



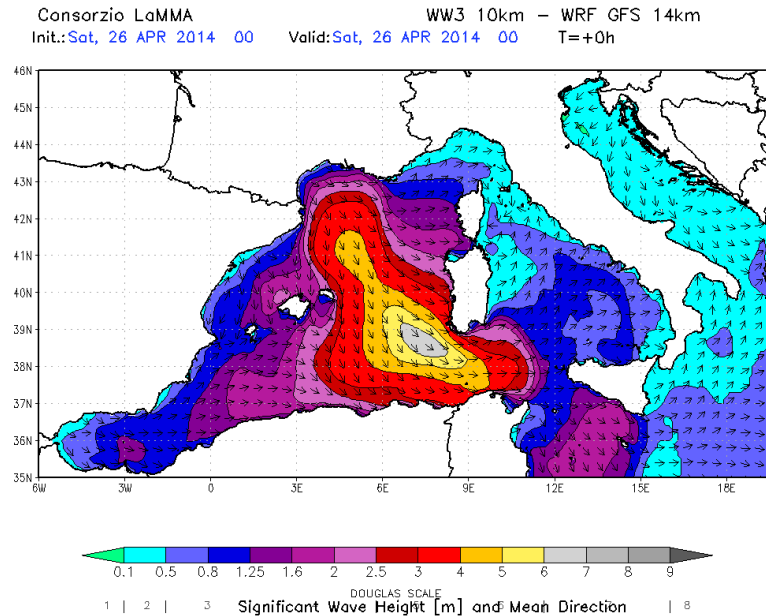
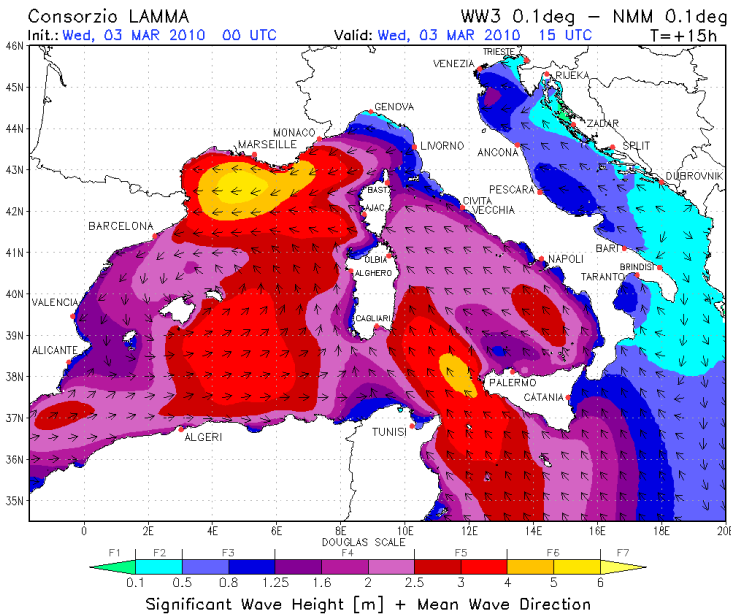
Analysis of Dangerous Sea States in the Northwestern Mediterranean Area

A. Innocenti, C. Brandini

LaMMA Consortium, Environmental Modelling and Monitoring Laboratory for the Sustainable
Development

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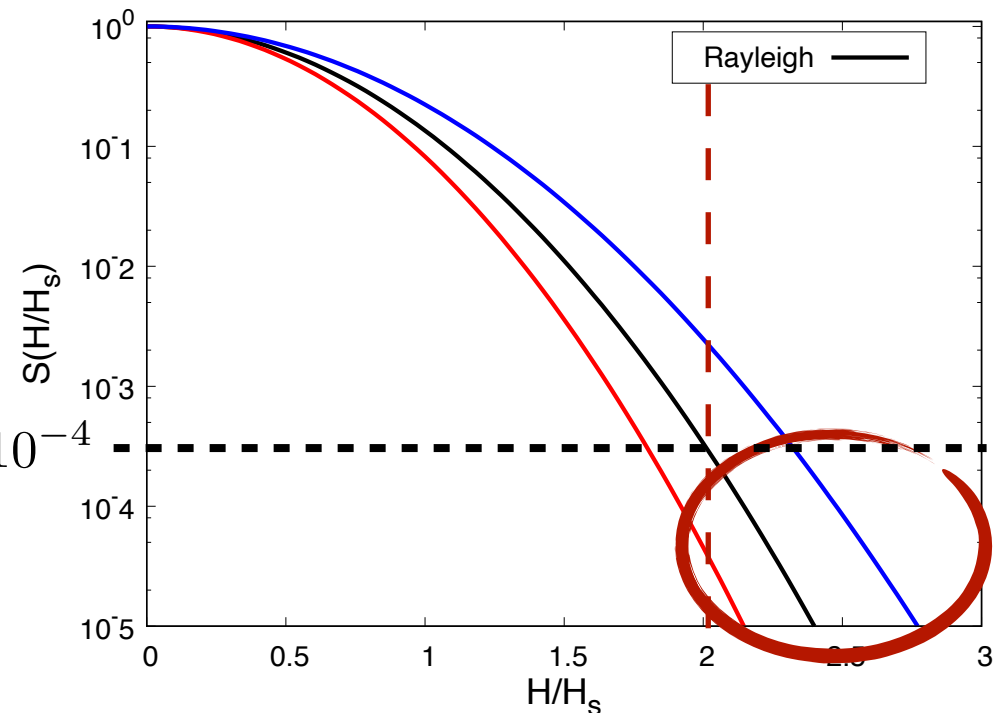
Extreme waves



Different sea conditions
can give rather different
wave distributions even
if we fix a point with
the same H_s

A rogue wave is defined as a **wave higher than twice H_s** $H > 2H_s$, or in terms of crests from $\eta_c > 1.25H_s$

$$P_R \simeq 3.35 \cdot 10^{-4}$$



Methodology: phase resolved models

Wave distributions and other statistical informations can be obtained with phase resolving models

Time resolution of this set of partial differential equation, derived from the Euler equation for potential flow, with a dynamic and a kinematic boundary condition

$\Delta\phi = 0$ Mass conservation

$\phi(x, y, t)$ Velocity potential $\vec{V} = \vec{\nabla}\phi$

$\eta(x, y, t)$ Free surface elevation

$$\frac{\partial\phi_s}{\partial t} = -g\eta - \frac{1}{2}|\nabla\phi_s|^2 + \frac{1}{2}\left(1 + |\nabla\eta|^2\right)\left(\frac{\partial\phi}{\partial z}\right)^2$$

