Sizing the largest ocean waves using the SWOT mission

Fabrice Ardhuin[1], **Taina Postec**[1], Mickael Accensi[1], Jean-François Piolle[1], Guillaume Dodet[1], Marcello Passaro[2], Marine De Carlo[3], Romain Husson[3], Gilles Guitton[4] , Fabrice Collard[4]
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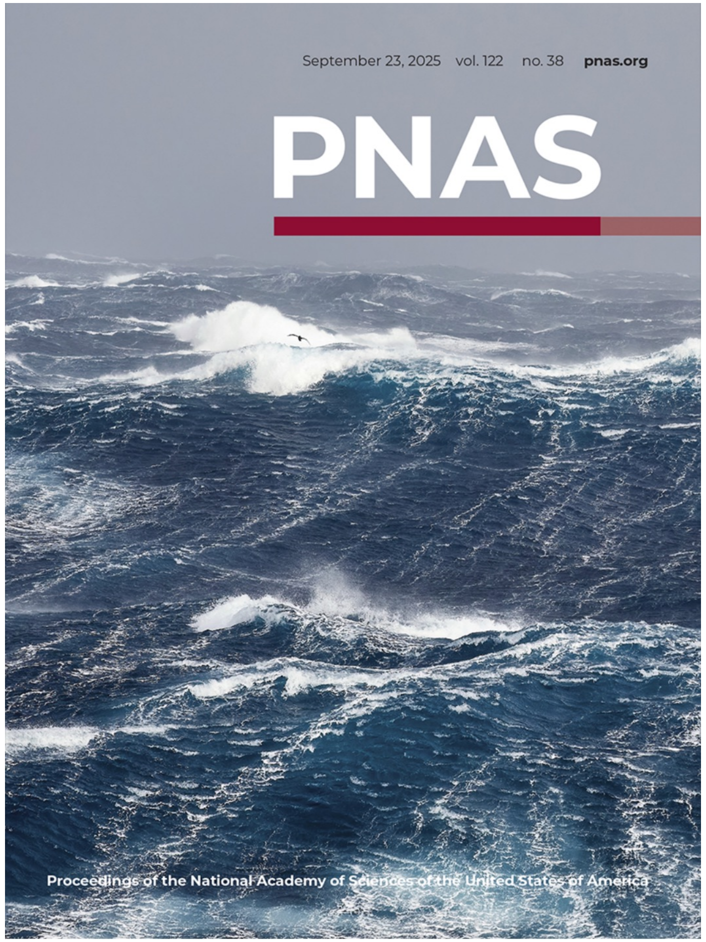
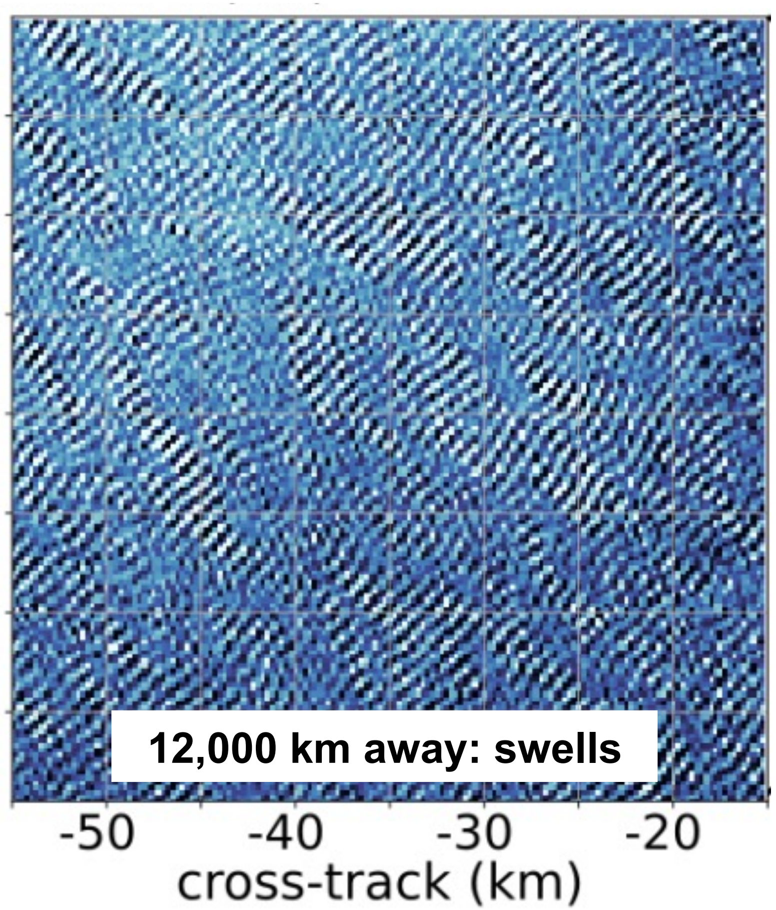


photographer: Benoit Stichelbaut



SWOT cycle 005 track 328, 38.1° S

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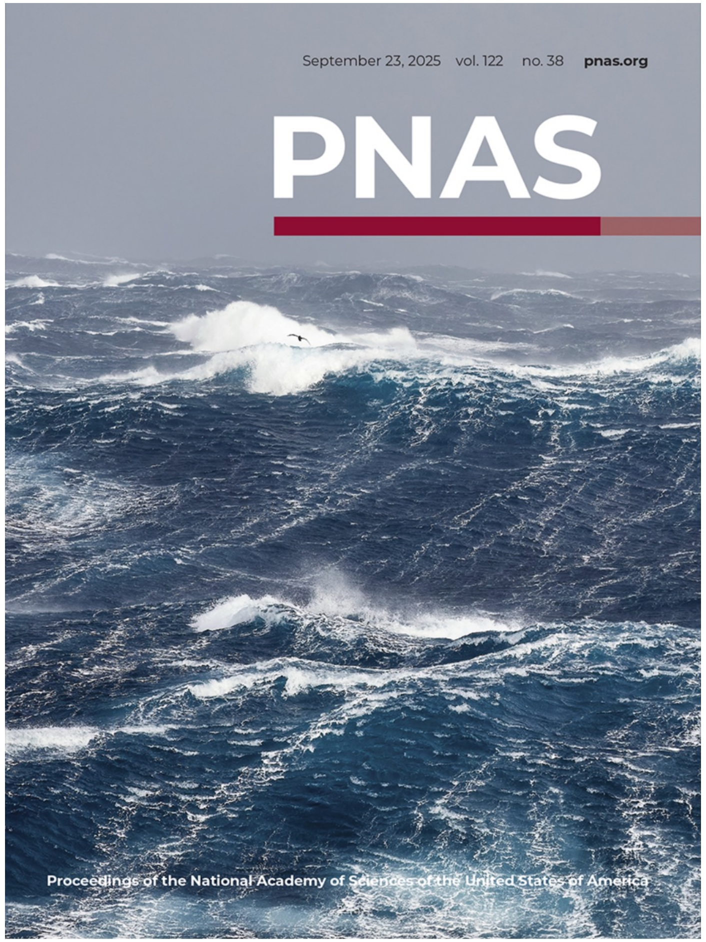

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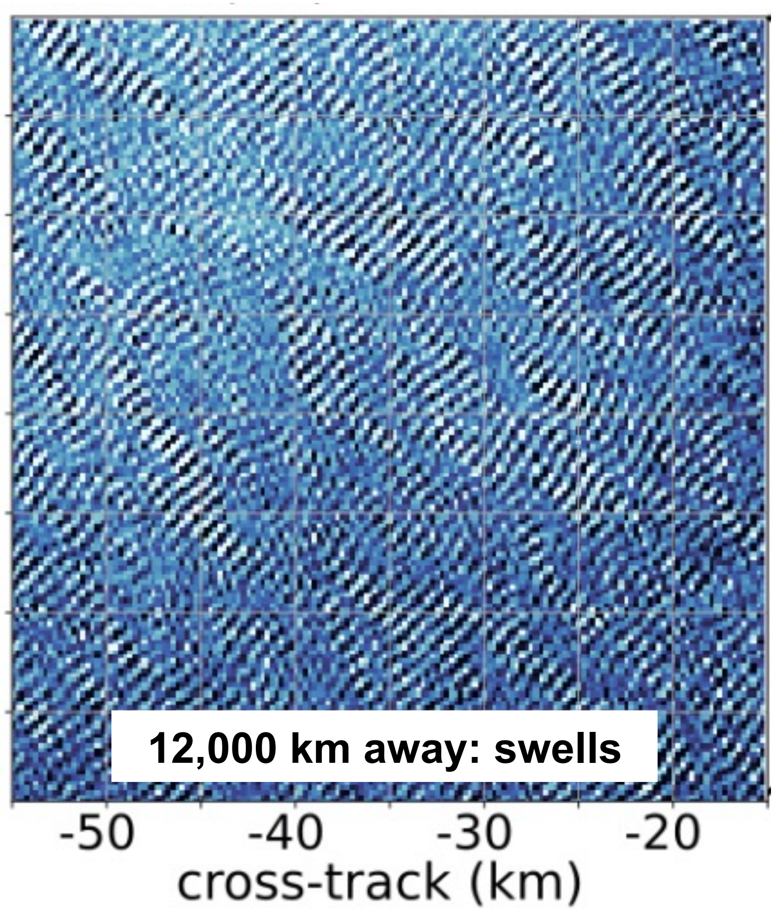


SWOT cycle 005 track 328, 38.1° S

Main results:
Altimeters OK for SWH > 20 m
Near nadir SWH saturates at 10-12 m

- Swell energies are related to wave spectrum E(f) in storm

- $E(f) \propto f^{17}$ for f < fp : inverse cascade 4-wave interaction (Hasselmann 1962)

- JONSWAP spectrum bad for f < fp
(Hasselmann et al. 1973)
IS IT TRUE FOR ALL STORMS?

Eddie storm (20 December 2025):
- **SWOT measured Hs =19.7± 0.3 m**
- **swell gives Tp = 20.2 s**
- **"SWH noise" and peaky spectrum**

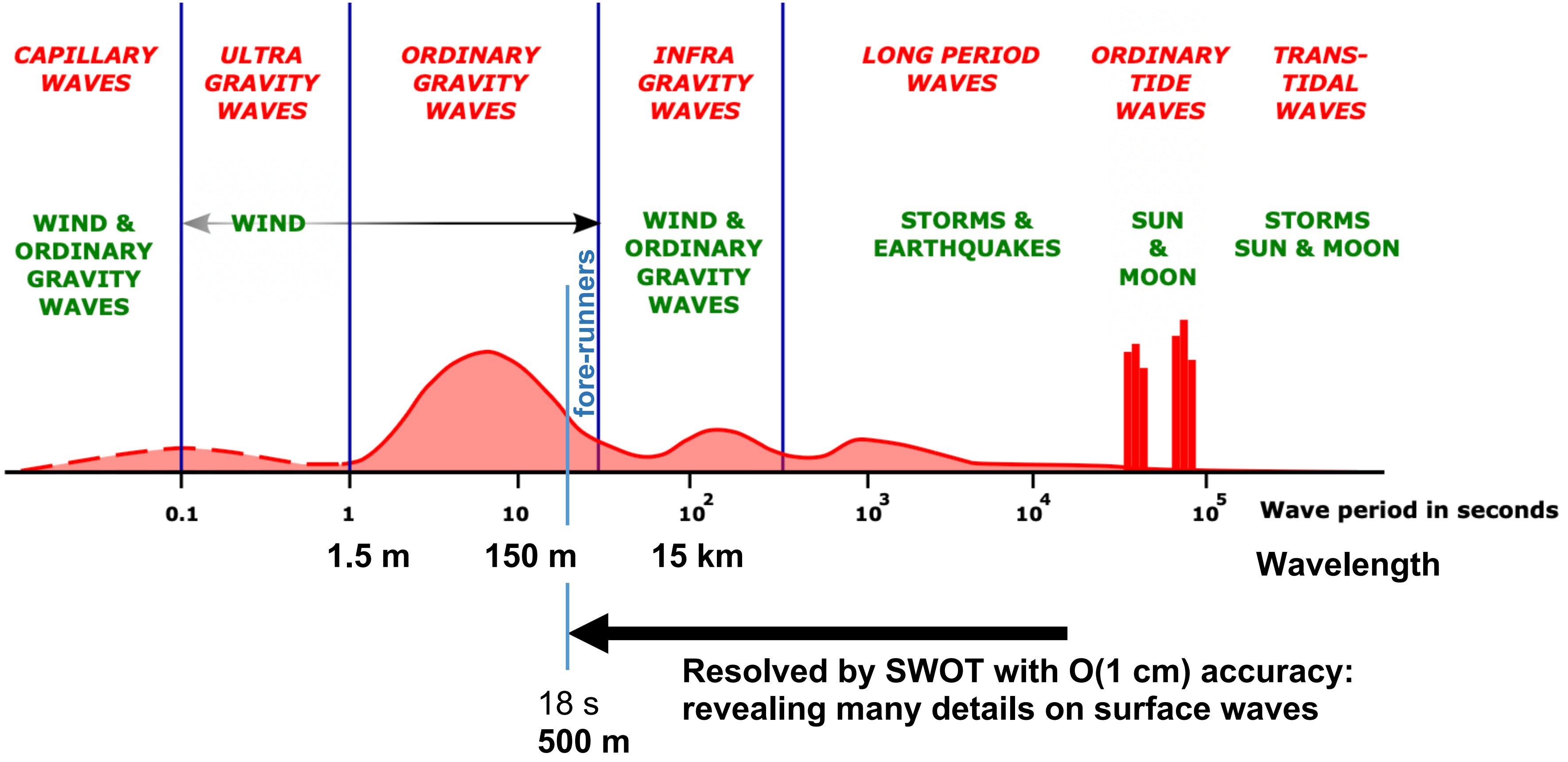
...

Big waves are beautiful
And we have very little data about them …

Hokusai (1831)
The Great Wave off Kanagawa
(神奈川沖浪裏,)

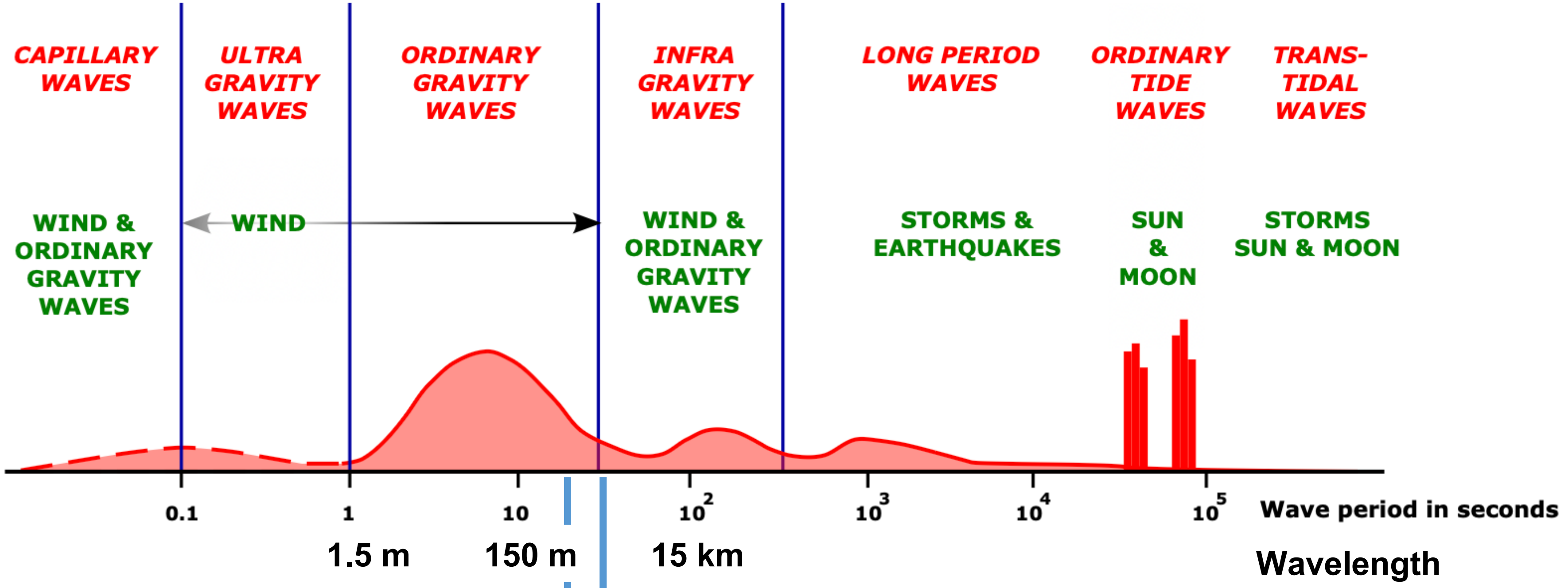
© Benoit Stichelbaut, from R/V Marion Dufresne, between Crozet & Kerguelen, 09 avril 2018. 08h17

Big waves are also very long: resolved in SWOT LR data



Adapted from Munk (ICCE 1950)

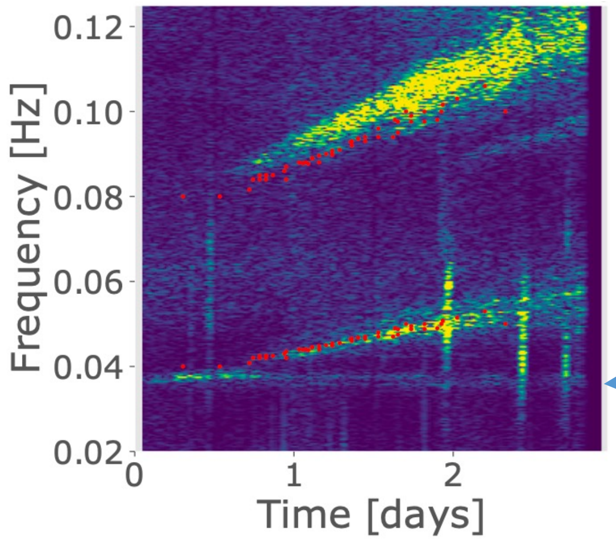
Big waves are also very long: resolved in SWOT LR data



Adapted from Munk (ICCE 1950)

Resolved by SWOT with O(1 cm) accuracy: revealing many details on surface waves

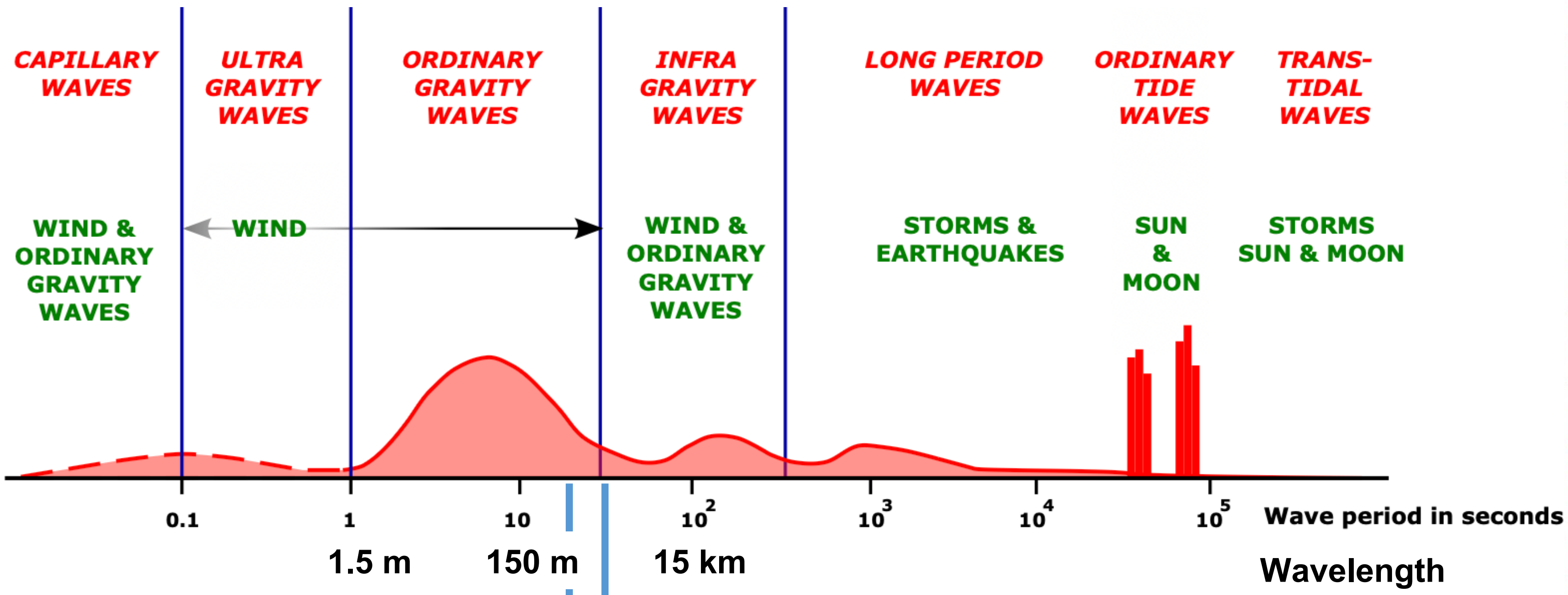
18 s
500 m



26 s
1 km

Bruland & Hadziioannou (2023): G-TAM seismometer

Big waves are also very long: resolved by SWOT LR



Resolved by SWOT with O(1 cm) accuracy: revealing many details on surface waves

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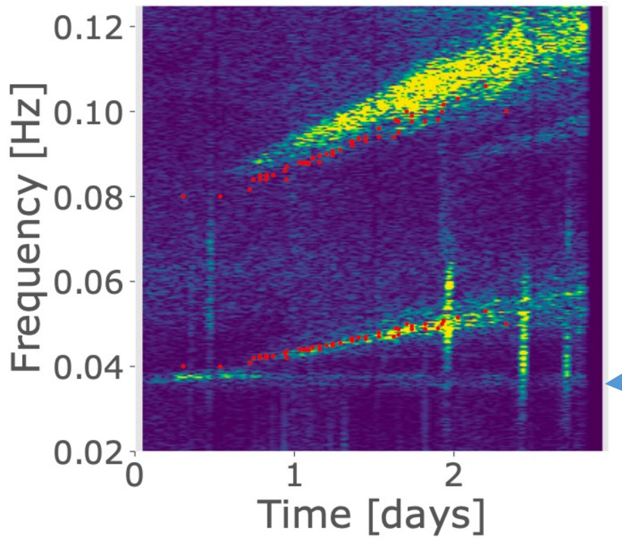
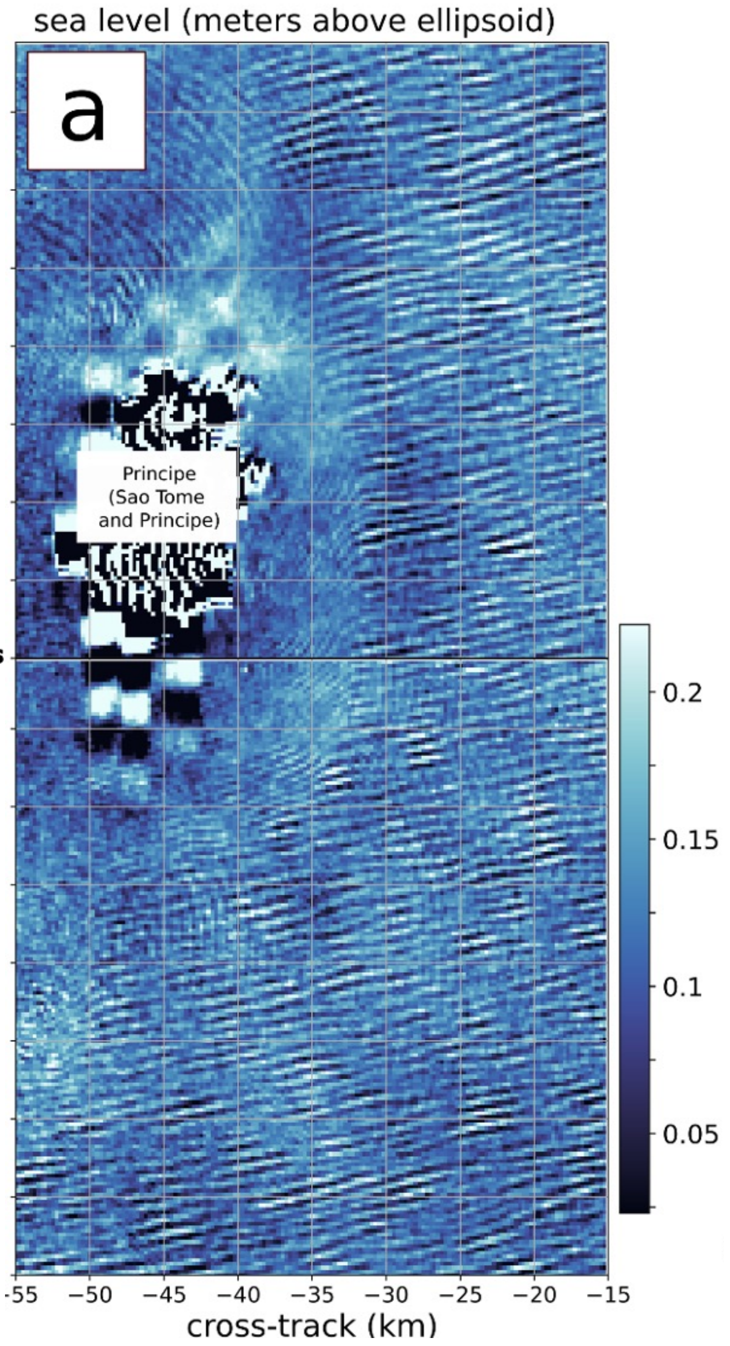


Bruland & Hadziioannou (2023): G-TAM seismometer



Poli et al. (2025): In review (revised)

1. high waves (Hs > 14 m): how often do they occur?

