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

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Outline

Space-Time extremes of sea states in WAVEWATCH III

Objective

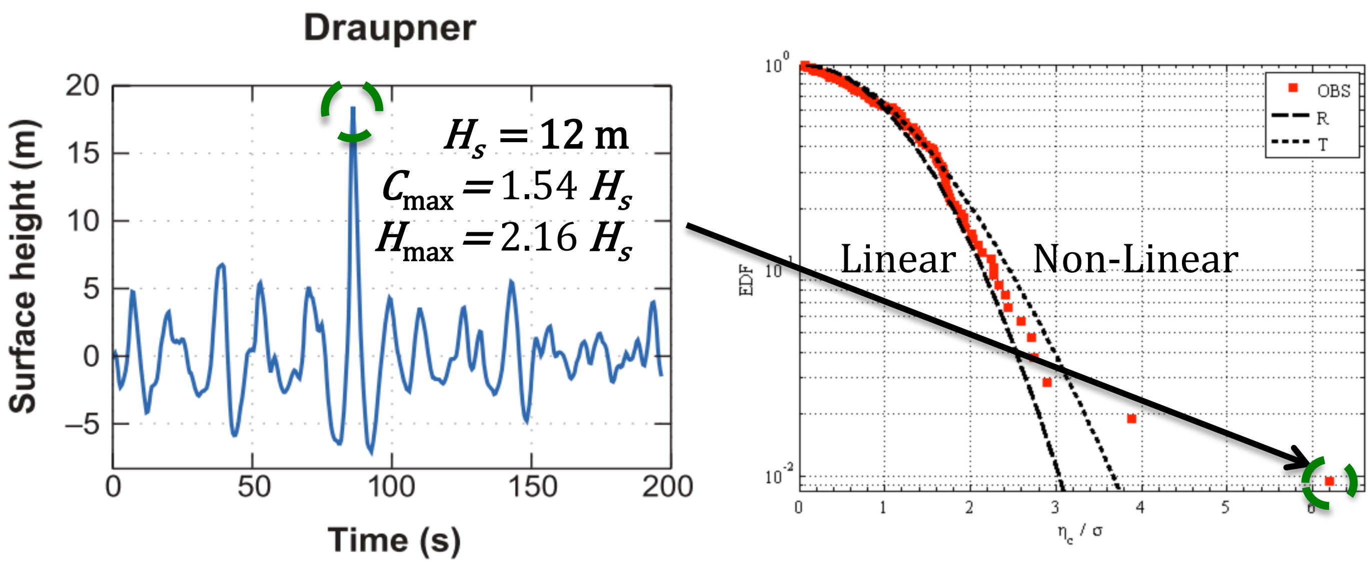
- Develop experimental approach to estimate Space-Time Extremes using a spectral wave model

1. Motivations
2. Framework
   - Theoretical prediction of ST extremes (Fedele Model)
   - Verification using stereo data
   - Implementation and Validation of ST extremes using WW3
3. Next steps

Motivations

Why try to estimate extreme waves with operational wave model?

1. Extreme waves are dangerous for marine activities
2. But still not completely understood:
   - Outliers of standard statistical wave models,

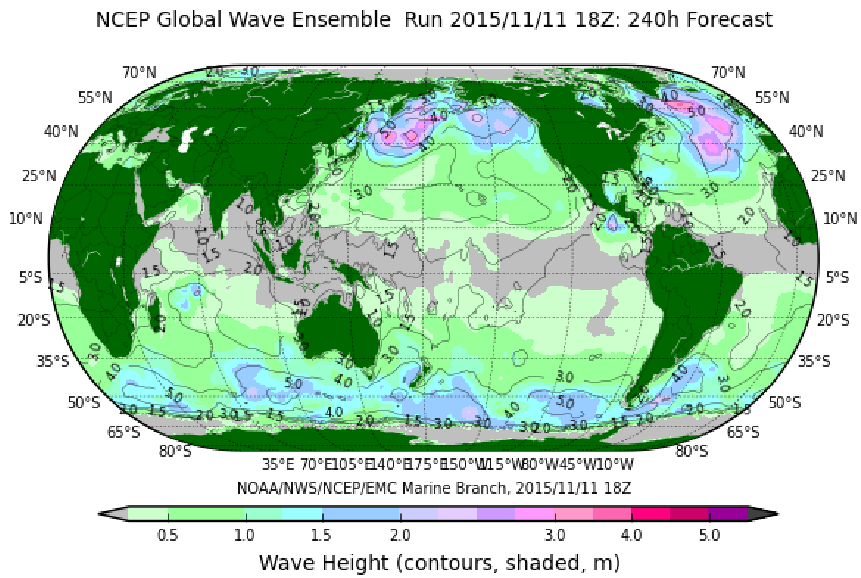


   - Require new approach to predict them.