$\phi_s(x, y, t) = \phi(x, y, \eta(x, y, t), t)$ Surface potential

Dynamic boundary condition: continuity of pressure through the surface

$$P_{inside} = P_{atm}$$

$$\frac{\partial\eta}{\partial t} = \left(1 + |\nabla\eta|^2\right)\frac{\partial\phi}{\partial z} - \nabla\phi_s \cdot \nabla\eta$$

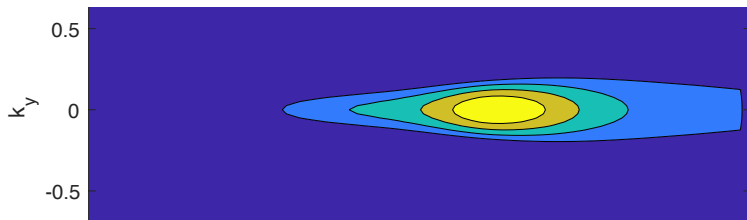
Kinematic boundary condition: null flux through the free surface

$$\frac{\partial F}{\partial t} + \vec{V} \cdot \vec{\nabla} F = 0$$

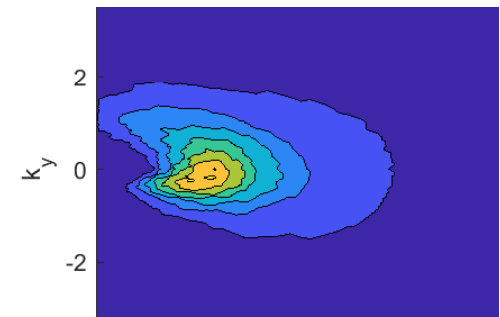
Iterative solution of the non-linear series expansion of this term up to a given order

Methodology: phase resolving models

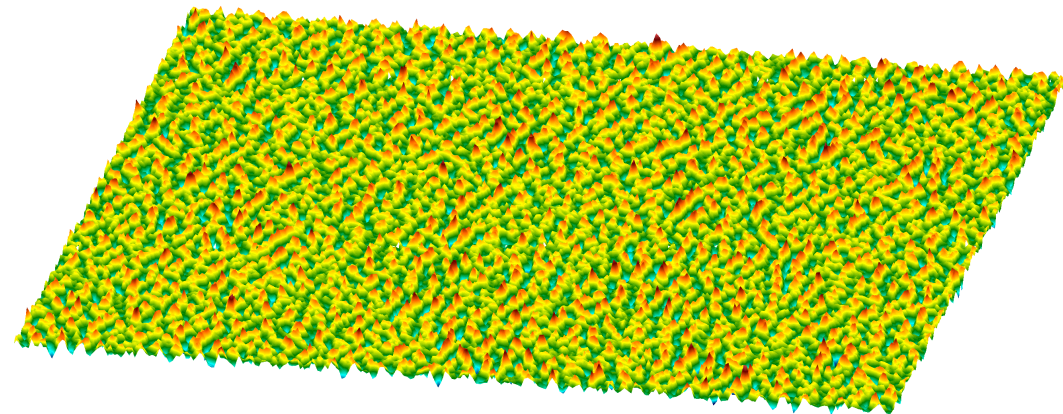
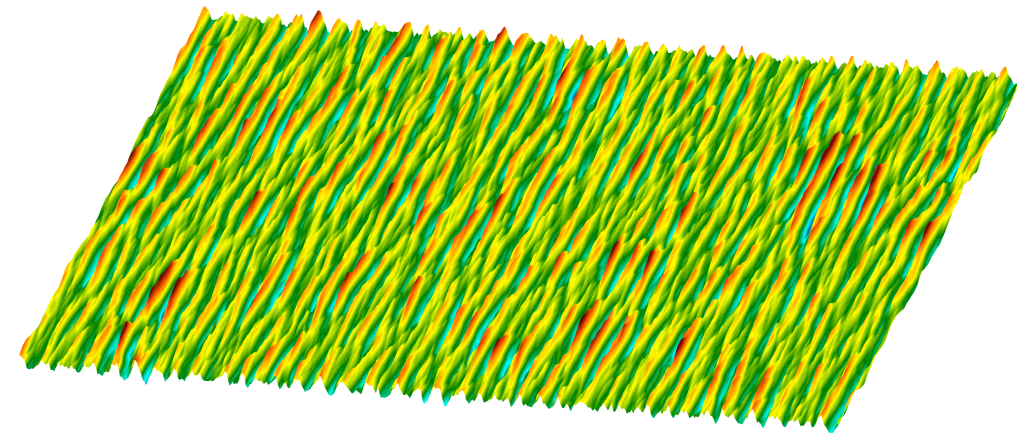
With the Higher Order Spectral Method these equations are solved on a pseudo-spectral grid with a direct correspondence between the physical and the spectral space



