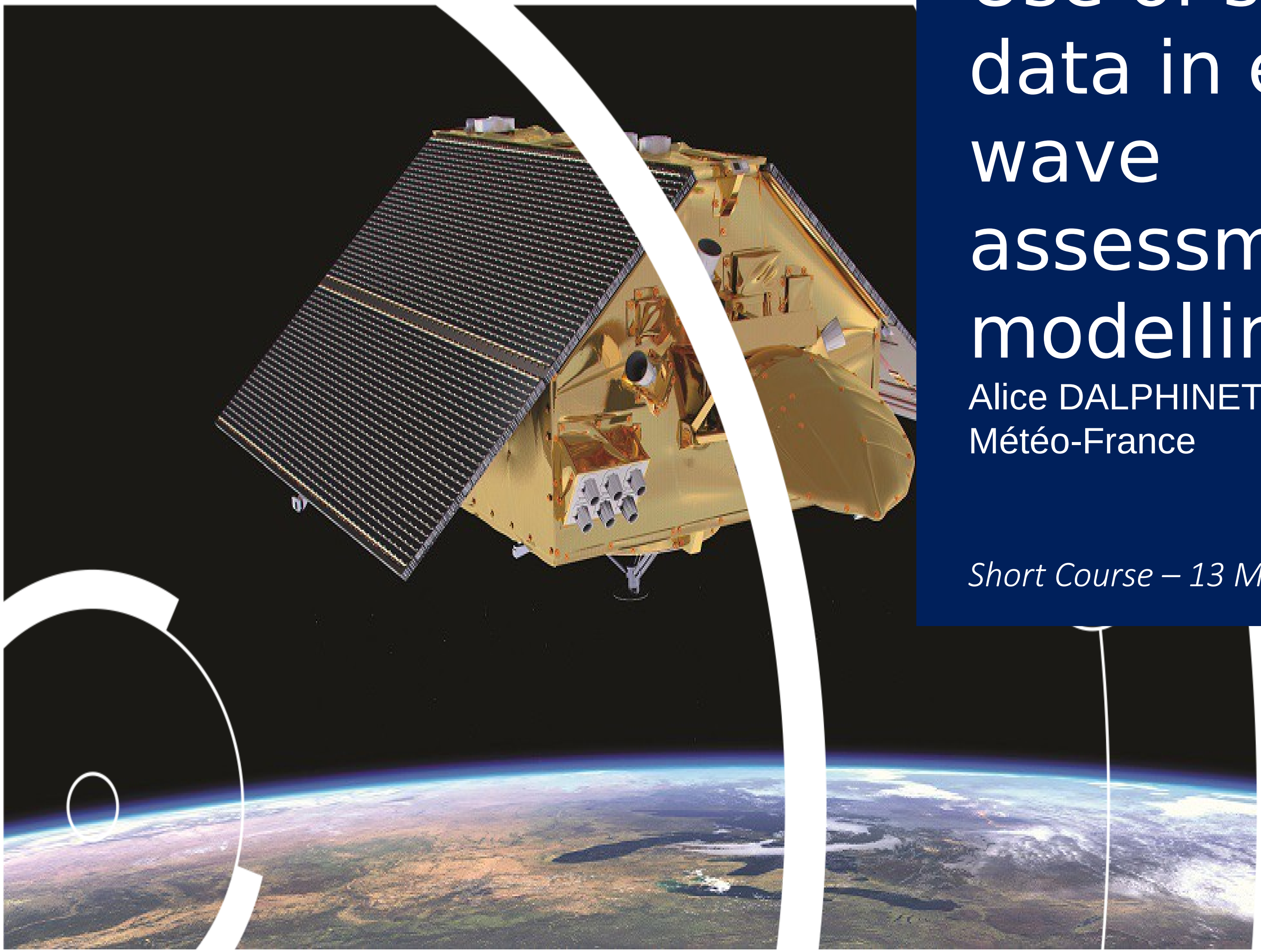

Use of satellite data in extreme wave assessment & modelling

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Météo-France

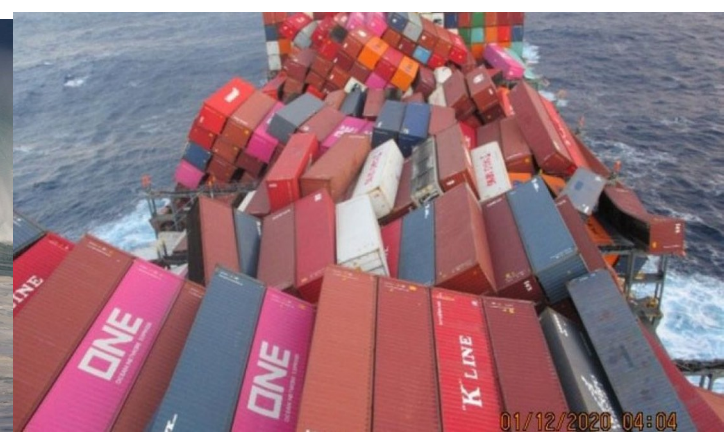
Short Course – 13 March 2024

Use of satellite data in extreme wave assessment and modelling

- **High value of altimeters significant wave height**
  - Reliability of high value of SWH
  - Some cases
  - Use for assimilation
  - Limitation for climatology

- **Indicator of dangerous sea thanks to spectral measurement**
  - spectral index describing dangerous sea state
  - Some cases with CFOSAT

High waves 29 June 2022 (La Réunion)



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

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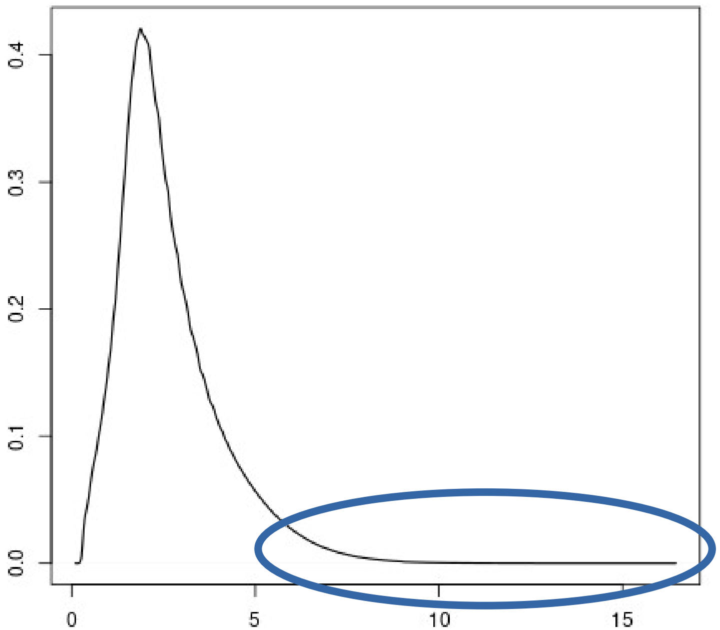
What is an extreme value of wave height ?

Altimeter data provide a good representation of the average wave climatology and the quantiles like deciles.

In the first part, we focus on high quantiles or maximum of SWH.
Extreme values of SWH ≠ Hmax

Significant wave height (SWH) is representative of the mean of highest third of waves.
On a 20 minutes record : Hmax ≈ 1,7 SWH in general

