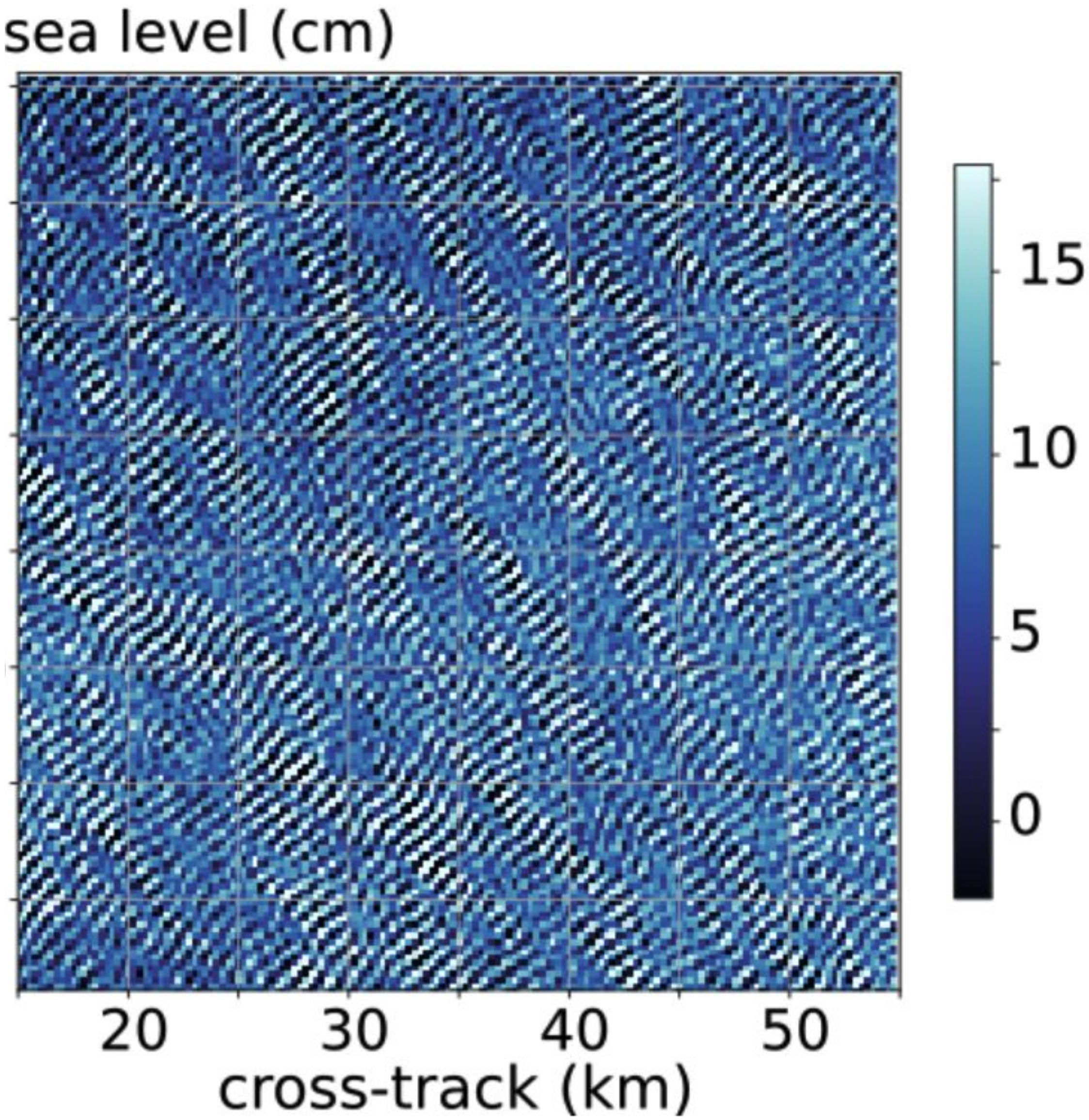
A new wave spectra dataset from SWOT

Fabrice Ardhuin (Lab. of Ocean Phys. and Satellite remote sensing)

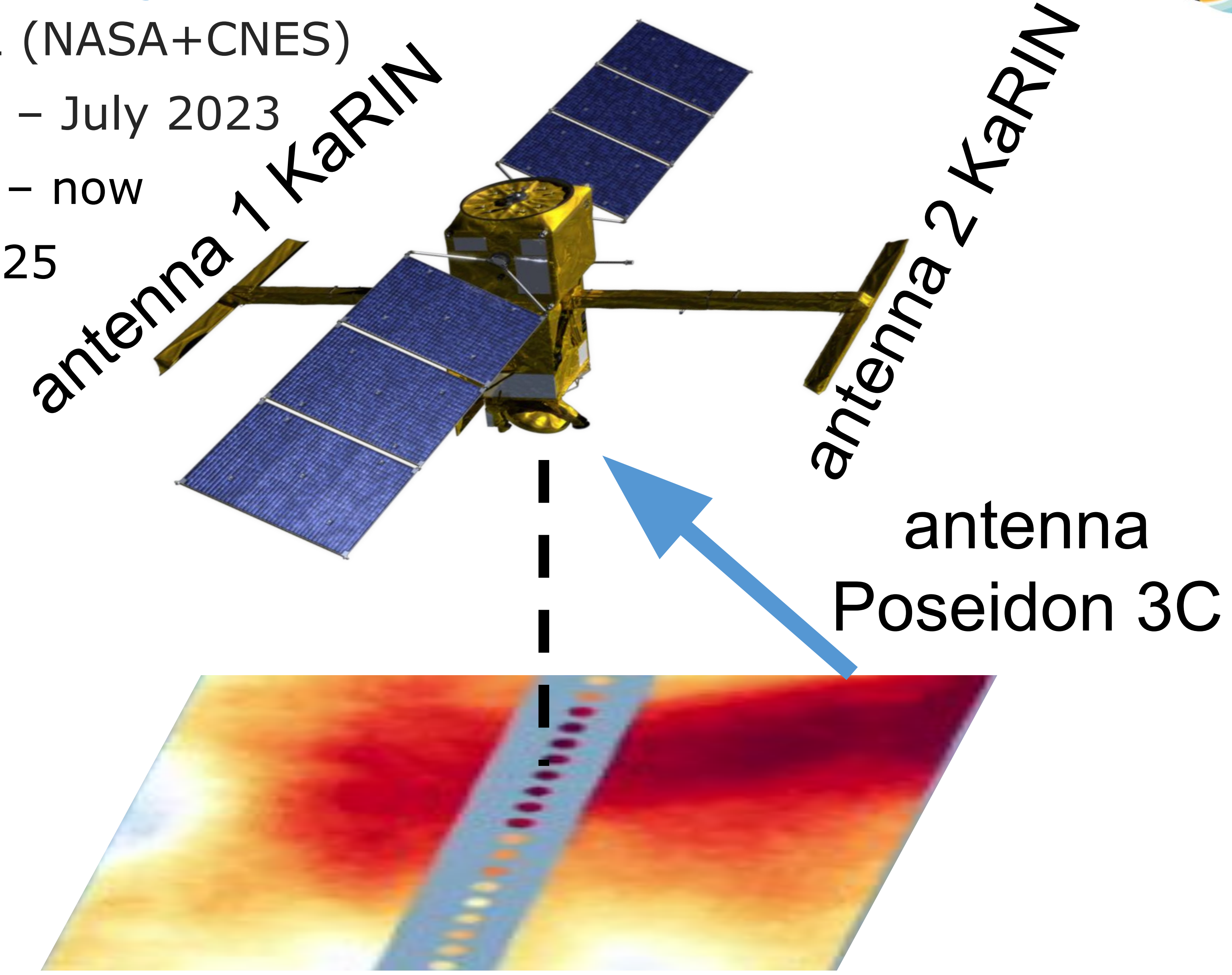
1. What SWOT measures (this talk: LR data only)
2. SWOT spectra compared to CFOSAT/SWIM,
   Sentinel 1 or buoys
3. example science application: the largest ocean waves



Miscellaneous announcements:
see https://wise.discourse.group
- new Seastate CCI (1991-2023) dataset (v4)
- training in Brest
(Nov. 2025) :
using WAVEWATCH III
and satellite data

1. Surface Water Ocean Topography (SWOT)

- Launched december 2022 (NASA+CNES)
- 1 day repeat orbit: March – July 2023
- 21 day repeat: July 2023 – now
- « D » processing: May 2025



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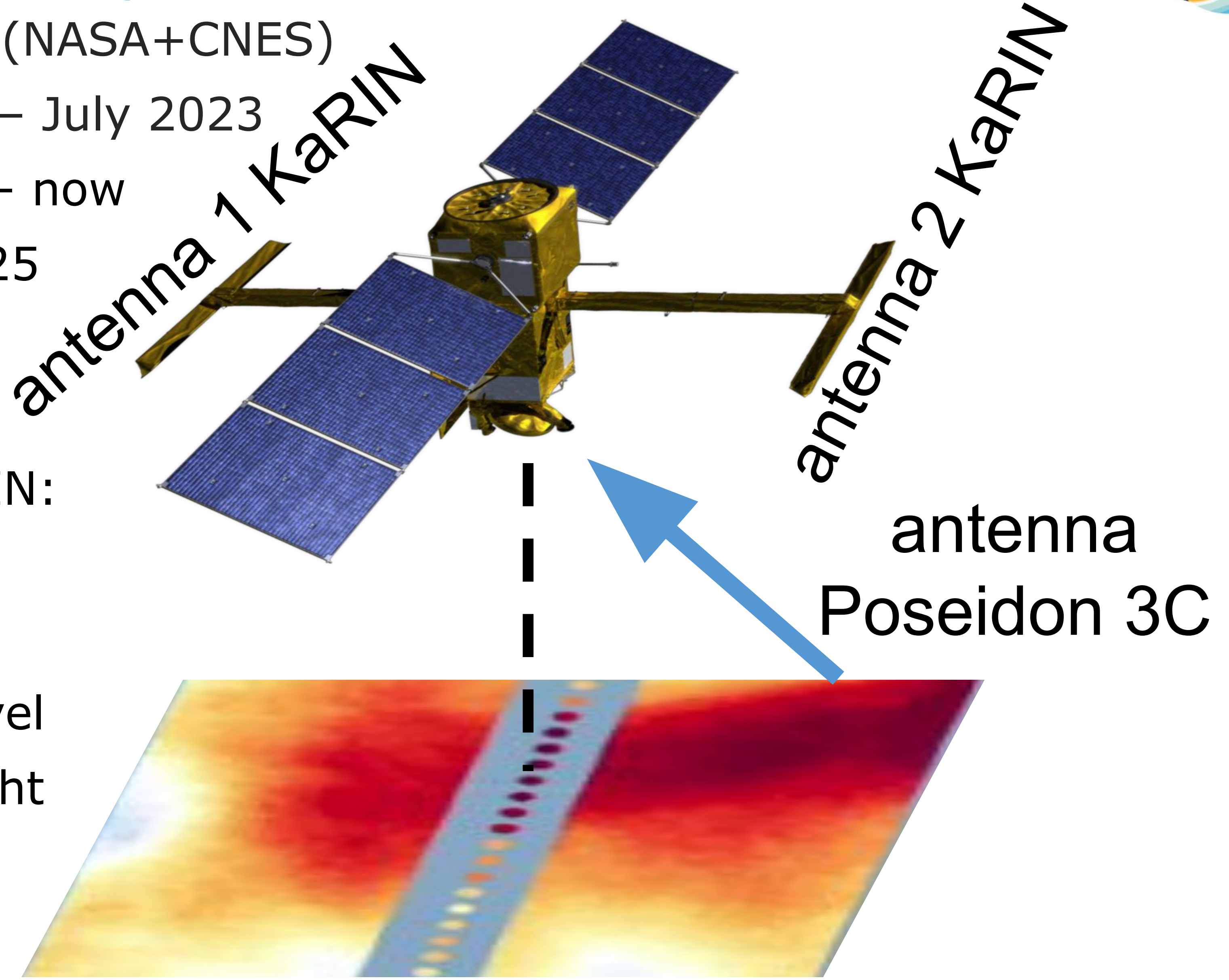
New measurement with KaRIN:
Interferometric phase

Mean value in pixel = sea level
« phase noise » = wave height



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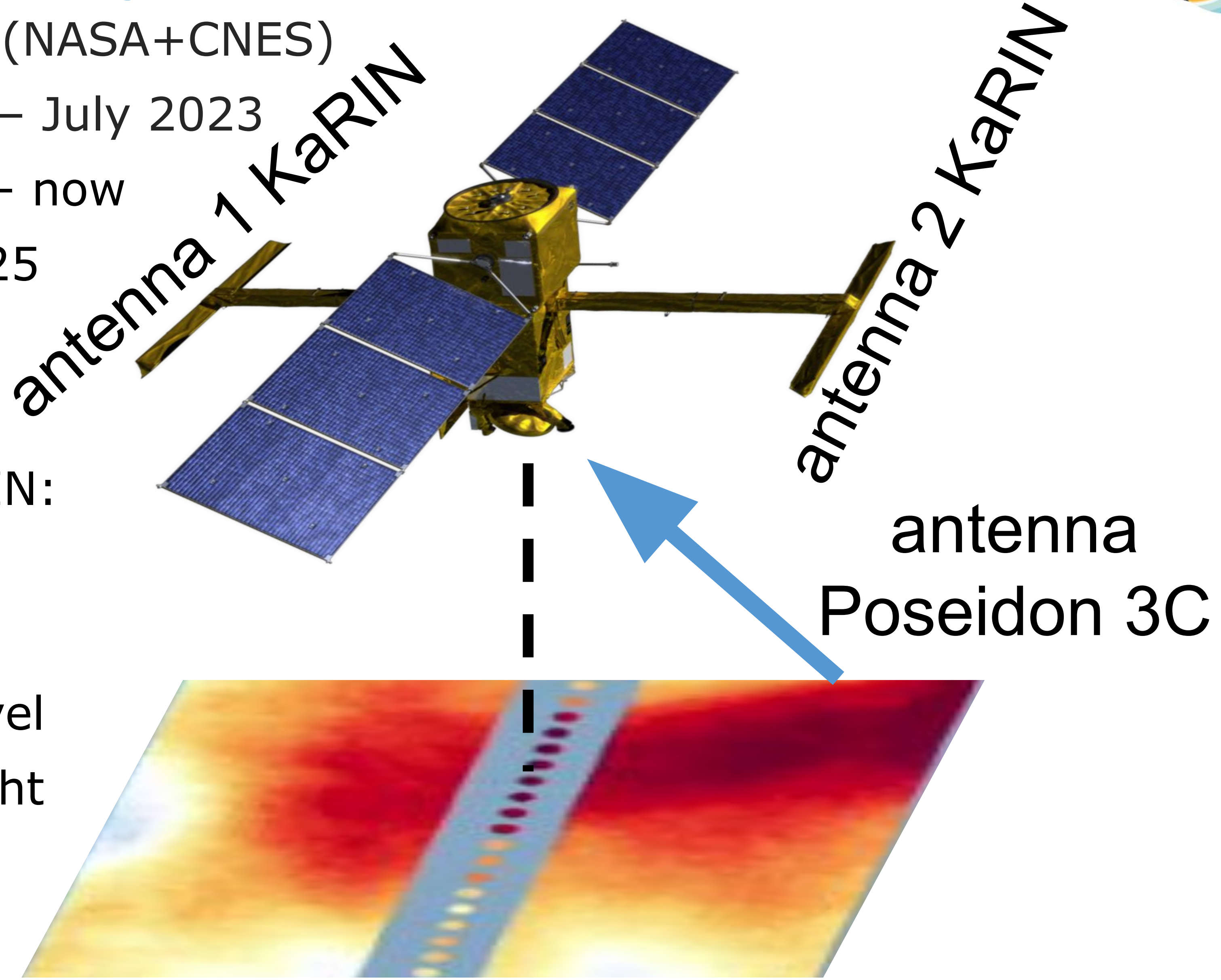