Pictures from Dysthe et al., 2008

Expected Outcome

Why try to estimate extreme waves with operational wave model?



- With good approach, collaboration is great opportunity for disseminating information via US National Weather Service wave guidance
  - NCEP data (models) are free,
  - Waves alone: > 1 million hits/downloads per day,
  - Inform a lot of users of enhanced danger.

Theoretical prediction of ST extremes

In our work, the theoretical framework comes from:

- Ground-breaking work of Fedele (2012) for linear ocean waves, based on Adler and Taylor (2007) and Baxevani and Rychlik (2006),
- Extension to nonlinear waves by Fedele et al. (2013), Benetazzo et al. (2015), and Fedele (2015)

Provide probability of crest-height maxima exceeding threshold for a *N*-dimensional domain, and its expected values.

The 2nd order Fedele Model allows us to calculate in WW3 the probability of exceedance and expected value of the random variable $\max(\eta)/\sigma$.

$$\Pr(\max(\eta)/\sigma \geq s) \text{ and } E[\max(\eta)/\sigma]$$

The 2nd Order Fedele Model, in a nutshell

How to estimate enhancement of likelihood of encounter?

1. **Exceedance probability of extreme crest heights:**

- Fedele et al. (2013) and Benetazzo et al. (2015), apply the Tayfun equation for 2nd order wave crest height to the linear form of Fedele (2012)

$$\xi = z + \frac{\mu}{2} z^2 \rightarrow z = \frac{-1 + \sqrt{1 + 2\mu\xi}}{\mu}$$

$$P_{\mathrm{FM2,max}}\{\eta_{\max}/\sigma > \xi \mid (N_\mathrm{V}, N_\mathrm{S}, N_\mathrm{B})\} \approx (N_V z^2 + N_S z + N_B)\, P_\mathrm{R}$$

Gumbel asymptotics

2. Expected maximum crest height

- Benetazzo et al. (2015), Fedele (2015)

$$E_{\mathrm{FM2,max}}\{\eta_{\max}/\sigma \mid (N_\mathrm{V}, N_\mathrm{S}, N_\mathrm{B})\} \approx \left(h_\mathrm{FM} + \frac{\mu}{2} h_\mathrm{FM}^2\right) + \frac{\gamma}{h_{FM} - \frac{2N_V h_\mathrm{FM} + N_S}{N_V h_\mathrm{FM}^2 + N_S h_\mathrm{FM} + N_P}} (1 + \mu h_\mathrm{FM})$$

Prob and expected value increase when

- N_V, N_S and N_B increase = larger number of waves
  - Larger ST domain
- Number of waves: quantity to be computed from spectra

WW3 to do list:

Average numbers of waves
N_V, N_S, N_B

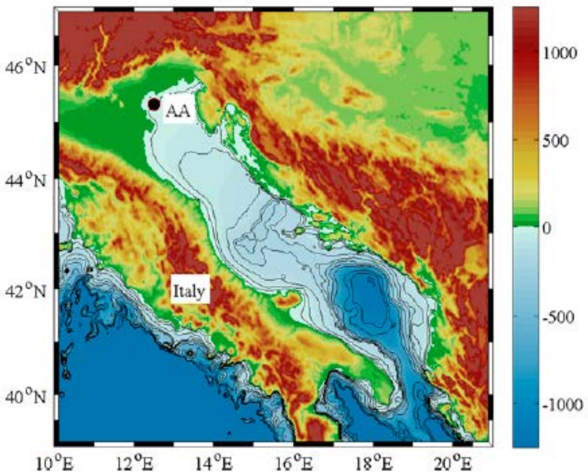
Space-time domain size
X, Y, T

Geometric spectral parameters
T_m, L_x, L_y

Kinematic spectral parameters
α_{xt}, α_{yt}, α_{xy}

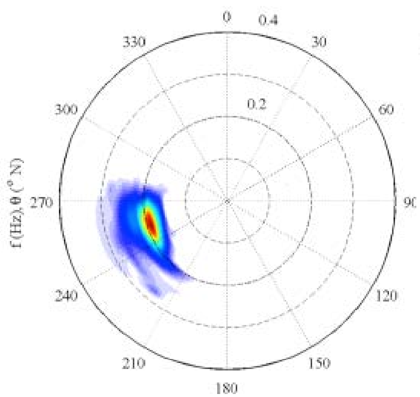
How can We Prove the Theory?

