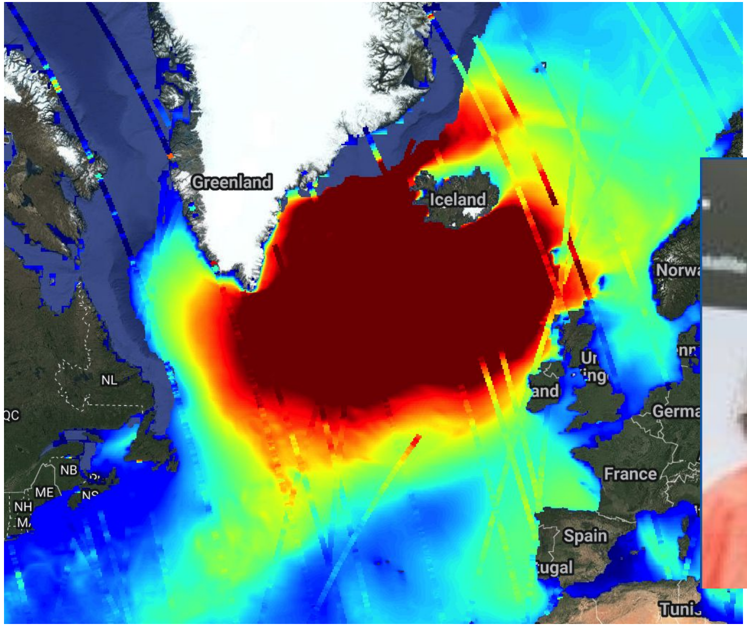
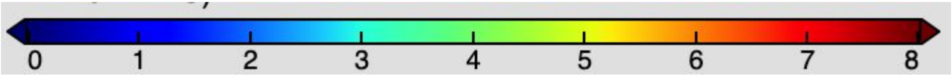


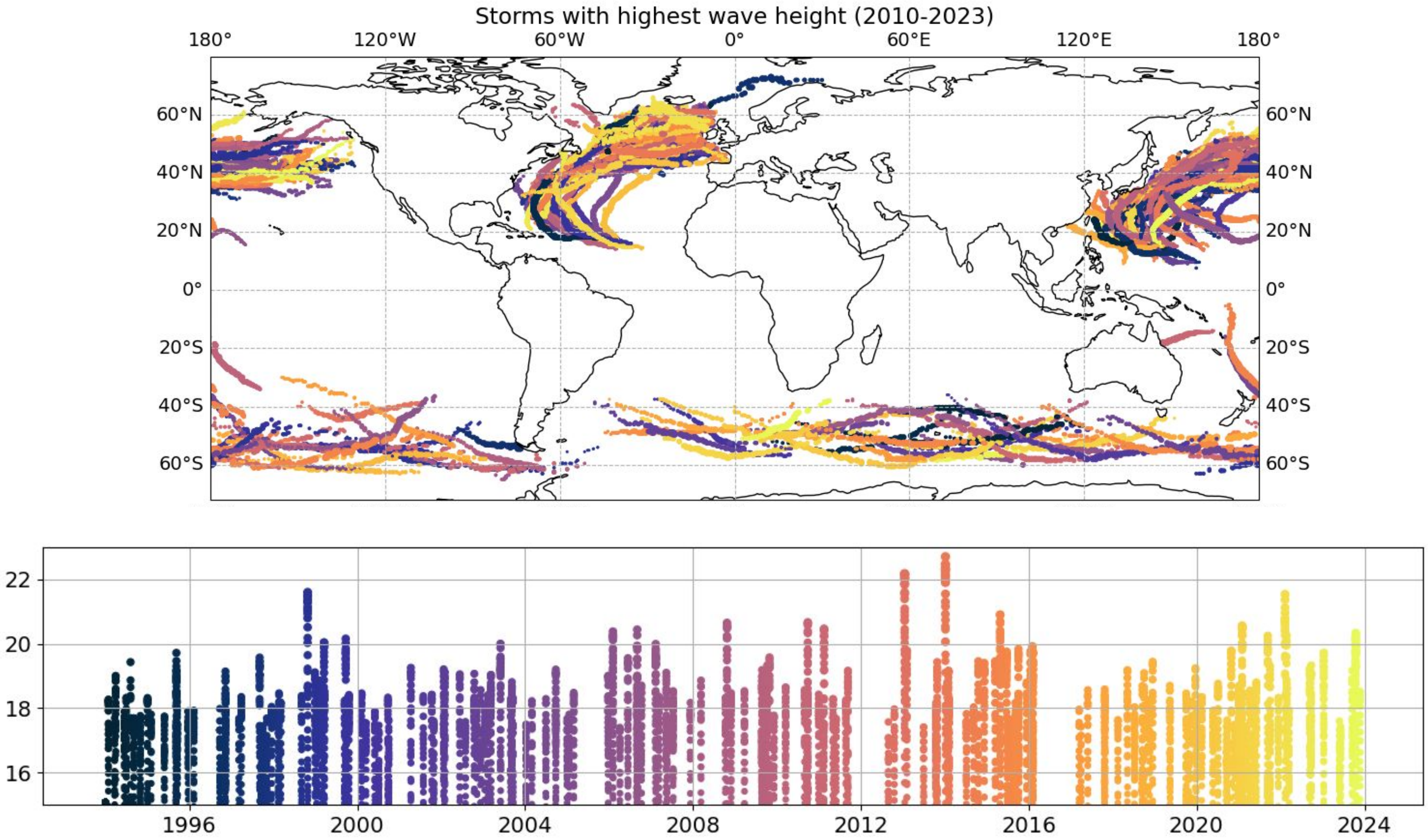


https://odl.bzh/QSkrv3Xj

Using off-nadir data to interpret nadir altimetry: phenomenal seas from storms Danièle and Eddie

Fabrice Ardhuin[1], Marcello Passaro[2], Guillaume Dodet[1]

Storm catalog: Ardhuin & De Carlo (2025)