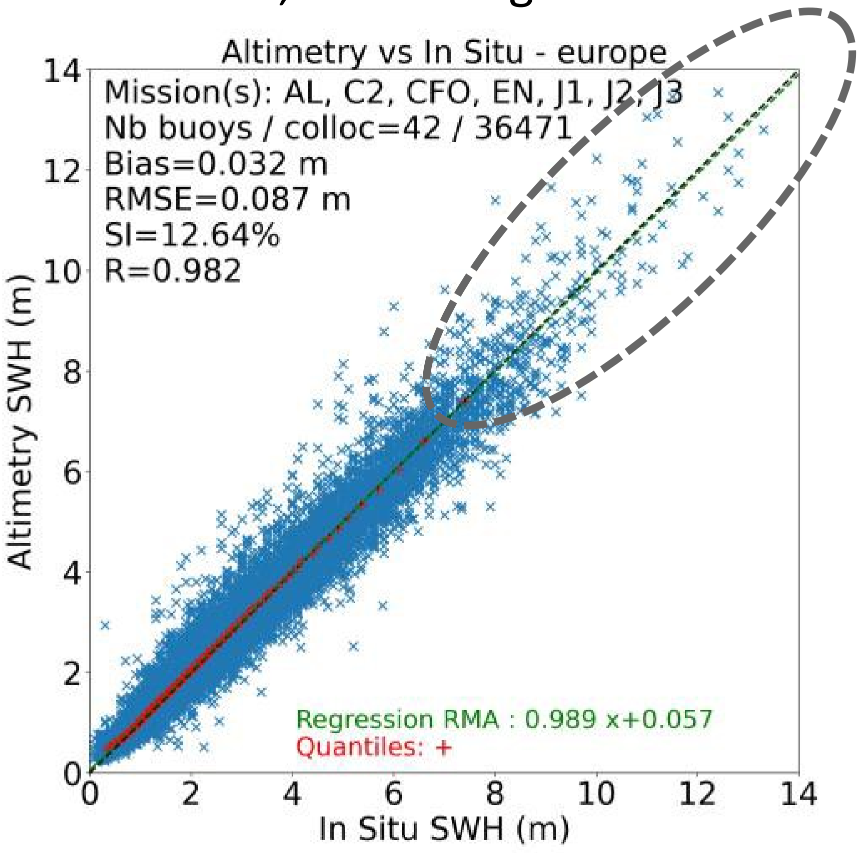


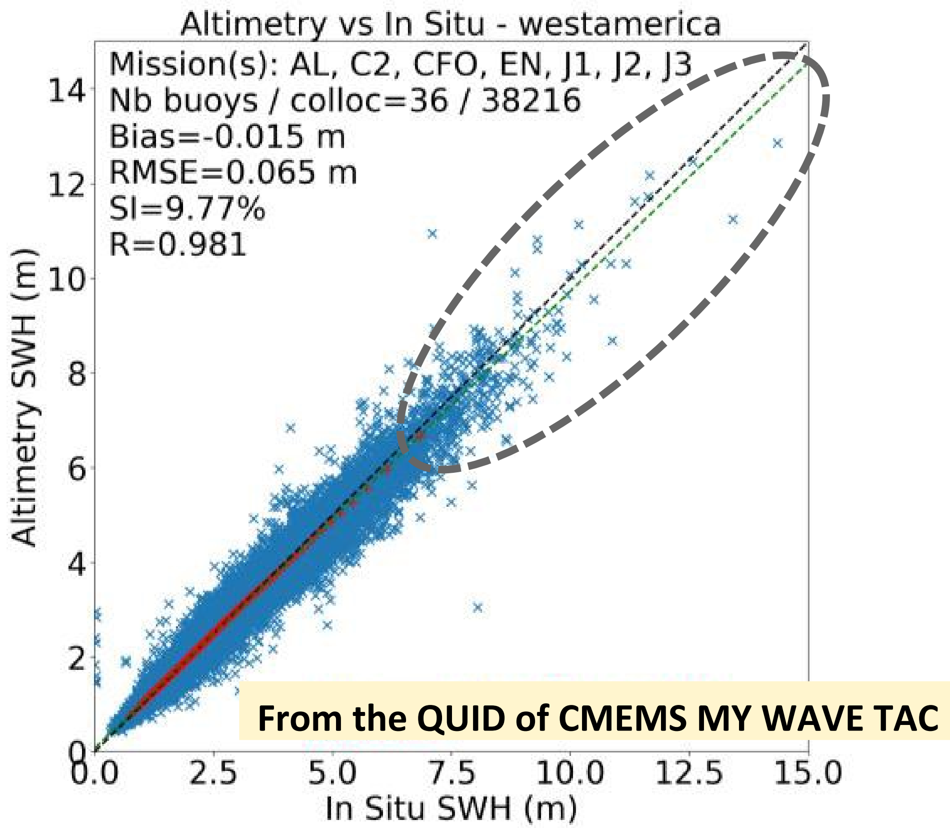
Probability density function of 1 year of altimeter data (2021) globally. 10^8 values.

Most probable SWH = 2 m
Average of SWH = 2,6 m
90^e percentile = 4,5 m
99° percentile = 7,1 m
Maximum = 16,4 m

Data quality of extreme value

According to Quality Information Document of Copernicus Marine for Multi-Year WAVE data, the average RMSD on all missions = **6,5 cm**.





From the QUID of CMEMS MY WAVE TAC

The RMSD is higher for high SWH, near 1 m in Europe for SWH > 8 m

near 60 cm in West America

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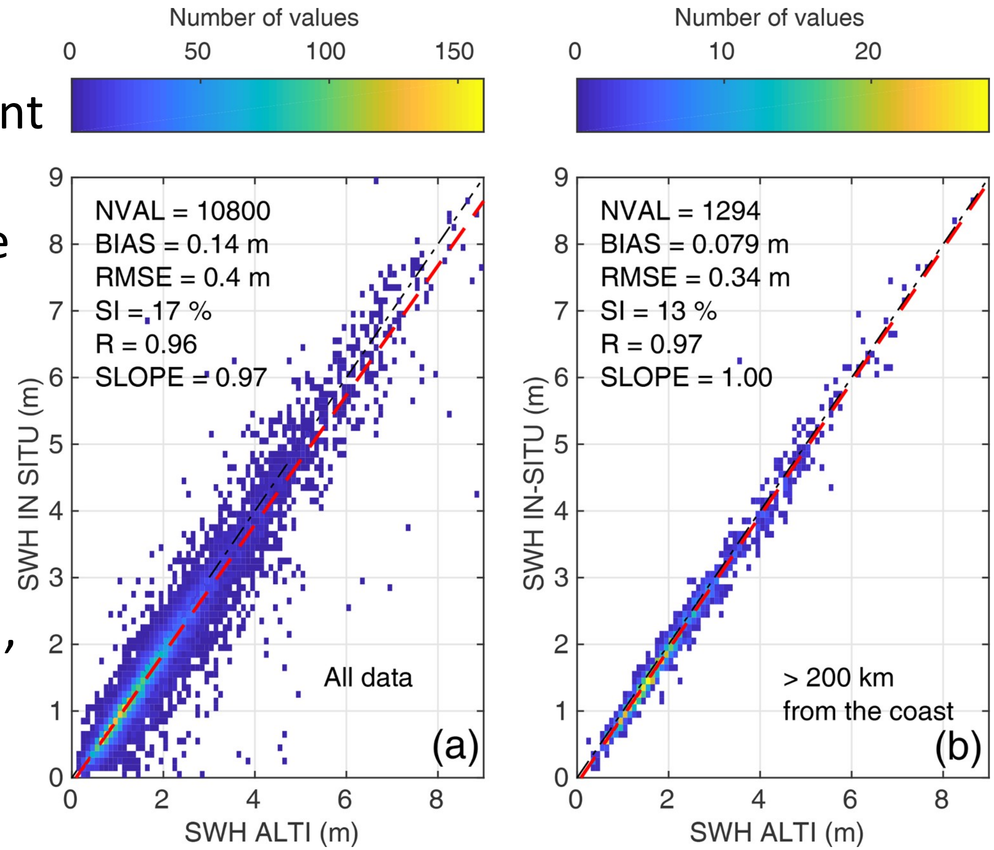
The relative error remains **near 10 % in average** and sometimes up to 20 %

Data quality of extreme value

BUT the difference between in-situ buoys and altimeter data is dependent on the distance from the coast :

- coast and islands interfere with the measurement
- in-situ buoy may not be representative of the average waves in the 7km area

By filtering only buoys in open ocean, the standard deviation between buoys and altimeters is strongly reduced.



Comparison between SARAL and wave in-situ buoys during the year 2017, for all in situ sites (a) or only locations 200 km away from the coast.

Dodet et al. 2020 about CCI sea state v1

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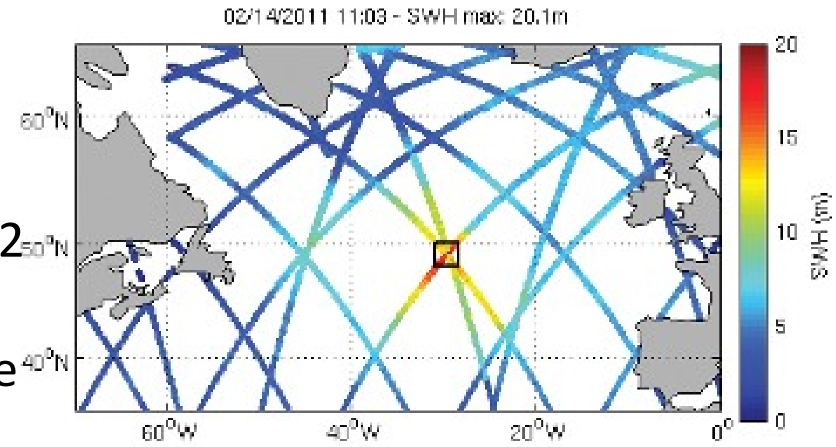
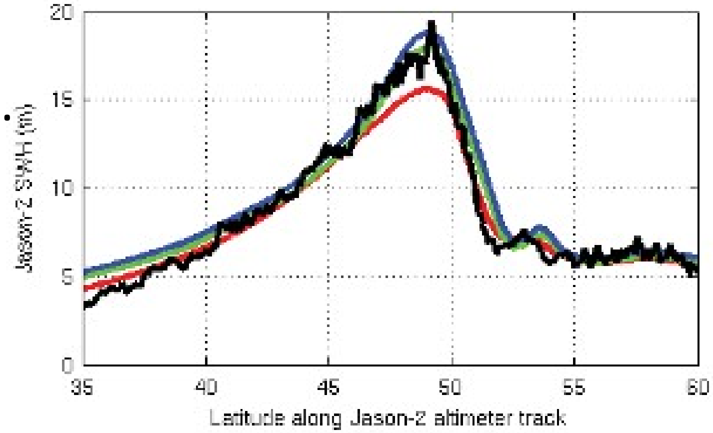
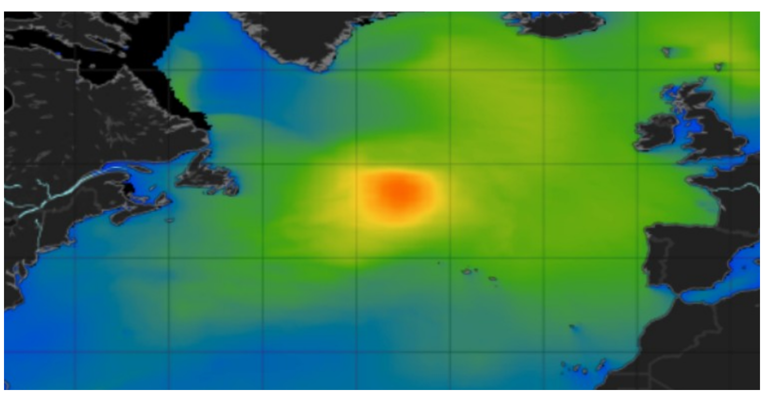
Example of extreme values
Case of Quirin storm in 2011

Very high SWH of 20,1 m measured by Jason 2 in north Atlantic during the storm Quirin.
SWH higher than 16 m measured on the same track over 500 km.



