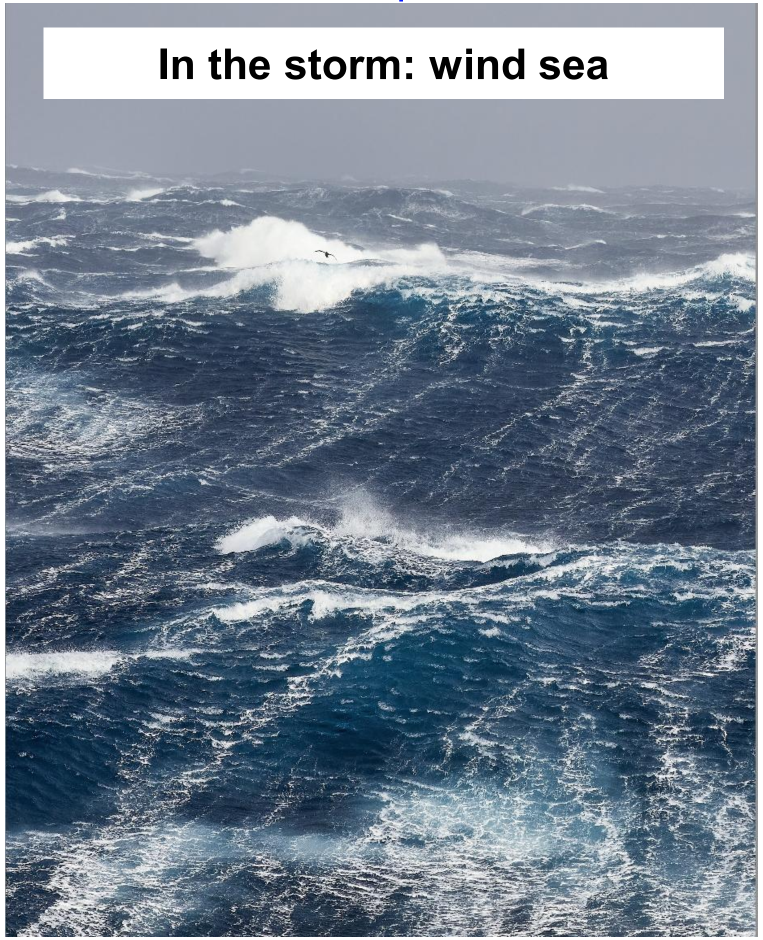
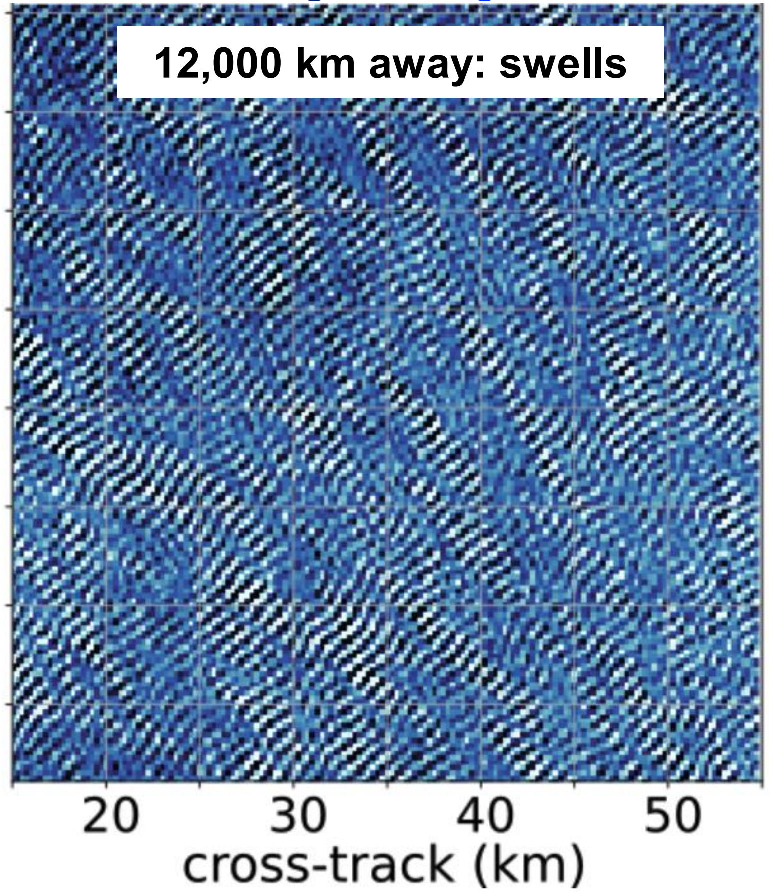
Generation and propagation of the largest ocean waves:
using SWOT wave spectra to validate and calibrate numerical models

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]

Laboratoire d'Océanographie Physique et Spatiale (LOPS), Brest, [2]TUM, [3]CLS, [4]OceanDataLab, Locmaria-Plouzané.

First part: PNAS, this week edition: "**Sizing the largest ocean waves using the SWOT mission**"





Spoiler:

- **new records : Hs =19.7± 0.3 m**
  Tp = 20.2 s
- **f < fp not good**
  in JONSWAP spectrum
- **Snl with DIA is not enough:**
  GQM works great!
- **propagation of narrow spectra:**
  more GSE…

Big waves are beautiful

This is not a Tropical Cyclone, not an Ex-Tropical Cyclone, not a freak wave …

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

1. storm catalogue

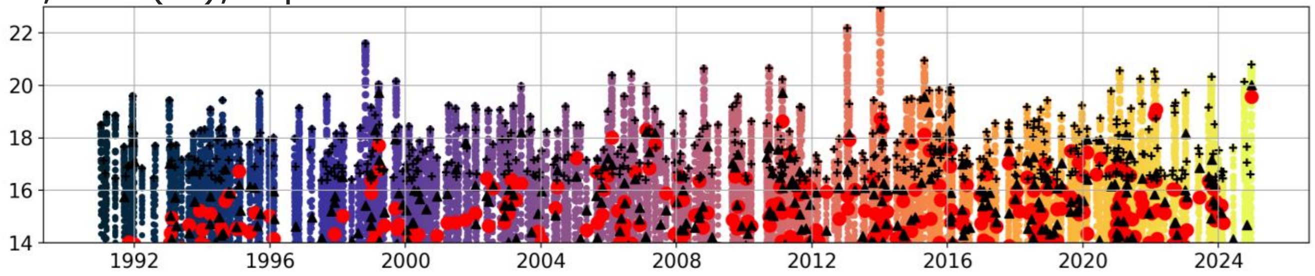
1: uses model hindcast (Accensi 2025, based on Alday & Ardhuin 2023)

http://tiny.cc/bigwaves

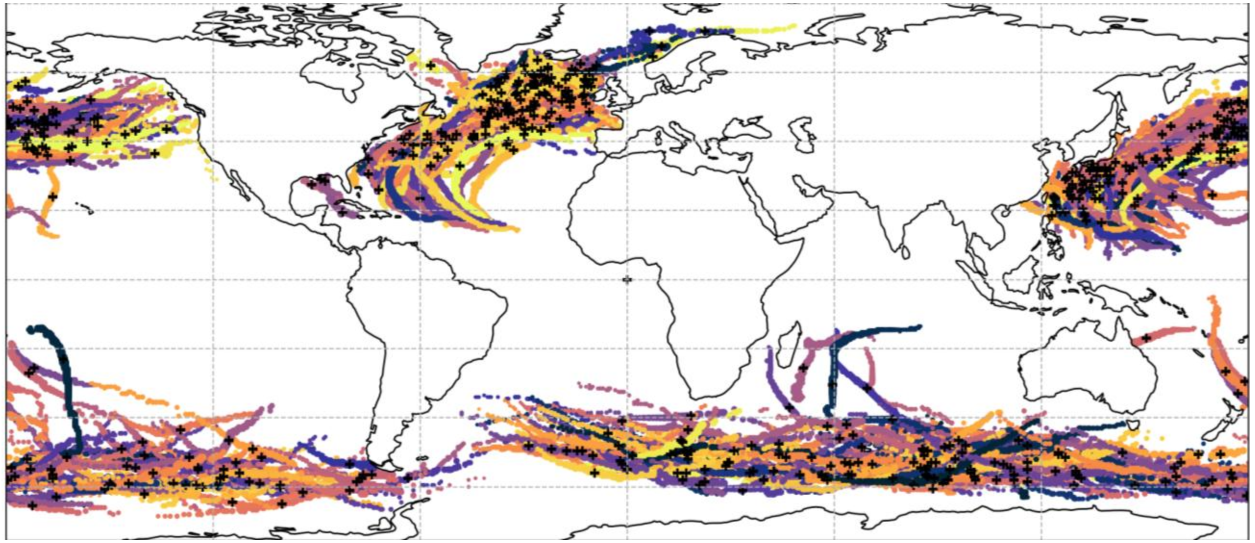
top storms. 1991 to 2024

rank	name	date	lon.(°)	lat.(°)	MMWH (m)
1	Hercules	20140105	031W	47N	23.0
2	Paul*	20130115	166E	39N	22.2
3	Yoshiaki*	19981026	177W	42N	21.6
4	Luigi*	20150427	138E	56S	21.0
5	Eddie*	20241221	161E	39N	20.8
12	Bolaven	20231016	174W	42N	20.3

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



tracks, top 500 storms. 1991 to 2024



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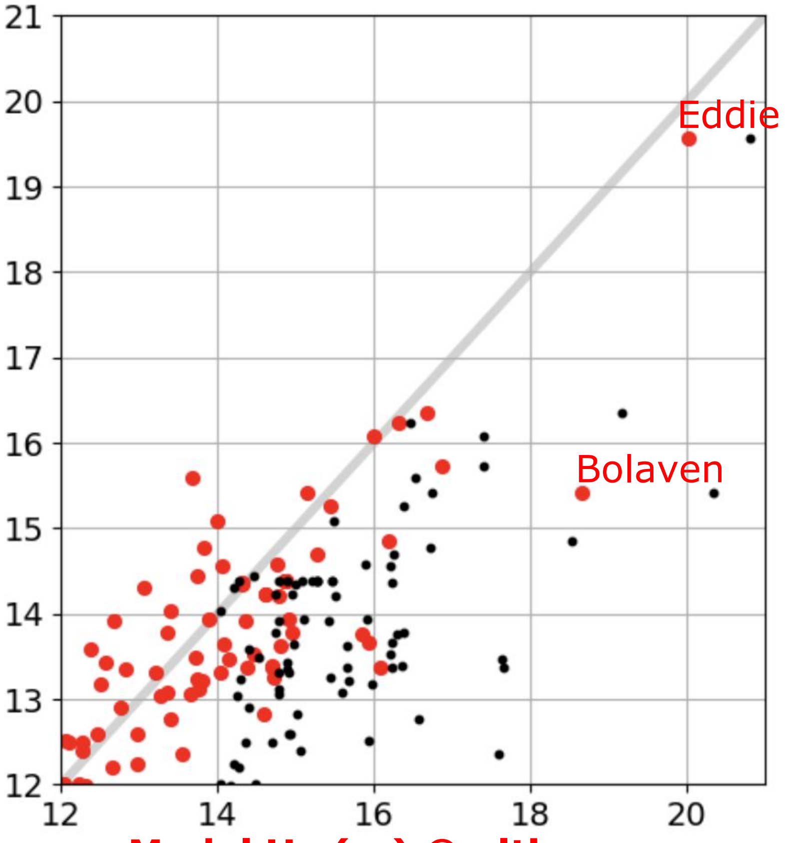
+ SWOT + CFOSAT

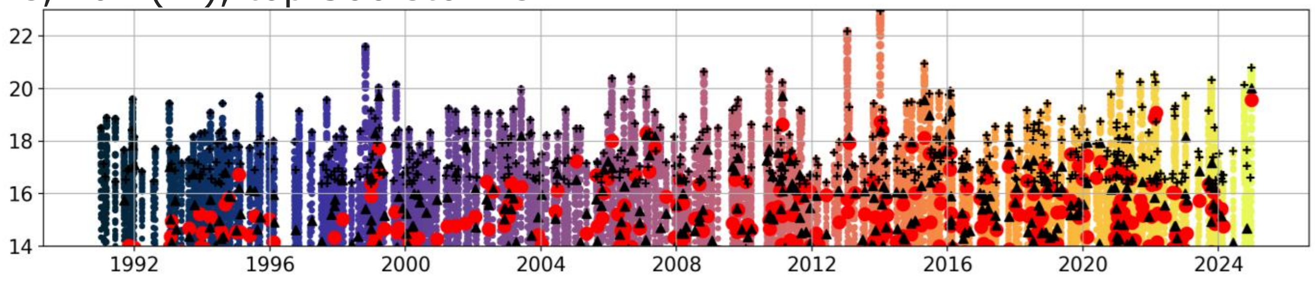
Max. altimeter Hs (m), 2023-2024



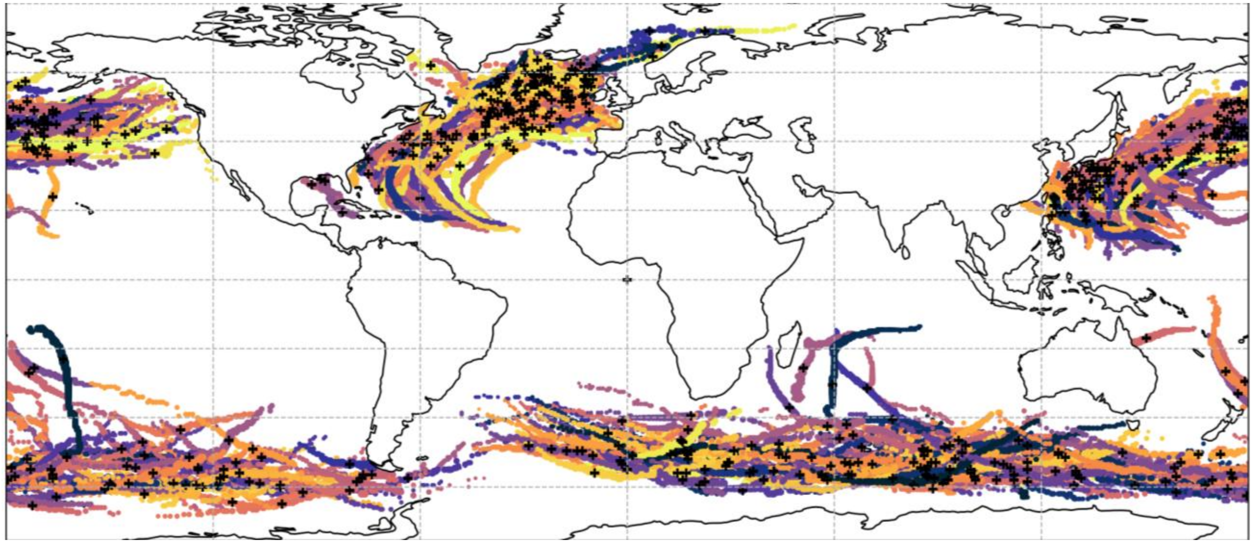
Model Hs (m) @ alti max.

Max model Hs (m)

Hs,max (m), top 500 storms



tracks, top 500 storms



1. storm catalogue: largest altimeter wave heights

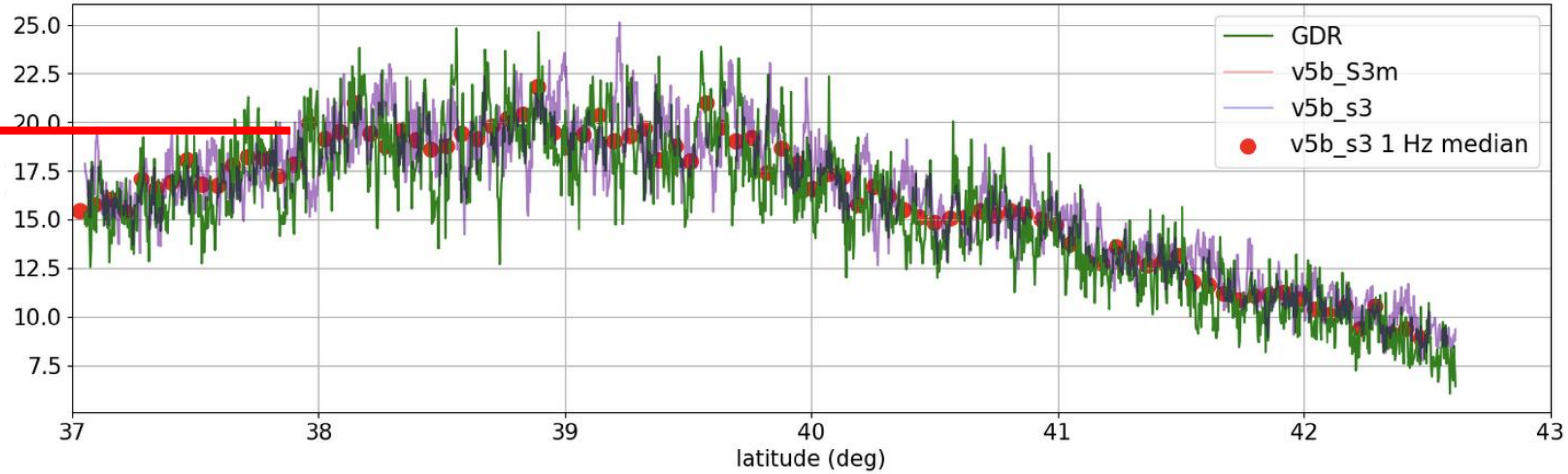
SWOT retracking (will be in SeaState CCI V5 dataset):

from the waveforms we re-computed the local wave height SWH (see De Carlo et al. JGR 2023)

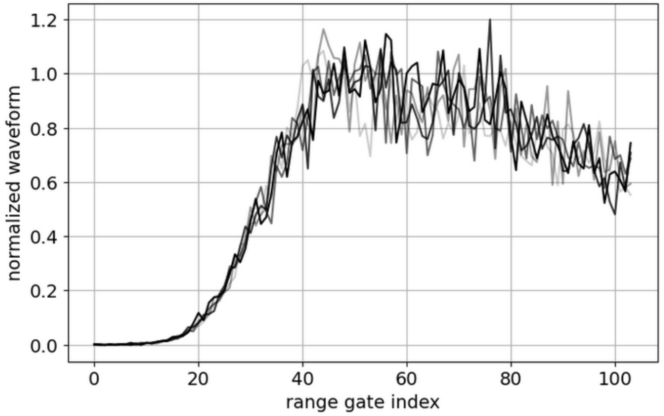
less noisy with WHALES retracker (problems with adaptive on SWOT)