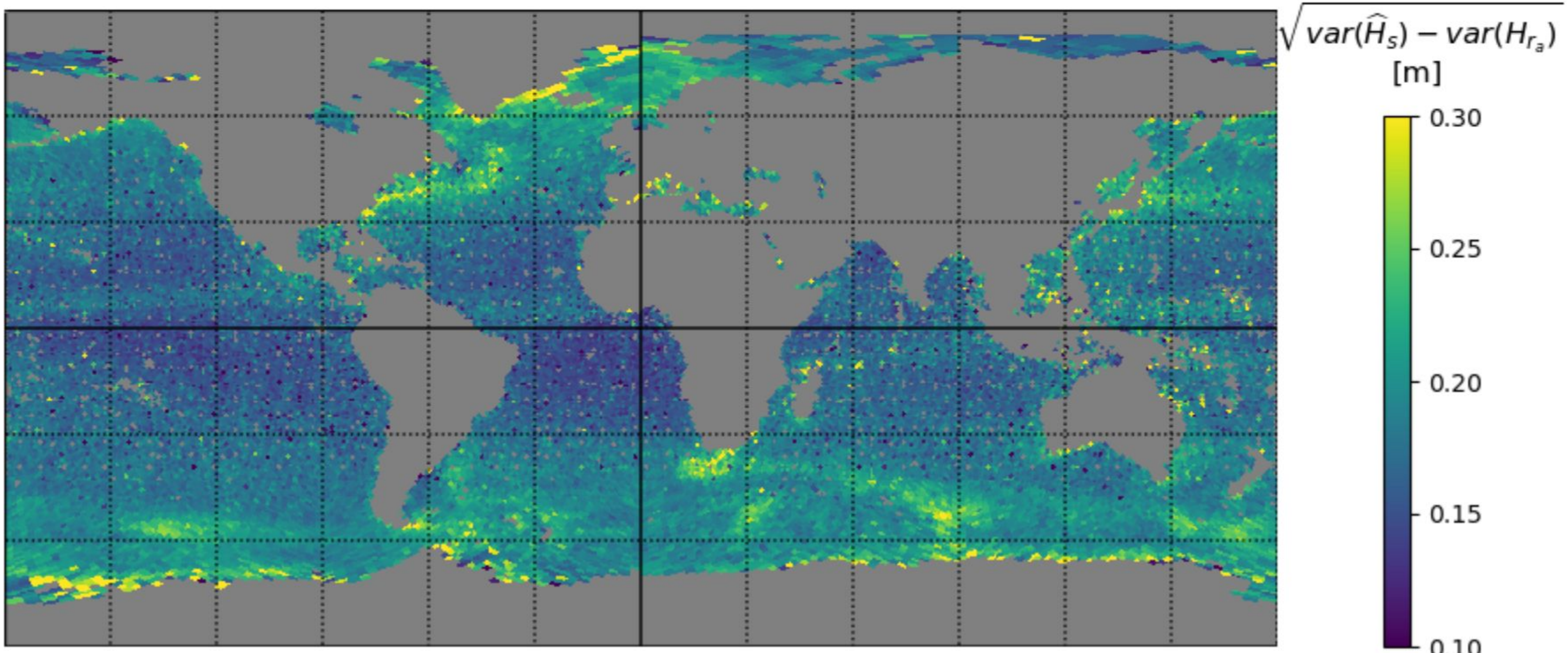
Naming storms:

big thanks to all who made wave observations possible

rank	date and hour of max Hs	lon	lat	Hs (m)	Tp (s)	nearest sat. max Hs (m)	max (m)	Storm name	satellite	reference	CFOSAT max(Hs)
1	2014-01-05T10	-31	46.5	23	20.4	18.7±0.2	18.4	Ronadh*	CS2	Cox et al. (2018	
2	2013-01-15T16	166	39	22.2	20	15.8±0.2	16.8	Paul*	JA1		
3	1998-10-26T15	177	41.5	21.6	20	12.6±0.2	15.4	Yoshiaki*	ERS2		
4	2015-04-27T00	-137.5	-56	21	20	18.1±0.3	19.6	Luigi*	CS2	Cavaleri et al. (2	
5	2024-12-21T15	-161	38.5	20.8	19.6	19.7±0.3	20	Eddie*	SWOT		
6	2010-09-25T23	155	42	20.7	19.6	15.0±0.2	17.7	Malakas	JA2	https://en.wikipe	17.5 m
7	2008-10-22T19	-172	49	20.7	19.2	11.2±0.1	11.7	Nobuhito*	Envisat		
8	2021-01-30T09	-44.5	41.5	20.6	18.9	18.3	13.8	Laurent*	CS2		
9	2022-02-08T00	-26	63.5	20.5	18.9	18.9±0.2	15.8	Danièle*	JA3		
10	2006-09-02T04	158	24	20.4	17.9	14.0±0.1	17.7	Ioke	JA1	Zhang et al. (GR	
11	2006-02-03T03	171	43.5	20.4	19.6	18.0±0.2	17	Helen*	JA1		**18.5 m**
12	2023-10-16T01	-173.5	42	20.3	19.6	15.4±0.2	17.2	Bolaven	S3B	Ardhuin et al. (in	
13	2022-02-21T02	-10.5	56	20.3	18.9	18.4	-	Eunice	S3B		
14	2021-09-10T20	-58	42	20.2	18.5	-	-	Larry	-		
15	2011-02-14T12	-28	49	20.2	19.2	18.6±0.2	19.7	Quirin	JA2	Hanafin et al. (B	
79	2022-02-23T12	-24	57.5	18.7	18.2	19.1±0.2	16.7	Nathalie*	SARAL		

Waves come from wind, but they respond to currents, sea ice, icebergs, water depth …

De Carlo et al. (JGR 2023, using SWIM L2S data)



Better understanding of wave spectra: better Hs , and (for example) currents

Advertising …

Most of this talk: new chapter

See also Young (1989), Krogstad et al. (1999)

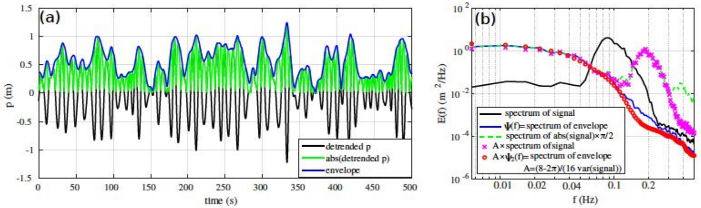
Chapter 5

Wave groups and fluctuations of wave parameters

Before we look at the evolution of the wave field over tens of kilometers and hours time scale, it is worth looking at consequences of the shape of the wave spectrum on fluctuations in wave properties at the scale of few minutes and kilometers. Indeed, the fact that waves are random introduces small scale variations. Most early work was focused on defining the statistics of series of high waves (Arhan and Ezraty, 1978; Masson and Chandler, 1993), which can be useful for example when catching waves on a surfboard, avoid the high waves when navigating a landing craft through the surf zone, or landing a helicopter on a ship. In this chapter we will start with another application which has become prominent as we are starting to look at smaller and smaller scale details in the wave field: estimating the expected fluctuations associated with groups (De Carlo et al., 2023), so that we may separate it from other effects, including refraction induced by currents and water depth, wave breaking, etc, which will be discussed in the following chapters. This investigation will also allow us to estimate lower bounds for uncertainties of wave measurements that will be defined from the time and space footprint of the measurements. The full uncertainty also contains instrument noise and measurement noise effects.

