Space-Time Wave Extremes in WAVEWATCH III: Implementation and Validation for the Adriatic Sea Case Study^{*}

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Abstract

Observations of short-crested waves have shown that the maximum crest height attained over a sea surface area is significantly larger than the value at a single point within the area. Thus, a new challenge for wave modeling is the prediction of the maximal sea surface elevation expected during a sea state over a given area, i.e. the so-called spacetime extreme. Once tackled, this outcome would be particularly fruitful for offshore industry applications and navigation, due to the potential of reducing the risk associated to extreme wave events. Recently, it has been shown that space-time extremes can be accurately estimated from the directional wave spectrum, relying upon the theoretical model by Fedele (2012), based on the Adler & Taylor (2007) Euler Characteristics approach. With the objective of generating forecasts, we have taken advantage of the directional spectra computed by third-generation spectral wave models, and we have implemented a second-order nonlinear extension of the Fedele (2012) linear model (Benetazzo et al. , 2015) in the state of the art WAVEWATCH III model, thus enabling it to compute the extreme sea surface elevation and associated wave parameters over given area and time duration. Given the complexity of the theoretical model, some approximations have been necessarily introduced to meet the requirements of computational efficiency. In order to test the model performance in spacetime extremes prediction, wave model hindcast has been produced simulating a sea state in the northern Adriatic Sea (Italy), where space-time extremes have been observed with a stereo-photogrammetric system during an experiment conducted in March 2014. The model has been forced by wind fields provided by the atmospheric model COSMO, and integral wave parameters validated by means of reference instrumentation.

1 Introduction

In this paper we describe the implementation and validation of space-time wave extremes computation in the WAVEWATCH III model (Tolman & Group, 2014). The space-time extremes represent the highest sea surface elevations occurring during a sea state of given duration and over a given area (Fedele, 2012). Recently, observations of short-crested waves have shown that the maximum crest height attained over a sea surface area is significantly larger than measurements made at a single point (Fedele *et al.* (2013); Benetazzo *et al.* (2015)). Therefore, several off-shore activ-

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ities could benefit from an accurate prediction of space-time extremes, e.g. oil and gas extraction, and navigation. Such prediction is nowadays possible thanks to recent developments in the evaluation of multidimensional random fields maxima: the Adler (1981) and Adler & Taylor (2007) approach on Euler Characteristics was applied to the statistics of linear wave extremes over space-time by Fedele (2012). An extension to account for second-order nonlinearities was proposed by Benetazzo et al. (2015), and the state-of-the-art thirdorder nonlinear model has been recently formulated by Fedele (2015). However, the prediction of spacetime extremes is submitted to the directional spectra availability. Barbariol et al. (2014) showed that space-time extremes hindcasts can be performed at a large scale with third-generation spectral wave models provided they are opportunely adapted to produce the integral parameters of the directional spectrum as outputs. Preliminary tests over the Italian seas were also performed by Sclavo et al. (2015).

More recently, in order to directly compute the expected space-time extremes as numerical model outputs, we have implemented the Fedele (2012) statistical model extended to the secondorder by Benetazzo *et al.* (2015) within the state of the art WAVEWATCH III (WW3) model. WW3 solves the wave action density balance equation for wavenumber-direction spectra (Tolman & Group, 2014). Physical processes modeled within the governing equation include refraction and frequency/wavenumber shifting due to water depth and mean current variations. Processes parameterized within the source term of the equation include wave growth and decay due to the actions of wind, nonlinear resonant interactions, whitecapping, bottom friction, depth-induced breaking and scattering due to wave-bottom interactions. Some approximations have been introduced to ensure that WW3 can compute the new outputs without losing computational efficiency.

Herein, we firstly describe the implementation procedures, and then we provide a validation of the results by comparing modeled to observed spacetime extremes. Observations were gathered in March 2014 during an experiment at the ISMAR-CNR "Acqua Alta" oceanographic tower (Figure 1), in the northern Adriatic Sea (Italy), using a stereo-photogrammetric system. Modeled extremes were obtained by simulating the Mediterranean Sea states during March 2014. To this end, WW3 was forced by the COSMO atmospheric model winds. In doing so, we put the bases for space-time extremes forecasts using WW3.