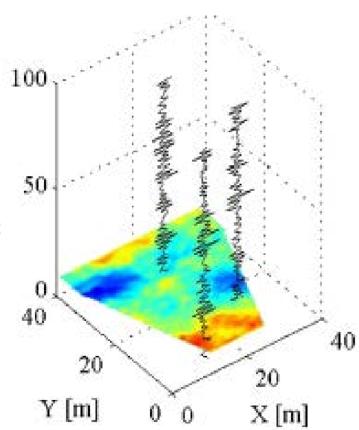
STEREO EXPERIMENT: Acqua Alta (30’ sequence, 15 Hz, 70 m x 60 m area)

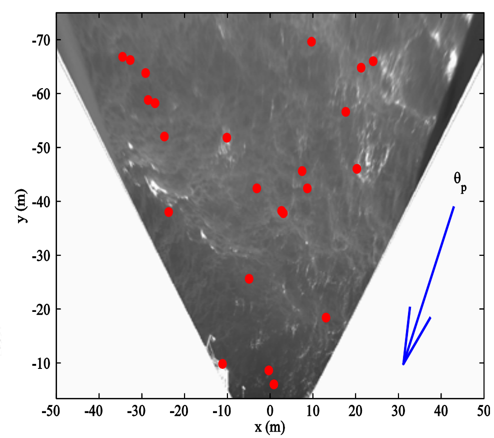


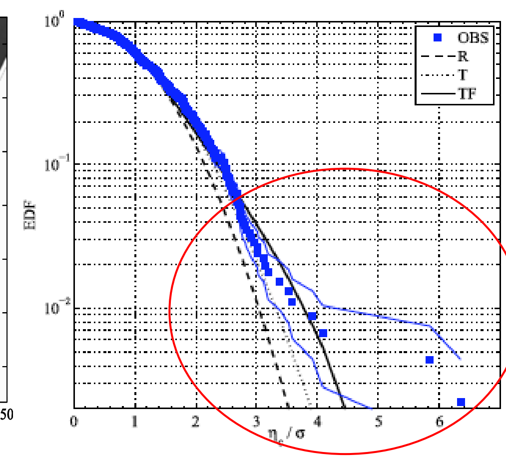
After 3D reconstruction:

- $\sigma = 0.334$ m
- $\lambda_3 = 0.16$
- $\lambda_4 = 3.22$
- $\mu = 0.06$
- $\nu = 0.47$
- Dir. Spread. = 39°
- # waves in time = 500









23 waves exceeding the freak wave limit (crest > 1.25 Hs)

- Not well described by standard statistical models.