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

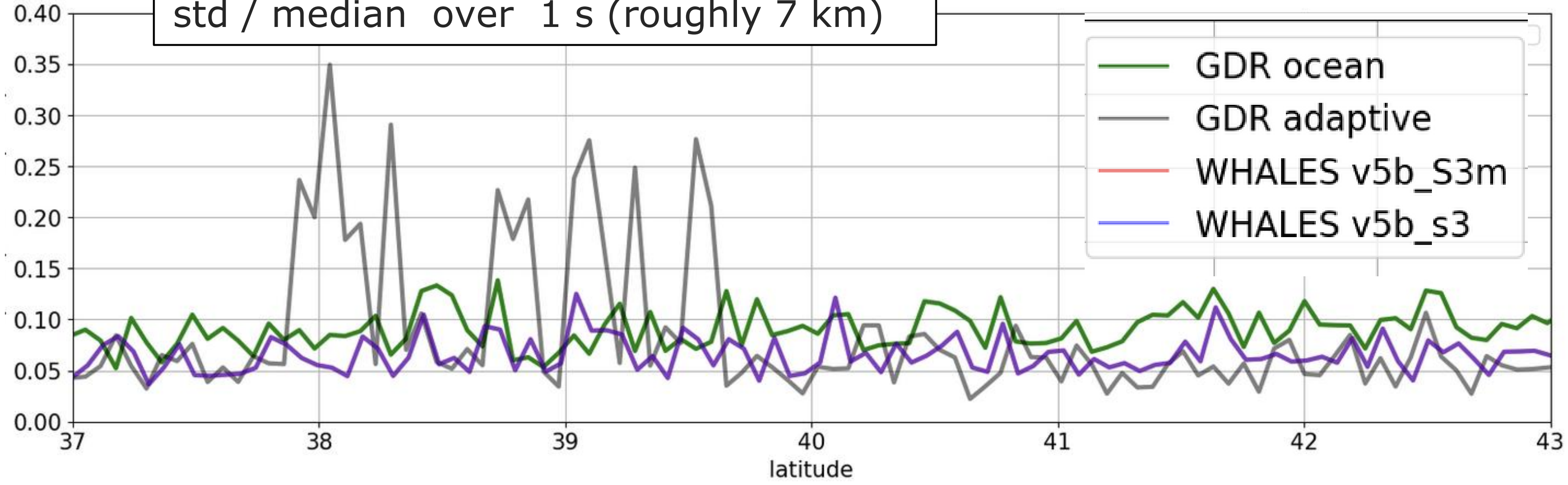
max (Hs) is 19.7± 0.3 m



Waveforms for SWH=20.1 m



std / median over 1 s (roughly 7 km)



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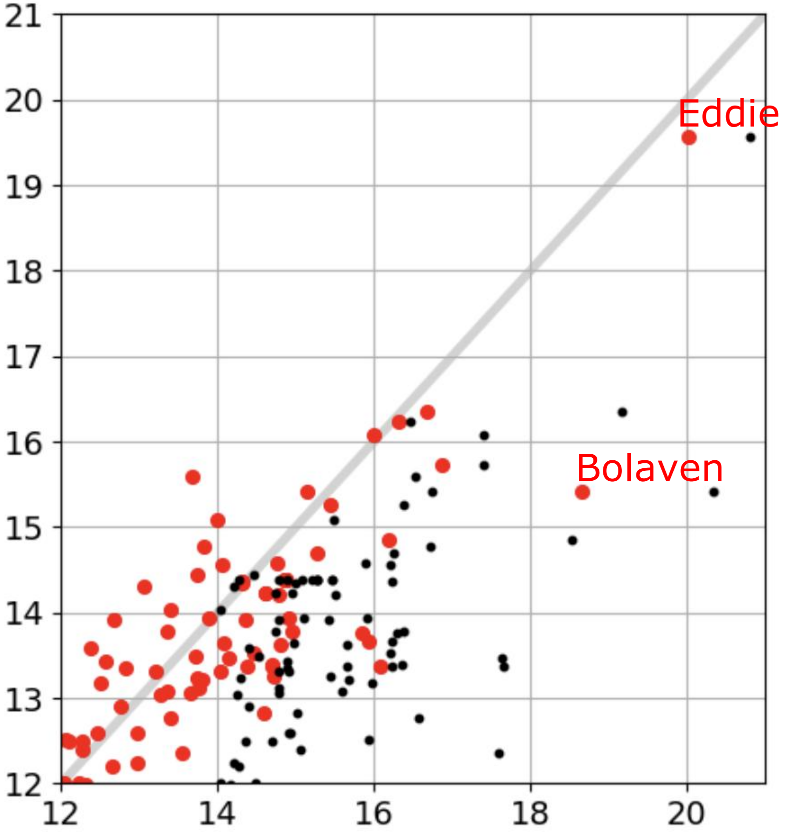
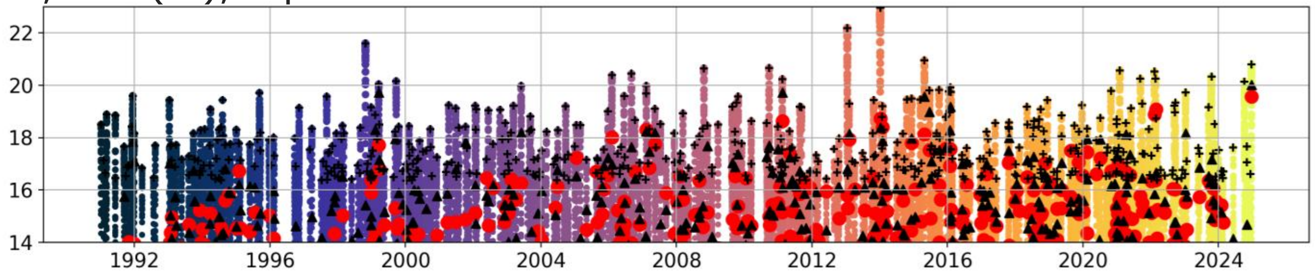


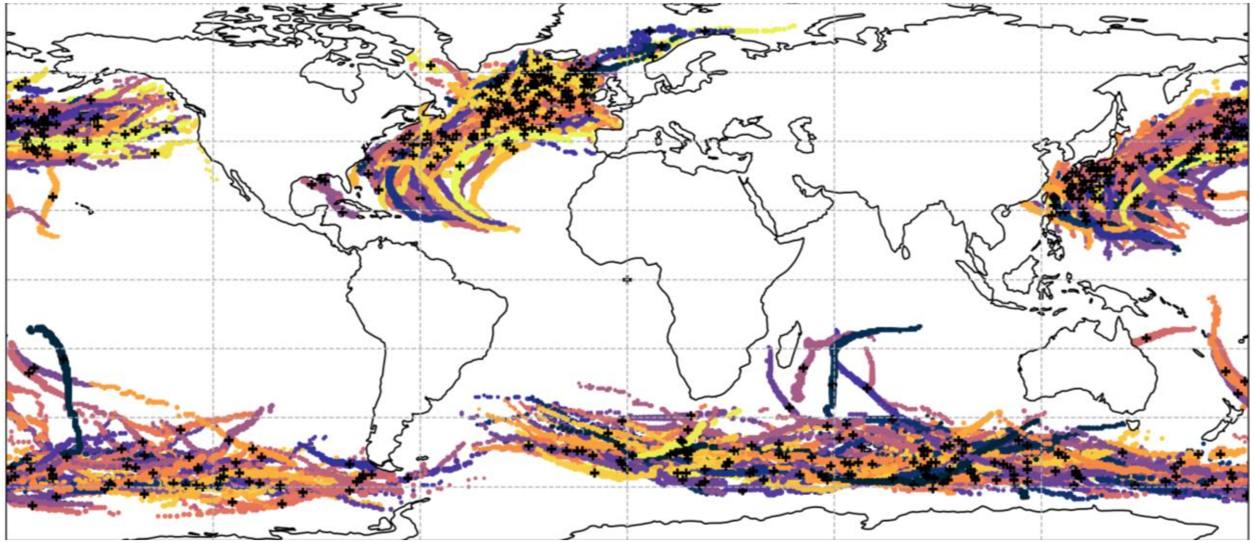
Model Hs (m) @ alti max.

Max model Hs (m)

Hs,max (m), top 500 storms



tracks, top 500 storms



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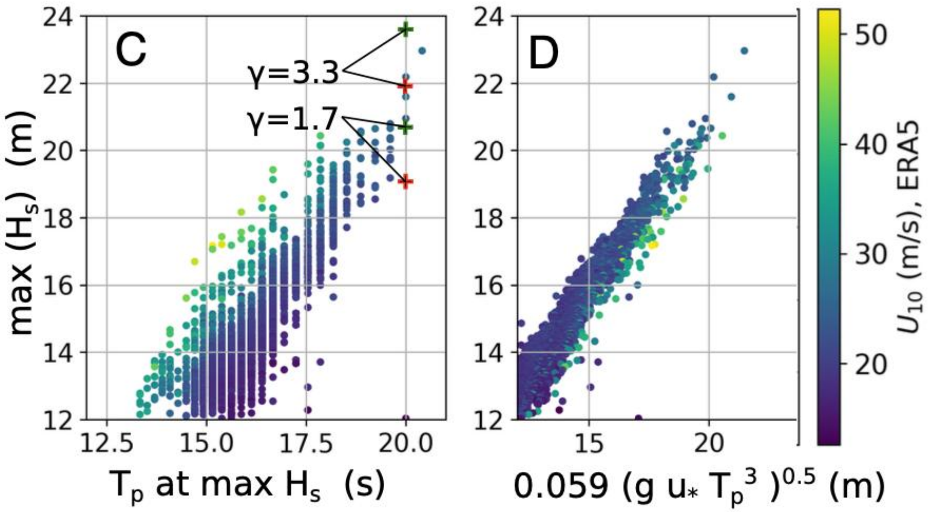
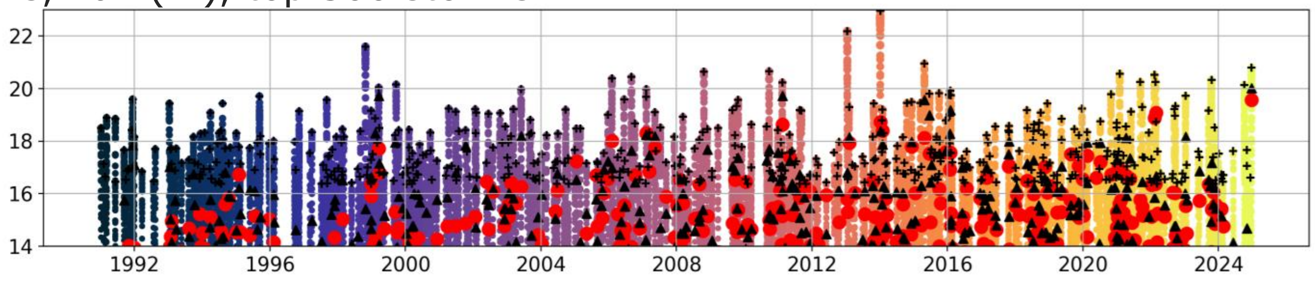
3: quantifying peak periods in storms (Ardhuin et al. PNAS 2025)



Hs,max (m), top 500 storms



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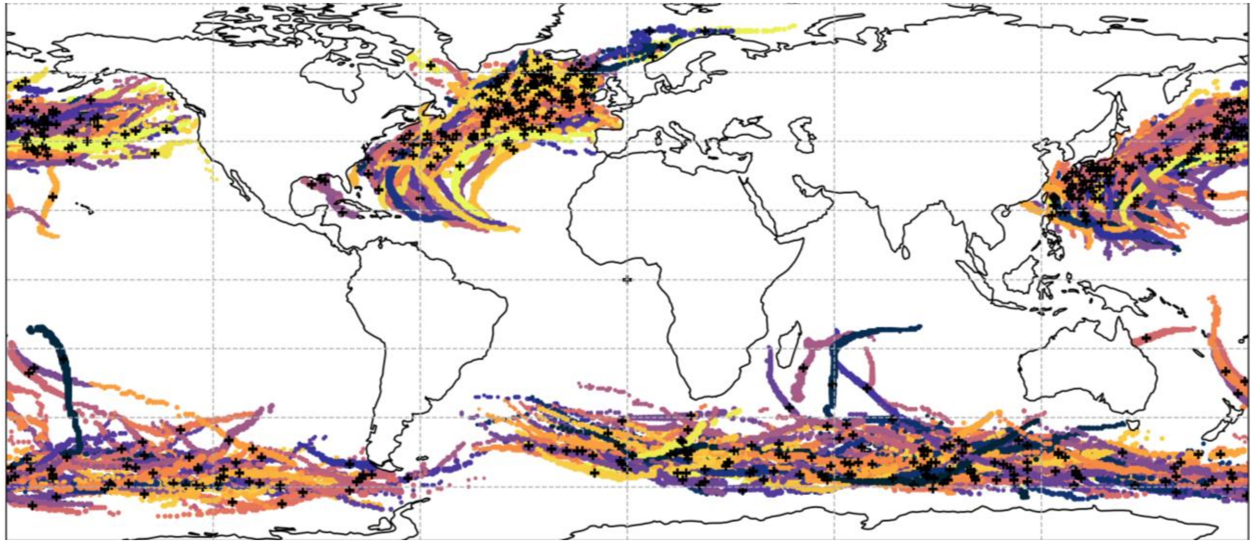

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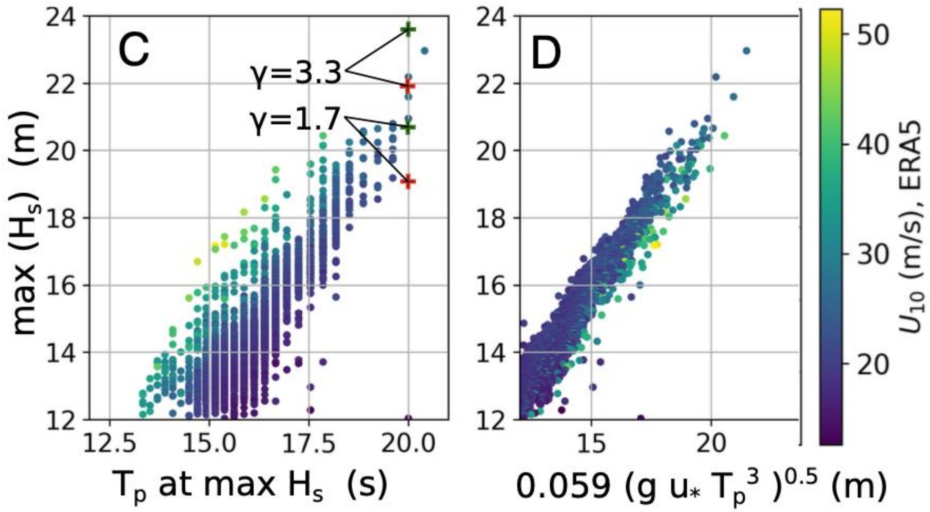

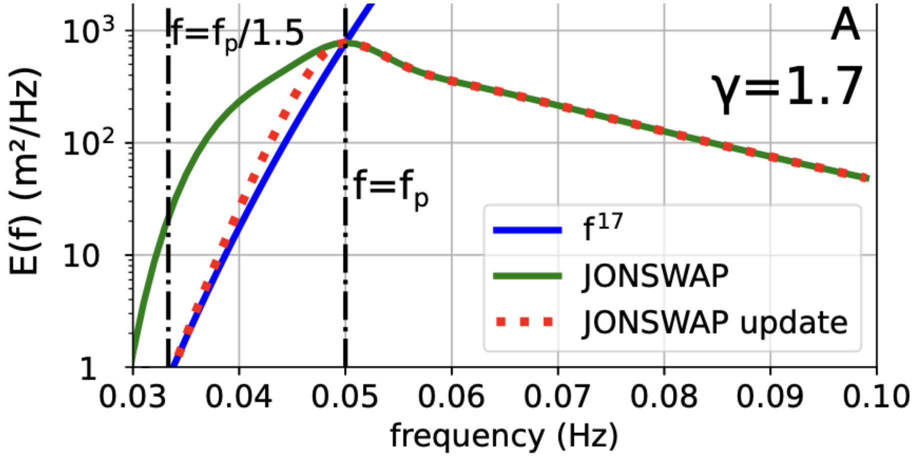

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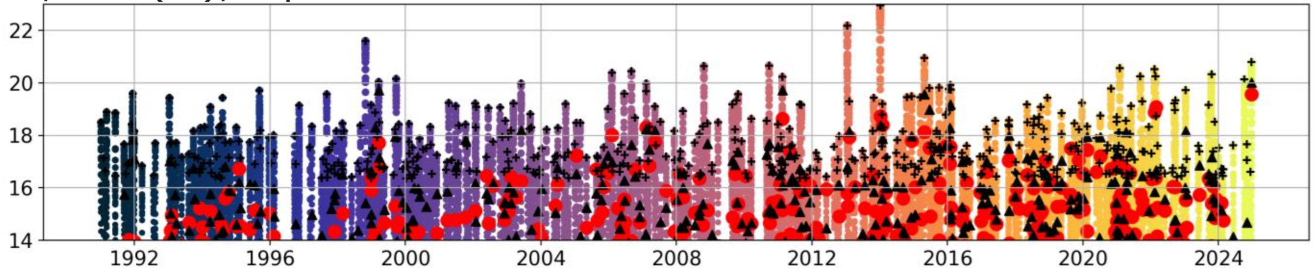