Figure 1: The "Acqua Alta" oceanographic tower (left), and the WASS stereo-photogrammetric system (right).

The document is structured as follows: in the next Section 2 the space-time extremes of sea states are introduced and formalized through the fundamental equations, and the experiment during which they were observed is described. The implementation of space-time extremes equations in WW3 is reported in Section 3. Section 4 describes the set-up of WW3 and the model validation during nearly a one-month period including the stereophotogrammetric experiment. In Section 5 the space-time extremes modeled over the Mediterranean Sea are compared to the values observed at "Acqua Alta" tower during the experiment in order to validate the new implementation. Finally, conclusions in Section 6 complete the study.

2 Space-time wave extremes

2.1 Theoretical background

For the implementation in WW3, drawing upon Fedele (2012), space time wave extremes η_{ST} are defined in terms of the moments of the directional spectrum $S(k,\theta)$, i.e. $m_{ijl} = \int \int k_x^i k_y^j \omega^l S(k,\theta) dk d\theta$ (ω being the angular wave frequency, k the wavenumber associated, and θ the wave direction), and its integral spectral parameters (Baxevani & Rychlik, 2006; Fedele, 2012):

$$T_{m} = 2\pi \sqrt{\frac{m_{000}}{m_{002}}} \quad L_{x} = 2\pi \sqrt{\frac{m_{000}}{m_{200}}}$$
$$L_{y} = 2\pi \sqrt{\frac{m_{000}}{m_{020}}} \quad \alpha_{xt} = \frac{m_{101}}{\sqrt{m_{200}m_{002}}} \quad (1)$$
$$\alpha_{yt} = \frac{m_{011}}{\sqrt{m_{020}m_{002}}} \quad \alpha_{xy} = \frac{m_{110}}{\sqrt{m_{200}m_{020}}}$$

Here, T_m is the mean wave period, L_x is the mean wavelength (i.e. related to the wavenumber component k_x , having chosen x as the mean propagation direction), L_y is the mean wave crest (i.e. related to the wavenumber component k_y , being y orthogonal to the mean propagation direction), and α_{xt} , α_{ut}, α_{xy} are the irregularity parameters which express the correlation between the gradients of the sea surface elevation along spatial and/or temporal domains. Spectral parameters of Eq. 1 synthesize geometric and kinematic properties of the sea state, for instance the degree of short-crestedness of the sea state $\gamma_s = L_x/L_y$ (tending to 0 for long-crested sea states and to 1 for short-crested sea states). They also define the average number of waves in a space-time volume V = XYD, i.e. N_V , on the surface of the volume S, i.e. N_S , and over the edge P, i.e. N_P (Fedele, 2012):

$$N_V = 2\pi \frac{XYD}{L_x L_y T_m} \sqrt{1 - \alpha_{xyt}} \tag{2}$$

$$N_{S} = \sqrt{2\pi} \left(\frac{XY}{L_{x}L_{y}} \sqrt{1 - \alpha_{xy}^{2}} + \frac{XD}{L_{x}T_{m}} \sqrt{1 - \alpha_{xt}^{2}} + \frac{DY}{T_{m}L_{y}} \sqrt{1 - \alpha_{yt}^{2}} \right)$$
(3)

$$N_P = \frac{X}{L_x} + \frac{Y}{L_y} + \frac{D}{T_m} \tag{4}$$

where $\alpha_{xyt} = \alpha_{xt}^2 + \alpha_{yt}^2 + \alpha_{xy}^2 - 2\alpha_{xt}\alpha_{yt}\alpha_{xy}$. Hence, according to the asymptotic Gumbel limit of the extreme value probability distribution for the dimensionless space-time extreme $\xi_{ST} = \eta_{ST}/\sigma$ (σ being the standard deviation of sea surface elevation)

$$P(\xi_{ST} > \xi) \approx (N_V h^2 + N_S h + N_P) \exp(-h^2/2)$$
(5)

and to Tayfun (1980) equation $\xi = h + \frac{\mu}{2}h^2$, the nonlinear second-order expected space-time extreme $\bar{\xi}_{ST}$ and its standard deviation $std(\xi_{ST})$ are obtained as (Benetazzo *et al.*, 2015; Fedele, 2015):