No buoy for validation on this area.
But the models confirm the very high sea state.





SWH from the reanalysis WAVERYS the 14/02/11 at 03h. Orange = 17 m.

Altimeter SWH measured the 14 Feb 2011 (top) SWH measured in black, computed from WW3 model forced by ECMWF (red), NCEP (green) and NCEP+10 % (blue) winds.

Hanafin et al. 2012 about north Atlantic storm en 2011

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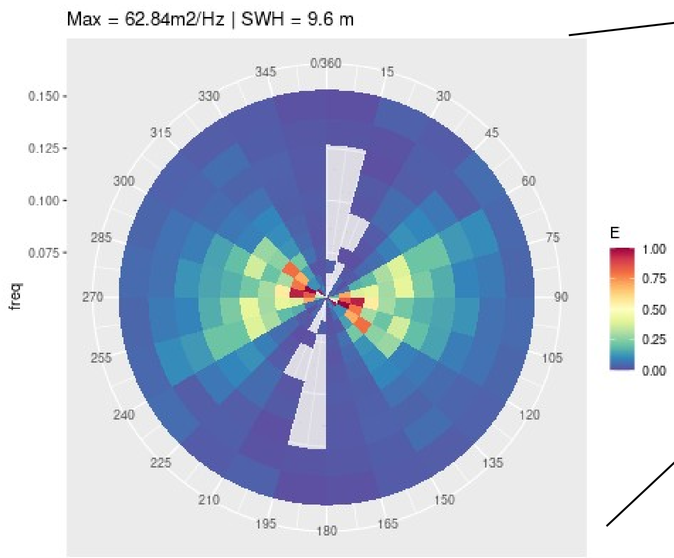
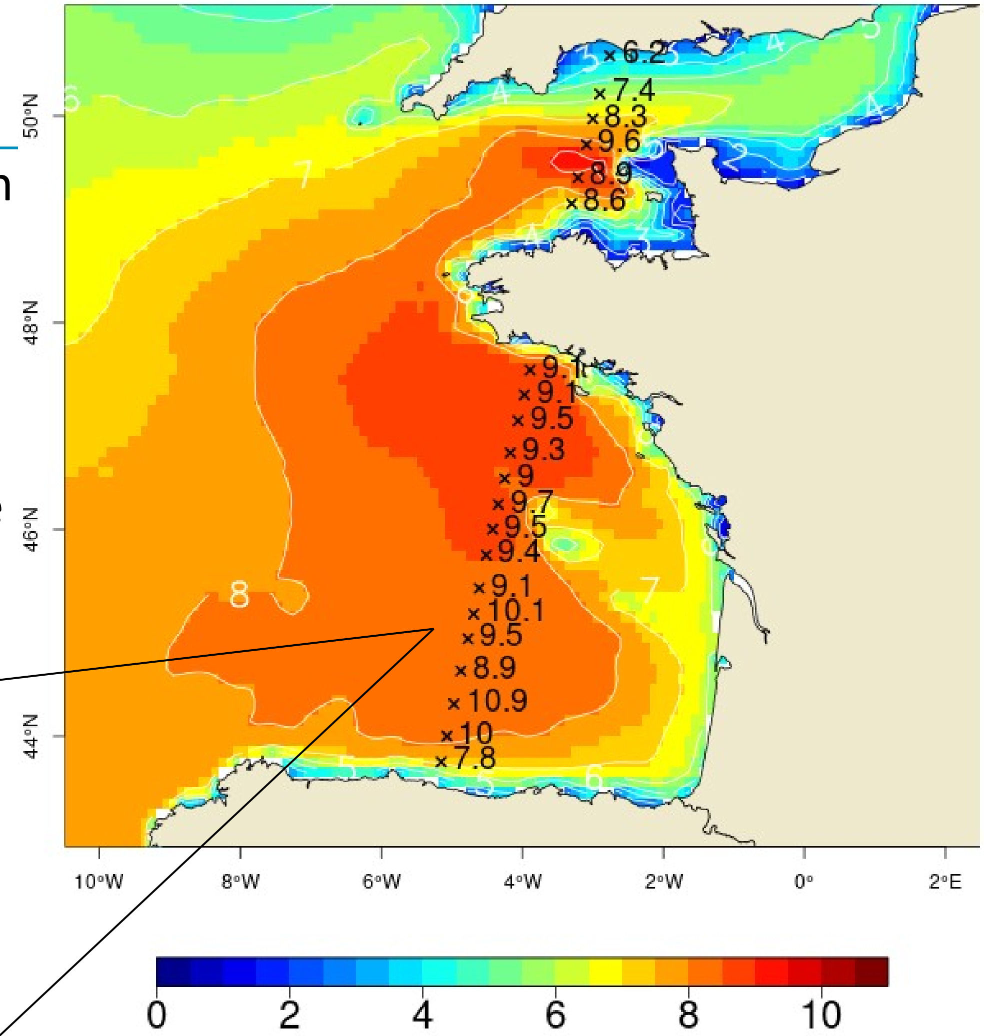
Example of extreme values
Case of Ciaran storm in 2023

Strong Atlantic storm with more than 25 m/s of steady wind. 10 years return period of wind and wave heights is reached in Brittany.

Good representation of the sea state by CFOSAT => **importance of assimilation**



Wave spectrum of CFOSAT the 02/11/23 at 7h30 in bay of Biscay



SWH forecasted at 8h the 02/11/23 by MFWAM (CMEMS WAVE GLO). SWH of CFOSAT at 7h30.

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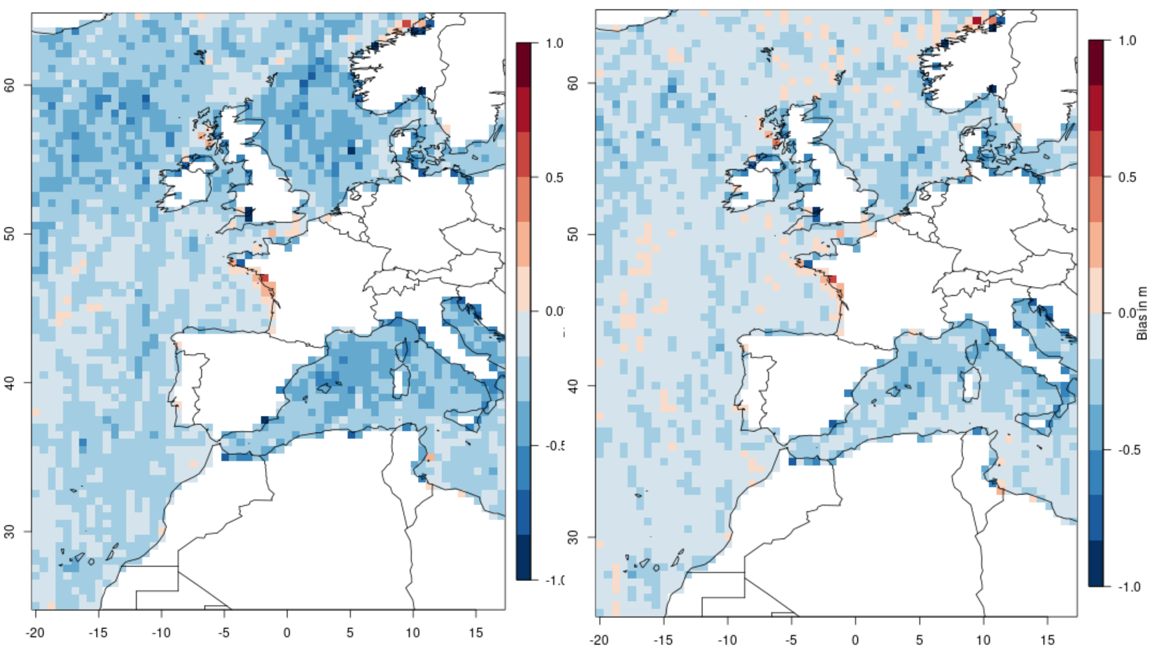
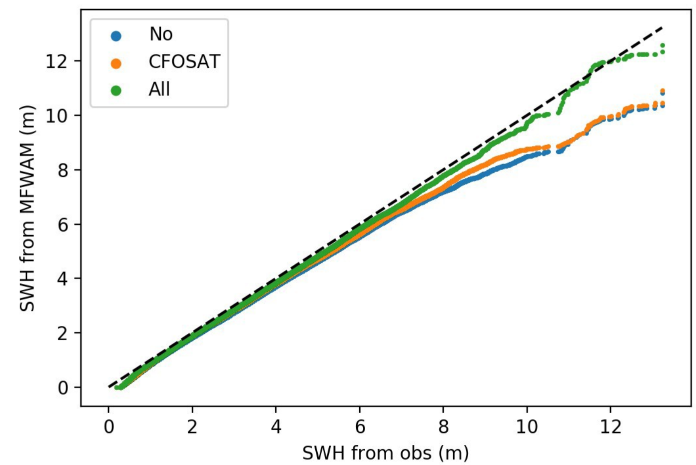
Improvement of wave model thanks to assimilation of altimeter

The assimilation of the altimeters permits to reduce the error of 20 % or more, depending on the number of satelllite.