JONSWAP quasi-unidirectional spectrum



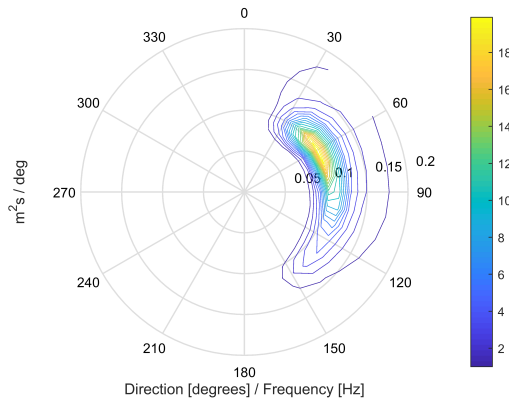
WaveWatch III spectrum



Periodic domain

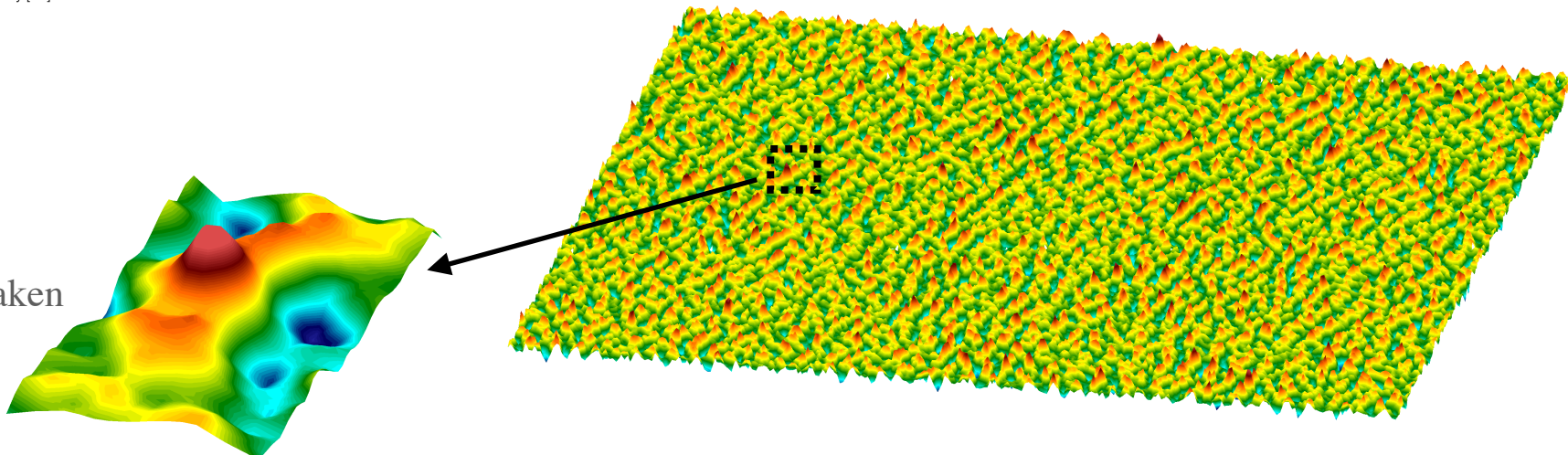
Coupling of WWIII with HOS Method

- We are using an open-source code, HOS-ocean¹, developed at Ecole Centrale de Nantes which apply the HOS method to a double periodic domain in deep water.
- No external forcing are present (wind, currents)
- The non-linearity order can be chosen through a parameter
- The simulations can be initialized with both WWIII spectra or with parametrized JONSWAP spectra

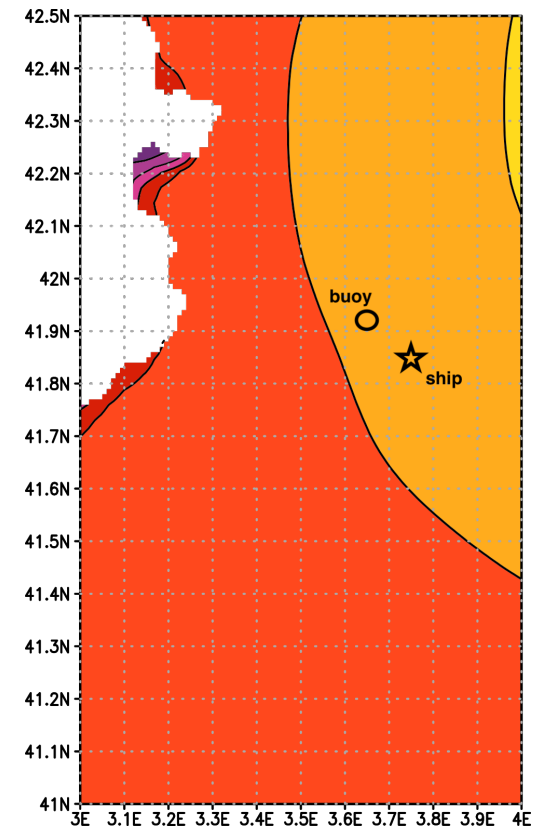
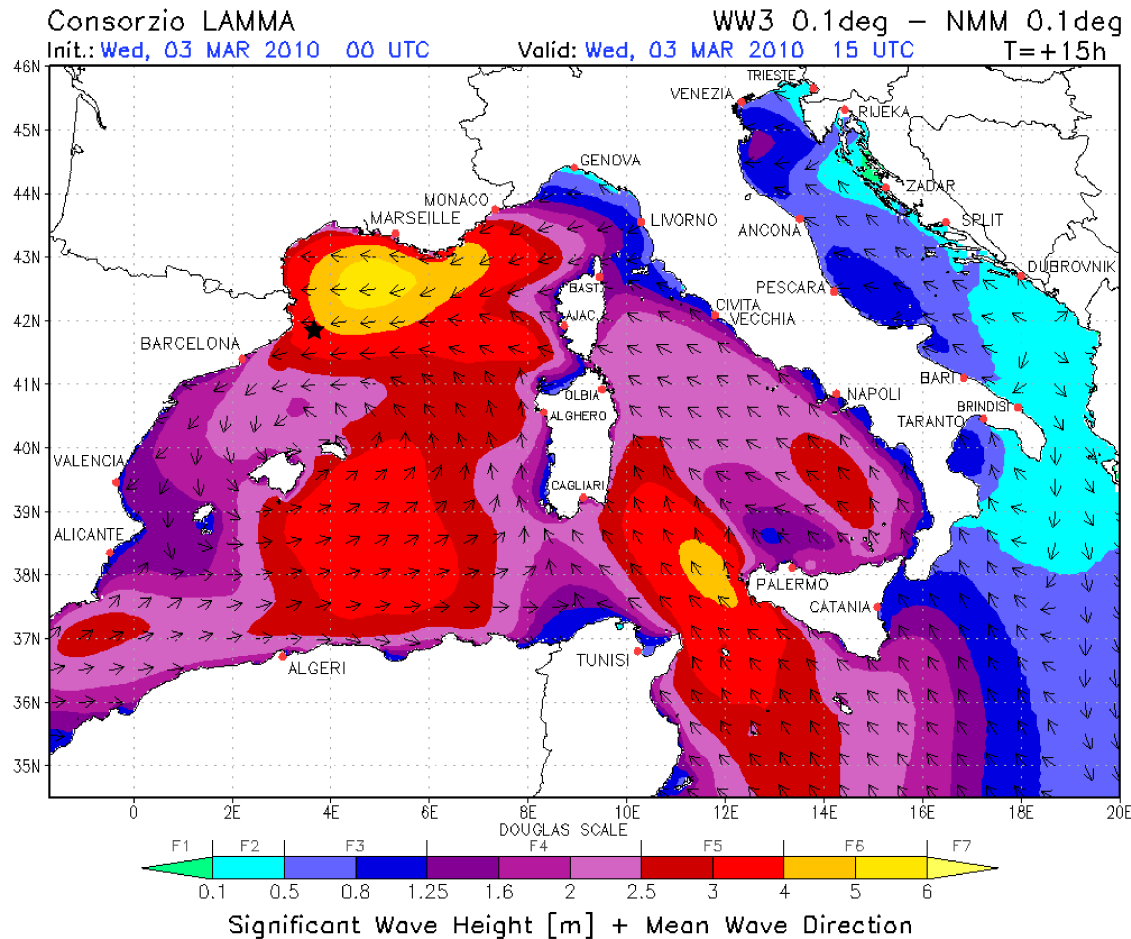