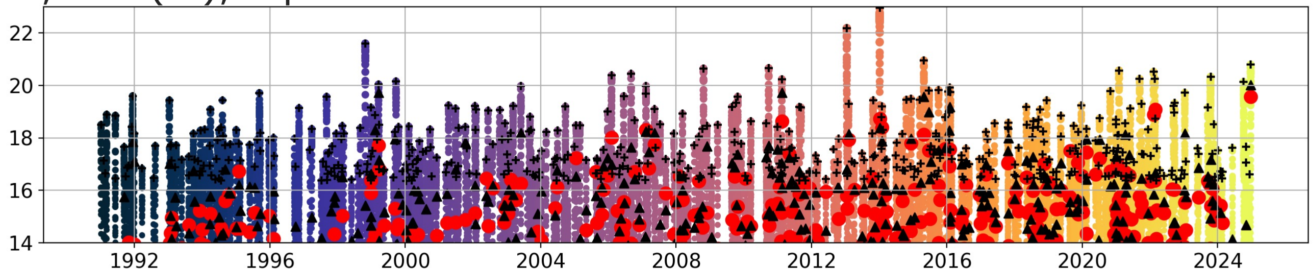
storm catalog from model (Accensi 2025, based on Alday & Ardhuin 2023)

+ altimeter wave heights from ESA Sea State CCI v4 (+ CFOSAT & SWOT for 2024)

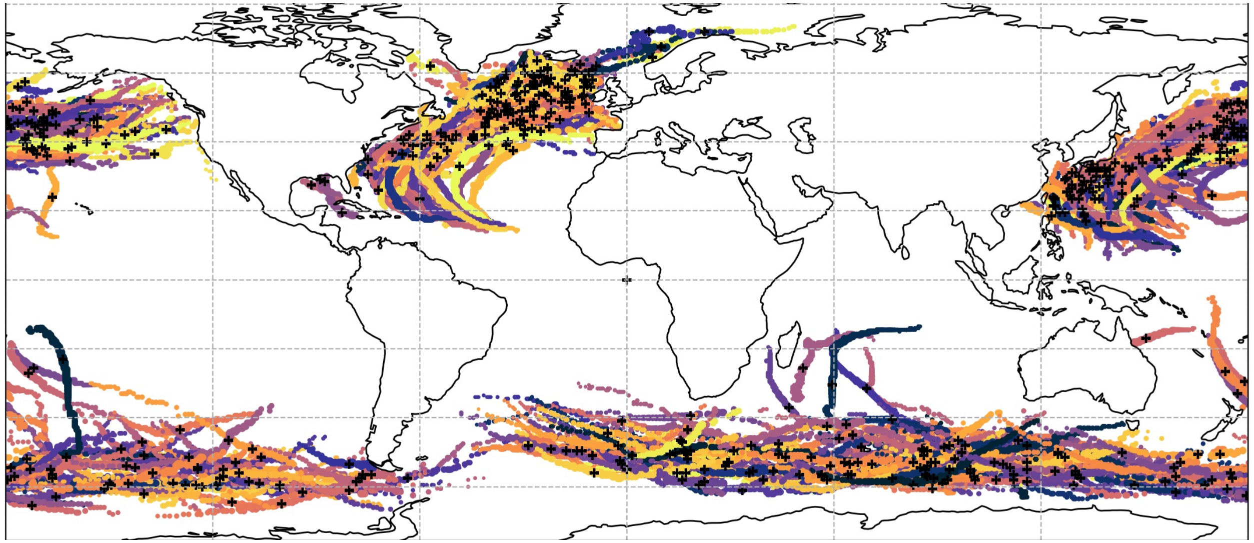
http://tiny.cc/bigwaves

rank	name	date	MMWH (m)	MAWH (m)	MSLA (m)
1	Hercules	20140105	23.0	18.7±0.2	18.4
2	Paul*	20130115	22.2	15.8±0.2	16.8
3	Yoshiaki*	19981026	21.6	12.6±0.2	15.4
4	Luigi*	20150427	21.0	18.1±0.3	19.6
5	Eddie*	20241221	20.8	19.7±0.3	20.2
12	Bolaven	20231016	20.3	15.4±0.2	17.2
17	Kirk	20241006	20.1		
56	Bertrand*	20230915	19.2	16.4±0.2	16.5
92	Romain*	20231122	18.5	15.0±0.2	16.1
192	Manoa*	20241102	17.7	13.4±0.2	14.7
206	Mawar	20230527	17.6	12.7±0.1	12.5
234	Rosemary	20230606	17.4	15.7±0.2	16.8
489	Moea*	20231012	16.4	13.7±0.2	14.9
569	Manaarii*	20231222	16.3	14.6±0.1	14.0

Hs,max (m), top 500 storms. 1991 to 2024



tracks, top 500 storms. 1991 to 2024



1. high waves (Hs > 14 m): how often do they occur?

altimeter max wave heights: not a good indicator of max(Hs)

storm catalog from model (Accensi 2025, based on Alday & Ardhuin 2023)

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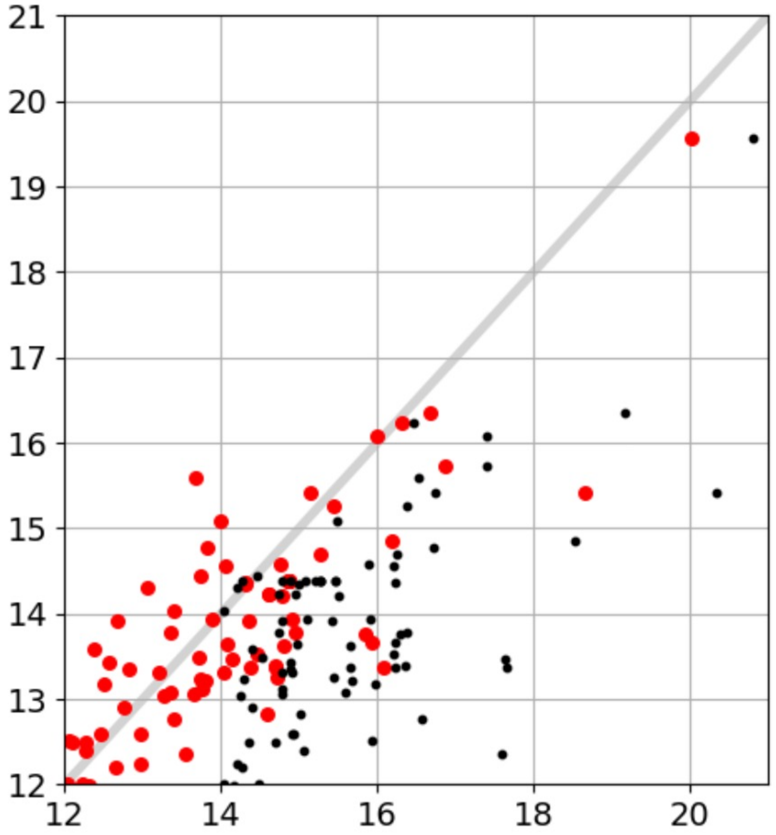
http://tiny.cc/bigwaves

Max. altimeter Hs (m)

2023-2024



Model Hs (m) @ alti max.

Max model Hs (m)

2. Periods: Tp at max(Hs): another indicator of storm intensity

For a given max(Hs), there is a wide variety of peak periods:

- tropical storms have more strongly forced waves (younger waves, higher wind speed)
- extra-tropical storms give longer periods
- this is related to the physics of wave generation

How is the local Tp related to the storm center Tp ?

rank	name	date	MMWH (m)	model T_p (s)	SWOT SPP (s)
1	Hercules	20140105	23.0	20.4	
2	Paul*	20130115	22.2	20.0	
3	Yoshiaki*	19981026	21.6	20.0	
4	Luigi*	20150427	21.0	20.0	
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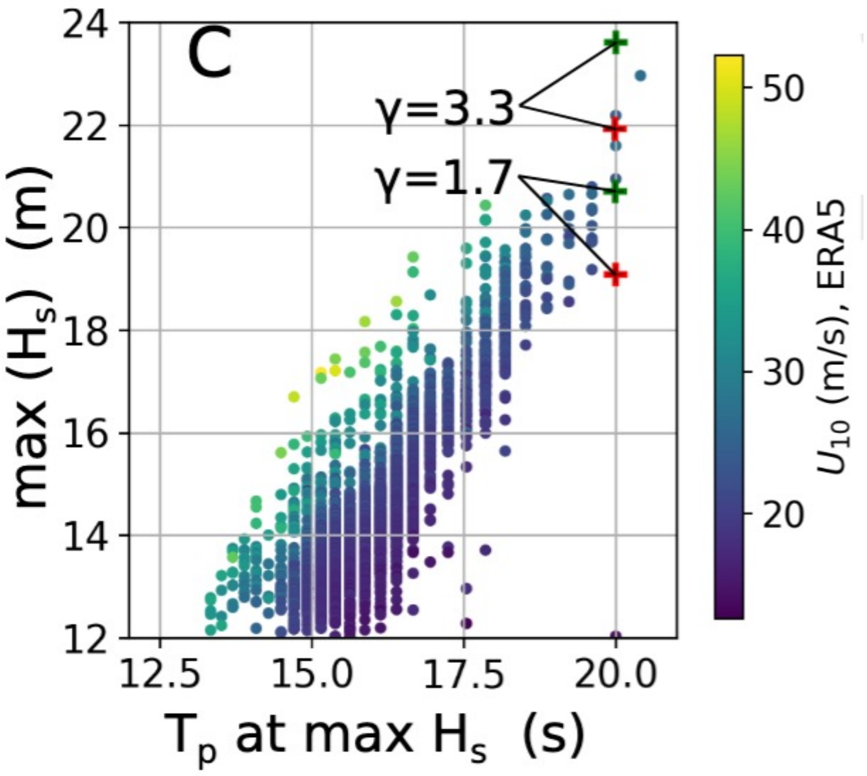
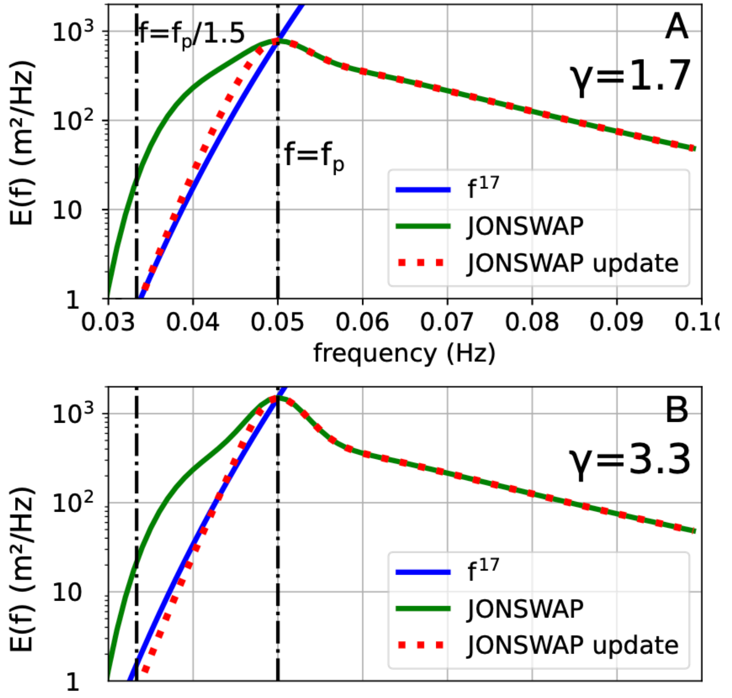
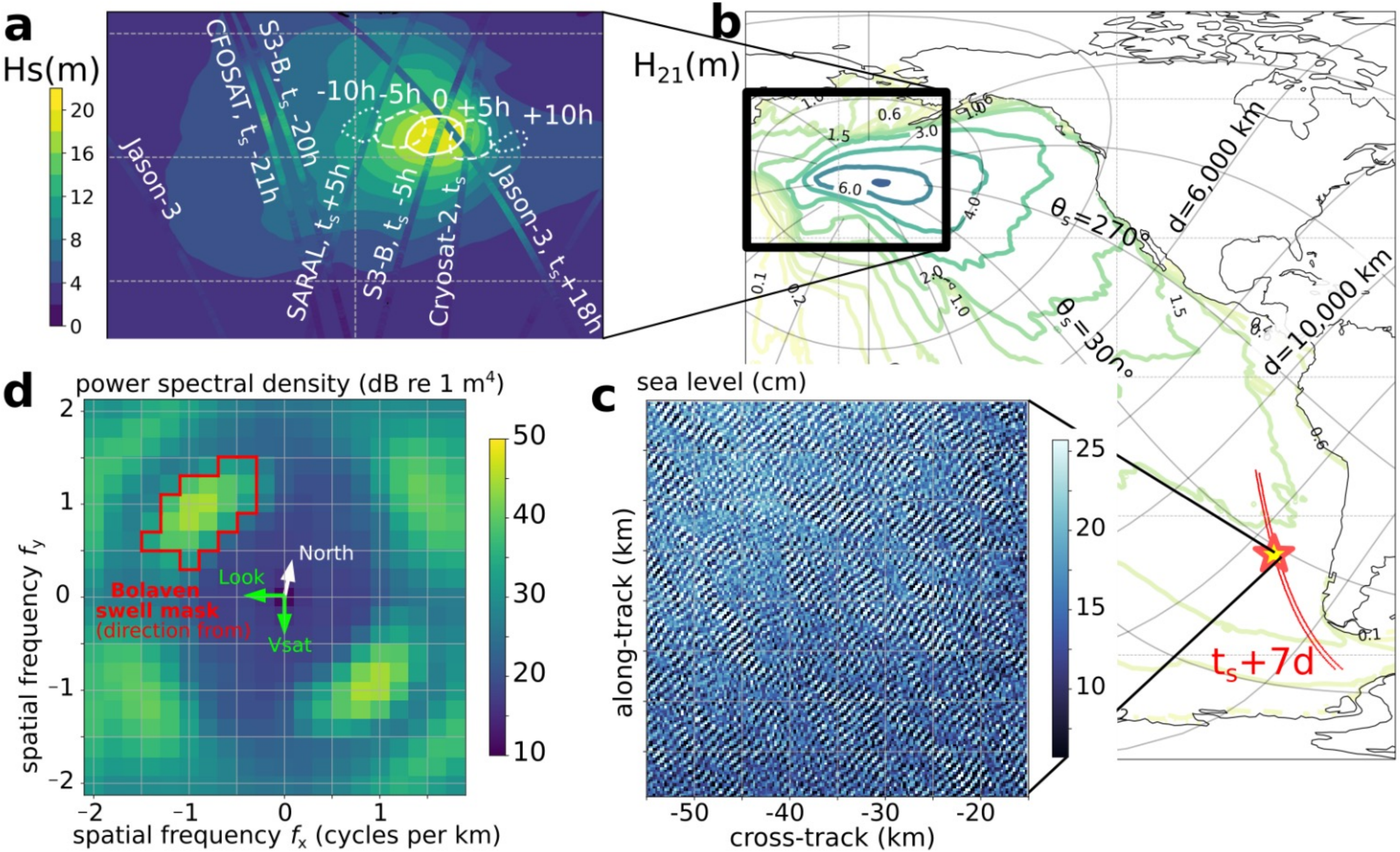
http://tiny.cc/bigwaves



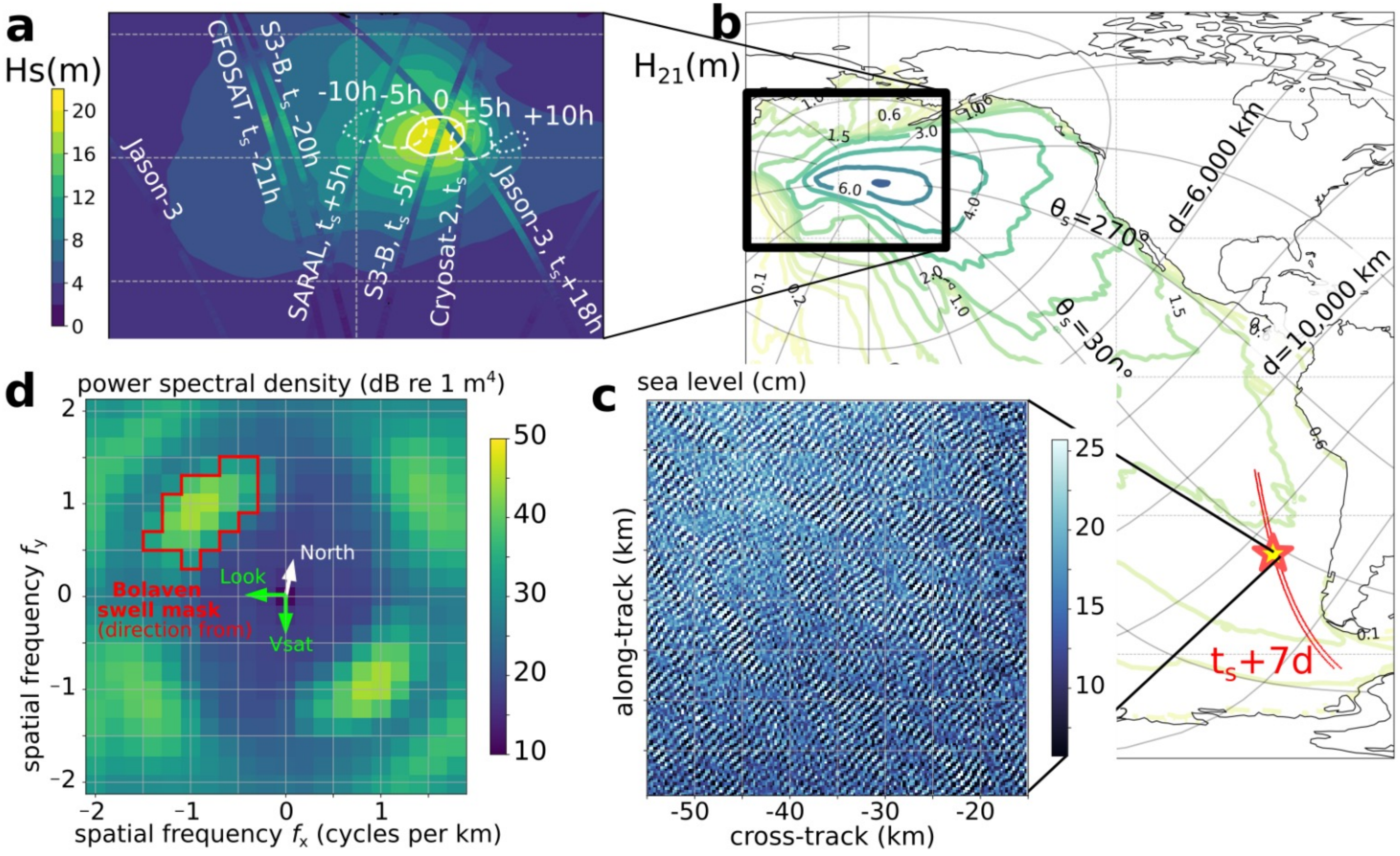


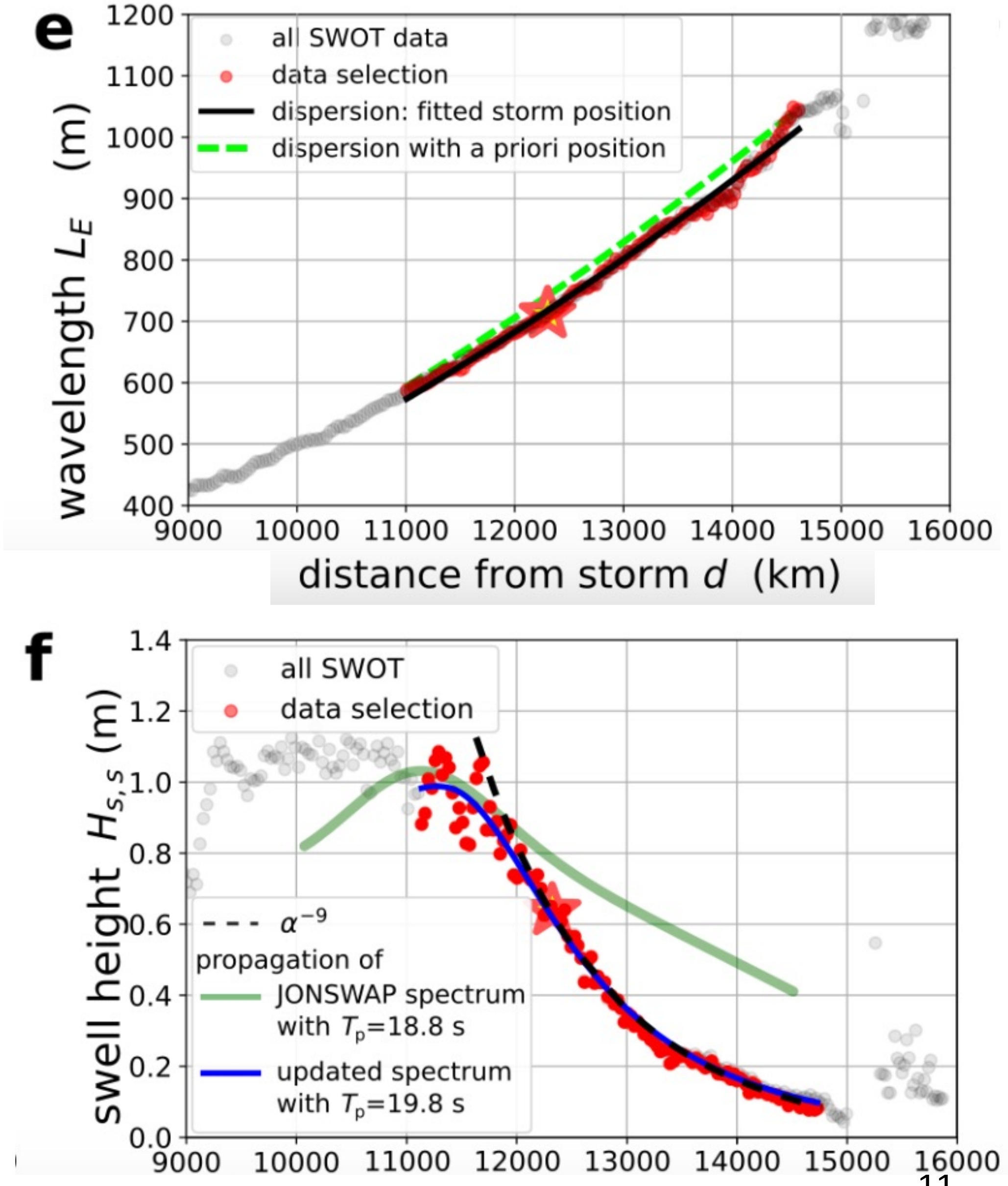
3. Swells from storm Bolaven

Swell measurements from Bolaven in 109 tracks, Covering 109 x 100 x 2 x 1600 km^2 , over 20,000 spectra. Each spectrum is a piece of the storm puzzle



3. Swells from storm Bolaven





4. 4-wave interactions and numerical wave modelling

Lavrenov’s exact Snl (GQM) gives f^{17} forward face, not the DIA used for forecasting

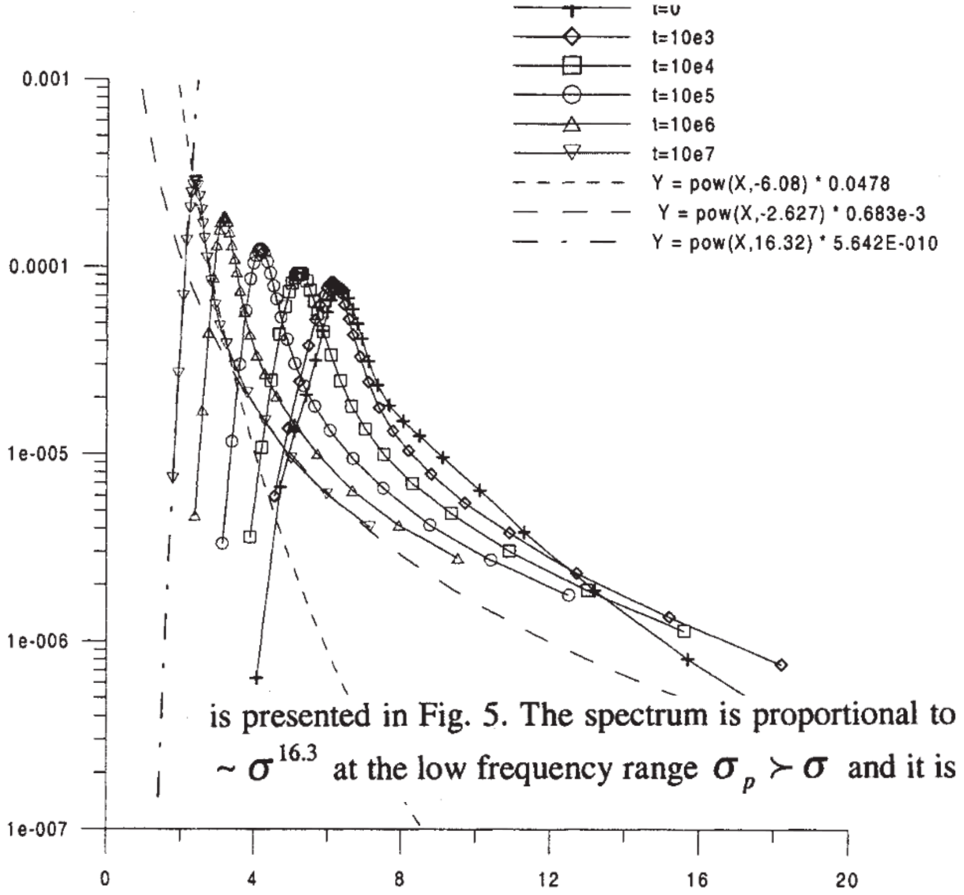


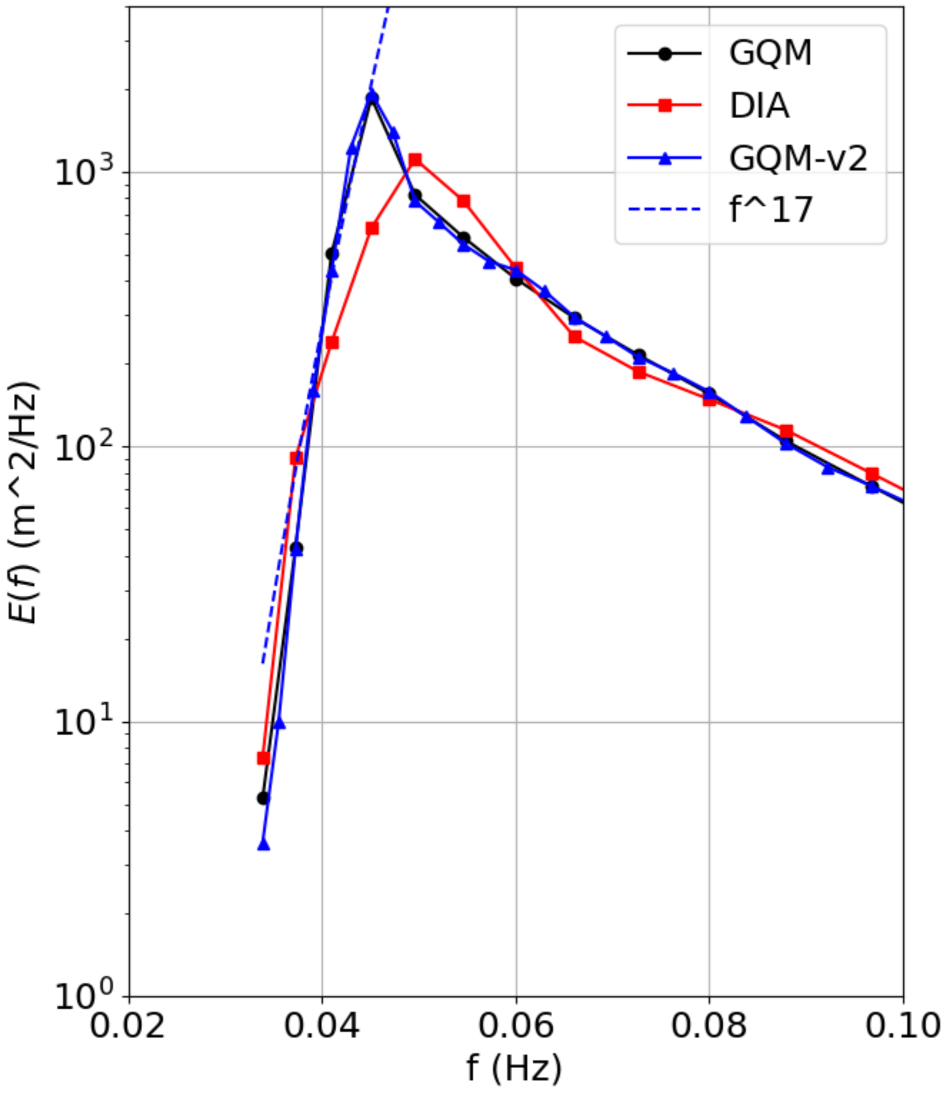
Fig.5

Frequency spectrum evolution

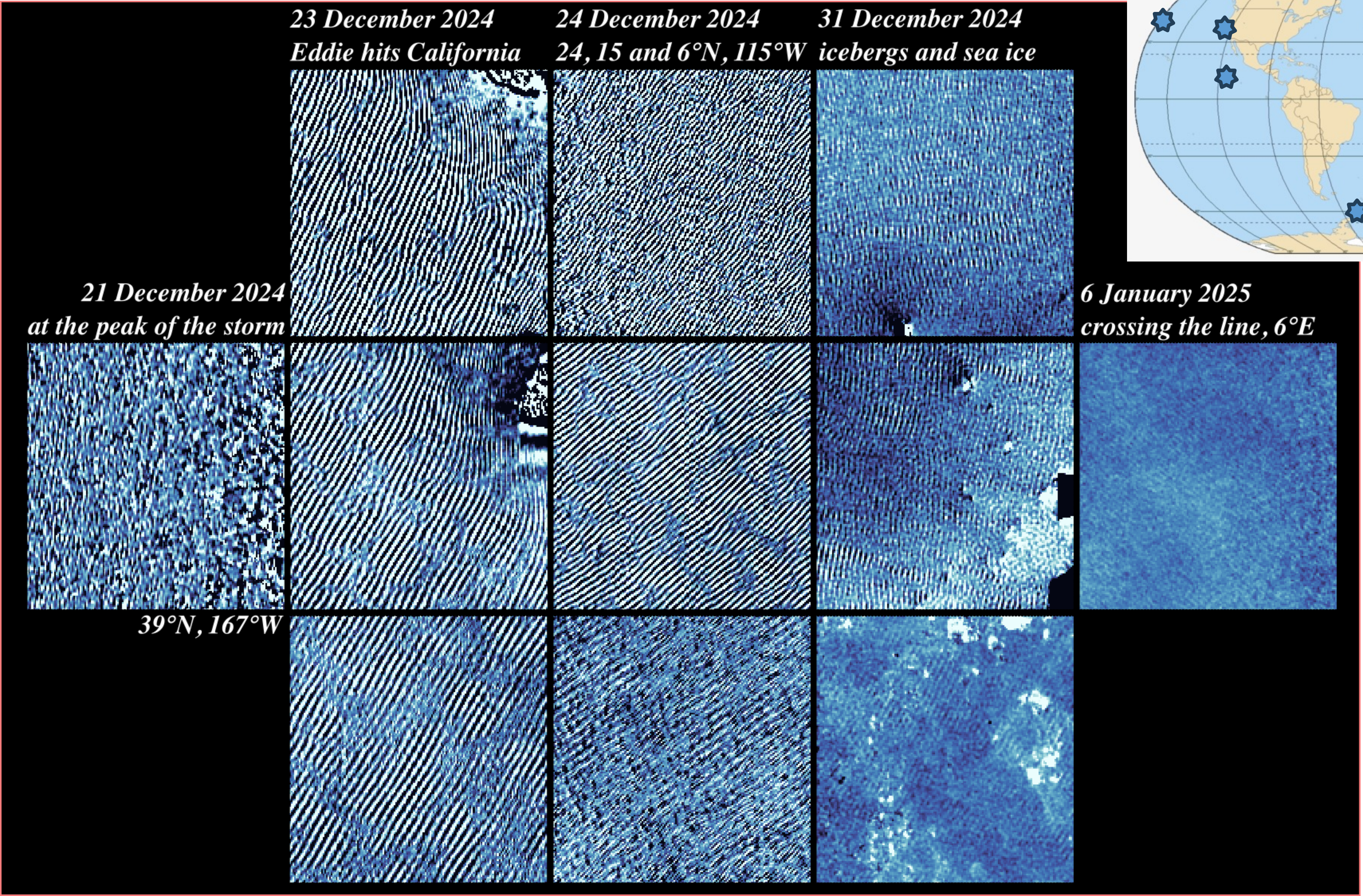
with the initial value (3.2) - (3.3) and $\gamma = 3.3, n = 2$ at different time moments:

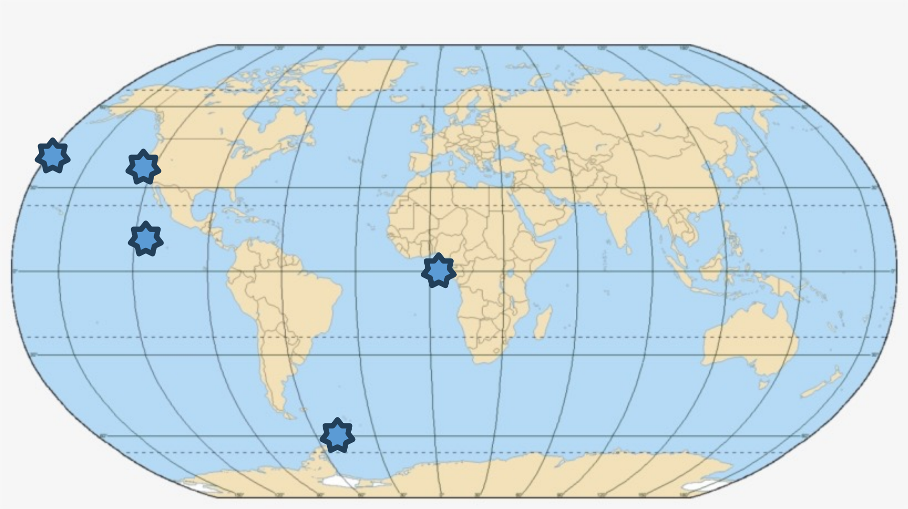
a)- . $\tilde{t} = 0$, b)- $\tilde{t} = 10^3$, c)- $\tilde{t} = 10^5$, d)- $\tilde{t} = 10^7$

Lavrenov (2000): proceedings of the 6th Workshop On Waves Hindcasting and Forecasting



5. Storm Eddie: SWOT hit the bull's eye?



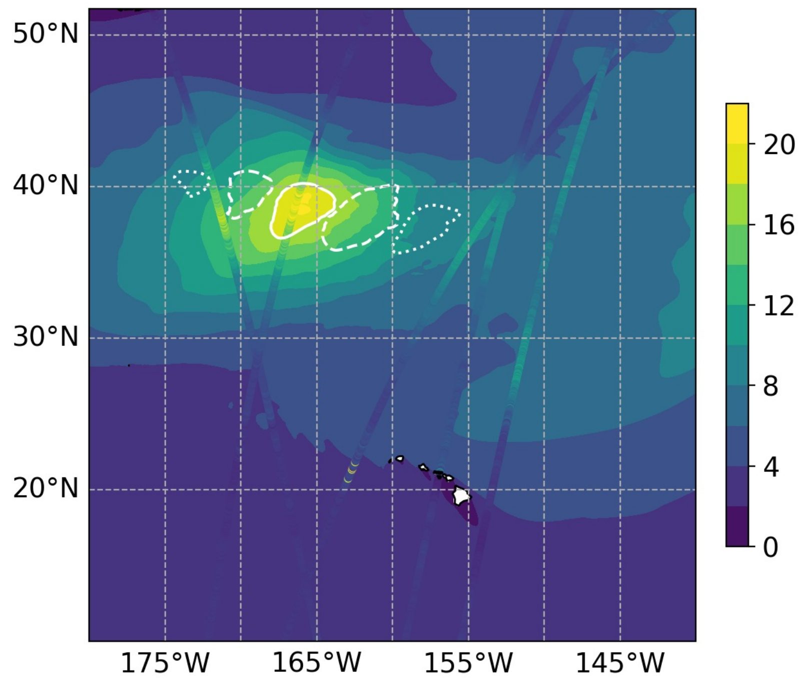


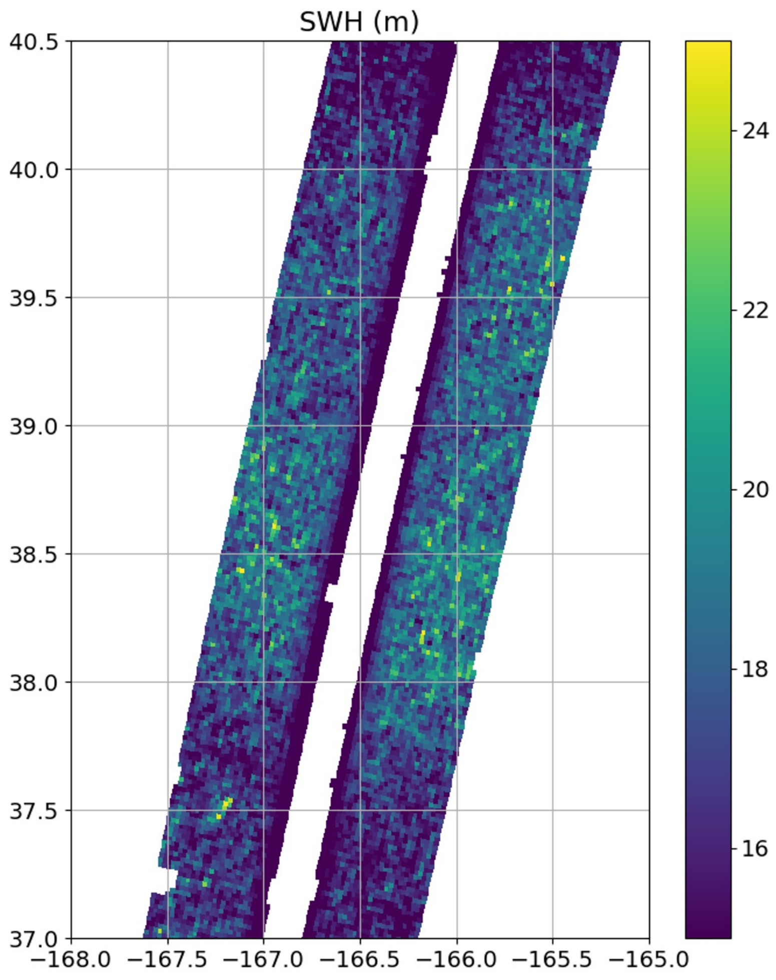
5. Storm Eddie: SWOT hit the bull's eye?

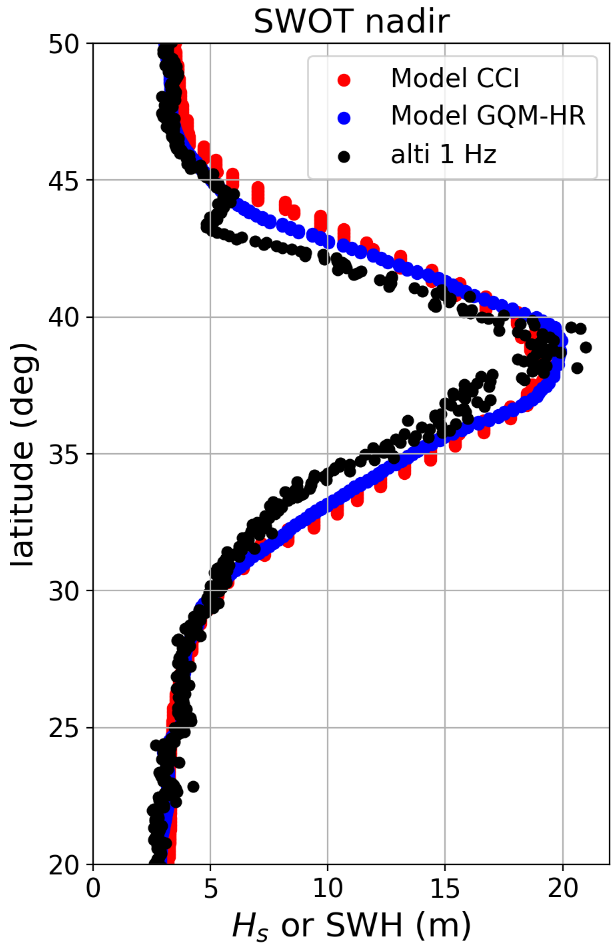
50-km smoothing of
SWOT sgdr gives 19.7 m +/- 0.3m

Storm peak may occur few hours later

Real max may be closer to 21 m ?







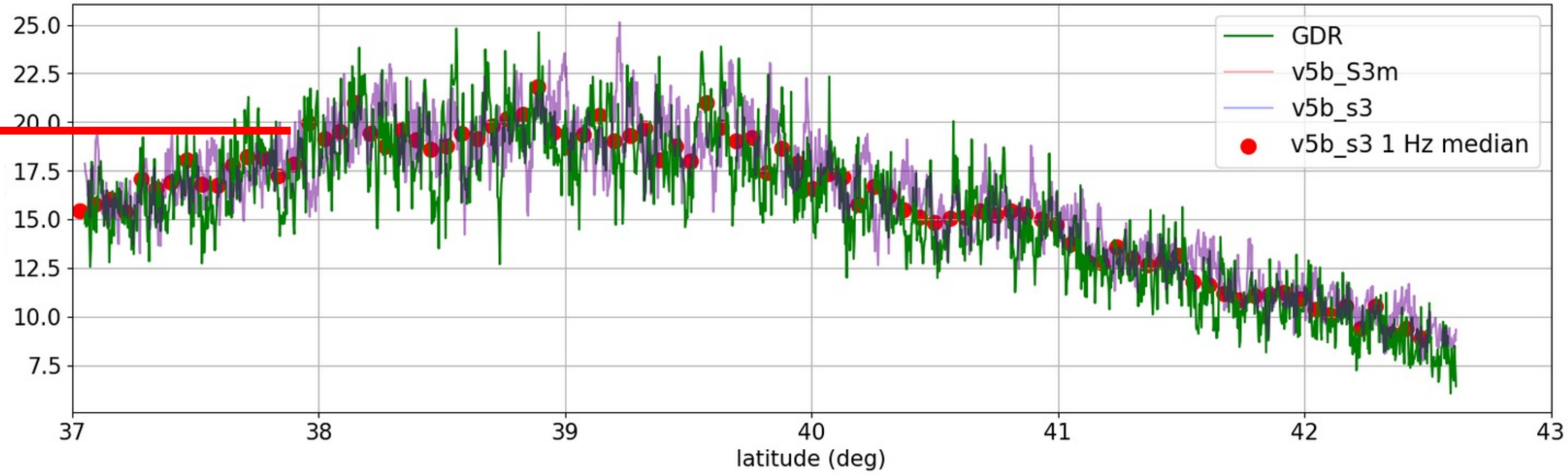
5. Storm Eddie: largest ever altimeter Hs

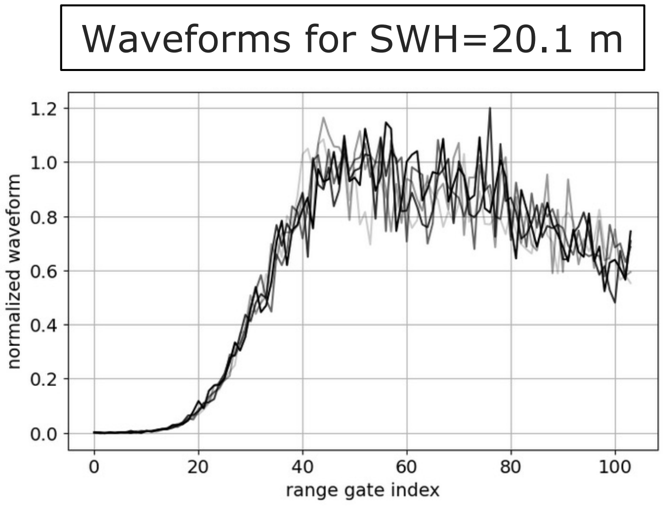
SWOT retracking (will be in SeaState CCI V5 dataset):

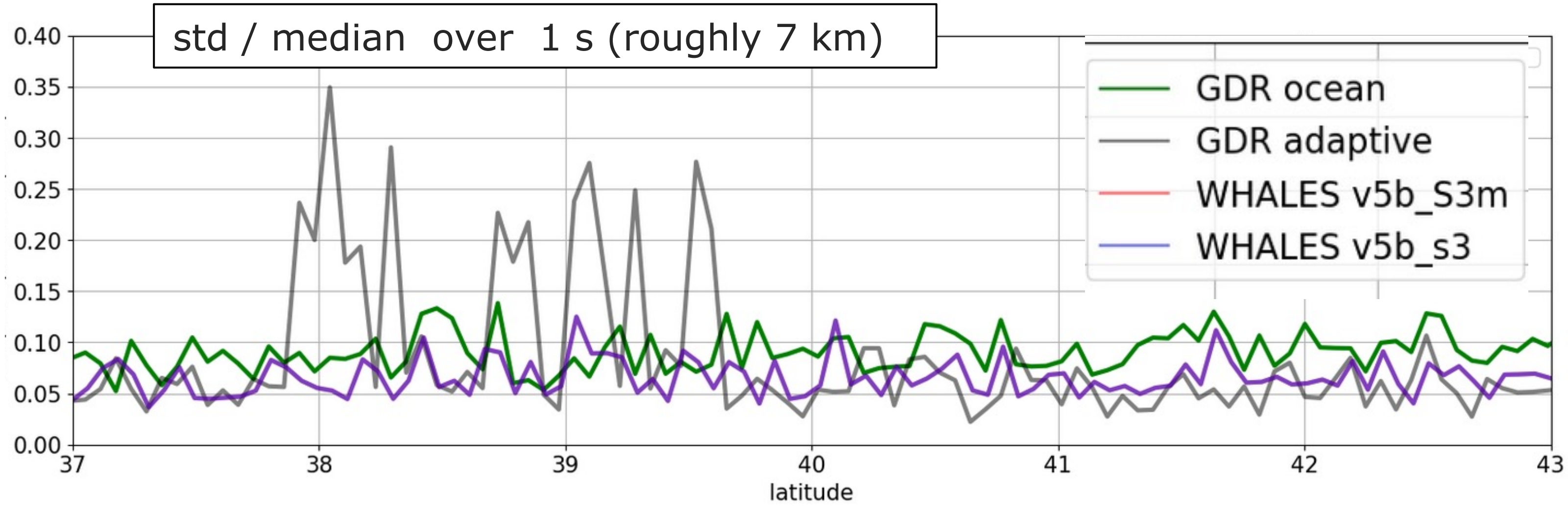
less noisy with WHALES retracker (problems with adaptive on SWOT)

Hs is taken to be a 50 km average of SWH (average over wave groups) :

max (Hs) is 19.7± 0.3 m



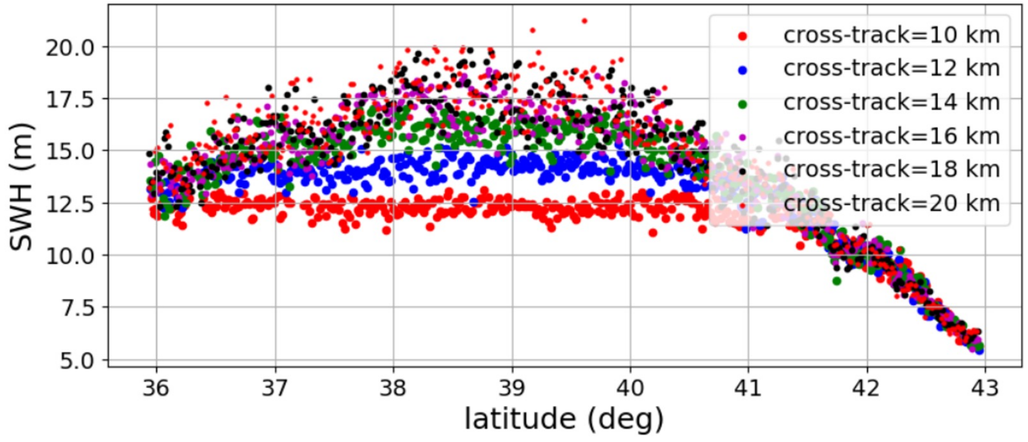




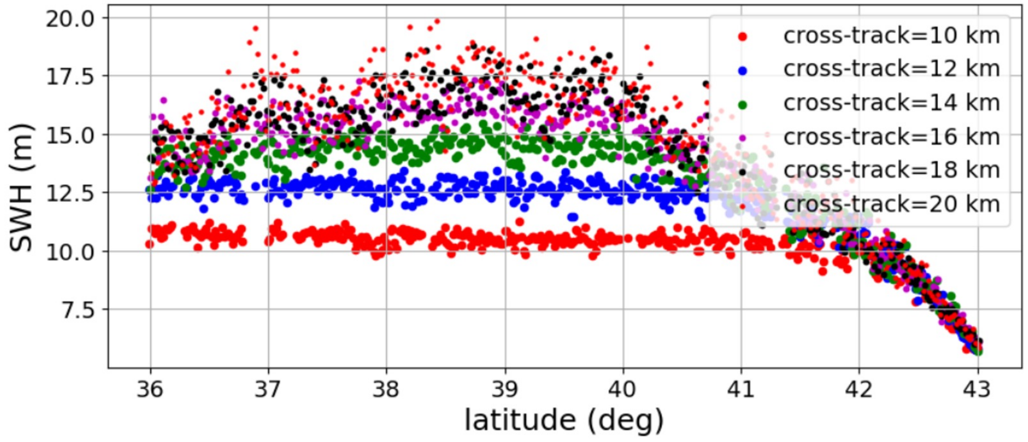
5. Storm Eddie: SWOT hit the bull's eye

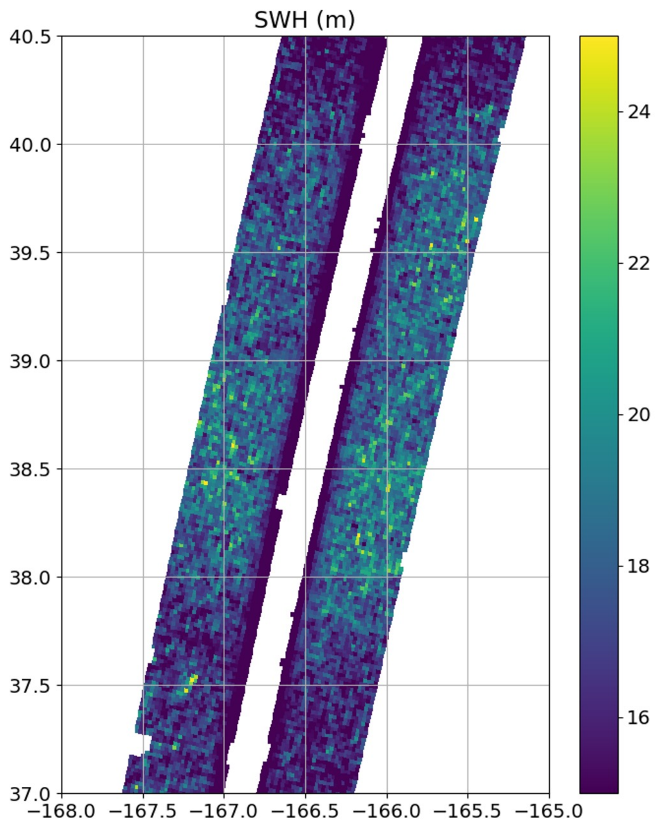
It looks like the coherence saturates towards nadir (see Bohe et al. 2025): good data for x > 20 km ?

right swath:
(indices 34+i)



left swath:
(indices 34-i)





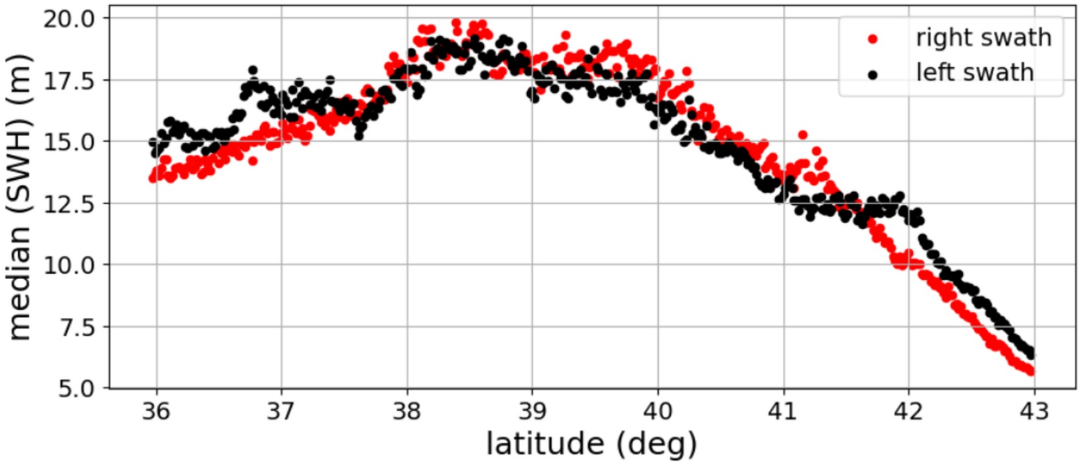
5. Storm Eddie: SWOT hit the bull's eye

NB: at 9 AM (close to SWOT pass at 8:55 AM), Q_{kk} for DIA run is 44 m, qkk for GQM run is 64 m

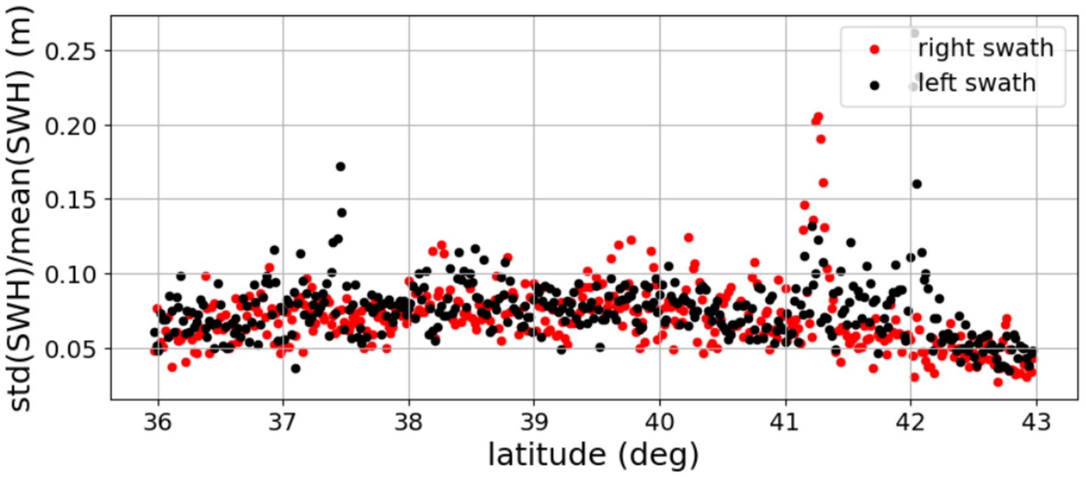
- with a L=17*250m=4.25 km averaging: expected
- std(SWH)/Hs = 0.067 m for Q_{kk} =64 m
- std(SWH)/Hs = 0.046 m for Q_{kk} =44 m

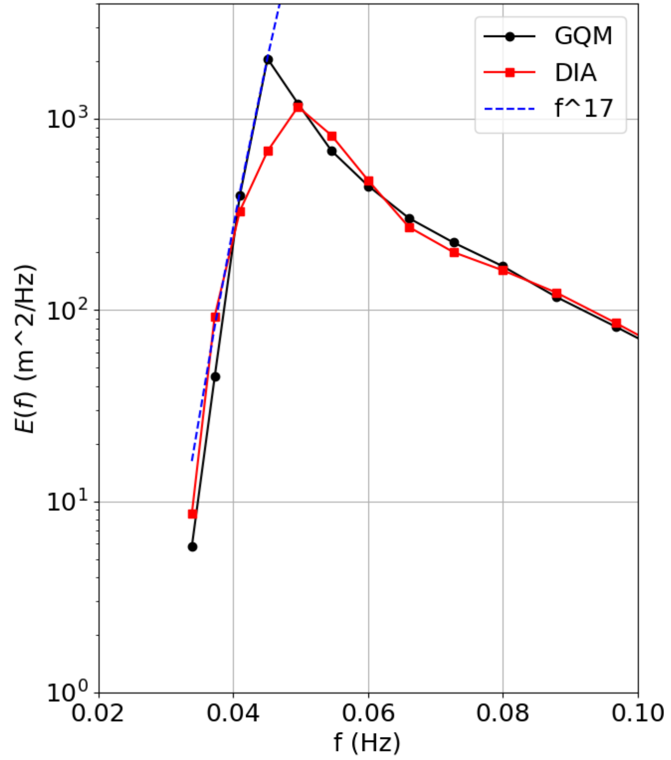
cross-track median:

Slightly lower than nadir?
Some waves too long?



normalized cross-track std:



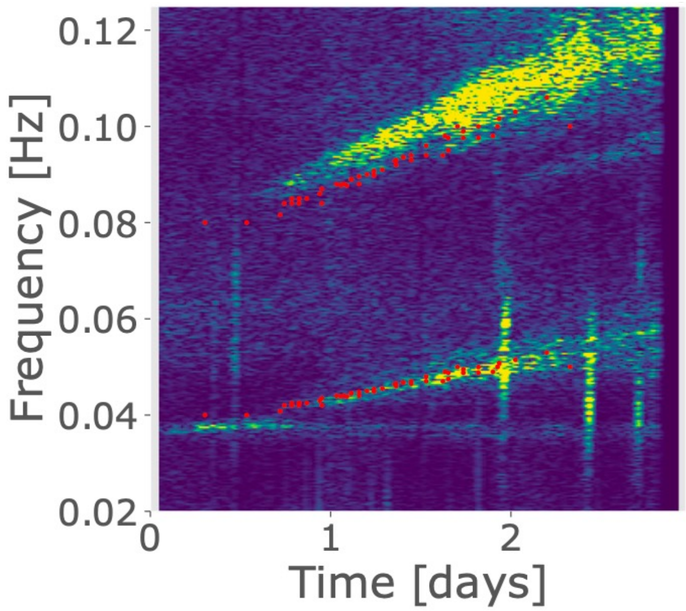


Conclusions

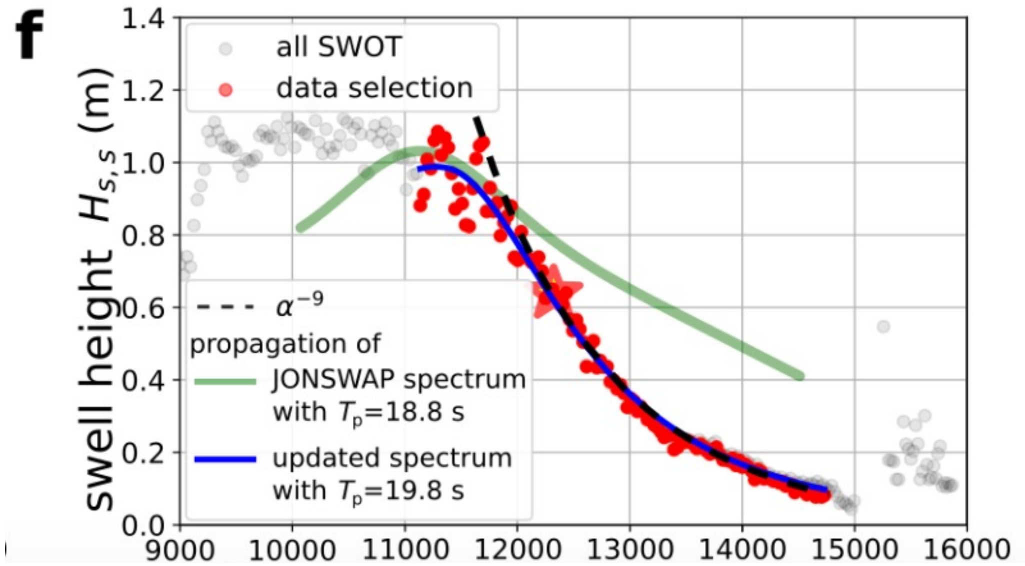
- Altimeters work well for SWH > 20 m, giving a robust Hs = 19.7± 0.3 m max value for Eddie
- SWOT swell energy consistent with f^{17} spectral shape as given by inverse cascade
- Swells from extreme extra-tropical storms cannot escape SWOT monitoring
- LR too coarse for tropical storms: 200 m resolution instead of 250 m would help a lot.

Future work:

- std(Hs) may provide spectral peakedness information (Qkk): we need a model for std(SWH)
- Routine analysis of all storms? … using L3 spectra from Aviso.
- Directional distribution
- Swell dissipation
- Synthetic swell fields: what storms gives swell heights > 3 cm for Tp=26 s?