$$\bar{\xi}_{ST} = \frac{\bar{\eta}_{ST}}{\sigma} = (h_0 + \frac{\mu}{2}h_0^2)$$
(6)
+
$$\frac{\gamma(1+\mu h_0)}{h_0 - \frac{2N_V h_0 + N_S}{N_V h_o^2 + N_S h_0 + N_P}}$$

$$std(\xi_{ST}) = \frac{std(\eta_{ST})}{\sigma} =$$

$$\frac{\pi}{\sqrt{6}} \frac{1 + \mu h_0}{h_0 - \frac{2N_V h_0 + N_S}{N_V h_o^2 + N_S h_0 + N_P}}$$
(7)

where h_0 is the solution of $(N_V h^2 + N_S h + N_P) = 1$, $\gamma \approx 0.5772$ is Euler-Mascheroni constant and μ is the integral steepness of the sea state estimated from the spectrum. Eqs. 5-7 are an extension of the linear space-time extreme model developed by Fedele (2012) to include second-order nonlinearities (see also the nonlinear second-order space extremes model proposed by Fedele *et al.* (2013)). A further extension of the space-time extreme model to account for third-order nonlinearities has been recently developed by Fedele (2015), but it is not herein considered.

2.2 Stereo-photogrammetric observation

An experiment aimed at observing wave extremes in the space-time domain was conducted on March 10th 2014 at the "Acqua Alta" (AA) oceanographic tower (12.5088°E, 45.3138°N, Figure 1left panel), in the northern Adriatic Sea (Italy), where a Wave Acquisition Stereo System (WASS, (Benetazzo et al., 2012), Figure 1-right panel) is mounted on top of the tower, at 12.5 m height. At 09:40UTC, during a well-established north-easterly wind storm, a 30-minute long sequence of stereo images grabbed at 15 Hz was recorded. The storm generated a fetch-limited sea state with significant wave height $H_s = 1.33$ m, mean wave propagation direction $\theta_m = 248^{\circ}$ N, and peak period $T_p = 5.4$ s. More details on the experiment set-up and on the WASS system are reported in Benetazzo et al. (2015). During the experiment 23 waves with crest height exceeding the freak wave threshold $\eta_{max} > 1.25H_s$ were observed, and their empirical probability distribution was found to be fairly represented by the predictions of Eq. 5 (see Figure 9 of Benetazzo *et al.* (2015)), assuming duration D = 1800 s and an area $S = 11.2 \cdot 11.2 = 126$ m², which is the area pertaining on average to each of the 23 high waves homogeneously distributed within the observed area of 2893 m². The sea state features, including the integral spectral parameters of Eq. 1 are summarized in Table 1.

H_s (m)	θ_m (°N)	$T_p(s)$
1.33	248	5.4
L_x (m)	L_y (m)	T_m (s)
13.6	14.6	3.6
α_{xt}	α_{yt}	α_{xy}
0.35	0.004	0.03
γ_s	$ar{\xi}_{ST}$	$std(\xi_{ST})$
0.93	5.52	0.36

Table 1: Wave conditions, integral parameters (Eq. 1) and space-time extremes observed by WASS at AA tower on March 10 2014, 09:40UTC-10:10UTC.

The sea state was short-crested, as indicated by $\gamma_s = 0.93$, and it was quite random along the wave propagation direction, as pointed out by the rather small value of α_{xt} , thus implying a high probability of encountering high waves. The mean value of the 23 crest heights (normalized on the standard deviation $\sigma = 0.334$ m) is 5.52 ± 0.36 (corresponding to $(1.38 \pm 0.09)H_s$), and it was in excellent agreement with the expected value and standard deviation (Eq. 6 and 7) of the space-time extremes model based on EC approach, i.e. 5.46 ± 0.39 .

3 Space-time extremes in WAVEWATCH III

3.1 Implementation

For the purpose of the study, we have modified the WW3 source code, version 5.08. The spacetime extremes computation has been added to the gridded output parameters calculation module, i.e. w3iogomd, in the W30UTG subroutine. Indeed, expected space-time extremes are computed as outputs of the model at each grid node and time step, once the directional spectra have been computed.