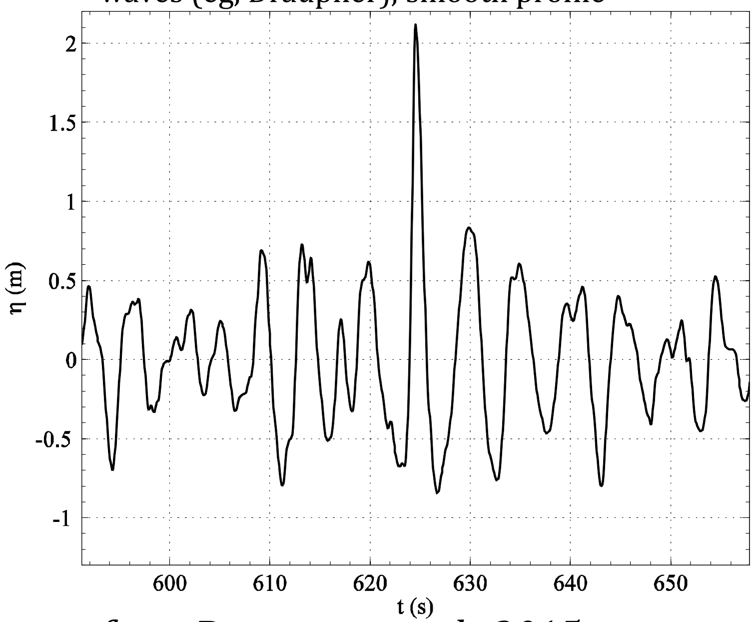
Pictures from Benetazzo et al., 2015

Observing Space-Time extremes

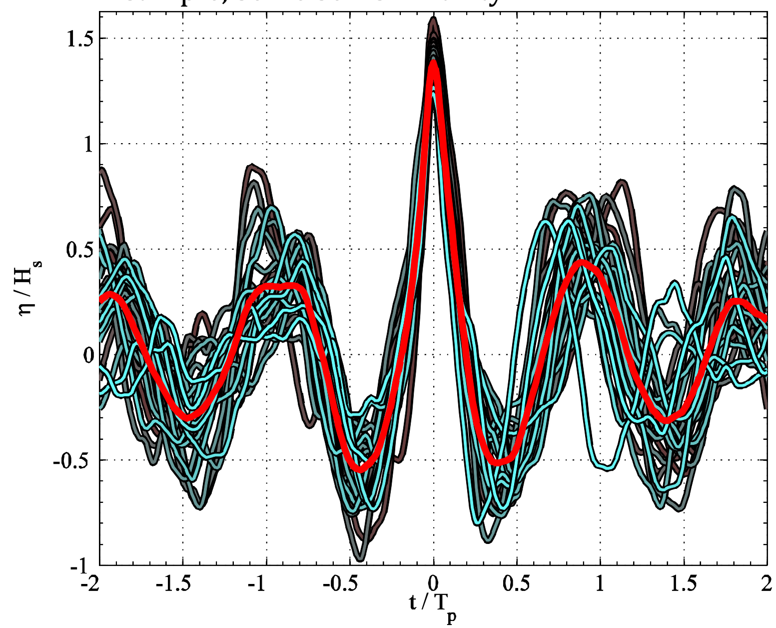
23 waves exceeding the freak wave limit (crest > 1.25 Hs)

Record	B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8	B_9	B_{10}	B_{11}	B_{12}
$\eta_{i,\max}/H_s$	1.59	1.52	1.49	1.48	1.47	1.45	1.45	1.43	1.41	1.38	1.38	1.37
$H_{i,\max}/H_s$	2.22	2.39	2.24	2.21	2.19	2.10	2.42	1.93	2.16	1.86	2.26	1.79
$\varepsilon_{i,\max}$	0.36	0.36	0.26	0.40	0.36	0.36	0.35	0.30	0.36	0.36	0.29	0.28
	B_{13}	B_{14}	B_{15}	B_{16}	B_{17}	B_{18}	B_{19}	B_{20}	B_{21}	B_{22}	B_{23}	Avg
$\eta_{i,\max}/H_s$	1.36	1.34	1.34	1.32	1.32	1.31	1.31	1.28	1.27	1.26	1.25	1.38
$H_{i,\max}/H_s$	1.99	2.11	2.03	2.05	2.07	1.92	1.93	1.98	2.01	2.06	1.96	2.08
$\varepsilon_{i,\max}$	0.29	0.41	0.38	0.34	0.33	0.33	0.31	0.34	0.34	0.45	0.31	0.34

Profile of B1 wave: consistent with other freak waves (eg, Draupner), smooth profile