We use a WWIII punctual spectrum to generate a **sea surface** (initialized with random phases) in a domain of length $40\lambda_p \times 40\lambda_p$

Non-linearities taken
into account



Louis-Majesty case study

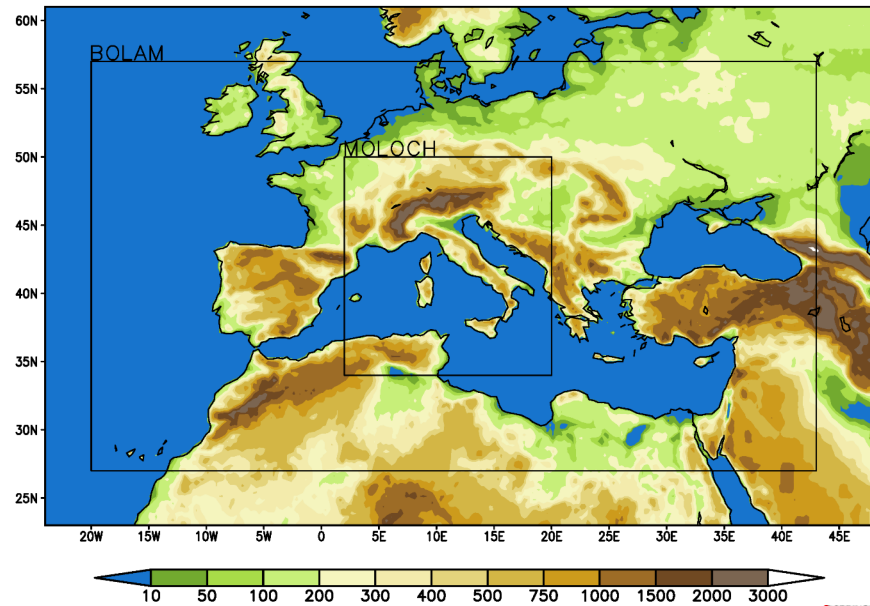


Innocenti et al. 2021, *Journal of Marine Science and Engineering*]

3/03/2010: Louis Majesty passenger ship on the route from Barcelona to Genova was hit by a rogue wave up to deck 5, 16m above the mean floating line smashing some windows of a living room; **two persons were killed and several injured.**

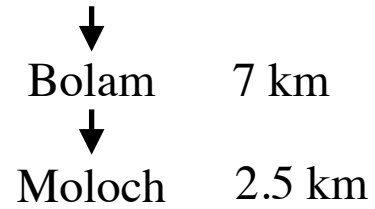
$H_s = 4-5\text{m}$; $H_{\text{rogue}} > 10\text{m}$

For the analysis of past events we have used wave hindcast data¹ produced with the WaveWatch III model²

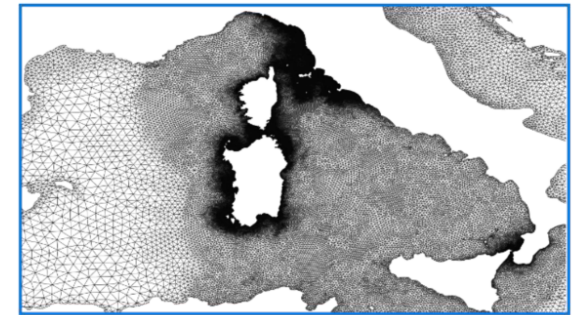
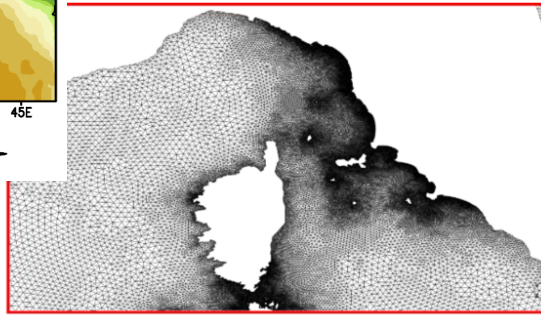


(a)

ERA5 dataset



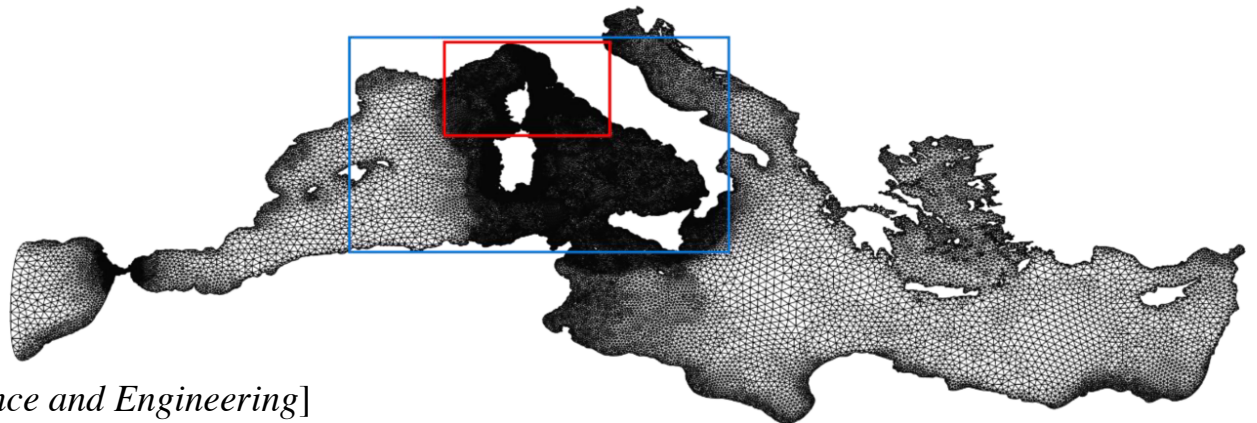
(b)



Unstructured grid :

- Finest resolution near coast 500m
- Average resolution at coast 3km
- Coarsest resolution offshore 30km

