On a novel approach of forecasting extreme waves : Thanks to satellite observations

***L. Aouf*[(1)], *A. Daliphinet*[(1)], *F. Collard*[(2)], *B. Chapron*[(3)], *J. Rapp*[(4)]**

[(1)] *Météo France, DirOP-MAR/CNRM*
[(2)] *Ocean Data Lab*
[(3)] *IFREMER*
[(4)] *CMA-CGM*

World Ocean Circulation-UCM workshop, 10-12 October 2022

Motivation

- **Implementing an efficient indicator for rogue waves and dangerous seas prediction : Skillfuless of directional wave observations from CFOSAT**

- **High request from marine forecasters and actors of ship routing and maritime safety**

- **Use of ensemble approach to better estimate true/false alarm for the prediction of dangerous seas (EFI)**

High waves 29 June 2022 (La Réunion)

Container ship damaged by a storm in Pacific (Dec. 2020)

METEO FRANCE

Dangerous seas -rogue waves mechanisms

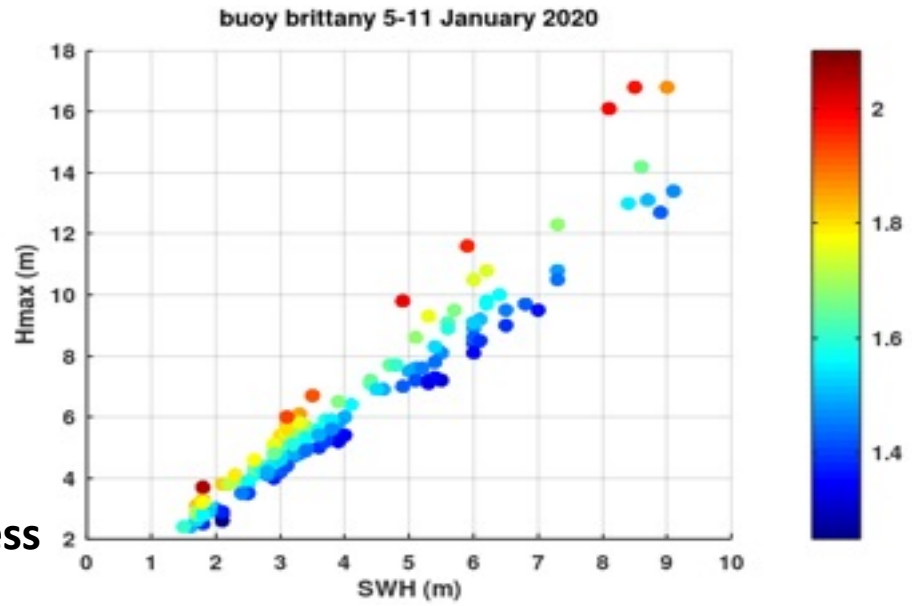
➔Non linear wave-wave interactions (close in frequency range and direction)

➔Wave-current interaction processess

➔Crossing seas conditions with specific scales in frequency and direction

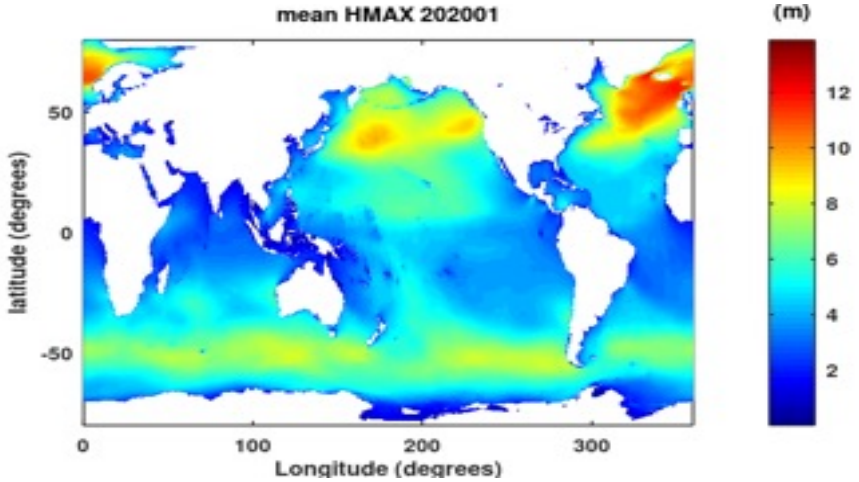
Rogue waves Hmax/SWH>~2

Example from buoy brittany 47.5° N-8.5° W

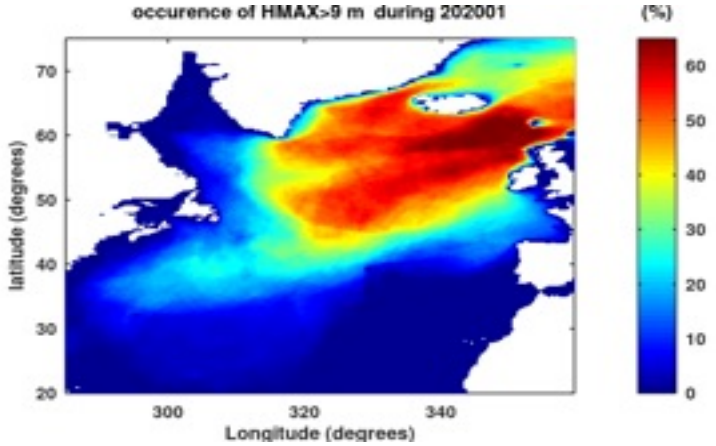


Hmax is computed from the model based on Probabilistic approach using kurtosis &skewness (Mori and Janssen 2006)