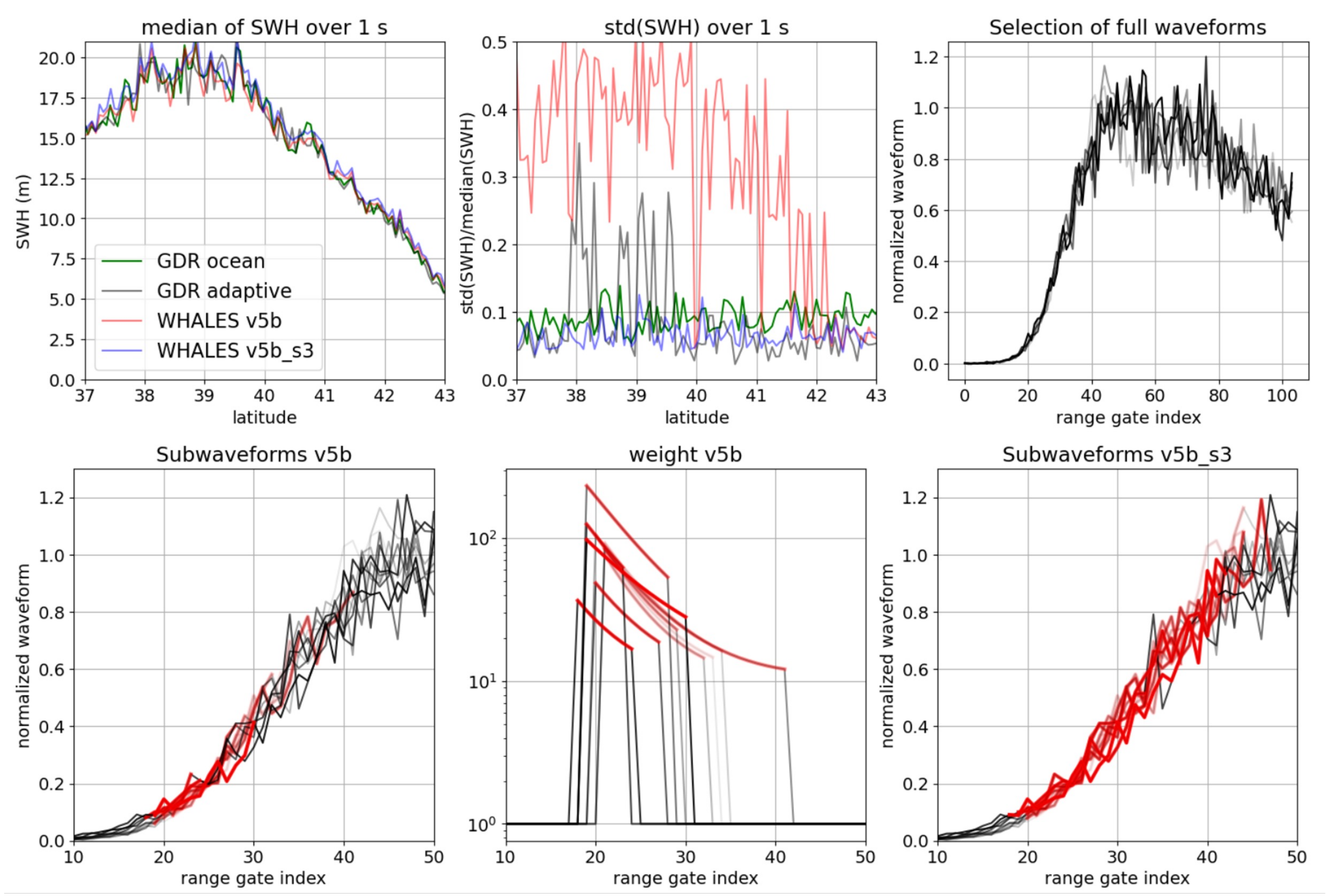
Bruland & Hadziioannou (2023):
G-TAM seismometer



BONUS SLIDES

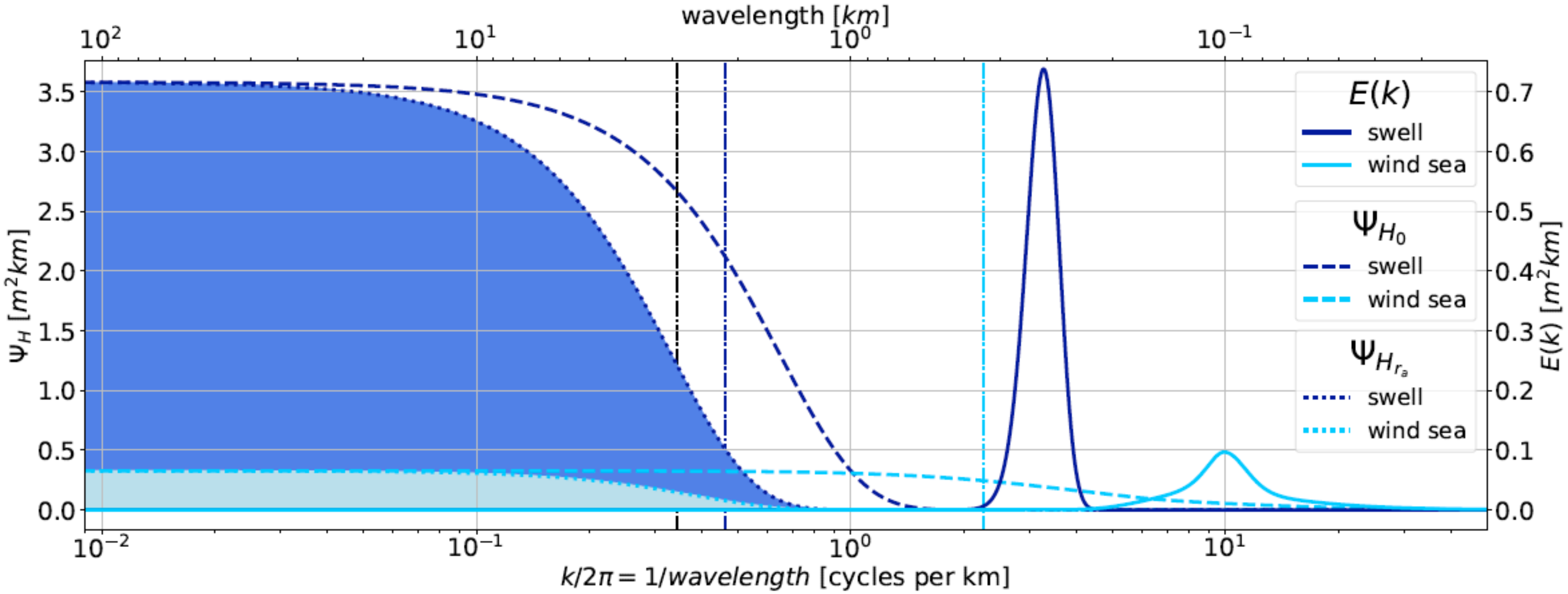
Preliminary analysis of Eddie: Hs fluctuations

Looking at 20 Hz data in nadir (Poseidon 3C): GDR (ocean) and WHALES retracking (with -s 3 smoothing)



1. Wave groups, effective altimeter footprints and Q_{kk}

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)

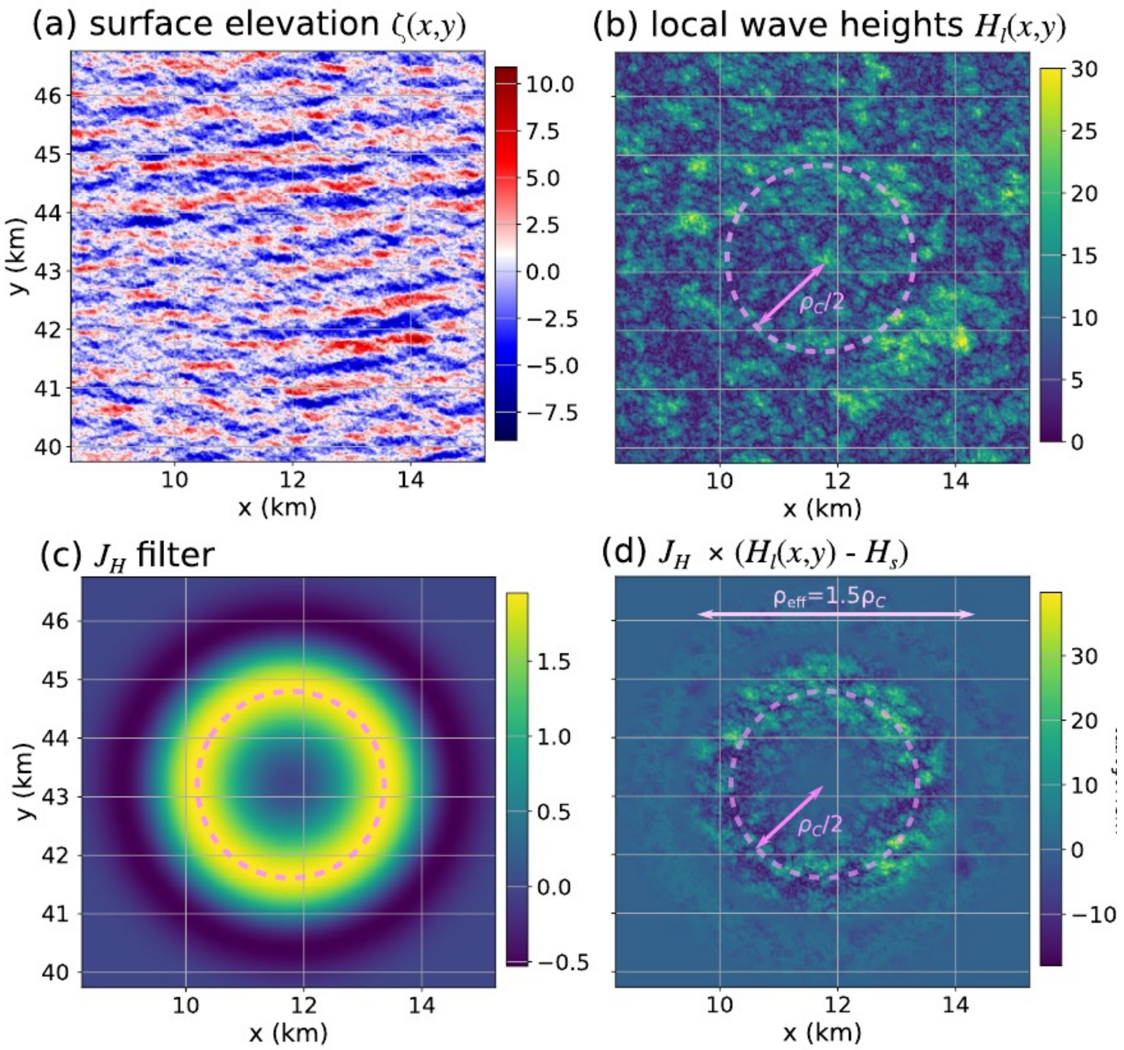


For random waves in 2D, the PSD of the envelope near k=0 is proportional to $H_s^2\ Q_{kk}^2$ with (can be computed from CFOSAT L2/L2S data)

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

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)

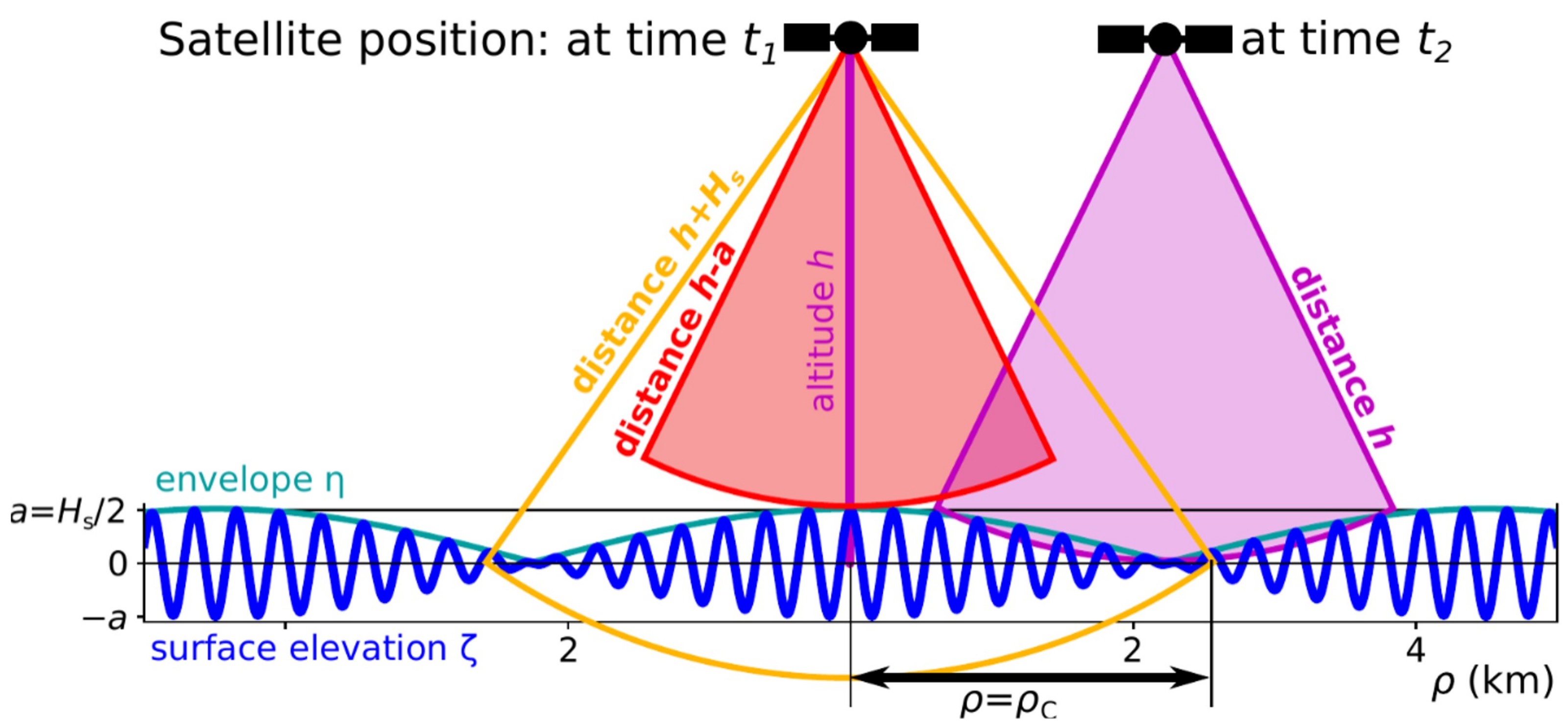
$$\hat{H}_s = H_s + \frac{aH_s}{2} J_H(b), \qquad J_H(b) = 2b\left(6 - 16b^2\right) \mathrm{e}^{-4b^2},$$

$$\hat{z}_e = -c\hat{\tau}/2 = -\frac{aH_s}{16} J_z(b), \qquad J_z(b) = \left(2 - 16b^2\right) \mathrm{e}^{-4b^2}.$$

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

Ongoing work: extention to WHALES retracker

Wave groups and effective altimeter footprints



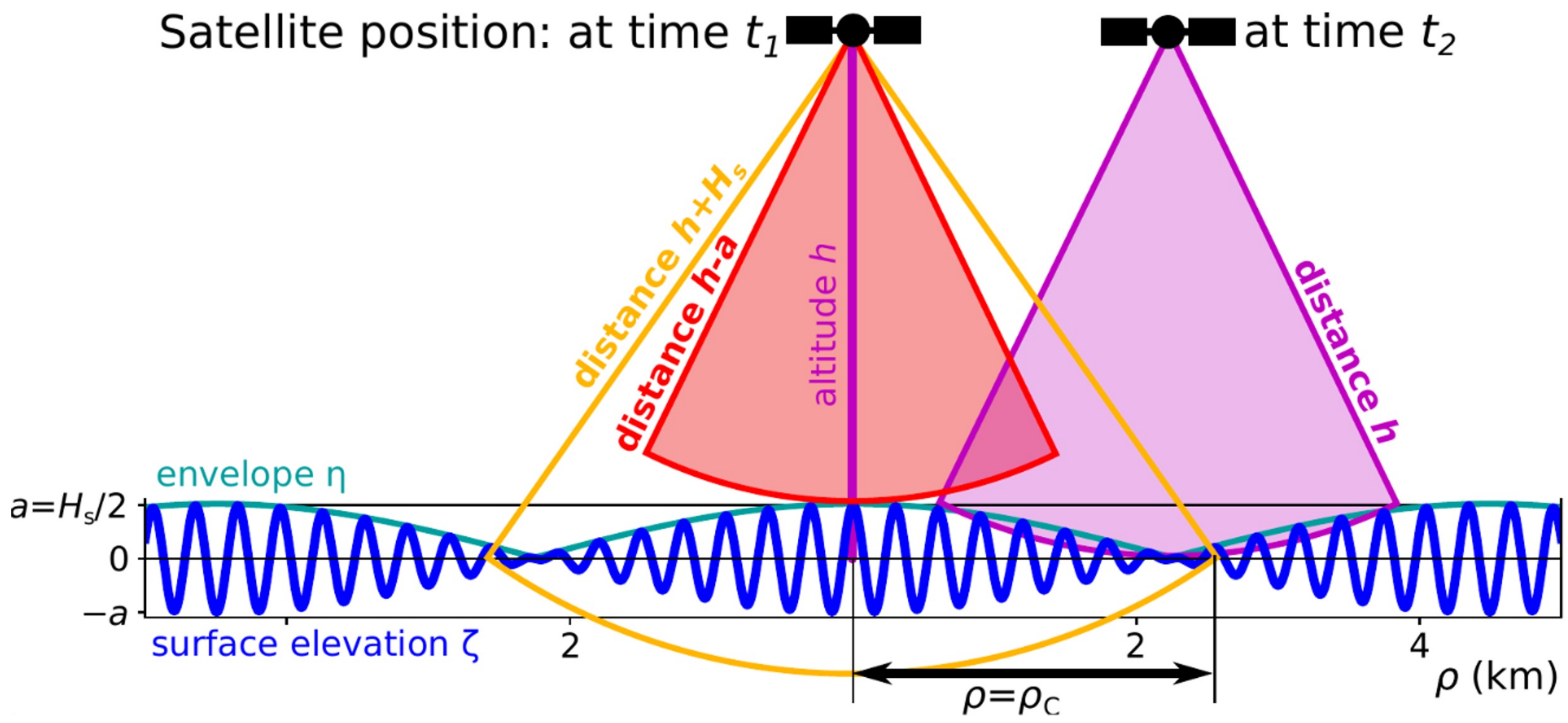
what is measured by the altimeter?

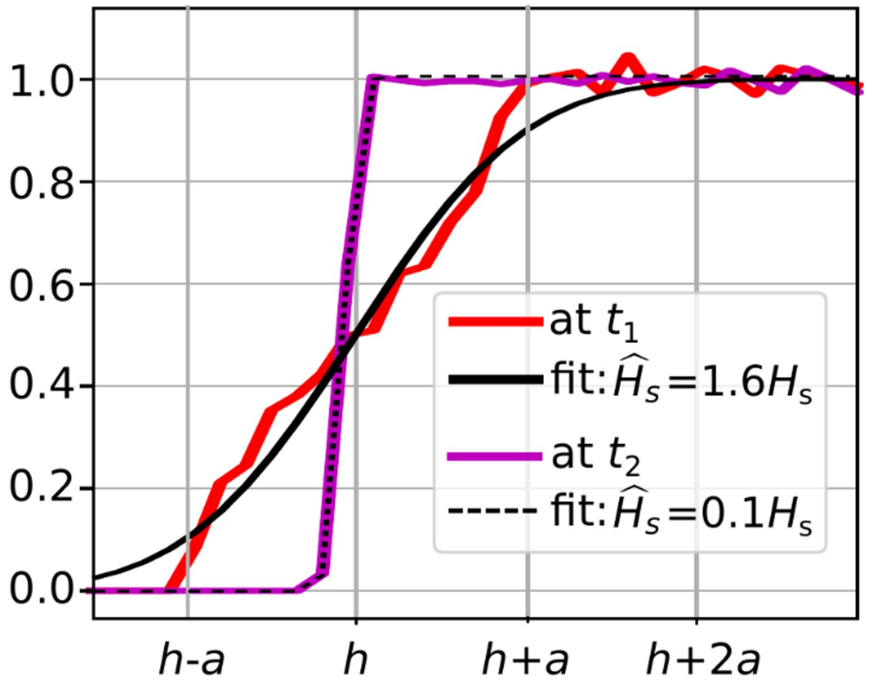
Here the max amplitude is $H_s/2$, with $H_s = 4\sqrt{<\zeta^2>}$

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

Wave groups and effective altimeter footprints





In this case: altimeter retracking gives $\hat{H} \cong$ **H_l** … not H_s !!!

0.1 Hs is **H_l** averaged over 500 m

Note: here the group wavelength is 4.5 km,
larger than the "oceanographic footprint" scale given by Chelton's radius $\rho_C=\sqrt{(2\ h\ H_s)}=2.4$ km.
Hs=2 m for Jason or Hs=5 m for CFOSAT (Chelton et al., JTECH 1989)

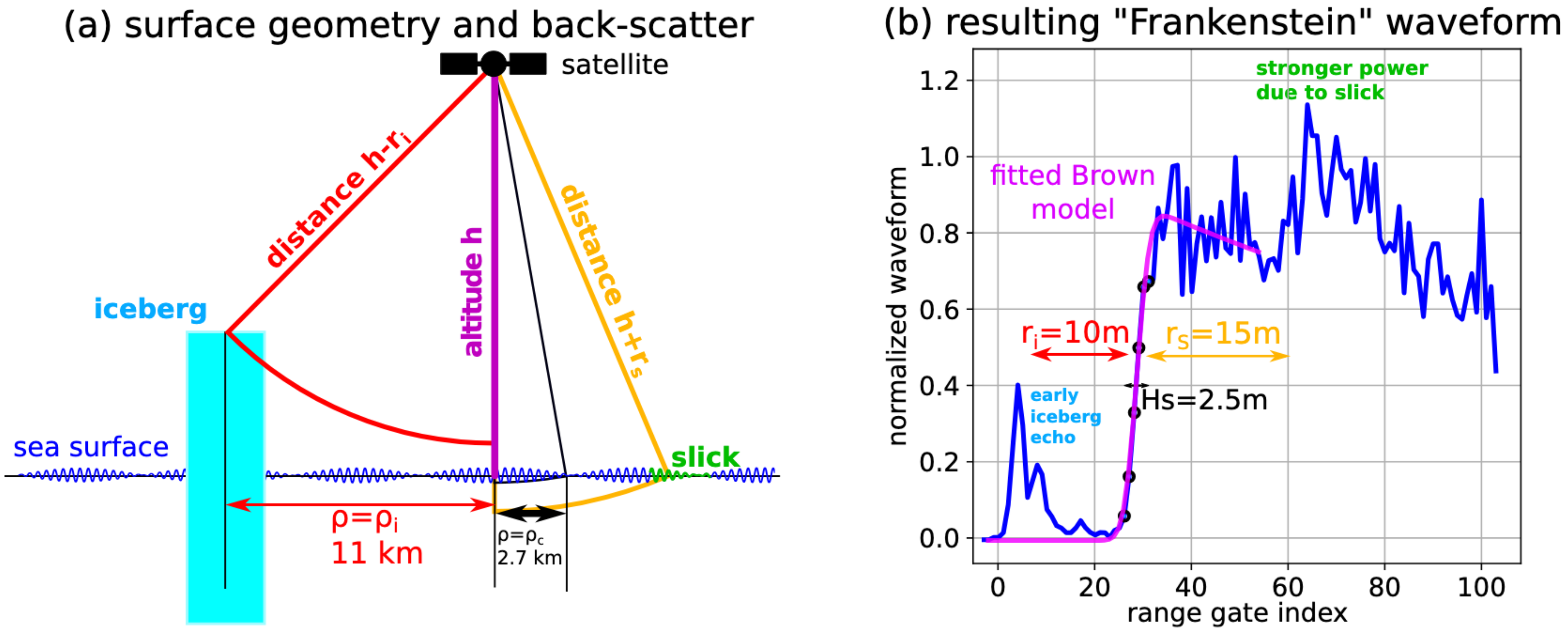
What happens for shorter wave groups? It depends on the retracking cost function…

2. WHALES tuning for large SWH

What is WHALES? An open source weighted least-squares sub-waveform retracker

(all details in Passaro et al. 2025, https://doi.org/10.48550/arXiv.2505.12881 , https://github.com/ne62rut/whales)

Why subwaveform?

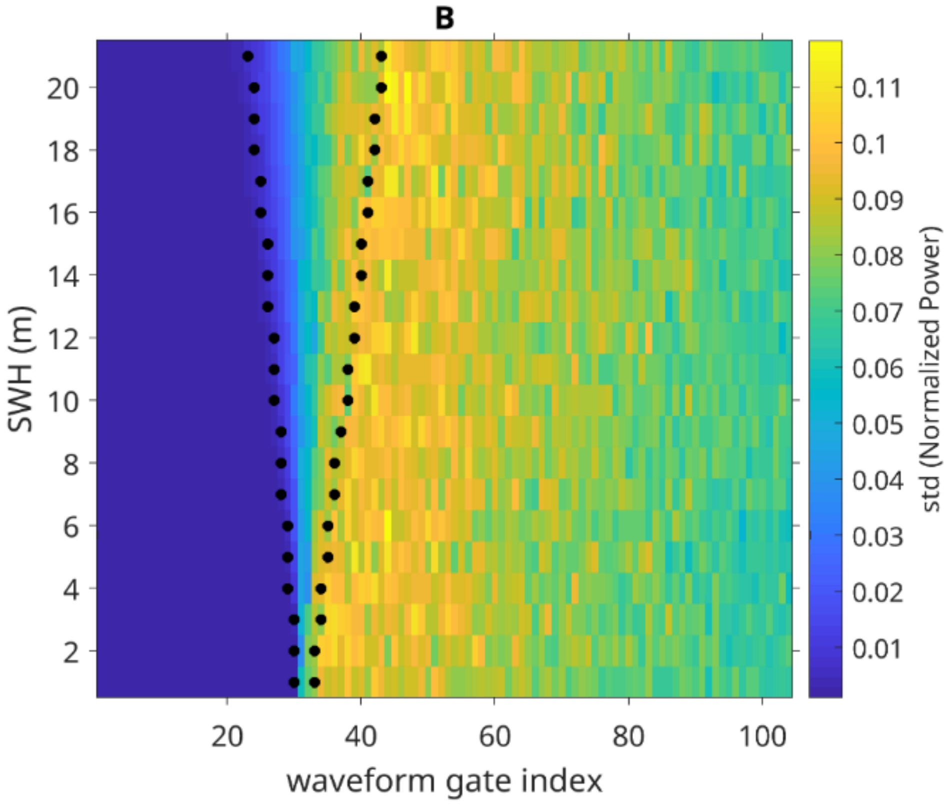


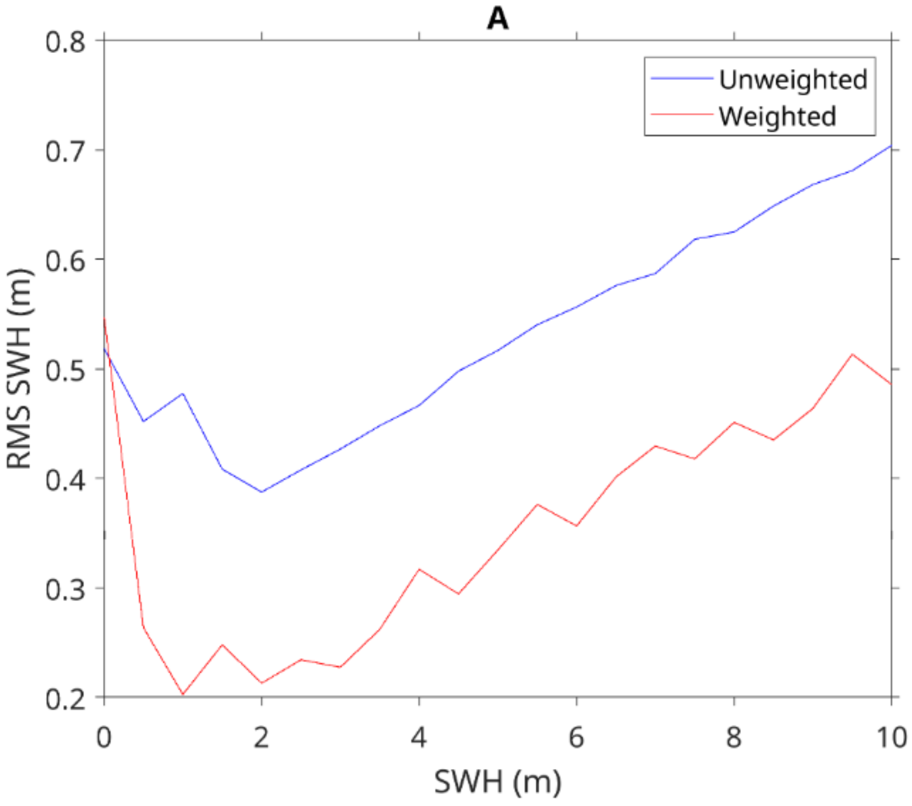
2. WHALES tuning for large SWH

What is WHALES? An open source weighted least-squares sub-waveform retracker

(all details in Passaro et al. 2025, https://doi.org/10.48550/arXiv.2505.12881 ,
https://github.com/ne62rut/whales)

Why weighted? It's all about noise … speckle noise and « wave group noise »
it goes back to the Maximum Likelihood vs Least Squares debate (cf Challenor & Srokosz 1989)… and ERS 1





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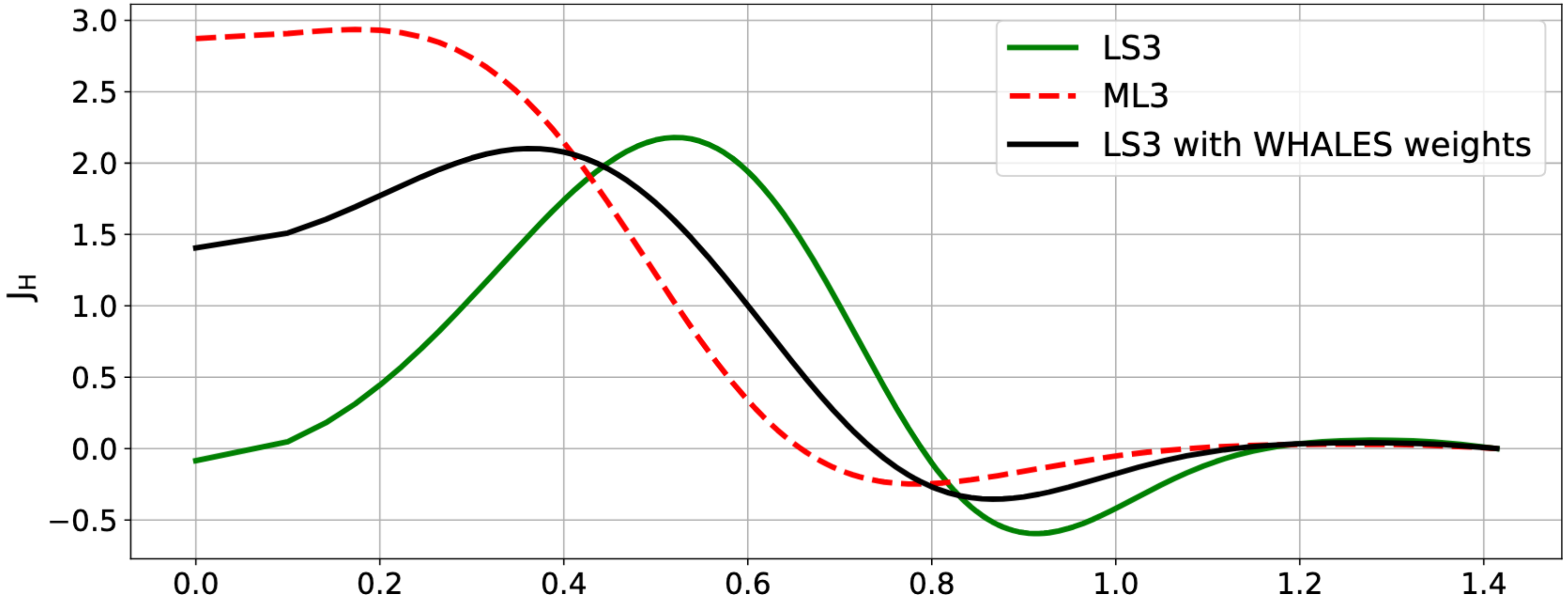
Why weighted? It's all about noise … speckle noise and « wave group noise »
ML or WLS gives smaller footprint … AND less noise!

