Previsione numerica di onde anomale (freak waves) ed estreme durante le tempeste marine

Relazione scientifica sui risultati ottenuti durante il programma CNR Short Term Mobility 2015 (in inglese)

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Introduction

This report describes scientific activities and results achieved within the Short-Term mobility program that dr. Francesco Barbariol (ISMAR-CNR) spent from October 11th, 2015 to November 2nd, 2015 in College Park (MD, USA), hosted by dr. Jose-Henrique Alves and dr. Arun Chawla at the Environmental Modeling Center (EMC). EMC is part of the National Centers for Environmental Prediction (NCEP), a branch of the National Oceanic and Atmospheric Administration (NOAA). It is a world-leading center for the development of numerical models of the atmosphere and ocean, supporting the United States and international administrations with ocean and atmosphere forecasts.

Dr. Barbariol was hosted by the Marine Modeling and Analysis Branch (MMAB) of EMC, that develops and maintains the state-of-the-art numerical wave model WAVEWATCH III (WW3). WW3 is a third generation spectral wave model that simulates the generation, propagation and dissipation of sea wave states under the action of wind over complex bathymetries (Tolman & Group, 2014). WW3 is regularly updated by an international community of developers in order to include the most recent results on ocean wave research.

Description of activities

At present, numerical prediction of stormy seas provides guidance on integral wave parameters such as the significant wave height. Nevertheless, seafarers and offshore structures need for reliable information about the expected maximum wave heights, which have been found to be higher over a space-time than in time (Forristall, 2006; Fedele *et al.* , 2013; Benetazzo *et al.* , 2015). Recent results in the wave statistics (see for instance Fedele (2012); Fedele *et al.* (2013); Barbariol *et al.* (2015); Benetazzo *et al.* (2015)) have shown that the directional wave spectrum (an output of numerical spectral wave models) can lead to accurate estimates of expected maximum wave heights over time (sea state duration) and space (sea surface area). Hence, the idea of providing spectral numerical wave models with a new feature, in order to compute the maximum expected space-time wave height. Therefore, aimed at investigating the WW3 performance in wave extremes prediction, dr. Barbariol worked together with dr. Alves on:

- WW3 source code development, in order to include space-time extremes computation (drawing upon recent results on extreme wave statistics due to Fedele (2012));
- simulation of stormy sea states in the Mediterranean Sea with WW3;
- comparison of modeled space-time wave extremes with stereo-photogrammetric observations at ISMAR-CNR *Acqua Alta* oceanographic tower, in the northern Adriatic Sea (Italy).

Space-time extremes implementation in WW3

For the implementation in WW3, drawing upon Fedele (2012), space time extreme crest η_{ST} and wave height H_{ST} are defined in terms of the moments of the directional spectrum $S(k,\theta)$, i.e. $m_{ijl} = \iint k_x^i k_y^j \omega^l S(k,\theta) dk d\theta$ (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)

$$\begin{aligned} T_m &= 2\pi\sqrt{\frac{m_{000}}{m_{002}}} \quad & L_x &= 2\pi\sqrt{\frac{m_{000}}{m_{200}}} \\ L_y &= 2\pi\sqrt{\frac{m_{000}}{m_{020}}} \quad & \alpha_{xt} &= \frac{m_{101}}{\sqrt{m_{200}m_{002}}} \\ \alpha_{yt} &= \frac{m_{011}}{\sqrt{m_{020}m_{002}}} \quad & \alpha_{xy} &= \frac{m_{110}}{\sqrt{m_{200}m_{020}}} \end{aligned} \tag{1}$$

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_{yt}, 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):

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

$$\begin{aligned} N_S = \sqrt{2\pi}(& \frac{XY}{L_x L_y} \sqrt{1 - \alpha_{xy}^2} \\ & + \frac{XD}{L_x T_m} \sqrt{1 - \alpha_{xt}^2} \\ & + \frac{DY}{T_m L_y} \sqrt{1 - \alpha_{yt}^2}) \end{aligned} \tag{3}$$

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

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 crest height $z = \eta_{ST}/\sigma$ (σ being the standard deviation of sea surface elevation)

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

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

$$\bar{\xi}_{ST} = \bar{z}_{ST}/4 = \frac{1}{4}\left[(h_0 + \frac{\mu}{2}h_0^2) + \gamma(1+\mu h_0)\left(h_0 - \frac{2N_V h_0 + N_S}{N_V h_o^2 + N_S h_0 + N_P}\right)^{-1}\right] \tag{6}$$

$$std(\xi_{ST}) = std(z_{ST})/4 = \frac{1}{4}\left[\frac{\pi(1+\mu h_0)}{\sqrt{6}}\left(h_0 - \frac{2N_V h_0 + N_S}{N_V h_o^2 + N_S h_0 + N_P}\right)^{-1}\right] \tag{7}$$

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.