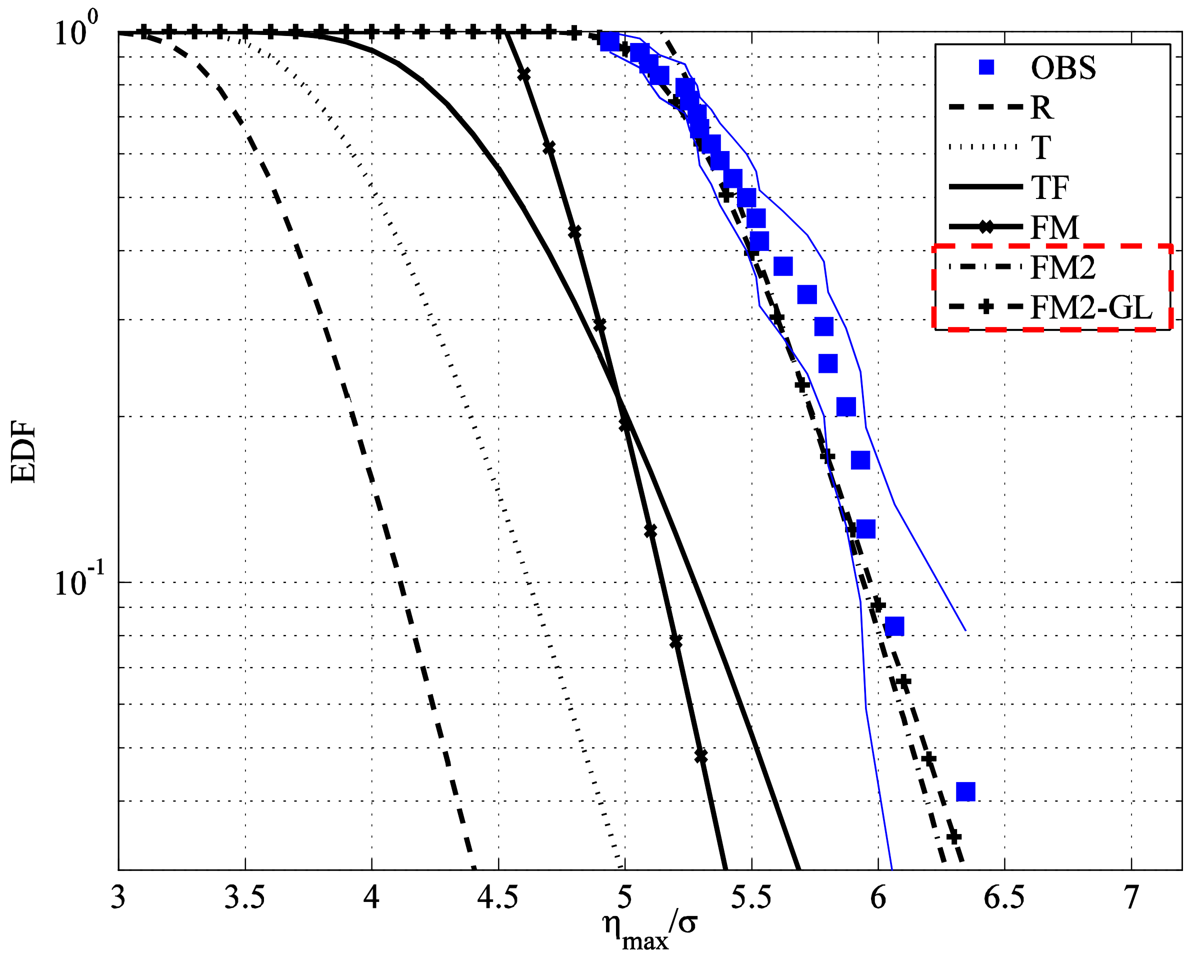
Profiles of all cases: consistent across whole sample, some self-similarity



Pictures from Benetazzo et al., 2015

Verifying the Theoretical Estimates

1. Exceedance Probabilities



Computed on XY=11x11 m^2 (domain/23), 30'

2. Expected values

$< \eta_{R,max} > = 0.92\ H_s$

$< \eta_{T,max} > = 1.03\ H_s$

$< \eta_{TF,max} > = 1.17\ H_s$

$< \eta_{FM,max} > = 1.19\ H_s$

$\mathbf{< \eta_{FM2,max} > = 1.37\ H_s}$

THEORETICAL

$\mathbf{< \eta_{i,max} > = 1.38\ H_s}$

OBS.

Picture from Benetazzo et al., 2015

Simulating ST extremes in WW3

Can we use spectra computed by numerical wave prediction models, such as WAVEAWTCH III, to estimate Space-Time extremes on realistic domains?