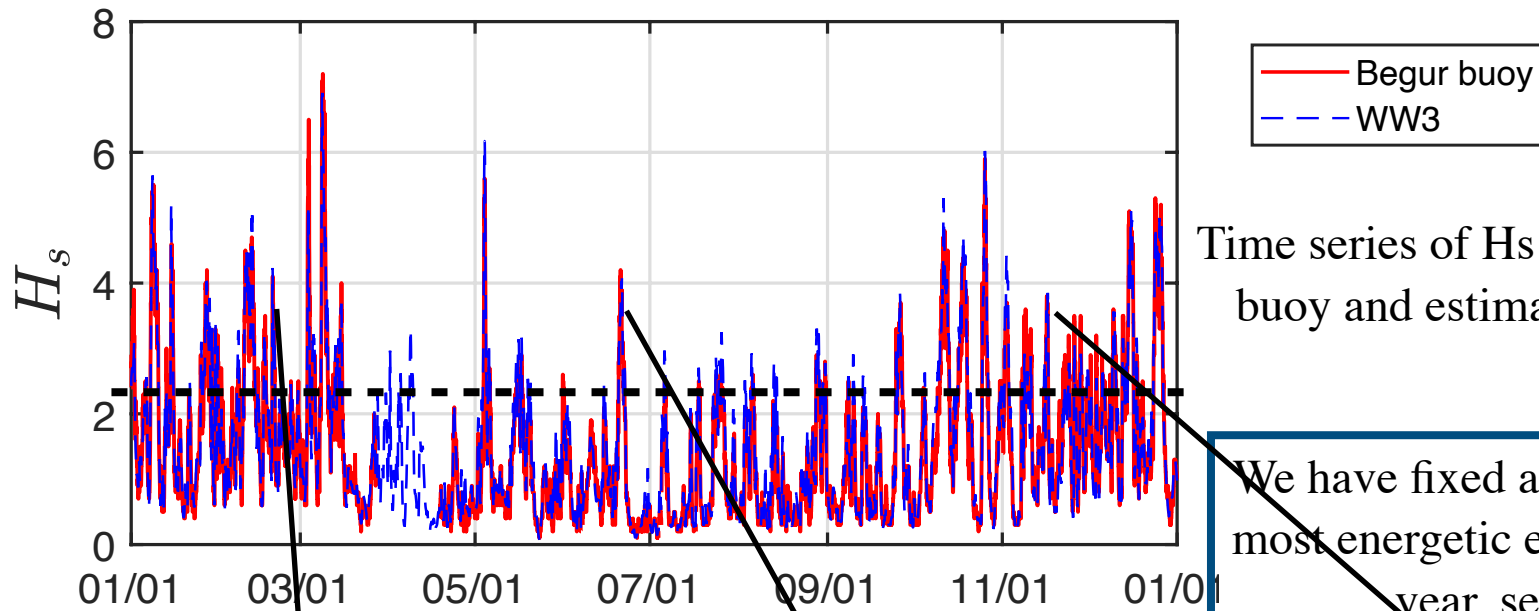
The hindcast has been intensively validated with buoy data in a recent publication¹



¹, a, b Vannucchi et al. 2021, *Journal of Marine Science and Engineering*]

² Tolman 2009, *WaveWatch III User Manual*]

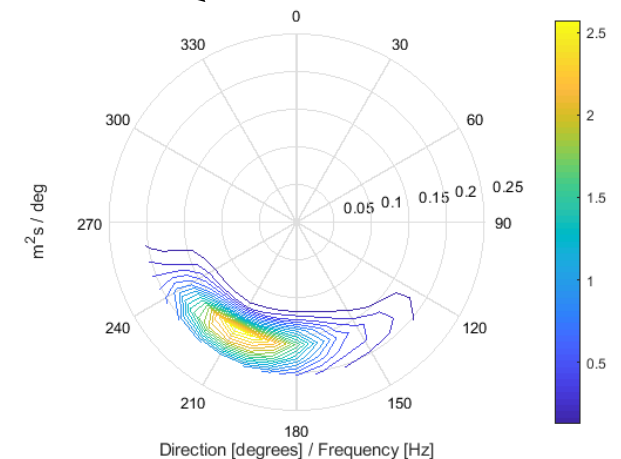
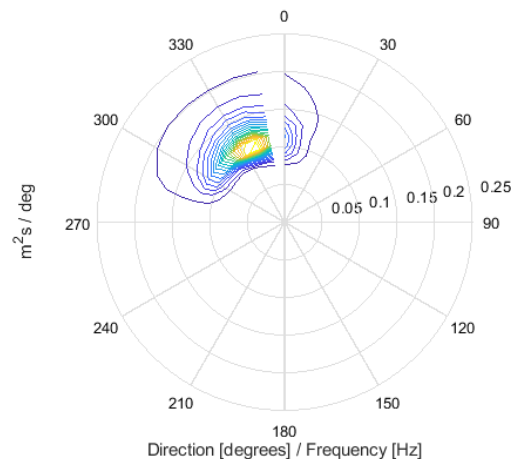
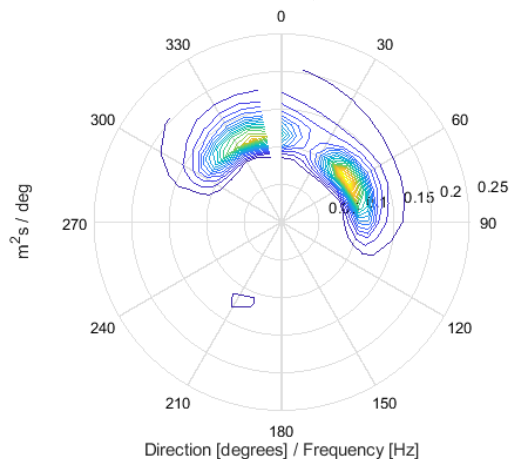
Louis-Majesty / Begur buoy position



Time series of H_s registered from the Begur buoy and estimated from WW3 for year 2010