The expected maximum wave height $\bar{\chi}_{ST}$ (i.e. $\bar{H}_{ST}$ normalized on H_s) and the wave height associated to the expected maximum crest height $\bar{\chi}^*_{ST}$ (i.e. $\bar{H}^*_{ST}$ normalized on H_s) are estimated according to the linear version of the Quasi-Determinism theory (Boccotti, 2000), as:

$$\bar{\chi}_{ST} = \frac{1}{4}\left[h_0 + \gamma\left(h_0 - \frac{2N_V h_0 + N_S}{N_V h_o^2 + N_S h_0 + N_P}\right)^{-1}\right]\sqrt{2(1+\psi^*)} \tag{8}$$

$$\bar{\chi}^*_{ST} = \frac{1}{4}\left[h_0 + \gamma\left(h_0 - \frac{2N_V h_0 + N_S}{N_V h_o^2 + N_S h_0 + N_P}\right)^{-1}\right](1+\psi^*) \tag{9}$$

where the first term between brackets in both Equations represents the linear estimate of the expected maximum crest height over space-time, and ψ^* is the first minimum of the time autocovariance function of the sea surface elevation $\psi(T)$. ψ^* is an indicator of the spectral bandwidth and it generally ranges between 0.65 and 0.75 in wind generated sea states (Boccotti, 2000). The autocovariance function $\psi(T)$ can be computed as:

$$\psi(T) = \int S(\omega)\cos(\omega T)d\omega \tag{10}$$

being $S(\omega) = \int S(\omega,\theta)d\theta$ the frequency spectrum computed from the directional frequency spectrum $S(\omega,\theta)$, and T a time lag.

The standard deviations of the maximum wave height, i.e. $std(\chi_{ST})$, and of the wave height associated with the maximum crest height, i.e. $std(\chi^*_{ST})$, are computed as:

$$std(\chi_{ST}) = \frac{1}{4}\left[\frac{\pi}{\sqrt{6}}\left(h_0 - \frac{2N_V h_0 + N_S}{N_V h_o^2 + N_S h_0 + N_P}\right)^{-1}\right]\sqrt{2(1+\psi^*)} \tag{11}$$

$$std(\chi^*_{ST}) = \frac{1}{4}\left[\frac{\pi}{\sqrt{6}}\left(h_0 - \frac{2N_V h_0 + N_S}{N_V h_o^2 + N_S h_0 + N_P}\right)^{-1}\right](1+\psi^*) \tag{12}$$

where the first term between brackets in both Equations represents the linear estimate of the standard deviation of the maximum crest height over space-time.

For the purpose of this study, we have modified the WW3 source code, version 5.08. The space-time extremes computation has been added to the gridded output parameters calculation module. Indeed, expected space-time extremes and standard deviations are computed as outputs of the model at each grid node and time step, once the directional spectra $S(k,\theta)$ have been computed.

Simulation of stormy sea states with WW3

In order to simulate events in the Mediterranean Sea, a curvilinear Lambert conformal grid was set-up 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 1), 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.

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 1 for code names of the stations) and

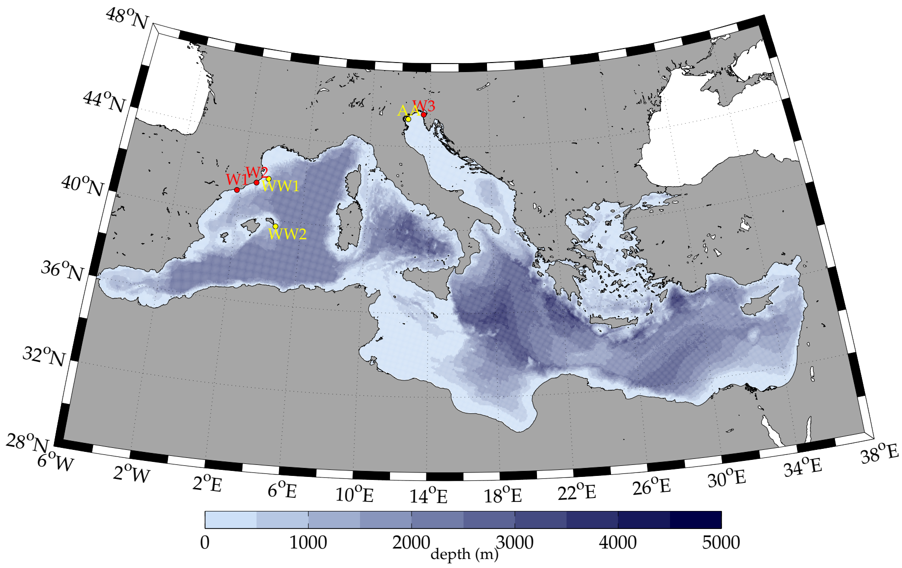

Fig. 1: WW3 computational domain over the Mediterranean Sea with depths and observational stations used for model validation. In yellow the stations gathering wind and wave data, and in red the stations providing only wave data.