Mean Hmax during January 2020

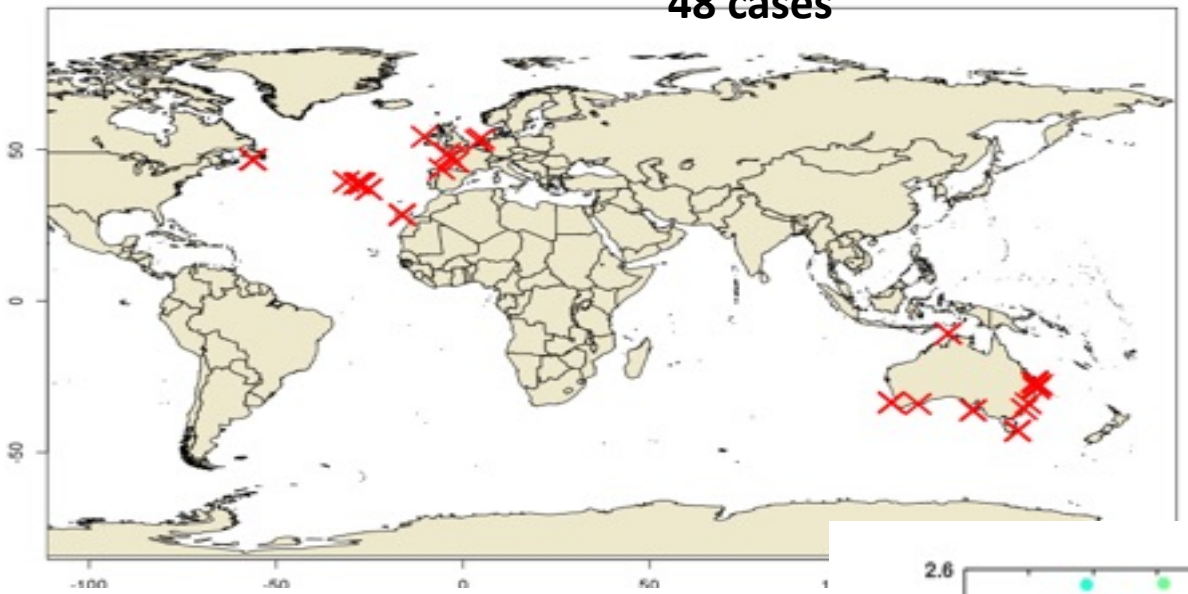


Probability of occurrence of Hmax>10 m Jan. 2020



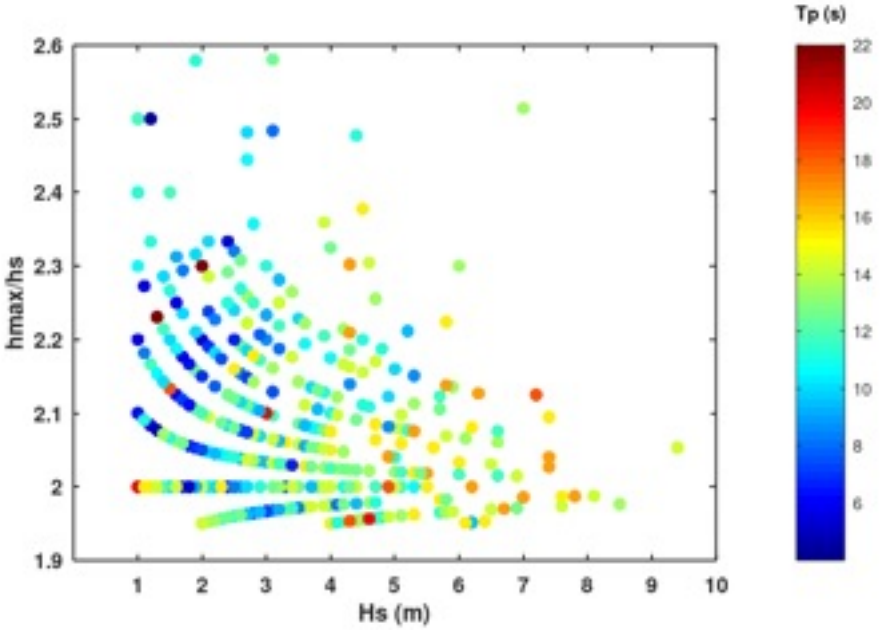
Observations of rogue waves

Collected rogue waves at buoys locations from January 2020 to July 2022
48 cases



Selection from the in-situ TAC of Copernicus Marine Service

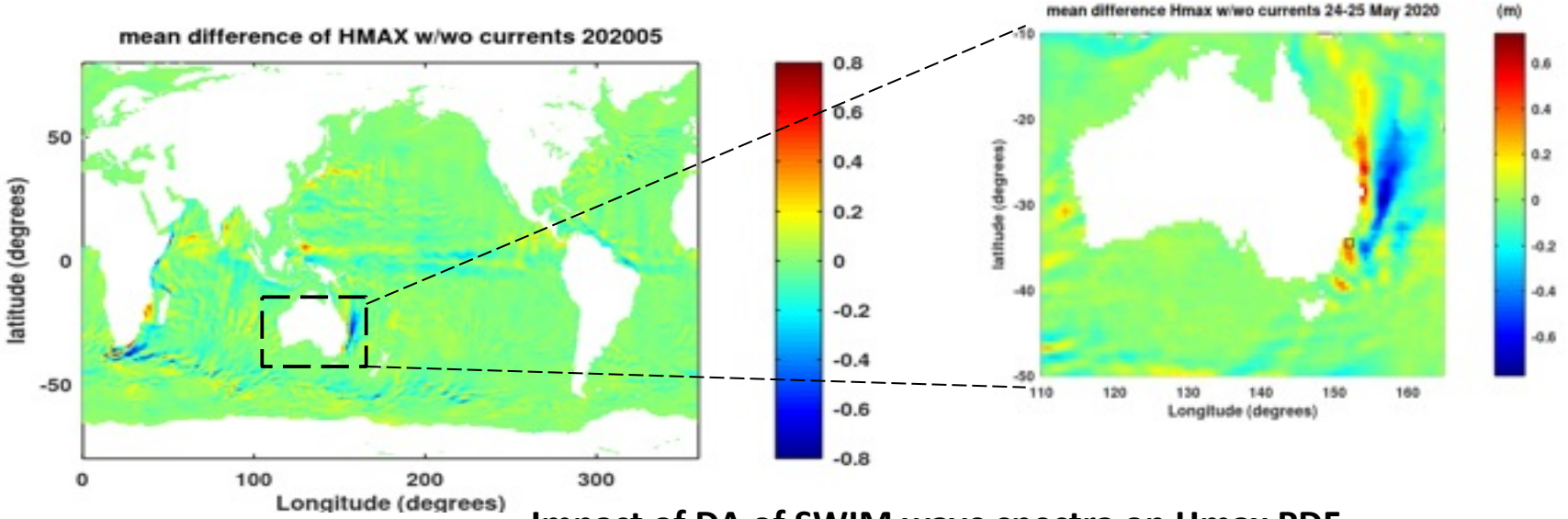
Statistics at 2 NE Atlantic buoys during 2 years
Rogue waves occur oftenly for peak period range 10 to 14 sec



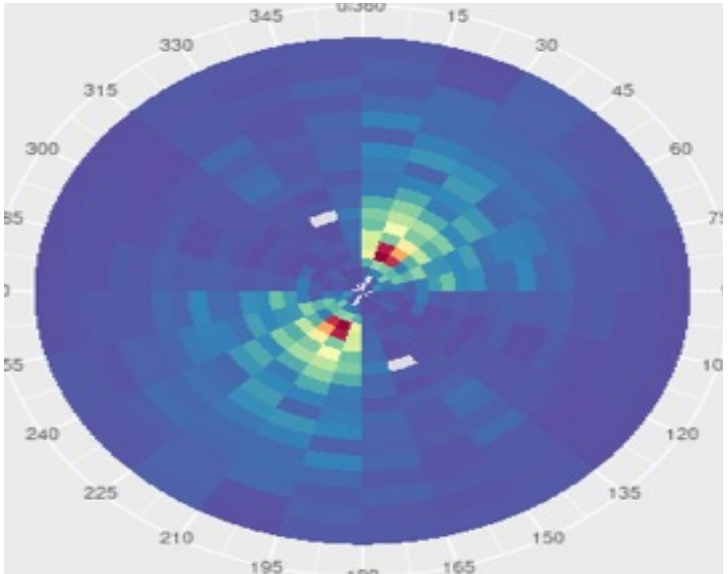
Relevance of wave spectra and surface currents on extreme waves

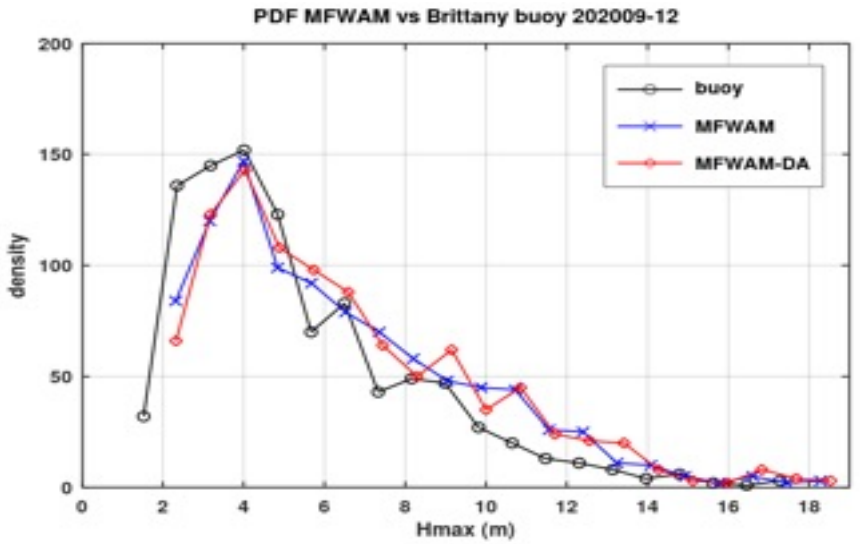
Hmax mean difference induced by including currents (May 2020)

Zoom on east of Australia



Impact of DA of SWIM wave spectra on Hmax PDF
Comparison with brittany buoy (Sep-Dec. 2020)





2021/06/18 at 23h
56006 (Australia)

