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

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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 Modelling System 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

→ **G Fig. 1:** Schematic representation of the WaveForUs forecasting system: The lower panel End-users i (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: $\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} - fu + g\frac{\partial z}{\partial x} = -\frac{1}{\rho_{o}}\frac{\partial P}{\partial x} + \frac{1}{\rho_{o}}\frac{\tau_{\chi}}{(h+z)} - k\frac{u\sqrt{u^{2} + v^{2}}}{\rho_{o}(h+z)} - \frac{g}{\rho_{o}}\frac{0.9\partial z - 0.7\partial z_{o}}{\partial x}$ $\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + fu + g \frac{\partial z}{\partial y} = -\frac{1}{\rho_o} \frac{\partial P}{\partial y} + \frac{1}{\rho_o} \frac{\tau_v}{(h+z)} - k \frac{u \sqrt{u^2 + v^2}}{\rho_o(h+z)} - \frac{g}{\rho_o} \frac{0.9 \partial z - 0.7 \partial z_o}{\partial y}$ $\frac{\partial z}{\partial t} + \frac{\partial (h+z)u}{\partial (h+z)v} + \frac{\partial (h+z)v}{\partial (h+z)v} = 0$ ∂x ∂t **C**Tidal Parameterization included in the momentum equations \Im 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:

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

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

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 $n = k_0 \sin^2(\phi) \cos(\sigma t + x + 2\lambda)$ Semi-diurnal signal ⇒Diurnal signal $n = k_{o} \sin(2\phi) \cos(\sigma t + x + 2\lambda)$ The endistance of sun $h_0 = 279.69668 + 36000.768930485T_d + 3.03 \cdot 10^{-4} T_d^2$ The mean distance of moon $s_0 = 270.434358 + 481267.88314137T_d - 0.001133T_d^2 + 1.9 \cdot 10^{-6}T_d^3$ $(T_d = (27392.500528 + 1.000000356D)/36525)$ **O**where: $D = day + 365 \cdot (yr - 1975) + int[(yr - 1973)/4]$

SHarmonic equation is also applied for Gibraltar open boundary.

3. HRSS Calibration Experiments

Table: List of main parameterisations in each calibration experiment

5. Results: 3-day Forecast Products



1/2/2015 11:00 SLP Domain 3 (Thermaikos Gulf)