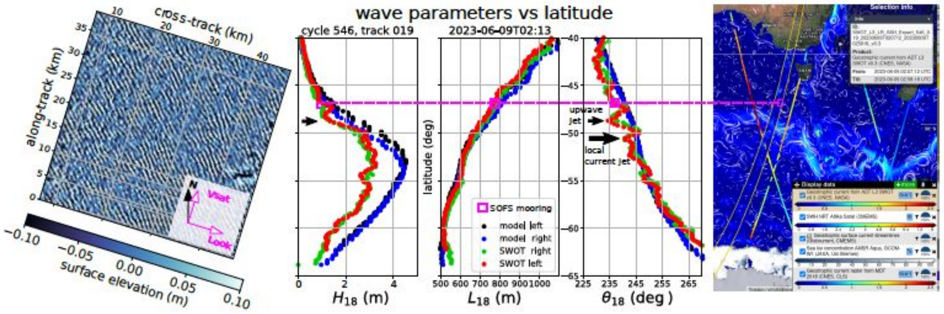
5.1 Wave envelope, local amplitudes and their statistics

Let ζ_c be the complex number such that $\zeta = \mathrm{Re}(\zeta_c)$ is the free surface, ζ_c is usally called the analytic signal. The envelope η of the signal is defined by $\eta = |\zeta_c|$, with an example shown in Fig. 5.1, using bottom pressure $p(z = -h)$ instead of surface elevation ζ. This defines a local amplitude of the signal



Ocean waves in geosciences

parts 1 and 2: general wave topics from deep to shallow water



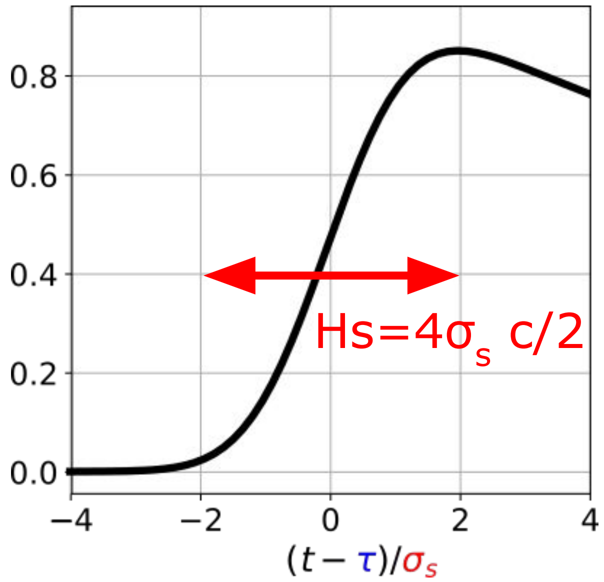
Fabrice Ardhuin,

Laboratoire d'Océanographie Physique et Spatiale, Brest, France

doi: 10.13140/RG.2.2.16019.78888/11, https://github.com/ardhuin/waves_in_geosciences

1. Back to basics: the Brown waveform

Basic idea of altimetry: waveform contain information about
a) mean surface elevation = “sea surface height”, b) standard deviation = Hs / 4
c) the slope variance : related to wind speed

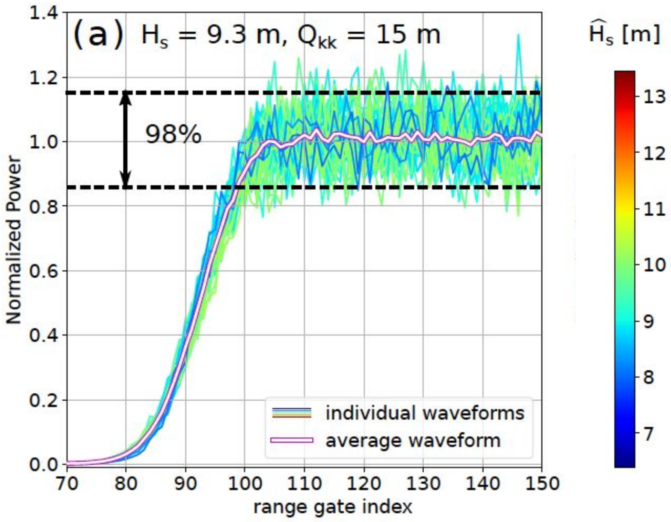


ideal Brown waveform

1. Back to basics: limitations of Brown model

Problems: The mean and std are defined over what **spatial scale**?
What about their **fluctuations**?

traditional view:
scale separation & spatial homogeneity,
Brown model with speckle noise
e.g. CFOSAT data (L1b, corrected for ant. pattern). See De Carlo et al. (JGR 2023)

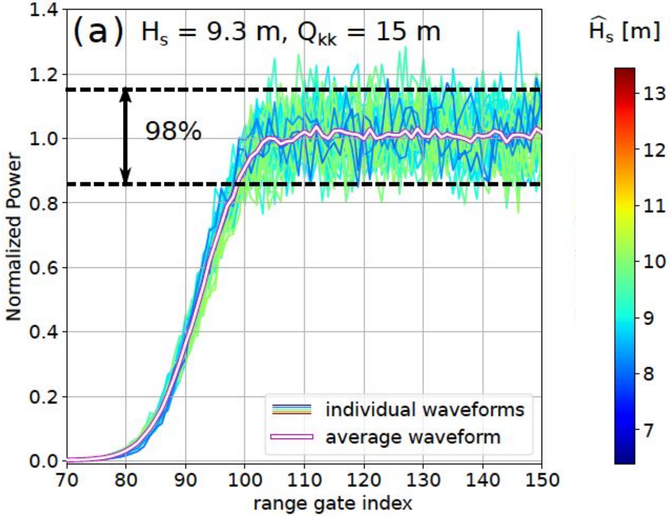


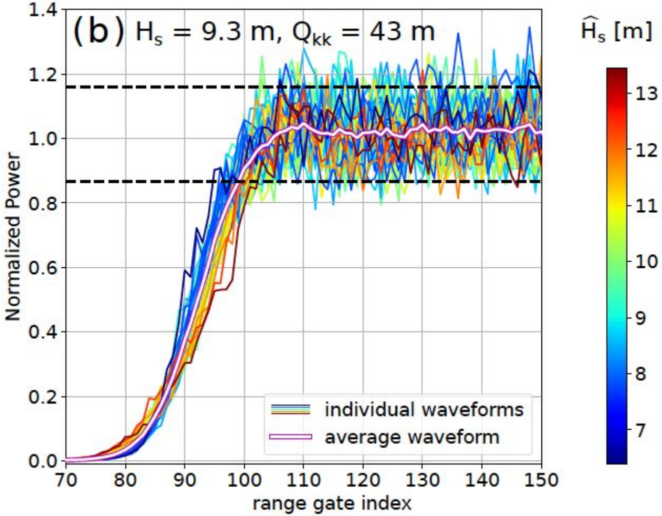
1. Back to basics: limitations of Brown-Hayne model

Problems: The mean and std are defined over what **spatial scale**?
What about their **fluctuations**?