New measurement with KaRIN:

Interferometric phase

Mean value in pixel = sea level

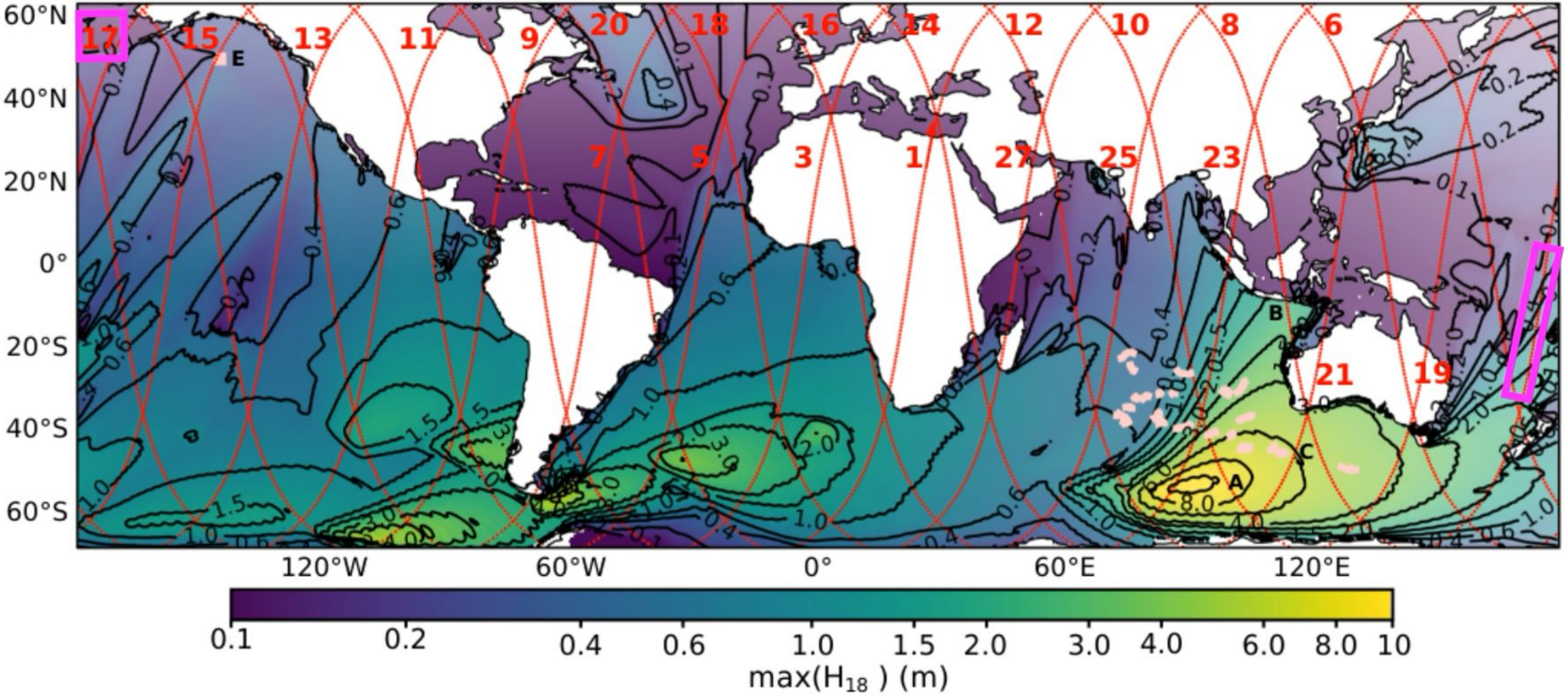
« phase noise » = wave height

But when the pixel < 250 m

… there are waves in the sea level

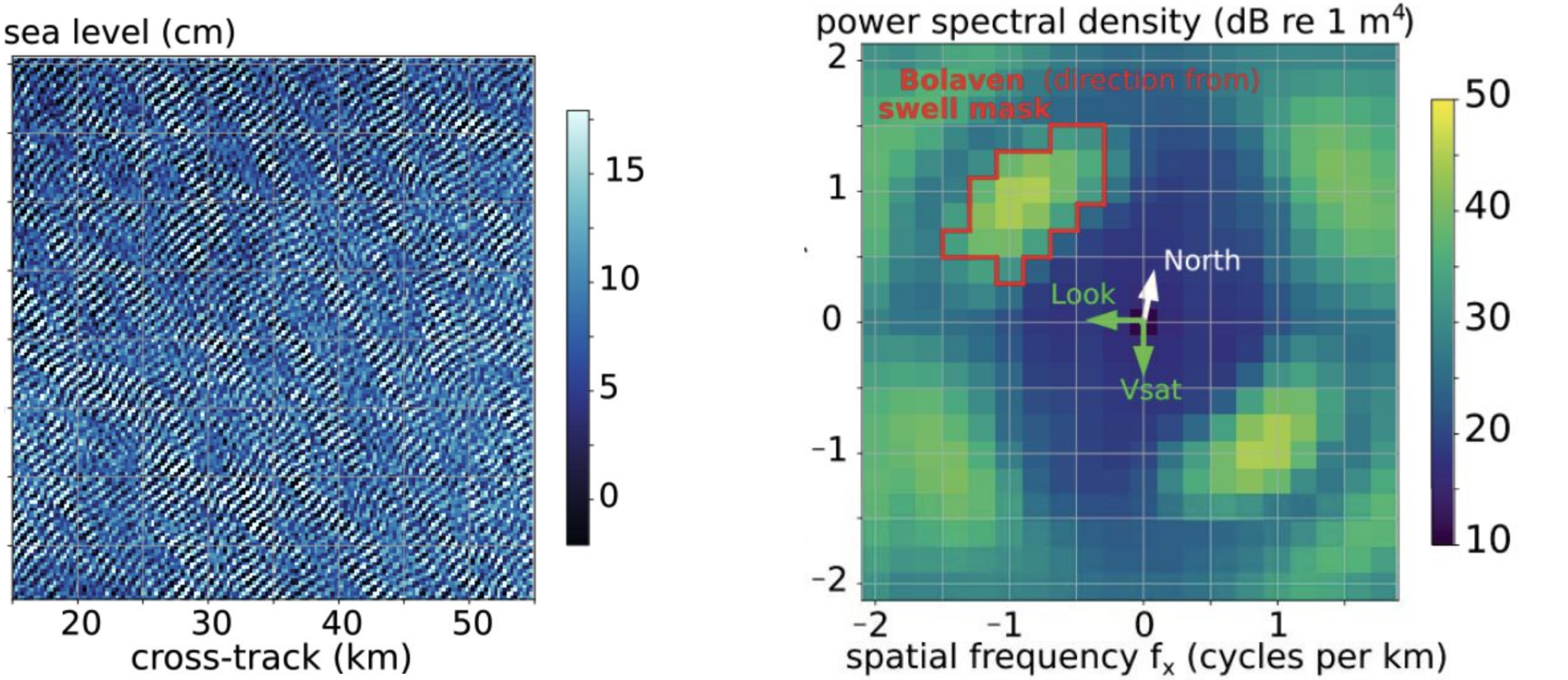
The ocean wears Denim: the swell fabric woven by storm Rosemary June 6 to 19, 2023

Pacific Pinball around Fiji
SWOT track 17, Cycle 549,
looking left, June 11 23:00 UTC.



2. SWOT spectra

- PSD of surface elevation (LR data): dx – 250 m -> Nyquist at 500 m
- Correction for instrument effects: antenna pattern, on board avg, cut-off
- Spectral resolution (and sampling noise) depends on « tile » size…

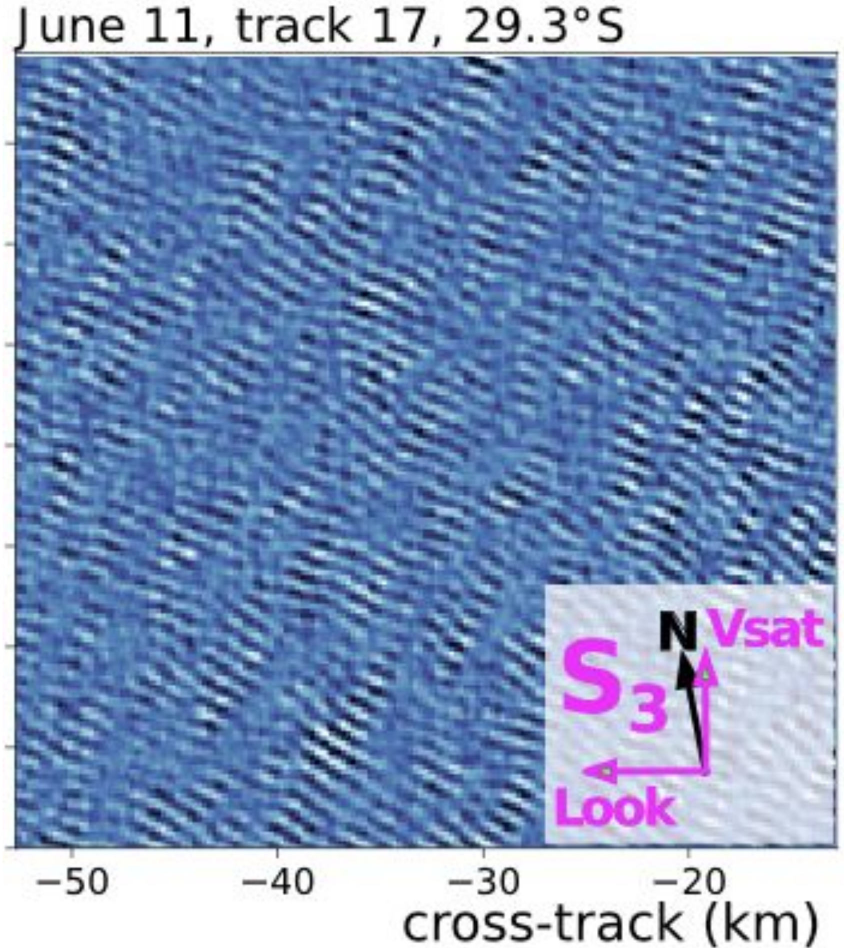


CNES product available on AVISO: **SWOT KaRIn Level-3 Wind Wave products**

see also https://wise.discourse.group/

2. SWOT spectra: how good are they?

- Low detection level (3 cm for T=20 s, better than Spotter buoy or CFOSAT)
- Low noise level



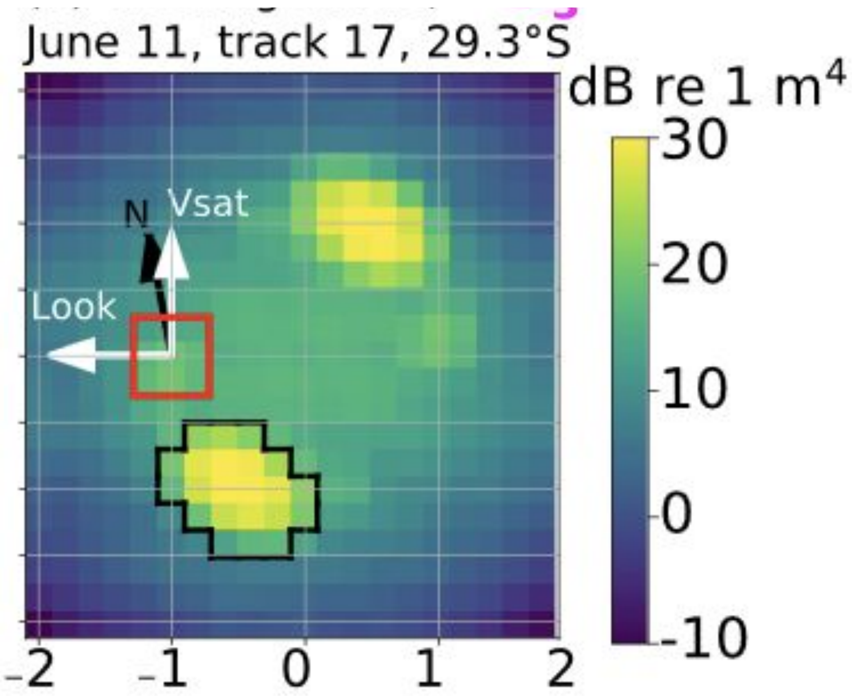
Geophysical Research Letters

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]

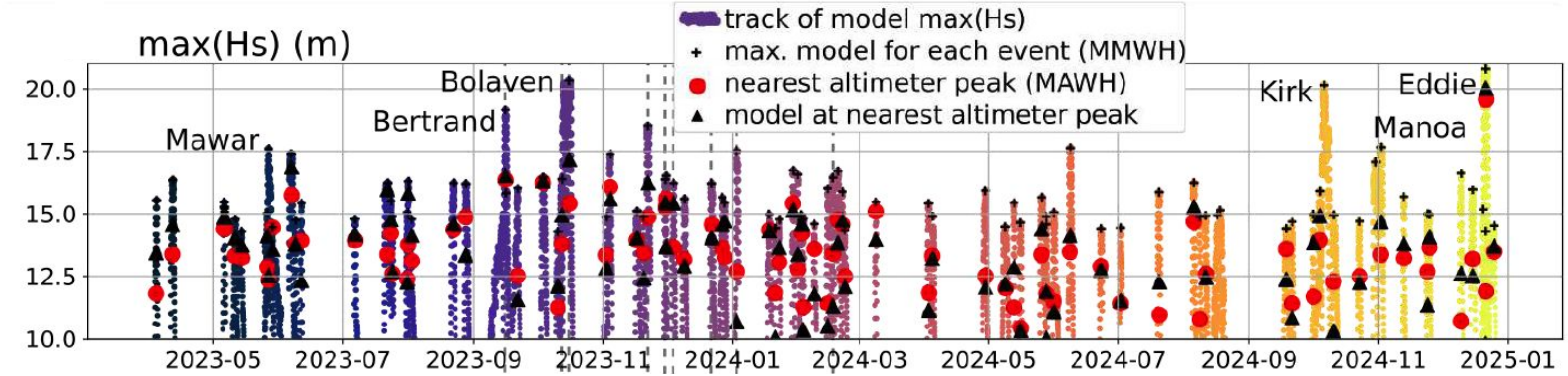


Sizing the largest*ocean waves using the SWOT mission

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

largest*: for this talk 2023 only

Hs probably exceeded 18 m,
with Tp around 19.3 s



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largest*: for this talk 2023 only