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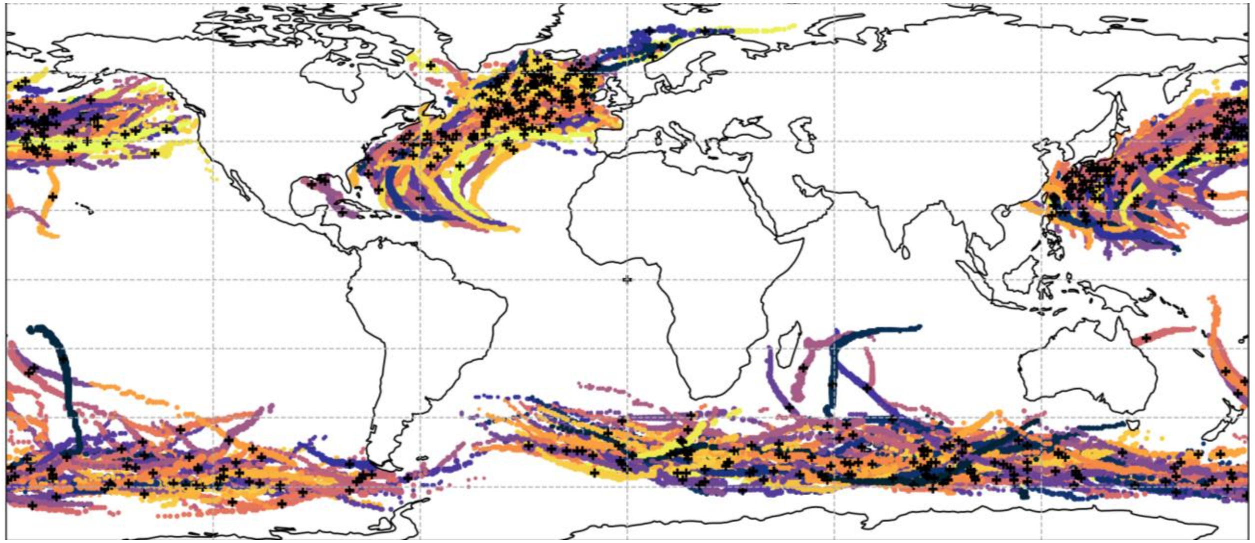
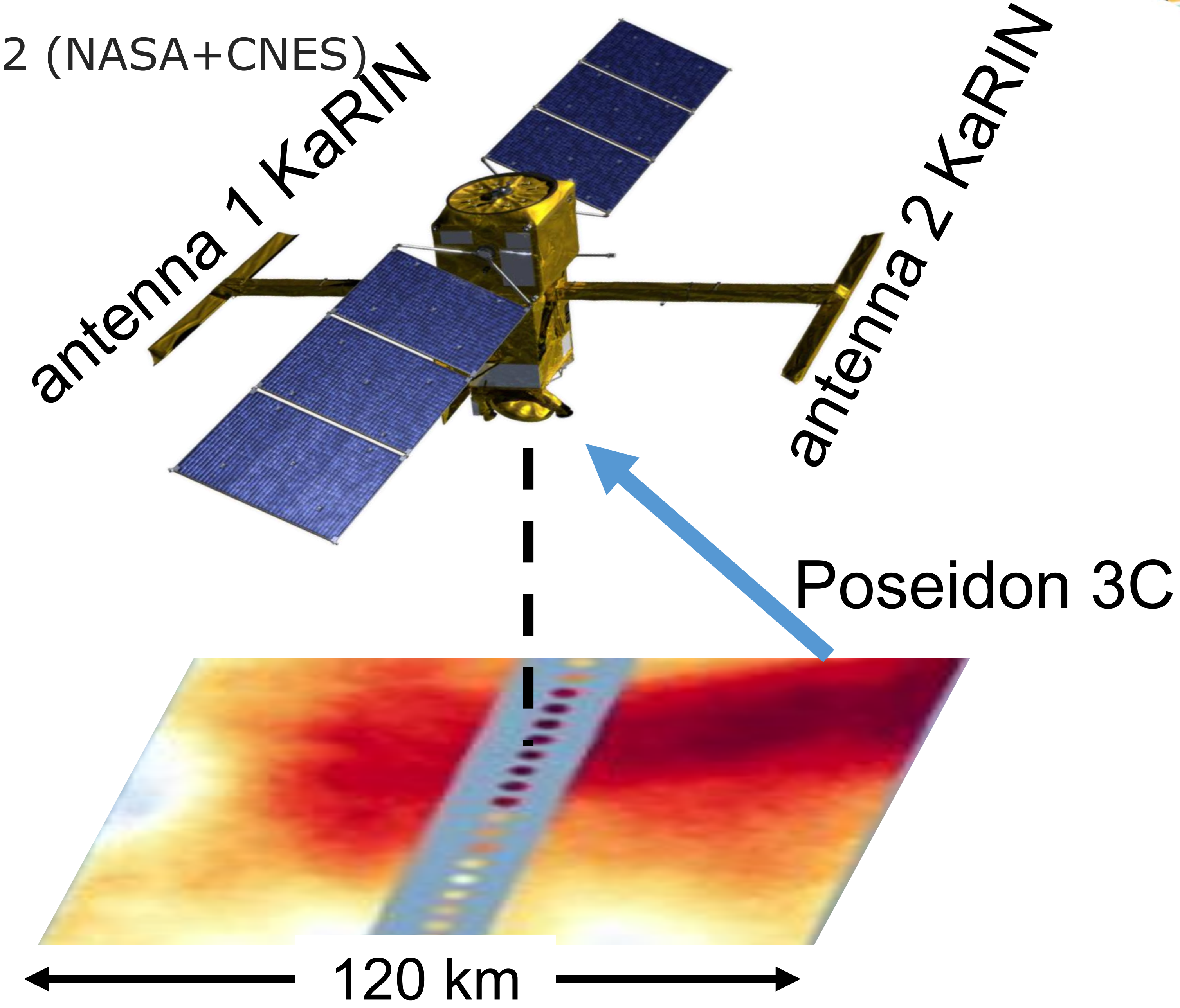


2. Surface Water Ocean Topography (SWOT)

- Launched december 2022 (NASA+CNES)
- 2 different altimeters
- KaRIN provides maps



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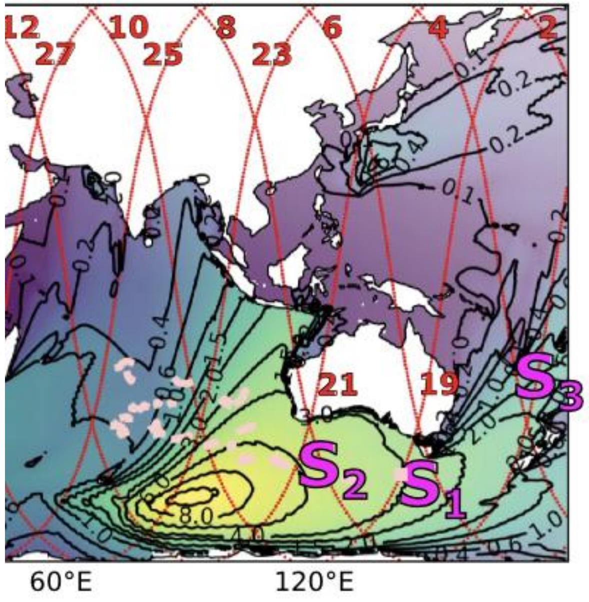


- Spectra available from CNES (Aviso)

- New version in 2025 (work on partitions …)

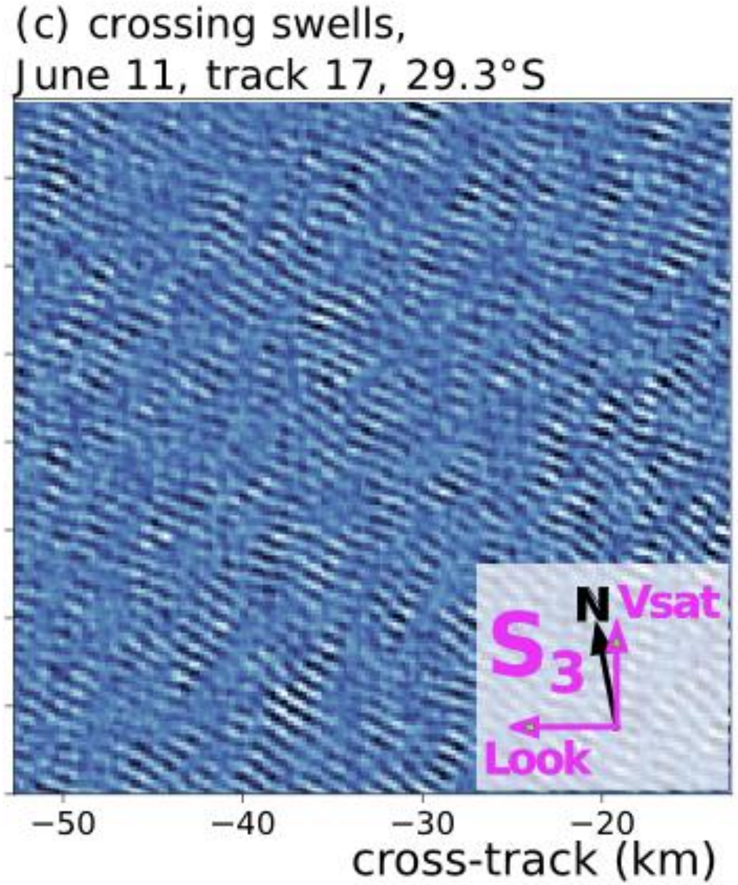
Geophysical Research Letters

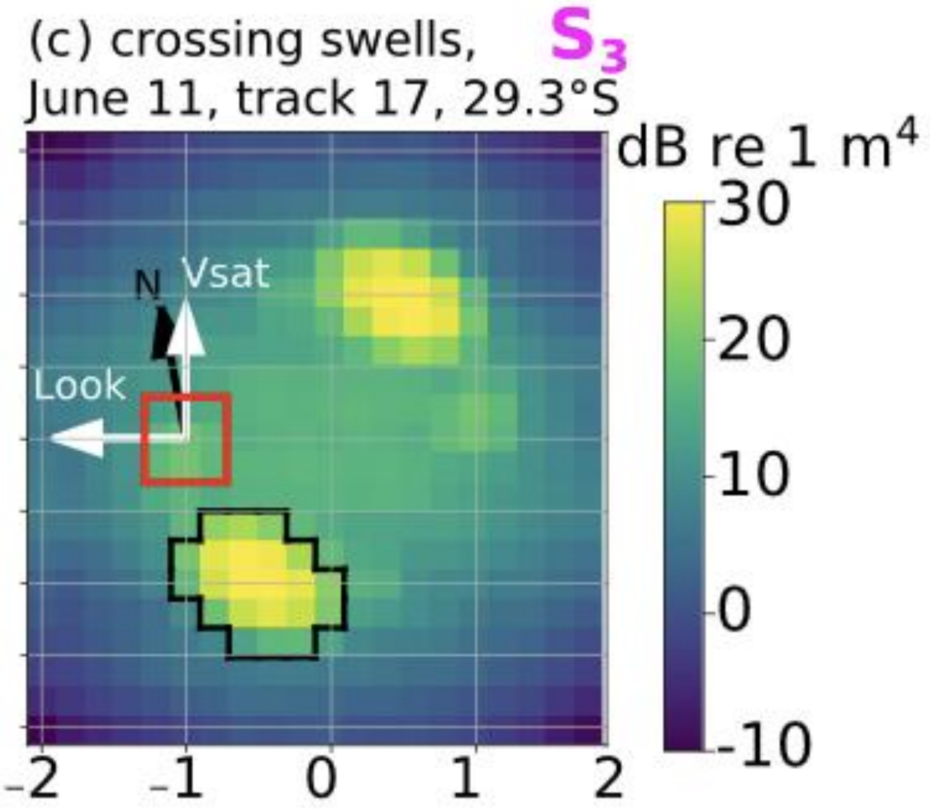
RESEARCH LETTER
10.1029/2024GL109658

Special Collection:
Science from the Surface Water and Ocean Topography Satellite Mission

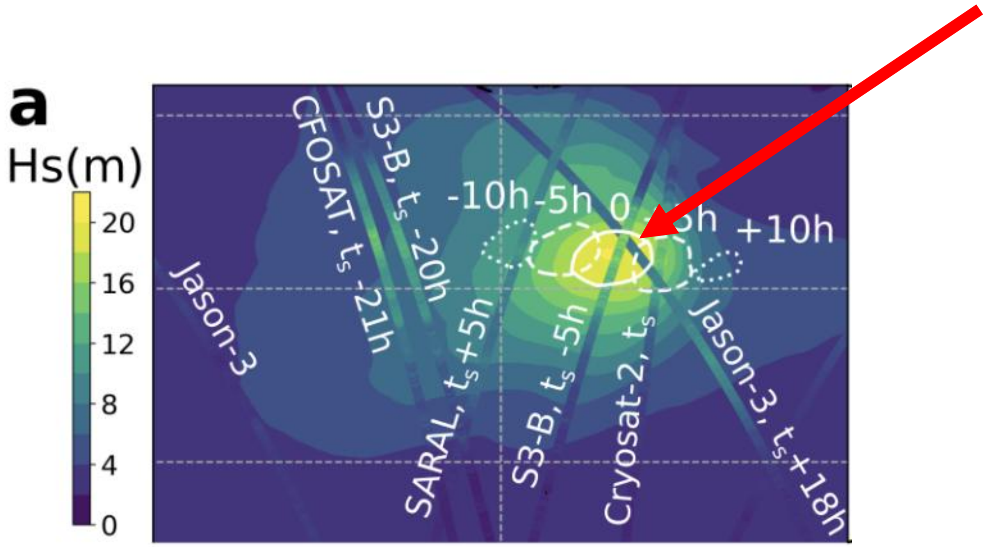
Phase-Resolved Swells Across Ocean Basins in SWOT Altimetry Data: Revealing Centimeter-Scale Wave Heights Including Coastal Reflection

Fabrice Ardhuin[1], Beatriz Molero[2], Alejandro Bohé[3], Frédéric Nouguier[1], Fabrice Collard[4], Isabel Houghton[5], Andrea Hay[6,7], and Benoit Legresy[6,7,8]





3. Swells from storm Bolaven

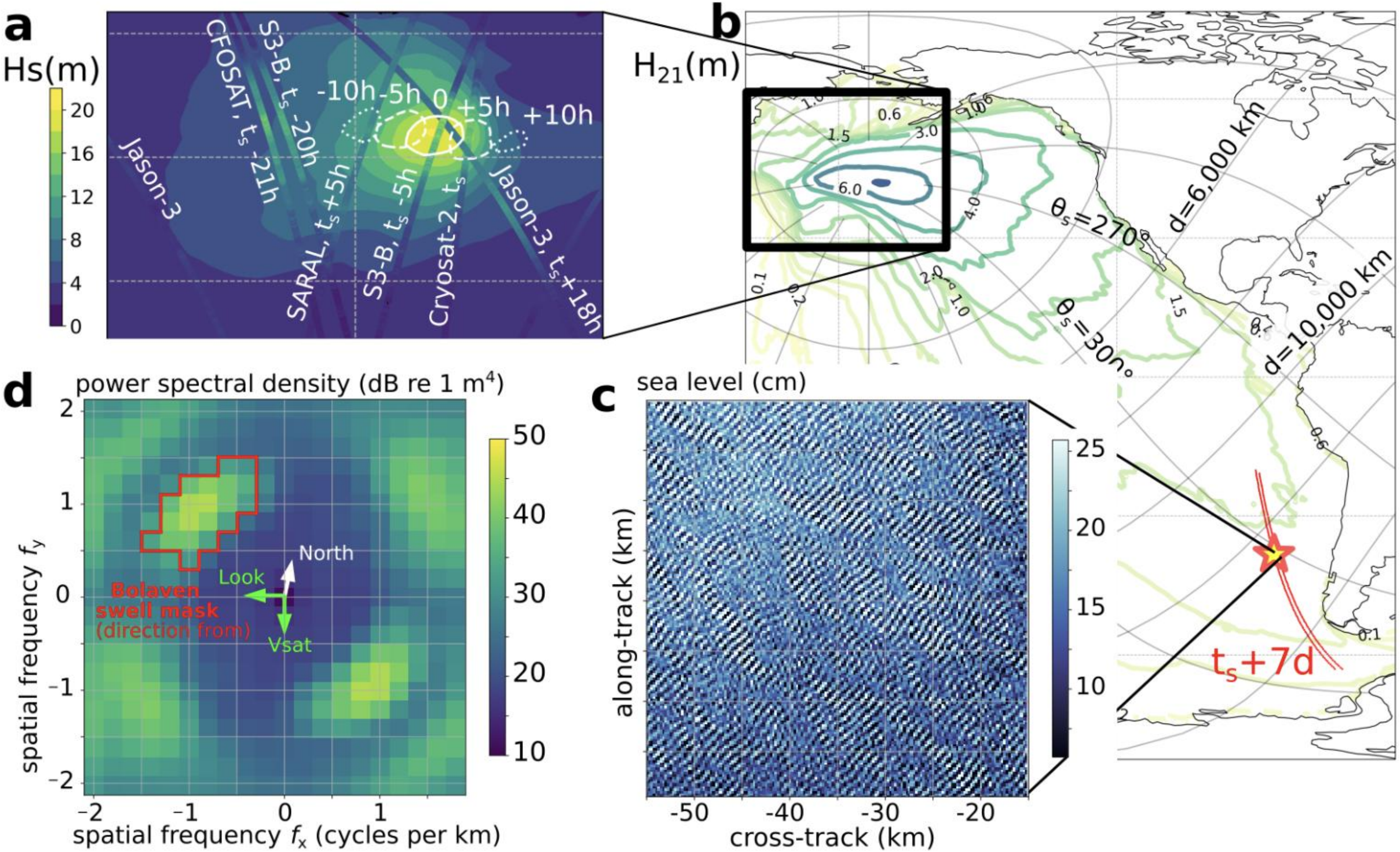


Hs > 18 m in model.