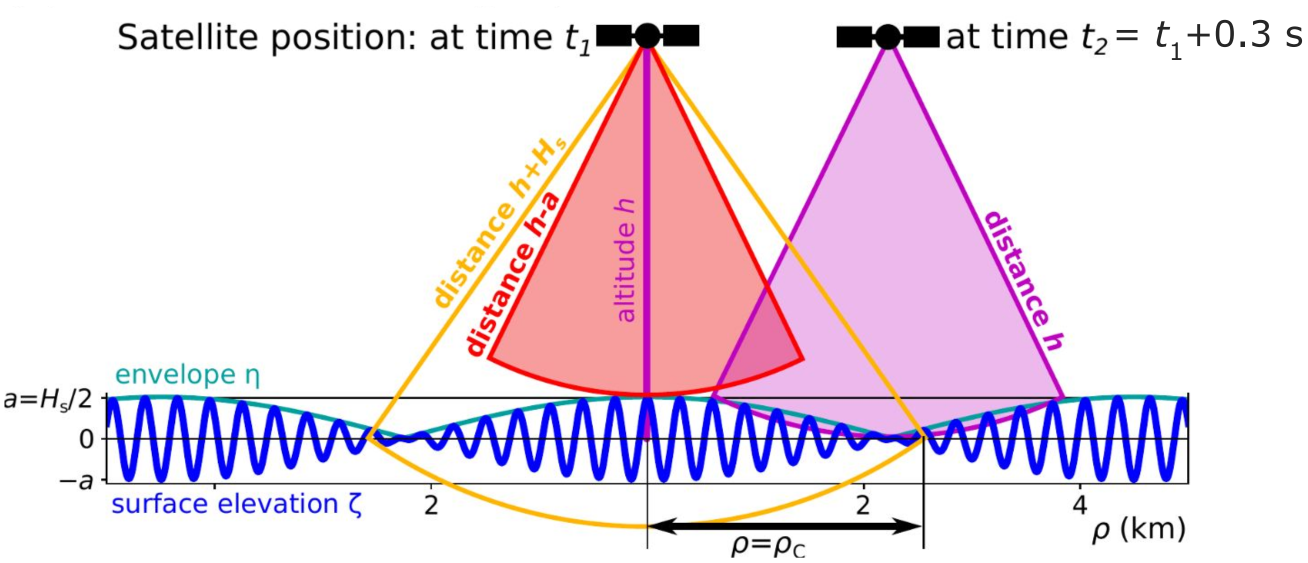
traditional view:
scale separation & spatial homogeneity,
Brown model with speckle noise
e.g. CFOSAT data (L1b, corrected for ant. pattern)

but some waveforms
really do not fit very well…





2. Wave groups, Q_{kk} and doughnut footprints

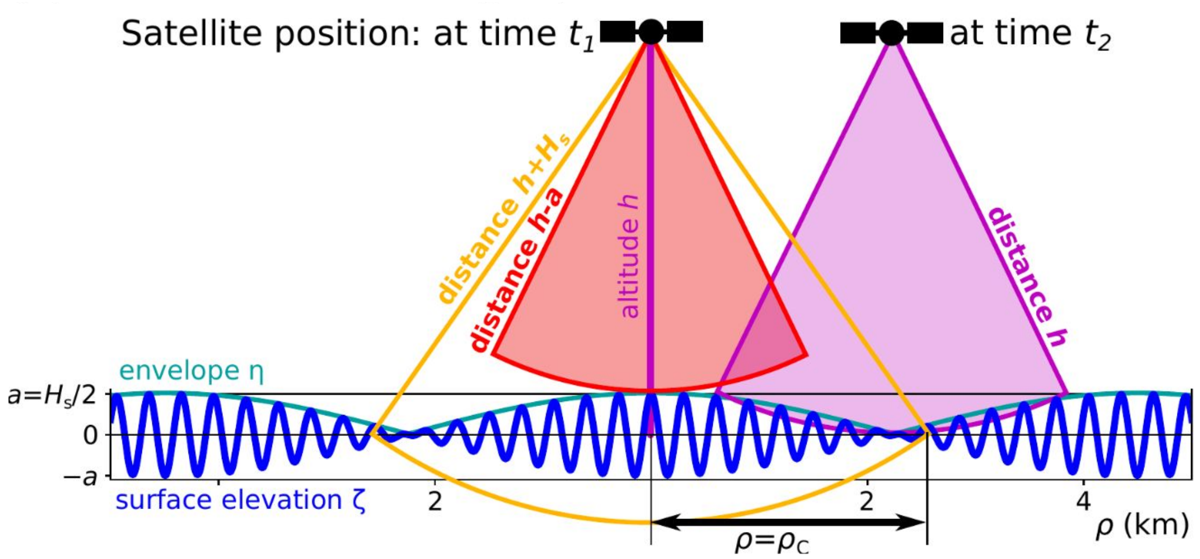


Here the max amplitude is $H_s/2$, with $H_s = 4\sqrt{<\zeta^2>}$

ζ = **$\eta(x)$** × cos (k x) , envelope is **η**(x),

local wave height **H_l** = 4 **η** $\sqrt{(2/\pi)}$, so that <**H_l**> = H_s **here H_s is constant**

2. Wave groups, Q_{kk} and doughnut footprints



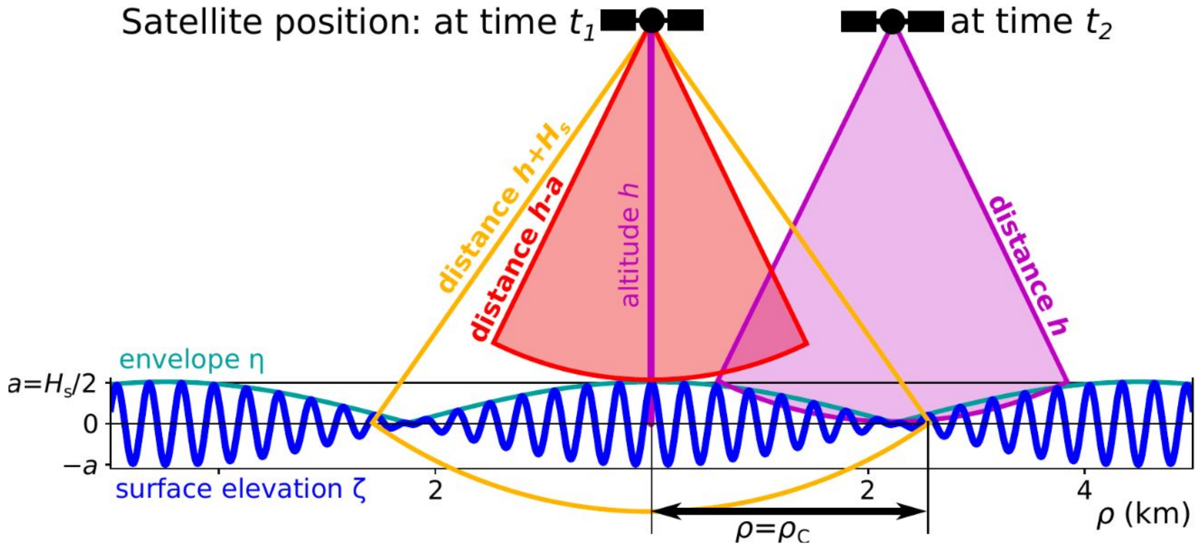
what is measured by the altimeter?