the oceanographic tower *Acqua Alta*. The precise location of stations is depicted in Figure 1, 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.

The verification of wind input is provided in Table 1 for all the available stations as statistical indicators of the agreement between modeled and observed wind speed. As verified by Bertotti *et al.* (2013), performance of COSMO model, though in forecasting version, are quite good. Conventional output wave parameters (H_s and T_m) are compared to observed parameters in Table 1 for all the available stations. The agreement is generally fair for both H_s and T_m, having CC over 0.9 and 0.7, respectively, and low RMSE in all the stations.

station		U_{10} (m/s)			H_s (m)			T_m (s)		
#	code name	CC	RMSE	Bias	CC	RMSE	Bias	CC	RMSE	Bias
AA	**Acqua Alta**	0.86	1.81	-0.01	0.91	0.19	-0.06	0.74	0.60	-0.40
WW1	**61196**	0.61	3.93	3.67	0.91	0.38	0.12	0.69	0.67	-0.59
WW2	**61197**	0.86	2.08	1.80	0.94	0.34	0.02	0.86	0.55	-0.55
W1	**OBSEA**	0.74	2.79	-2.15	-	-	-	-	-	-
W2	**OOCS**	0.77	1.56	0.02	-	-	-	-	-	-
W3	**VIDA**	0.84	1.70	-0.30	-	-	-	-	-	-

Tab. 1: Output wave parameters verification at the available observational stations of Figure 1, 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. Compared period is March 05-30 2014.

Results

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 2-left panel), in the northern Adriatic Sea (Italy), where a Wave Acquisition Stereo System (WASS, (Benetazzo *et al.* , 2012), Figure 2-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 $\theta_m = 248$°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 $\eta_{max} > 1.25 H_s$ 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 $S = 11.2 \cdot 11.2 = 126$ m^2, which is the area pertaining on average to each of the 23 high waves homogeneously distributed within the observed area of 2893 m^2. The sea state features, including the integral spectral parameters of Eq. 1 are summarized in Table 2.

Fig. 2: The “Acqua Alta” oceanographic tower (left), and the WASS stereo-photogrammetric system (right).

H_s (m)	θ_m (°N)	T_p(s)	T_m (s)
1.33	248	5.4	3.6
L_x (m)	L_y (m)	α_{xt}	α_{yt}
13.6	14.6	0.35	0.004
α_{xy}	γ_s	$\bar{\xi}_{ST}$	$std(\xi_{ST})$
0.03	0.93	1.38	0.09
$\bar{\chi}_{ST}$	$std(\chi_{ST})$	$\bar{\chi^*}_{ST}$	$std(\chi^*_{ST})$
-	-	2.08	0.16

Tab. 2: 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 significant wave height) is 1.38 ± 0.09, while the mean value of the wave heights associated to these 23 wave crests is 2.08 ± 0.16. With the analysis technique chosen it was not possible to estimate the maximum expected wave height, which is supposed to be 9% higher than the wave height associated with the expected maximum wave crest, being the first minimum of the autocovariance function $\psi^* = 0.67$.

H_s (m)	θ_m (°N)	T_p(s)	T_m (s)
1.60	258	5.7	3.9
L_x (m)	L_y (m)	α_{xt}	α_{yt}
17.3	20.3	0.8	-0.22
α_{xy}	γ_s	$\bar{\xi}_{ST}$	$std(\xi_{ST})$
-0.16	0.85	1.28	0.10
$\bar{\chi}_{ST}$	$std(\chi_{ST})$	$\bar{\chi^*}_{ST}$	$std(\chi^*_{ST})$
2.02	0.24	1.83	0.21

Tab. 3: Wave conditions, integral parameters (Eq. 1) and space-time extremes computed by WW3 at AA tower on March 10 2014, 09:40UTC-10:10UTC.