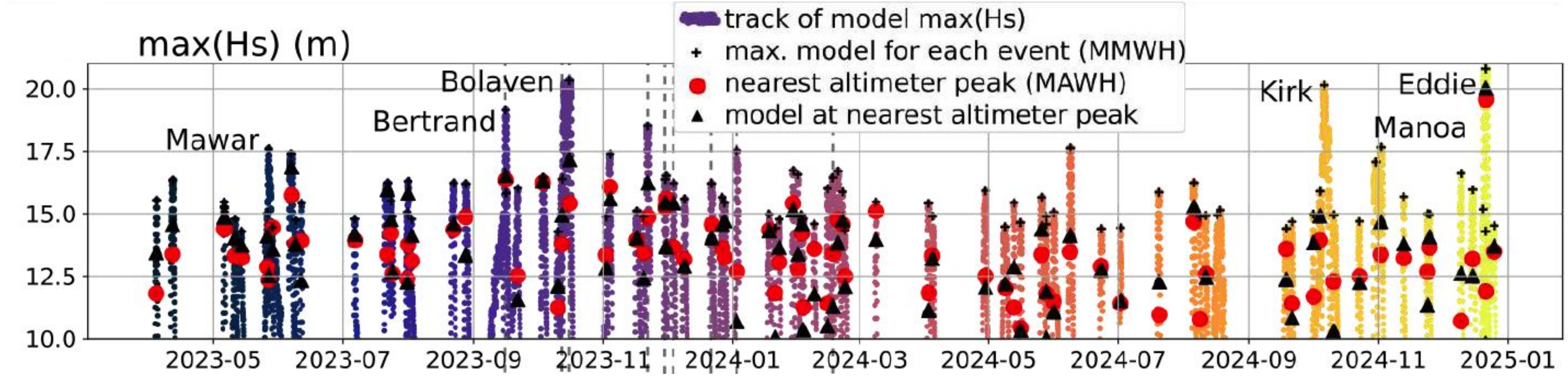
Hs probably exceeded 18 m, with Tp around 19.3 s

The « CCI » hindcast (based on Alday et al. 2023):

Largest Hs of 2023 is in storm « Bolaven »:

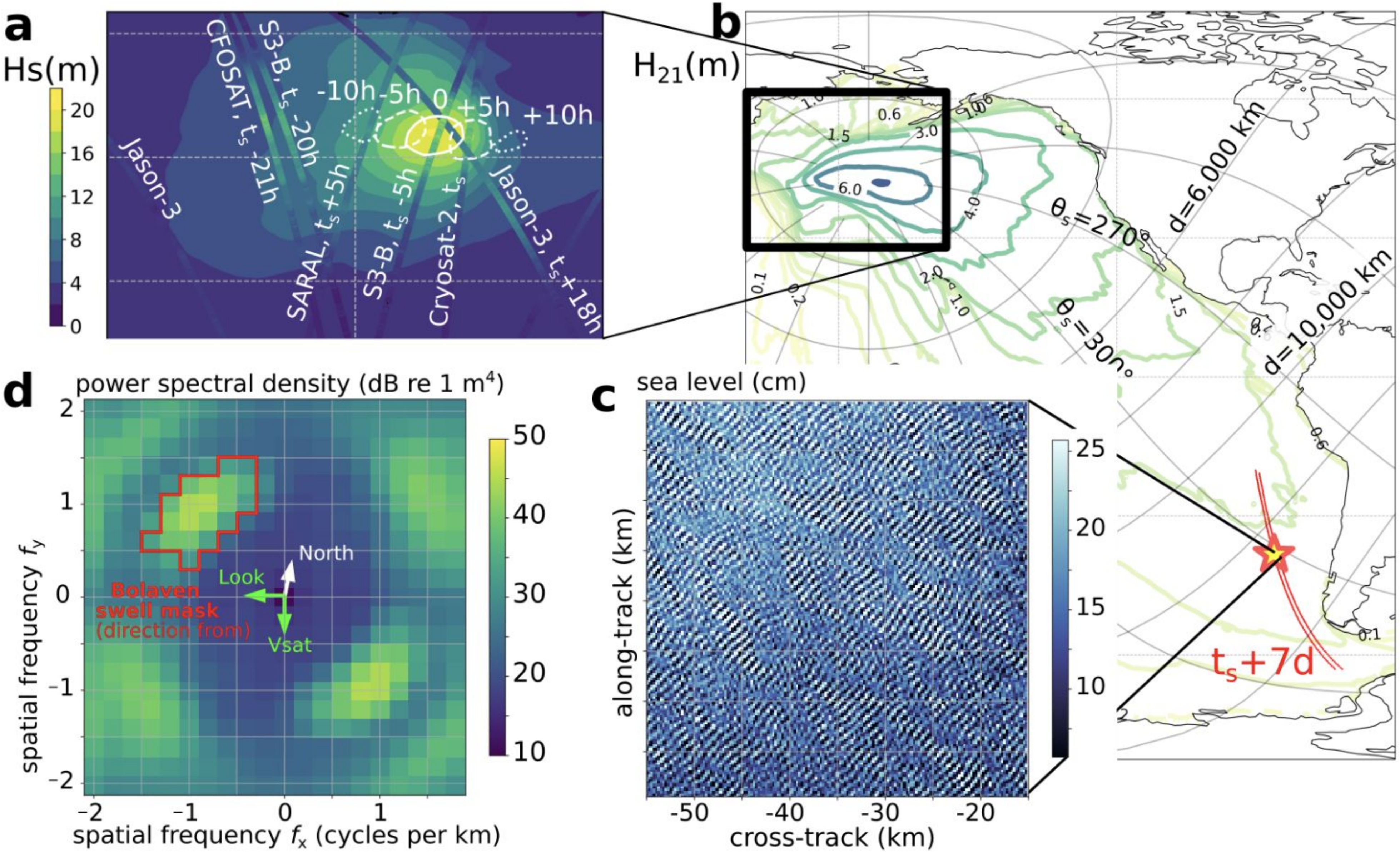
model up to **20.3 m**
altimeters up to **15.4±0.2 m**
CCI hindcast at alti. max: **17.2 m**

CCI hindcast for all sat. max : r=0.98, bias =0.3 rmsd =0.95 m



3. Sizing the largest waves

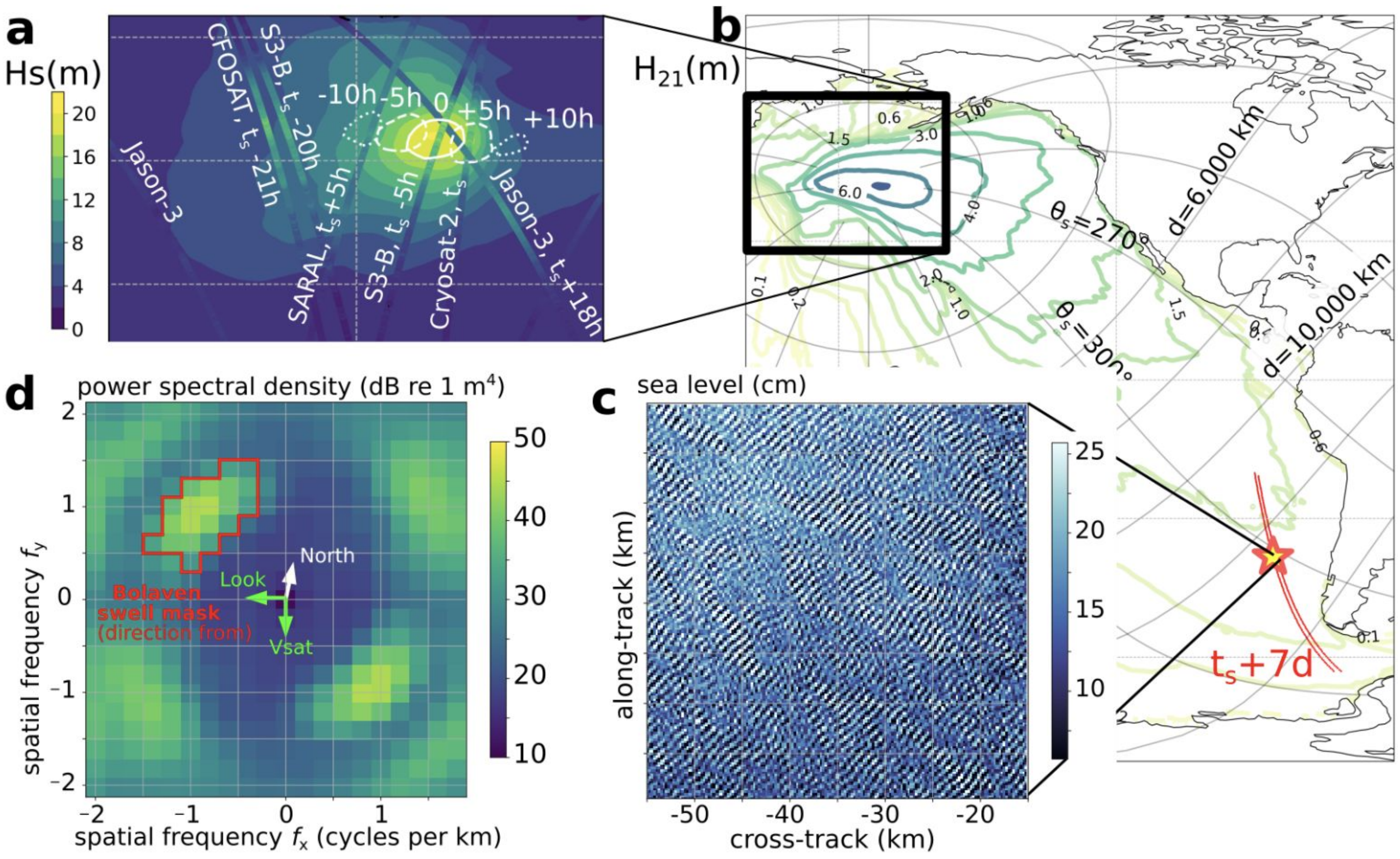
Altimeters: model max is 300 km away …

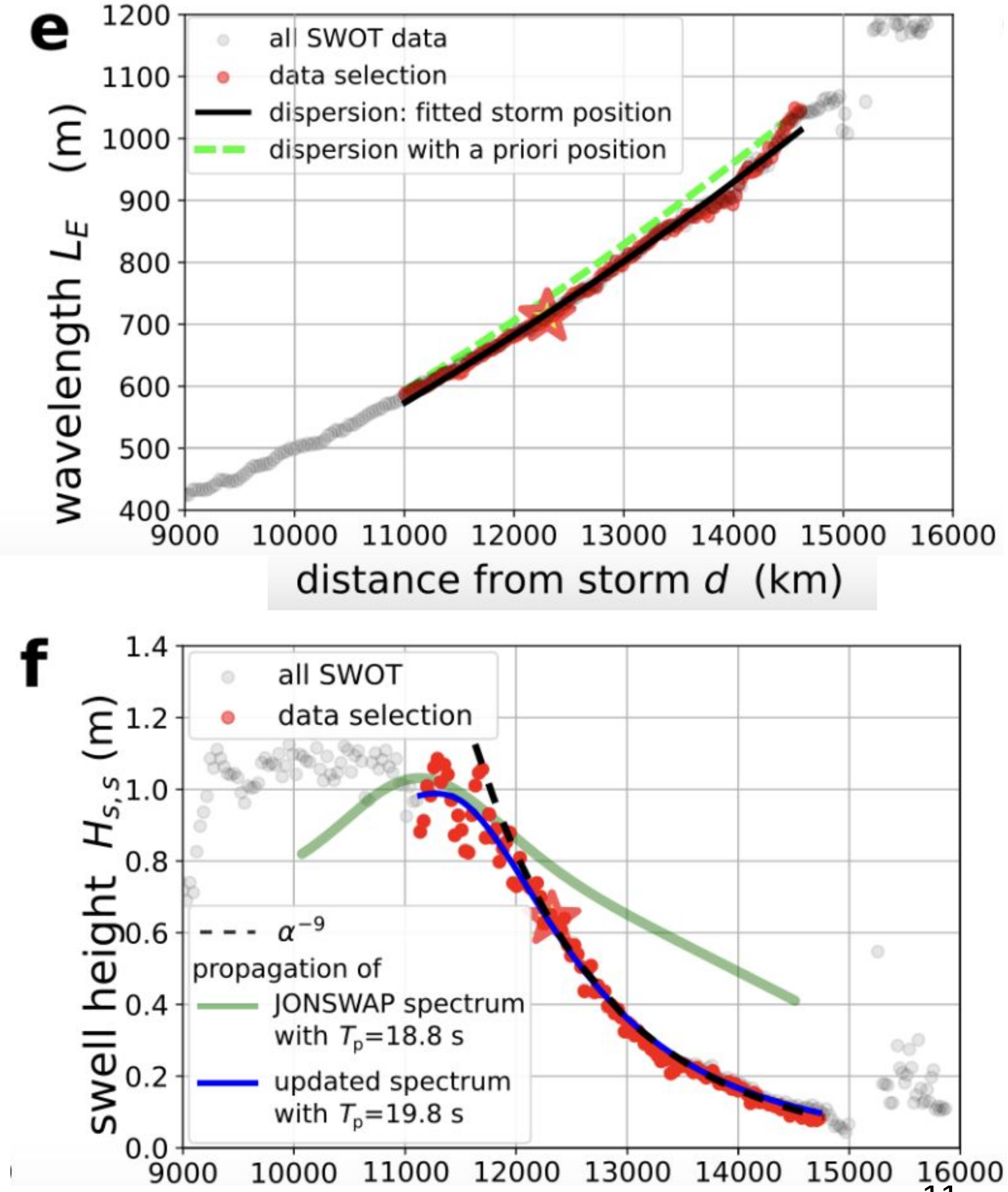


What about swell? now we got SWOT swells!