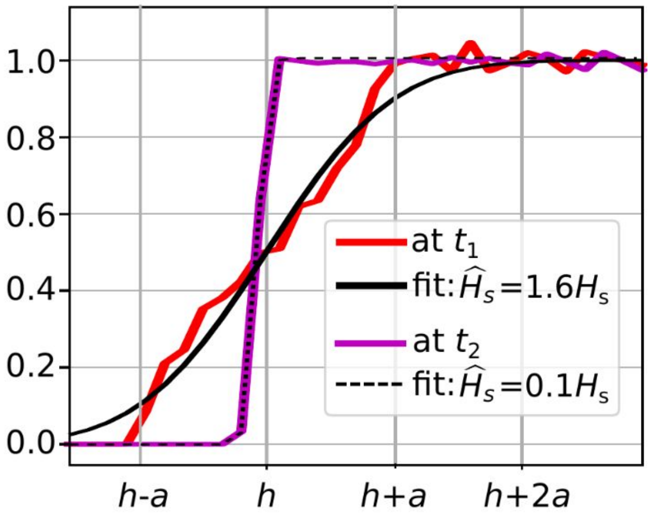
Here the max amplitude is $H_s/2$, with $H_s = 4\sqrt{<\zeta^2>}$

ζ = **η(x)** × cos (k x) , envelope is **η**(x),

local wave height **H_l** = 4 **η** √(2/π), so that <**H_l**> = H_s

2. Wave groups, Q_{kk} and doughnut footprints



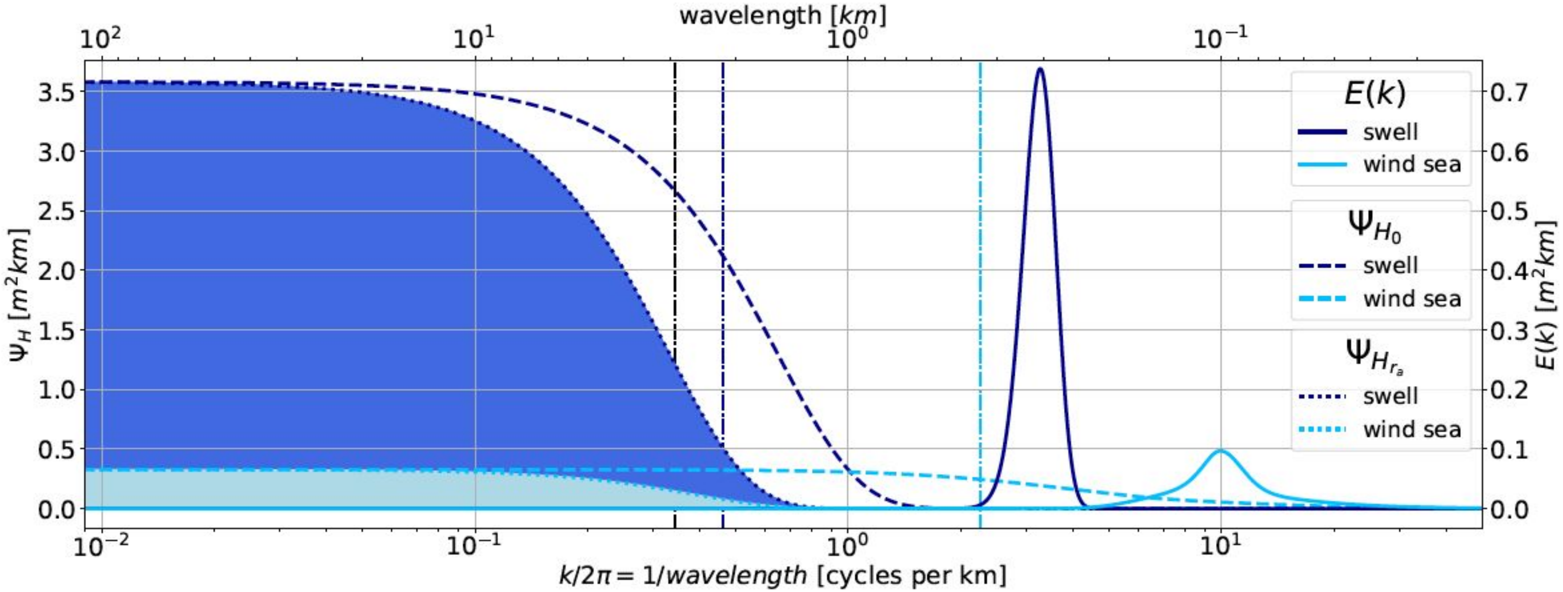


Here, **Lg=4.5 km : long wave groups**
longer than the "oceanographic footprint" scale of Chelton et al. (JTECH 1989)
$\rho_C=\sqrt{(2\ h\ H_s)}$=2.4 km → Hs=2 m for Jason or Hs=5 m for CFOSAT

With **Lg >> ρ_C**: retracking gives **SWH from 0.1 to 1.6 H_s , i.e. SWH ≅ H_l** … not H_s !!!
What about **Lg < ρ_C**?

2. Wave groups, Q_{kk} and doughnut footprints

For random waves in 1D, the PSD of the envelope near k=0 is proportional to $H_s^2\ Q_k^2$
Here are 2 sea states with same Hs: a wind sea and a swell (De Carlo et al., JGR 2023)

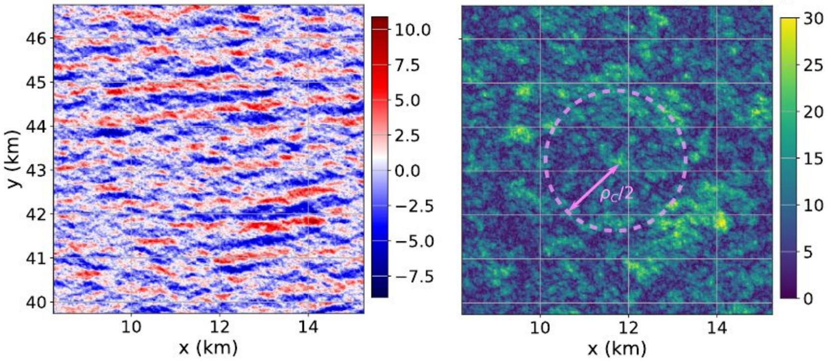


For random waves in 2D, the PSD of the envelope near k=0 is proportional to $H_s^2\ Q_{kk}^2$ with
(can be computed from CFOSAT L2/L2S data)

$$Q_{\mathrm{kk}}^2 = \frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E^2(k_x,k_y)\mathrm{d}k_x\mathrm{d}k_y}{\left(\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E(k_x,k_y)\mathrm{d}k_x\mathrm{d}k_y\right)^2}$$