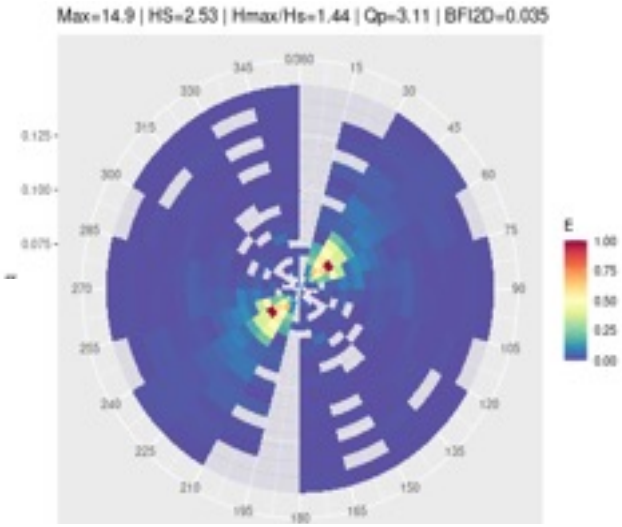
Computation of spectral indexes

- **Spectral peakedness thanks to Goda parameter**

$$Qp = \frac{2\sum_{f_{min}}^{f_{max}} f\, F^2(f)\, df}{\left[\sum_{f_{min}}^{f_{max}} F(f)\, df\right]^2}$$

Goda, 1976

Qp higher
steepness higher
=> higher BFI

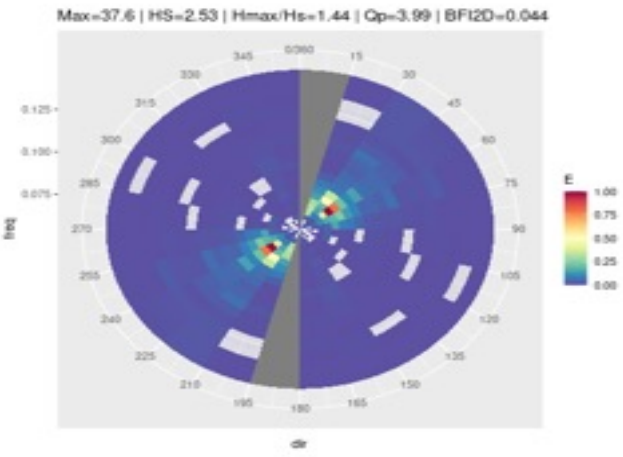


- **Benjamin Fair index : indicator of non-linearities of wave interactions and probability of occurrence of extreme waves in the case of unidirectional seas**

$$BFI = k_0\sqrt{m_0}Qp\sqrt{2\pi}$$

Mori et al, 2011

k_0 : mean wavenumber
m_0 : 0th order moment of the energy of the spectrum



Higher the steepness is, the higher the BFI

Computation of spectral indexes

2020/04/28 at 23h
56006 (Australia)

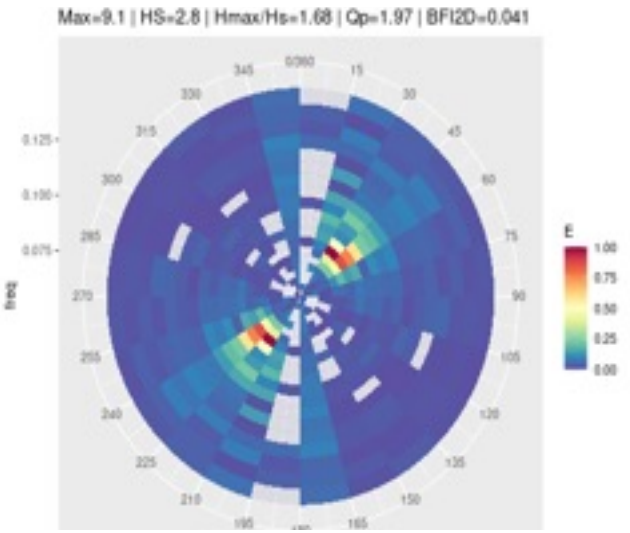
- **Directional spread (a_1/b_1 Fourier coefficients)**

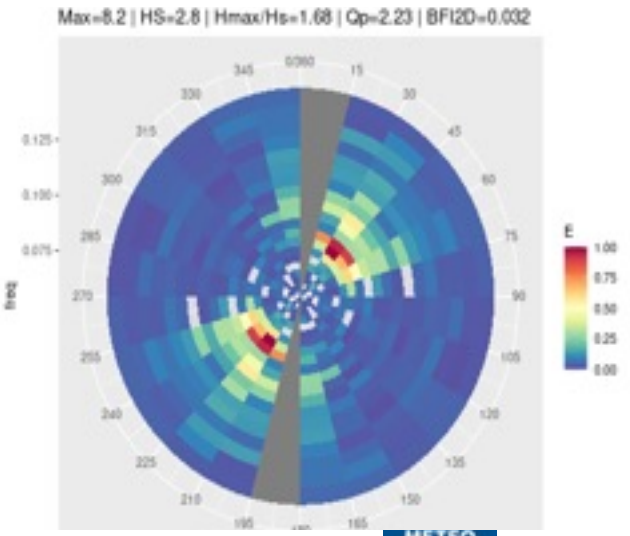
$$\sigma_\phi(f) = \sqrt{2 \times \left(1 - \sqrt{a_1(f)^2 + b_1(f)^2}\right)}$$

- **Benjamin Fair index 2D : inclusion of directional effects**
  Mori et al, 2011

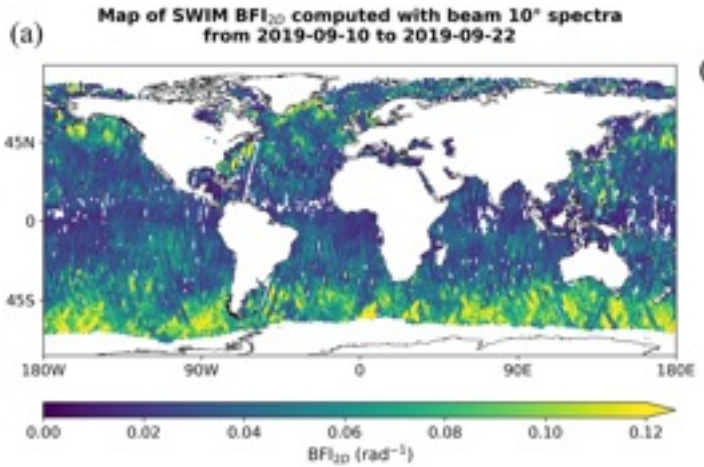
$$BFI_{2D} = \frac{BFI}{\sqrt{1 + \alpha_2 R}} \qquad R = \frac{1}{2}\sigma_\phi^2 \pi Q p^2$$

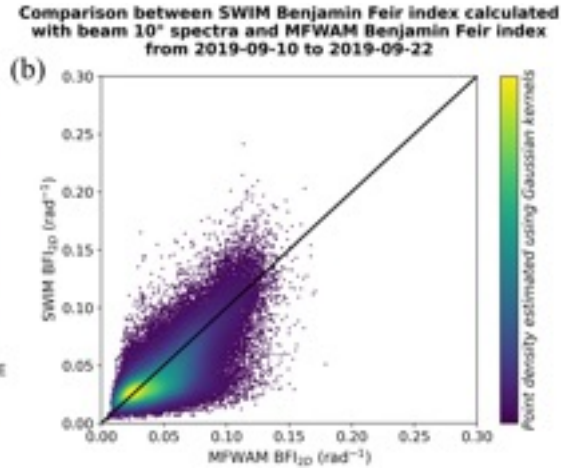
Smaller the directional spread, higher the BFI





Study of spectral indexes on SWIM spectral data : *Le Merle et al, 2021*





More recent index computed from wave spectrum of spectral indexes
British Columbia case 11 Nov. 2020

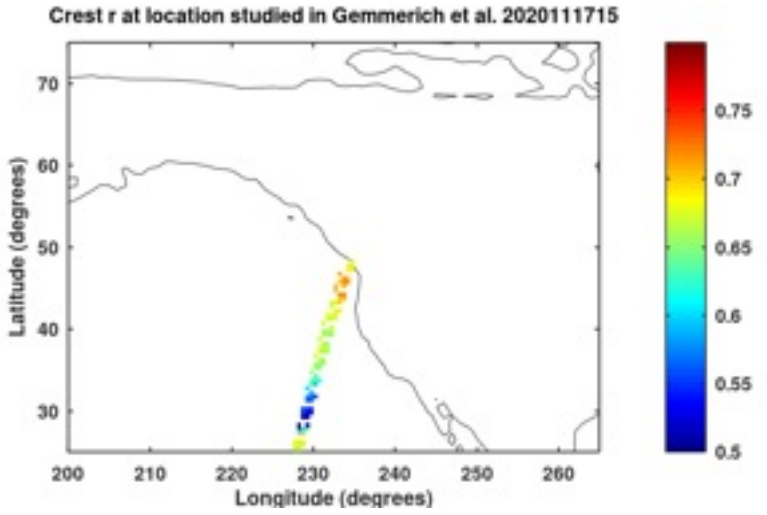
- **Crest-trough correlation r calculated from the spectrum (Gemmrich et al. 2022) :**