1. What evidence do we have?

SWOT swell partitions Hss and LE for **one** SWOT track
(7 days after storm peak)





We have swell measurements from Bolaven in 109 tracks,
Covering 109 x 100 x 2 x 1600 km^2 , over 20,000 spectra

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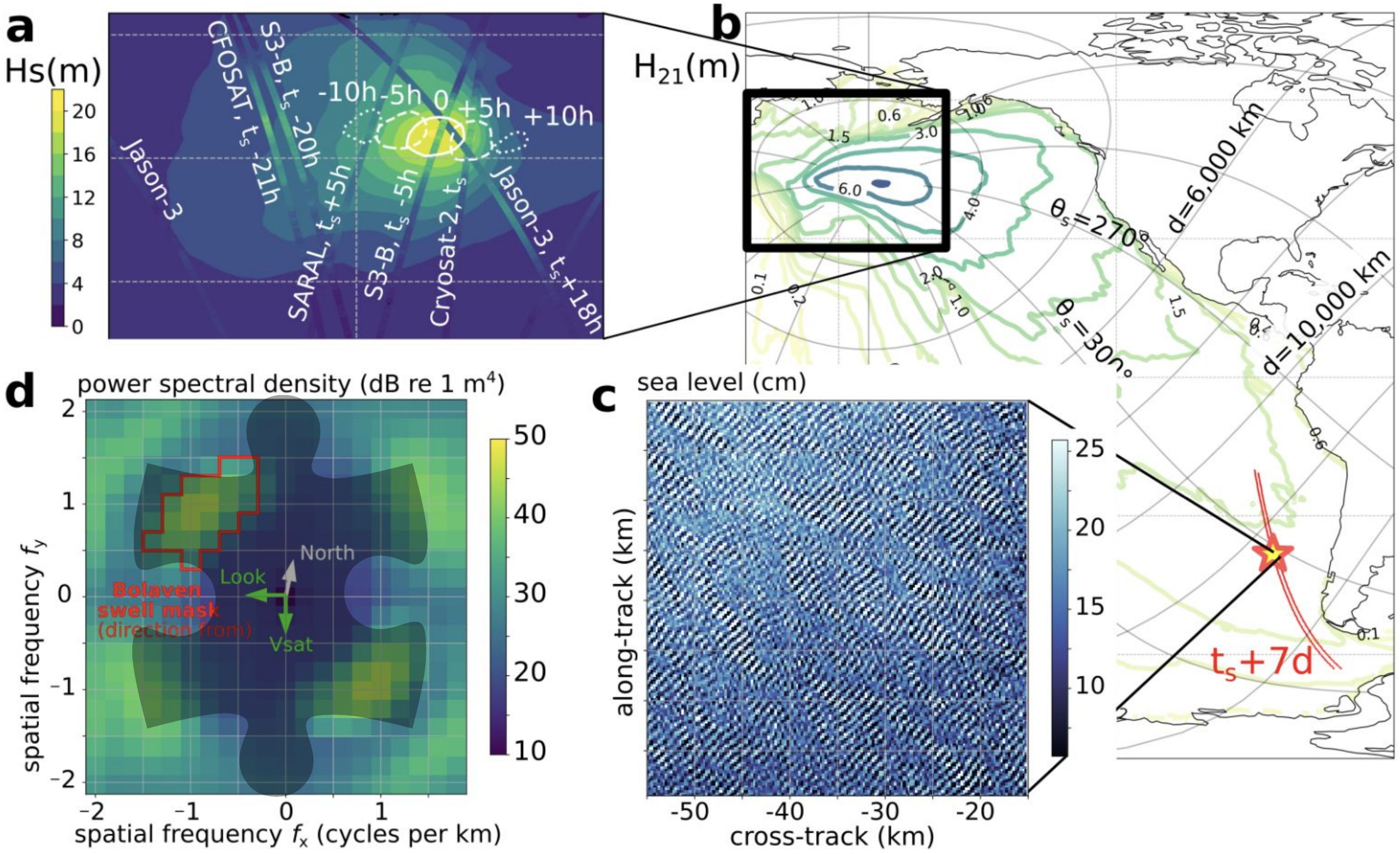
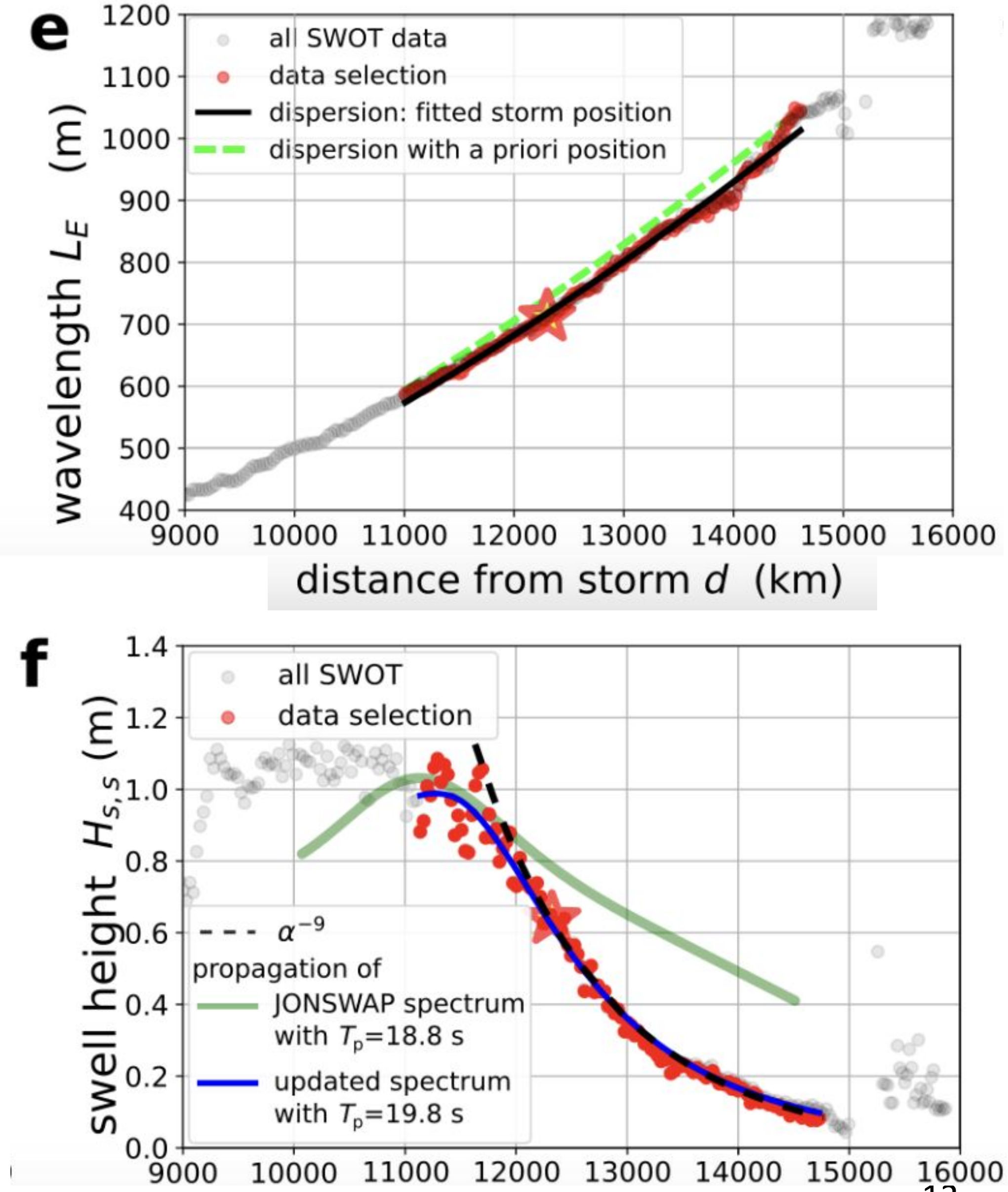




We have swell measurements from Bolaven in 109 tracks,
Covering 109 x 100 x 2 x 1600 km^2 , over 20,000 spectra
Each spectrum is a piece of the storm puzzle

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

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

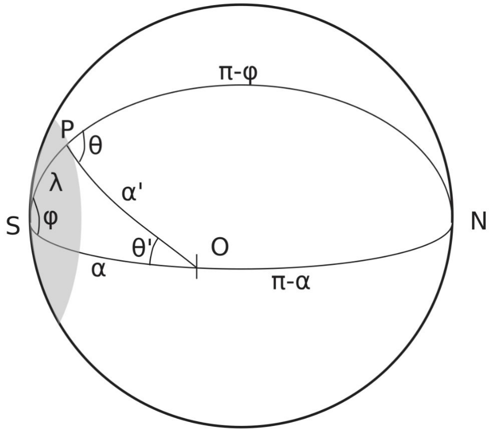
This integral can be evaluated numerically using any analytic expression for the source spectrum, which can be the JONSWAP spectrum[8] or the update proposed below with eqs. (8) and (9).

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

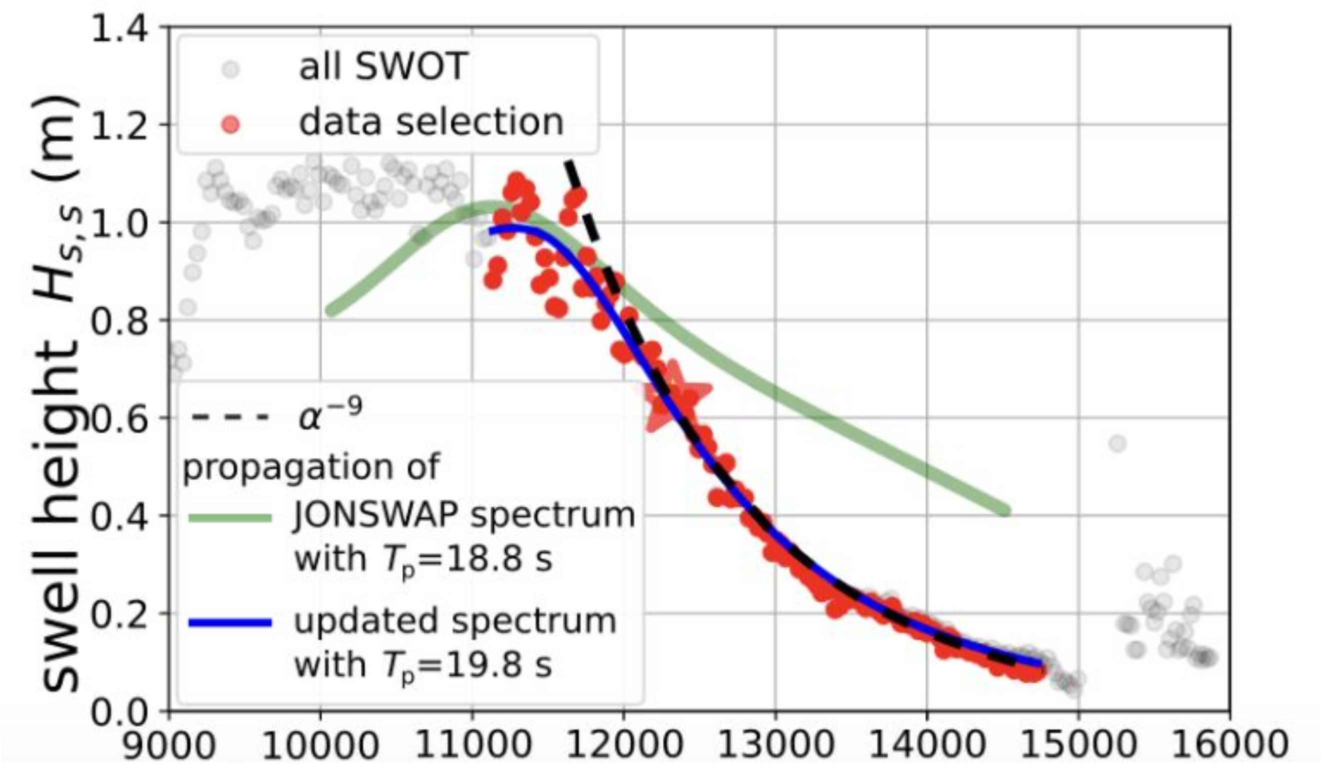
$$E_0(\alpha, SPP, r) = f_\alpha\, E_{S.iso}(f_\alpha)(r/R_E)^2/(2\,\alpha\,\sin\alpha) \quad (7)$$

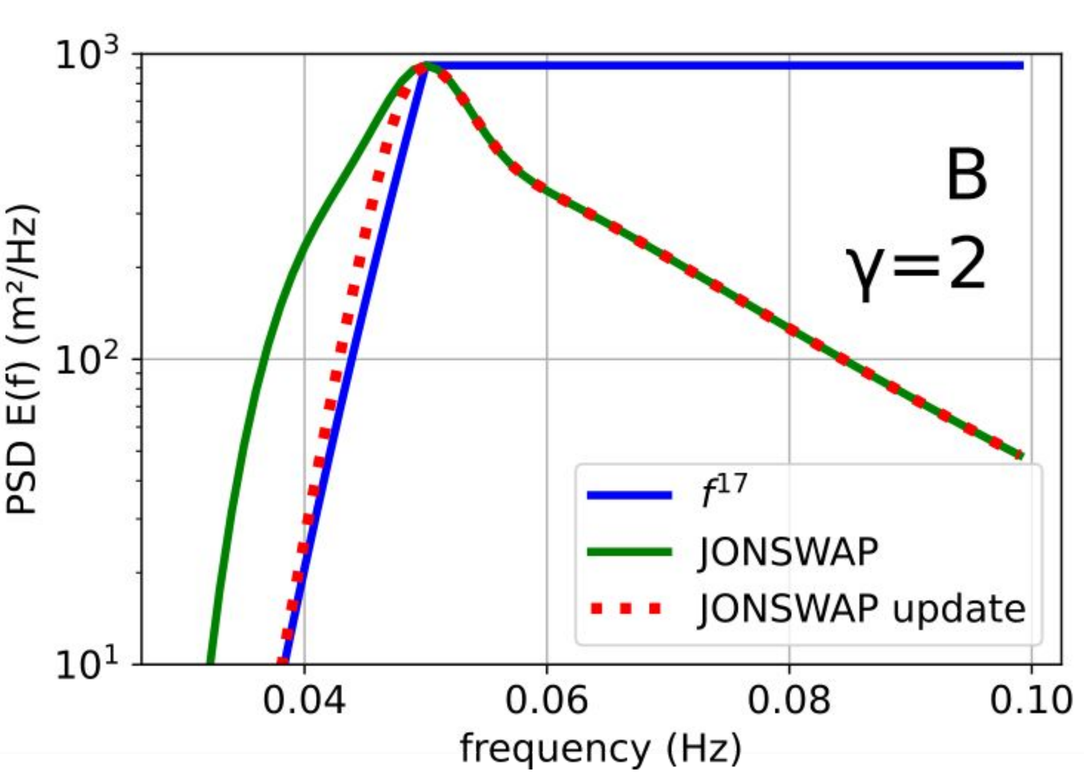


3.2. what it tell about 4-wave interactions

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



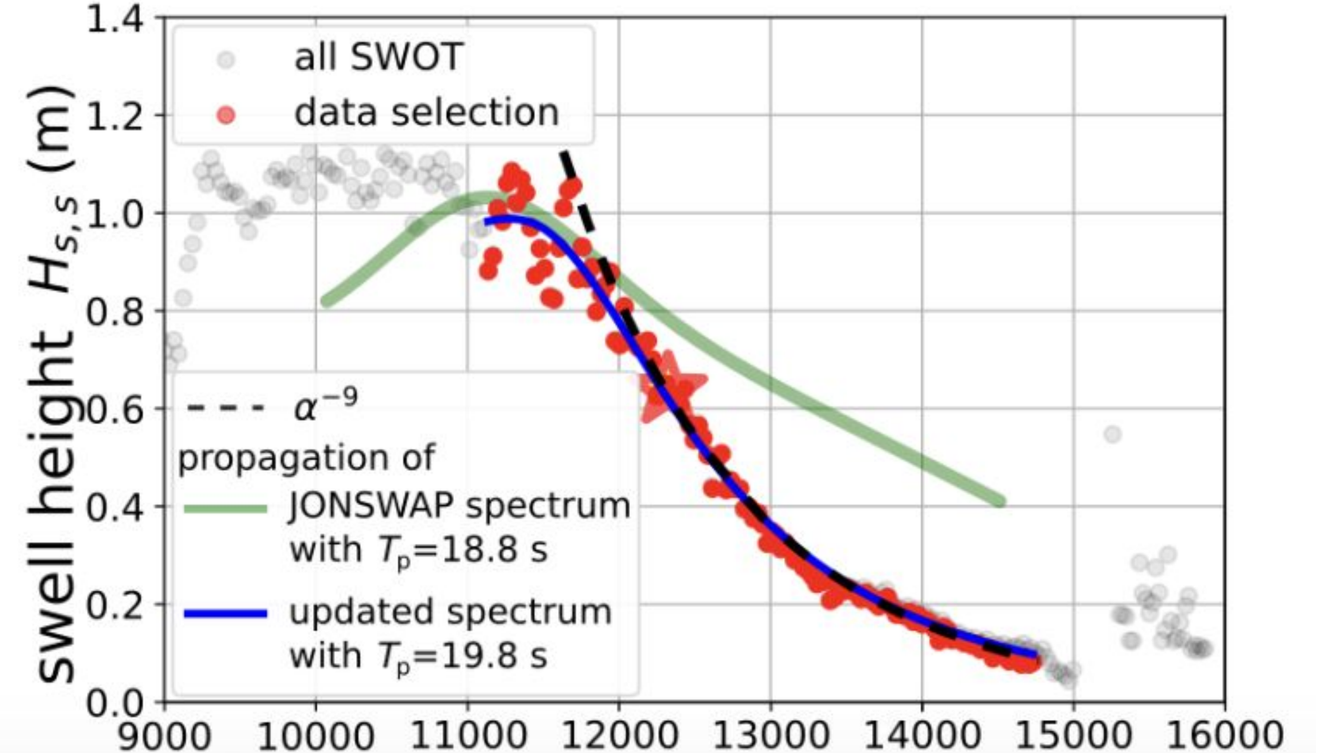


2. what it tell about 4-wave interactions: putting the puzzle together

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)