2. MLE3/MLE4 retrackers : « doughnut » footprint for Hs

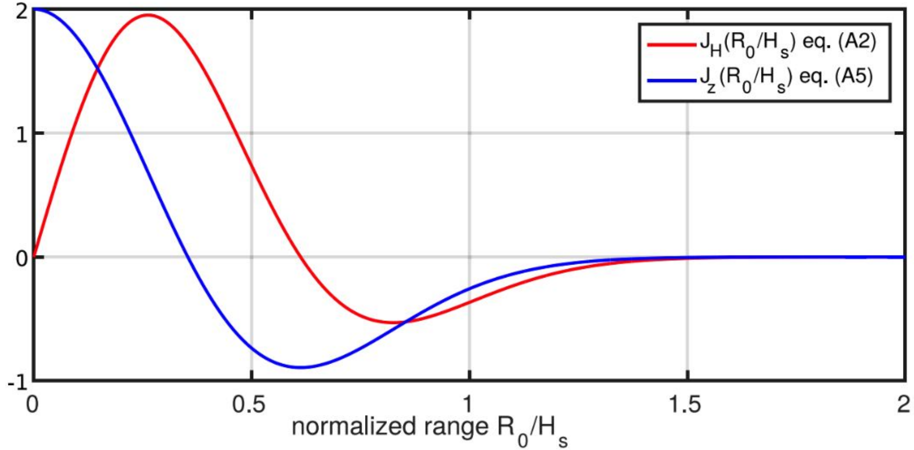
Brown waveforms perturbed by analytical groups can be retracked … analytically
For Least Squares cost functions: random groups impact on Hs & SSH = sum of perturbations



For MLE3, here is the analytical solution:
(De Carlo et al. JGR 2023)

$$\hat{H}_s = H_s + \frac{aH_s}{2} J_H(b), \qquad J_H(b) = 2b\left(6 - 16b^2\right) e^{-4b^2},$$

$$b = \rho_0^2/\rho_C^2 = \rho_0^2/(2hH_s)$$



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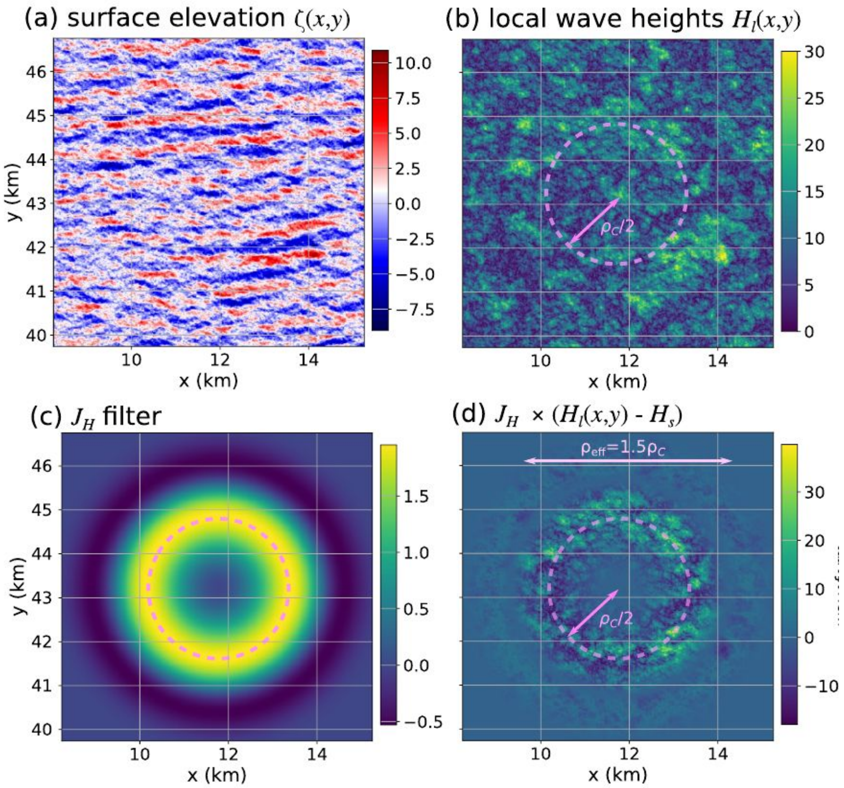

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$$b = \rho_0^2/\rho_C^2 = \rho_0^2/(2hH_s)$$

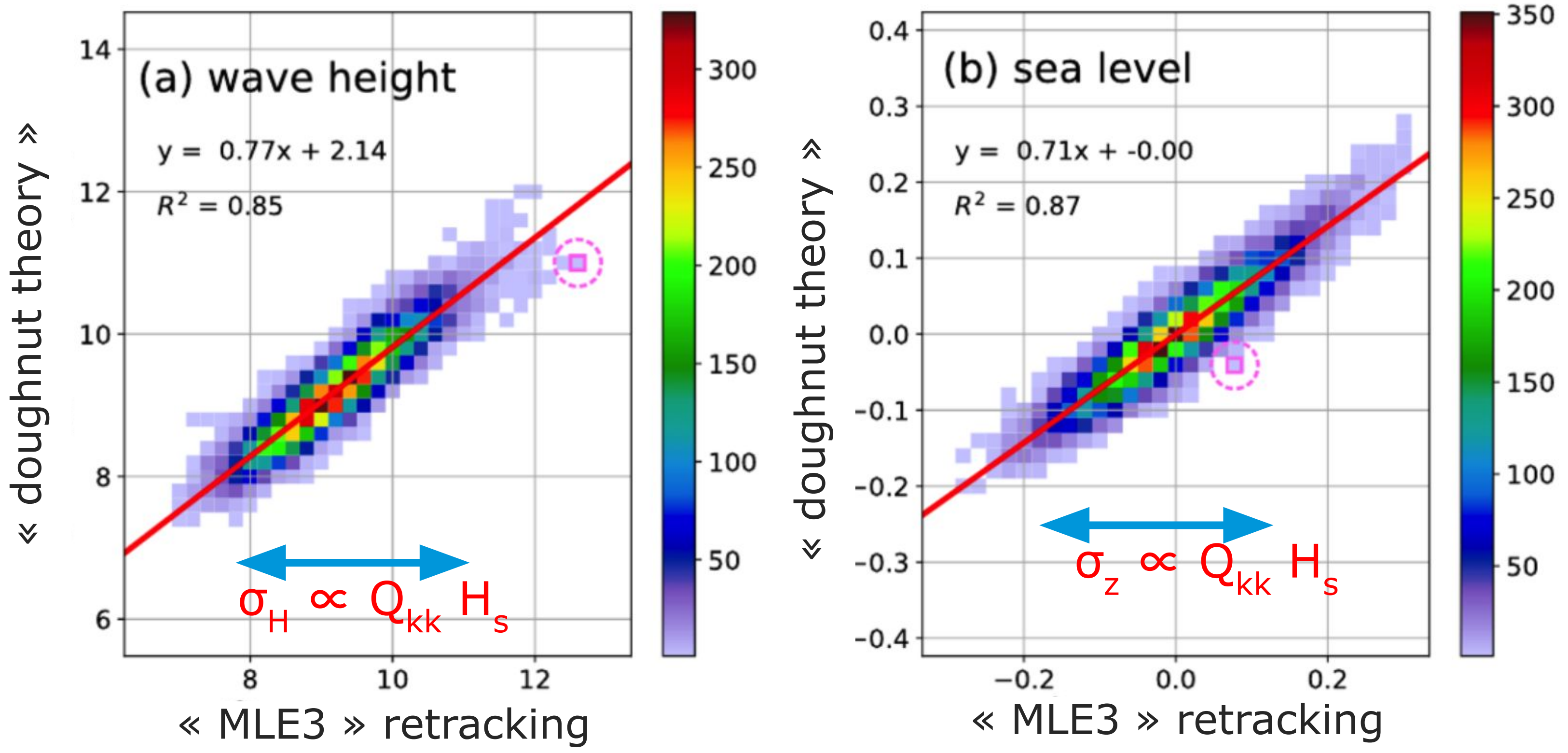
in 2D : doughnut shape

MLE3 retracker gives values that are equivalent to a doughnut-shape filter of the local wave height map