Smoothing kernel



Normalized distance to nadir: $\rho/\sqrt{2hH_s}$

2. WHALES tuning for large SWH

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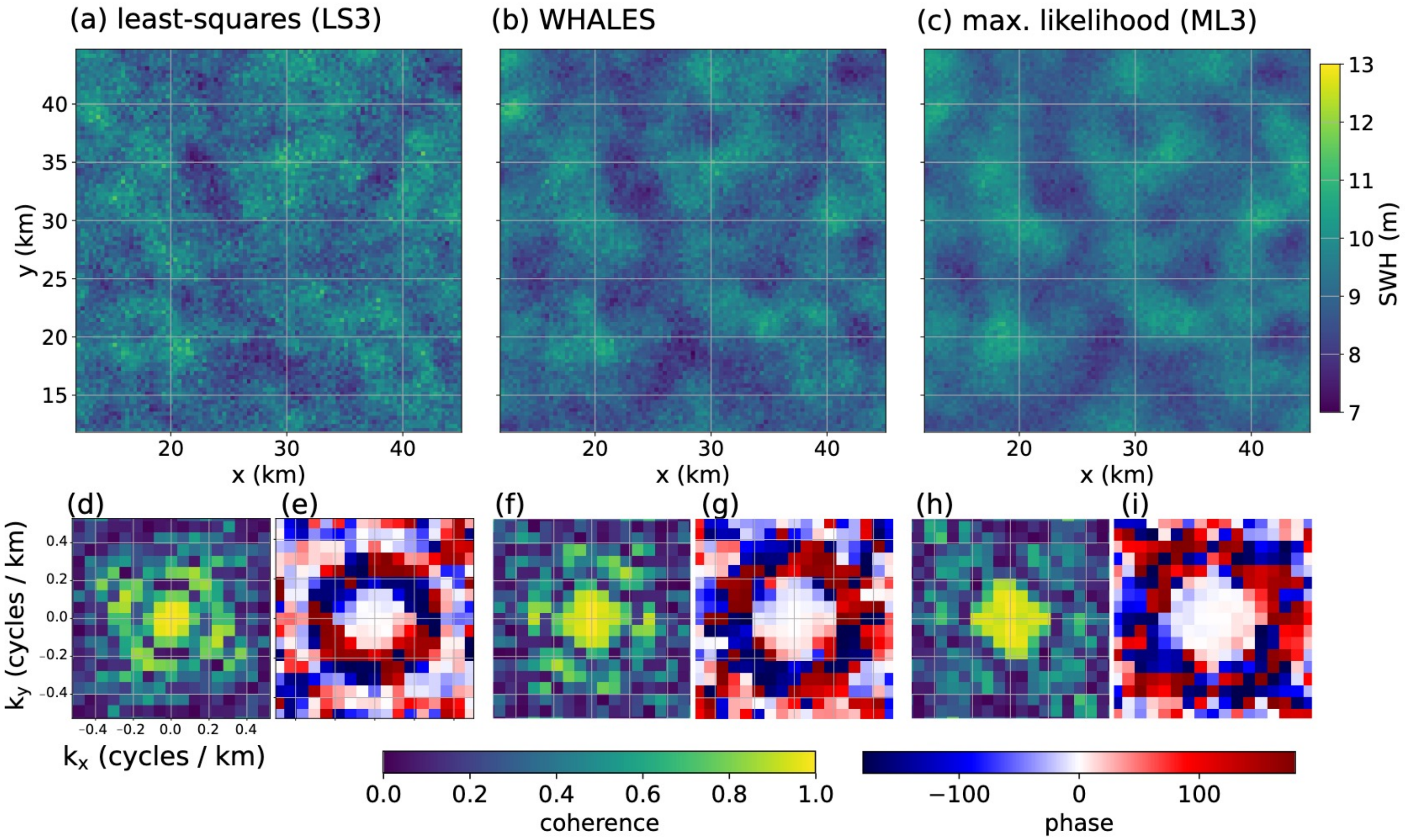
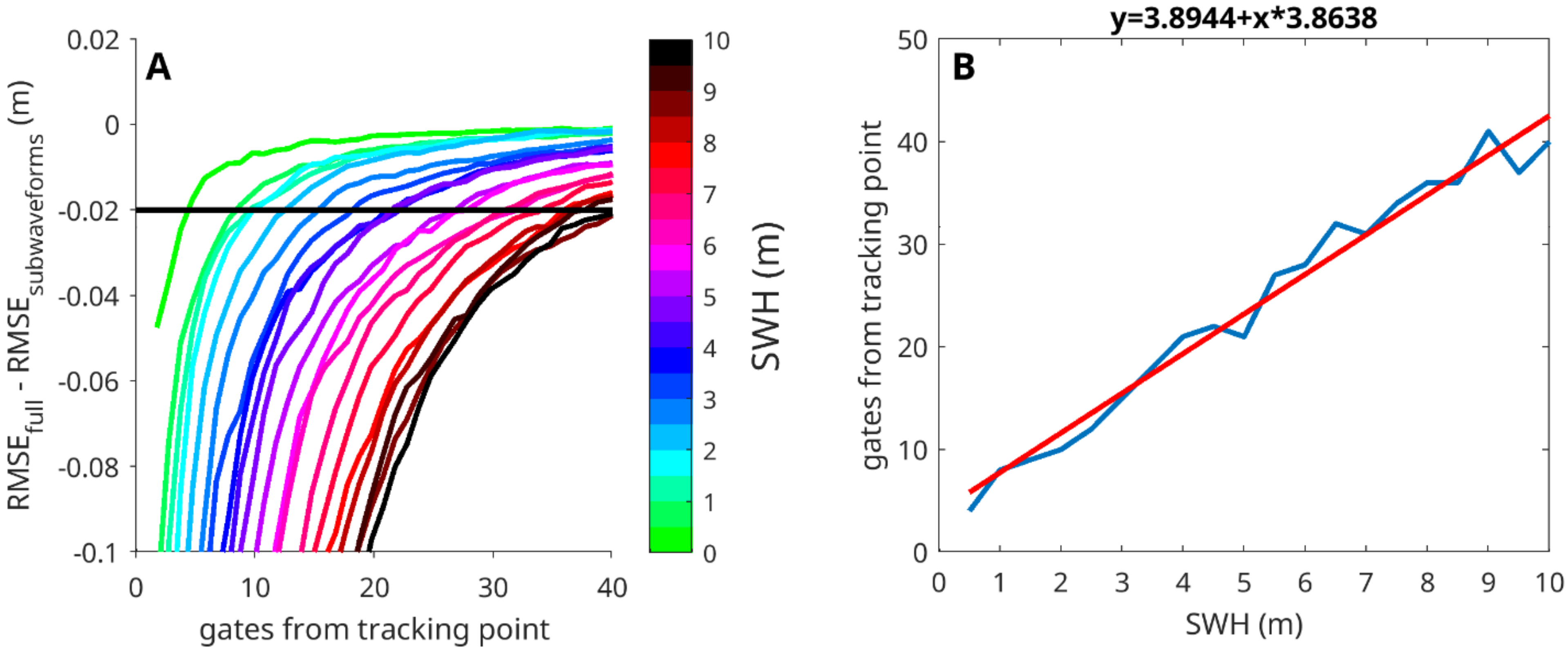


2. WHALES tuning for large SWH

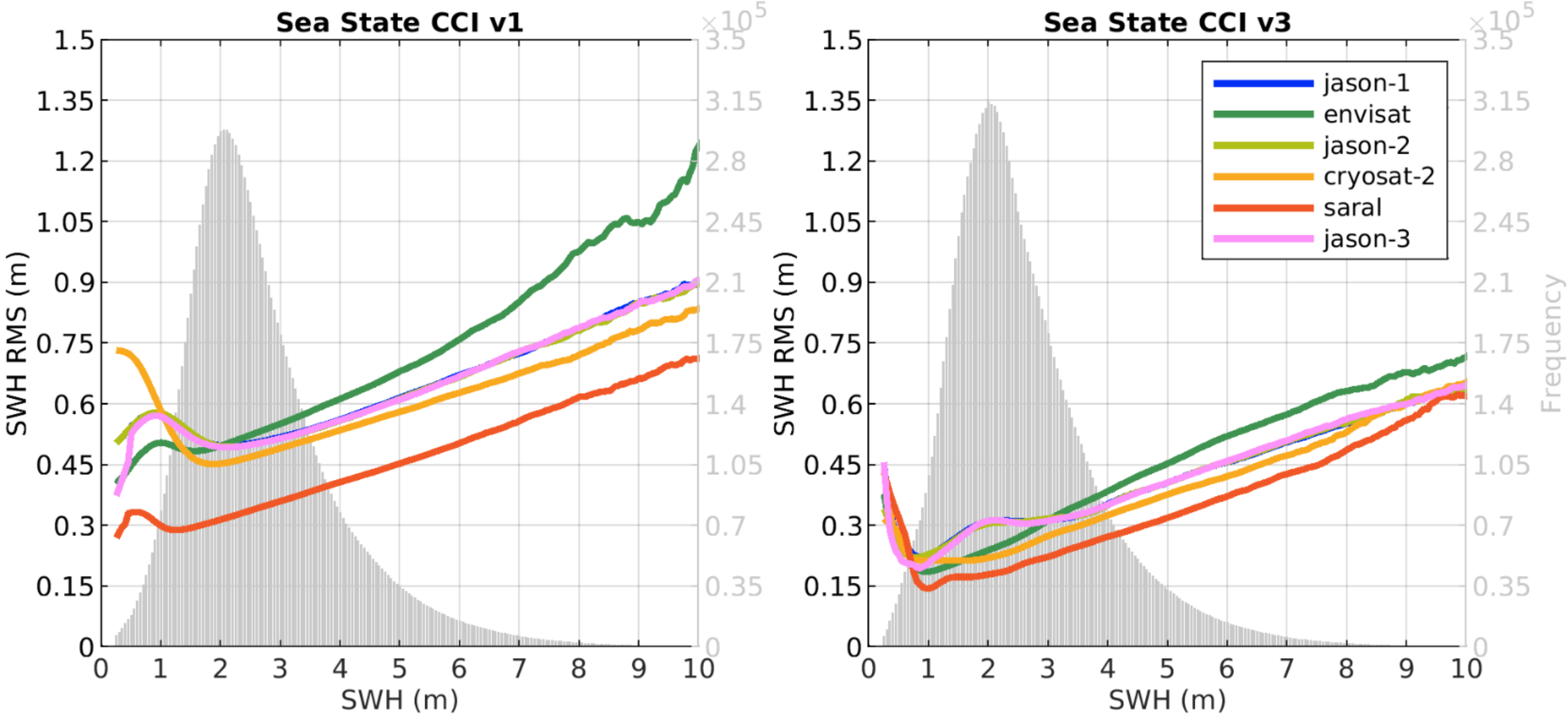
WHALES was designed and tested for SWH up to 10 m:

- definition of leading edge
- look-up table of weights
- WHALES with default parameters is very noisy for Hs > 10 m: leading edge often too short.
- OK for median values over 20 Hz



2. WHALES tuning for large SWH

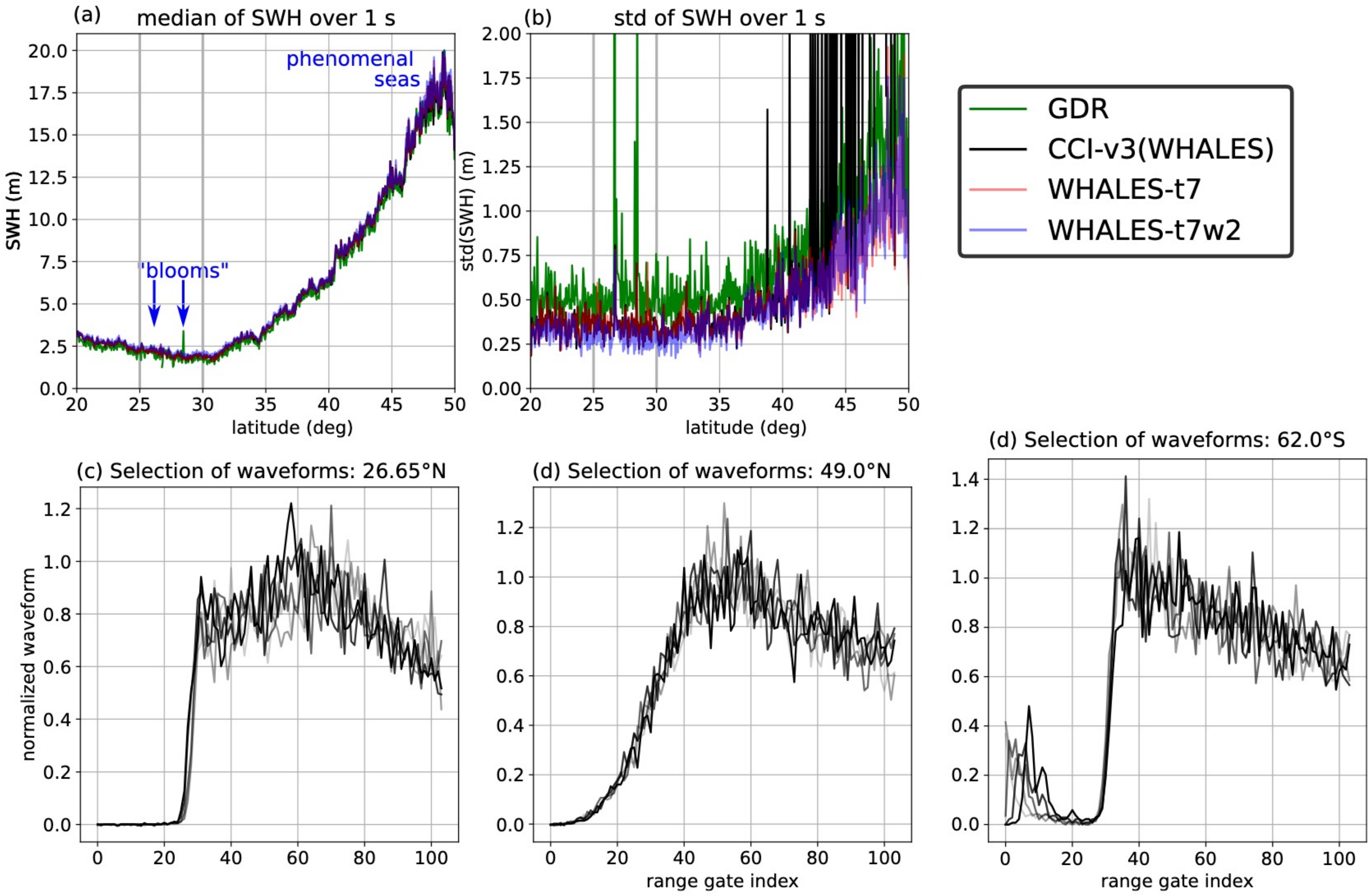
WHALES is better than GDRs for SWH <10 m



2. WHALES tuning for large SWH

WHALES with default parameters is very noisy for Hs > 10 m

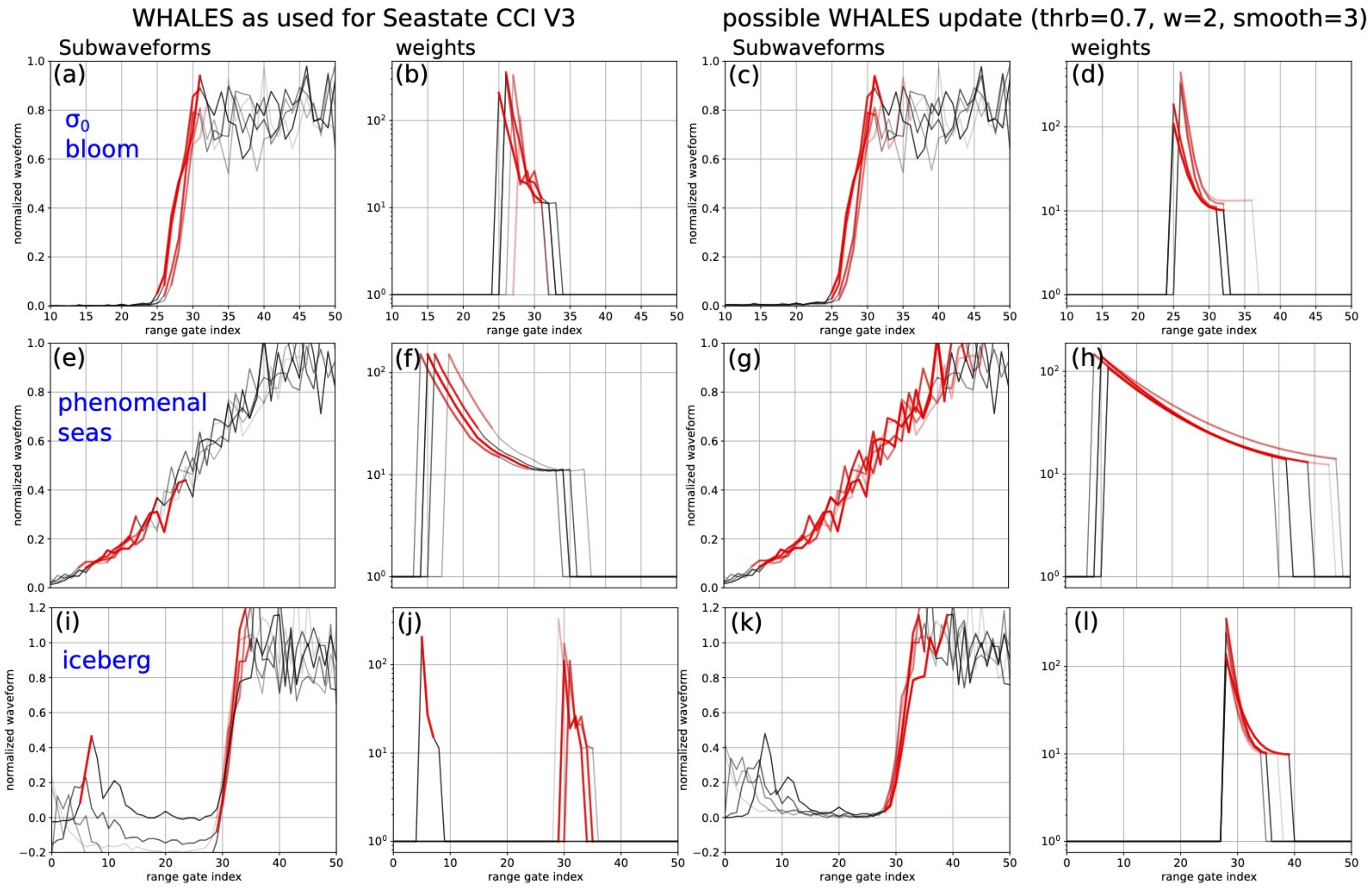
- OK for median values over 20 Hz
- Std(Hs) becomes meaningless



2. WHALES tuning for large SWH

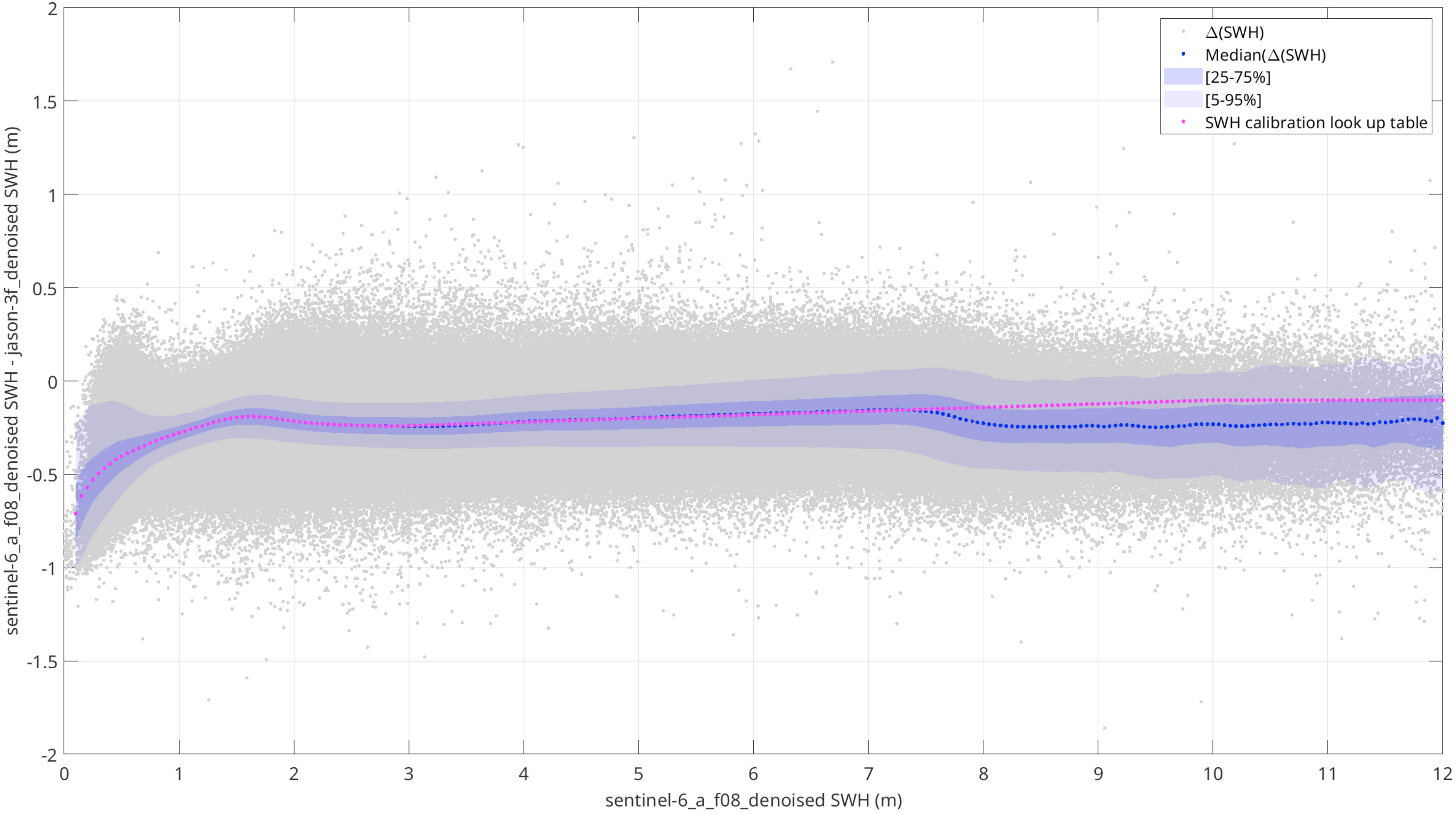
Why is it noisy for Hs > 10 m? leading edge often too short. Can we fix this ?

Same problem as found for SARAL by Marine de Carlo: let's smooth the WF for leading edge detection



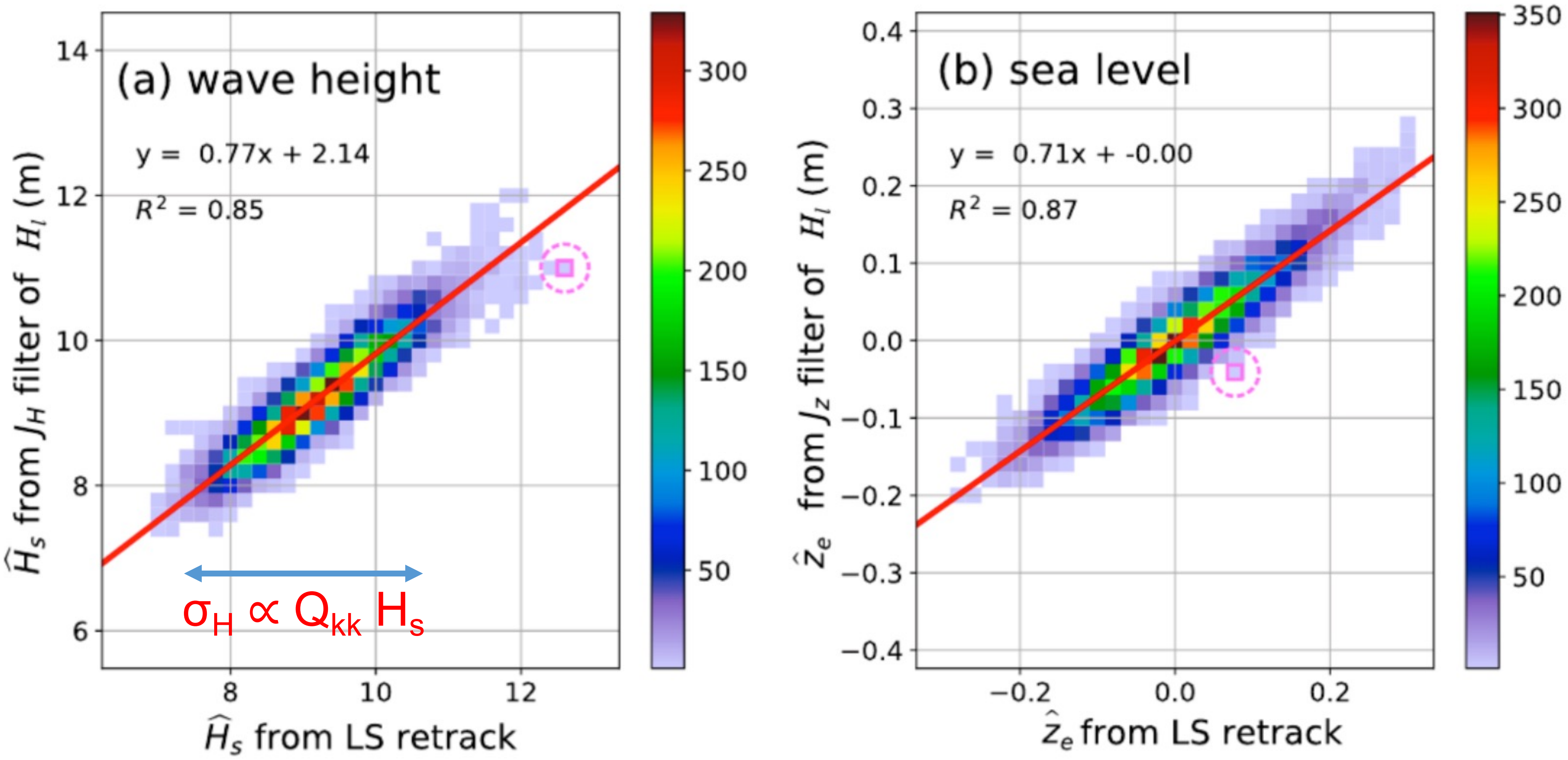
2. WHALES tuning for large SWH

In v4 we have applied this smoothing for J1, J2, J3 … only for SWH > 8 m…
Only issue: this smoothing introduces a +12 cm shift … which looks constant from 8 to 12 m…
This is corrected in v4 based on the SWH value.