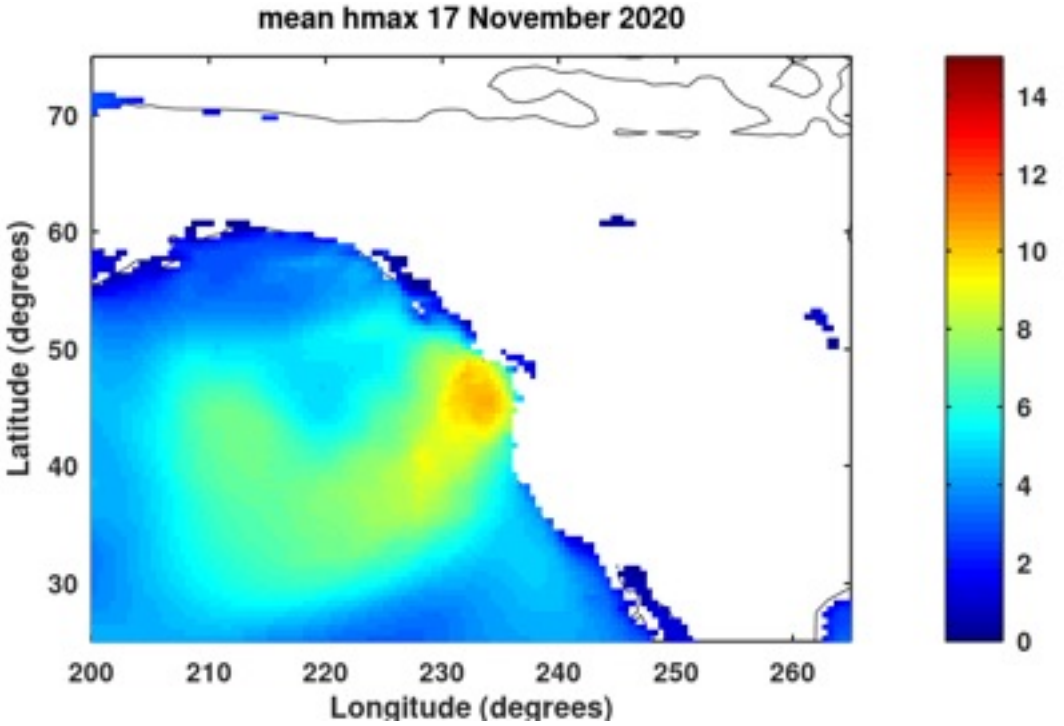
Auto-correlation of the sea surface elevation at half the wave period.

$$r = \frac{1}{m_0}\sqrt{\rho^2 + \lambda^2}, \text{ where } \rho = \int_0^\infty S(f)\cos(2\pi f\tau)df \text{ and } \lambda = \int_0^\infty S(f)\sin(2\pi f\tau)df,$$

where $\tau = \frac{\bar{T}}{2}$ is the lag time at half the spectral mean period $\bar{T} = \frac{m_0}{m_1}$.

High crest correlation by the model





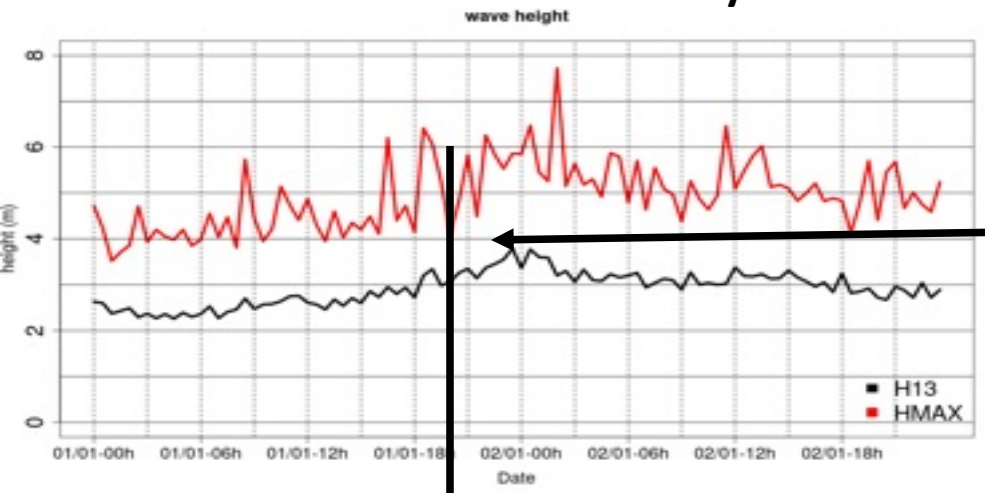
Skilled to characterise rogue waves conditions dangerous seas

