and}\quad\zeta_{rms}=\frac{0.01\cdot H_{s,o}{}'}{\sqrt{H_{s,o}{}'/L_o\left(1+d_b/H_{s,o}{}'\right)}}$$

Breaking wave characteristics are calculated through analytical expressions (Goda, 1985).

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Smith S.D. and Banke E.G. (1975). Variation of the sea surface drag coefficient with wind speed. *Quarterly Journal of the Royal Meteorological Society*, 101(429), 665-673.

5. Results: 3-day Forecast Products

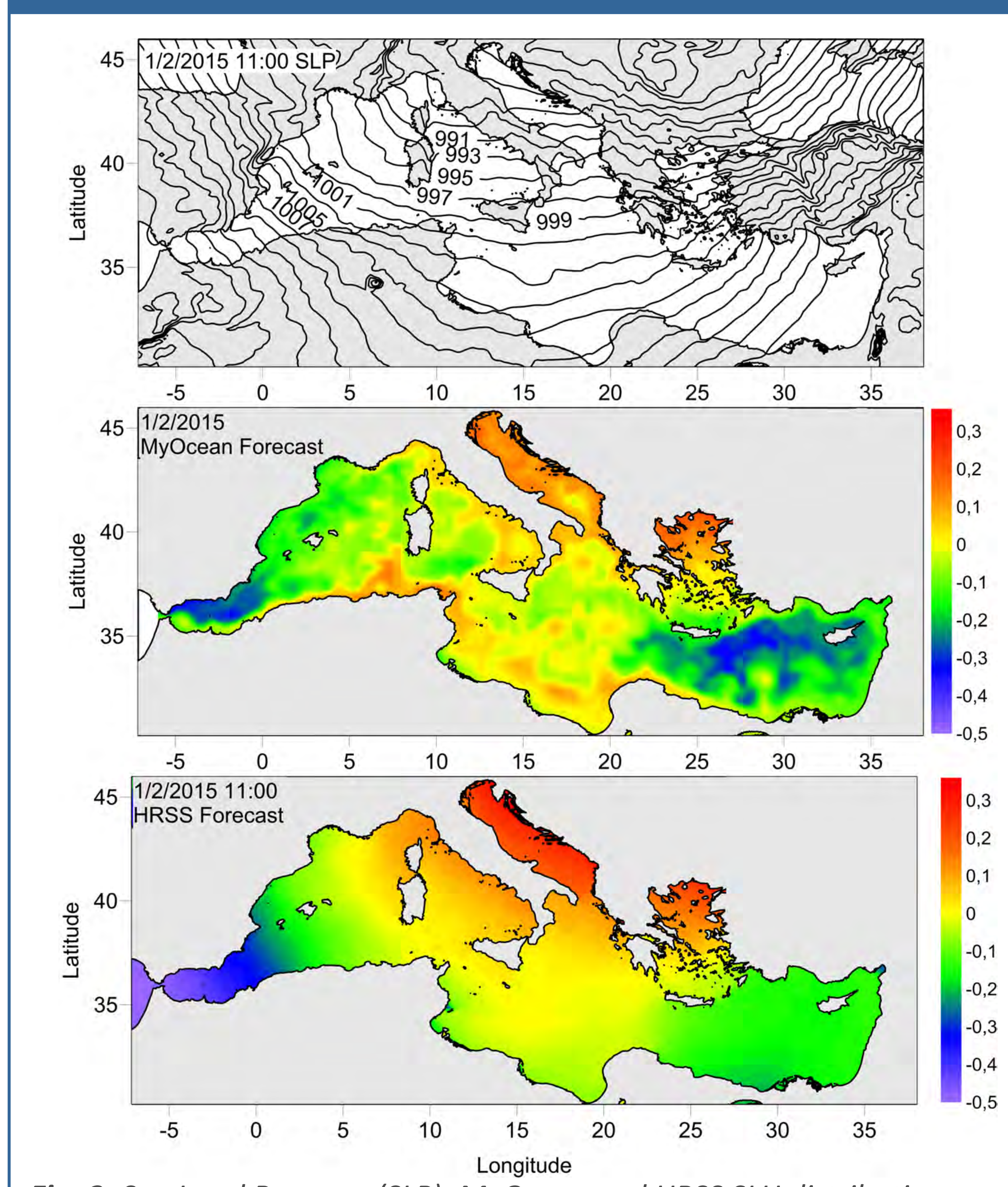

Fig. 2: Sea Level Pressure (SLP), MyOcean and HRSS SLH distribution over Domain 1 (Mediterranean Sea) on 1/2/2015