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

« doughnut theory » works (De Carlo & Ardhuin JGR 2024)



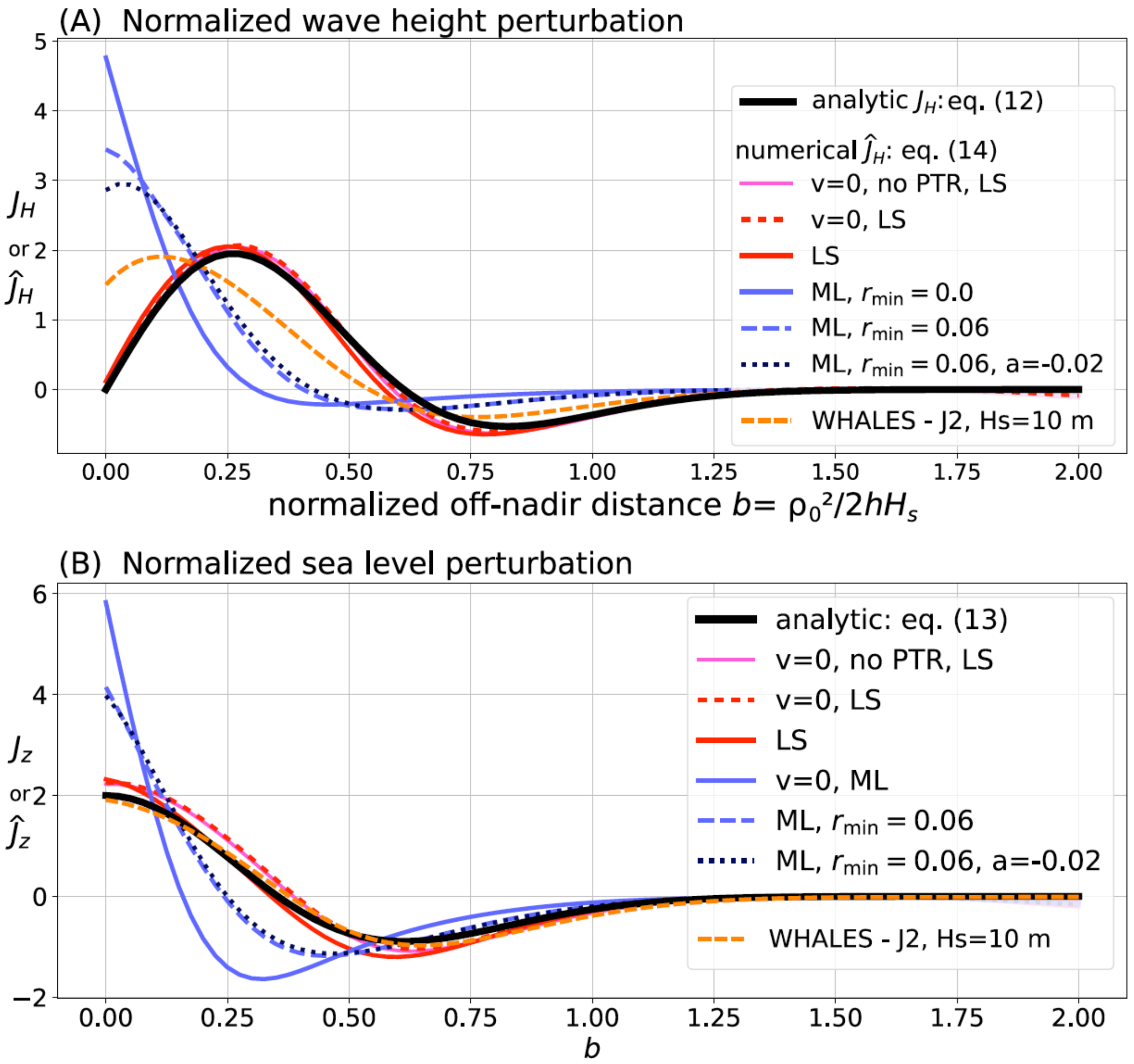
3. Different retrackers: different wave group effects

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.

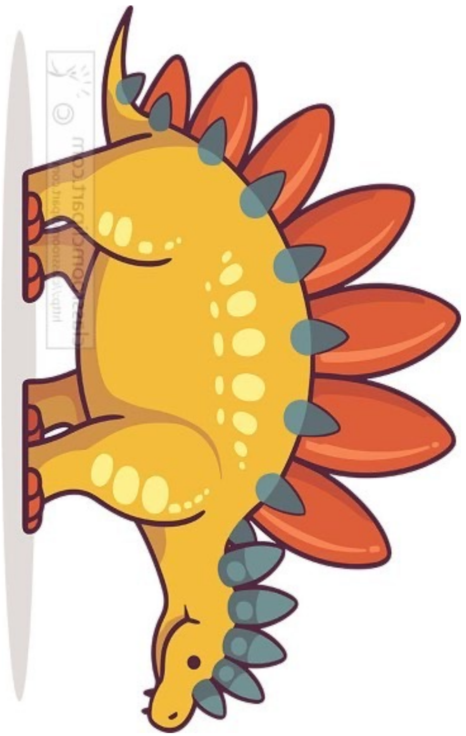
It is
- open source (https://github.com/ardhuin/wavesALTI)
- weighted least-square
- and partial waveform

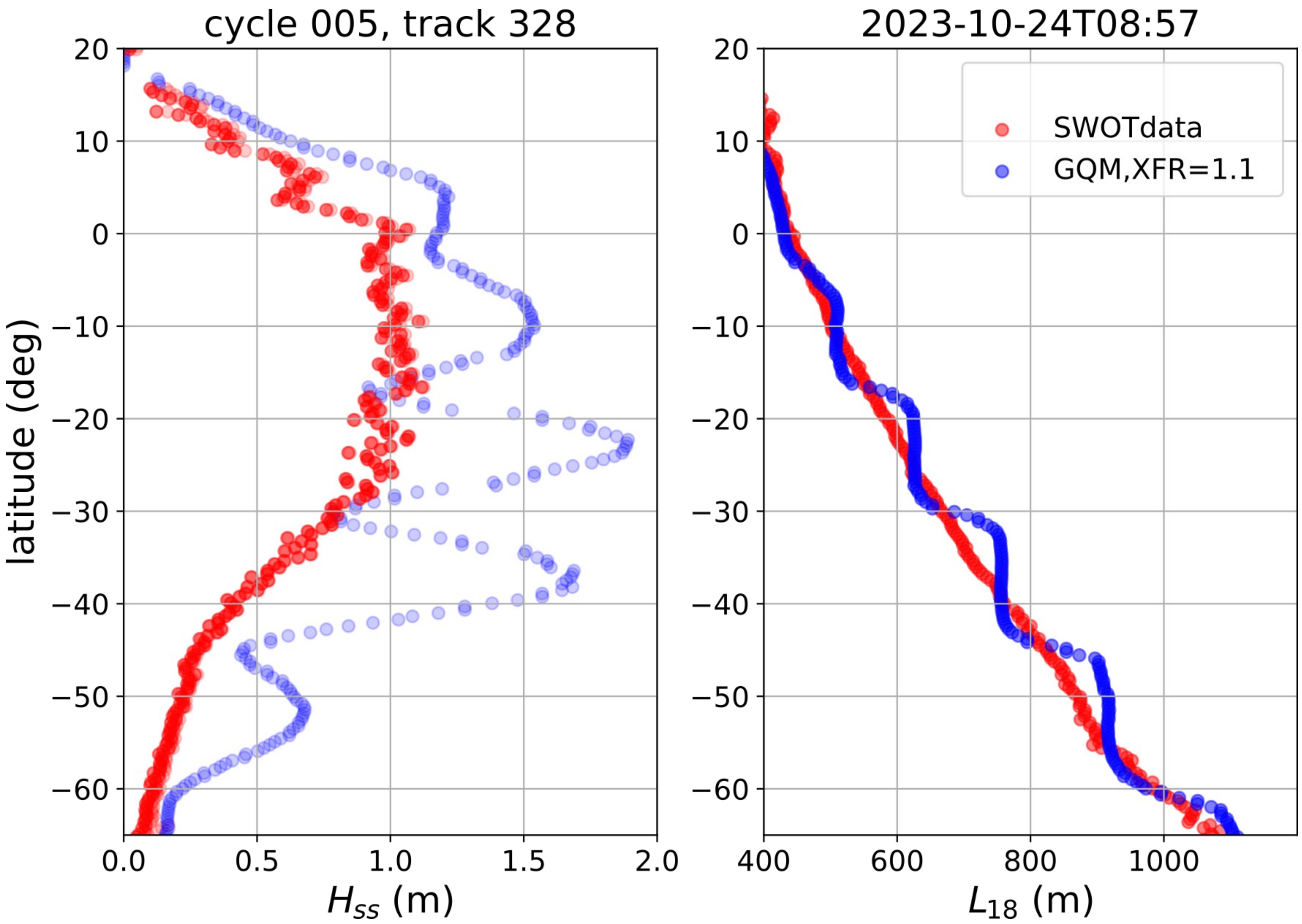
weights = 1 / waveform:
  - lower speckle noise than MLE3
  - limited wave group noise
  - smaller footprint that MLE3



4. How good are the models?

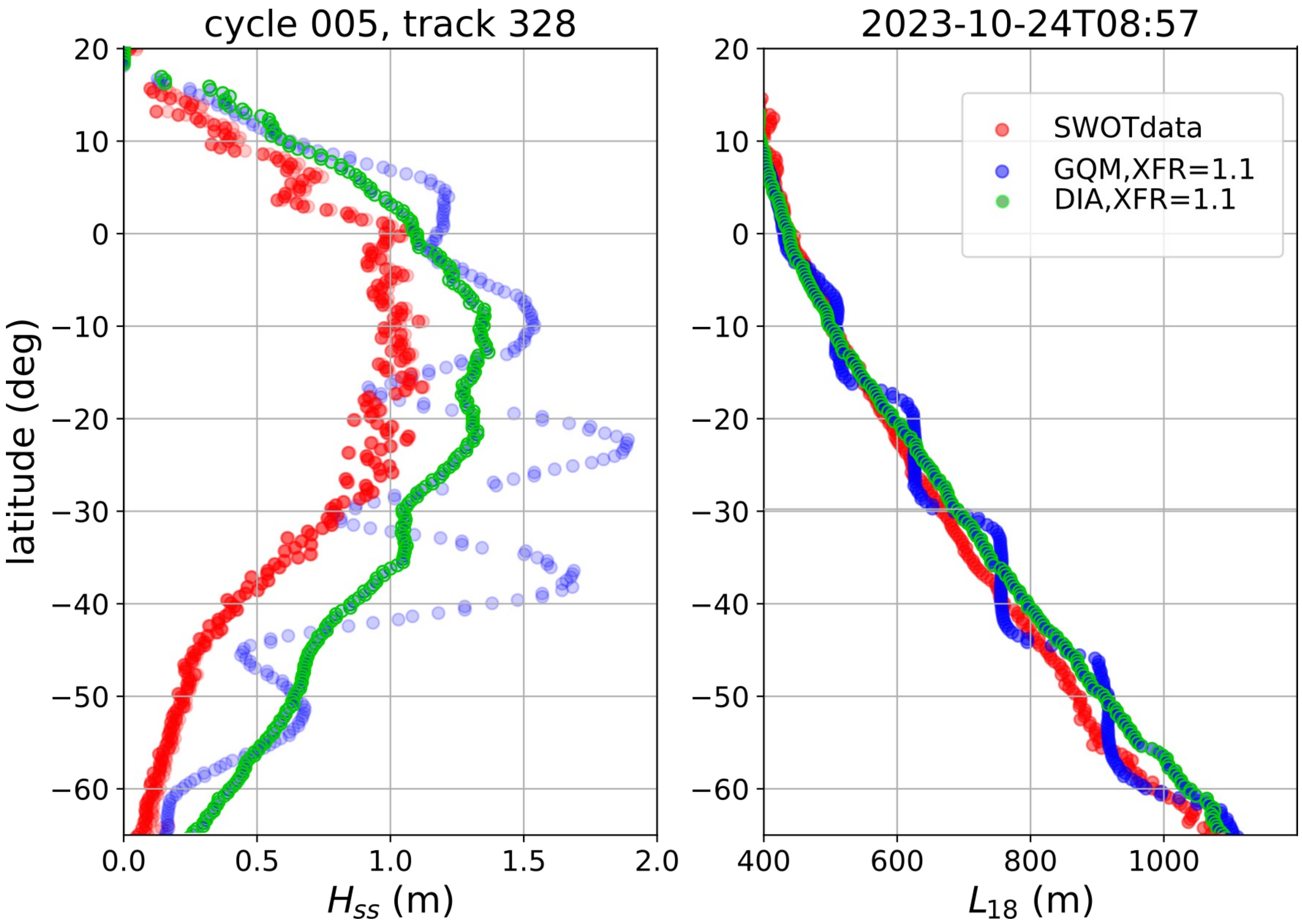
Narrow spectrum + high order scheme = Great Stegosaurus-down-the-stairs Effect (GSE)





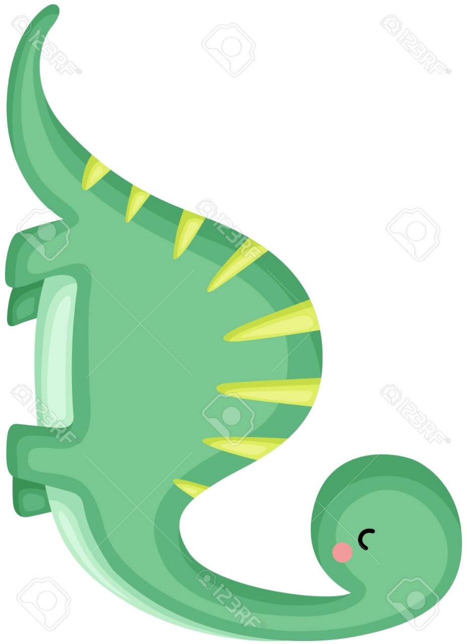
4. How good are the models?

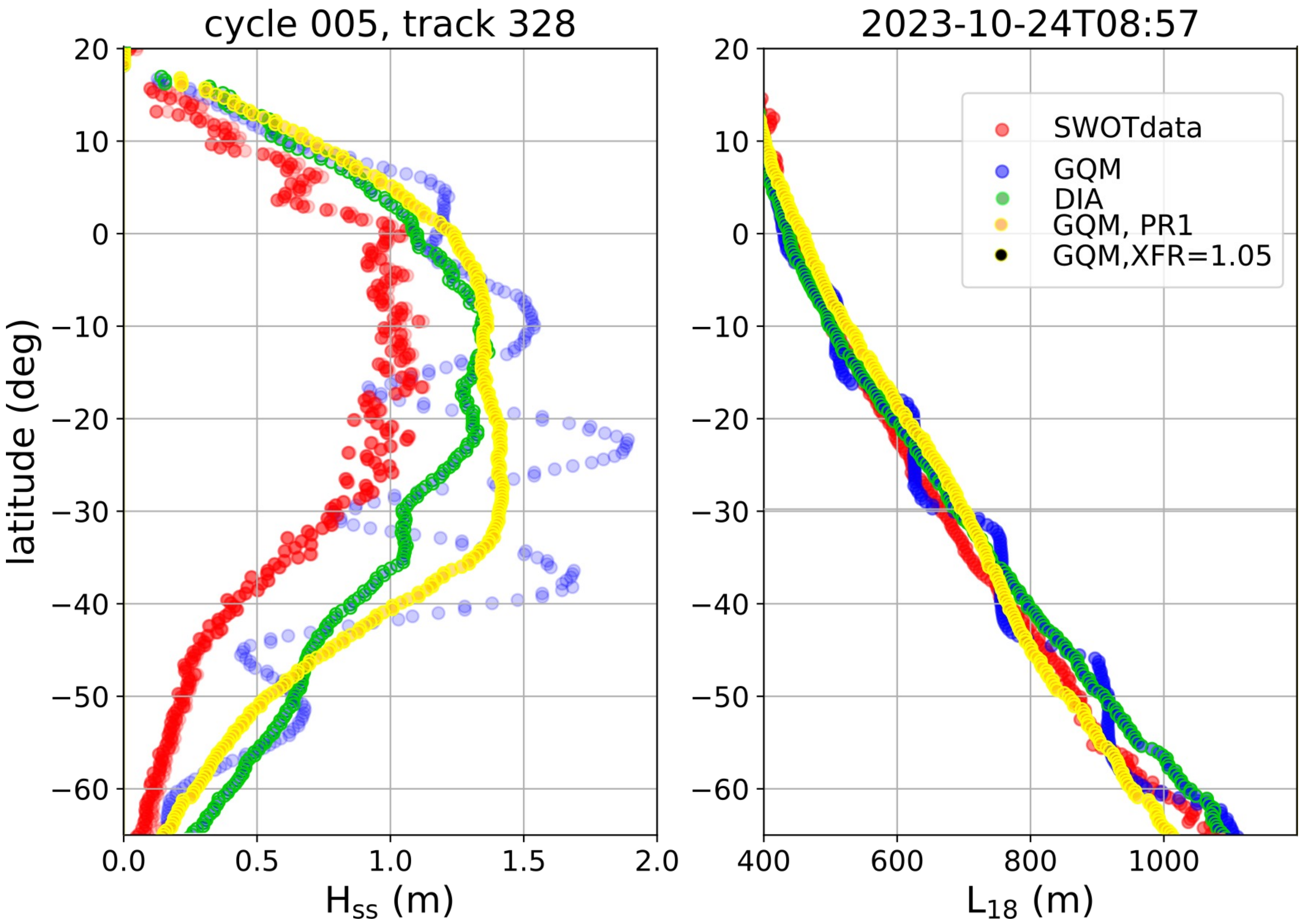
broad spectrum + low order scheme = swell arriving too early



4. How good are the models?

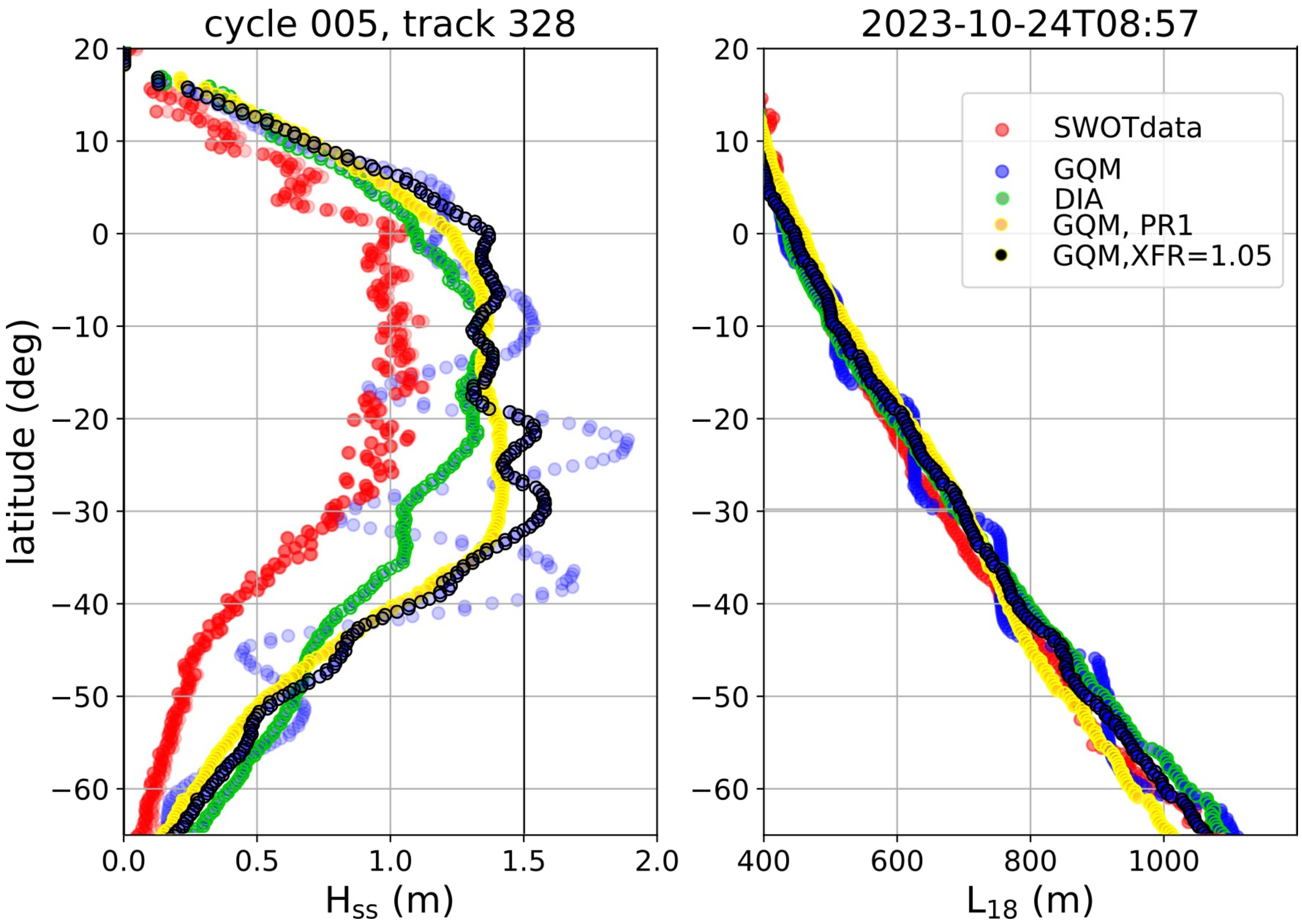
1st order scheme = perfect?





4. How good are the models?

Other option: increase spectral resolution ...



Preliminary analysis of Eddie: Hs estimates

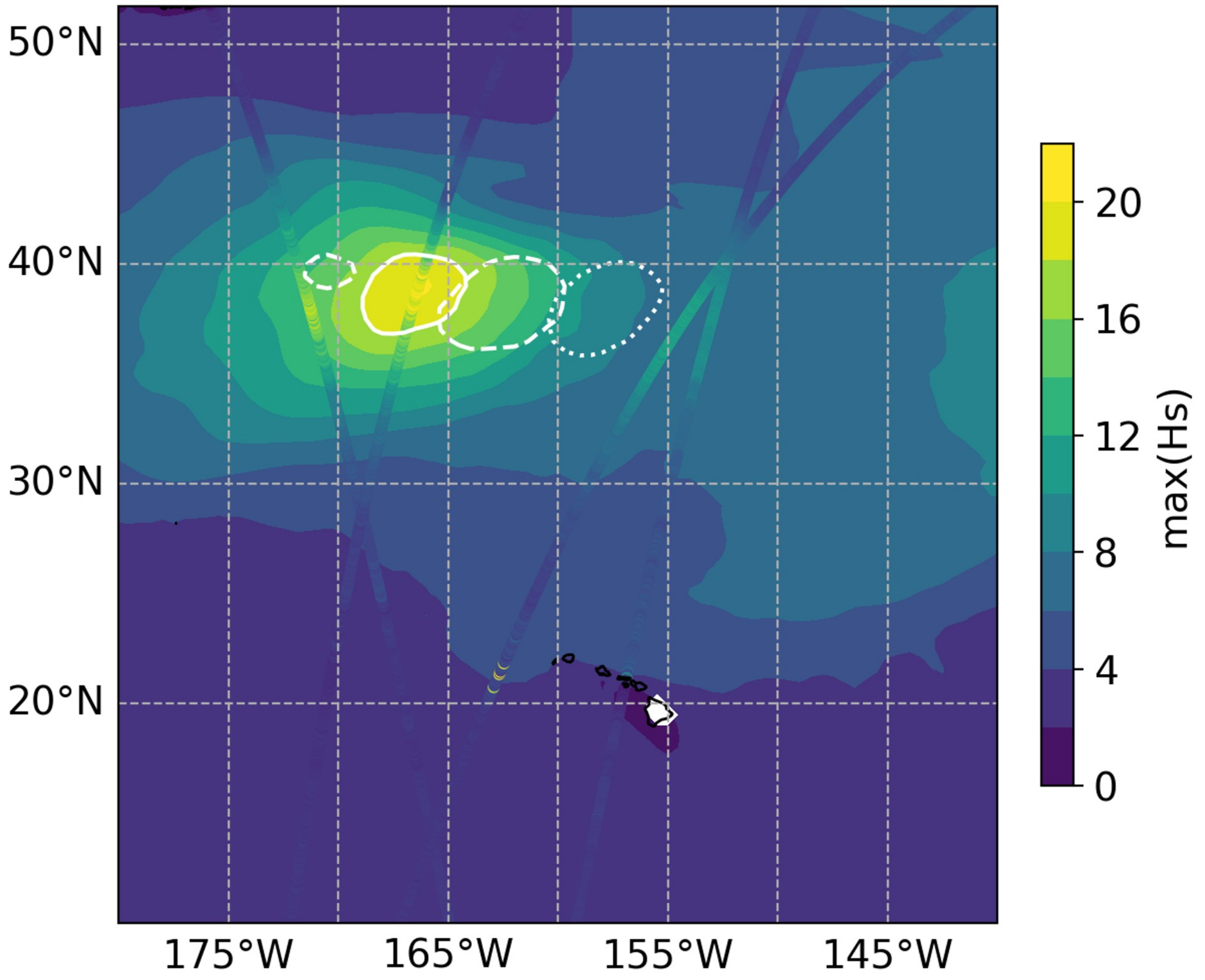
Hs (in model) peaked at 15:00 UTC on 21/12/2024.
We were very lucky to get a SWOT pass right through the peak a little earlier: 9:00 UTC

Here is the map of model Hs (CCI run, using DIA) at 9:00. white contours: Hs=18 at 4 AM, 9 AM, 2 PM, 7 PM

Satellite tracks from left to right (all on 21/12):

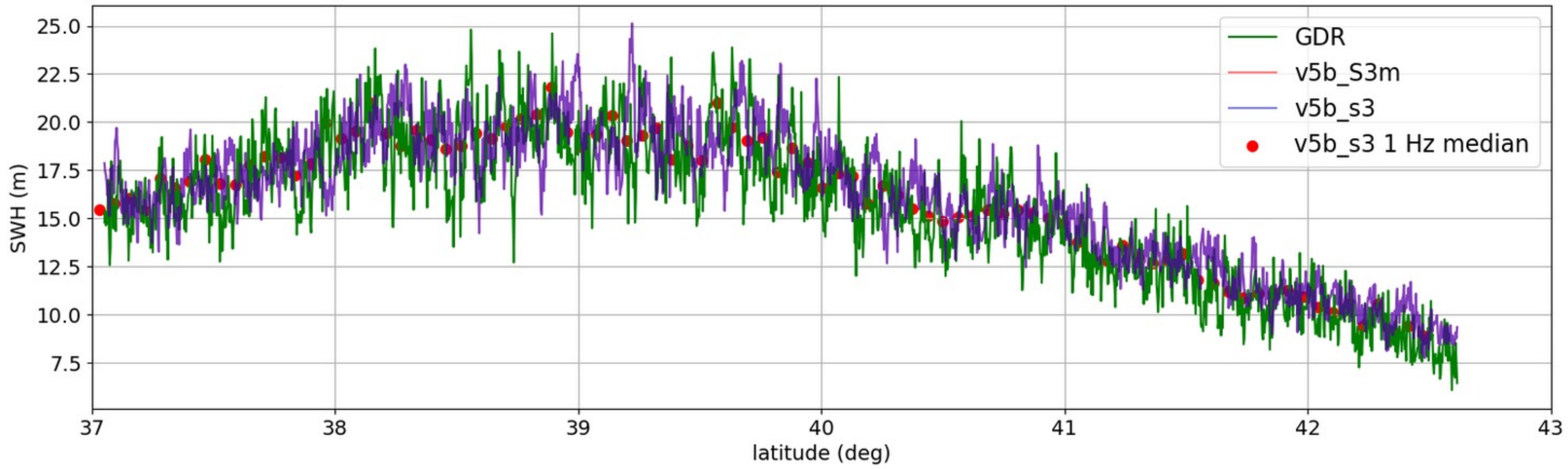
CFOSAT (5 AM)
SWOT (9 AM)
J3 (5 PM)
CFOSAT (5 PM)