Passaro et al. (in prep):
extention to WHALES retracker

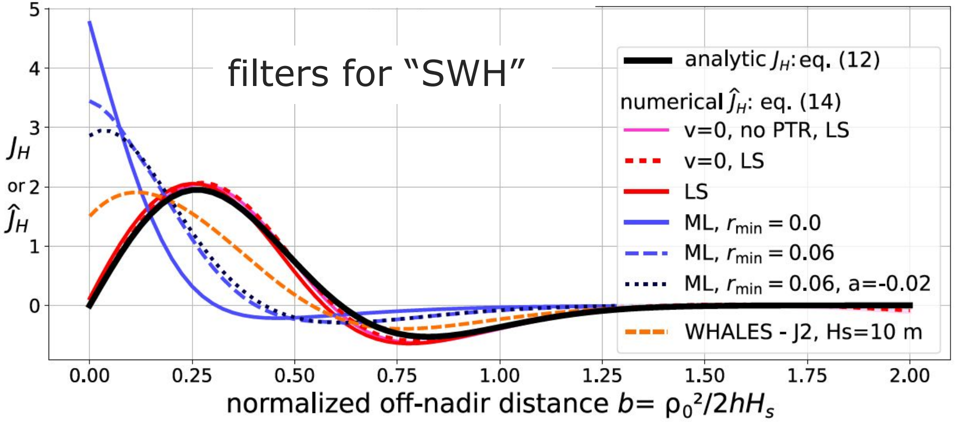
2. « MLE3/MLE4 » retrackers : « doughnut » footprint for Hs

« doughnut theory » works: simulations without speckle (De Carlo & Ardhuin JGR 2024)



3. Different retrackers: different wave group effects

Cost function can be optimised for
- reducing speckle noise (Maximum Likelihood)
- reducing speckle noise AND wave groups
- maximizing correlation between SWH and SSH



WHALES is the retracker selected by ESA Seastate CCI project.

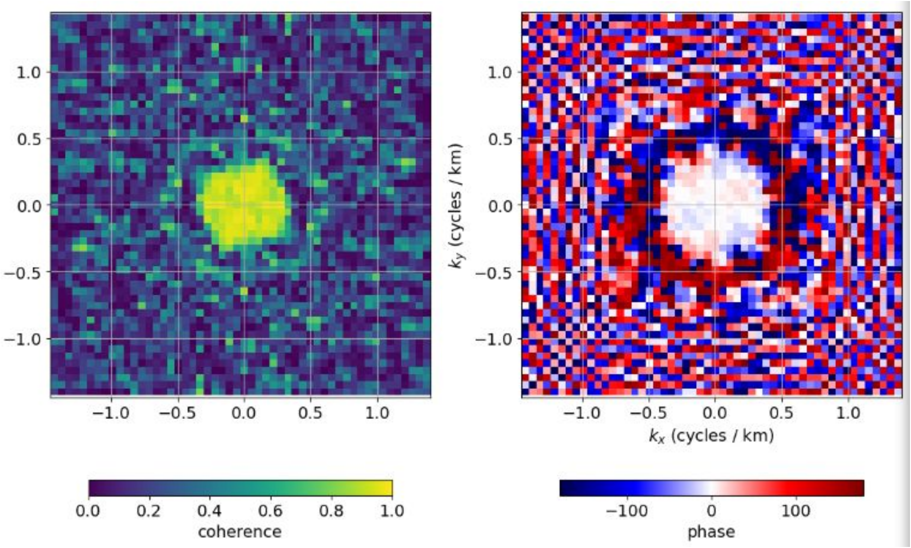
(Schlembach et al., Remote sensing, 2020)

It
- is open source (https://github.com/ardhuin/wavesALTI)
- uses weighted least-square
- only fits the leading edge

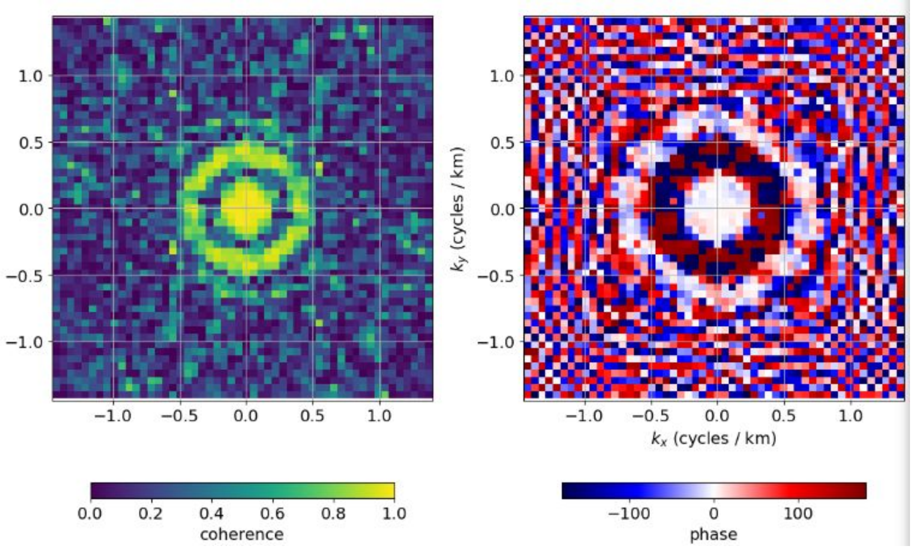
weights = 1 / waveform:
- lower speckle noise than MLE3
- limited wave group noise
- smaller footprint that MLE3

3. Different retrackers: different wave group effects

WHALES has a smaller footprint that « MLE3 »