Simulating ST extremes in WW3

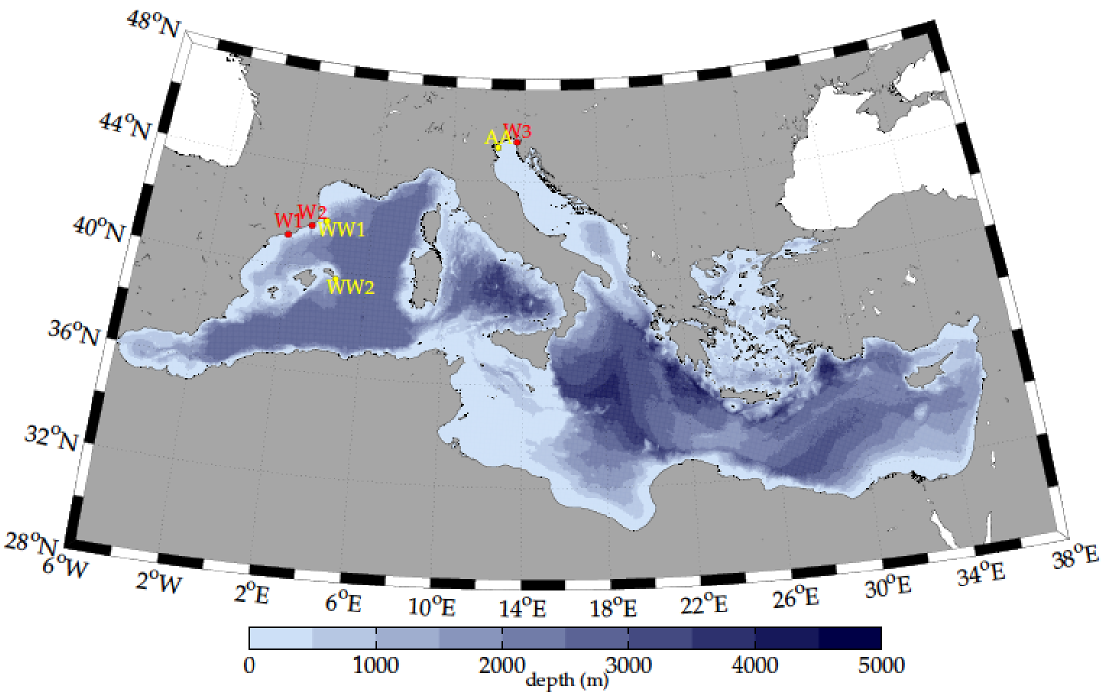
Game plan

1. Implement parameters from ST extremes theory in WW3:
   - Geometric spectral parameters (T_m, L_x, L_y),
   - Kinematic spectral parameters (α_{xt}, α_{yt}, α_{xy}),
   - Expected ST extreme crest height ($E[\max(\eta)/\sigma]$) and its standard deviation ($STD[\max(\eta)/\sigma]$),
   - Short-crestedness parameter (γ_{sc}).