Results of 3 months experiences in western Europe



Error of SWH (m) against independant altimeter for the experience without assimilation (left) and with assimilation (right)



QQ plot of SWH for an experience without assimilation (No), with assimilation of only CFOSAT (CFOSAT) and with 4 altimeters

Example of extreme values
Case of Ciaran storm in 2023

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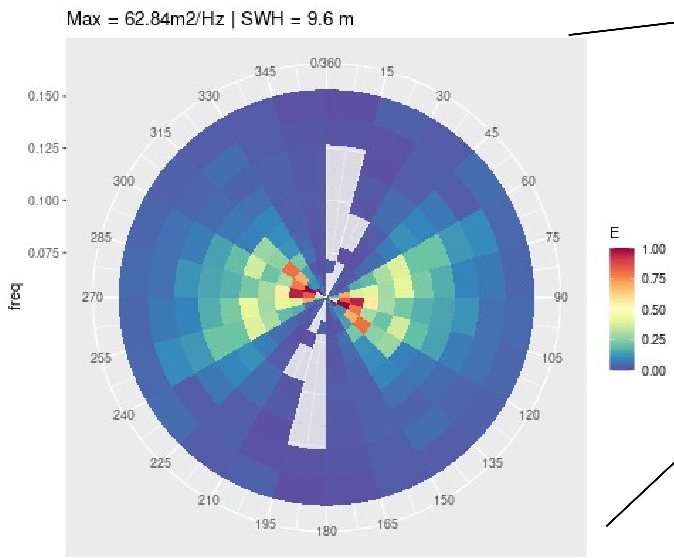

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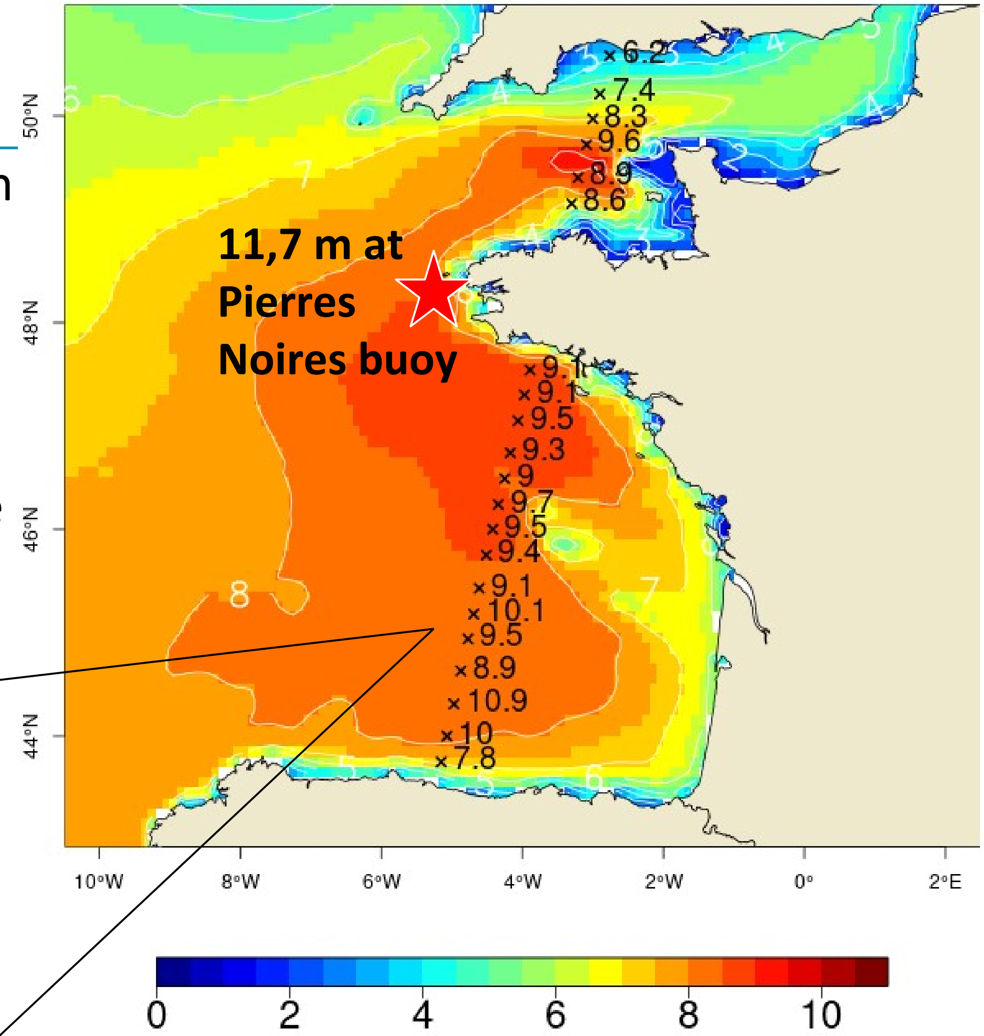
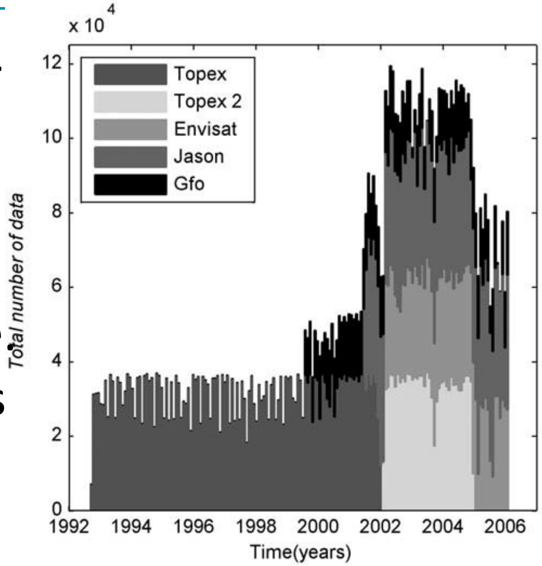


SWH forecasted at 8h the 02/11/23 by MFWAM (CMEMS WAVE GLO). SWH of CFOSAT at 7h30.

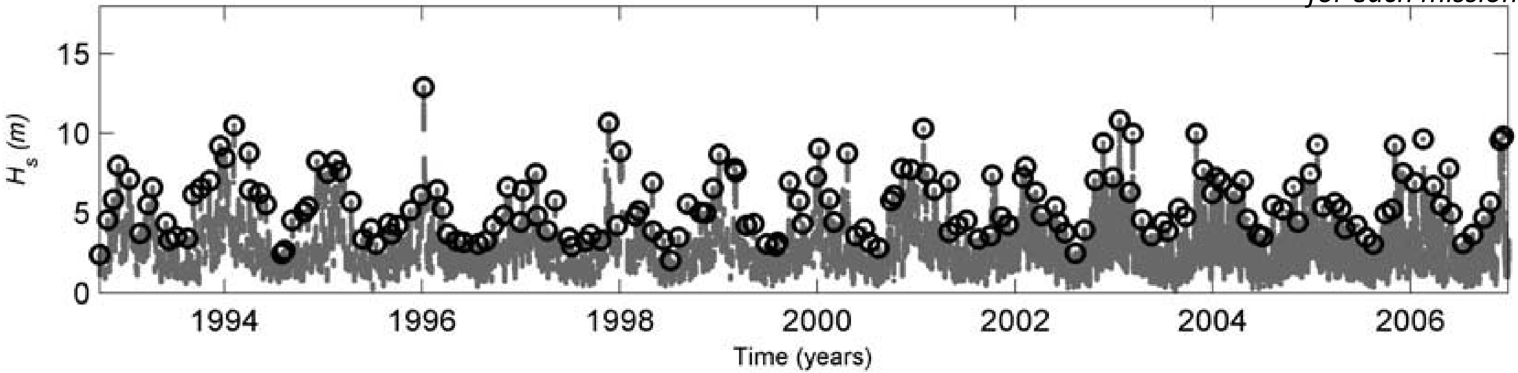
Variability of maximum of SWH

Altimeter tracks often miss the maximum of a storm or hurricane. The capacity to catch the peak of SWH depends on the number of altimeters.

=> important variability of mensual maximum measure.
=> this variability depends on the number of altimeters



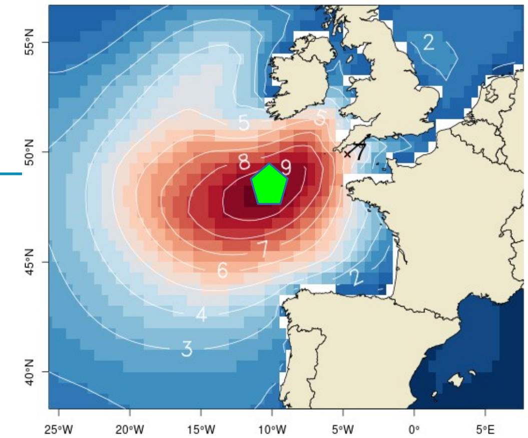
Number of measurements per month for each mission