Altimeters: model max is 300 km away …
only 15.4±0.2 m

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



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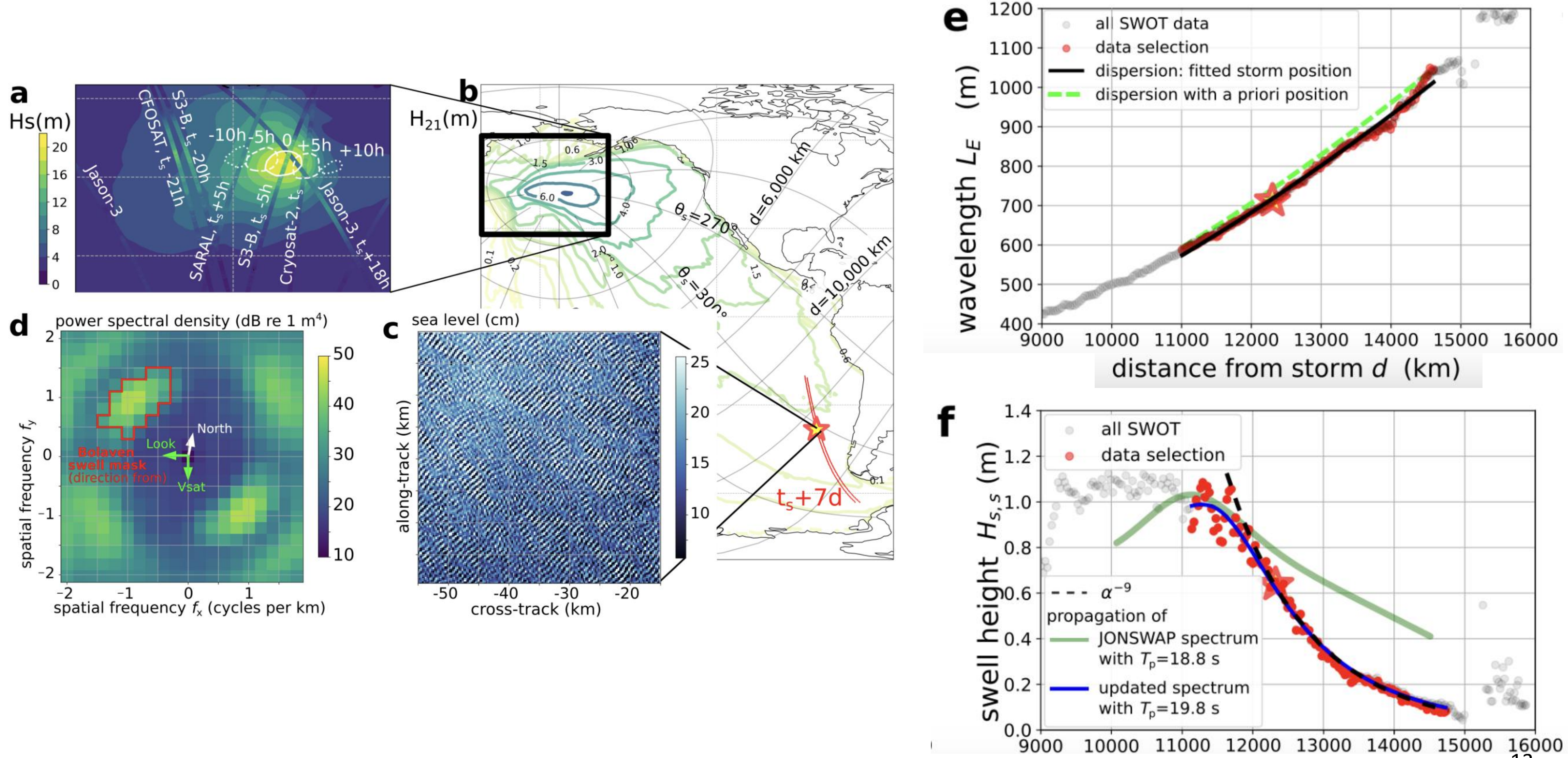


4. How good are the models?

Consistent with Lavrenov's exact Snl (GQM) gives f^{17} forward face, not the DIA

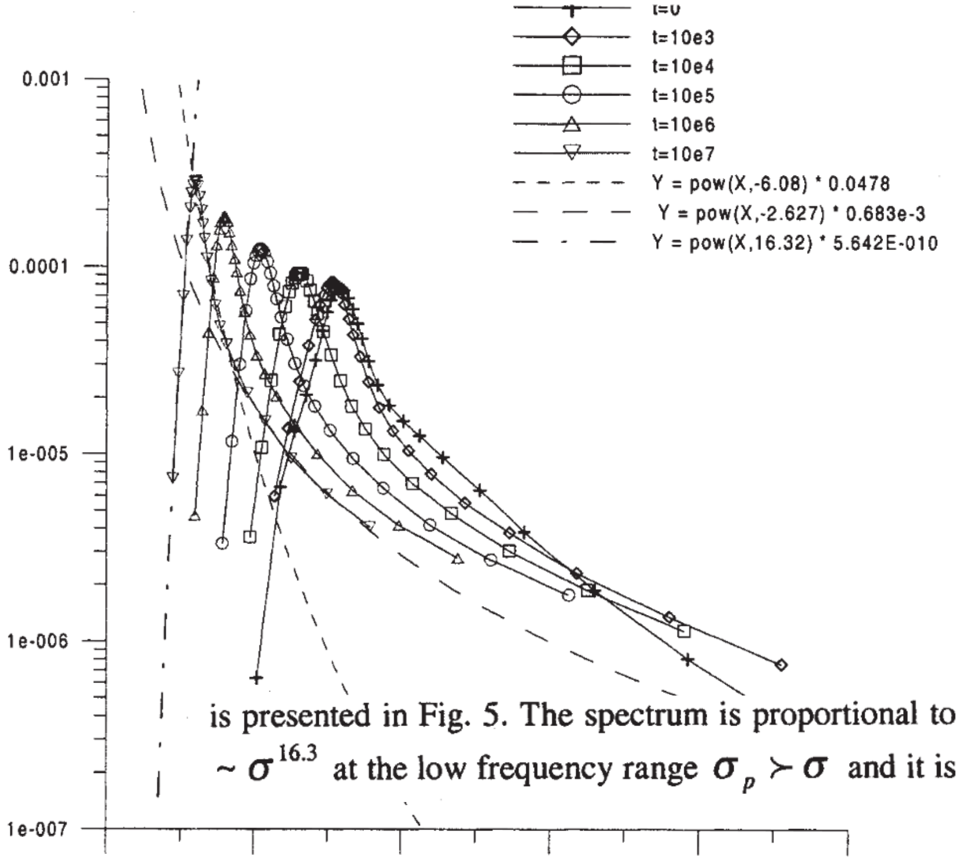
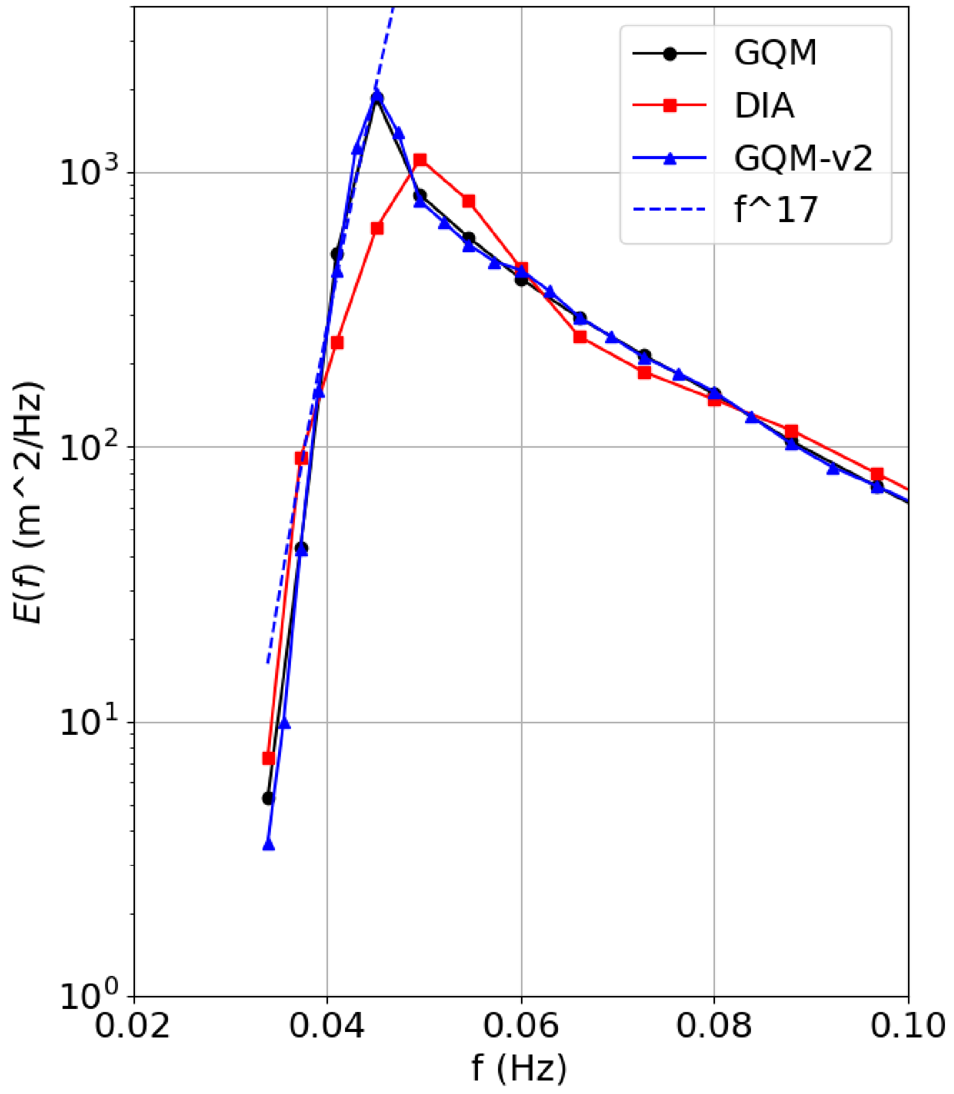


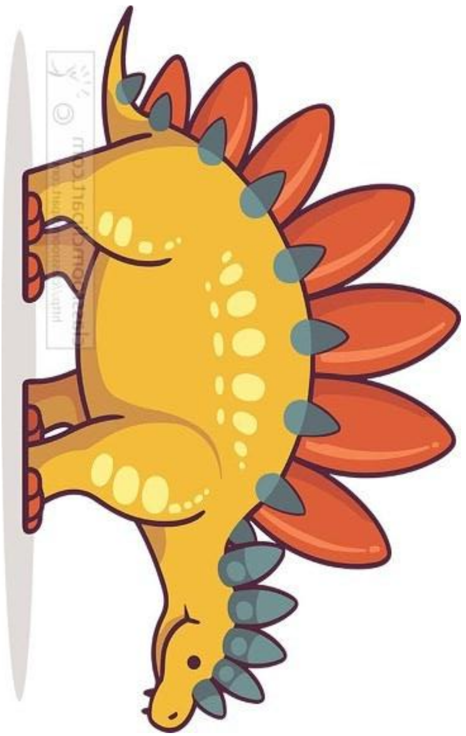
Fig.5
Frequency spectrum evolution
with the initial value (3.2) - (3.3) and $\gamma = 3.3, n = 2$ at different time moments:
a)- . $\tilde{t} = 0$, b)- $\tilde{t} = 10^3$, c)- $\tilde{t} = 10^5$, d)- $\tilde{t} = 10^7$

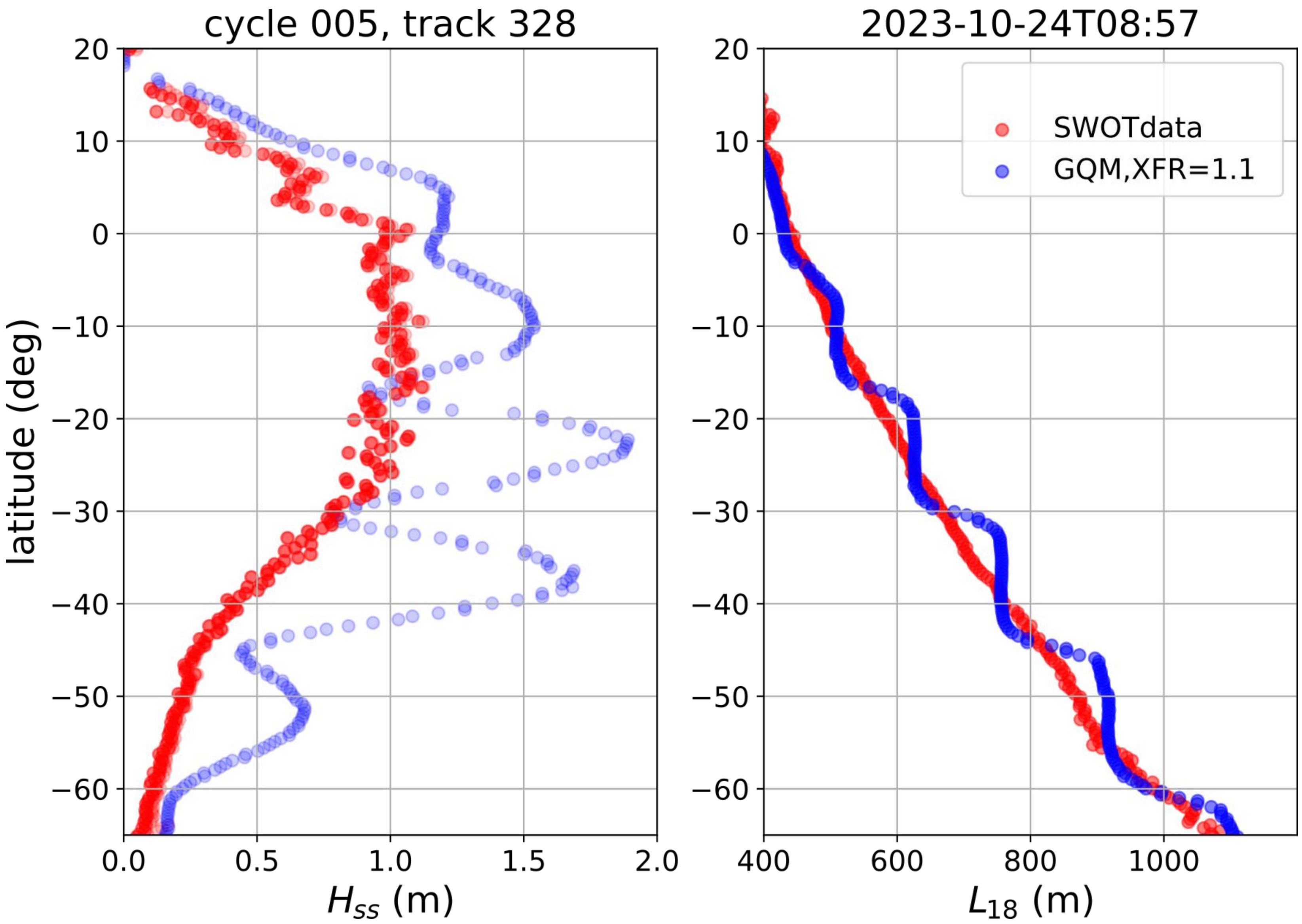
Lavrenov (2000): proceedings of the 6th Workshop
On Waves Hindcasting and Forecasting



4. How good are the models?

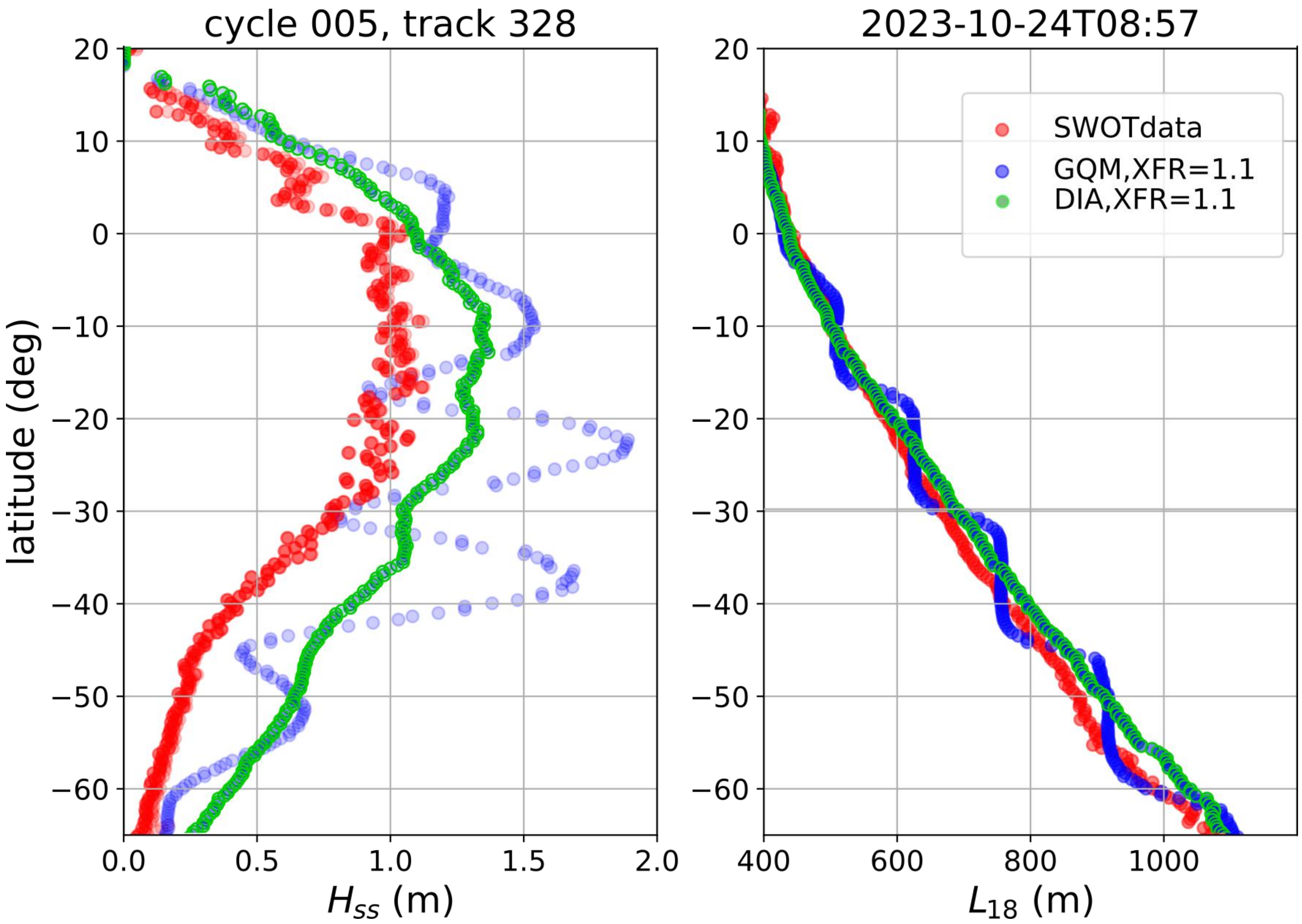
Narrow spectrum + high order scheme = Great Stegosaurus-down-the-stairs Effect (GSE)





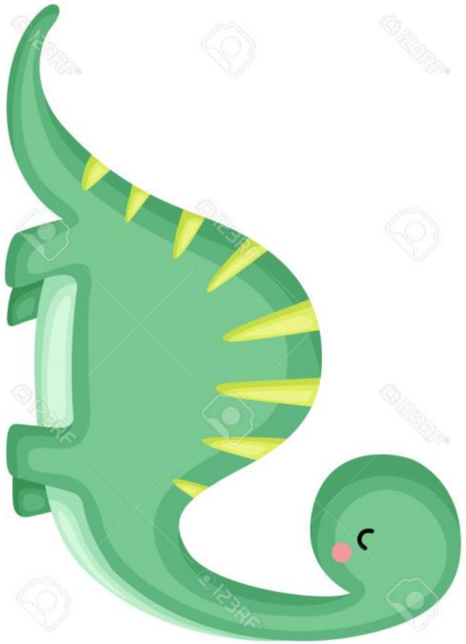
4. How good are the models?