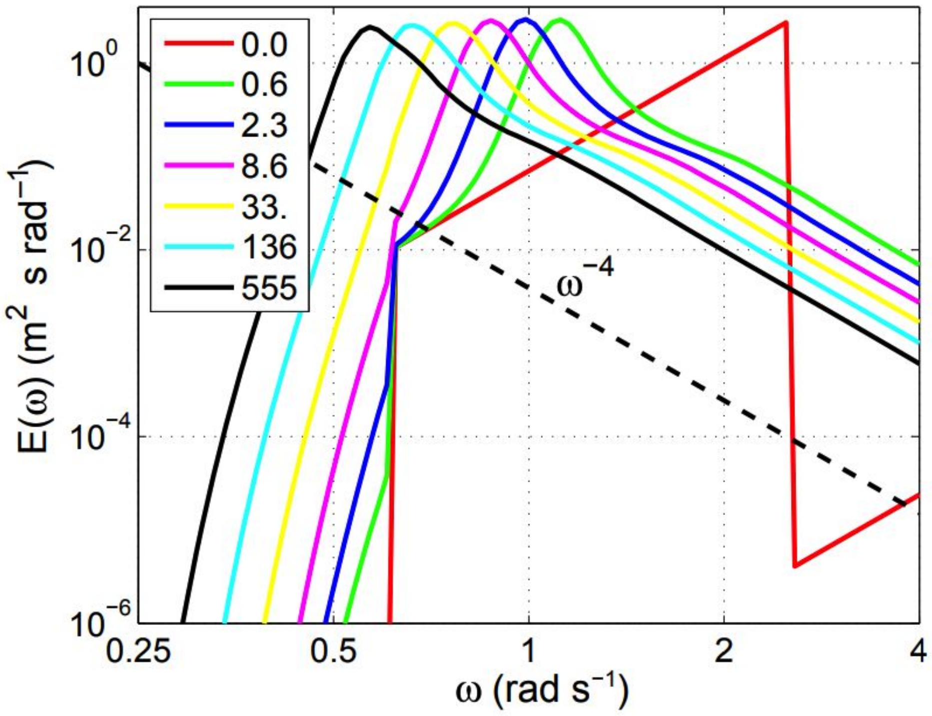
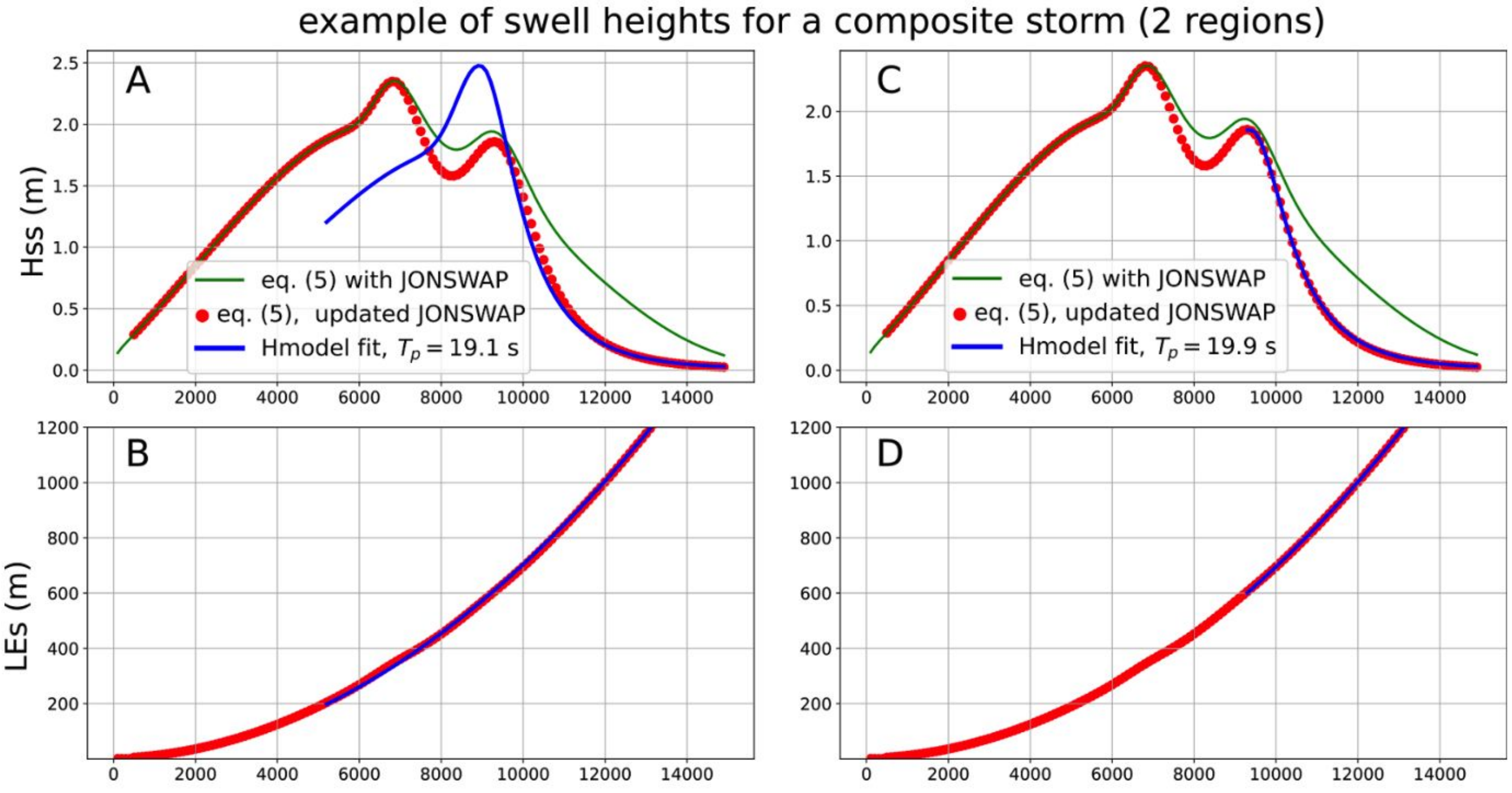
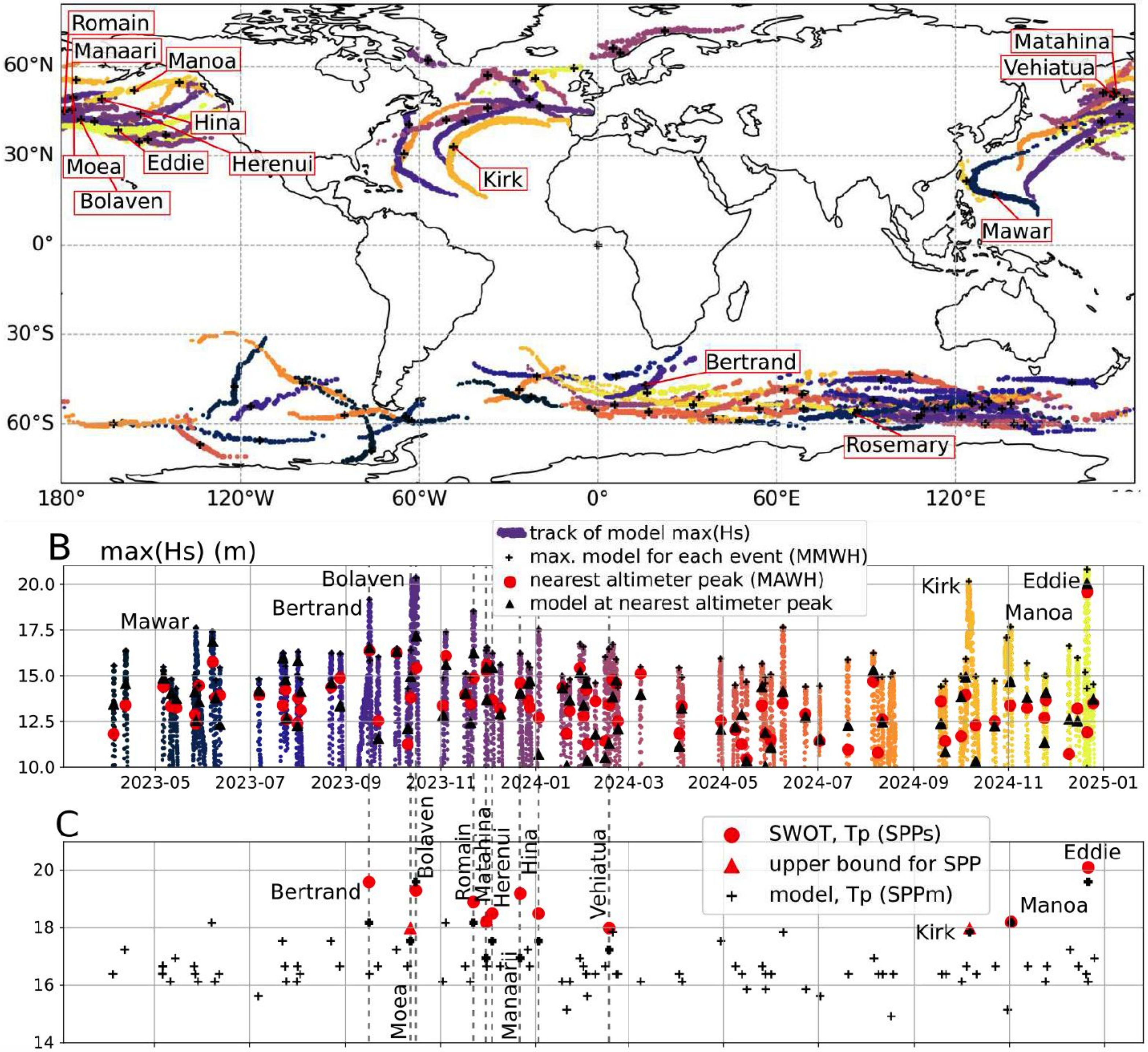


Figure 1. Frequency spectra of energy at different times (legend, in hours) for case sw330 (Θ = 330°).

2. Adjusting the JONSWAP spectrum



3. Adding Storm peak Periods to the climate record

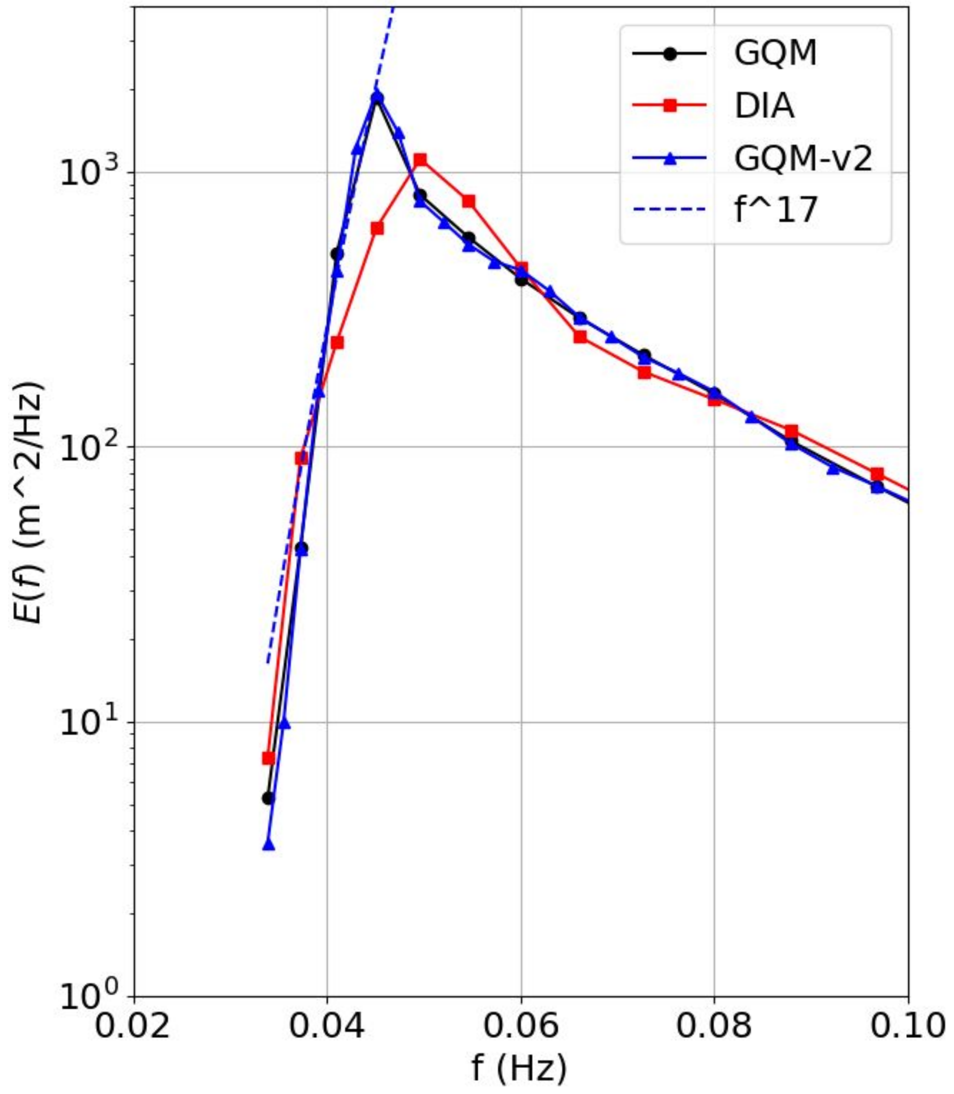


SWOT era (2023/04 – now)

10 storms analyzed by Taina Postec

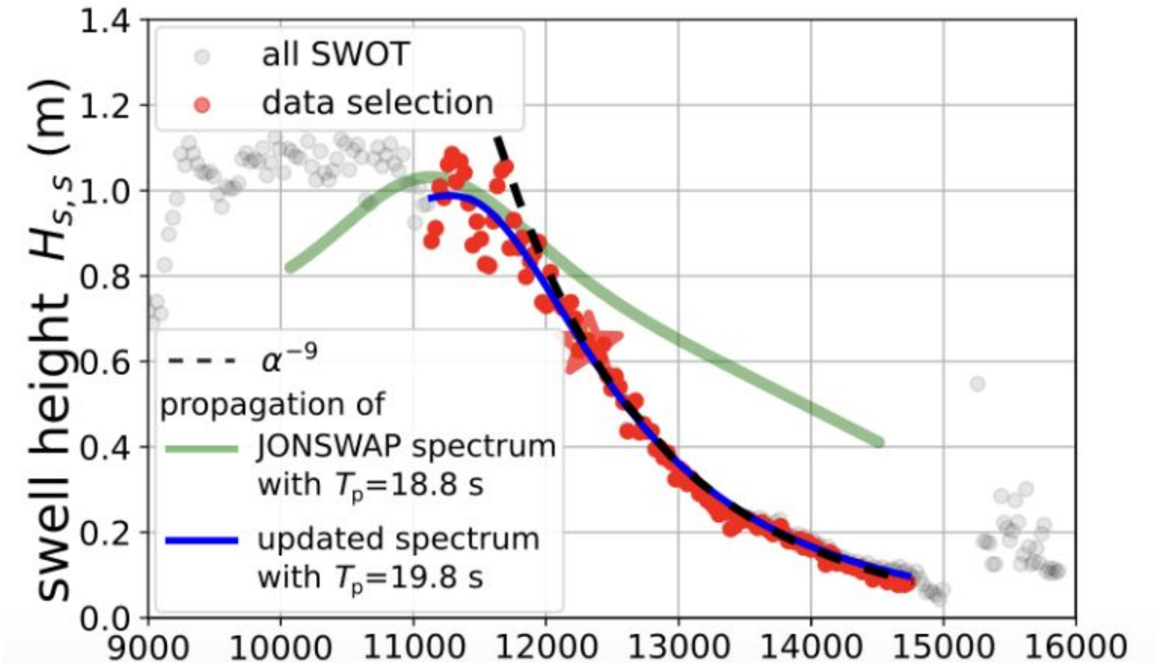
4. How good are the models?