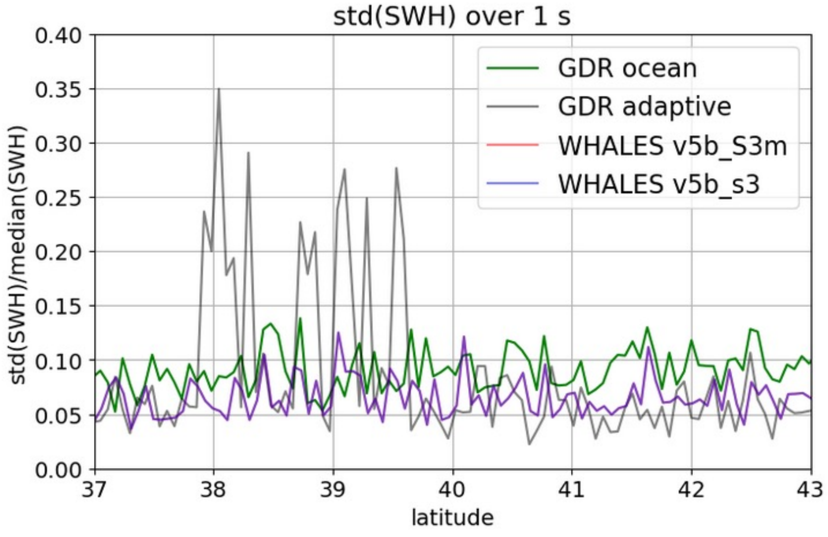
note: S3A (10 AM) is not plotted

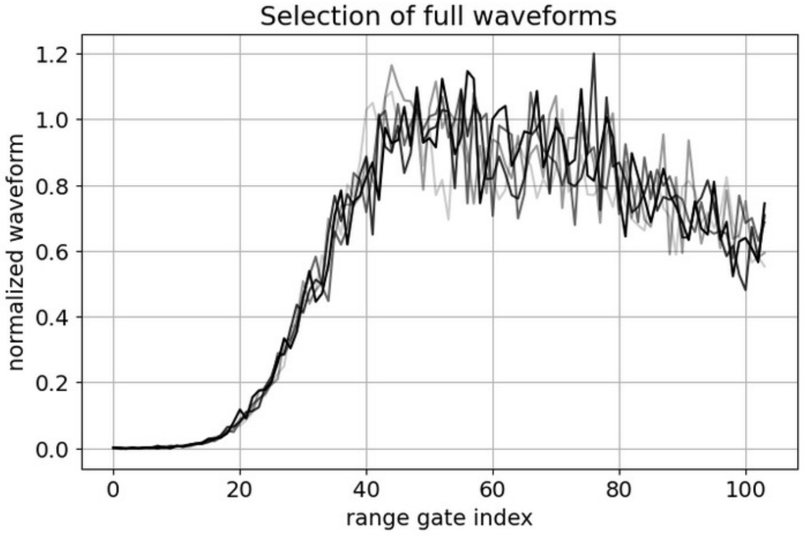


Preliminary analysis of Eddie: Hs estimates

SWOT retracking







Preliminary analysis of Eddie: Hs estimates

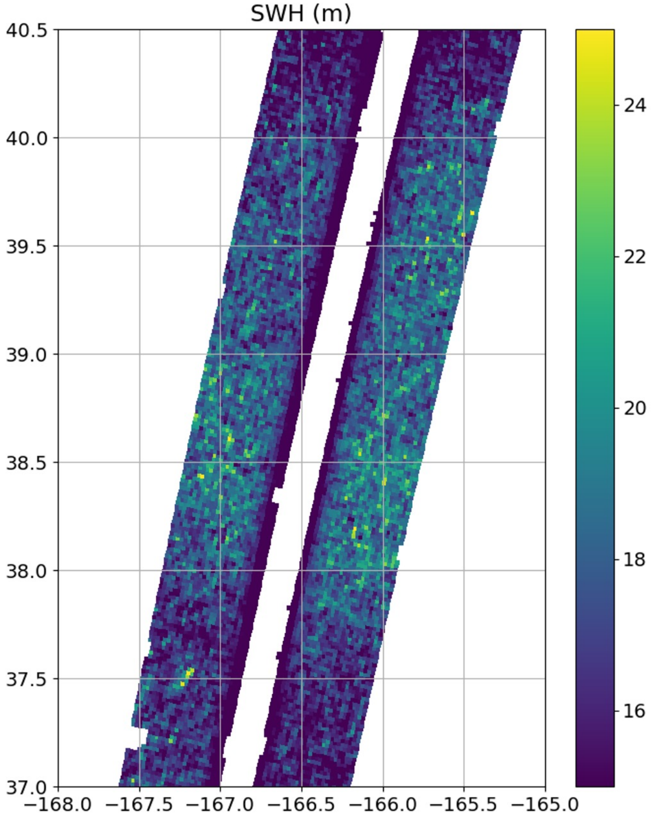
Along-track Hs: (preliminary)
- SWOT (no smoothing, no retracking …)
- GQM run: Hs rescaled by 0.95

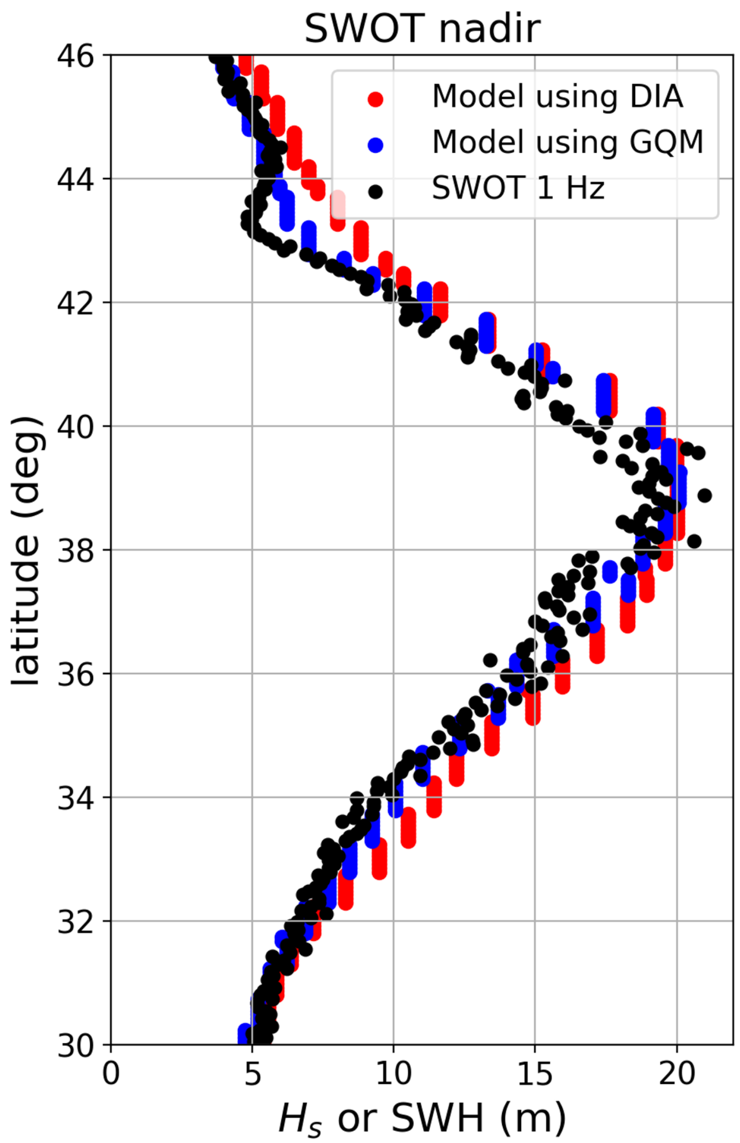
NB: ECMWF IFS max value for Eddie is 17.2 m

50-km smoothing of
SWOT sgdr gives 19.7 m +/- 0.3m

Storm peak probably occurs later

Real max may be closer to 21 m ?





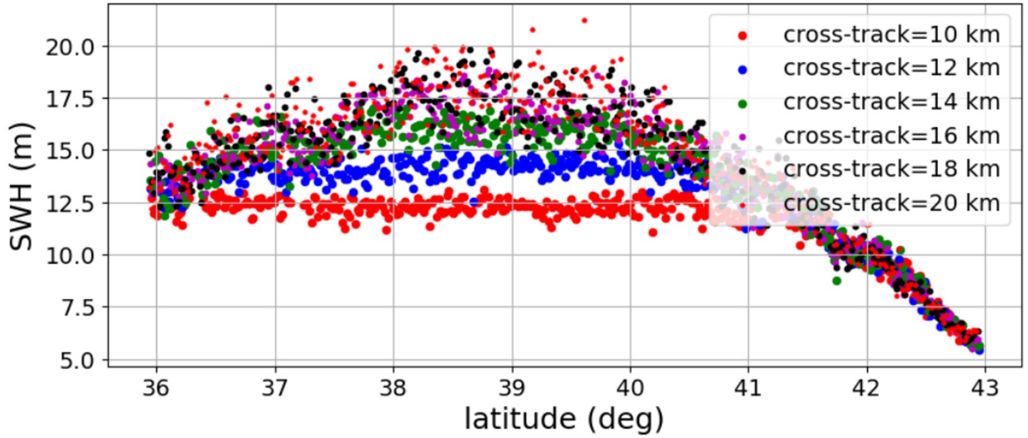
Preliminary analysis of Eddie: Hs fluctuations

NB: at 9 AM (close to SWOT pass at 8:55 AM), qkk for DIA run is 44 m, qkk for GQM run is 64 m

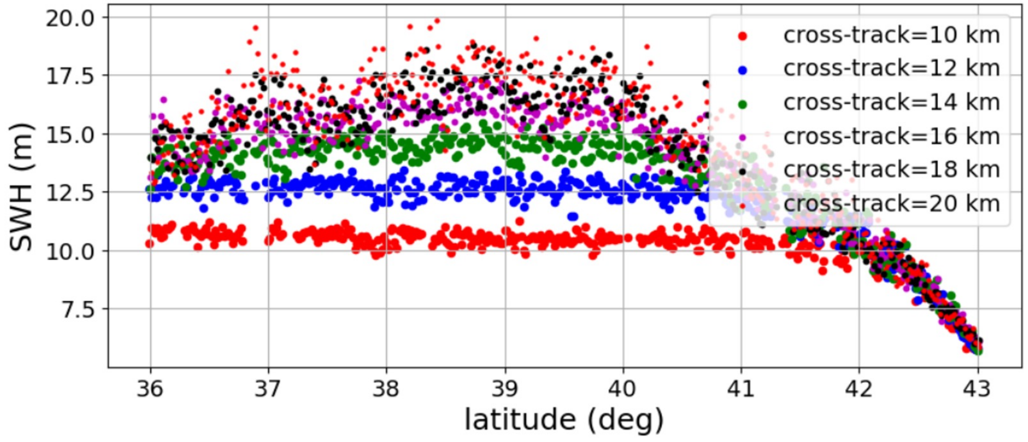
- with a L=17*250m=4.25 km averaging the expected std(Hs)/Hs is 0.067 m for qkk=64 m, and 0.046 m for qkk=44 m
- what part of the swath can we use ?

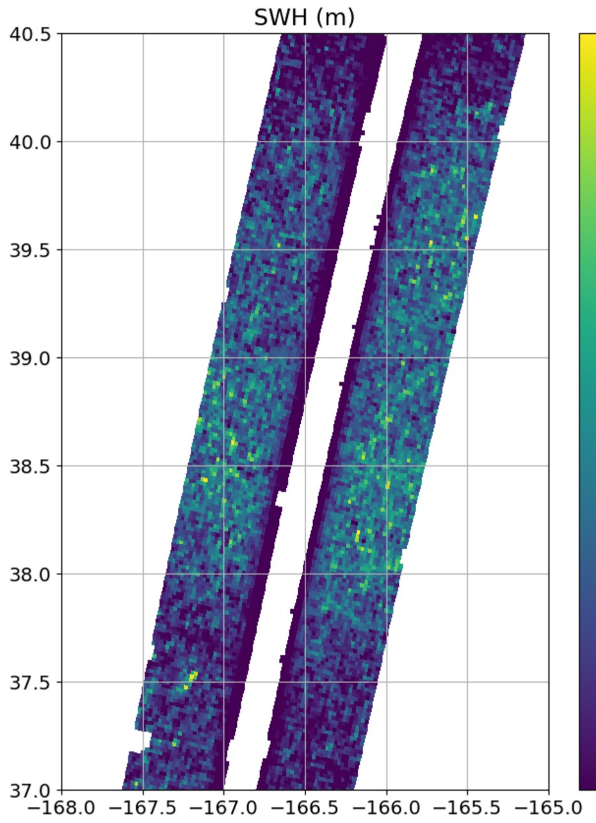
It looks like the coherence saturates towards nadir (see Bohe et al. 2025): good data for x > 20 km ?

right swath:
(indices 34+i)



left swath:
(indices 34-i)

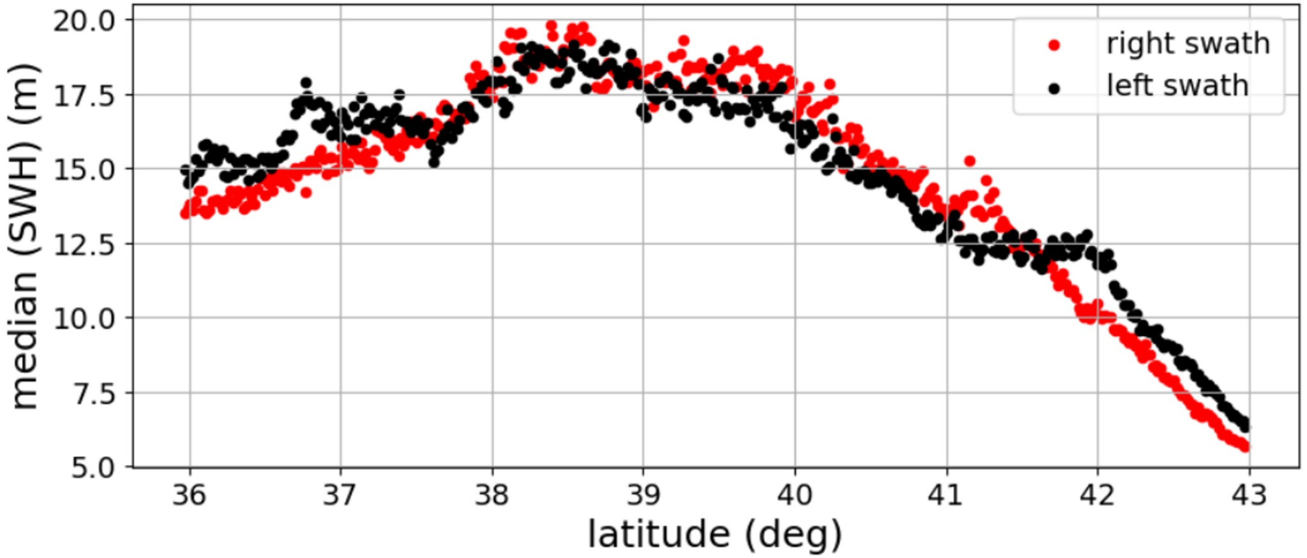




Preliminary analysis of Eddie: Hs fluctuations

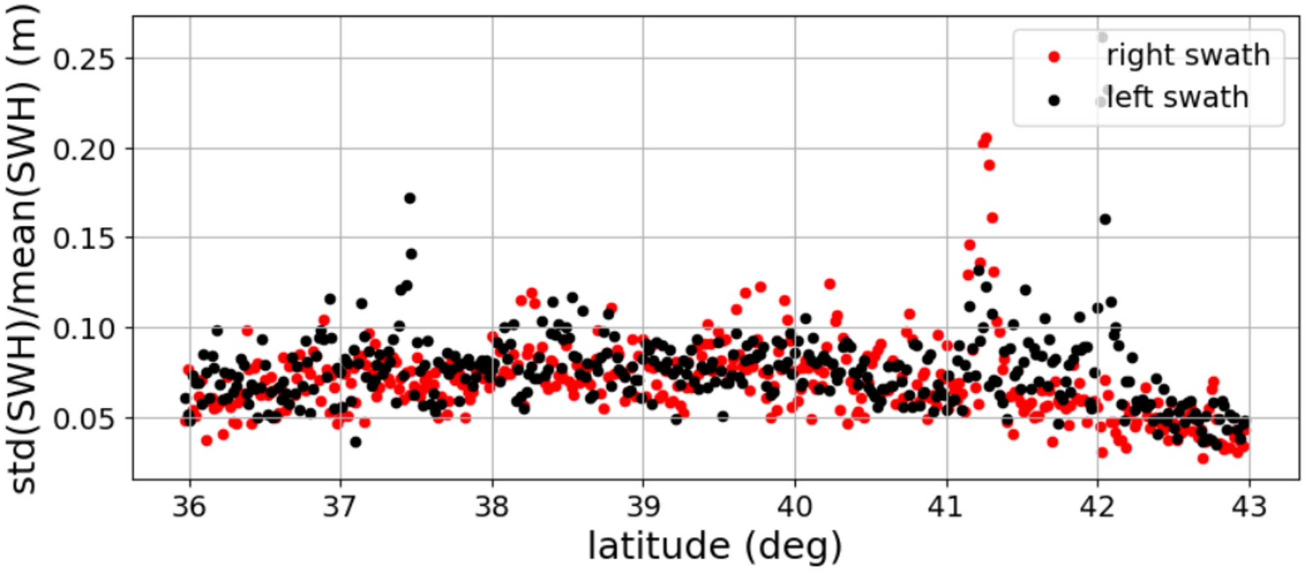
Using indices i=10 to i=29 we get these values of std(Hs)/mean(Hs) from KaRIN:

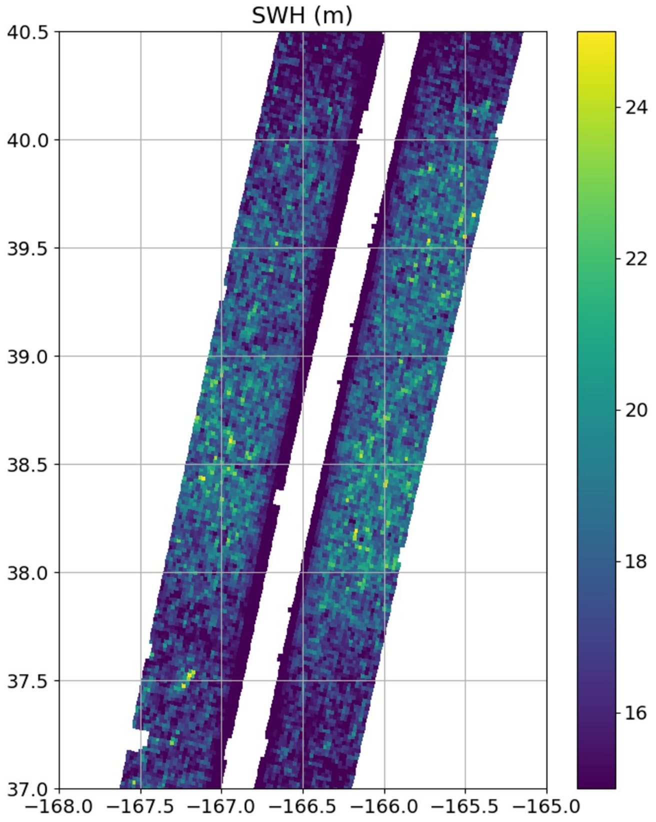
cross-track median:



normalized cross-track std:

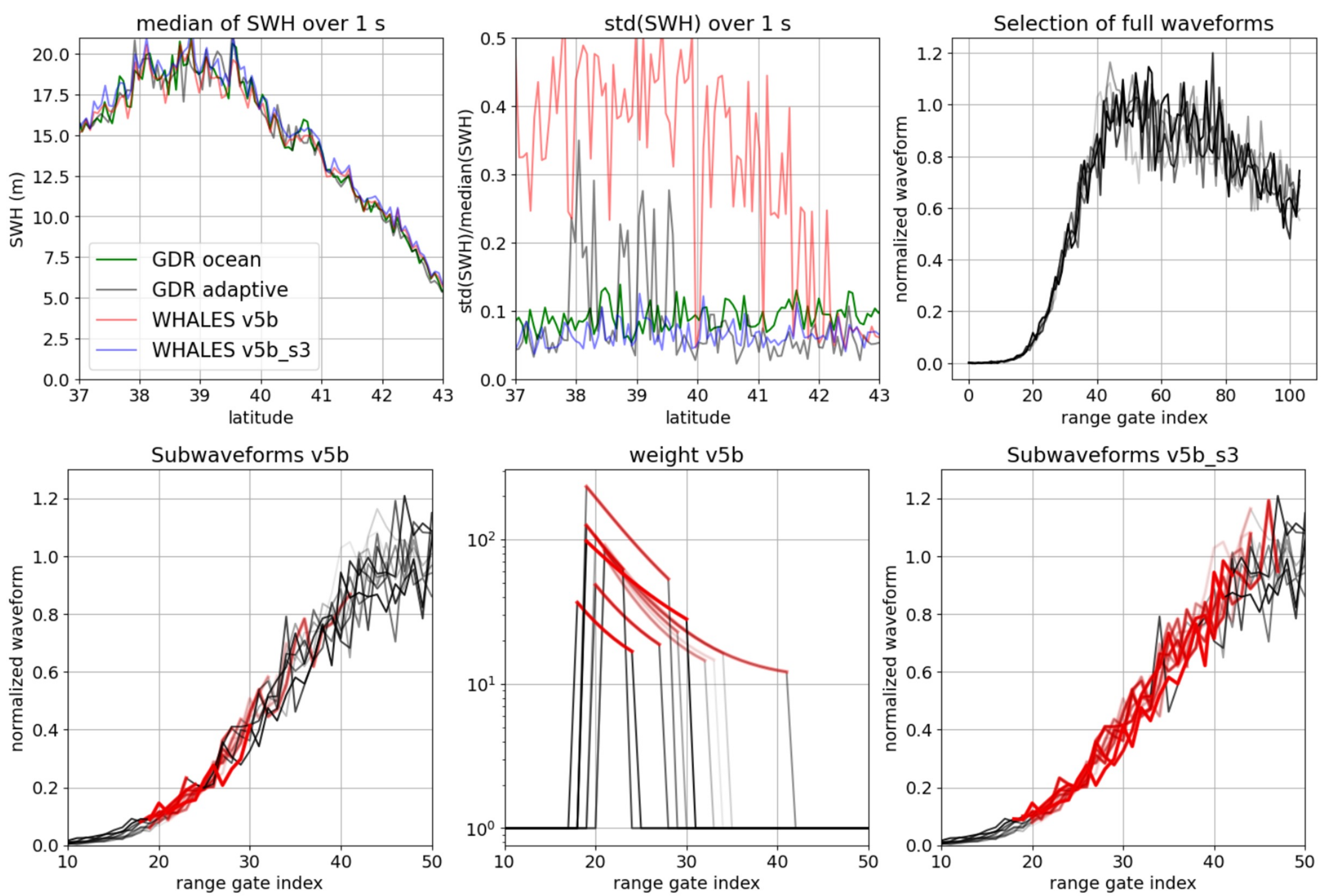
(NB: DIA values look closer… saturation??)





Preliminary analysis of Eddie: Hs fluctuations

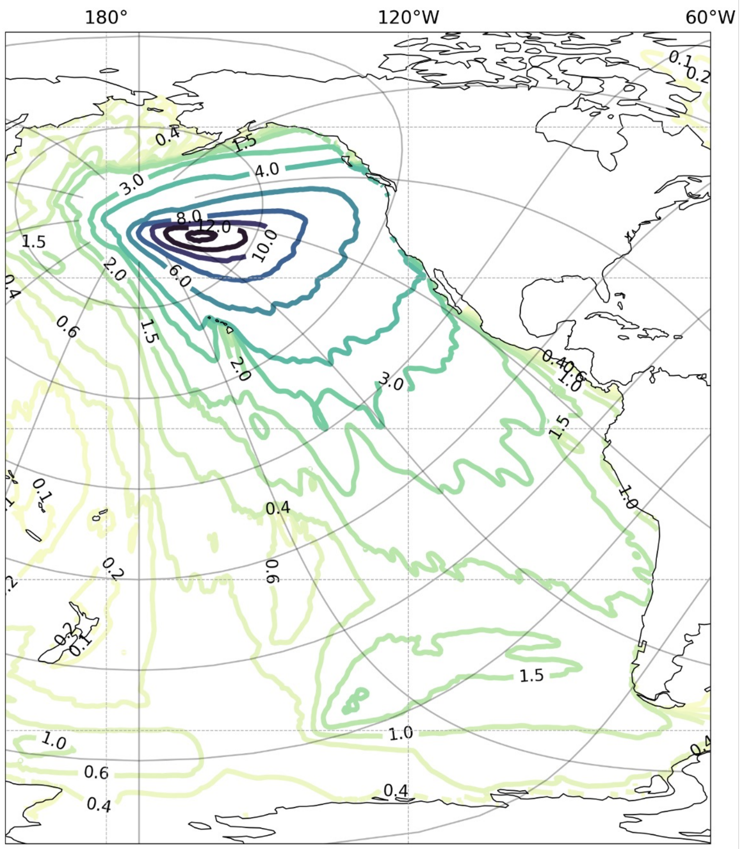
Looking at 20 Hz data in nadir (Poseidon 3C): GDR (ocean) and WHALES retracking (with -s 3 smoothing)



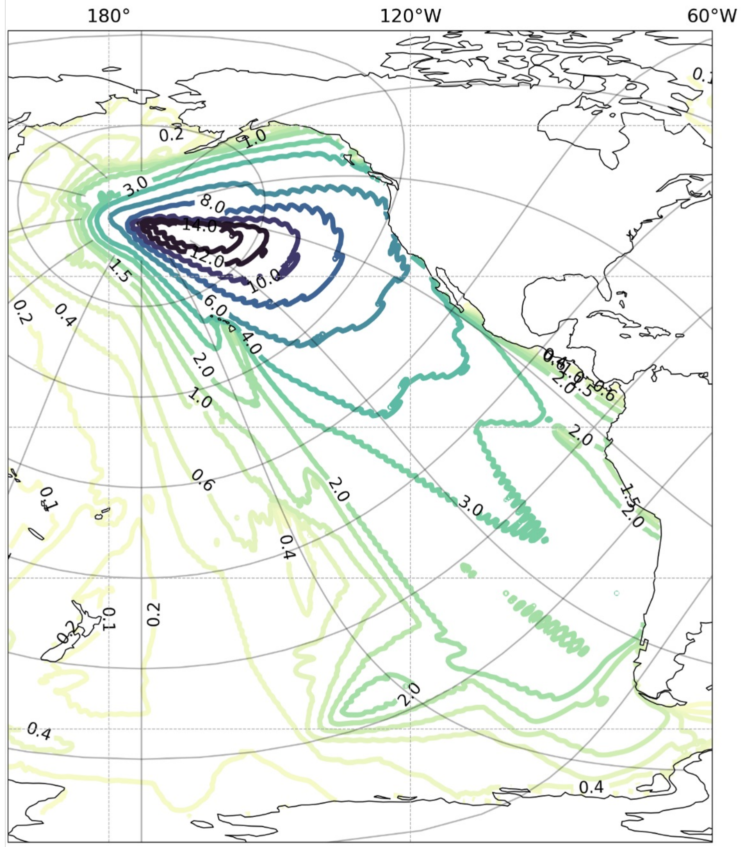
Preliminary analysis of storm Eddie: swells

Maps of H18 (max of H18 from Dec. 20 to Dec. 29):

with DIA (and currents)



with GQM



2. what it tell about 4-wave interactions: putting the puzzle together

We assume that wave with periods > 18 s are:

- generated in small area (R < 1000 km)
- are all generated before October 17.

So … on Oct. 17 at 00:00, all the 18 s waves have been generated and are in a small region.

Groves (JGR 1966): the spectra density is conserved along rays.