Dangerous seas event near Belle-Ile 1 January 2022

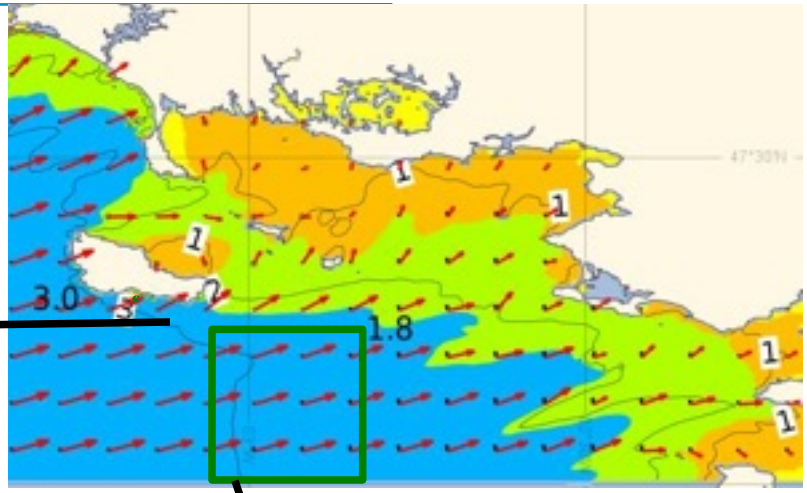
Buoy and SWIM observation

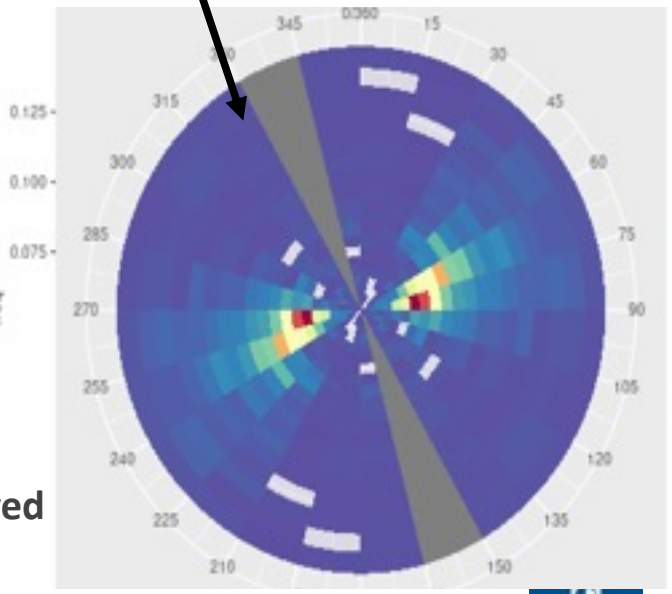
Rogues waves : Hmax/SWH>2

Time series at Belle-Ile buoy

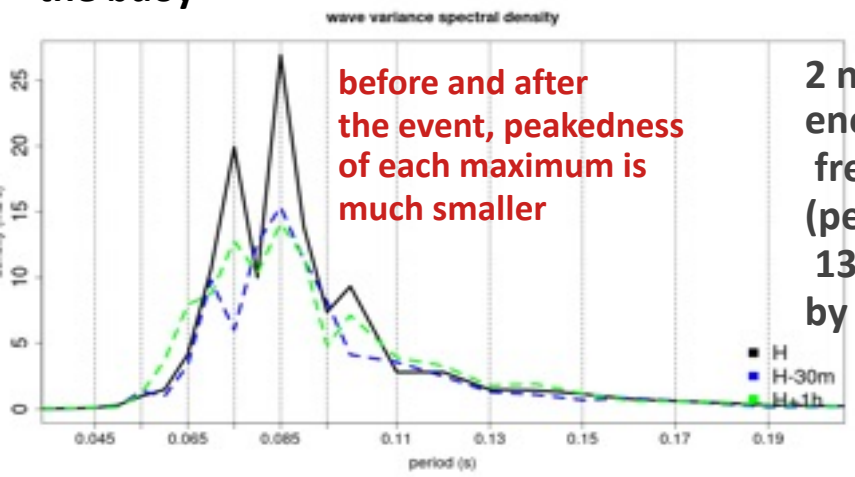


SWH of 3,1 m and Hmax of 6,4 m





1D spectrum from the buoy



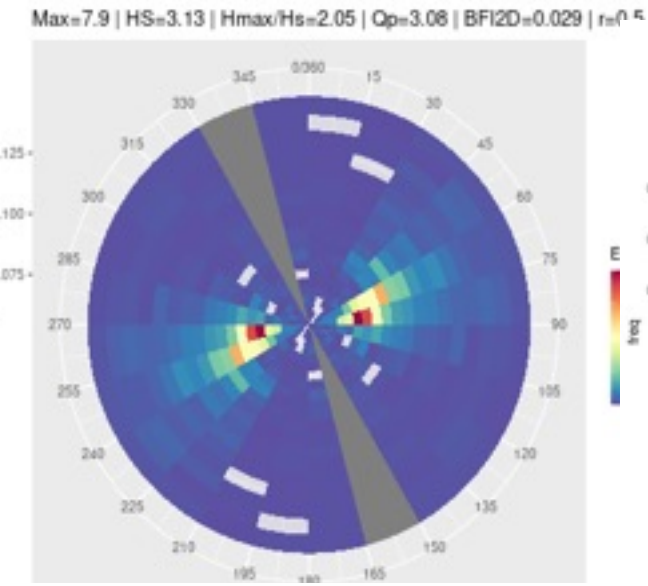
before and after the event, peakedness of each maximum is much smaller

2 narrow peaks of energy with close frequencies (period : 11,8 s and 13,3 s) well observed by SWIM

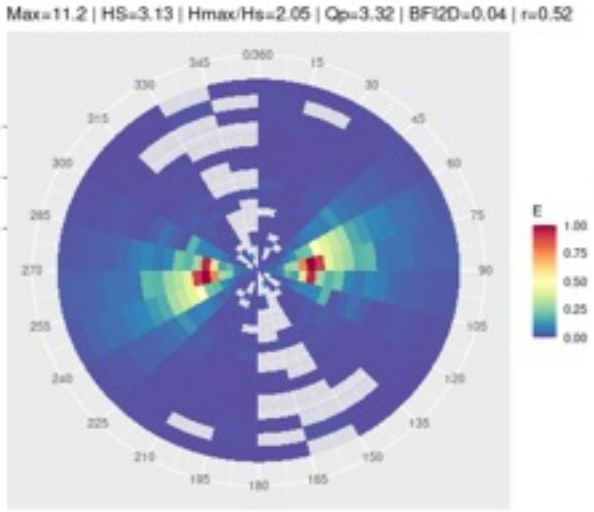
2022/01/01 at 18h43 UTC

METEO FRANCE

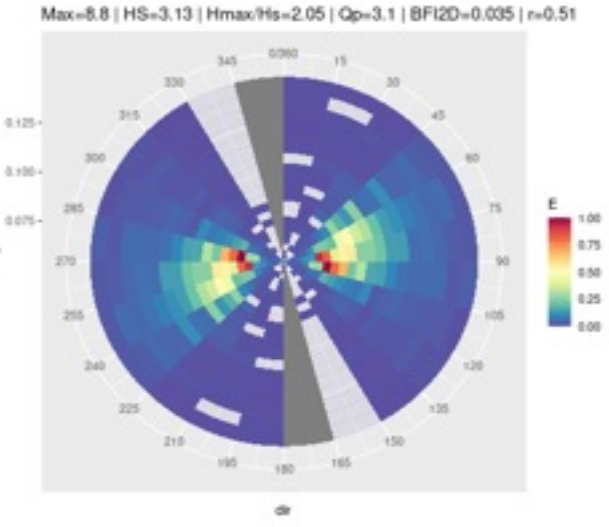
Spectral variability according to SWIM : Belle-ile case



Rogue wave location



80 km at the south

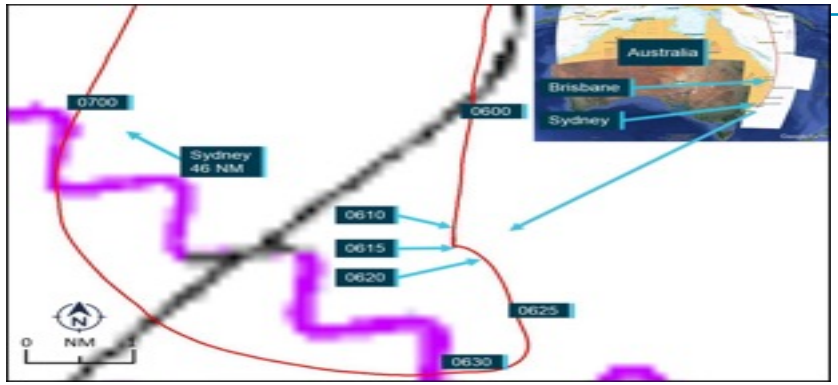


160 km at the south

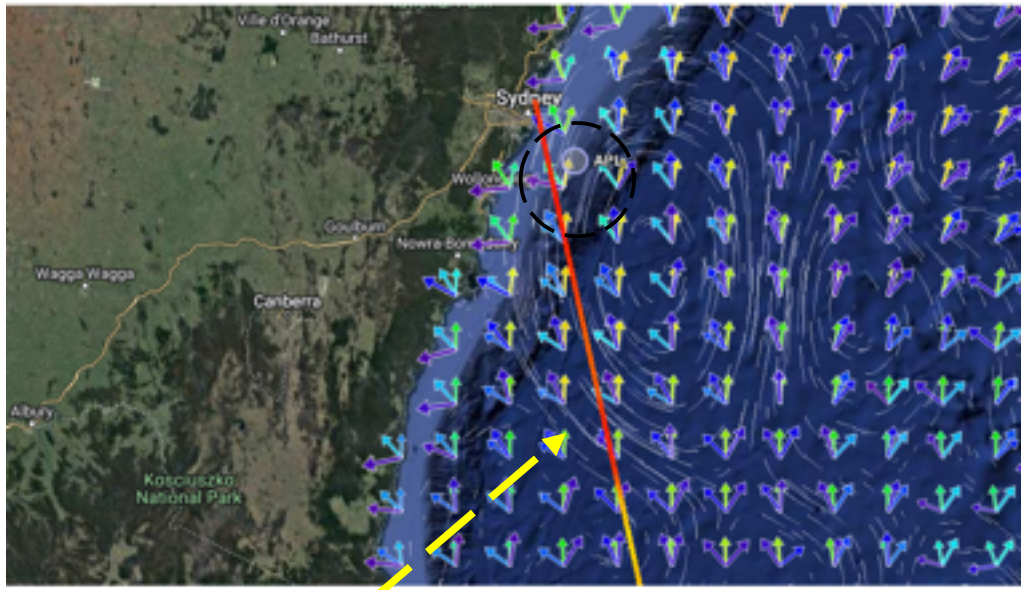
peaks at the rogue wave place. 1 peak elsewhere with less variability of energy in frequency and direction space.