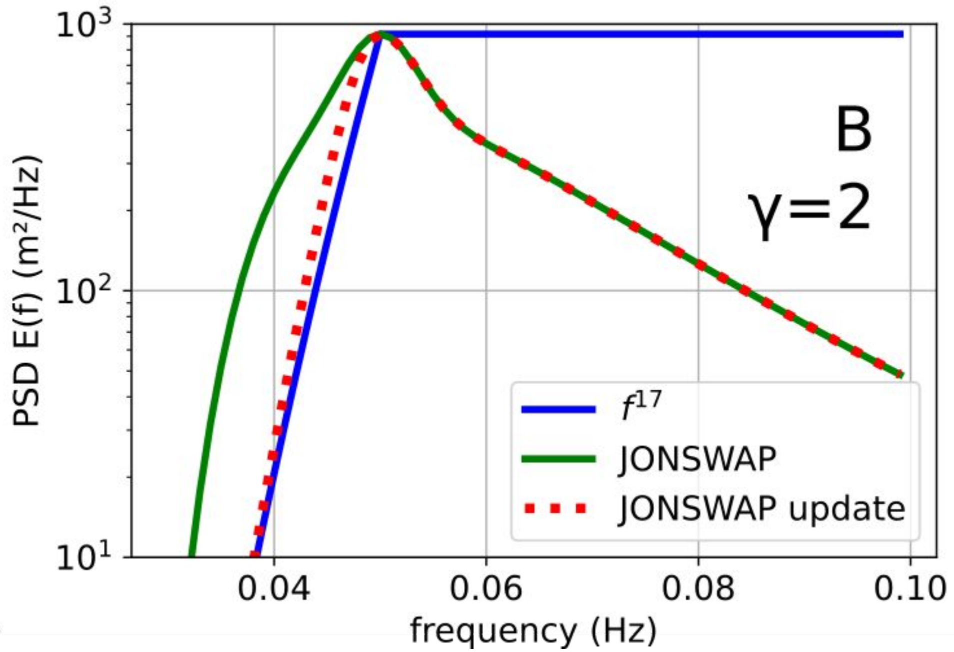
Consistent with Lavrenov's (2003), exact Snl (GQM) gives f^{17} forward face, not the DIA



Conclusions

- SWOT swells are fantastic (see https://wise.discourse.group/ for data access and more)
- CFOSAT gives complementary shorter swells … but… uncertainty higher (my advice: use L2S data)
- SWOT also has SWH and much more …
- Wind sea to swell transition and propagation consistent with “updated JONSWAP” shape
- Models will have to be updated …
- Next work: directional shape, swell dissipation rates, coastal impacts (storm Eddie) …





BONUS SLIDES

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

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

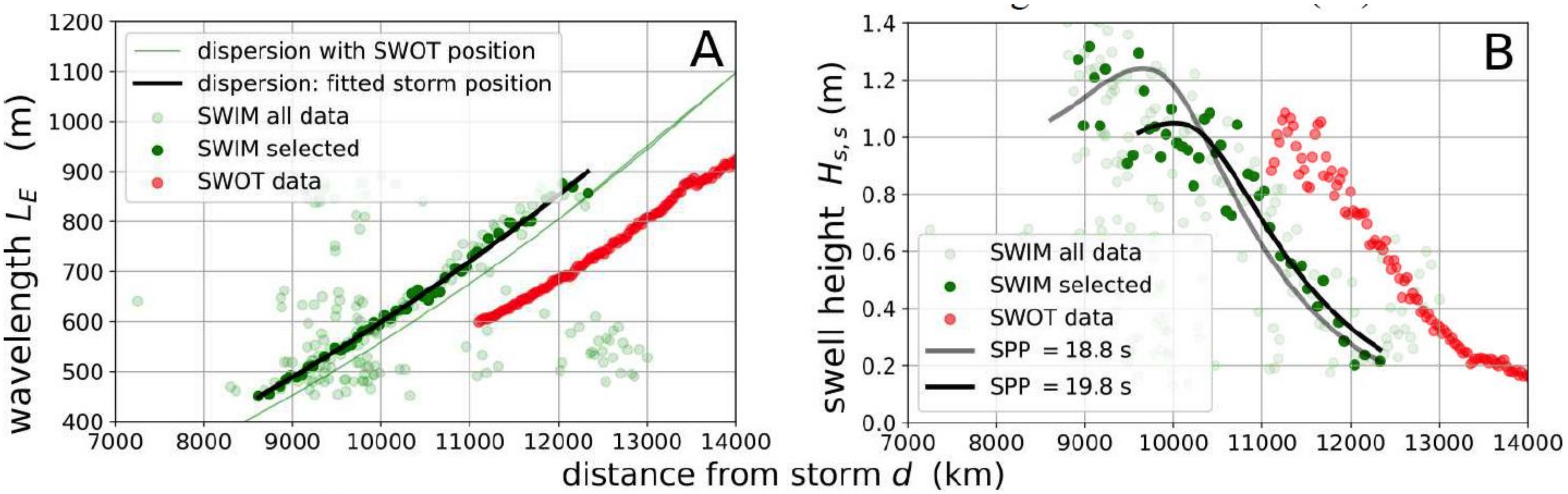
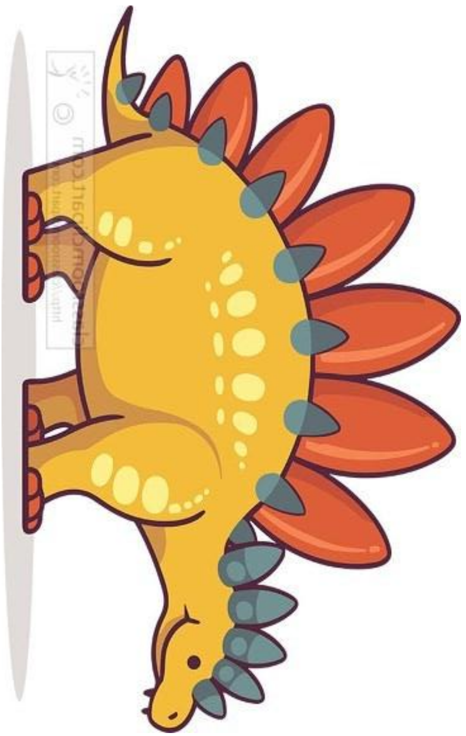
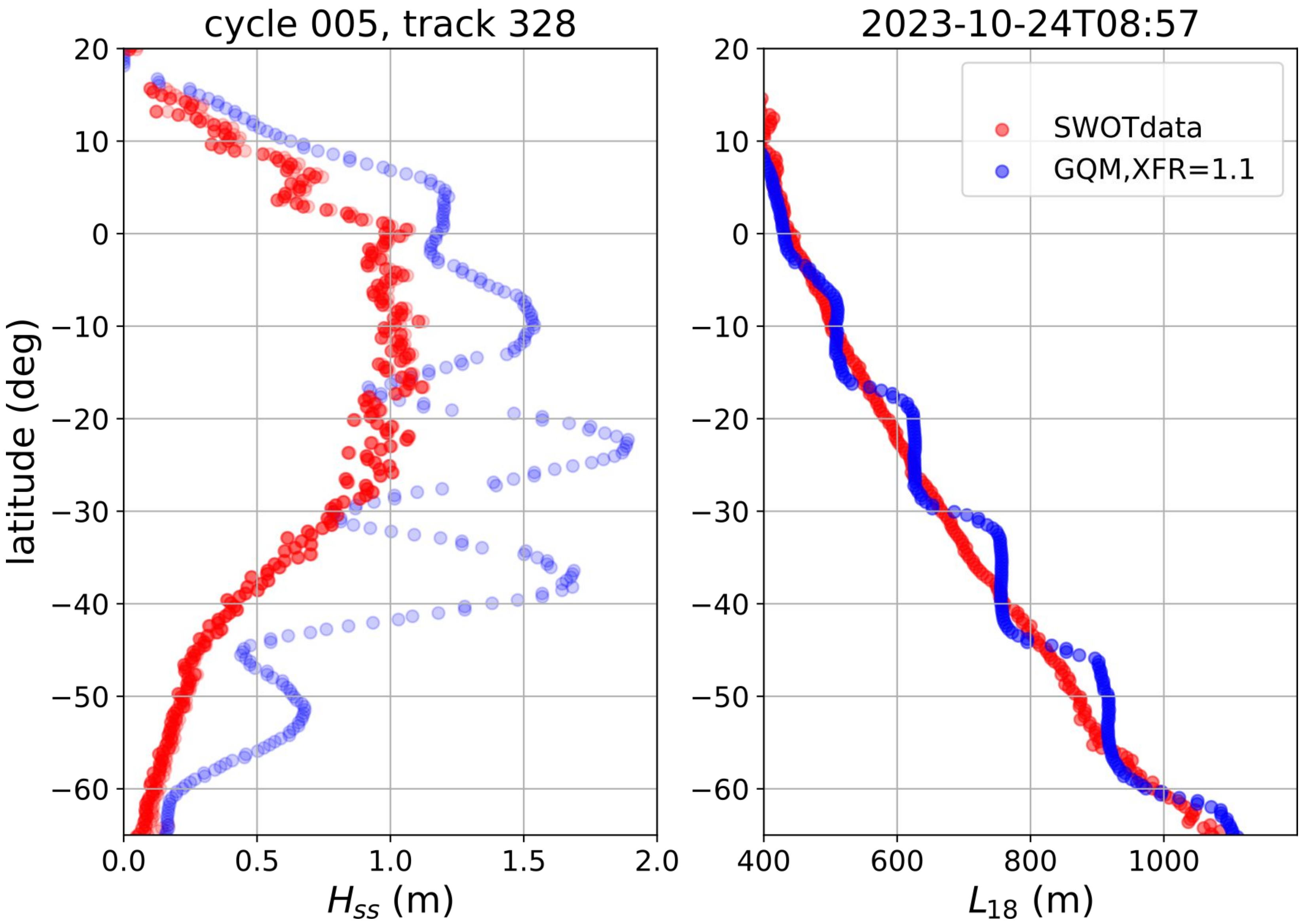


Fig. 4. Estimation of storm peak period using SWIM 10° beam data, acquired along the green track of Fig. 1.B, 9 hours before the SWOT data along the red track. (A) wavelength and (B) swell heights and fitted swell height (grey and black curves) using either all good data or only data with $L_E > 550$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

4. How good are the models?

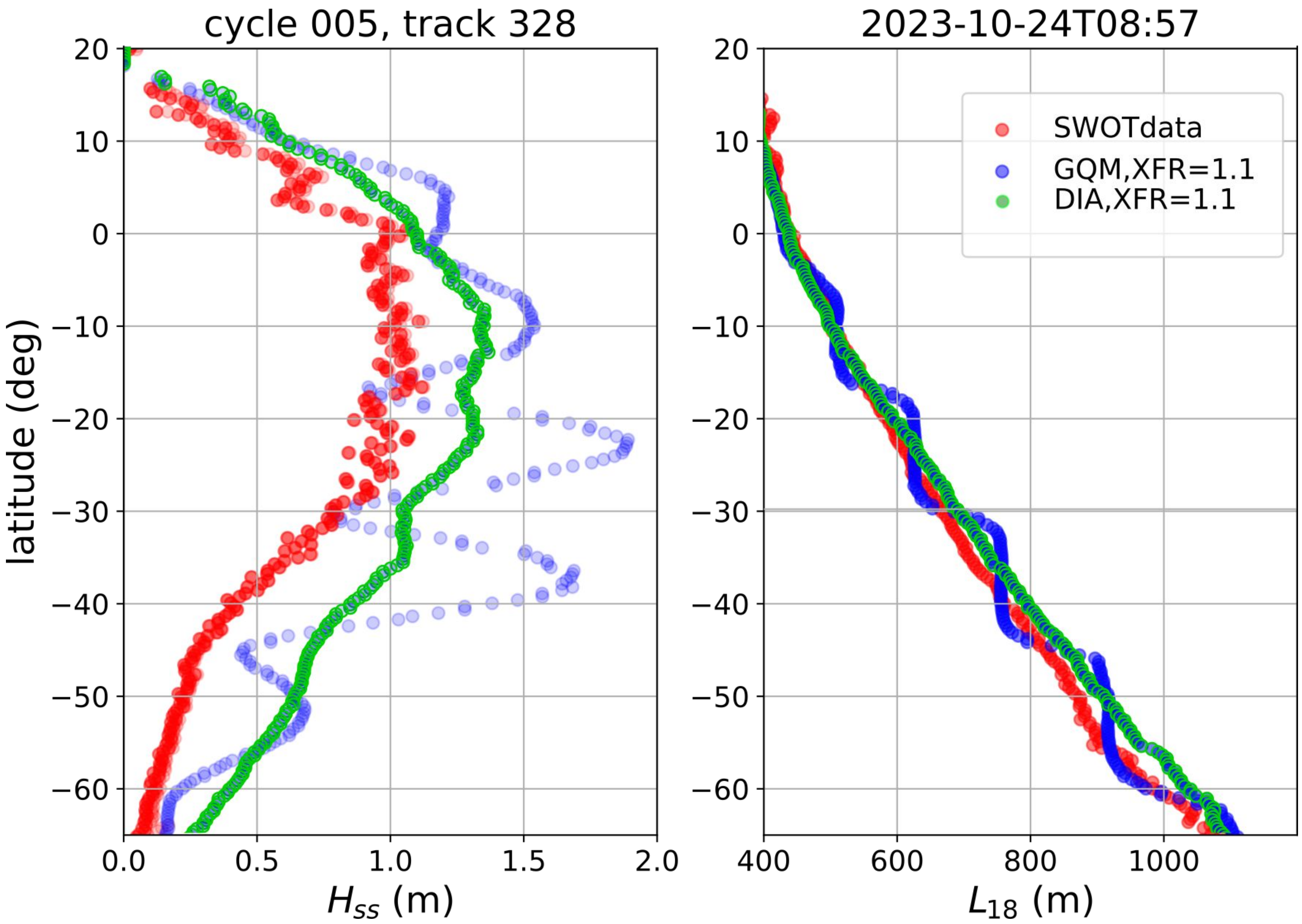
Narrow spectrum + high order scheme = Great Stegosaurus-down-the-stairs Effect (GSE)





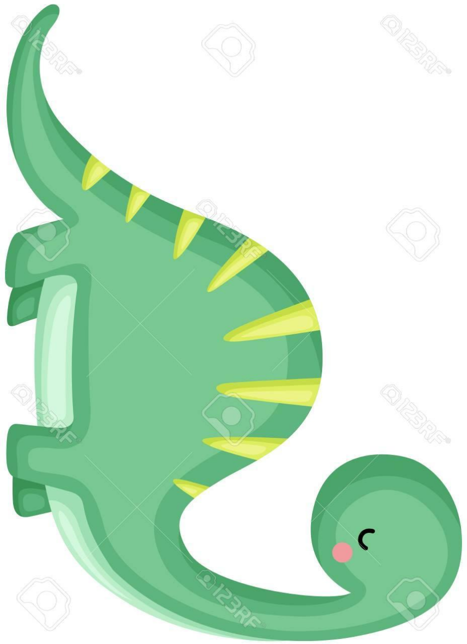
4. How good are the models?