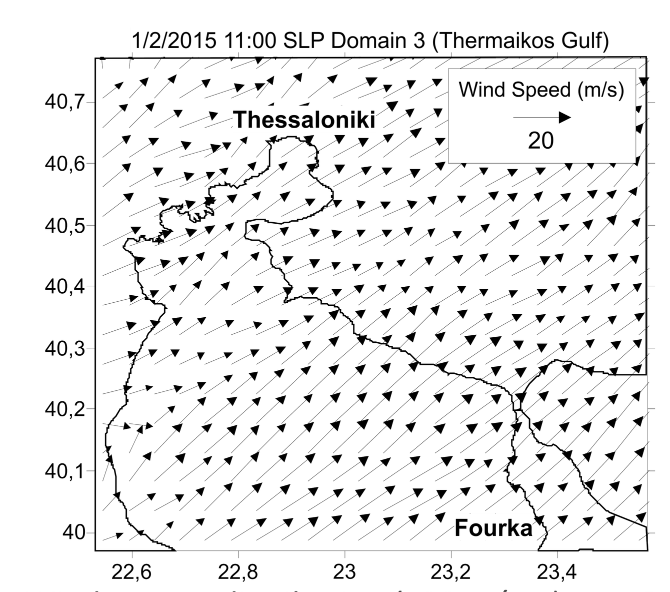

Fig. 3: Wind vectors distribution (~20 m/sec) over Domain 3 on 1/2/2005 (Extreme Event)

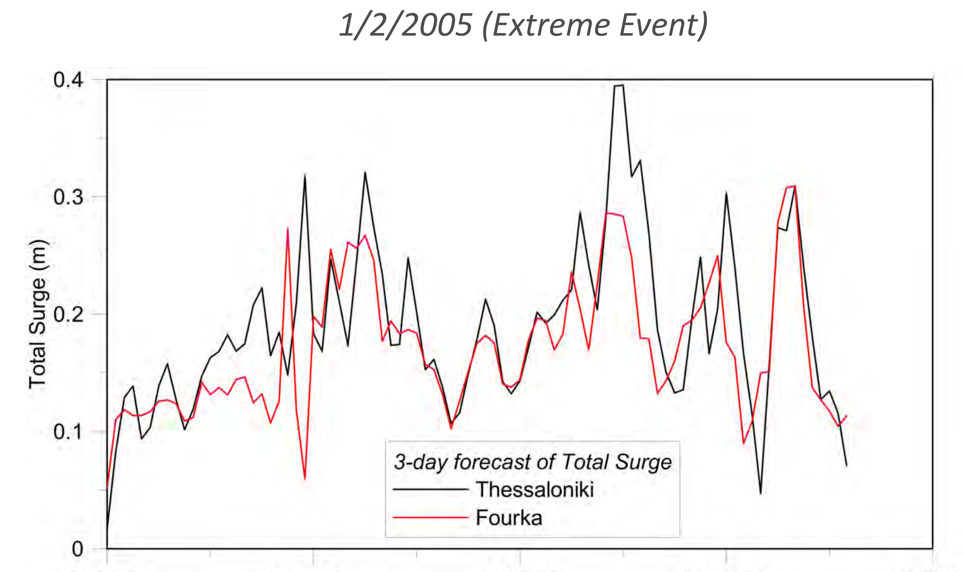

Fig. 4: 3-day forecast from HRSS simulations at two Domain 3 stations during 1/2/2015 extreme storm surge conditions

Conclusions

- Validation of the models with available in situ observations and satellite data showed that the operational WaveForUs system is an adequate and useful tool on the prediction of the short-term sea-state
- The higher resolution of Domain 3 improves the forecast storm surge product over regional areas of the Mediterranean Sea
- The finer Domain 3 simulations predict higher SLH values along specific coastal zones where the higher resolution of the area's topography describes the details of coastline that are not apparent in coarser grids
- Simulation of severe meteorological events that may induce inundation phenomena over low-land areas provides a daily alerting system along the entire coastal zone.
- The computation of the astronomical tide based on Schwiderski (1980) parameterization improved the performance of the simulations.
- Sea-state products, provided to the public with several different ways, covers the different needs of potential users in the complicated Thermaikos environment under the high spatial and temporal resolution.

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National Action: **"COOPERATION 2011 - Partnerships of Production and Research Institutions in Focused Research and Technology Sectors"**
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