The case of APL England (24 May 2020 at 6-9h (UTC)

Pitching and rolling of the container ship

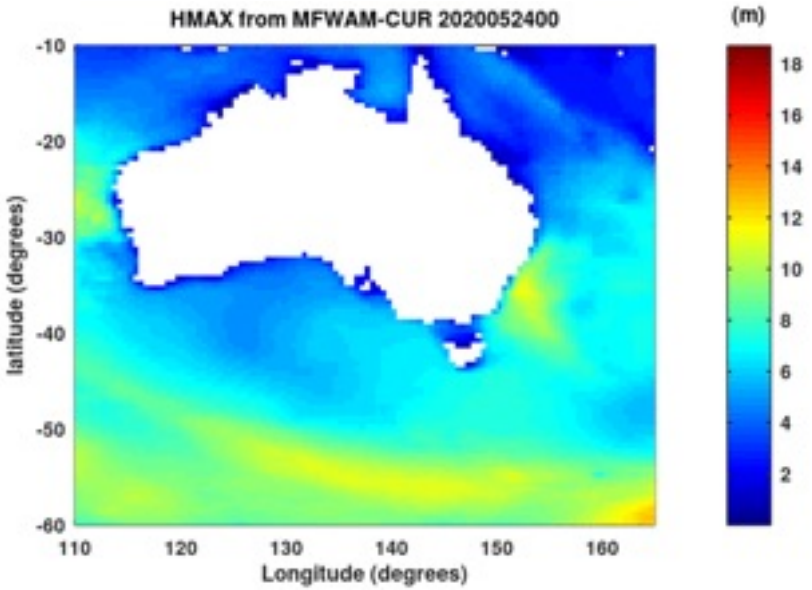


Wind-wave 8.6 sec, 1st swell:9.5sec 2nd swell 12.6 sec



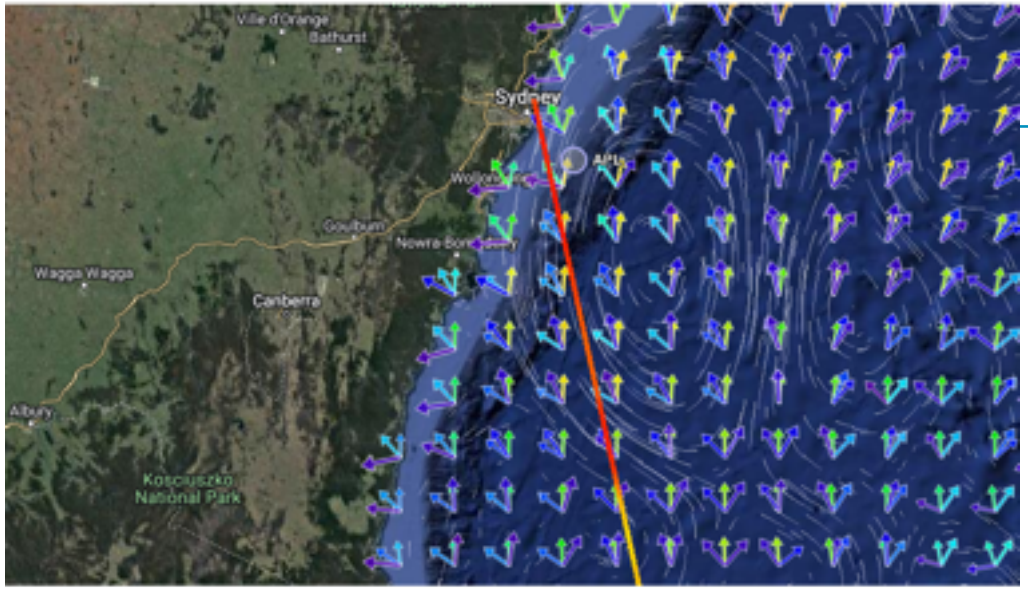
CFOSAT track at 9:25 UTC

Animation of hmax snapshots during the event (3-hourly from 0:00-21:00)

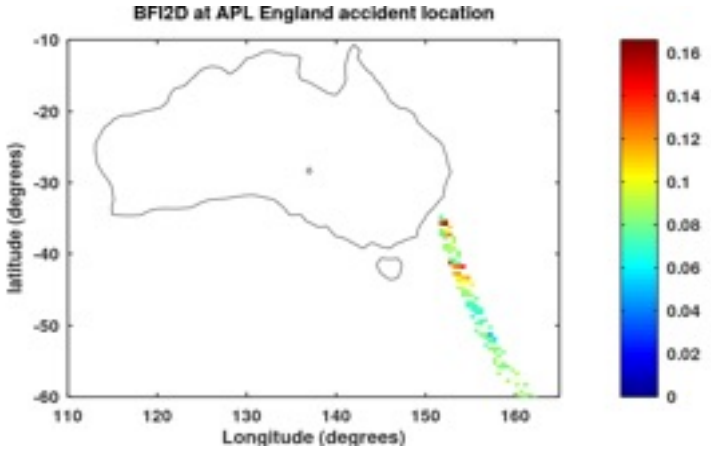


Strong increase of Hmax more than 16 m at the accident location

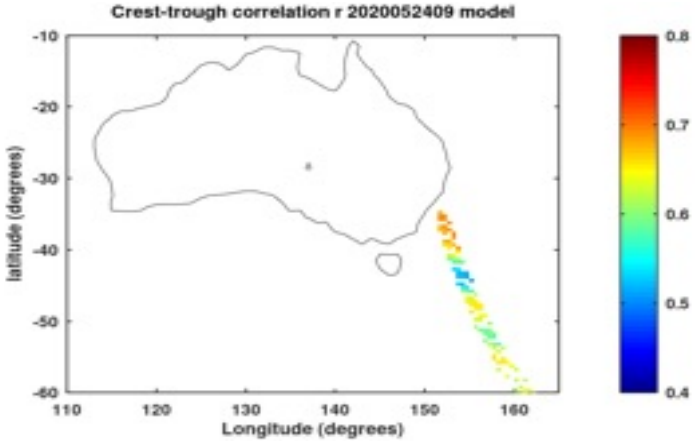
Wind-wave 8.6 sec, 1st swell:9.5sec 2nd swell 12.6 sec