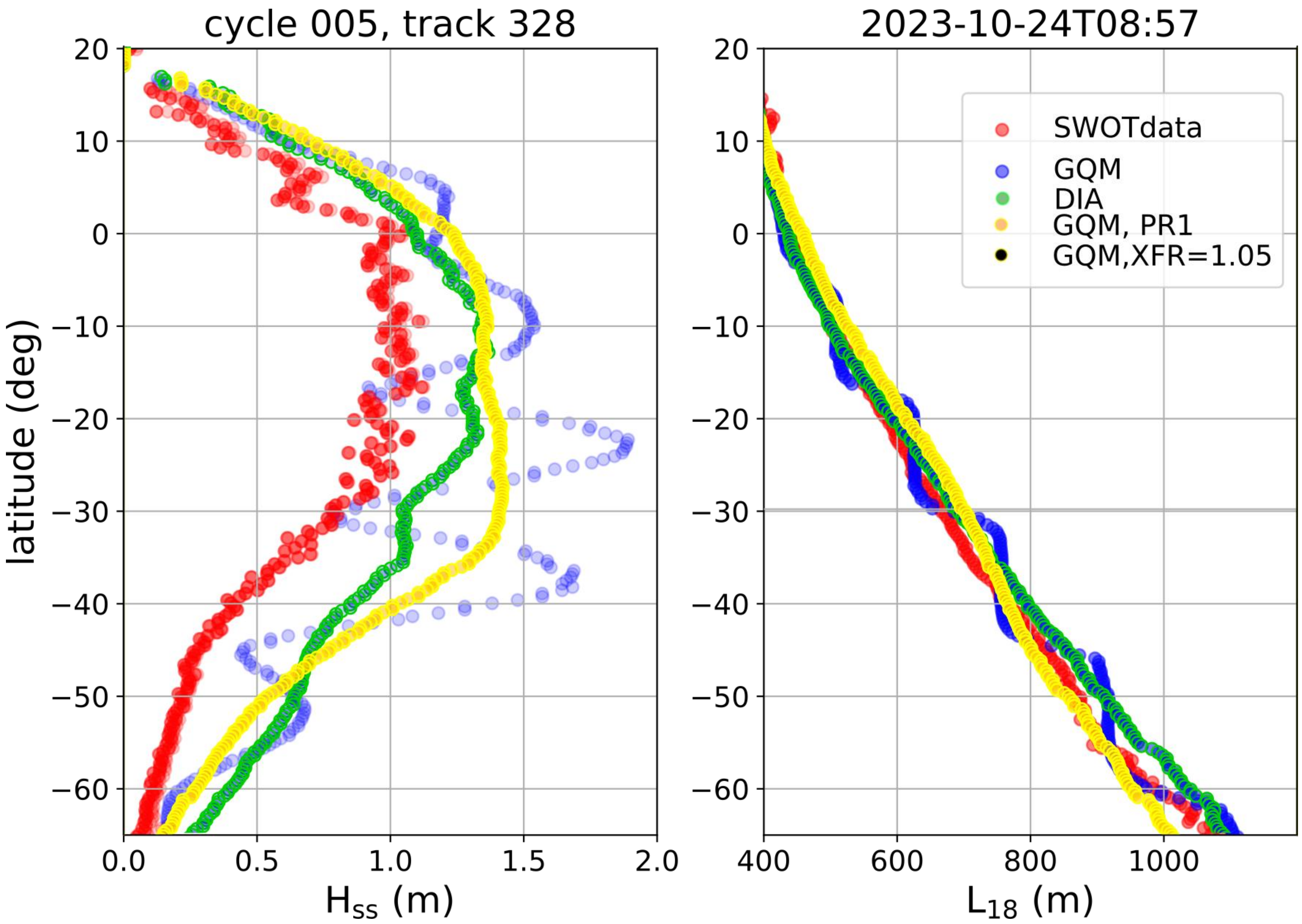
broad spectrum + low order scheme = swell arriving too early



4. How good are the models?

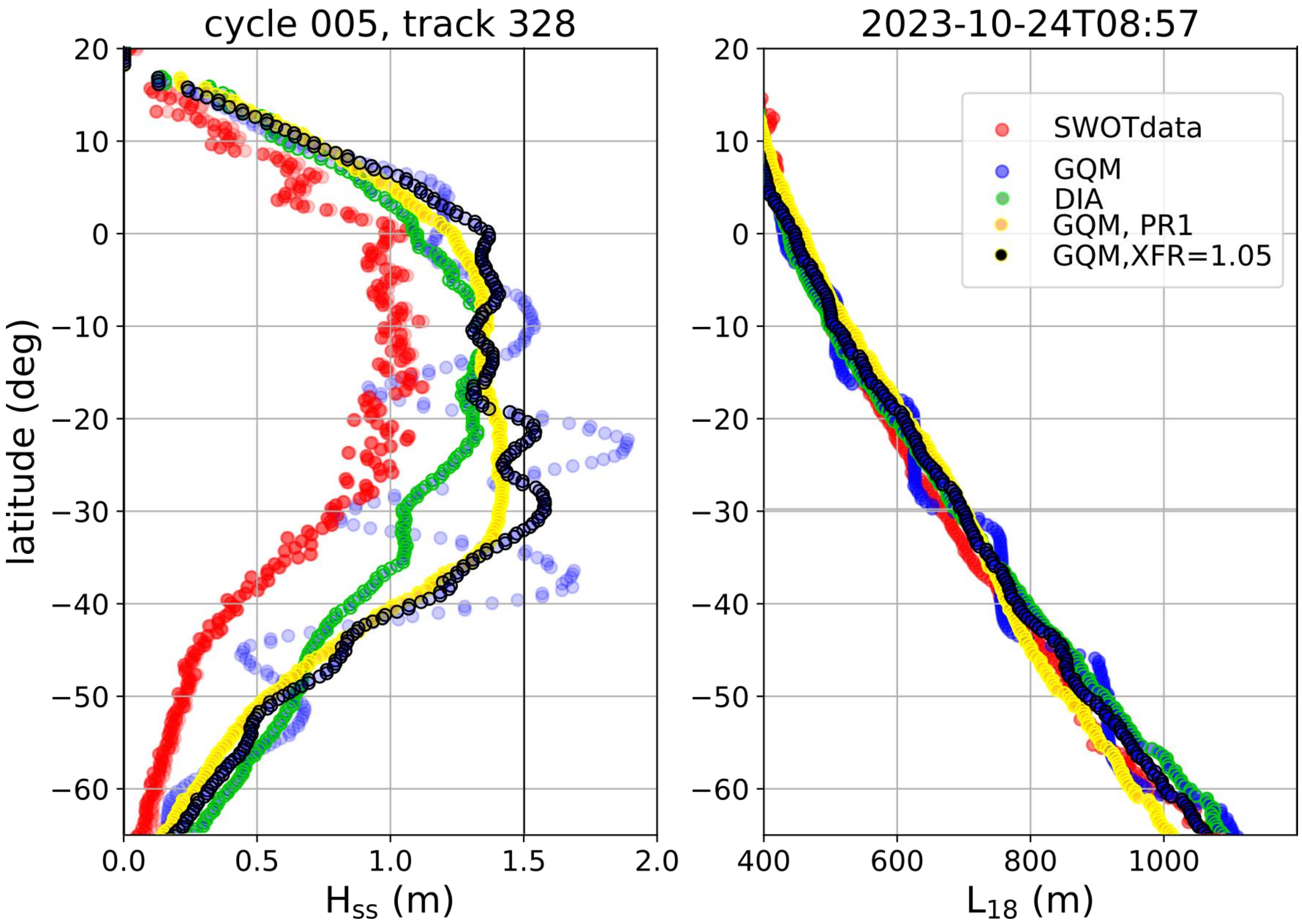
1st order scheme = perfect?





4. How good are the models?

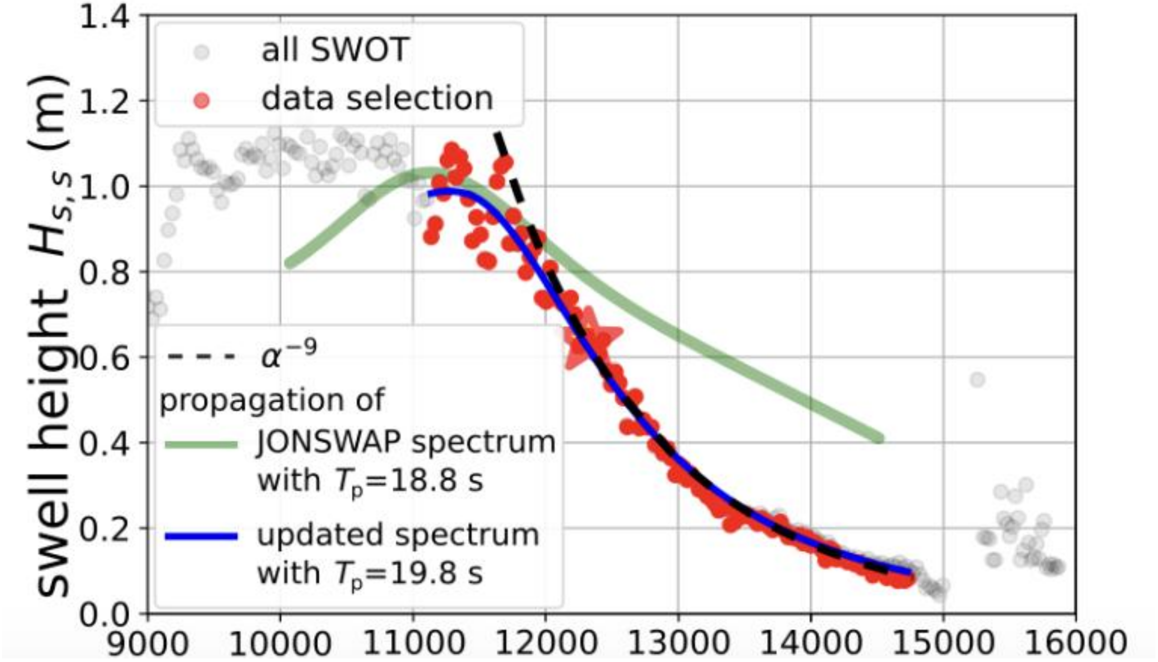
Other option: increase spectral resolution …

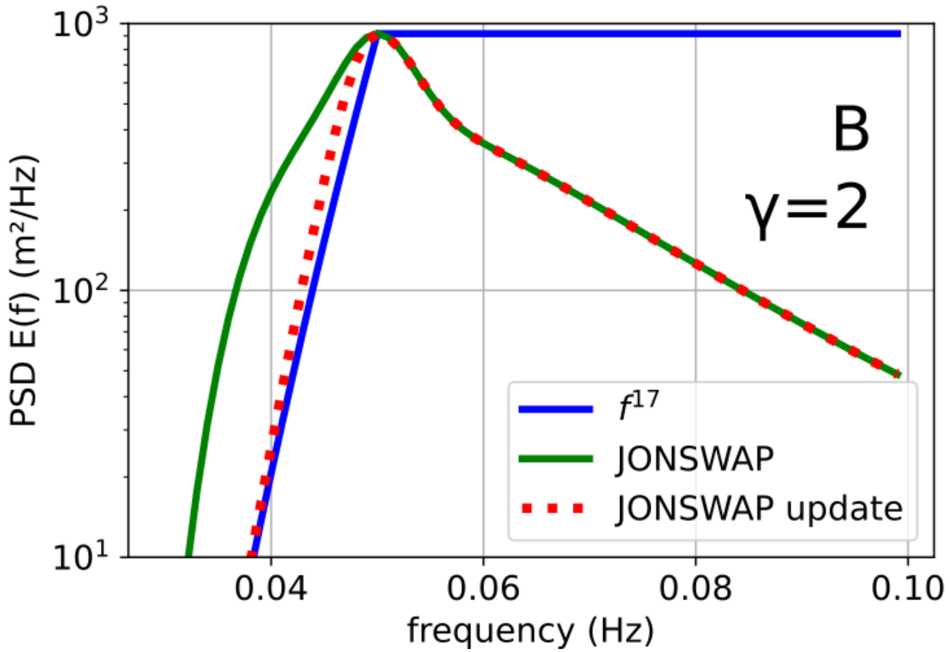


Conclusions

- Altimeters work well for SWH > 20 m, giving a robust Hs = 19.7± 0.3 m max value for Eddie
- SWOT swells are fantastic (see https://wise.discourse.group/ for data access and more)
- Wind sea to swell transition and propagation consistent with “updated JONSWAP” shape
- Exact Snl calculation with GQM gives observed spectral shape
- Propagating narrow spectra in high order scheme may require high spectral resolution

Next works: directional shape, swell dissipation rates, coastal impacts (storm Eddie) …





BONUS SLIDES

Preliminary analysis of Eddie: Hs estimates

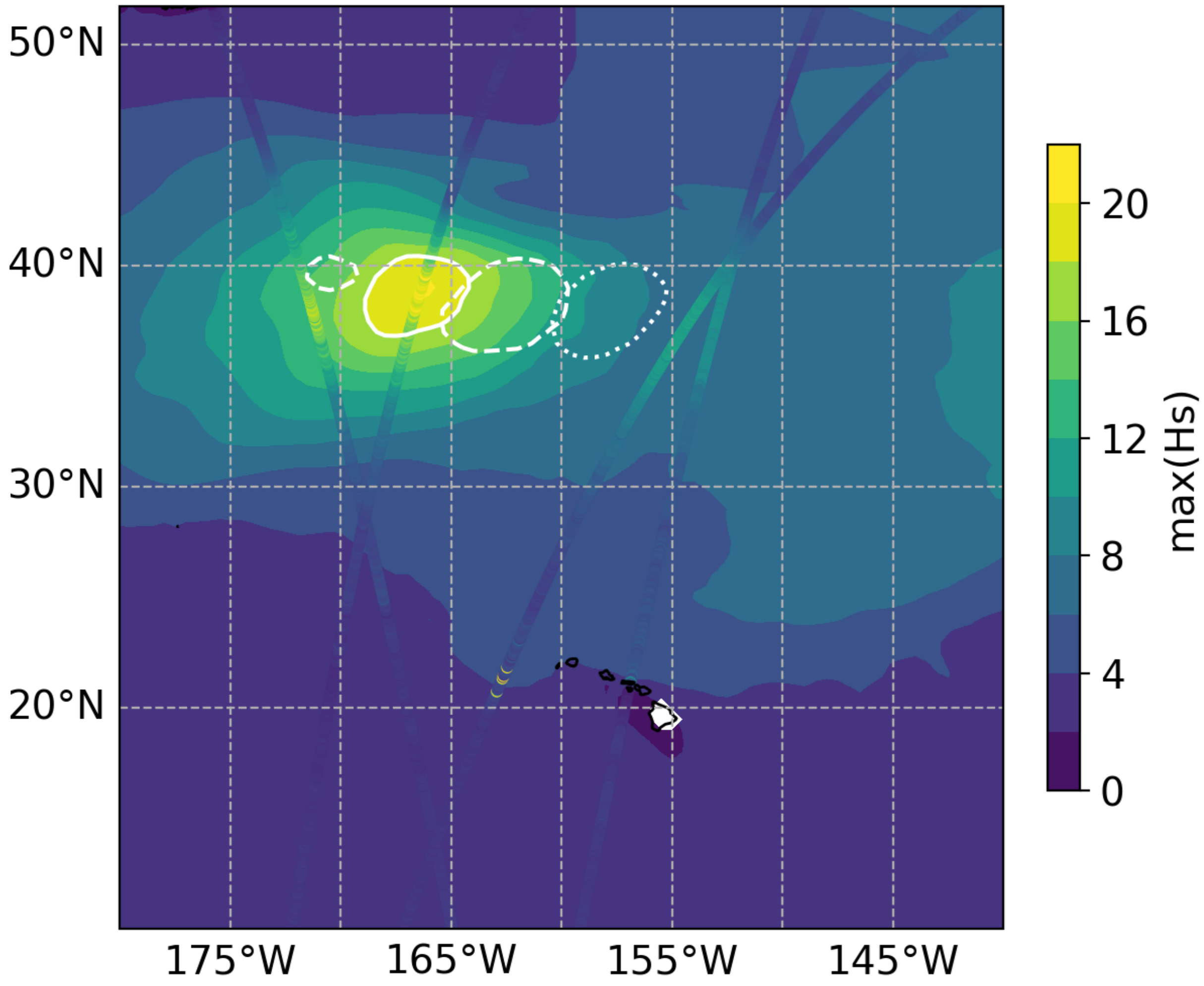
Hs (in model) peaked at 15:00 UTC on 21/12/2024.
We were very lucky to get a SWOT pass right through the peak a little earlier: 9:00 UTC