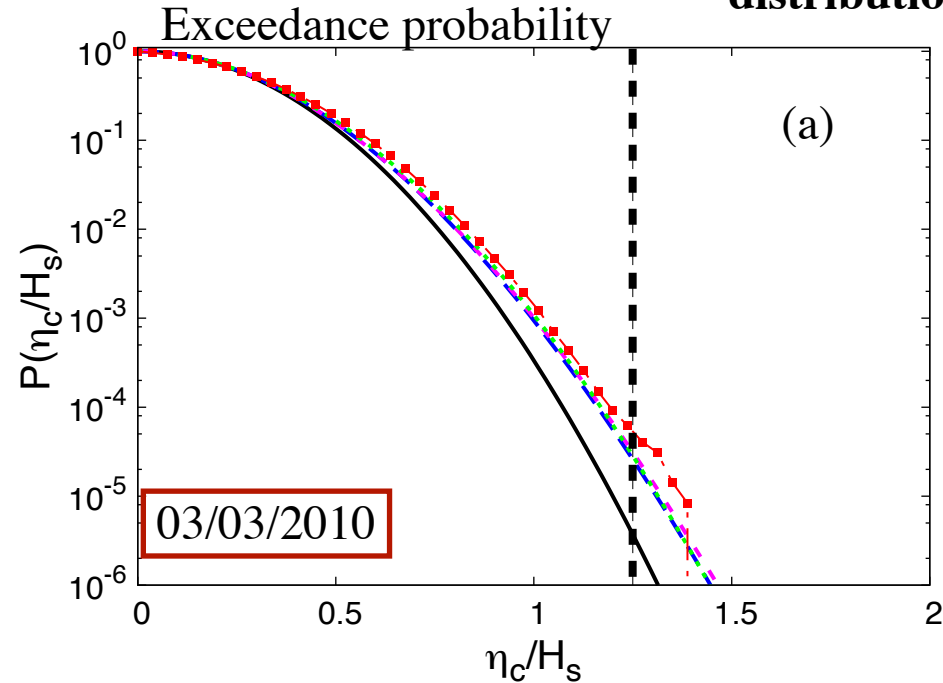
We have fixed a threshold to analyse the most energetic events of the whole 2010 year, selecting 54 cases

Innocenti et al. 2021, *Journal of Marine Science and Engineering* 2010



Statistical Analysis (crests)

- From the analysis of the sea surface over a long time we can extract statistical informations, like the **distributions of crests (or waves)**



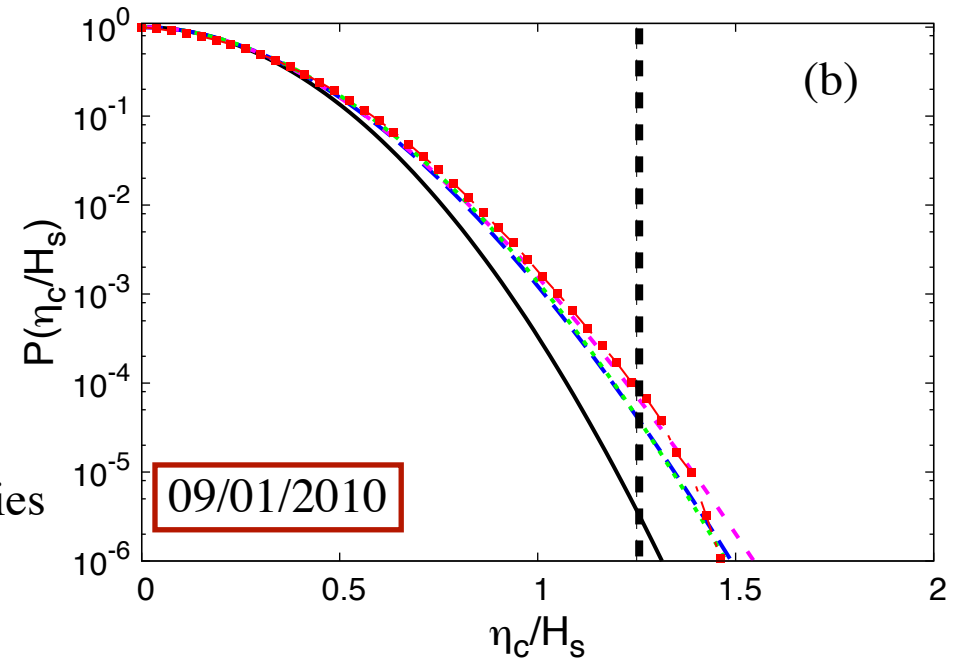
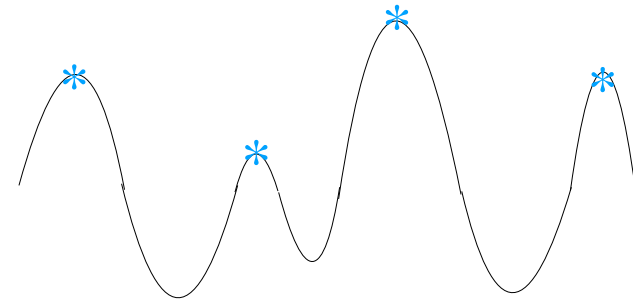
- Rayleigh
- - - Tayfun 2nd order
- · · Tayfun 3rd order
- · - Forristall
- ■ HOS simulations

$$S(\eta_c/H_s) = \exp\left[-\alpha\zeta_0^\beta\right]$$

$\alpha, \beta, \zeta_0 = f\left(\frac{\eta_c}{H_s}, \lambda_3, \lambda_4, \dots\right) + \text{other mean spectral quantities}$