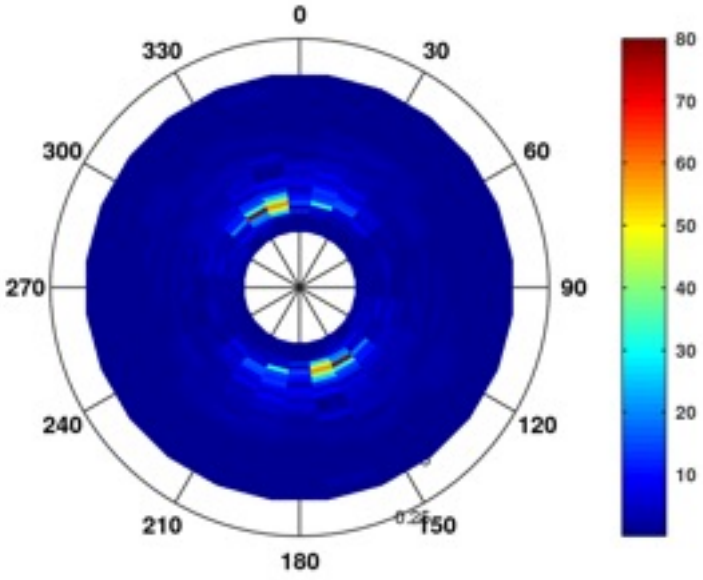
BFI2D from model at CFOSAT tracks



Crest/trough correlation

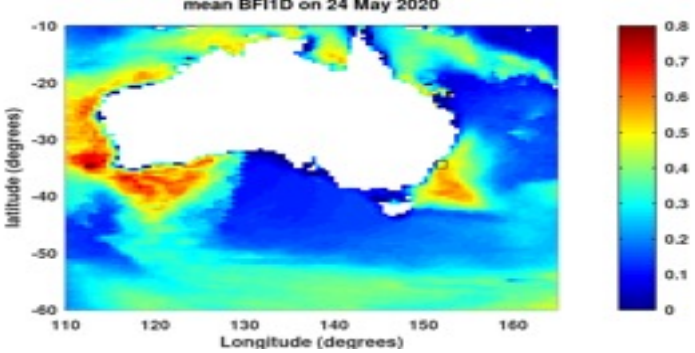


SWIM wave spectrum nearby

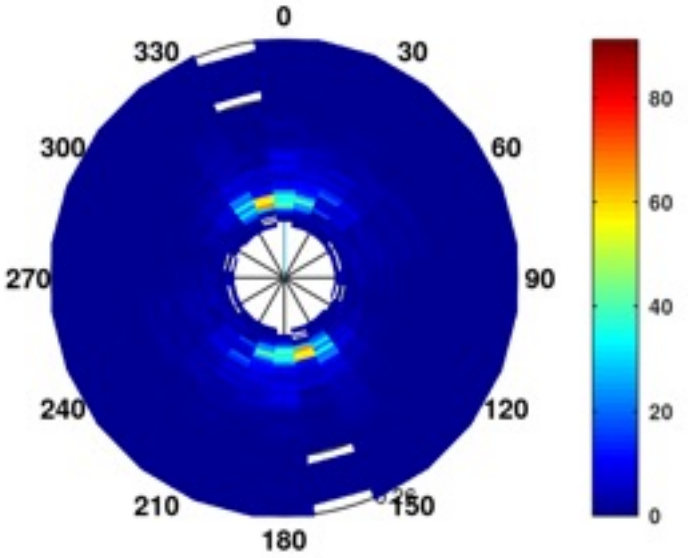


Higher values for BFI2D and Crest Correlation and consistent with those computed SWIM wave spectra

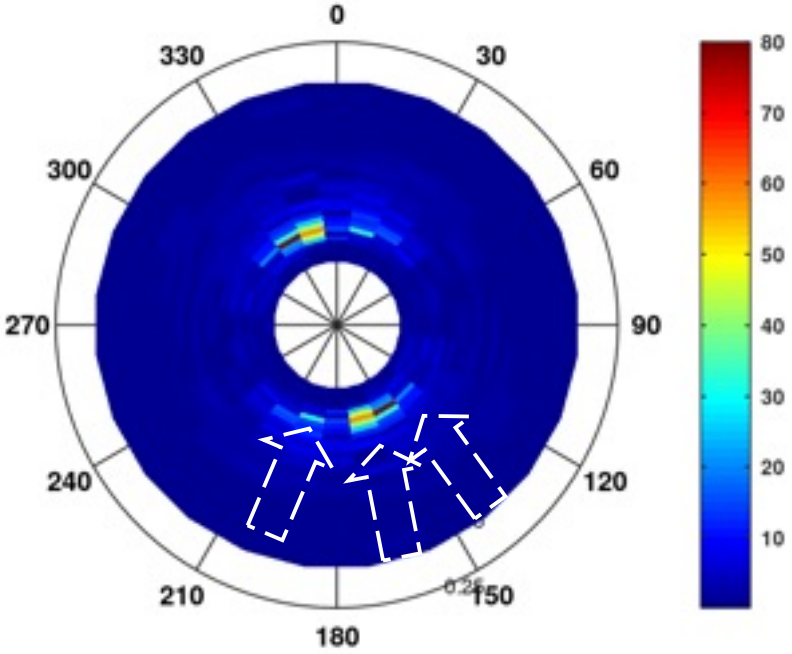
METEO FRANCE

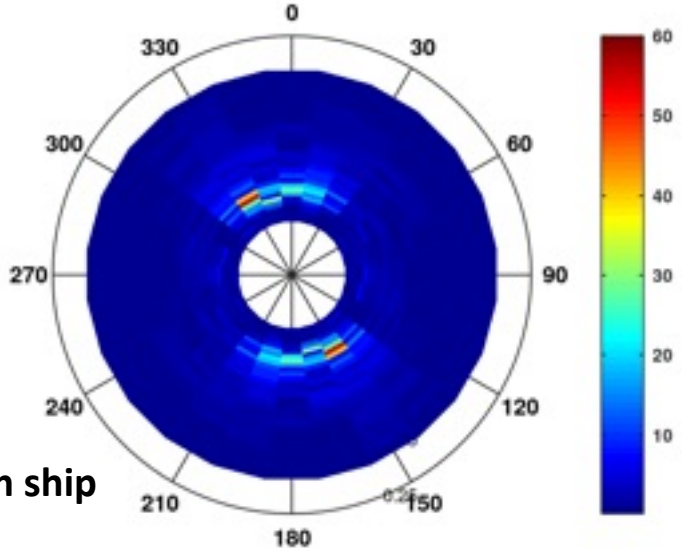


50 km northern from ship
R=0.55 & BFI2D=0.11



40 km from the location
R=0.6 & BFI2D=0.13





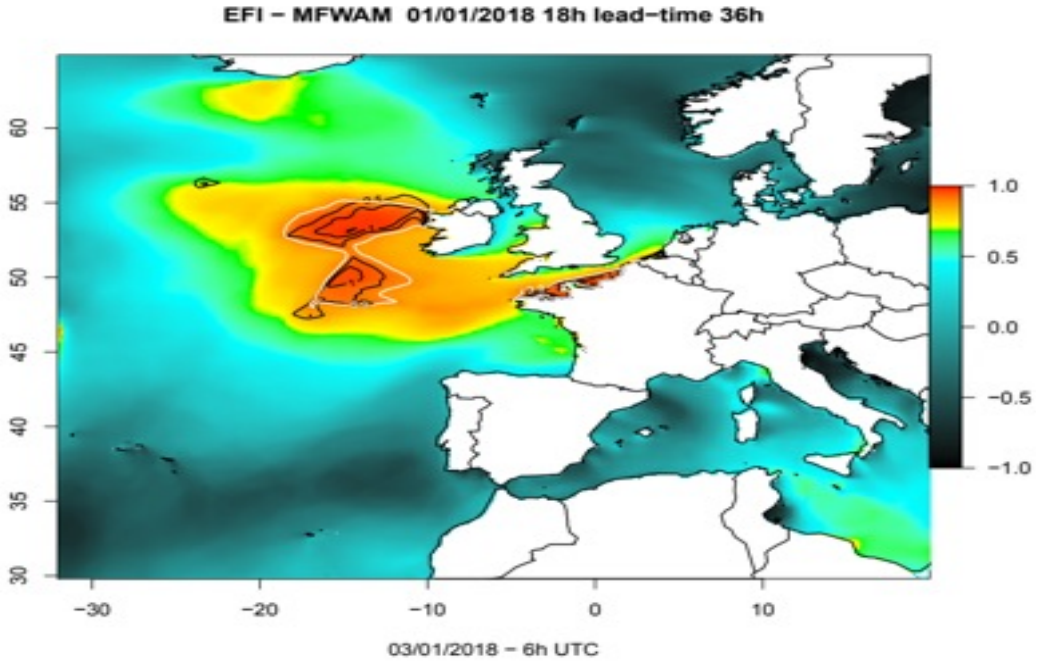
Increase of the energy before the ship
Accident and icrease of R and BFI2D

150 km southern from ship
R=0.55 & BFI2D=0.11

Novelty approach : Extreme Forecast Index based on wave ensemble

Exploitation of indexes (BFI, crest correlation) of rogue waves by EFI

EFI of Hmax exceeding 10 m at 36 hour forecast



➔Collecting a pseudo-climate of wave Ensemble (10 members) during long Period (example of 15-20 years)

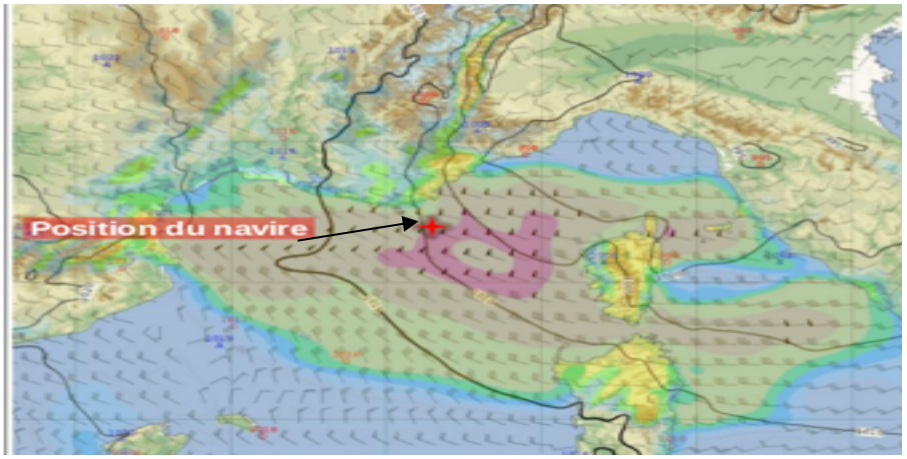
➔Comparison of PDF of the operational wave ensemble (35 members) to the pseudo-climate (threshold of Hmax, BFI, Crest R,…)