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):

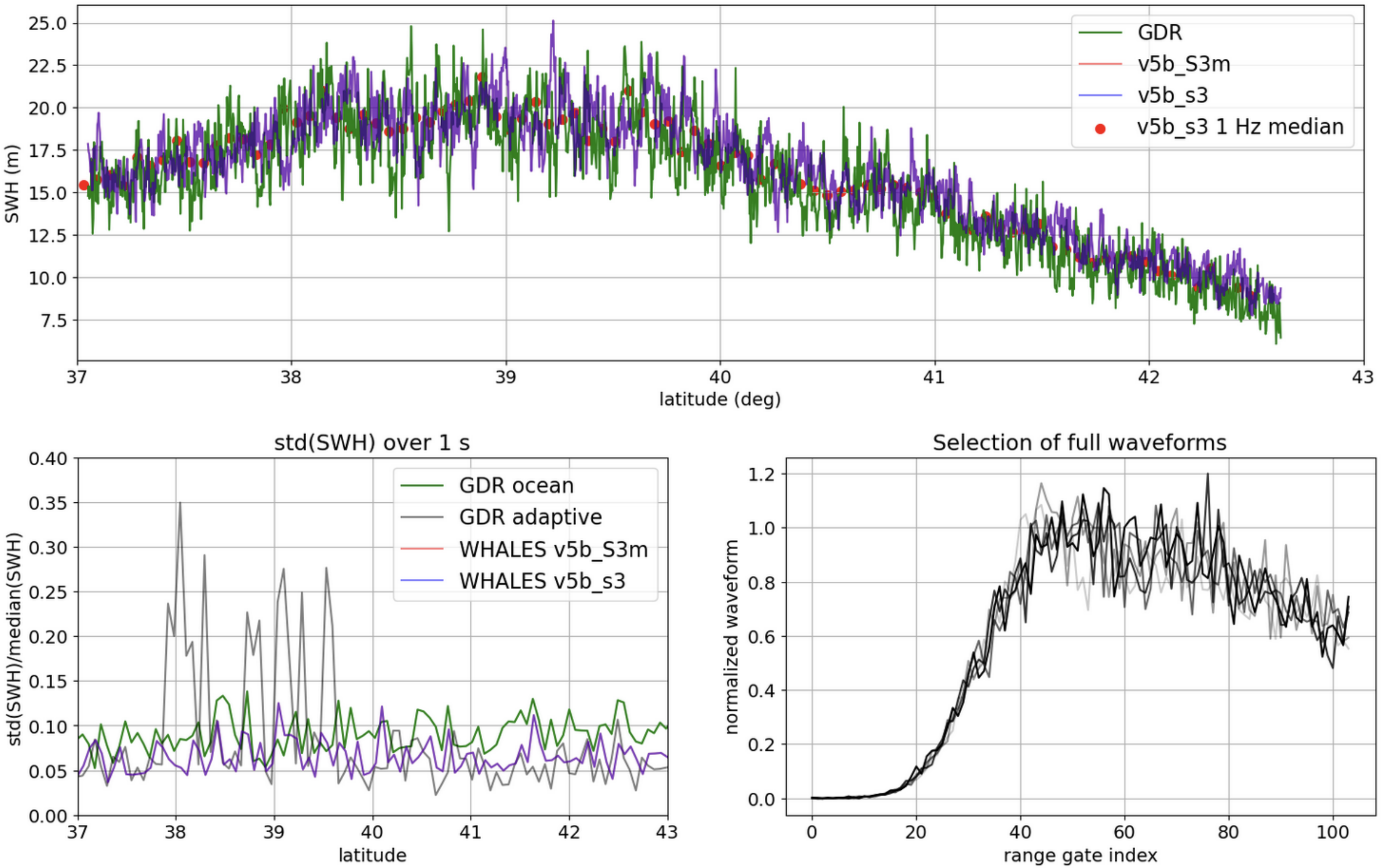
CFOSAT (5 AM)
SWOT (9 AM)
J3 (5 PM)
CFOSAT (5 PM)

note: S3A (10 AM) is not plotted



Preliminary analysis of Eddie: Hs estimates

SWOT retracking



Preliminary analysis of Eddie: Hs estimates

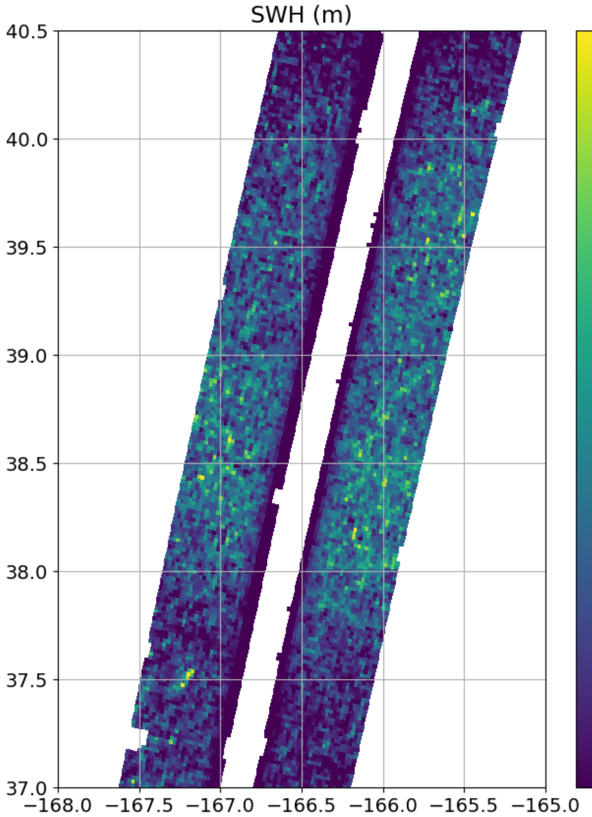
Along-track Hs: (preliminary)
- SWOT (no smoothing, no retracking …)
- GQM run: Hs rescaled by 0.95

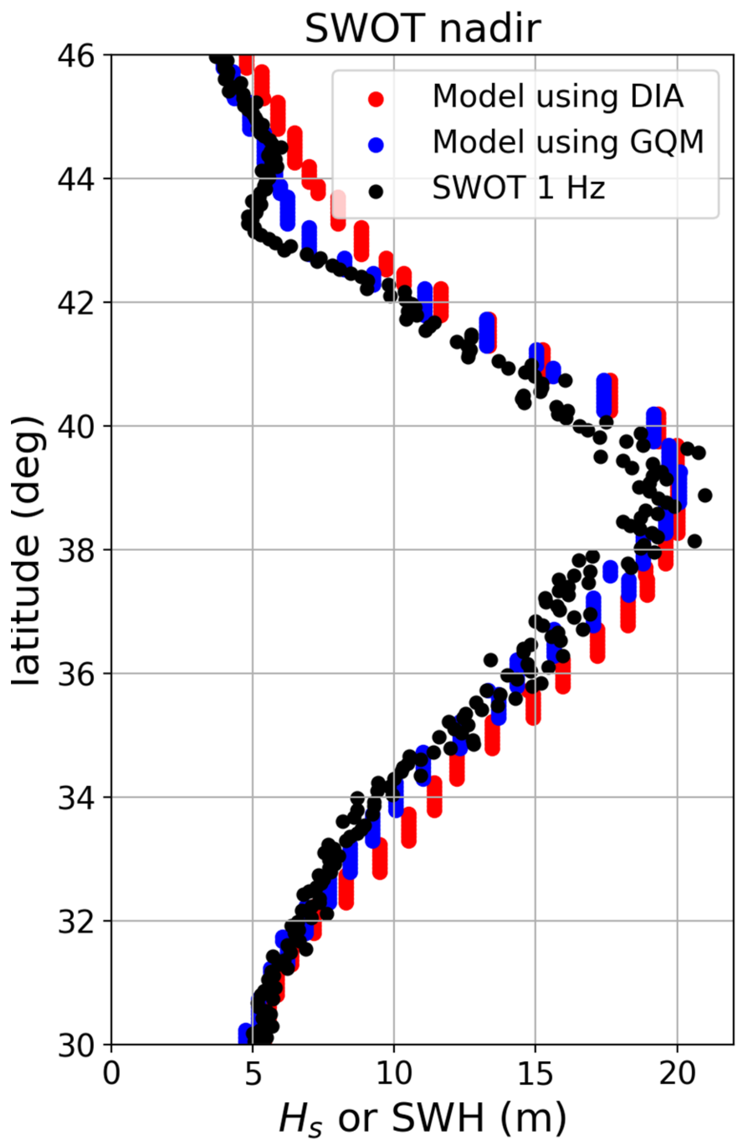
NB: ECMWF IFS max value for Eddie is 17.2 m

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 ?





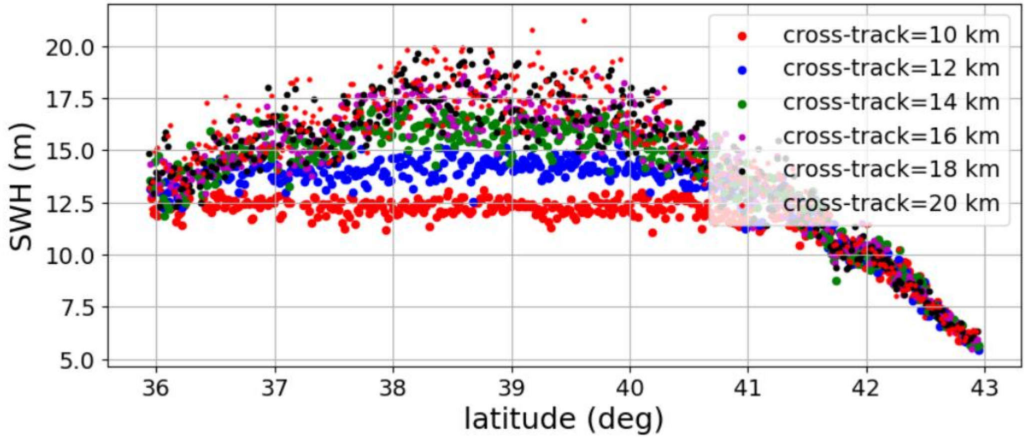
Preliminary analysis of Eddie: Hs fluctuations

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

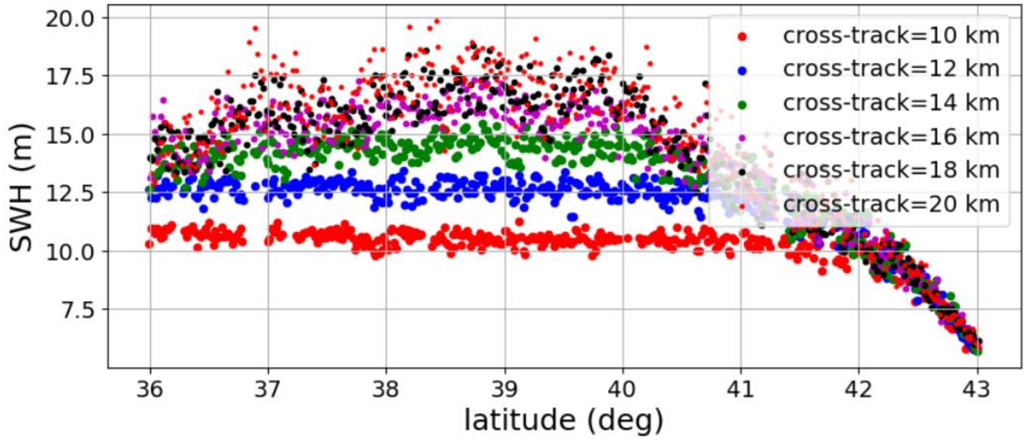
- with a L=17*250m=4.25 km averaging the expected std(Hs)/Hs is 0.067 m for qkk=64 m, and 0.046 m for qkk=44 m
- what part of the swath can we use ?

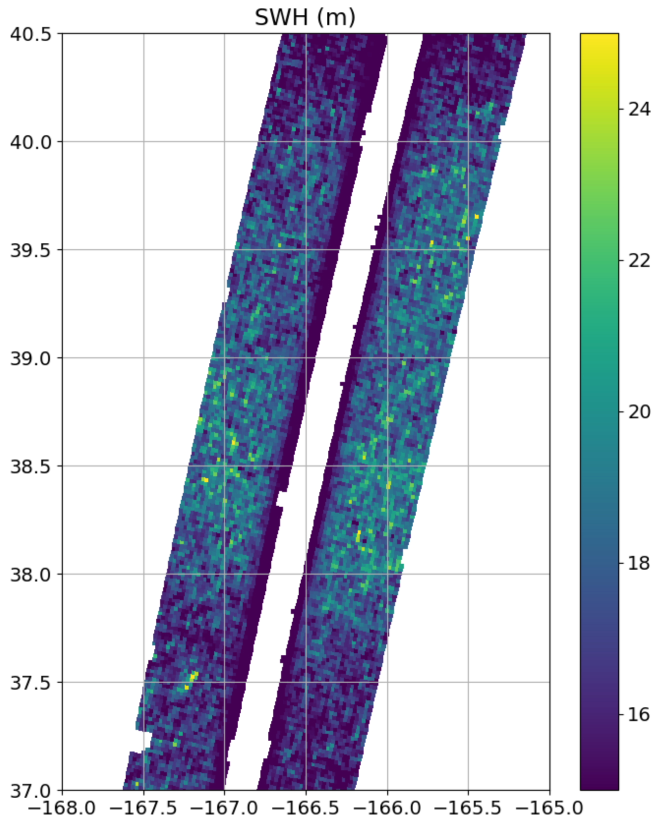
It looks like the coherence saturates towards nadir (see Bohe et al. 2025): good data for x > 20 km ?

right swath:
(indices 34+i)



left swath:
(indices 34-i)

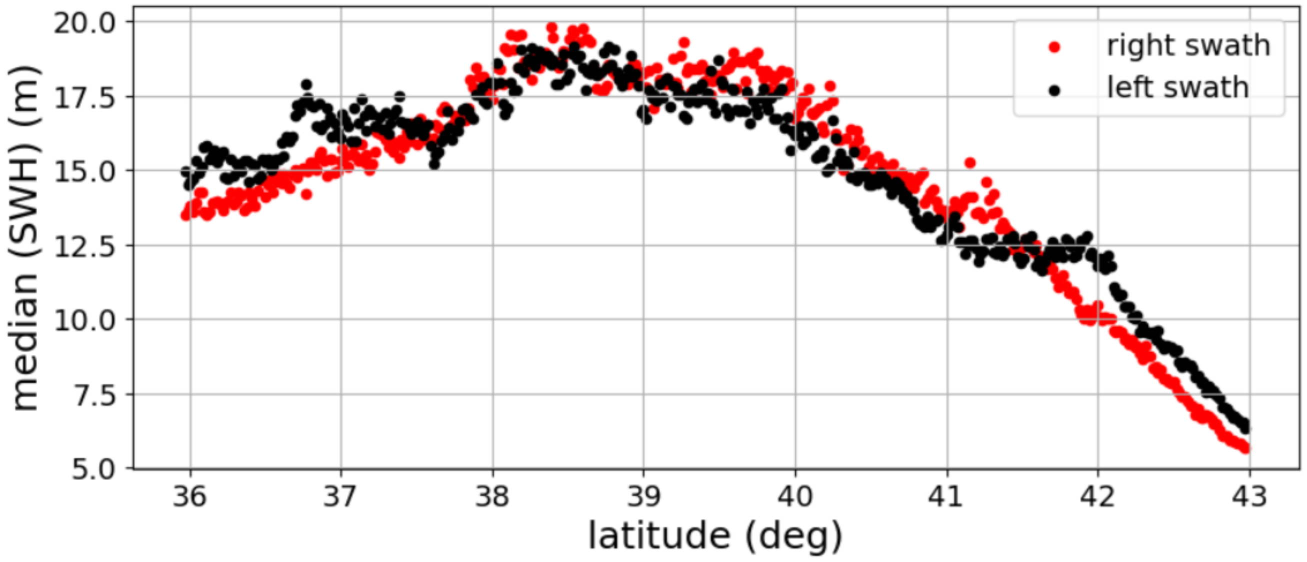




Preliminary analysis of Eddie: Hs fluctuations

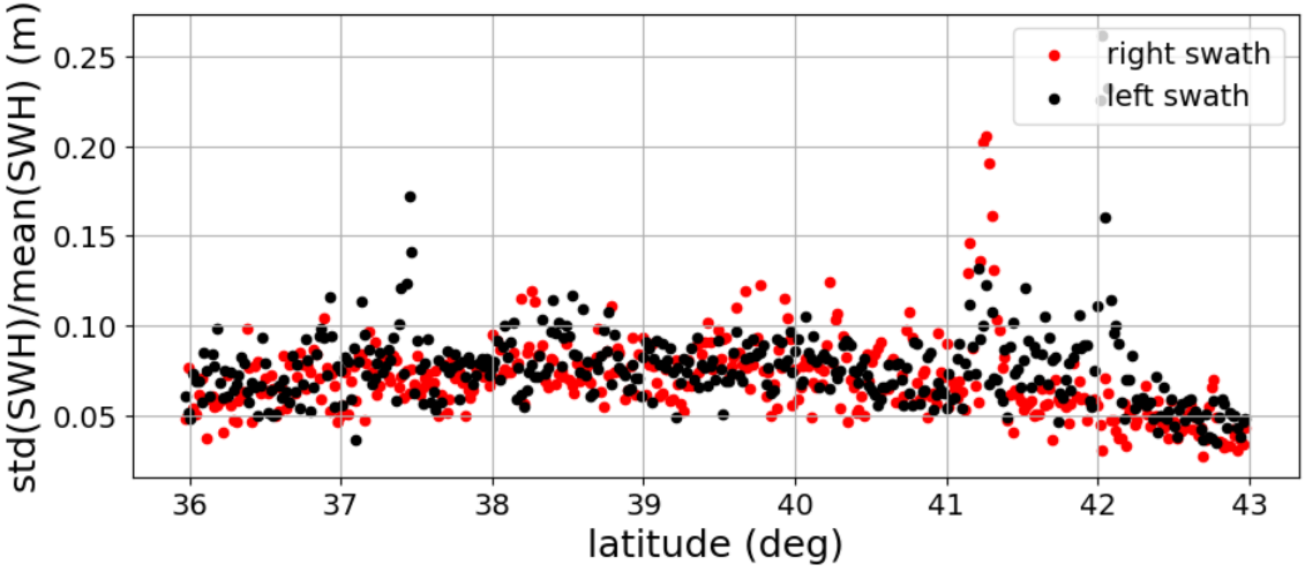
Using indices i=10 to i=29 we get these values of std(Hs)/mean(Hs) from KaRIN:

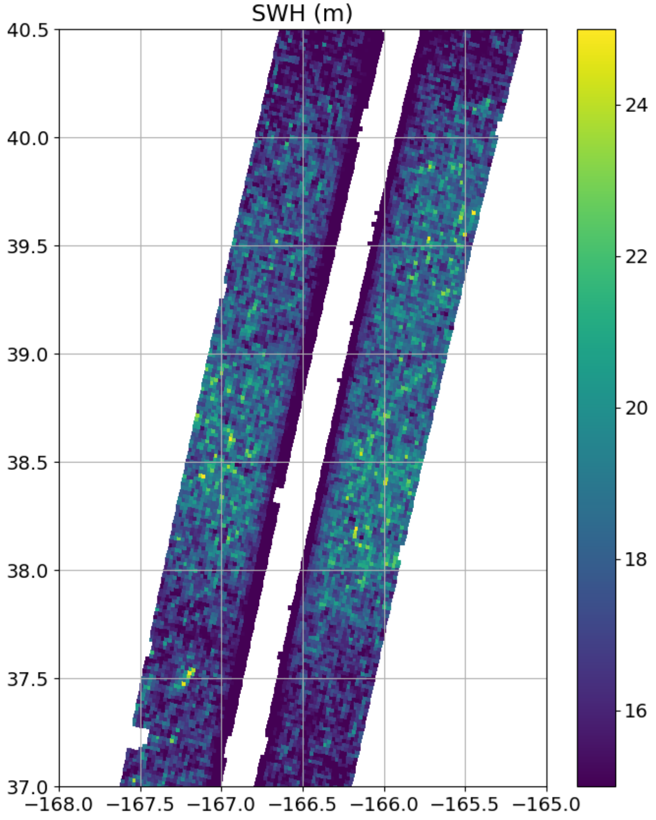
cross-track median:



normalized cross-track std:

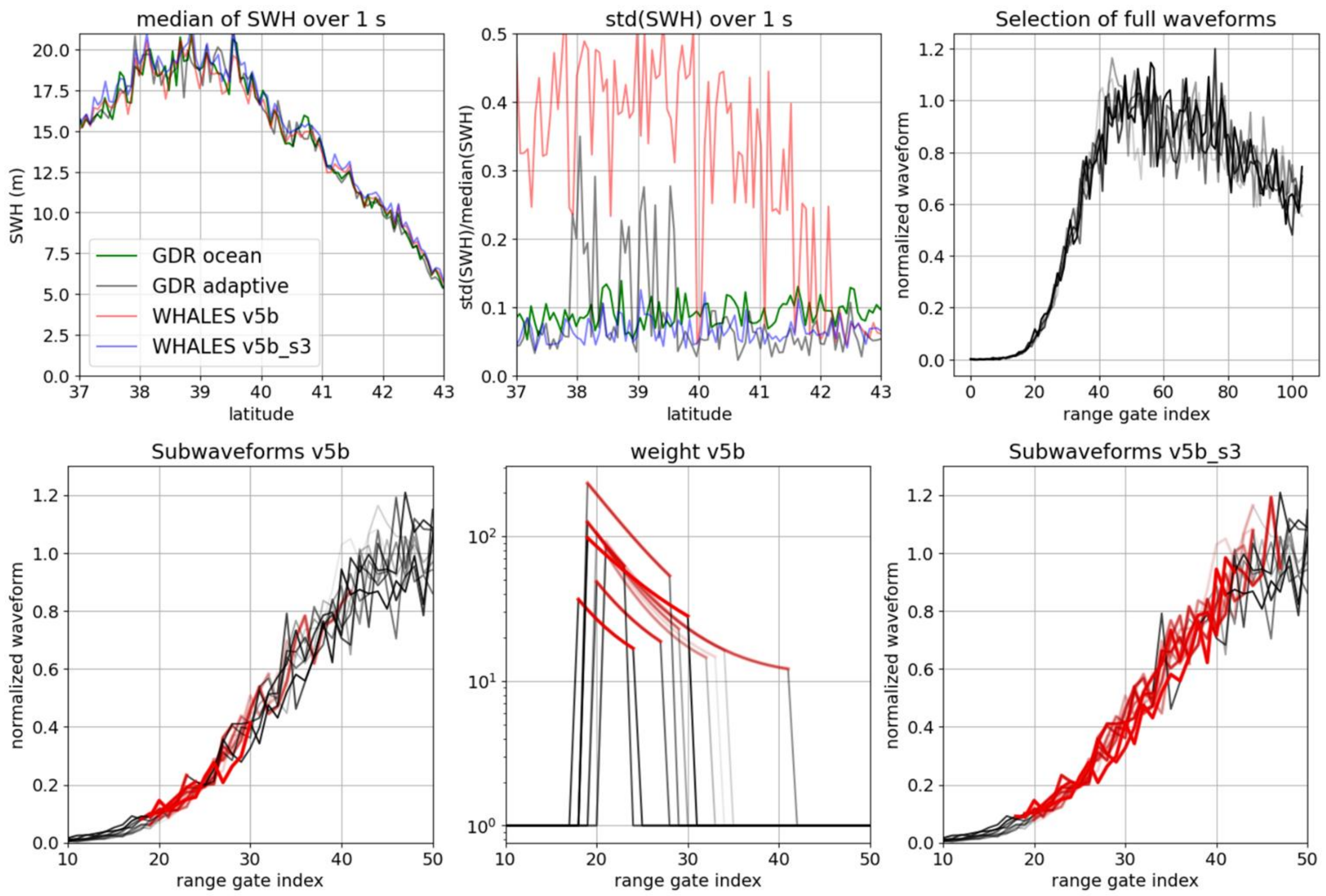
(NB: DIA values look closer… saturation??)





Preliminary analysis of Eddie: Hs fluctuations

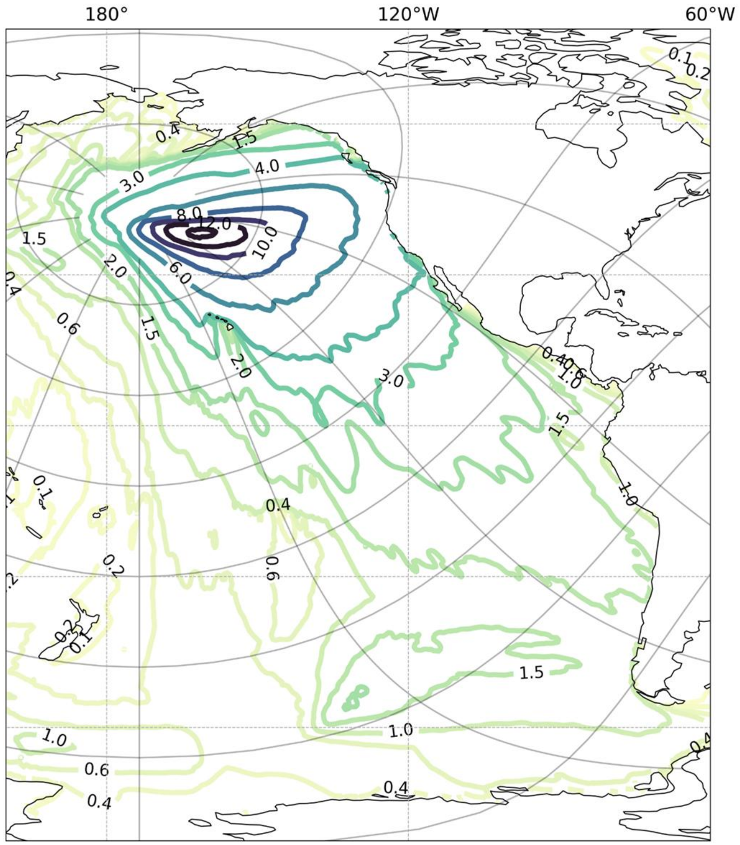
Looking at 20 Hz data in nadir (Poseidon 3C): GDR (ocean) and WHALES retracking (with -s 3 smoothing)



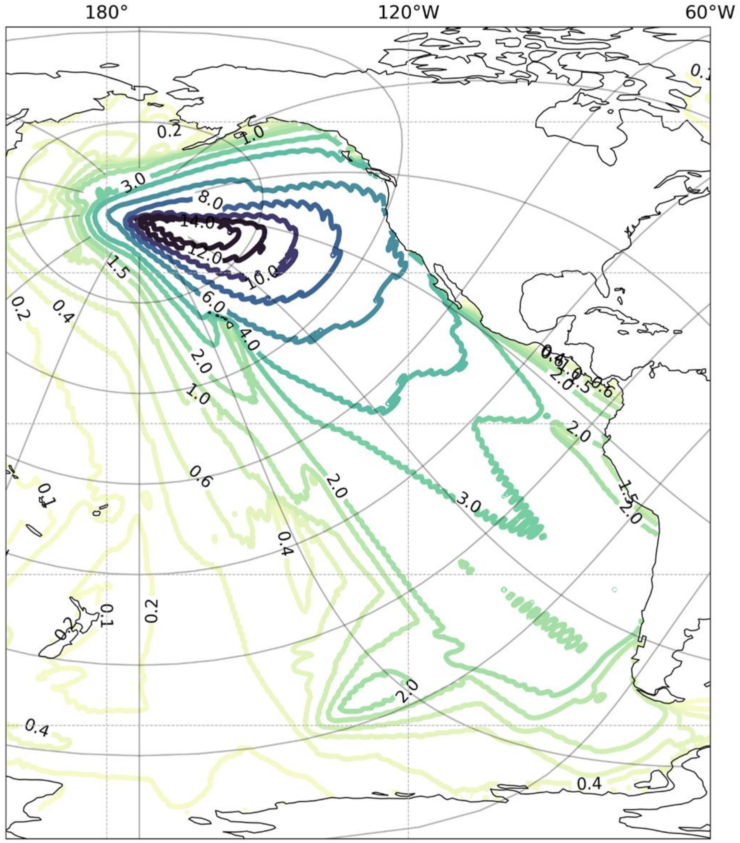
Preliminary analysis of storm Eddie: swells

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

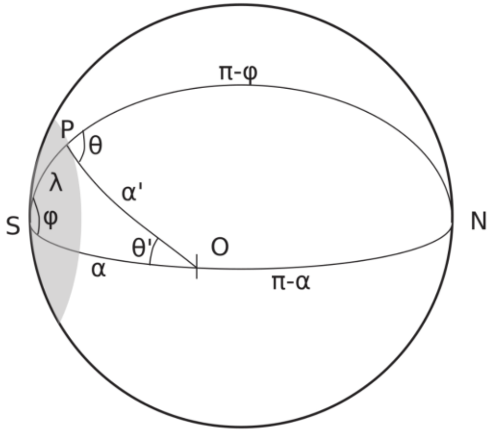
This integral can be evaluated numerically using any analytic expression for the source spectrum, which can be the JONSWAP spectrum[8] or the update proposed below with eqs. (8) and (9).

In the limit $|\alpha'-\alpha| \ll \alpha$ and $r \ll R_E$, 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

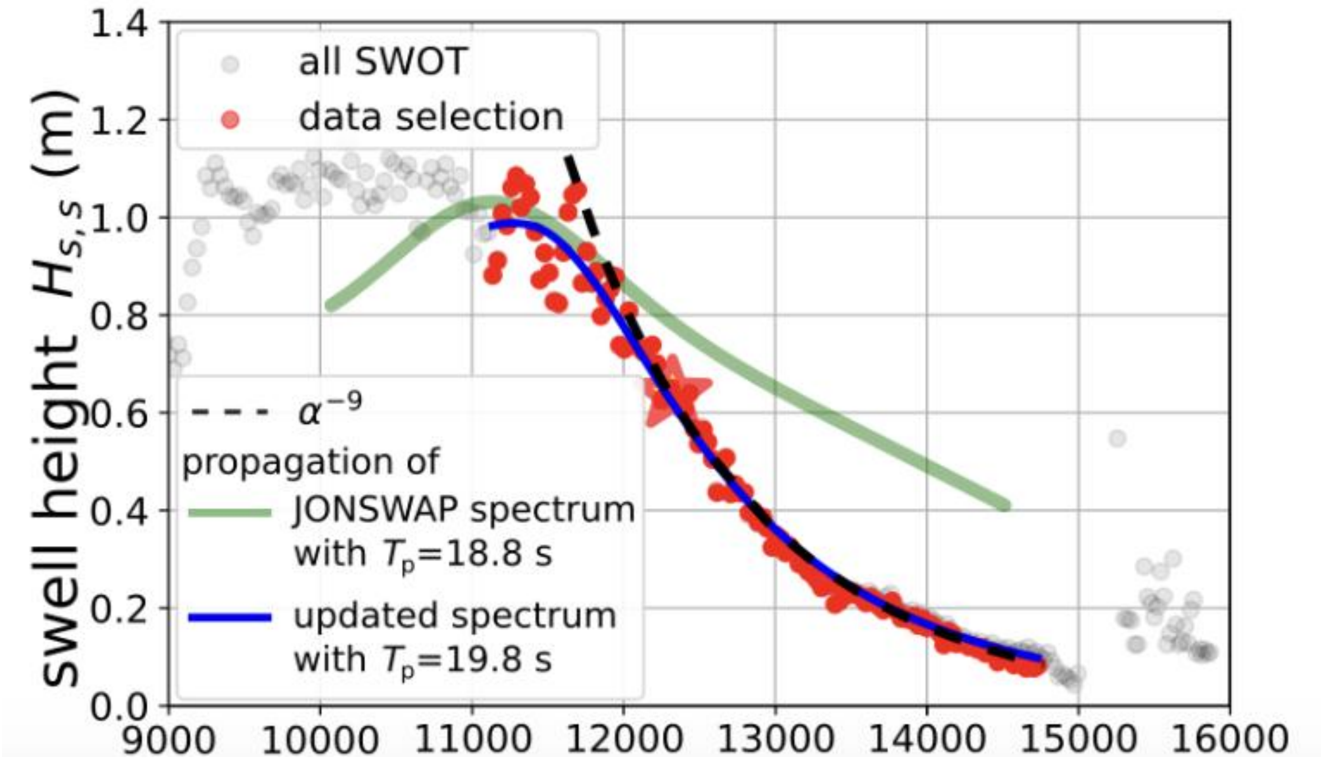
$$E_0(\alpha, SPP, r) = f_\alpha\, E_{S.iso}(f_\alpha)(r/R_E)^2/(2\,\alpha\,\sin\alpha) \quad (7)$$