Firstly, the integral parameters of Eq. 1 are calculated by integrating the prognostic part of the spectrum to derive the spectral moments. At this stage, no diagnostic spectral tail is added. As we need integral parameters with respect to the mean wave direction of propagation θ_m (e.g. to estimate the short-crestedness γ_s), we have considered a rotated (\hat{x}, \hat{y}) reference frame where directions θ have turned to $\hat{\theta} = \theta - \theta_m$. Thus, wavenumber components (k_x, k_y) become

$$k_{\hat{x}} = k \cos \theta = k \cos(\theta - \theta_m)$$

= $k(\cos \theta \cos \theta_m + \sin \theta \sin \theta_m)$
 $k_{\hat{y}} = k \sin \hat{\theta} = k \sin(\theta - \theta_m)$
= $k(\sin \theta \cos \theta_m - \cos \theta \sin \theta_m)$

having applied trigonometric identities. Although spectral moments and integral parameters are different in the original (i.e. model) and rotated reference frames, expected space-time extremes are not affected by the rotation. Then, integral parameters are used together with user-defined space-time domain size to compute the average numbers of 3D, 2D and 1D waves, i.e. Eqs. 2-4. The expected second-order space-time extreme and the standard deviation from Eqs. 6 and 7, respectively, are finally computed after the steepness μ and the mode of the probability distribution h_0 are estimated. A statistically stable estimate of μ , strictly valid in deep waters, is obtained according to Fedele & Tayfun (2009) as $\mu = \mu_o(1 - \nu + \nu^2) = g^{-1}m_{001}^2m_{000}^{-3/2}(1 - \nu + \nu^2)$, accounting for the spectral bandwidth $\nu = \sqrt{m_{000}m_{200}/m_{100}^2 - 1}$ (g being gravitational acceleration). This formulation has been herein adopted also for transitional waters as a first approximation, and preferred to the depth-dependent narrow-band formulation of Tayfun (2006) as the effect of water depth on μ becomes strong only for very shallow waters. The modal space-time extreme h_0 is estimated according to Krogstad *et al.* (2004) as:

$$h_0 \approx \sqrt{2 \ln(N_V)} + 2 \ln(2 \ln(N_V) + 2 \ln(2 \ln(N_V)))$$

which strictly holds for large areas, i.e. if $XY \gg L_x L_y$ but can considered a good approximation

also for smaller areas. Indeed, assuming for instance a \cos^2 directional distribution spectrum whose $\alpha_{xt} = 0.7$ (and the other irregularity parameters are null), the error with respect to the mode obtained as the exact solution of the implicit equation $(N_V h^2 + N_S h + N_P) = 1$ is 1% for $X/L_x = 1$ and fall bellow 0.1% for $X/L_x > 15$. In WW3 the space-time extremes are provided as dimensional variables, i.e. η_{ST} and $std(\eta_{ST})$ in meters, by means of $\sigma = \sqrt{m_{000}}$. The new outputs of WW3 are the expected space-time extreme of a sea state STMAXE, the standard deviation STMAXD and the short-crestedness parameter SCREST.

3.2 Regression testing

In order to assess the code modification in WW3 we ran a regression test. It consists of the 1D propagation along the equator forced by an imposed directional wave spectrum: a Pierson-Moskowitz spectrum ($H_s = 0.5$ m, $T_p = 3.5$ s) combined with a \cos^2 directional distribution function (mean and peak wave direction imposed are 90°N). The spectrum is resolved with 32 frequencies between 0.05 and 1.00 Hz, and 360 directions covering the whole circle. The comparison of imposed and computed spectral parameters, short-crestedness, and spacetime extremes is provided in Table 2. It is shown that values computed by WW3 are in excellent agreement with the values imposed. Despite differences in the spectral parameters (2% at most for) L_x and L_y), the agreement for $\bar{\xi}_{ST}$ and $std(\xi_{ST})$ is perfect. Indeed, Barbariol et al. (2015) showed that even non negligible errors in the spectral parameters have very small effects on the expected space-time extremes.