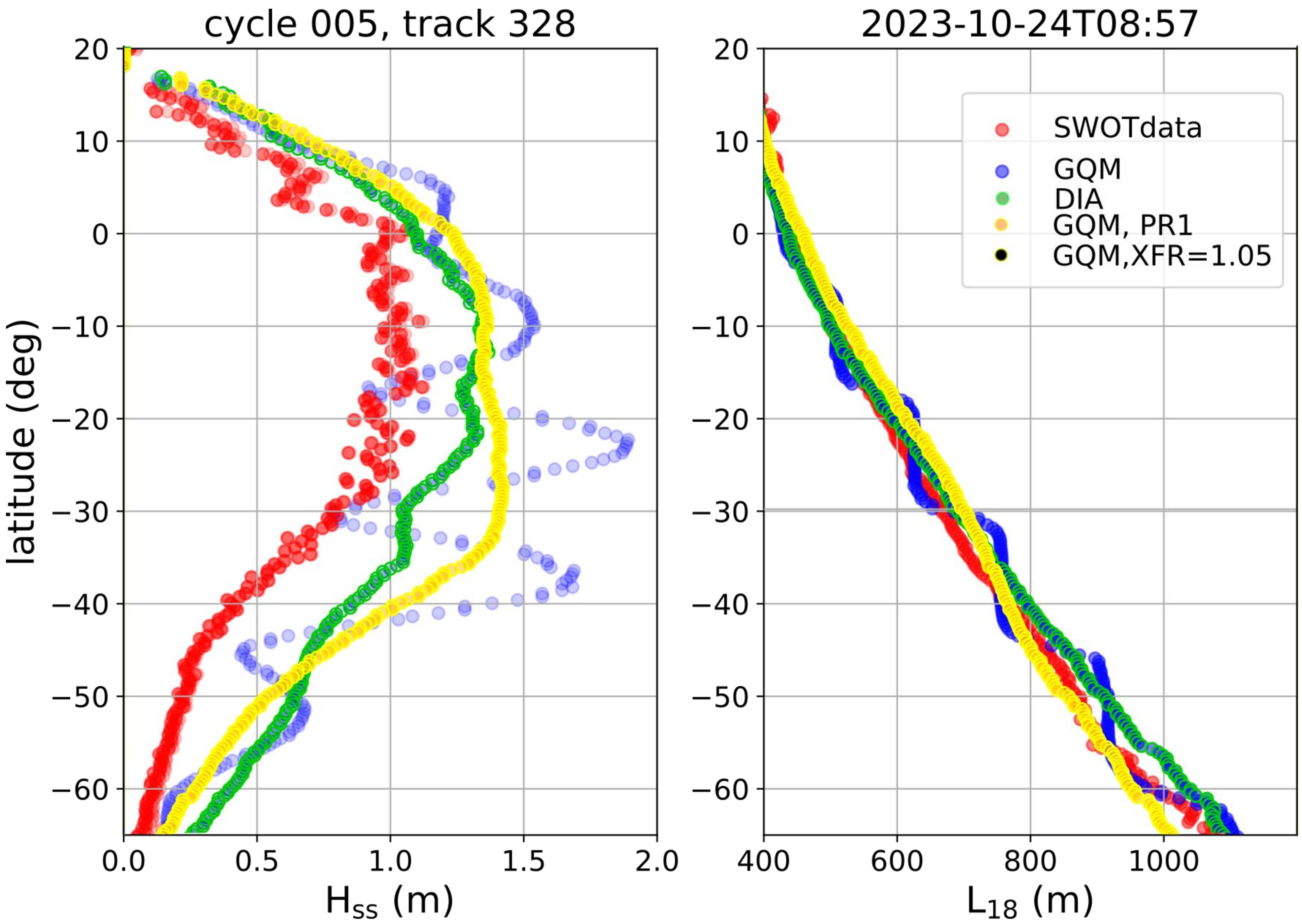
broad spectrum + high order scheme = swell arriving too early



4. How good are the models?

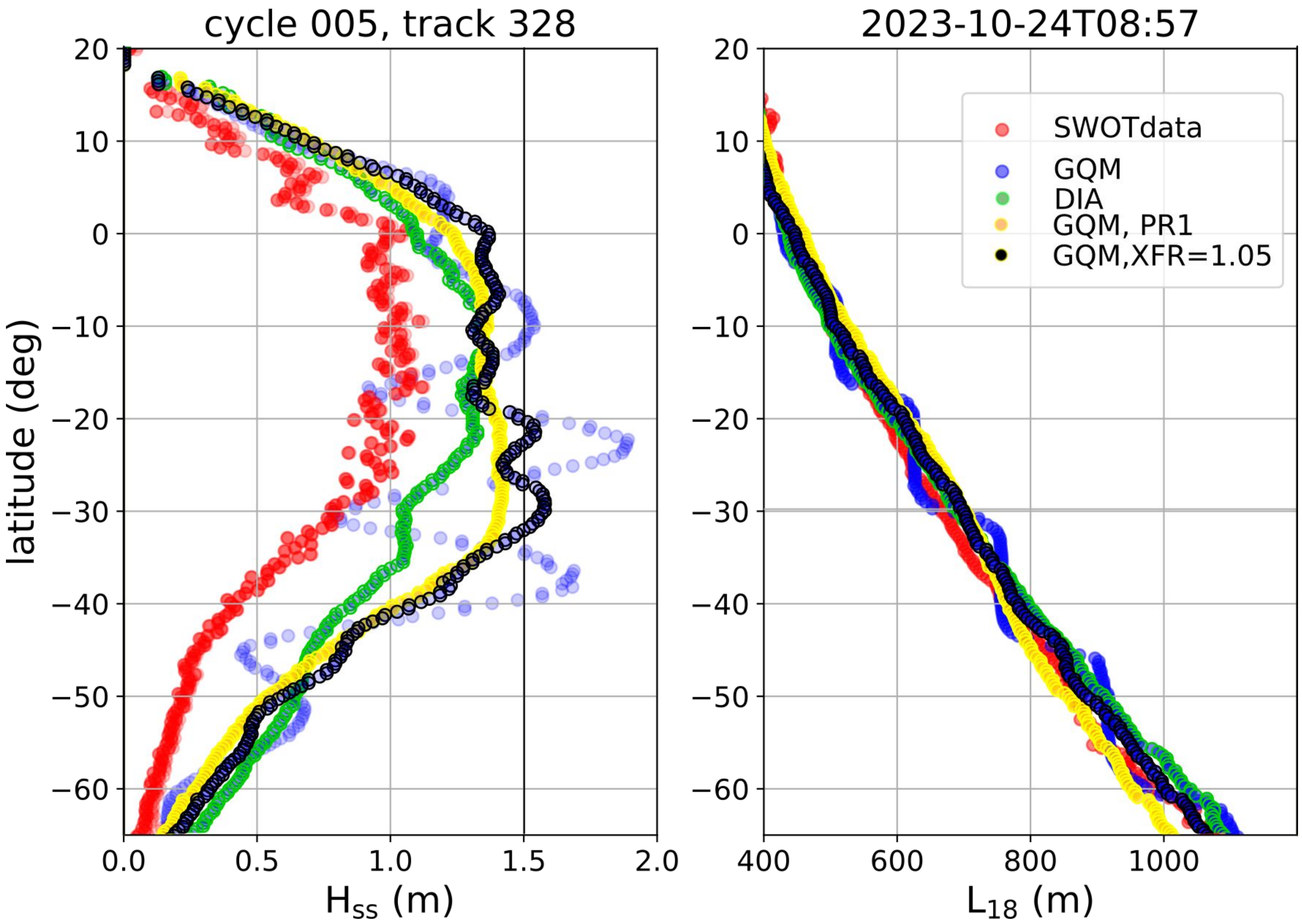
1st order scheme = perfect?





4. How good are the models?

Other option: increase spectral resolution …



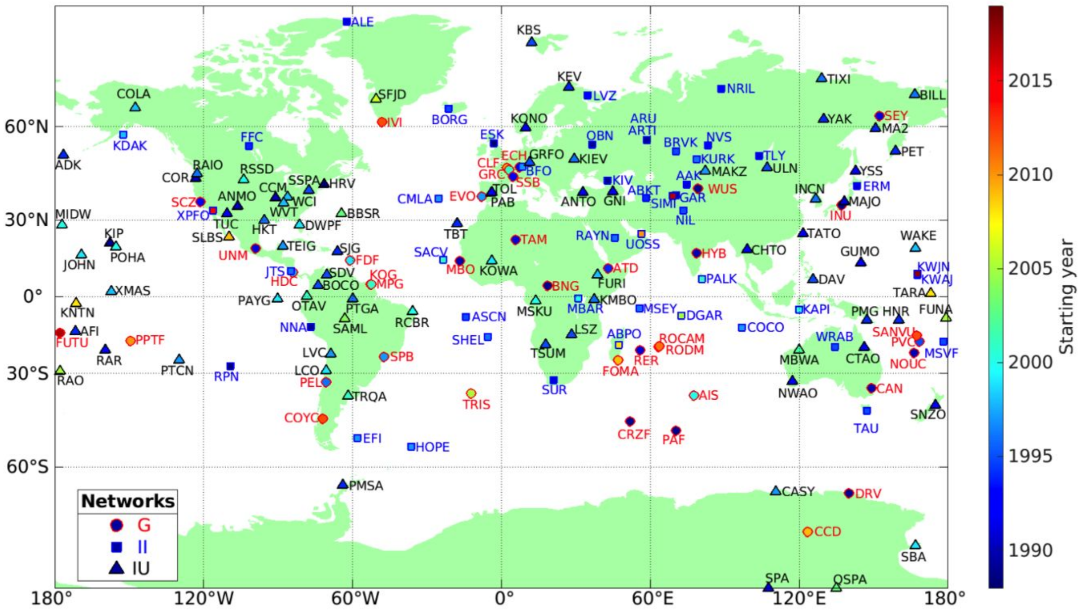
Part of my motivation: long period signals in the Earth system

no « big storm » catalogue

(well, there is Lodise et al. 2022)

Not easy for a seismologist to know
Where to find long period waves.

... Even for us !



communications (2023)
earth & environment

ARTICLE

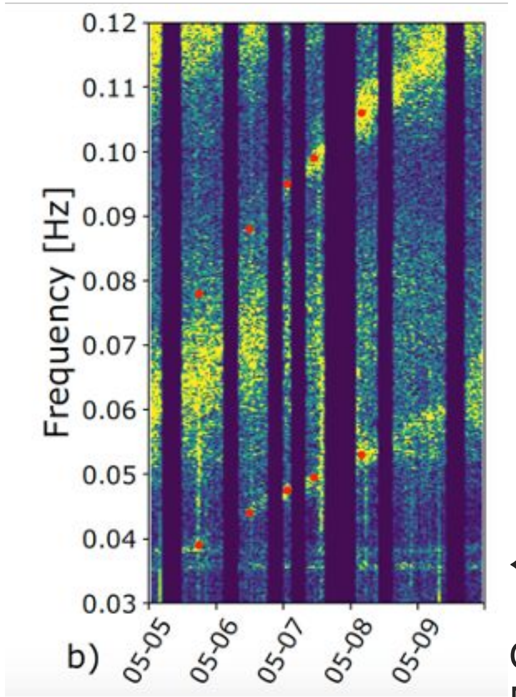
Check for updates

https://doi.org/10.1038/s43247-023-00837-y

OPEN

Gliding tremors associated with the 26 second microseism in the Gulf of Guinea

Charlotte Bruland[1,2] & Celine Hadzioannou[1]



How can we simply explain wind-wave energy with Tp=26 s?

← 26 s signal ...

Recorded everywhere on Earth.
Comes from gulf of Guinea
More about that: Poli et al. (submitted).
Next year at WISE?