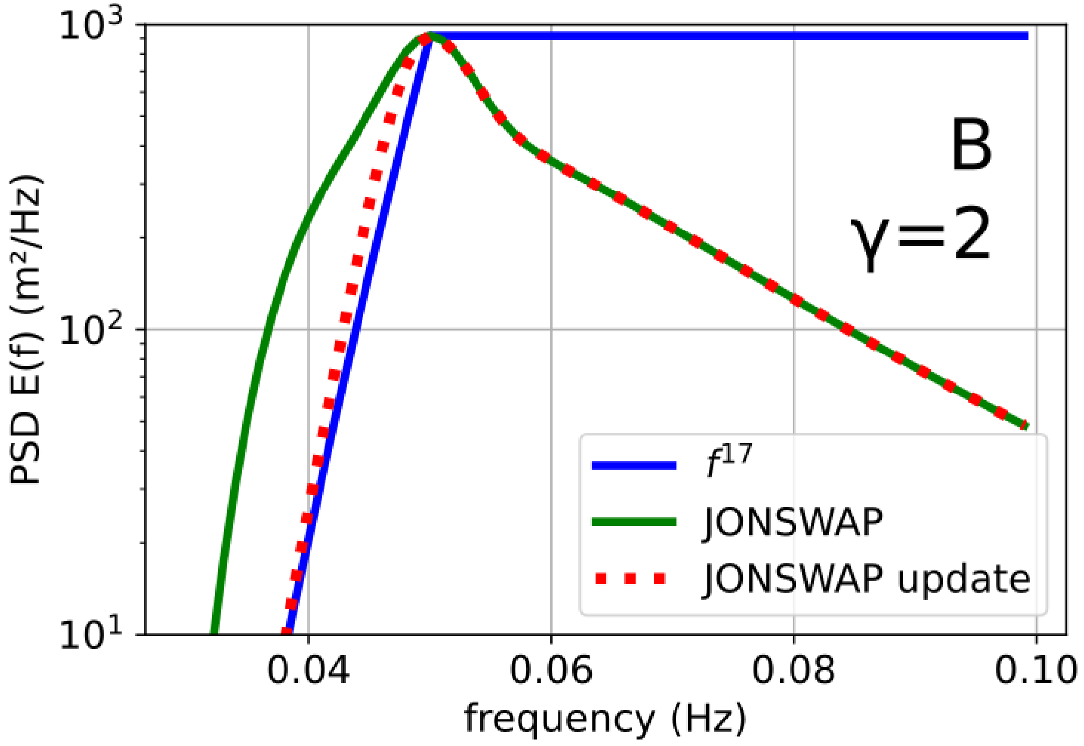


2. what it tell about 4-wave interactions: putting the puzzle together

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





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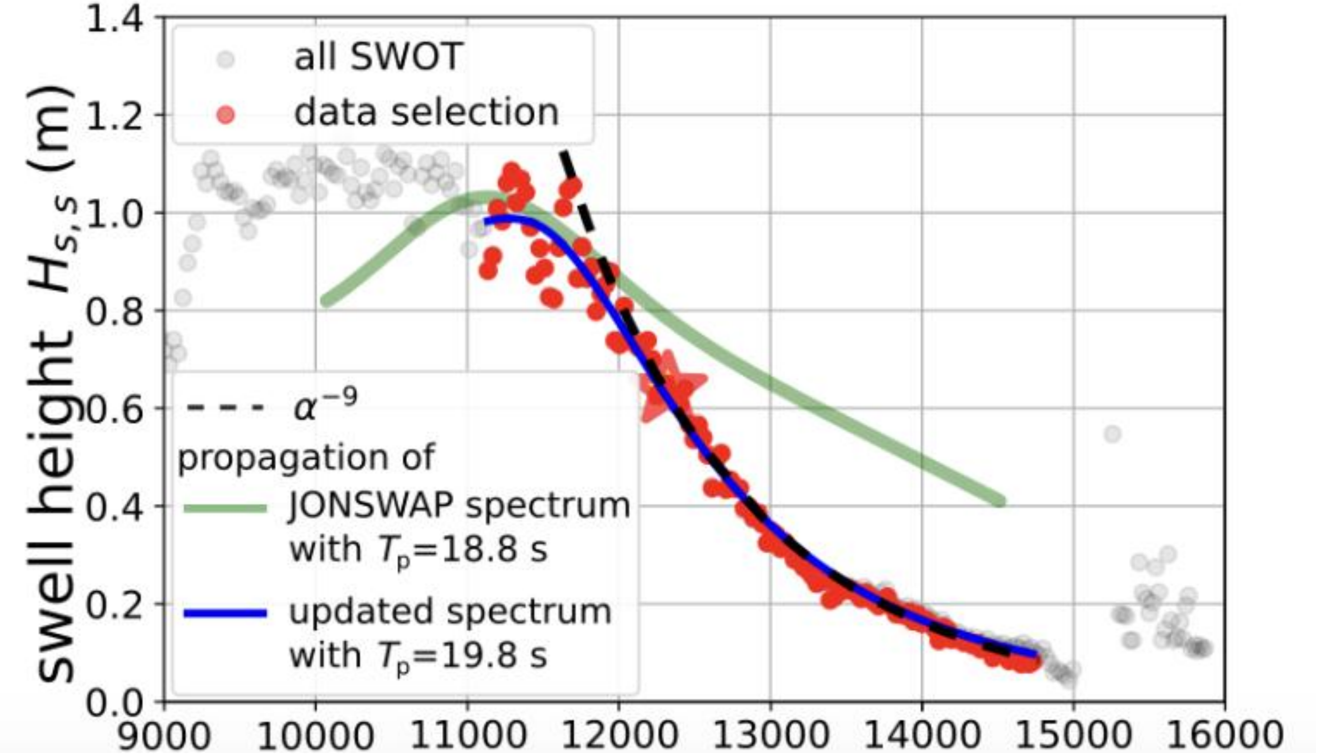
which is actually consistent with Snl calculations for swell (Lavrenov 2003, Badulin & Zakharov NPG 2017)



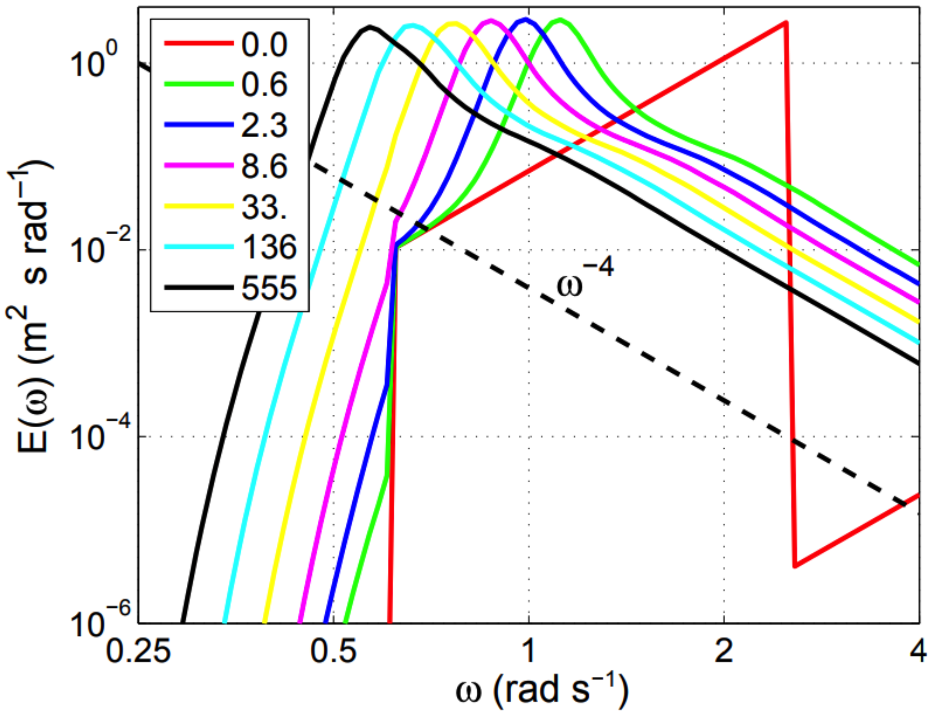
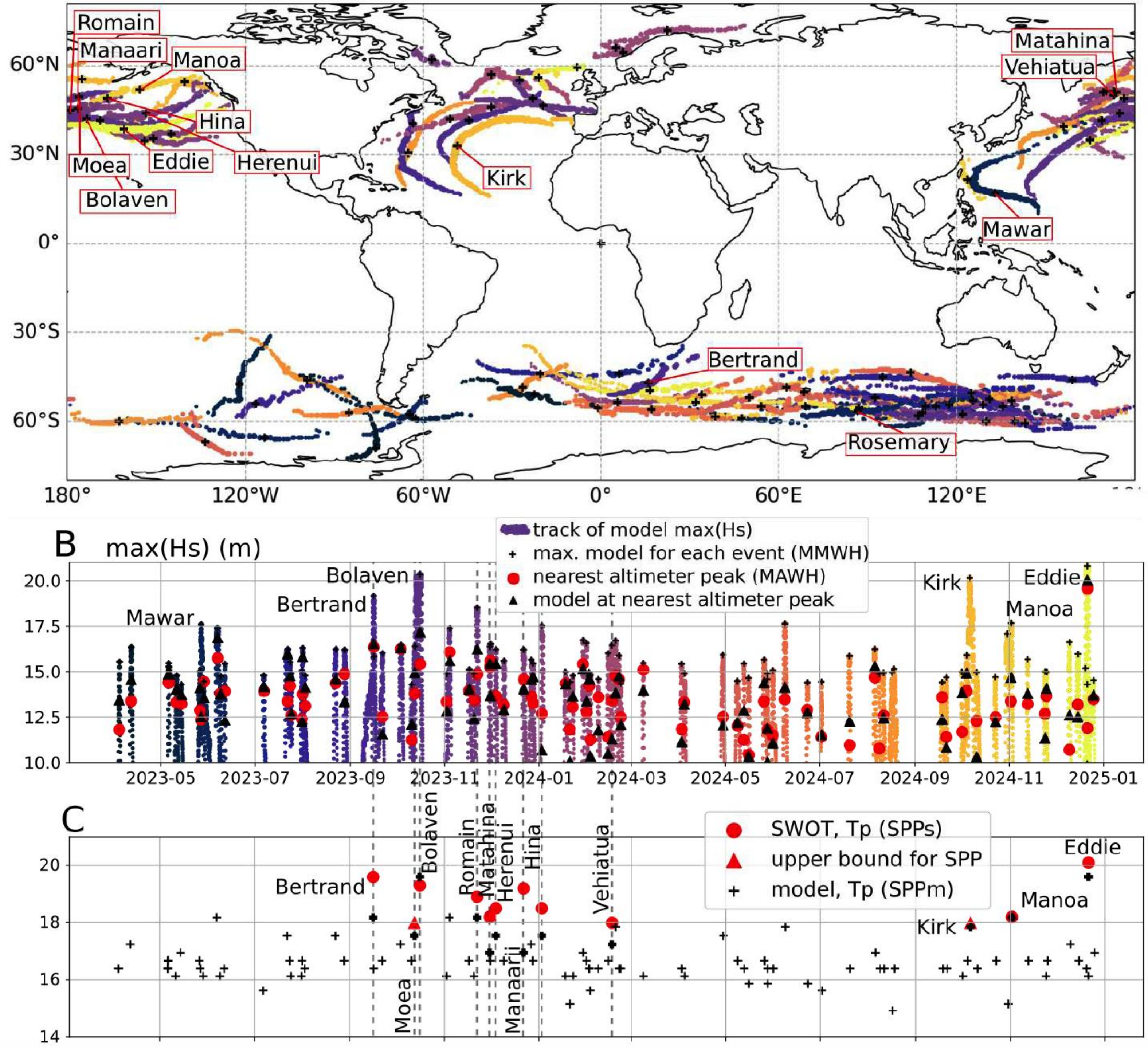


Figure 1. Frequency spectra of energy at different times (legend, in hours) for case sw330 (Θ = 330°).



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

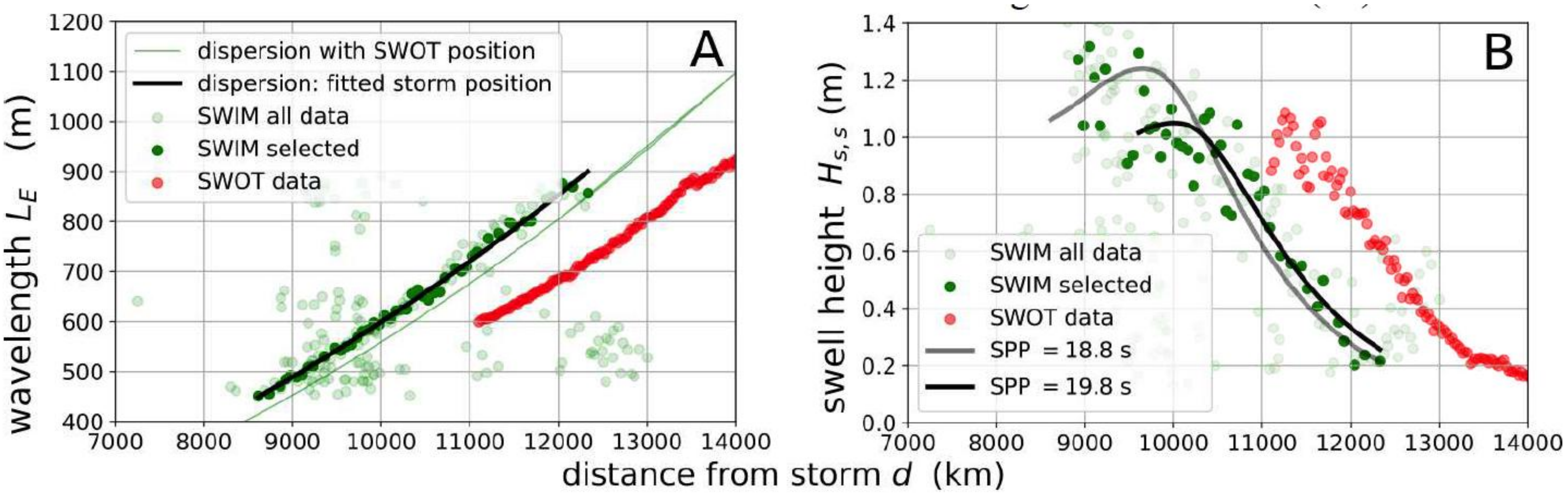


Fig. 4. Estimation of storm peak period using SWIM 10° beam data, acquired along the green track of Fig. 1.B, 9 hours before the SWOT data along the red track. (A) wavelength and (B) swell heights and fitted swell height (grey and black curves) using either all good data or only data with $L_E > 550$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

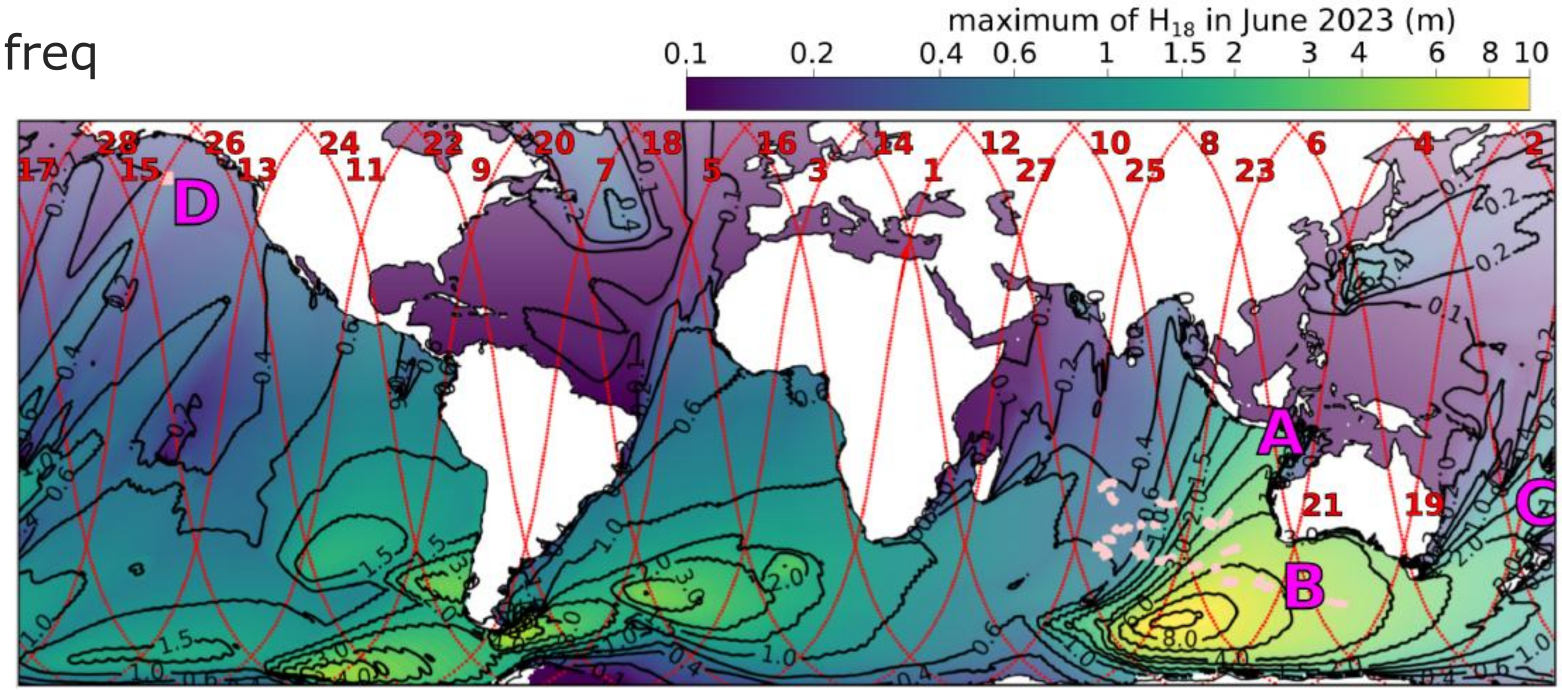
this GQM configuration uses : 11×6×6=396 points for integration along resonant manifold
- filter on coupling coef. amplitude (0.05): keeps 202 out of 396 quadruplets
- filter on spectral saturation (5E-5): 50% more cost reduction

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

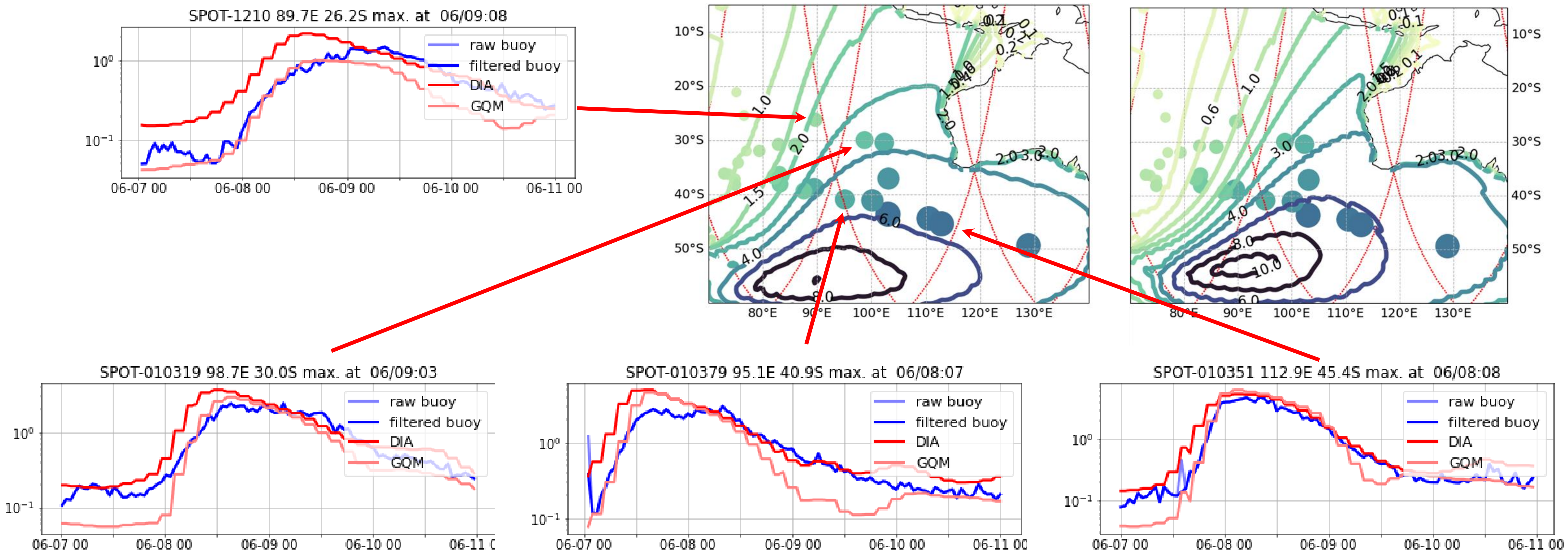
Global 0.5° model with 24 dir, 32 freq
48h for 1 year on 500 procs

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 …)