4 WAVEWATCH III set-up and validation

4.1 Model set-up

In order to simulate events in the Mediterranean Sea, a curvilinear Lambert conformal grid was setup with a 5 km x 5 km resolution. The bathymetric domain was obtained by interpolation of the EMODNET bathymetry dataset (1/8 minutes x 1/8 minutes, www.emodnet-bathymetry.eu) on the grid (Figure 2), and sub-grid representation of unresolved islands was considered. Wave energy spectra were discretized using a constant 10° directional increment (covering all directions), and a spatially varying wavenumber grid (corresponding to an invariant logarithmic intrinsic frequency grid covering from 0.05 Hz to 2.00 Hz, i.e. deep water wave components in the 0.5 to 20 s range). Herein, the wind growth and whitecapping dissipation were modeled according to Ardhuin et al. (2010), the nonlinear interactions using the Discrete Interaction Approximation (DIA), the bottom friction according to JONSWAP formulation, and the depth-induced breaking following Battjes & Janssen (1978). To describe wave propagation, a third order accurate numerical scheme was used. WW3 was compiled for a shared memory parallel environment using the OpenMP (OMP) protocol, and ran on one node of a IBM cluster machine (2 CPUs with 14 2.3 GHz processors).

WW3 was forced by the 10-m height wind speed horizontal components produced by the COSMO atmospheric model (Steppeler *et al.*, 2003) in its operational version maintained by the Meteorological Service of the Italian Aeronautics (CNMCA), as a part of the NETTUNO forecasting system (Bertotti et al. (2013) described in details the system, the models involved and their performance). Wind fields were provided every 3 hours on a regular 7 km resolute grid and linearly interpolated by WW3, in space and time. We simulated a 30-day period to verify and validate the wind inputs and the wave parameters outputs. Hence, WW3 runs cover the March 01-30 2014 period, while the outputs are shown for the March 05-30 2014 period, having considered a sufficient warm-up time of the model.

4.2 Model validation

Wind input from the COSMO model and wave results from the WW3 model have been compared against data gathered over the Mediterranean Sea by an observational network of buoys (belonging to the EMODNET network, www.emodnet.eu, see Table 3 for code names of the stations) and the oceanographic tower "Acqua Alta". Observational stations have different temporal coverage and are mainly located along the Spanish, French and Italian coastlines (western Mediterranean Sea and northern Adriatic Sea). The precise location of sta-

	T_m (s)	L_x (m)	L_y (m)	α_{xt}	α_{yt}	α_{xy}	γ_s	$\bar{\xi}_{ST}$	$std(\xi_{ST})$
imposed	2.64	9.6	16.7	0.91	0.0	0.0	0.58	5.20	0.38
computed	2.65	9.8	17.0	0.91	0.0	0.0	0.58	5.20	0.38

Table 2: Regression test to assess the correctness of space-time extremes equations implementation in WW3. Comparison between imposed and computed spectral parameters, short-crestedness and space-time extreme values (expected and standard deviation computed over an area $S = 11.2 \cdot 11.2 \text{ m}^2$ and a duration D = 1800 s).

tions is depicted in Figure 2, where red labels "W" indicates stations collecting wind measurements, yellow labels "WW" stations gathering wind and wave measurements, and "AA" the "Acqua Alta" oceanographic tower, which collects wind and wave measurements too. Satellite data have not been herein considered due to the short duration of the simulation.

4.2.1 Wind input

The verification of wind inputs is provided in Figure 5 (in APPENDIX) for "Acqua Alta" tower as time series of wind speed and direction, and in Table 3 for all the available stations as statistical indicators of the agreement between modeled and observed wind speed and direction: correlation coefficient (CC) and scatter index (SI) for wind speed U_{10} , and directional bias (Bias[°]) and variance of the model-observed residuals (var°) for wind direction θ_U (according to Mardia & Jupp (2009)). As verified by Bertotti et al. (2013), performance of COSMO model, though in forecasting version, are quite good. Indeed, at "Acqua Alta" tower, for instance, wind speed CC is 0.86 and SI is 0.37, which are values pointing out a good simulation of winds, although some differences both in the dynamics and in the intensity of winds are evident. In particular, during the event observed by stereo experiment in its descending phase (Figure 5) the peak wind speed is underestimated (12.5 instead of 15.2 m/s) and delayed in time (6 hours) with respect to the actual observed peak. The results is that according to the model at the experiment time the event was already in the growing phase. Wind direction at "Acqua Alta" was correctly simulated (Figure 5).