➔Analysis on Shift Of Tail (SOT) indicator

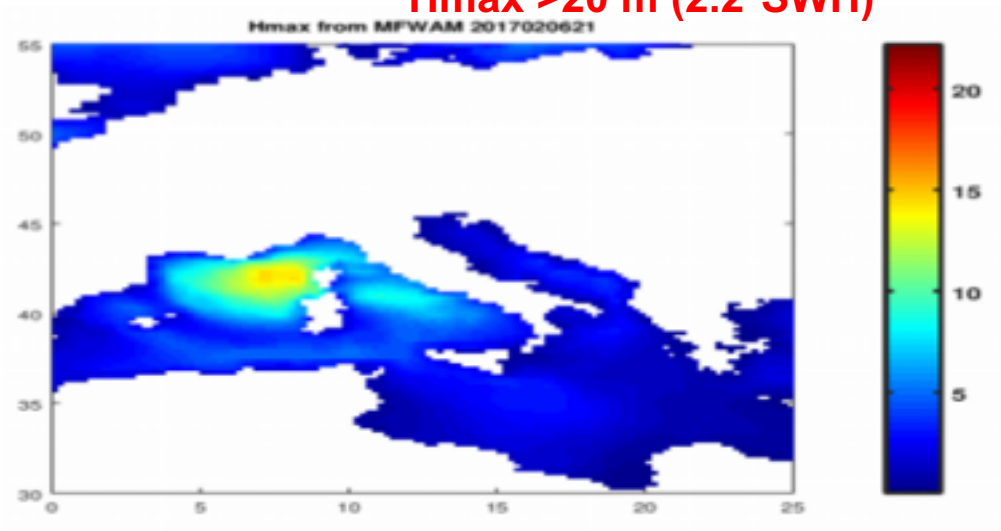
Red color shows under-represented the event and dark green Indicates over-represented in the climate (EFI >0.9 very strong probability to happend)

METEO FRANCE

Rogue waves case in Mediterranean Sea (line Ajaccio-Marseille) : On 6 March 2017 at 21:00 UTC, the ferry Jean Nicoli was hit by a rogue waves damaging the bridge of ~22 m



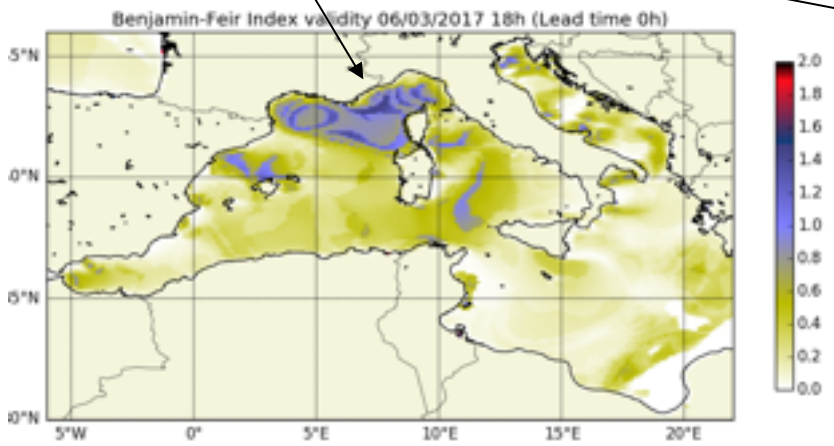
Hmax >20 m (2.2*SWH)



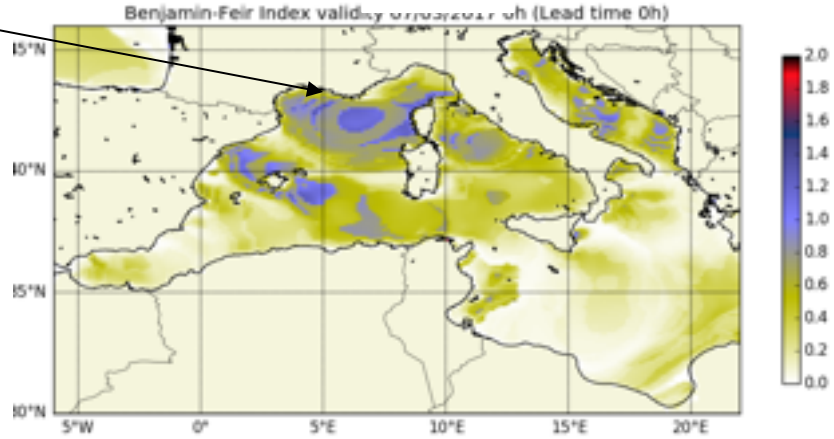
EFI maps indicate high BFI values early lead time in forecast at the accident location

6 March 2017 at 21:00

EFI of BFI1D 24 hours forecast



EFI of BFI1D 54 hours forecast

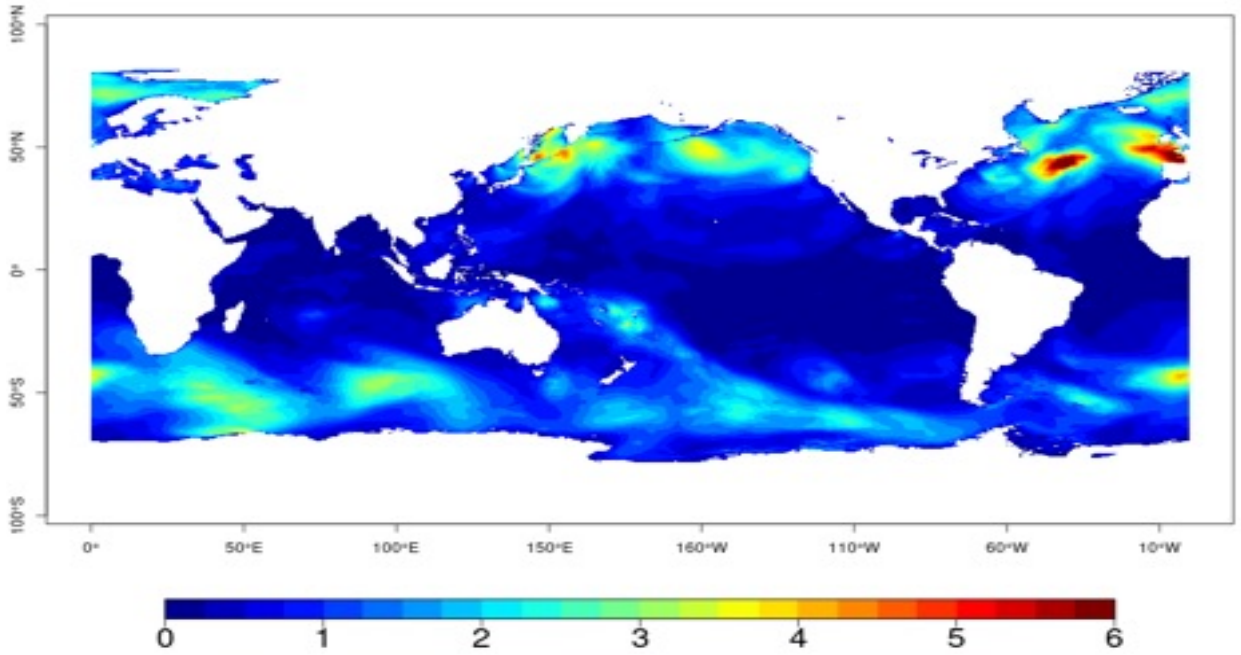


Key messages

➔Directional wave spectra from CFOSAT has captured several cases of rogue waves Which leads to set indicators (BFI and Crest R) level to warning of dangerous seas

➔Surface currents impact significanly the presence of dangerous seas

➔Implementation of operational wave ensemble and EFI will give accurately the probability of occurrence of dangerous seas.



Standard deviation of Hmax between ensemble members at 102h lead Time in forecast : storm Justine 26 January 2021