23,4

02/02/15

03/02/15

	EXP# ATMOSHPERIC FORCING		Tide Schwiderski (1980)		GIBRALTAR BOUNDARY		Other Parameterisations			s	Махімим D ертн H		
	1	YES	NO		NO		C _D (Smith and Banke, 1975)			'5)	Realistic		
	2	YES		NO		YES		C _D (Smitl	h and Ba	nke, 197	'5)	Realistic	
	3	YES		YES		NO		C _D (Smitl	h and Ba	nke, 197	'5)	Realistic	
	4	YES		YES		YES		C _D (Smitl	h and Ba	nke, 197	'5)	Realistic	
	5	YES		NO		NO			$C_{\rm D} = 10^{-10}$.5		Realistic	
	6	YES		NO		NO			$C_{\rm D} = 10^{-1}$	-6		Realistic	
	7	YES		NO		NO		C _D (Smitl	h and Ba	nke, 197	'5)	100	
	8	YES		NO		NO			$C_D = 10^{\circ}$.5		100	
L	9	YES		YES		YES			$C_D = 10^{\circ}$	·5		Realistic	
	10	YES		YES		YES			$C_{\rm D} = 10^{-1}$	·0		Realistic	
	11 YES		NO		NO		C _D (Smith and Banke, 1975) Eddy Viscosity (CCC=0.24)			'5) 4)	Realistic		
	12	YES		YES		YES			$C_{\rm D} = 10^{-10}$	·5		Realistic	
L	Wil	llmott Skill ('	WS) sco	ore bet	ween								
	Wil obs	llmott Skill (^v served (SLH _c Tabl e	WS) sco ₅) and n e: WS s	ore bet nodele core vo	ween d (SLH _m alues a) SLH: t select	WS = 1 ed sta	 Σ(s tions for	2 <u>ک</u> LH _m – S r the 20	$\frac{ LH_{m} }{ LH_{o} + }$	SLH _o SLH _o – S	$\overline{LH_{o}}\Big)^{2}$	
STATION	Wil obs /Experin	llmott Skill (served (SLH _c Tabl e MENT EXP1	WS) sco ,) and n e: WS s Exp2	ore bet nodeled core vo Exp3	ween d (SLH _m alues a Exp4) SLH: t select Exp5	WS = 1 ed star Exp6	.— (S tions for Ехр7	ے ا <u>ک</u> LH _m – S r the 20 Exp8	LH _m – S LH _o + S D12 per Exp9	SLH _o – S SLH _o – S <i>iod</i> Exp10	$\frac{\left LH_{\circ} \right ^{2}}{Exp11}$	Exp12
Station The	Wil obs /Experin ssalonik	llmott Skill (served (SLH _c Table MENT Exp1 1 0.48	WS) sco) and n e: WS s <u>ExP2</u> 0.59	ore bet nodeled core va Exp3 0.53	ween d (SLH _m alues a Exp4 0.57) SLH: t select Ехр5 0.62	WS = 1 ed stat Exp6 0.53	.— <u> </u> <u> </u> <u> </u> <u> </u> <u> </u> <u> </u> <u> </u> <u> </u>	ے ا LH _m – S the 20 Exp8 0.56	LH _m – S LH _o + S D12 per Exp9 0.68	SLH _o SLH _o — S iod Exp10 0.55	LH _o)	Ехр12 0.65
Station The G	Wil obs /Experin ssalonik Genova	Ilmott Skill (Served (SLH _c Table MENT Exp1 1 0.48 0.72	WS) sco ,) and n e: WS s ExP2 0.59 0.76	ore bet nodeled core vo Exp3 0.53 0.76	ween d (SLH _m alues a Exp4 0.57 0.77) SLH: t select Ехр5 0.62 0.71	WS = 1 ed stat Exp6 0.53 0.73	 <u> </u> <u> </u> <u> </u> <u> </u> <u> </u>	<u></u> LH _m – S the 20 Exp8 0.56 0.77	LH _o + LH _o + 12 рег 0.68 0.79	SLH _o SLH _o — S iod Exp10 0.55 0.76	LH _o) Exp11 0.51 0.72	Ехр12 0.65 0.61
STATION THE G	Wil obs /Experin ssalonik Senova Ancona	Ilmott Skill (Served (SLH _c Table MENT Exp1 I 0.48 0.72 0.61	WS) sco ,) and n e: WS s Exp2 0.59 0.76 0.68	ore bet nodeled core va 0.53 0.76 0.68	ween d (SLH _m alues a Exp4 0.57 0.77 0.69) SLH: t select Exp5 0.62 0.71 0.67	WS = 1 ed stat Exp6 0.53 0.73 0.63	<u> </u>	<u>L</u> H _m – S the 20 Exp8 0.56 0.77 0.70	LH _m – S LH _o + S 12 per 0.68 0.79 0.72	SLH _o SLH _o – S iod 0.55 0.76 0.67	LH _o) Exp11 0.51 0.72 0.64	Exp12 0.65 0.61 0.69