$\eta_c/H_s > 1.25$ To identify extreme waves

We identify crests by a local maxima criterion

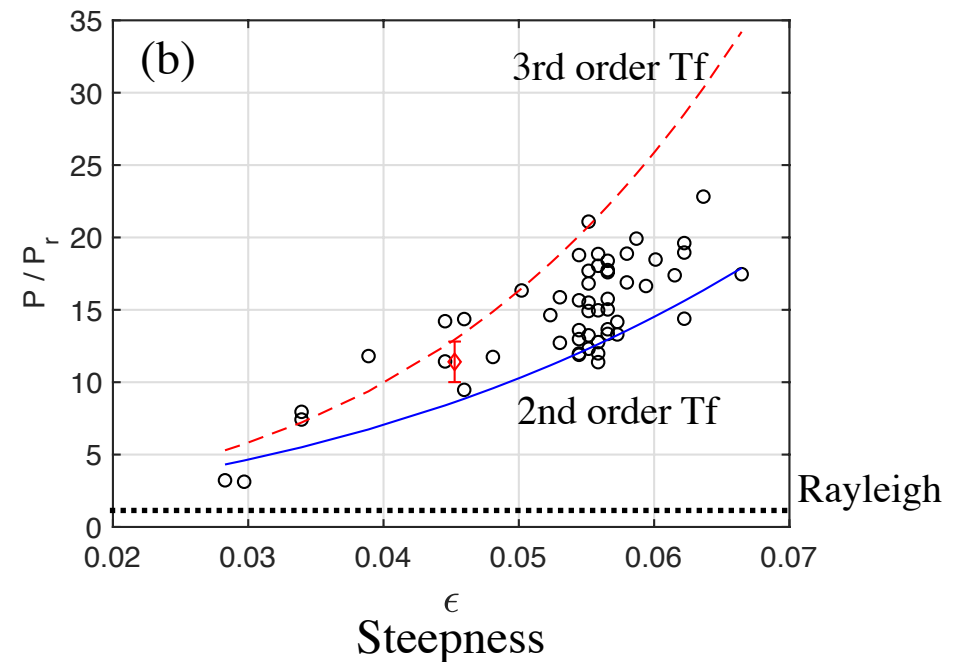
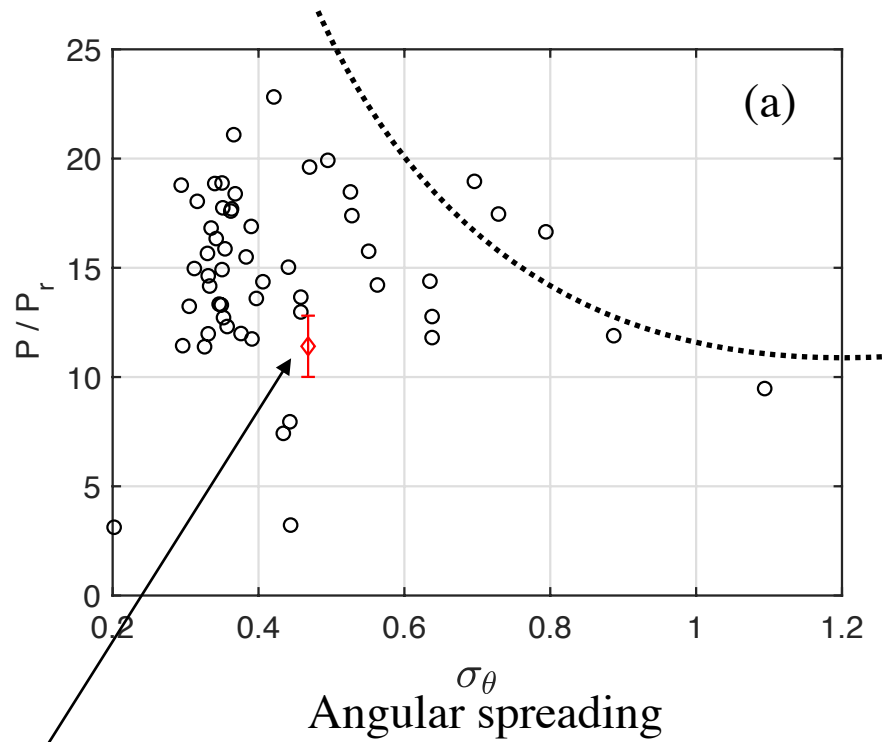


Extreme waves vs spectral parameters

Every point corresponds to a **different realization** of a HOS simulation initialized with a WWIII spectrum relative to the location of the Louis Majesty incident in different days over a year.

The idea is:

- find any kind of correlations between macroscopic observables that can be directly obtained from WW3 simulations ($H_s, T_p, T_m, \sigma_\theta, Dir_p, Dir_m$) and the probability of extreme waves;
- verify if with theoretical distributions it is possible to predict accurately those trends;



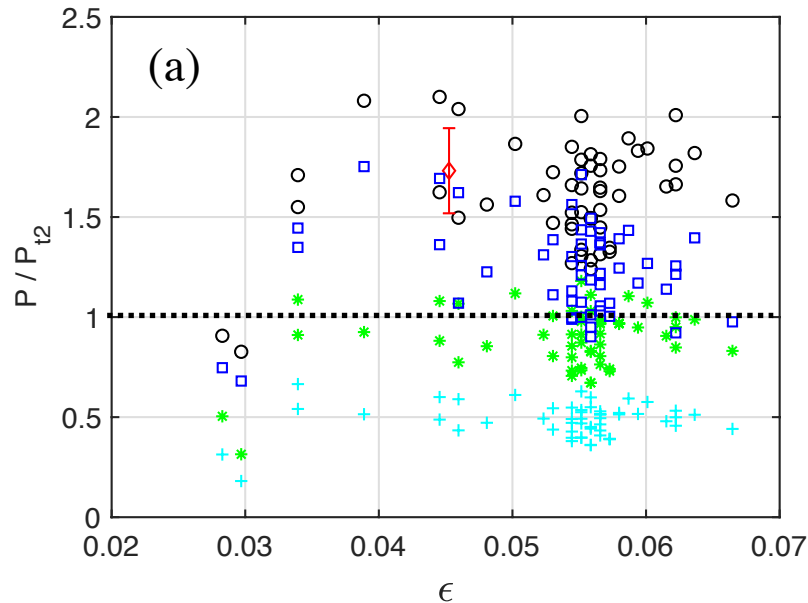
P/P_r = probability of extreme waves from HOS simulation, divided by probability of extreme waves for the Rayleigh distribution

$$\frac{P\left(\frac{\eta_c}{H_s} > 1.25\right)}{P_r\left(\frac{\eta_c}{H_s} > 1.25\right)}$$

Louis-Majesty accident

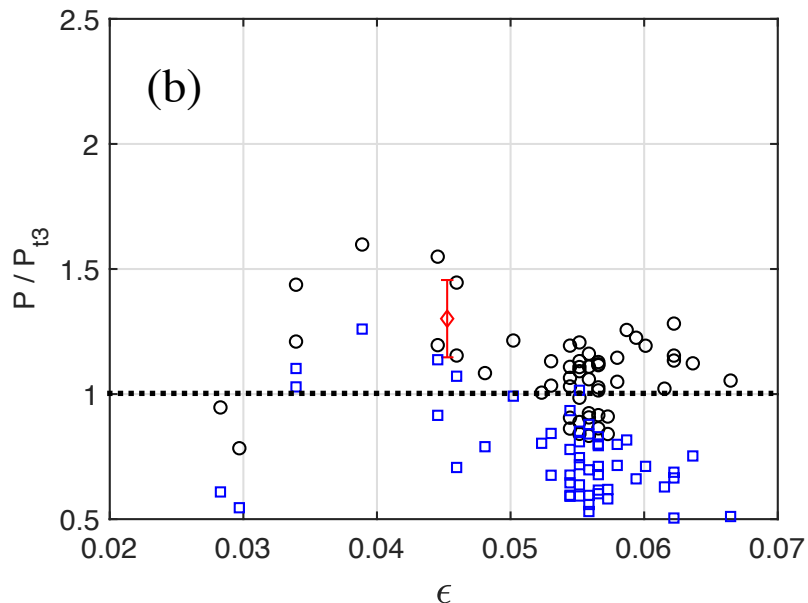
Comparison with higher order distributions