Collard et al. (2009): the observed swell energy is an average wave spectrum over the source

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$$E_0 = \int_{f_1}^{f_2} E_{S,iso}(f)/(2\pi)\, \Delta\theta'\, df = \int_{\alpha_1}^{\alpha_2} E_{S,iso}(g(t_o - t_s)/(4\pi\alpha' R_E))\, \Delta\theta'\, (df/d\alpha')\, d\alpha'/(2\pi) \quad (5)$$

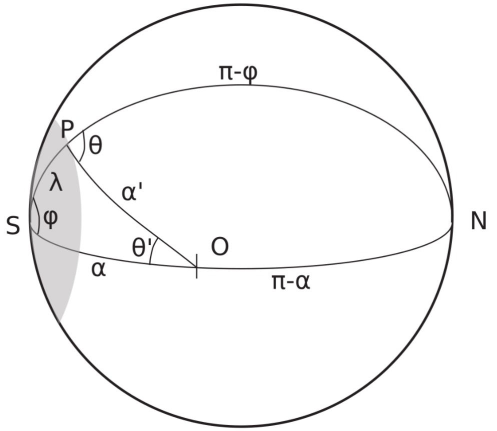
This integral can be evaluated numerically using any analytic expression for the source spectrum, which can be the JONSWAP spectrum[8] or the update proposed below with eqs. (8) and (9).

In the limit $|\alpha' - \alpha| << \alpha$ and $r << R_E$, which is appropriate far from the storm, we find $\Delta\theta' \simeq \pi(r/R_E)/(2 \sin\alpha)$ when averaged from α_1 to α_2 and $df/d\alpha' \simeq f_\alpha/\alpha$ with

$$f_\alpha = g(t_o - t_s)/(4\pi\alpha R_E) \quad (6)$$

and we get the asymptotic form

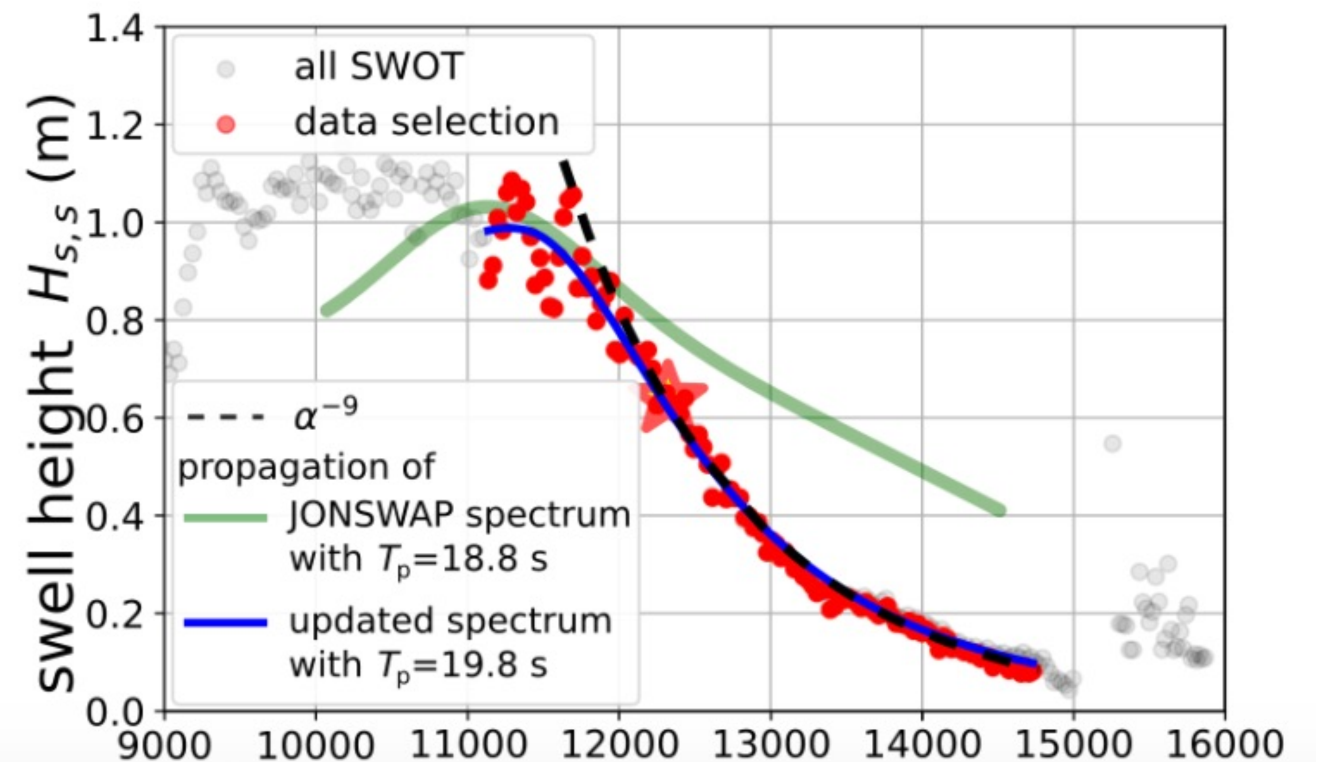
$$E_0(\alpha, SPP, r) = f_\alpha\, E_{S.iso}(f_\alpha)(r/R_E)^2/(2\, \alpha \sin\alpha) \quad (7)$$

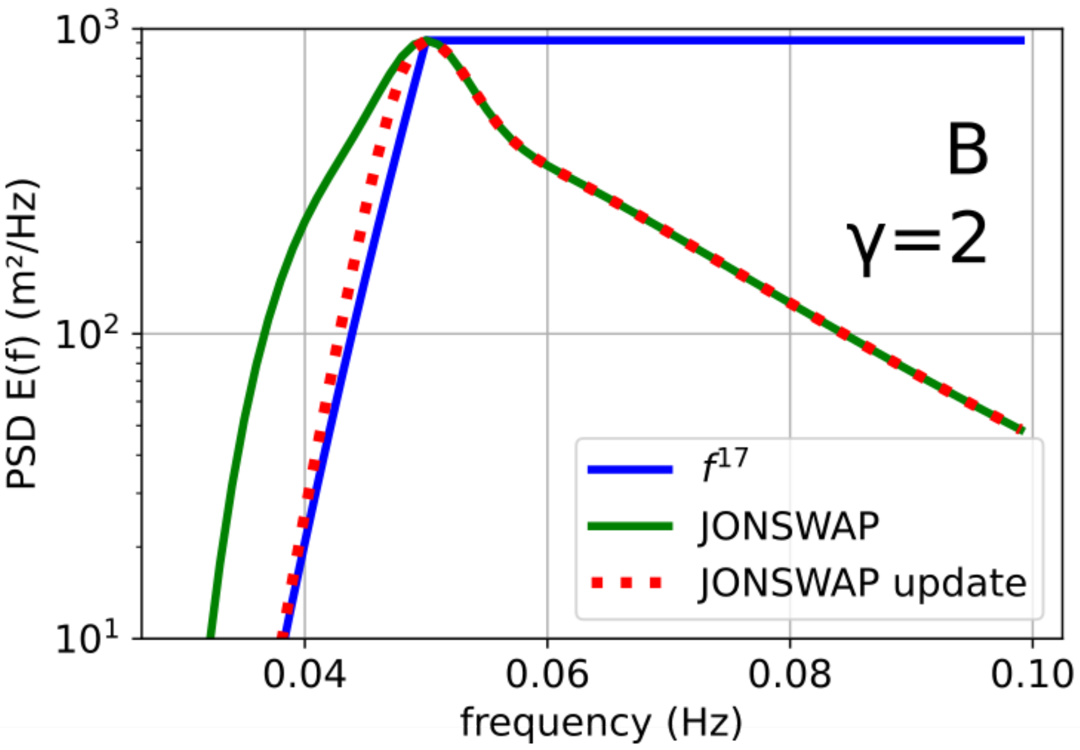


2. what it tell about 4-wave interactions: putting the puzzle together

So … the shape of the spectrum in the source region is related to the swell field…

thus Hss ≅ d^{-9} means E(f) ≅ f^{17}, a really steep forward face of the spectrum



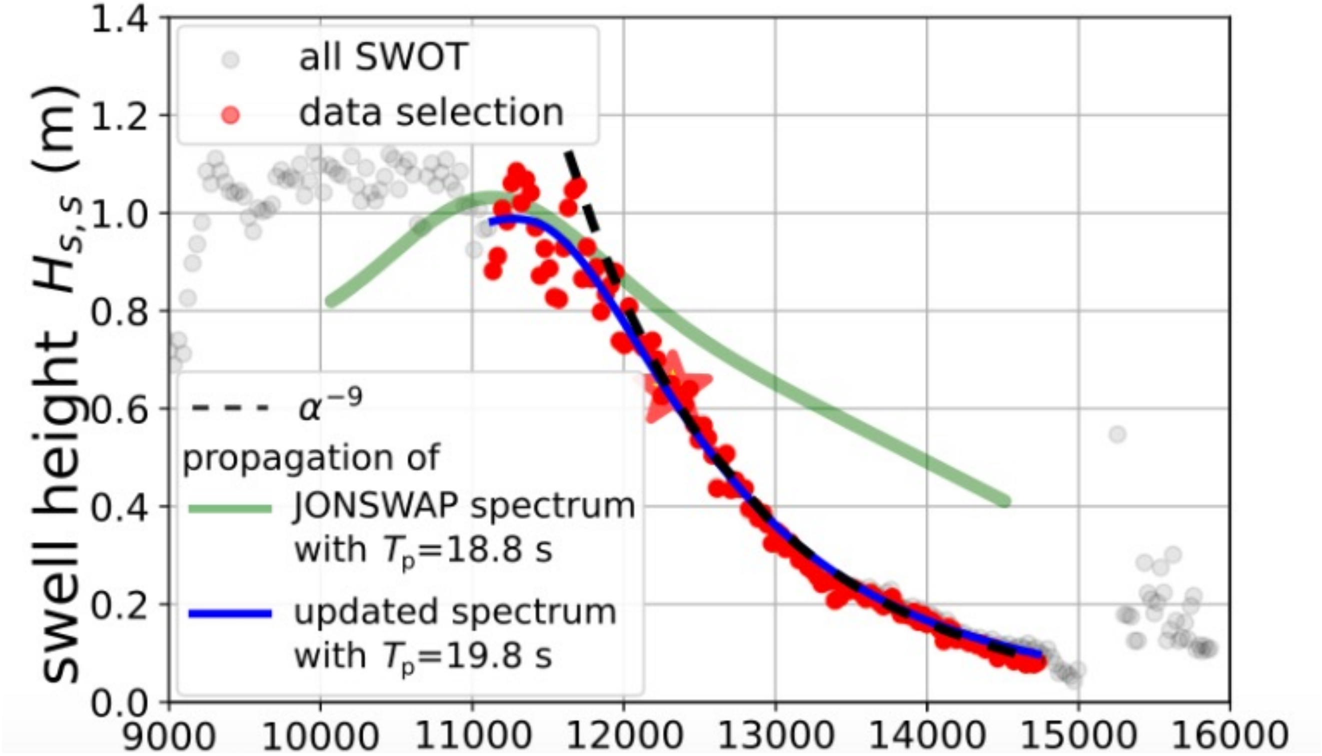


2. what it tell about 4-wave interactions: putting the puzzle together

So … the shape of the spectrum in the source region is related to the swell field…

thus Hss ≅ d^{-9} means E(f) ≅ f^{17}, a really steep forward face of the spectrum

which is actually consistent with Snl calculations for swell (Lavrenov 2003, Badulin & Zakharov NPG 2017)



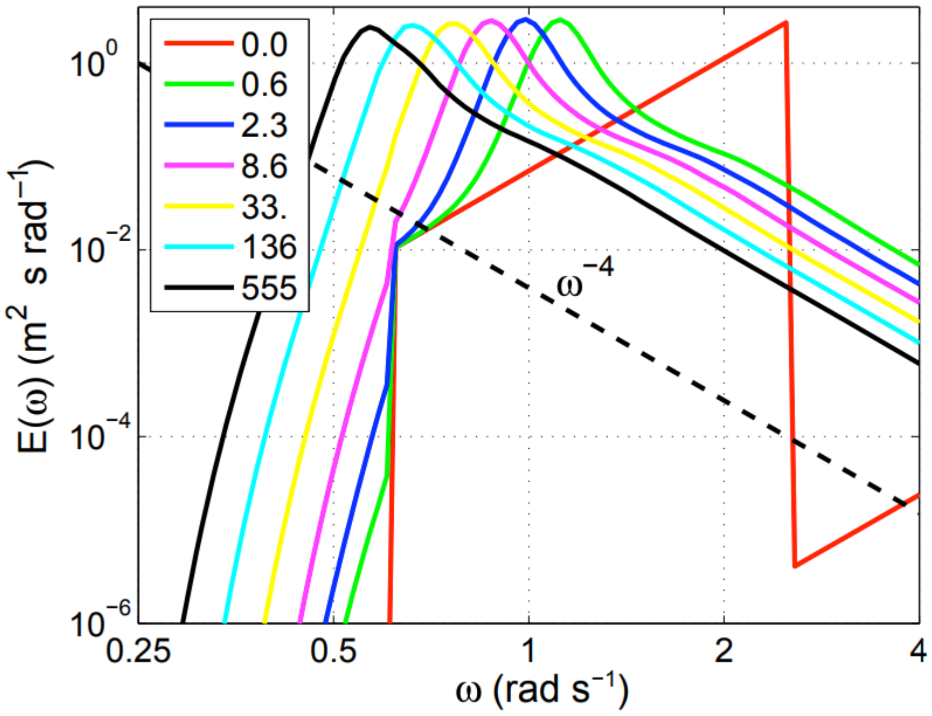
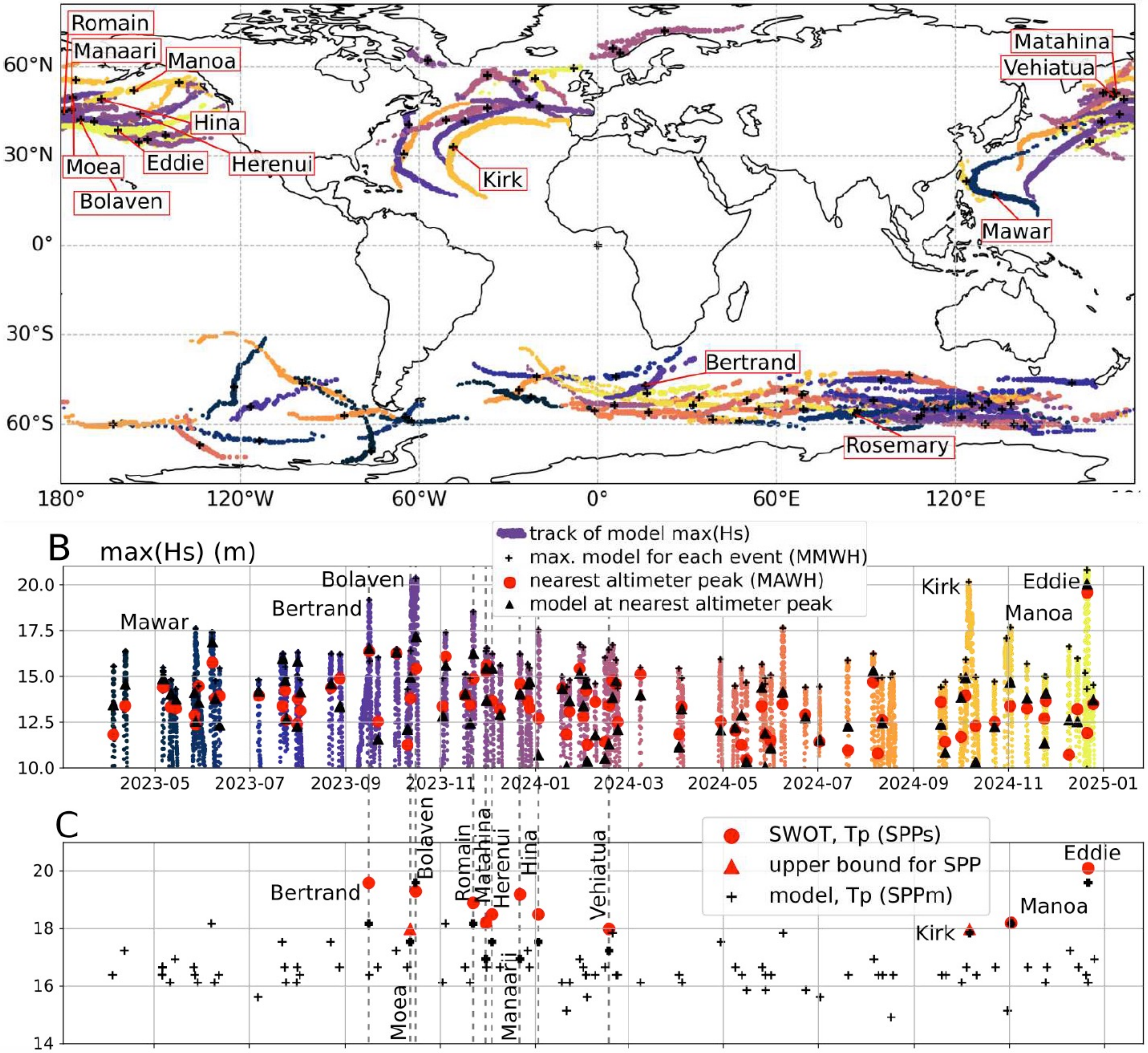


Figure 1. Frequency spectra of energy at different times (legend, in hours) for case sw330 ($\Theta = 330°$).



3. Adding Storm peak Periods to the climate record

SWOT era (2023/04 – now)

10 storms analyzed by Taina Postec

3. Adding Storm peak Periods to the climate record: CFOSAT data

Using L2S data (with new MTF v2) produced by Ifremer

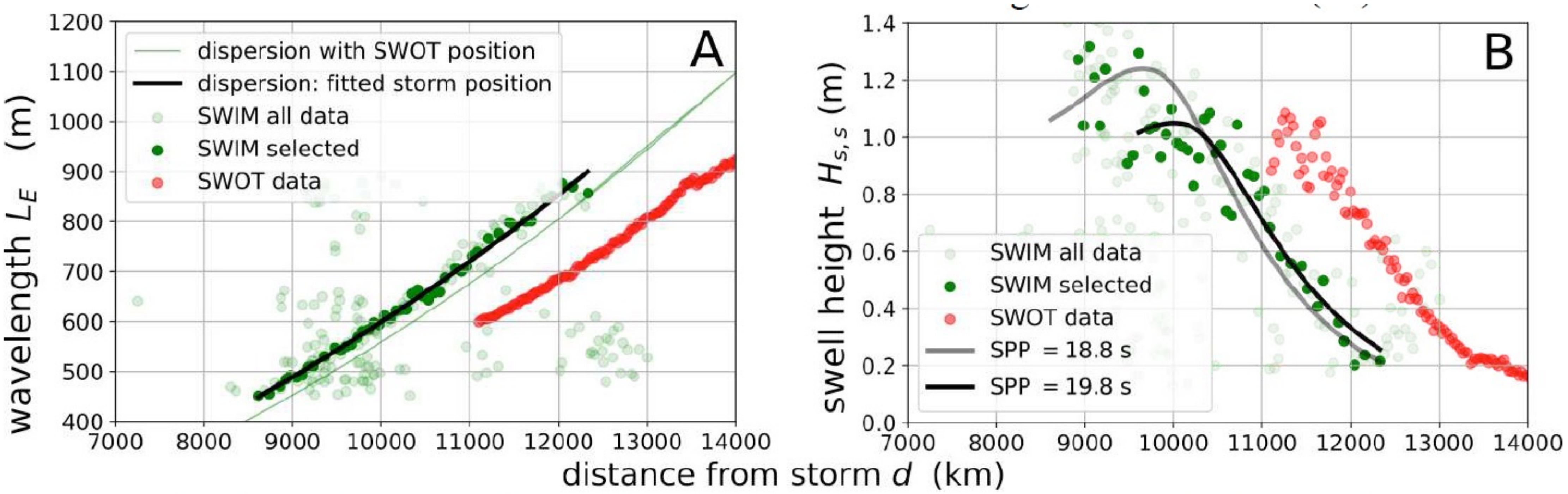


Fig. 4. Estimation of storm peak period using SWIM 10° beam data, acquired along the green track of Fig. 1.B, 9 hours before the SWOT data along the red track. (A) wavelength and (B) swell heights and fitted swell height (grey and black curves) using either all good data or only data with $L_E > 550$ m.

5. The spectral energy balance: from DIA to GQM

48 direct connections to other spectral components sounds like a lot…
enough to get a decent inverse energy cascade, and wave growth.

- many drawbacks: spurious dissipation-like at high frequency (Banner and Young 1994 …)

If you are doing research on source terms, you should use exact NL calculations.
Webb-Resio-Tracy method (see also van Vledder): not so fast, feasible for few cases
(e.g. Ardhuin et al. JPO 2007, Romero and Melville 2010 https://doi.org/10.1175/2009JPO4128.1)

Lavrenov (2001) proposed a faster method to compute the full 4-wave interactions: adapted by Michel Benoit, see Gagnaire-Renou (2009) for details and talks on Wednesday.

- allows filtering and “detailed balance”
- makes forecasts feasible (for an already expensive WAVEWATCH III run, the cost is x8)
- we can now look at nonlinear wave evolution and spectral balance in all conditions
- Some retuning of wind-wave and wave-ocean terms will be needed.

5. The spectral energy balance: from DIA to GQM

Here is one example: simulation of swells from storm "Rosemary", June 6, 2023

this GQM configuration uses : 11×6×6=396 points for integration along resonant manifold

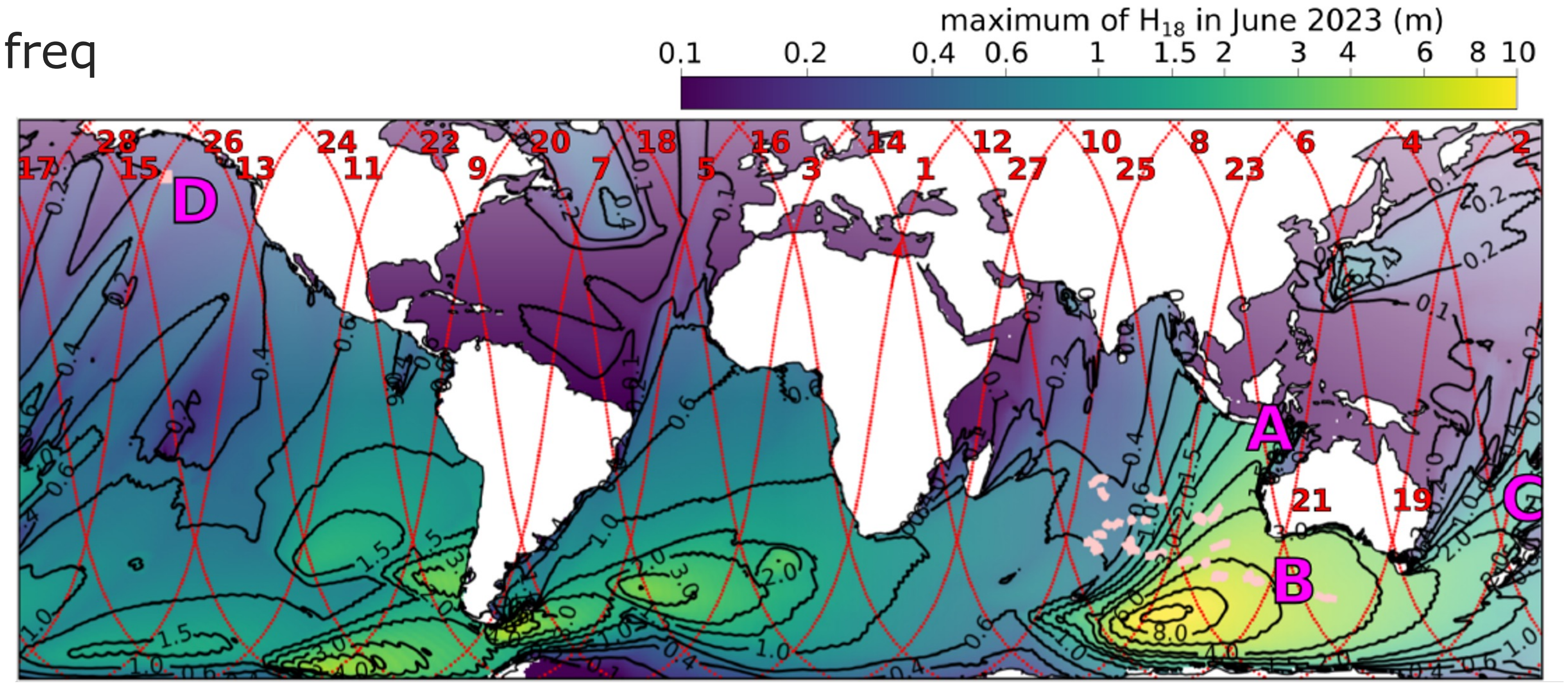
- filter on coupling coef. amplitude (0.05): keeps 202 out of 396 quadruplets
- filter on spectral saturation (5E-5): 50% more cost reduction

WAVEWATCH III namelist: &SNL1 IQTYPE = -2, GQMNF1 = 11, GQMNT1 = 6, GQMNQ_OM2 = 6,
TAILNL=-5.0, GQMTHRSAT=5E-5, GQMTHRCOU = 0.05, GQAMP1=1.,
GQAMP2=0.0022, GQAMP3=2. /

NB: contrary to DIA, no bilinear interpolation: each quadruplet gives 6 source term updates

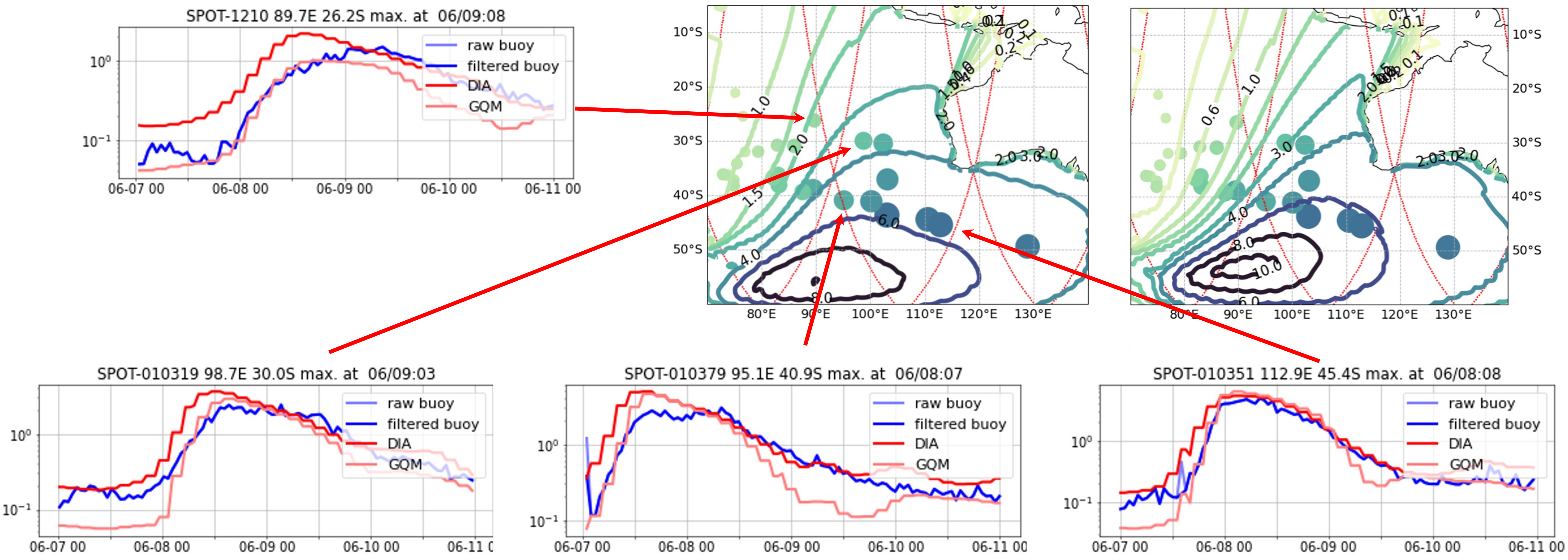
Global 0.5° model with 24 dir, 32 freq
48h for 1 year on 500 procs

NB: 2 known bugs in wind stress calc.
(table + reset of ustar in w3wave)
more bugs on gustiness not used here.



5. The spectral energy balance: from DIA to GQM

Long period energy pattern (here H_{18}) is different with DIA and GQM: broader field with DIA



What about shorter components ? We now have to talk about dissipation …

Summary

- Wind-generated waves can be modeled by a spectrum which may include nonlinear effects

- For spectral wave evolution: assumptions about dispersion, physical processes and their parameterization as **source terms**

- Integrals of **sources terms** give fluxes (air-wave, wave-ocean, wave-ice …)

- parameterization can have very strange side-effects ("unphysical features", not "coding bugs")
    - wind-sea / swell cross-talk in WAM Cycle 3 & 4 (mean steepness in Komen et al. 1984)
    - sharp laminar to turbulent swell dissipation in Ardhuin et al. (2010)
    - choice of "long wave direction" in Romero (2019)
    - DIA spurious dissipation (Banner and Young 1994) …
    - …
- similar things about numerics … another time: diffusion, GSE, non-convergent limiters…
- some parameterizations work better (like Romero 2019): what does it tell us about physics?
    - let's look critically at all the bits and pieces of parameterizations
    - let's look critically at remote sensing "Geophysical Model Functions"
      (includes empirical corrections: roughness correction for salinity, sea state bias for altimetry, wave-induced Doppler shifts …)