The outputs of WW3 have been compared to observations during the stereo experiment. To this end, space-time extremes have been computed taking into account an area $S = 11.2 \cdot 11.2$ m^2 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 3, once compared to values in Table 2, 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 an effect of wind speed overestimation on the directional spectrum of the event 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 over-prediction is that smaller average numbers of waves in the domain (Eqs. 2-4) are expected and, in turn, lower $\bar{\xi}_{ST}$ and $\bar{\chi}_{ST}$. Indeed, the space-time extreme WW3 prediction are 1.28 ± 0.10 and 1.83 ± 0.21, respectively, which are lower than the observed values. Nevertheless, the difference with observations is only 7% and 12%, respectively, hence the errors on the space-time extreme are much smaller than the errors on the integral parameters. The reason for this is that the expected values of the space-time extremes are weakly sensitive to variations in the average number of waves (Barbariol *et al.* , 2015). The expected maximum wave height is 2.02 ± 0.24 which is 10% higher than the wave height associated with the expected maximum crest height, in agreement with the estimate based on ψ^*, which, however, is 0.64 for the WW3 frequency spectrum.

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References

Ardhuin, Fabrice, Rogers, Erick, Babanin, Alexander V., Filipot, Jean-François, Magne, Rudy, Roland, Aaron, van der Westhuysen, Andre, Queffeulou, Pierre, Lefevre, Jean-Michel, Aouf, Lotfi, & Collard, Fabrice. 2010. Semiempirical Dissipation Source Functions for Ocean Waves. Part I: Definition, Calibration, and Validation. *Journal of Physical Oceanography*, **40**(9), 1917–1941.

Barbariol, Francesco, Benetazzo, Alvise, Carniel, Sandro, & Sclavo, Mauro. 2015. Space-Time Wave Extremes: The Role of Metocean Forcings. *Journal of Physical Oceanography*, **45**(7), 1897–1916.

Battjes, J, & Janssen, J.P.F.M. 1978. Energy loss and set-up due to breaking of random waves. *Proceedings of the 16th international conference on coastal engineering*, **1**(1), 569–587.

Baxevani, Anastassia, & Rychlik, Igor. 2006. Maxima for Gaussian seas. *Ocean Engineering*, **33**, 895–911.

Benetazzo, Alvise, Fedele, Francesco, Gallego, Guillermo, Shih, Ping Chang, & Yezzi, Anthony. 2012. Offshore stereo measurements of gravity waves. *Coastal Engineering*, **64**, 127–138.

Benetazzo, Alvise, Barbariol, Francesco, Bergamasco, Filippo, Torsello, Andrea, Carniel, Sandro, & Sclavo, Mauro. 2015. Observation of extreme sea waves in a space-time ensemble. *Journal of Physical Oceanography*, **45**(In press), 2261–2275.

Bertotti, Luciana, Cavaleri, Luigi, Loffredo, Layla, & Torrisi, Lucio. 2013. Nettuno: Analysis of a Wind and Wave Forecast System for the Mediterranean Sea. *Monthly Weather Review*, **141**(9), 3130–3141.

Boccotti, Paolo. 2000. *Wave mechanics for ocean engineering*. Vol. 64. Elsevier Science.

Fedele, Francesco. 2012. Space–Time Extremes in Short-Crested Storm Seas. *Journal of Physical Oceanography*, **42**(9), 1601–1615.

Fedele, Francesco. 2015. On Oceanic Rogue Waves. *arXiv:1501.03370*.

Fedele, Francesco, Benetazzo, Alvise, Gallego, Guillermo, Shih, Ping Chang, Yezzi, Anthony, Barbariol, Francesco, & Ardhuin, Fabrice. 2013. Space-time measurements of oceanic sea states. *Ocean Modelling*, **70**, 103–115.

Forristall, George Z. 2006. Maximum wave heights over an area and the air gap problem. *Pages 11–15 of: Proc. ASME 25th Inter. Conf. Off. Mech. Arc. Eng., Hamburg, OMAE2006-92022*.

Steppeler, J, Doms, G, Schättler, U, Bitzer, H W, Gassmann, A, Damrath, U, & Gregoric, G. 2003. Meso-gamma scale forecasts using the nonhydrostatic model {LM}. *Meteorology and Atmospheric Physics*, **82**(1), 75–96.

Tayfun, M Aziz. 1980. Narrow-Band Nonlinear Sea Waves. *Journal of Geophysical Research*, **85**(C3), 1548–1552.

Tolman, Hendrik L, & Group, WAVEWATCH Development. 2014. User manual and system documentation of WAVEWATCH III version 4.18. *NOAA / NWS / NCEP / MMAB Technical Note*, 311.

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