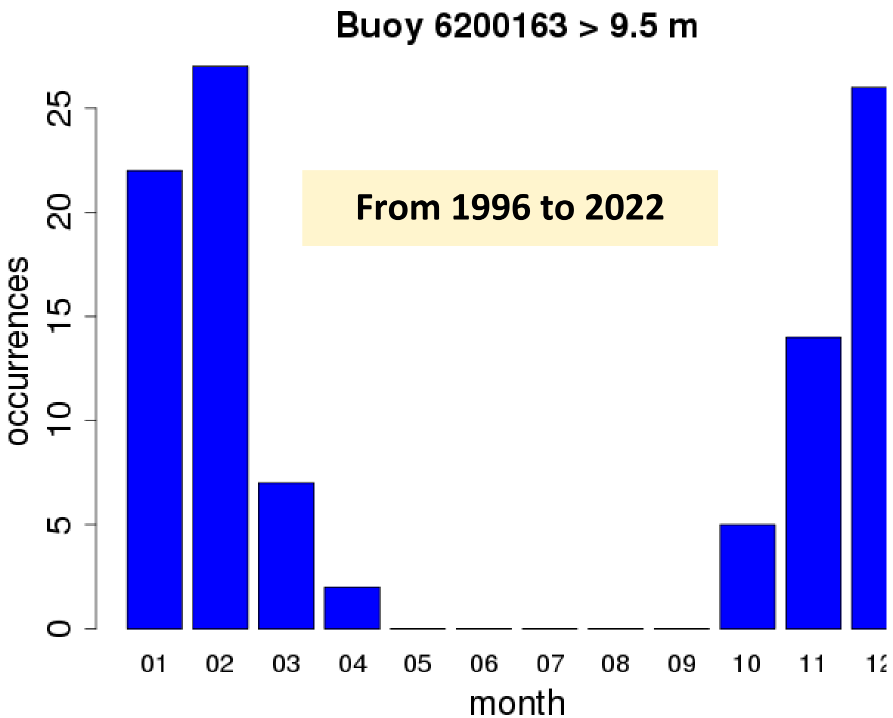
Time series of SWH (dots) and monthly maxima (circles) in a limited area in southern Europe

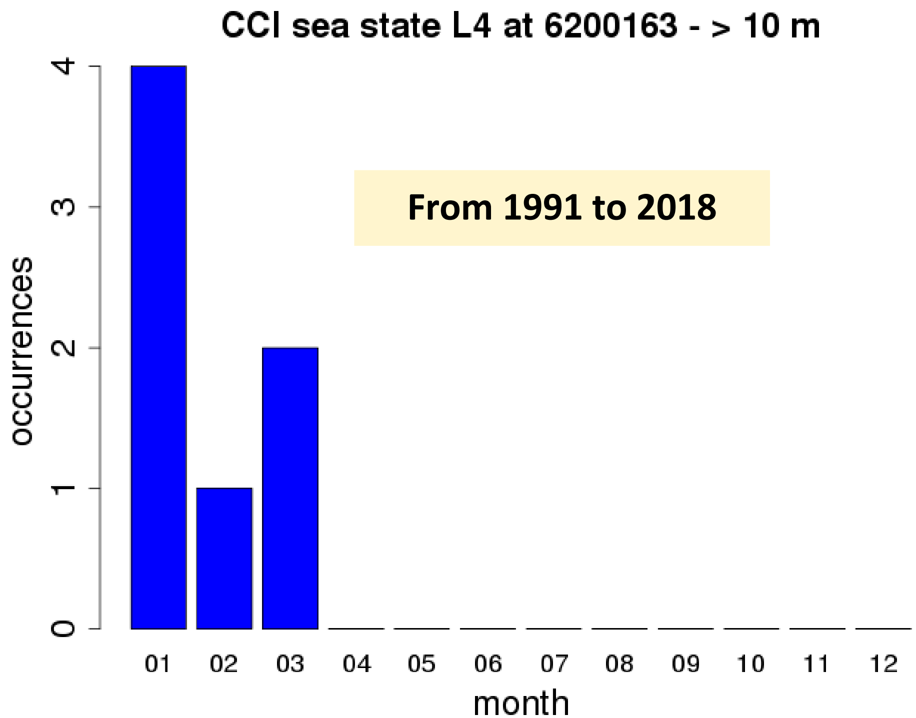
Izaguirre et al 2009 about extreme wave climate variability in southern Europe using satellite

Climatology of maximum is incomplete



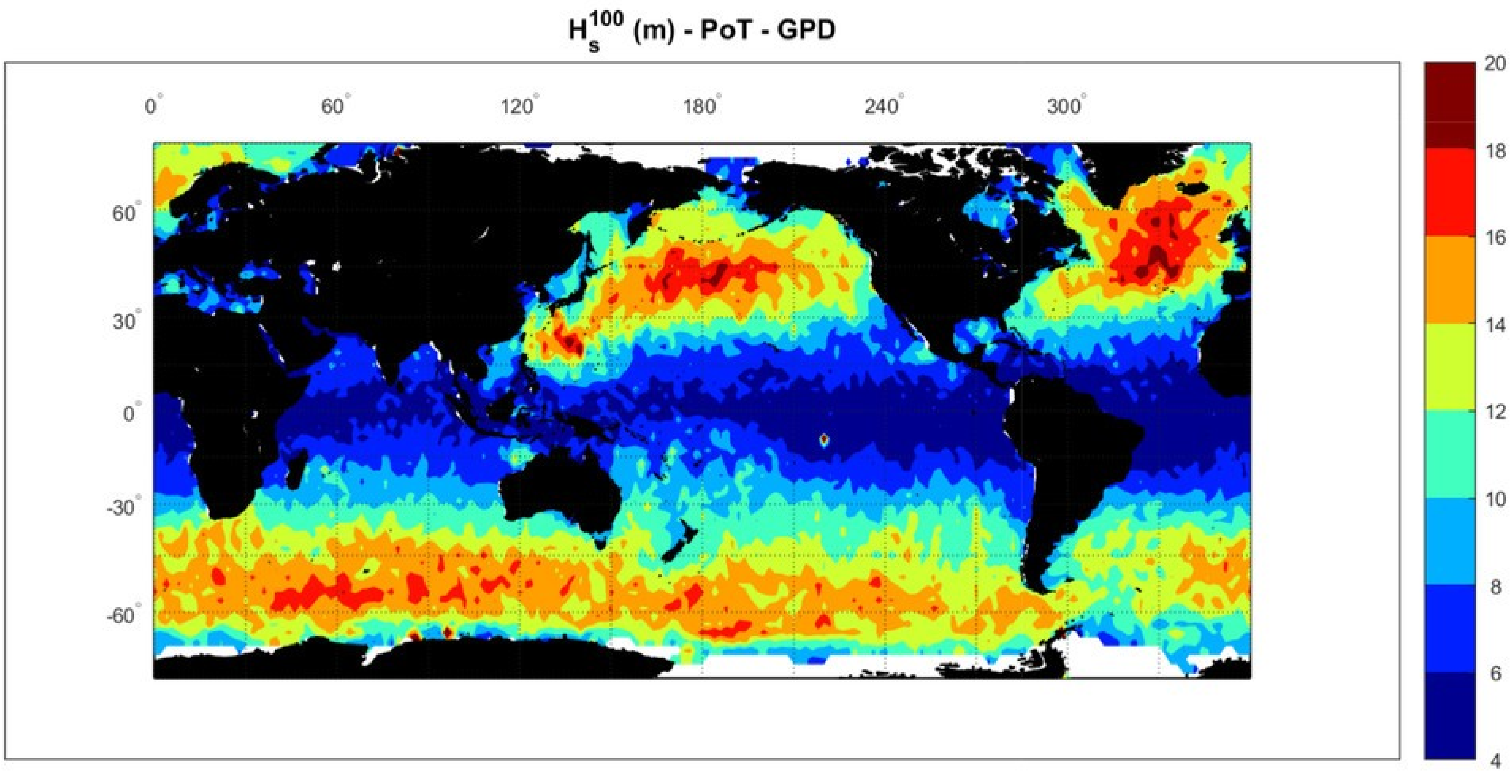
CCI sea state provides occurrences of SWH > threshold
Comparison of SWH > 10 m against a 26 years serie of a buoy in north Atlantic.
A lot of cases are missed by the altimeters.
The mensual climatology isn't representative.





100 years return period from altimeter data

Takbash et al. determined a method to compute 100 years return period from altimeter data. They estime the average error around -8 % thanks to some long series of buoys



100 years return period of SWH estimated from wave height satellite measurement

Takbash et al. 2019 about wave height extremes derived from satellite

Use of satellite data in extreme wave assessment and modelling

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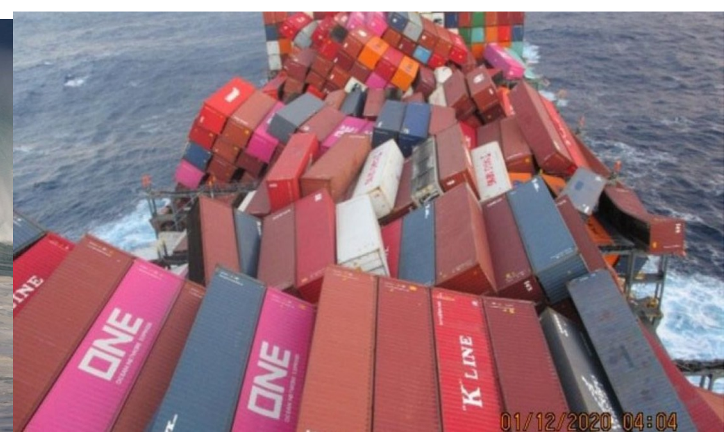
High waves 29 June 2022 (La Réunion)



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

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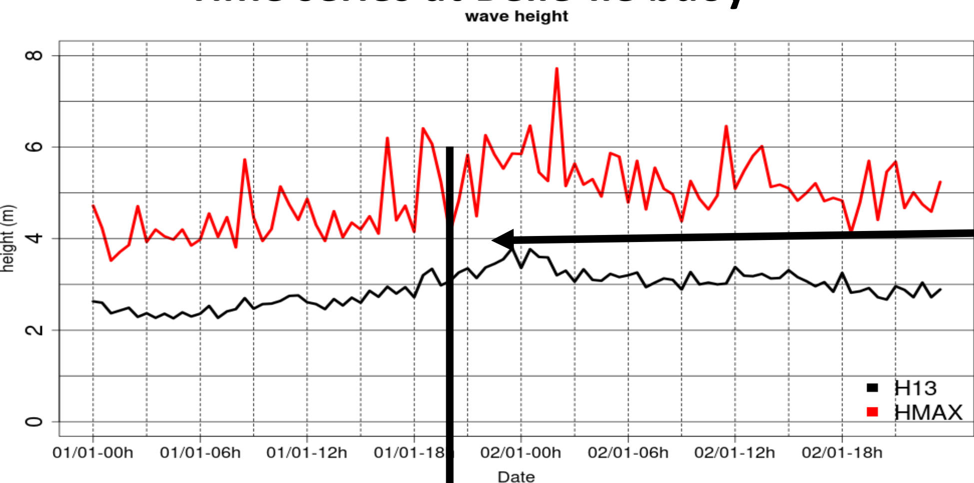
Skilled to characterise rogue waves conditions dangerous seas