4.2.2 Output wave parameters

Conventional output wave parameters $(H_s, T_m \text{ and } \theta_m)$ are compared to observed parameters in Fig-

ure 6 (in APPENDIX) at "Acqua Alta" tower and in Table 3 for all the available stations. The agreement is generally fair, particularly for H_s and T_m having CC over 0.9 and 0.7, respectively, in all the stations. However, the underestimation and delay pointed out in the wind forcing affect the wave parameters during the experiment, especially H_s that is under-predicted at the growing and peak phases of the event (1.69 m instead of 1.97 m at the peak), while it is over-predicted due to wind speed delay in the descending (i.e. observed by stereo) phase of the event (Figure 6). Wave parameters at "Acqua Alta" at the time of the experiment are summarized in Table 4, and compared to values in Table 1 they point out a good modeling performance as a whole, though characterized by some small differences mostly ascribable to the forecasting character of the wind forcing.

H_s (m)	θ_m (°N)	$T_p(\mathbf{s})$
1.60	258	5.7
L_x (m)	L_y (m)	T_m (s)
17.3	20.3	3.9
α_{xt}	α_{yt}	α_{xy}
0.8	-0.22	-0.16
γ_s	$\bar{\xi}_{ST}$	$std(\xi_{ST})$
0.85	5.11	0.42

Table 4: Wave conditions, integral parameters (Eq. 1) and space-time extremes computed by WW3 at AA tower on March 10 2014, 09:40UTC-10:10UTC.

5 Space-time extremes validation

The space-time extremes outputs of WW3 have been compared to observations during the stereo experiment. To this end, $\bar{\xi}_{ST}$ and $std(\xi_{ST})$ (i.e.



Figure 2: WW3 computational domain over the Mediterranean Sea with depths and observational stations used for model validation. In yellow the stations gathering wind and wave data, and in red the stations providing only wave data.

station		U_{10}		θ_U		H_s		T_m		θ_m	
#	code name	CC	SI	Bias° (°)	var°	CC	SI	CC	SI	Bias° (°)	var°
AA	Acqua Alta	0.86	0.37	1.39	0.32	0.91	0.37	0.74	0.23	0.26	0.14
WW1	61196	0.61	0.76	-6.10	0.52	0.91	0.30	0.69	0.15	-0.22	0.39
WW2	61197	0.86	0.34	18.83	0.11	0.94	0.23	0.86	0.11	-2.74	0.16
W1	OBSEA	0.74	0.40	11.07	0.43	-	-	-	-	-	-
W2	OOCS	0.77	0.38	30.26	0.77	-	-	-	-	-	-
W3	VIDA	0.84	0.33	-32.17	0.30	-	-	-	-	-	-

Table 3: Output wave parameters verification at the available observational stations of Figure 2, as statistical indicators of the agreement between modeled and observed parameters: correlation coefficient (CC) and scatter index (SI) for wind speed U_{10} , significant wave height H_s and mean wave period T_m ; directional bias (Bias°) and variance of the model-observed residuals (var°) for wind direction θ_U and mean wave direction θ_m (according to Mardia & Jupp (2009)). Compared period is March 05-30 2014.

STMAXE and STMAXD, respectively) have been computed taking into account an area $S = 11.2 \cdot 11.2$ m² and a duration D = 1800 s, corresponding to the domain size of the stereo experiment. Also, the model and the experiment share the same frequency and direction spectral range. Results summarized in Table 4, once compared to values in Table 1, show that WW3 fairly reproduced the observed integral spectral parameters. The resulting differences however, are in some cases relatively large, in particular for L_x , L_y and α_{xt} . This is mainly imputable to the effect of the wind speed overestimation on the directional spectrum which causes, beside a larger H_s , larger T_m , L_x and L_y . In addition, there is also an effect on the irregularity parameters. The direct effect of such overprediction is that smaller average numbers of waves in the domain (Eqs. 2-4) are expected and, in turn, a lower $\bar{\xi}_{ST}$. Indeed, the space-time extreme WW3 prediction is 5.11 ± 0.42 (corresponding to $(1.28 \pm 0.11)H_s$), which is lower than the observed value. Nevertheless, the difference with observations is only 7%, hence the error on the space-time extreme is much smaller than the errors on the integral parameters. The reason for this is that the expected value of the space-time extremes is weakly sensitive to variations in the average number of waves (Barbariol *et al.*, 2015).