2. Validate WW3 results
   - Acqua Alta experiment event.

Simulating ST extremes in WW3

WW3 simulation of the Acqua Alta experiment, Med Sea



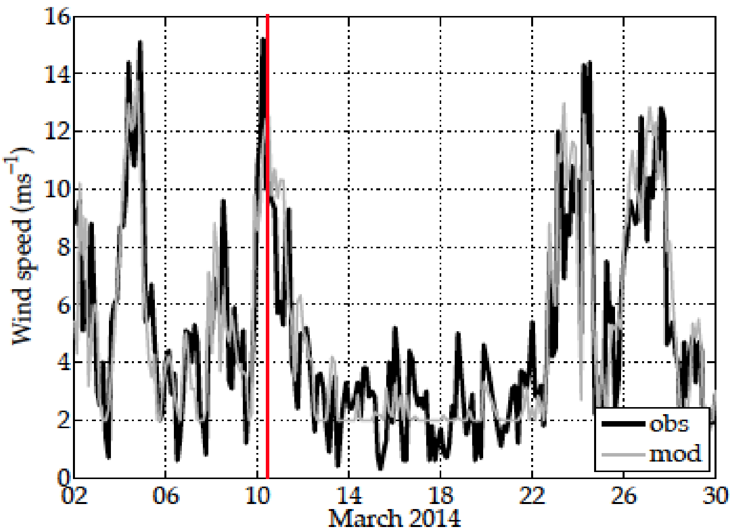
Experimental settings

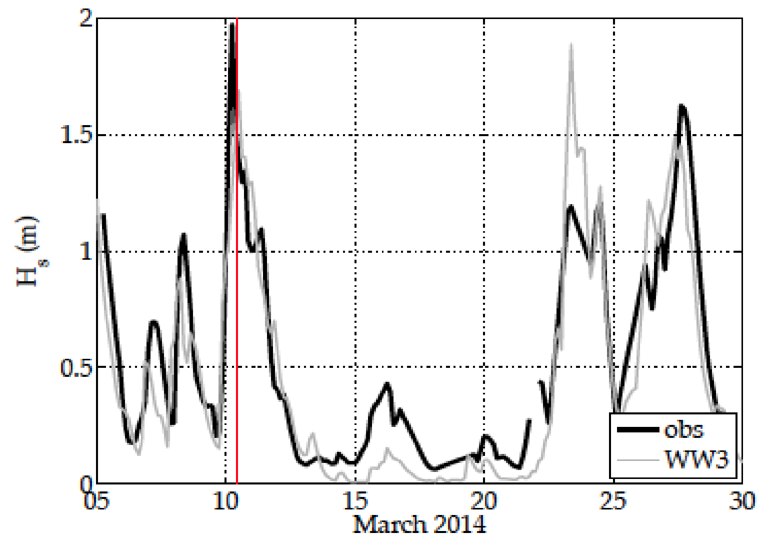
- MedSea 5km curvilinear grid
- 40 frequencies (0.05-2Hz)
- 36 directions
- COSMO wind input (7km, 3h), NETTUNO forecasting system (CNMCA)
- ST4 source terms (Ardhuin et al 2010)
- DIA Snl
- 10-day spinup

Validation

- 6 points for wind
- 3 sites for waves

Simulating ST extremes: Validation





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	-			-		

Wind data reproduces reasonably well during period of measurement (red line)
- Particularly near Acqua Alta

Wave predictions reproduce reasonably well observed Hs
- Wave validation statistics typical of an operational forecasting system

Simulated ST extremes, By WW3

Observed (stereo)

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	$\bar{\eta}_{ST}$	$std(\eta_{ST})$
0.93	$1.38H_s$	$0.09H_s$

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.

Modeled (WW3)

H_s (m)	θ_m (°N)	T_p(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	$\bar{\eta}_{ST}$	$std(\eta_{ST})$
0.85	$1.28H_s$	$0.11H_s$

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.

7% difference on expected ST extremes

(11 x 11 m^2, 30' – verified on 27 x 27 m^2, 30')

Simulating ST extremes in WW3

Can we use spectra computed by numerical wave to forecast Space-Time extremes on realistic domains?

YES, we have a proof of concept.

But we have to keep in mind:

- Experimental evidence based on small-scale data
  - Needs to be verified in open-ocean environment,
    - Measurements in small area, 2/3 wavelengths in viewing area precluded following the complete group dynamics
  - Still need larger areas to verify directly following complete dynamics

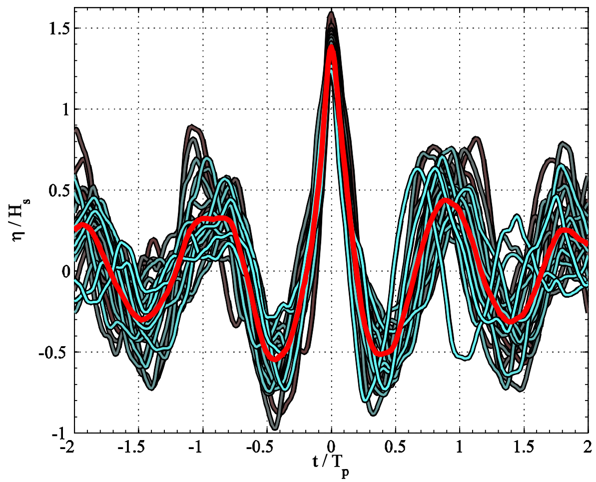
Therefore, we are working on:

- What are the best approximations (FM2, FM3)?
- Sensitivity analyses to investigate numerical model effect to STE prediction:
  - DIA straight jacket: constraint to spectral shape (shown here by TW)?
  - Other source functions?
  - Best spectral ranges to compute ST parameters (peak, added tail)?

In the Pipeline

We will now...

1. Investigate **limitations**/reduce **approximations**
2. Perform **new stereo experiments**.
3. Increase the space domain observed to **validate results over wider areas** (airborne stereo, coherent marine radars [Jochen Horstmann]).