Buoy and SWIM observation

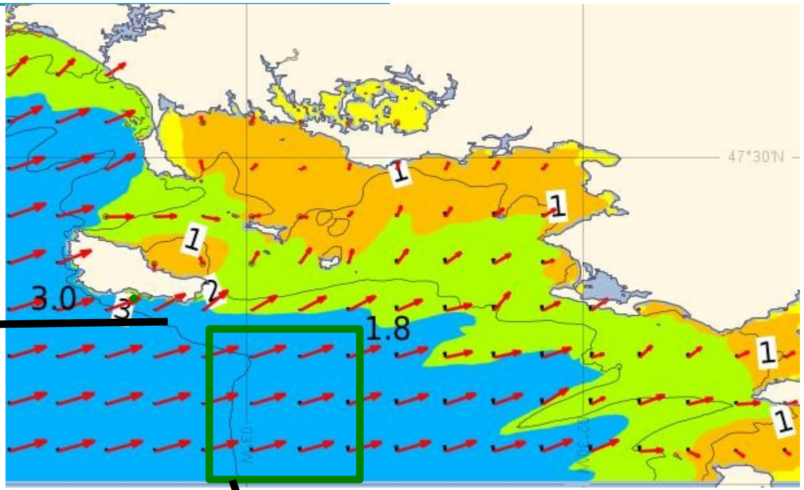
Dangerous seas event near Belle-Ile 1 January 2022

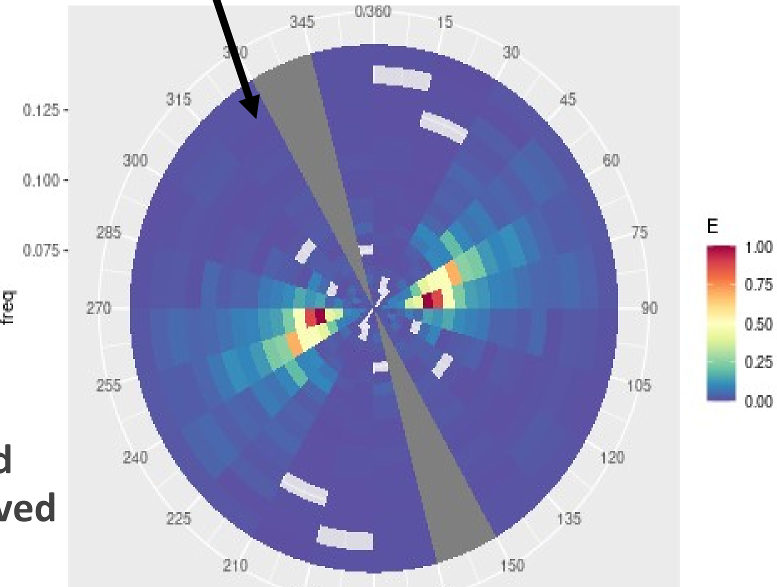
Rogues waves : Hmax/SWH>2

Time series at Belle-Ile buoy

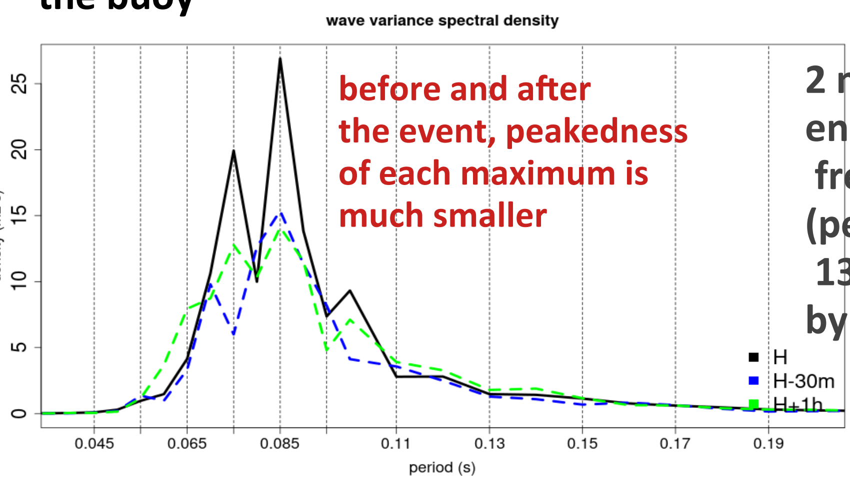


SWH of 3,1 m and Hmax of 6,4 m





1D spectrum from the buoy



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

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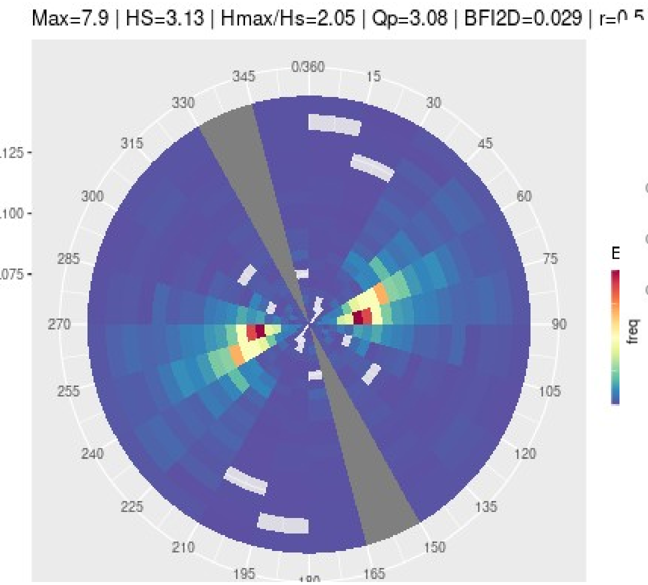
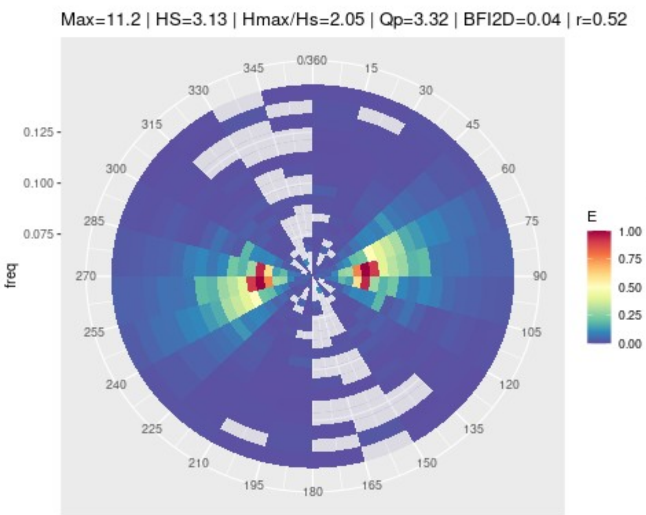
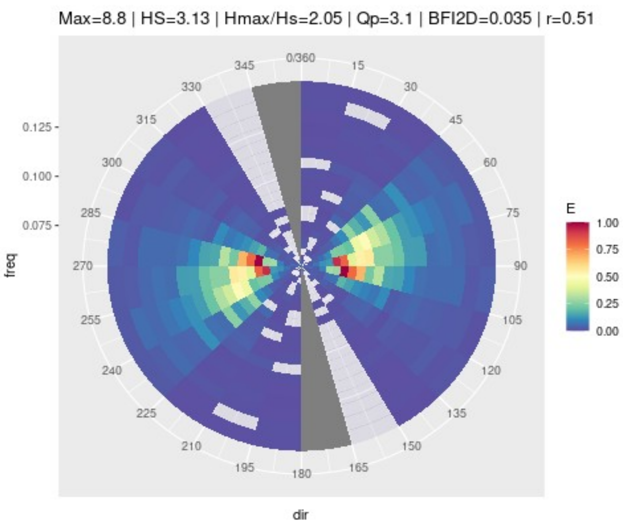
Spectral variability according to SWIM : Belle-ile case