We have repeated the same analysis normalizing now with higher order distributions

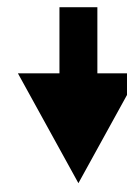


- $P_{hos}/P_{t2}(\lambda_3)$ ← Estimated from HOS statistics
 - $P_{hos}/P_{t2}(H_s, T_p)$
 - * $P_{hos}/P_{t2}(H_s, T_m, \nu)$
 - + $P_{hos}/P_{t2}(H_s, T_m)$
- Estimated from spectral parameters

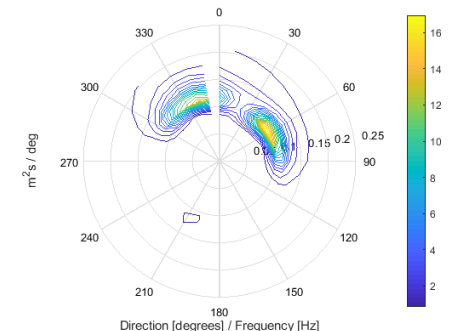
Normalizing with second and third order distributions the error is significantly reduced even if a few cases show still a larger probability than the predicted one



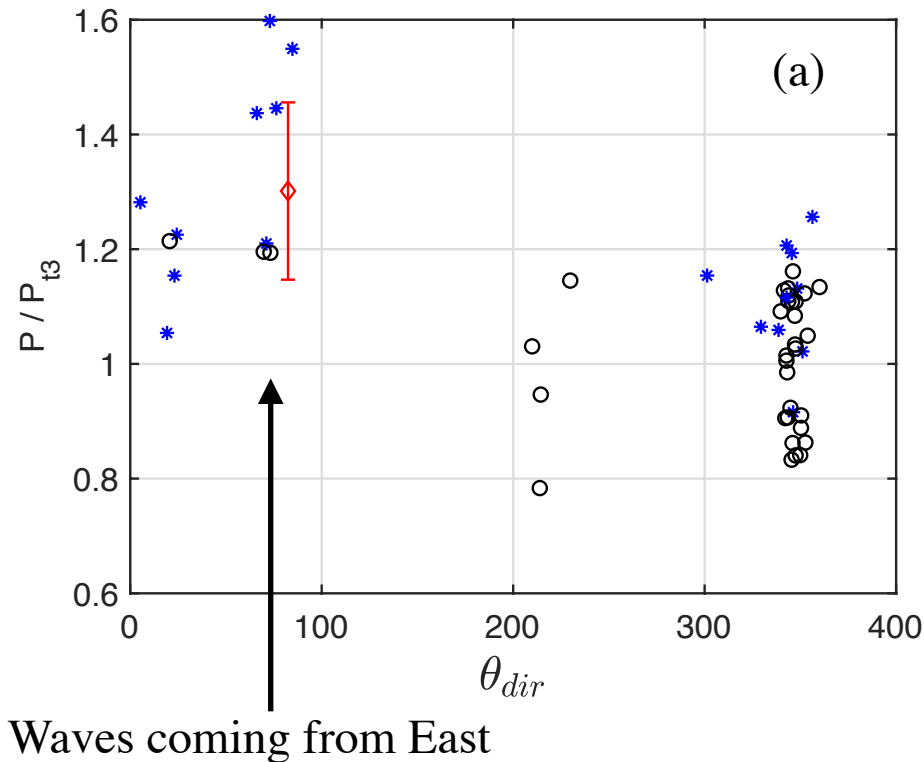
- $P_{hos}/P_{t3}(\lambda_3, \lambda_4)$
- $P_{hos}/P_{t3}(H_s, T_p)$



It could be related to different topologies of the wave spectrum



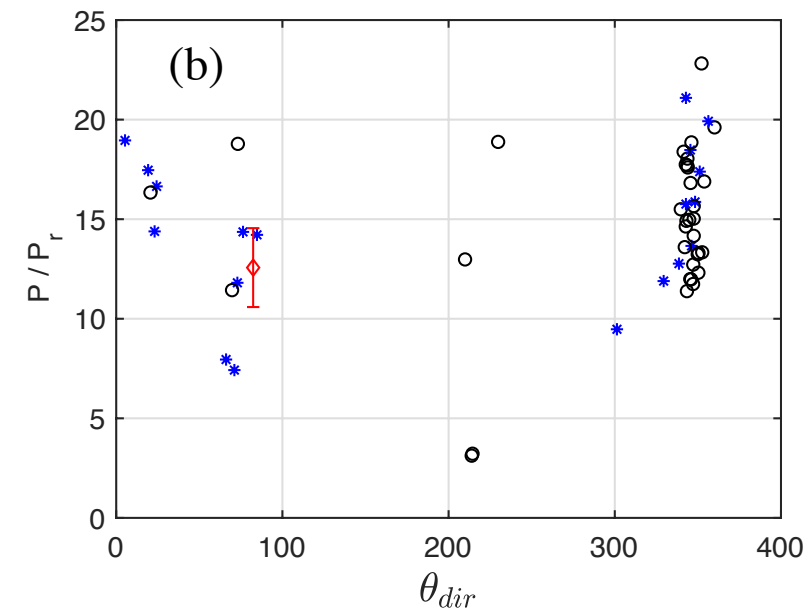
Crossing seas



* Crossing seas

Crossing sea conditions seems to be related to probabilities higher than those predicted by theoretical 2nd and 3rd order distributions

However they are not necessarily the most dangerous in absolute terms



In any case the agreement of theoretical distributions with HOS model is good and they can be considered a good starting point for operational forecasts

- The comparison of many different HOS realizations show that the day of the accident to the Louis Majesty ship the sea conditions were not amongst the worst in terms of absolute probability of extreme waves;
- There is not a clear correlation between angular spreading and probability of extreme events (smaller spreading, higher probability), which might be due to different topological structures (bimodal) of the spectra for higher angular spreading, corresponding therefore in an increase of the probability;
- Theoretical distributions predict reasonably well the probability of extreme waves (in terms of crests height), both using the skewness and kurtosis evaluated from the HOS simulations or the mean spectral quantities evaluated a-priori;
- A few cases show a probability of extreme waves higher than the third-order Tayfun distributions, and they correspond mainly to crossing seas, which indeed might not be correctly accounted for by such kind of distributions;