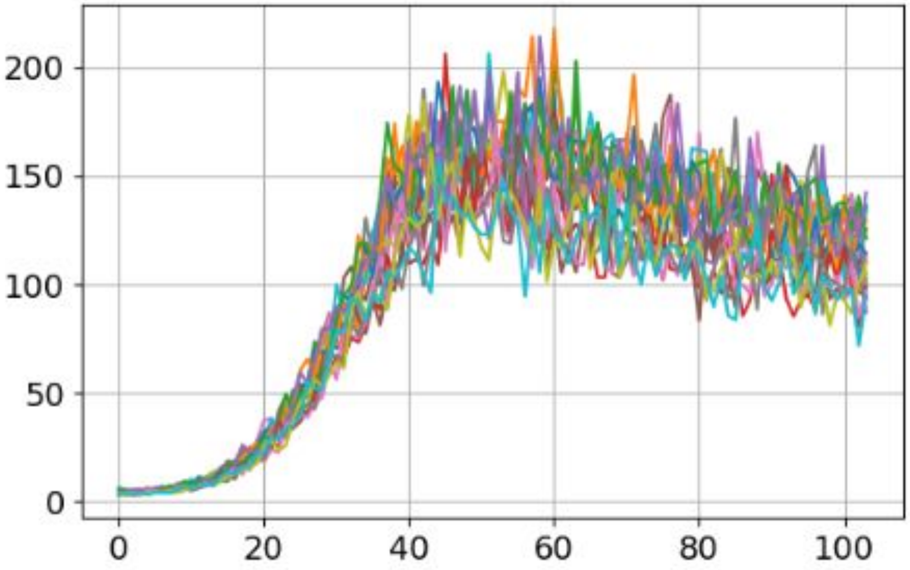


WHALES

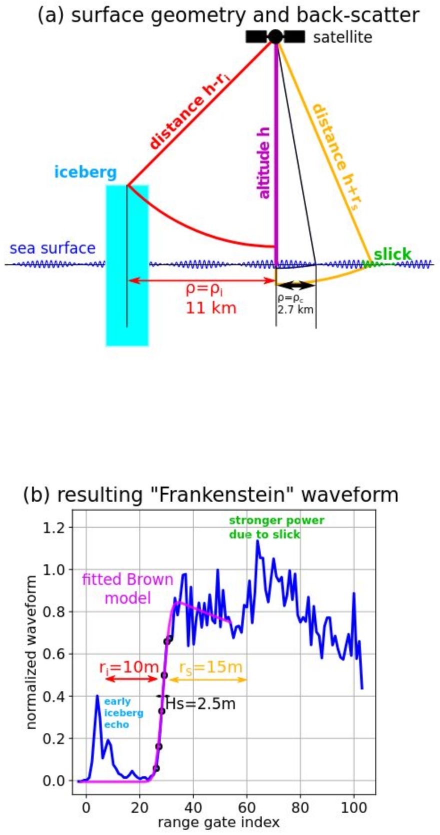


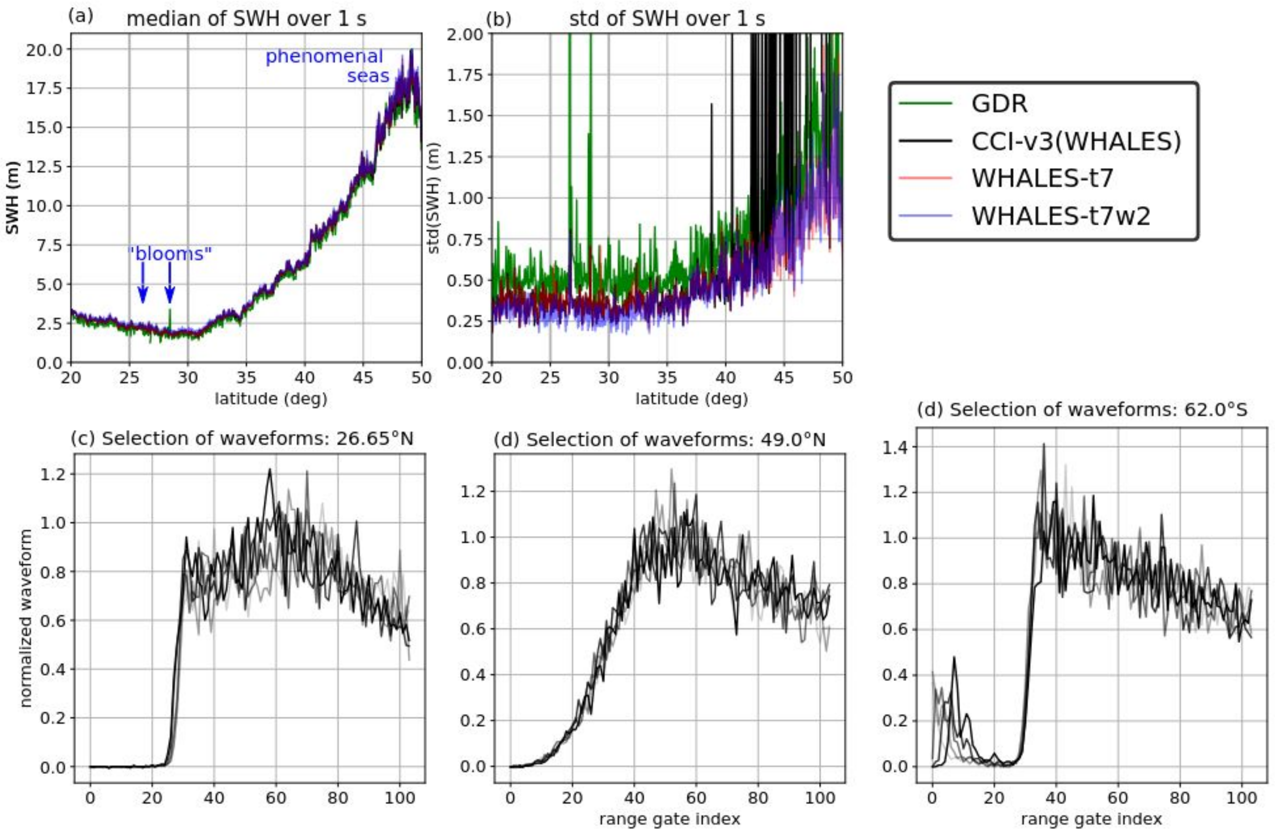
« MLE3 »=LS3

4. Waves for storm Danièle (this is Jason-3)



4. Issues on other tracks …





5. conclusion & recommandations

- After 30+ years of routine measurements, we are still making progress…
- 20 Hz or 1 Hz “SWH” contains wave groups. **SWH is not Hs**: one example « all time 1 Hz record » was SWH = 20.1 m (Hanafin et al. BAMS 2012) this corresponds to Hs = 18.2 ±0.2 m (Ardhuin & De Carlo, SEANOE 2025

By the way new records include storm Eddie (Hs=19.7±0.3 m with SWOT Poseidon 3C) and storm Danièle (Hs = 18.5 ±0.3 m)... These will be adjusted with intercalibration

We can start to use the « swh_1Hz_std » as a geophysical variable …
- But that works best with sub-waveform retracking (WHALES and updates)

More tomorrow on how we can use wave data to learn about wave physics and correct model parameterizations and forcing fields.

ADC Storm catalog and tracks: https://doi.org/10.17882/105378
Storm catalog (with list of altimeter tracks) : https://doi.org/10.17882/105378