Rogue wave location



80 km at the south

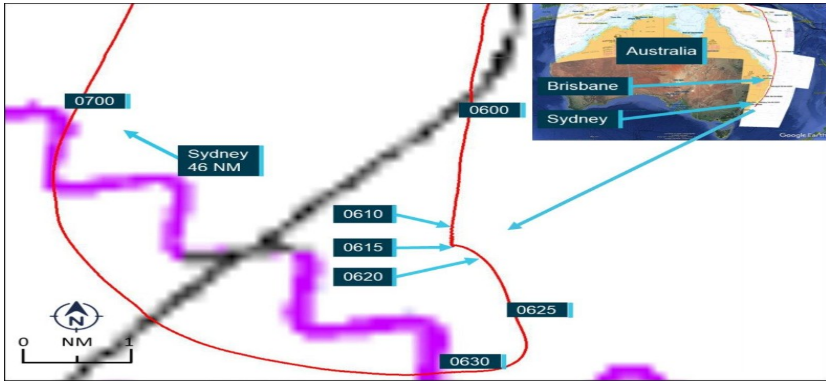


160 km at the south

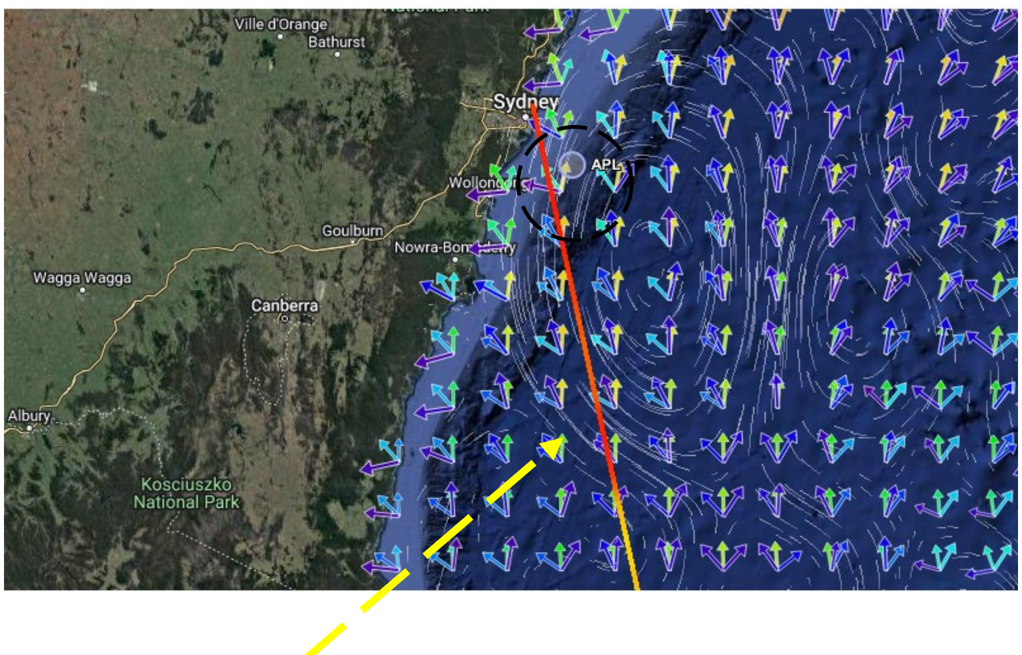
➡ **2 peaks at the rogue wave place. 1 peak elsewhere with less variability of energy in frequency and direction space.**

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

Pitching and rolling of the container ship

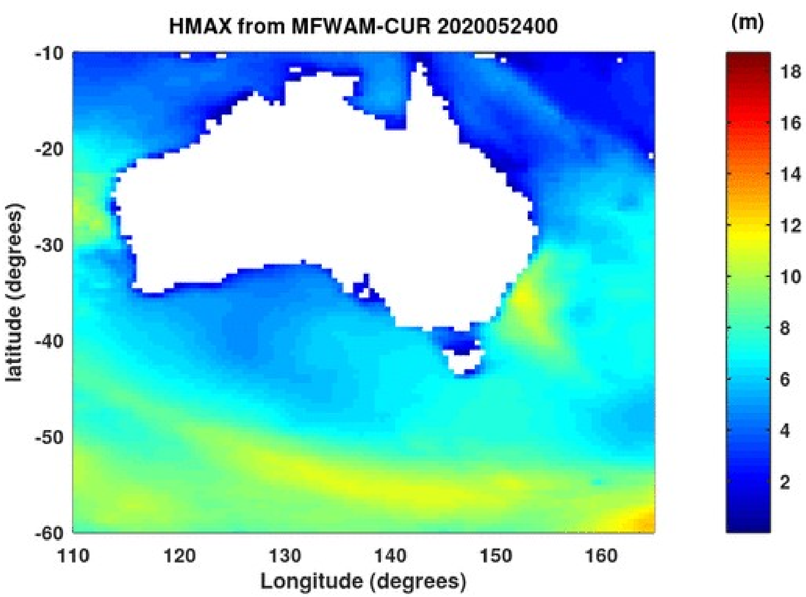


Wind-wave 8.6 sec, 1st swell:9.5sec 2nd swell 12.6 sec

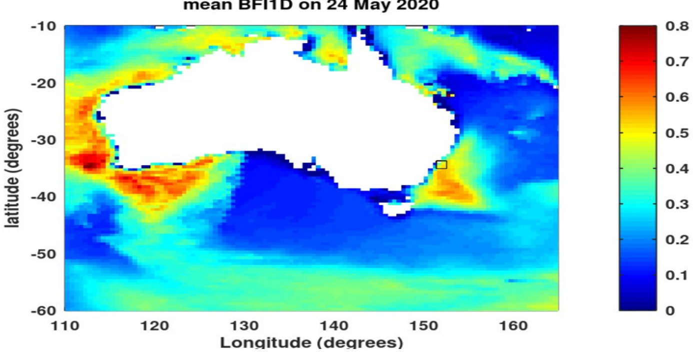


CFOSAT track at 9:25 UTC

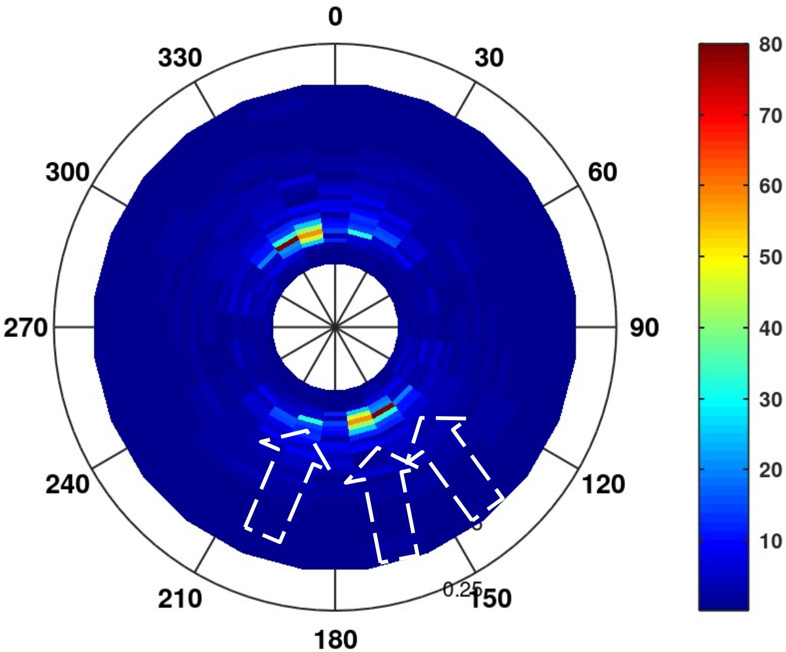
Animation of hmax snapshots during the event (3-hourly from 0:00-21:00)



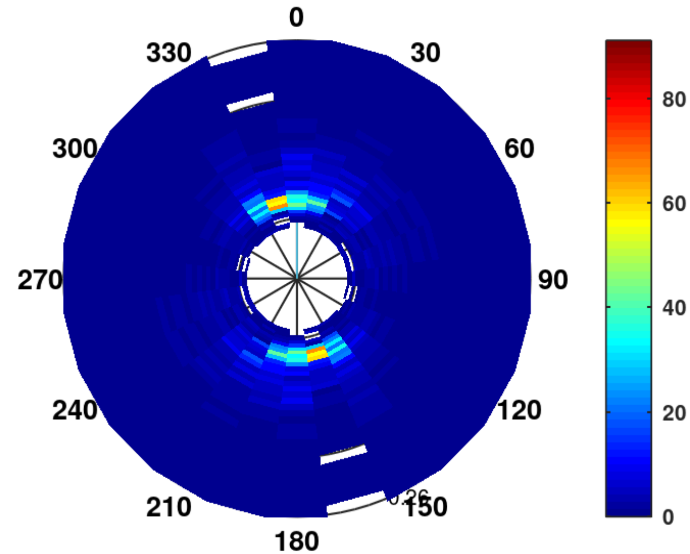
Strong increase of Hmax more than 16 m at the accident locatior