STATION THE G A	Wil obs /Experin ssalonik Senova Ncona Napoli	Ilmott Skill (Served (SLH _c Table MENT Exp1 0.48 0.72 0.61 0.56	WS) sco ,) and n e: WS s Exp2 0.59 0.76 0.68 0.62	ore bet nodeled core vo Exp3 0.53 0.76 0.68 0.59	ween d (SLH _m alues a Exp4 0.57 0.77 0.69 0.61) SLH: t select Exp5 0.62 0.71 0.67 0.59	WS = 1 ed stat 0.53 0.73 0.63 0.56	<u> </u>	<u></u> LH _m — S the 20 Exp8 0.56 0.77 0.70 0.66	LH _m — S LH _o + 12 рег 0.68 0.79 0.72 0.69	SLH _o SLH _o — S iod 0.55 0.76 0.67 0.61	LH _o) Exp11 0.51 0.72 0.64 0.56	Exp12 0.65 0.61 0.69 0.58
STATION THE G A N M	Wil obs /Experin ssalonik Senova Ncona Napoli Arseille	Ilmott Skill (Served (SLH _c Table MENT Exp1 1 0.48 0.72 0.61 0.56 0.50	WS) sco ,) and n e: WS s ExP2 0.59 0.76 0.68 0.62 0.51	ore bet nodeled core va Exp3 0.53 0.76 0.68 0.59 0.55	ween d (SLH _m alues a Exp4 0.57 0.77 0.69 0.61 0.52) SLH: t select Exp5 0.62 0.71 0.67 0.59 0.42	WS = 1 ed stat Exp6 0.53 0.73 0.63 0.56 0.51	L = L =	<u>L</u> H _m – S the 20 Exp8 0.56 0.77 0.70 0.66 0.43	LH _m – S LH _o + S 12 per 0.68 0.79 0.72 0.69 0.46	SLH _o SLH _o – S iod 0.55 0.76 0.67 0.61 0.52	LH _o) ² Exp11 0.51 0.72 0.64 0.56 0.81	Exp12 0.65 0.61 0.69 0.58 0.46
STATION THE G A M	Wil obs /Experin ssalonik Senova Napoli Arseille Venice	Ilmott Skill (Served (SLH _c Table MENT Exp1 0.48 0.72 0.61 0.56 0.50 0.61	WS) sco) and n e: WS s ExP2 0.59 0.76 0.68 0.62 0.51 0.71	ore bet nodeled core vo Exp3 0.53 0.76 0.68 0.59 0.55 0.71	ween d (SLH _m alues a Exp4 0.57 0.69 0.61 0.52 0.72) SLH: t select Exp5 0.62 0.71 0.67 0.59 0.42 0.80	WS = 1 ed stat Exp6 0.53 0.73 0.63 0.56 0.51 0.66	<u> </u>	∑_ S LH _m – S r the 20 Exp8 0.56 0.77 0.70 0.66 0.43 0.71	LH _o + LH _o + 12 per 6 .68 0.79 0.72 0.69 0.46 0.82	SLH _o SLH _o – S iod 0.55 0.76 0.61 0.52 0.69	Exp11 0.51 0.72 0.64 0.56 0.81 0.68	Exp12 0.65 0.61 0.69 0.58 0.46 0.68
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STATION THE G A M M C H	Wil obs /Experin ssalonik Senova Ncona Napoli Arseille Venice Atania Adera	Ilmott Skill (* served (SLH _c Table MENT Exp1 1 0.48 0.72 0.61 0.56 0.50 0.61 0.40 0.50	WS) sco) and n e: WS s ExP2 0.59 0.76 0.68 0.62 0.51 0.71 0.71 0.47 0.54	core bet nodeled Exp3 0.53 0.76 0.68 0.59 0.55 0.71 0.36 0.54	ween d (SLH _m alues a Exp4 0.57 0.77 0.69 0.61 0.52 0.72 0.72 0.43 0.55) SLH: t select Exp5 0.62 0.71 0.67 0.59 0.42 0.80 0.40 0.62	WS = 1 ed stat 0.53 0.73 0.63 0.56 0.51 0.66 0.38 0.50	<u> </u>	LH _m − S Exp8 0.56 0.77 0.70 0.66 0.43 0.71 0.44 0.65	LH _o + LH _o + 12 per 6.68 0.79 0.68 0.72 0.69 0.46 0.82 0.51 0.66	SLH _o – S iod Exp10 0.55 0.76 0.67 0.61 0.52 0.69 0.43 0.53	Exp11 0.51 0.72 0.64 0.56 0.81 0.68 0.36 0.51	Exp12 0.65 0.61 0.69 0.58 0.46 0.68 0.46 0.45
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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):

 $\eta_{s} = \frac{3\gamma^{2}/8}{1+3\gamma^{2}/8} \cdot d_{b} - \frac{\gamma^{2} \cdot d_{b}}{16} \text{ and } \zeta_{rms} = \frac{0.01 \cdot H_{s,o}'}{\sqrt{H_{s,o}'/L_{o}(1+d_{b}/H_{s,o}')}}$

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

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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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