We also computed the space-time extremes by taking into account a different domain size: $S = 26.9 \cdot 26.9 \text{ m}^2$ and D = 450 s (see Benetazzo *et al.* (2015)). Observed $\bar{\xi}_{ST}$ was 5.54 ± 0.38 and WW3 computed 5.23 ± 0.42 , hence the 6% difference is consistent with the previously obtained result.

The short-crestedness parameter SCREST computed by WW3 (i.e. 0.83) agrees with the observed value, indicating a short-crested sea state.



Figure 3: Space-time extremes at AA computed by WW3 during the simulated period ($S = 11.2 \cdot 11.2$ m², D = 1800 s). Red lines delimit the stereo-photogrammetric experiment.

Figures 3 and 4 show two examples of the outcomes that one can obtain with the new WW3 implementation. Figure 3 represent the time series of $\bar{\xi}_{ST}$ at a fixed location ("Acqua Alta" tower, with focus on a reduced time interval in the proximity of the experiment). It is noteworthy that all the expected space-time extremes exceed the limit conventionally adopted to define a rogue wave from its crest, i.e. 5σ (corresponding to $1.25H_s$).

Figure 4 offers another point of view that the new implementation can provide, since it represents the spatial distribution of $\bar{\xi}_{ST}$ over the whole Mediterranean Sea at the time of the stereo experiment. The gray line delimit the portion of the sea with $\bar{\xi}_{ST}$ below the rogue wave limit from the regions where the maximum expected crest height is expected to exceed 5σ . Herein, since the domain size is fixed for every grid node, the highest $\bar{\xi}_{ST}$ are expected in regions with lower sea severities (hence, shorter waves) and shallowest depths.

6 Conclusions

In this document we reported the introduction of space-time wave extremes computation in the WW3 model, and we demonstrated that the new implementation (based on the theoretical approach of Fedele (2012) and second-order nonlinear extension of Benetazzo et al. (2015), properly adapted to a numerical model context using some approximations) enables to estimate the new output parameters with a fair agreement. To this end, we compared model results with observations gathered by the stereo-photogrammetric WASS system at the "Acqua Alta" tower, in the northern Adriatic Sea. The wind forcings provided by the COSMO model (within the NETTUNO forecasting system) allowed us to simulate one month of sea states over the Mediterranean Sea. Results in terms of expected space-time extremes are definitely promising since WW3 was able to reproduce the observed value with a 7% error, which according to our analvsis is mainly ascribable to the over-prediction and delay in the wind speed during the experiment. However, we are planning further tests and investigations to quantify the numerical model effects (e.g. the modeling of nonlinear wave-wave interactions, the computation of modal value of the space-time extremes probability distribution) on the space-time extremes estimate and assess the limitations of the approach. In order to improve the results of the case study, we are also setting up the Weather Research Forecasting (WRF) model to force WW3 with reanalysis winds: preliminary



Figure 4: Space-time extremes computed by WW3 at the time of the stereo experiment ($S = 11.2 \cdot 11.2$ m², D = 1800 s). The gray line delimits the areas where $\bar{\xi}_{ST}$ fall below (yellow) and exceed (orange-red) the conventional rogue wave limit for crest heights, i.e. $5\sigma = 1.25H_s$.

results are promising. Finally, we are going to implement and validate the computation of the maximum expected wave height in space-time.

To conclude, we briefly showed potential outcomes of the new implementation, that are, for instance, the hindcasts and forecasts of the spacetime extremes expected at a fixed location and over a region of the sea.

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APPENDIX



Figure 5: Wind input verification at "Acqua Alta" tower: time series of observed (obs) and modeled (mod) wind speed and direction. Compared period is March 02-30 2014. Red lines delimit the stereo-photogrammetric experiment.



Figure 6: Output wave parameters verification at "Acqua Alta" tower: time series of observed (obs) and modeled (WW3) significant wave height H_s , mean wave period T_m and mean wave direction θ_m . Compared period is March 05-30 2014. Red lines delimit the stereo-photogrammetric experiment.