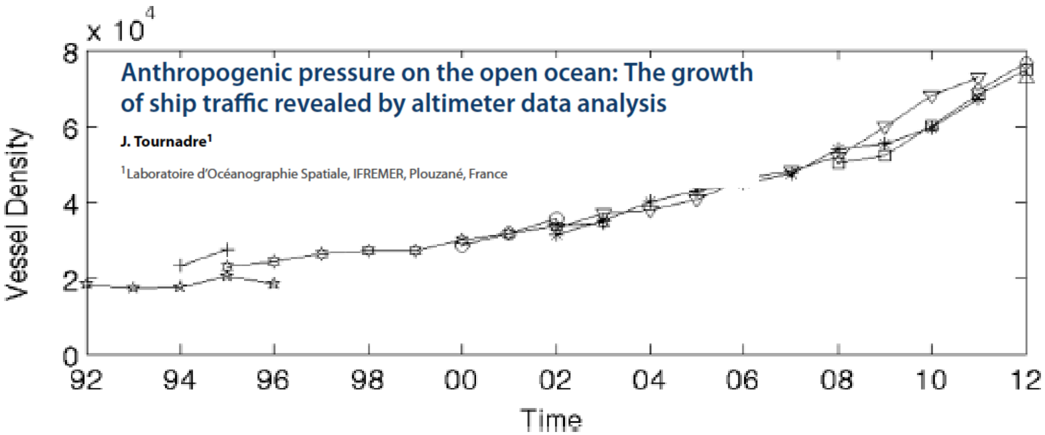


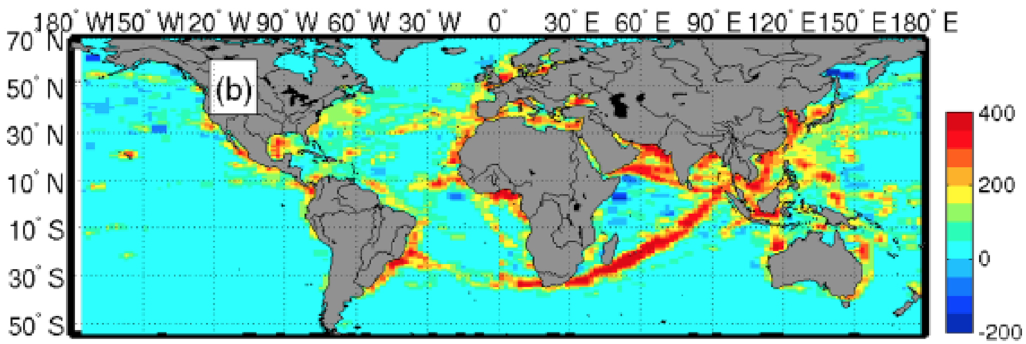
4. Implement new WW3 outputs: **maximum expected WAVE HEIGHT** (Boccotti's Quasi-Determinism).

5. **Validate** maximum expected WAVE HEIGHT at Acqua Alta and other sites.

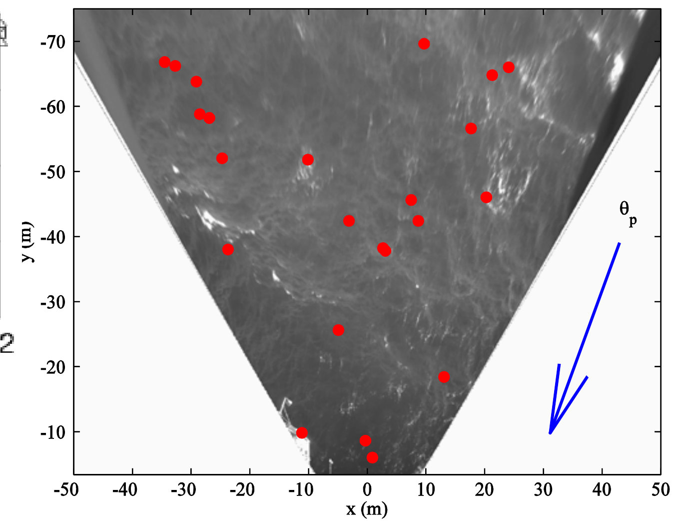
4. Run/validate new WW3 outputs in the **open ocean** – **comparison with buoy** observations of extreme waves (in collaboration with Johannes Gemmrich).

Discussion: A Sense of Purpose





"The analysis of the global ship density shows the dramatic fourfold increase of traffic between the 90's and present."



By increasing observation locations from a point to an area/grid: able to detect not one, but 23 occurrences of waves larger than freak wave limit.

Increasing the number of ships out at sea, equates to increasing points in space and time, in our experiment: increased likelihood of freak wave encounters.

- Urgent need of better forecasting tools.

Concluding Remarks

- We propose framework for applying new science to solve a very real world problem
  - Predicting extreme waves, and spreading the word to users at risk, using one of the main operational centers in the world,
- Improved predictability: reliable products with relevance to users

- Better predictability, in this case: being at the right place, in the right time
  → Saving lives and property.