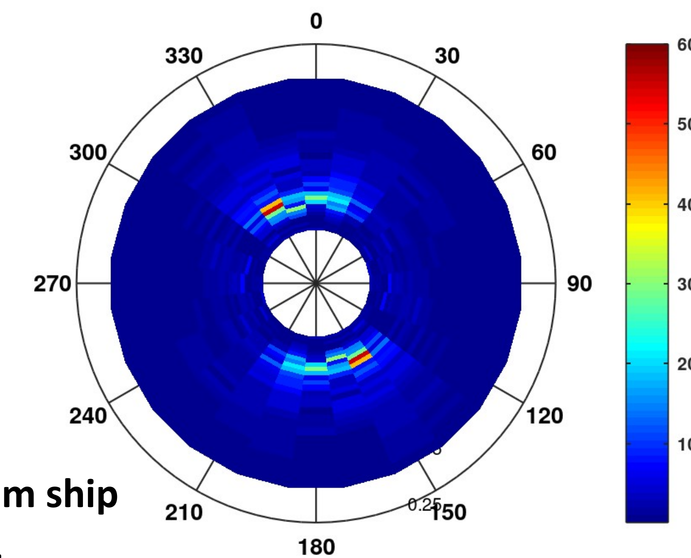


40 km from the location
R=0.6 & BFI2D=0.13



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



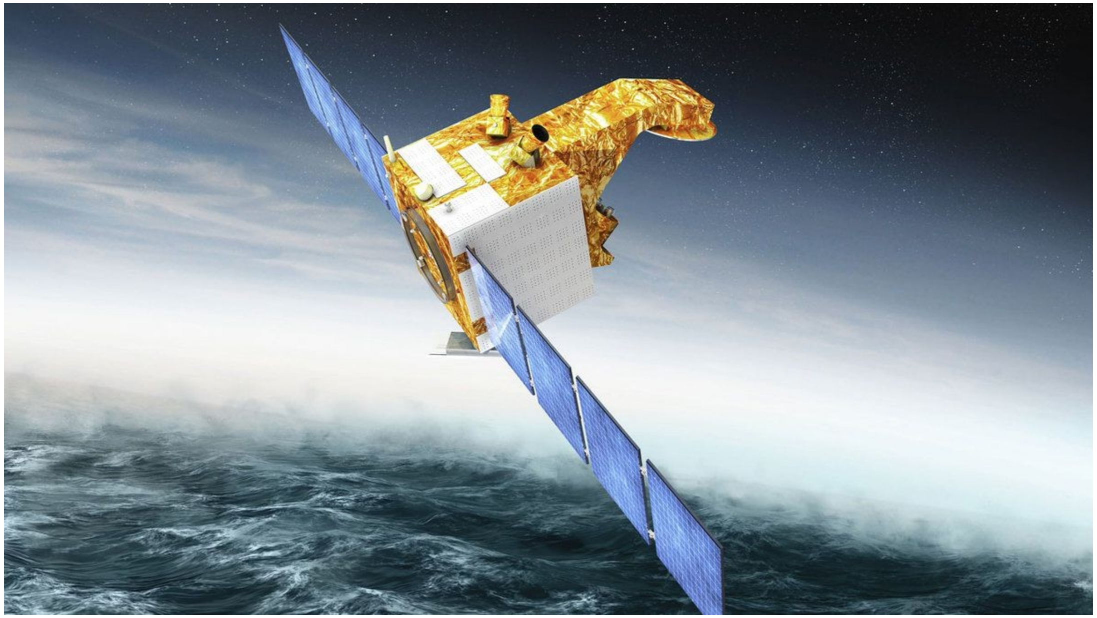


Increase of the energy before the ship Accident and icrease of R and BFI2D

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

Key messages

- ➔ Good reliability of nadir SWH from altimeters, even for high value. Very useful for validation and assimilation in the wave models, particularly today with 10 satellites available in NRT
- ➔ The database of CCI sea state (also on CMEMS) of 30 years of altimeter data permits to construct robust climatology except for rare value
- ➔ Directional wave spectra from CFOSAT has captured several cases of rogue waves. They can be interpreted thanks to some indicators (BFI2D or R crest).



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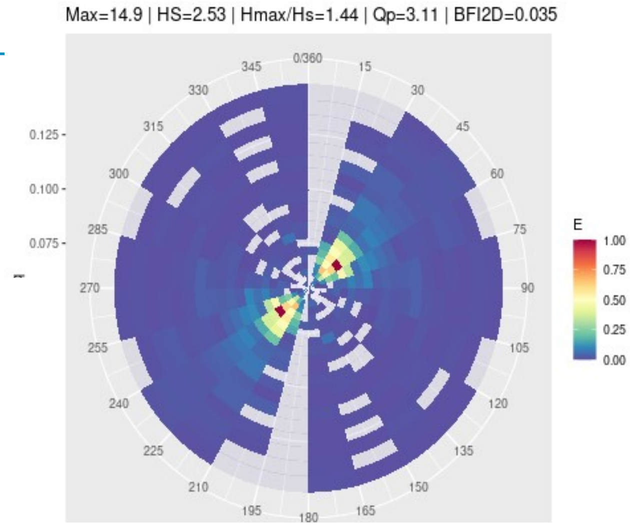
2021/06/18 at 23h
56006 (Australia)

Computation of spectral indexes



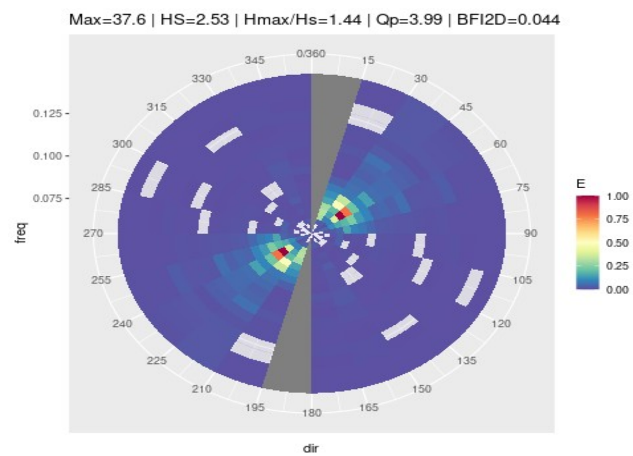
- **Spectral peakedness thanks to Goda parameter**

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

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
nergy of the spectrum

Higher the steepness is, the higher the BFI

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Computation of spectral indexes

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

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

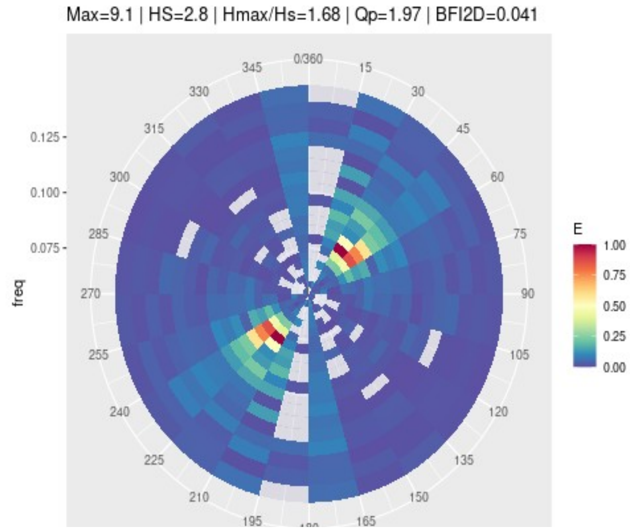
$$\sigma_\phi(f) = \sqrt{2 \times \left(1 - \sqrt{a_1(f)^2 + b_1(f)^2}\right)}$$

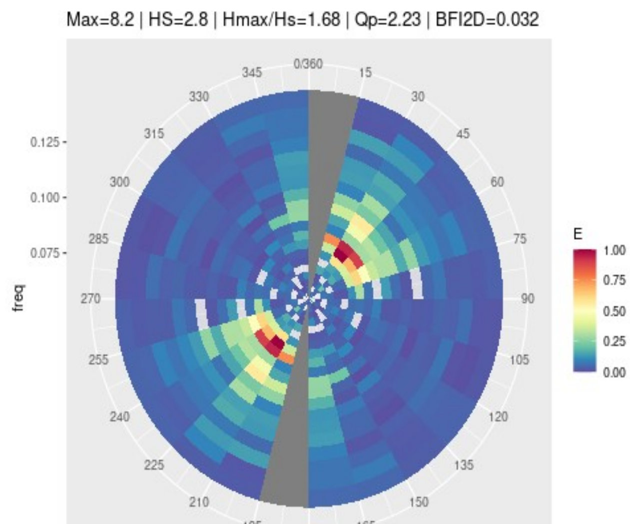
- **Benjamin Fair index 2D : inclusion of directional effects**
  Mori et al, 2011

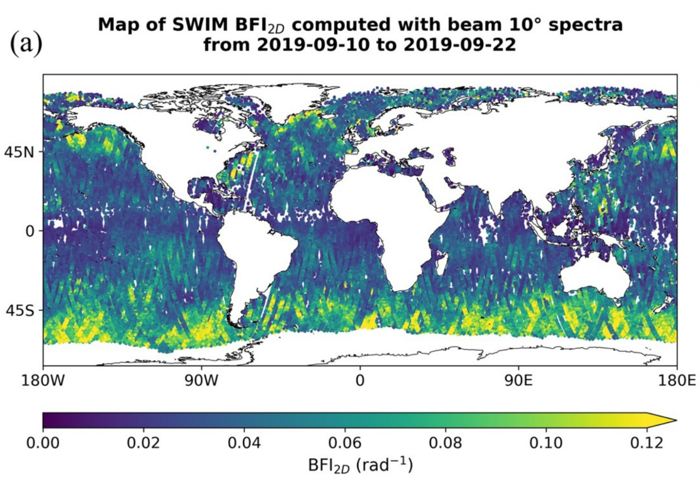
$$BFI_{2D} = \frac{BFI}{\sqrt{1 + \alpha_2 R}} \qquad R = \frac{1}{2}\sigma_\phi^2 \pi Q p^2$$

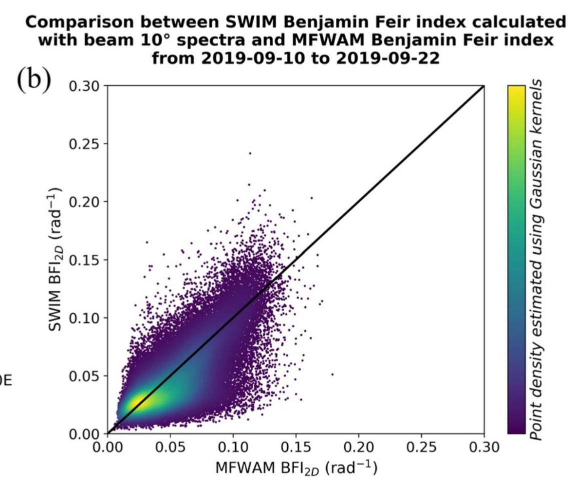
Smaller the directional spread, higher the BFI

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









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