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

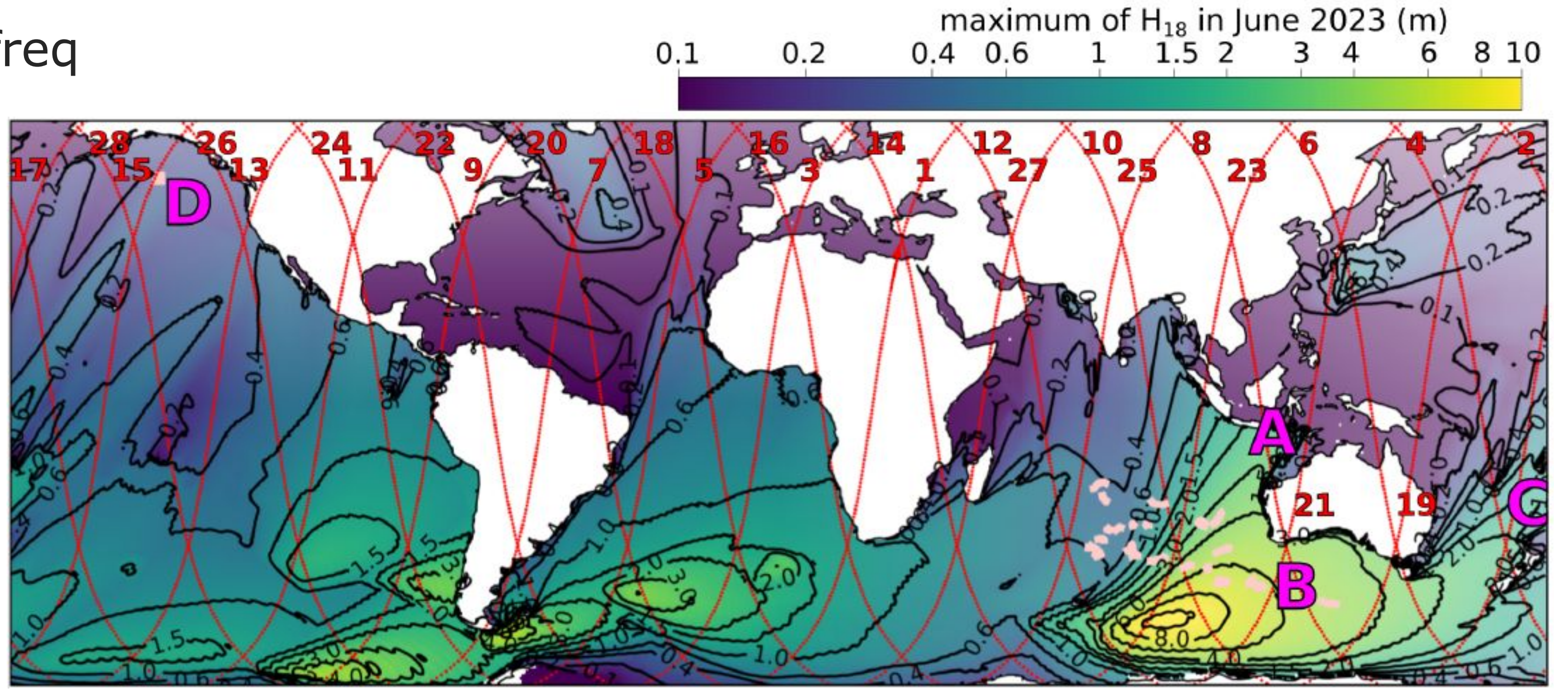
this GQM configuration uses : 11×6×6=396 points for integration along resonant manifold
- filter on coupling coef. amplitude (0.05): keeps 202 out of 396 quadruplets
- filter on spectral saturation (5E-5): 50% more cost reduction

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

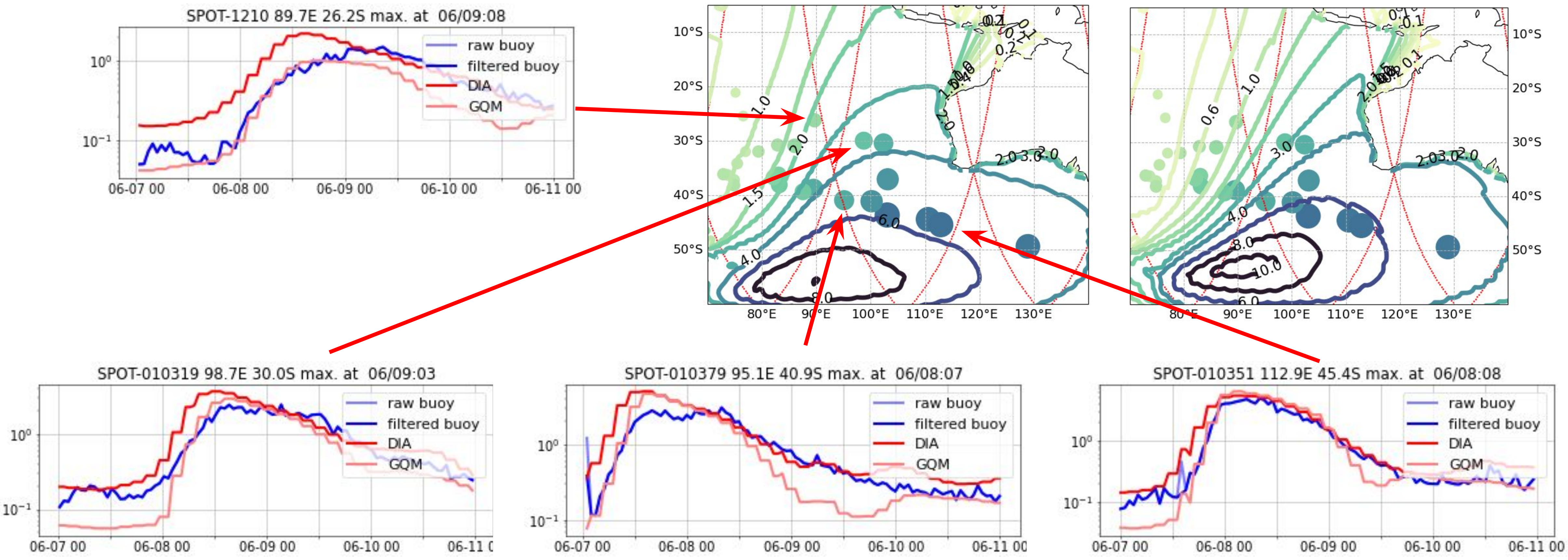
Global 0.5° model with 24 dir, 32 freq
48h for 1 year on 500 procs

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 …)

Surface Water Ocean Topography (SWOT)

GEOPHYSICS

Abyssal marine tectonics from the SWOT mission

Yao Yu[1]*, David T. Sandwell[1], Gerald Dibarboure[2]

The vertical gravity gradient (VGG) is measured in eotvos
g / 10 km: 1,000,000 eotvos

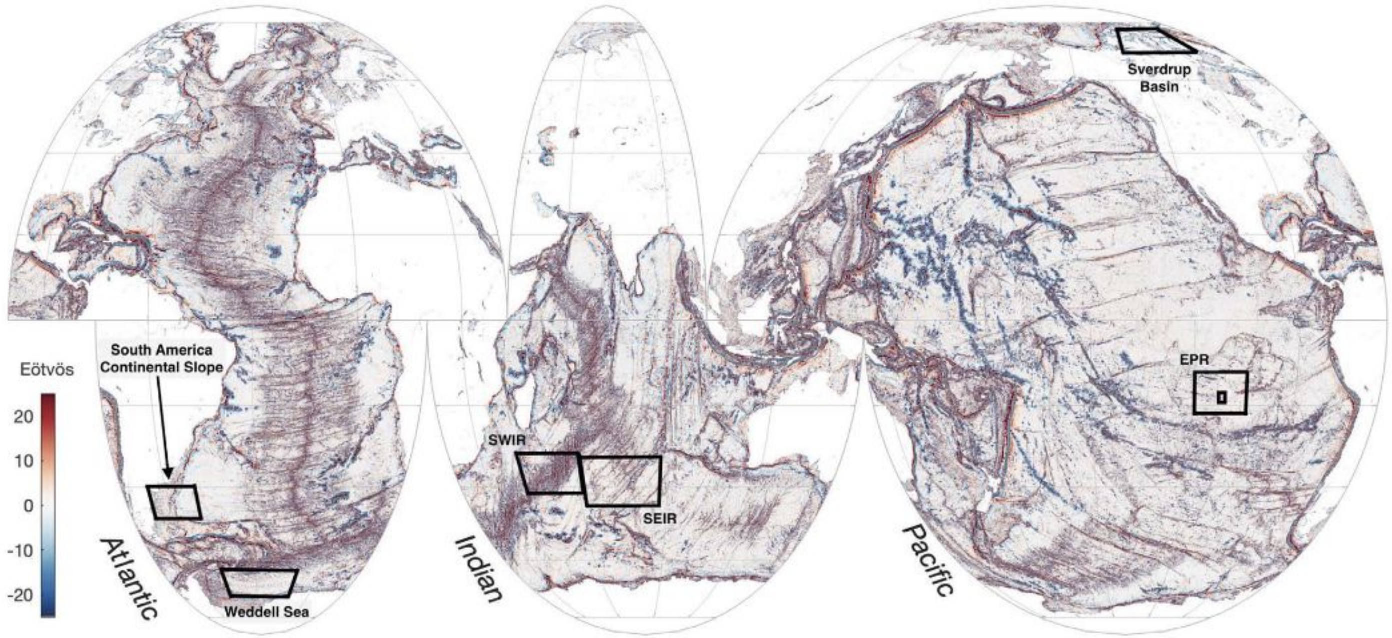


Fig. 1. Global map of SWOT VGG showing the Atlantic Ocean, the Indian Ocean, and the Pacific Ocean. Land is depicted in white. Black boxes highlight locations of the South America continental slope, Weddell Sea, SWIR, SEIR, Sverdrup Basin, and EPR, which are examined in detail in the text. 1 Eötvös = 10^{-9} s^{-2}. The full-resolution VGG model can be viewed in Google Earth and is available on Zenodo (*30*).

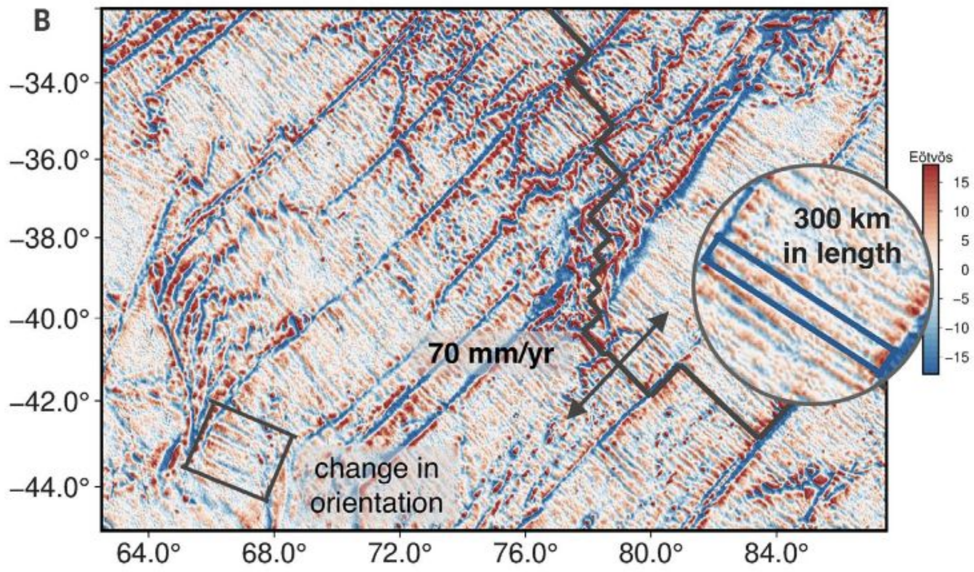


Fig. 2. Abyssal hills revealed by SWOT-derived global VGG. (**A** to **C**) Abyssal hills as elongated positive gravity anomalies are visible at the ultraslow spreading SWIR (A); the SEIR, where we highlight an unexpected long abyssal hill filling the space between two fracture zones (shown in the magnified circle) and a change in orientation (shown in the black box) (B); and the EPR (C). These maps highlight the orthogonal patterns of abyssal hills and fracture zones, with midocean ridges outlined in thick black, and plate separating direction indicated by black arrows.

Surface Water Ocean Topography (SWOT)

Article

Wide-swath satellite altimetry unveils global submesoscale ocean dynamics

https://doi.org/10.1038/s41586-025-08722-8

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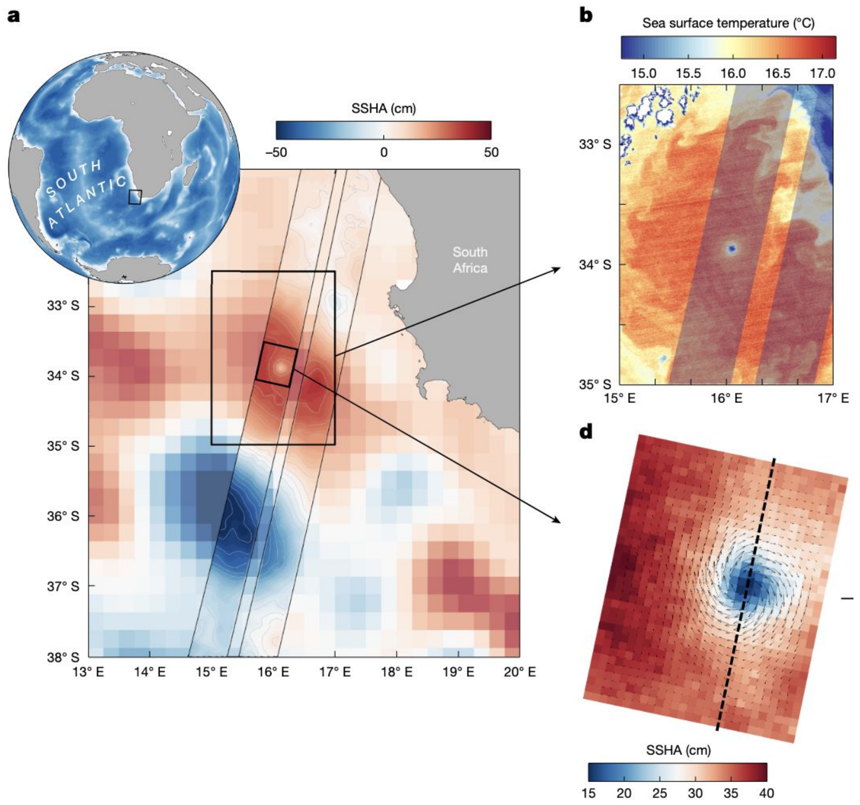
Open access

Check for updates

Matthew Archer[1✉], Jinbo Wang[1,2✉], Patrice Klein[1,3,4], Gerald Dibarboure[5] & Lee-Lueng Fu[1]

Ocean submesoscale (1–100 km) processes and their substantial impact on Earth's climate system have been increasingly emphasized in recent decades by high-resolution numerical models and regional observations[1–11]. However, the dynamics and energy associated with these processes, including submesoscale eddies and nonlinear internal waves, have never been observed from a global perspective. Where, when



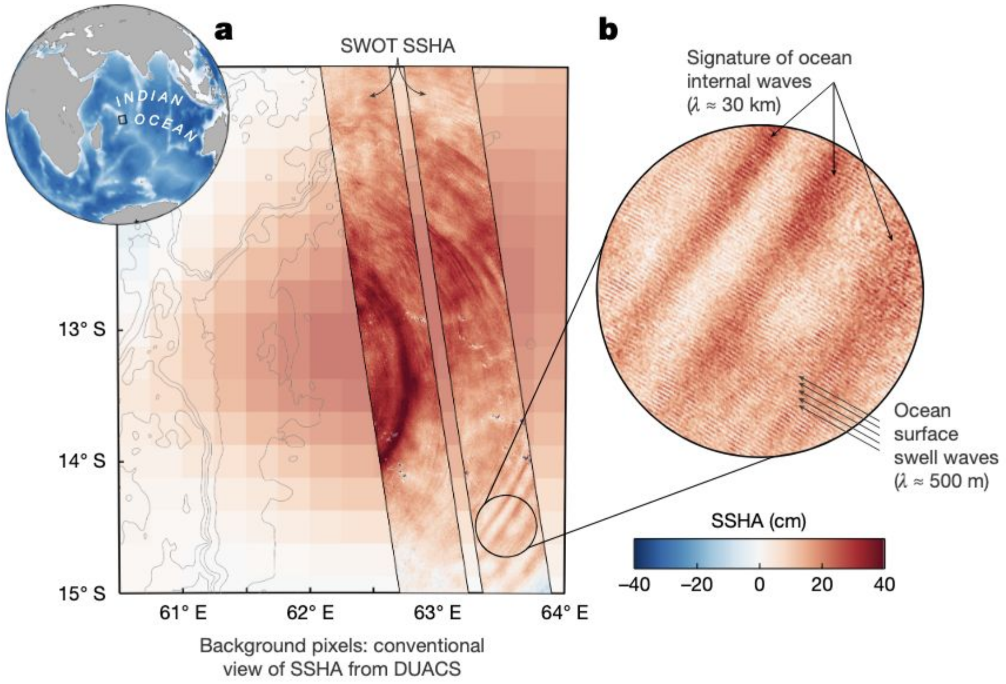
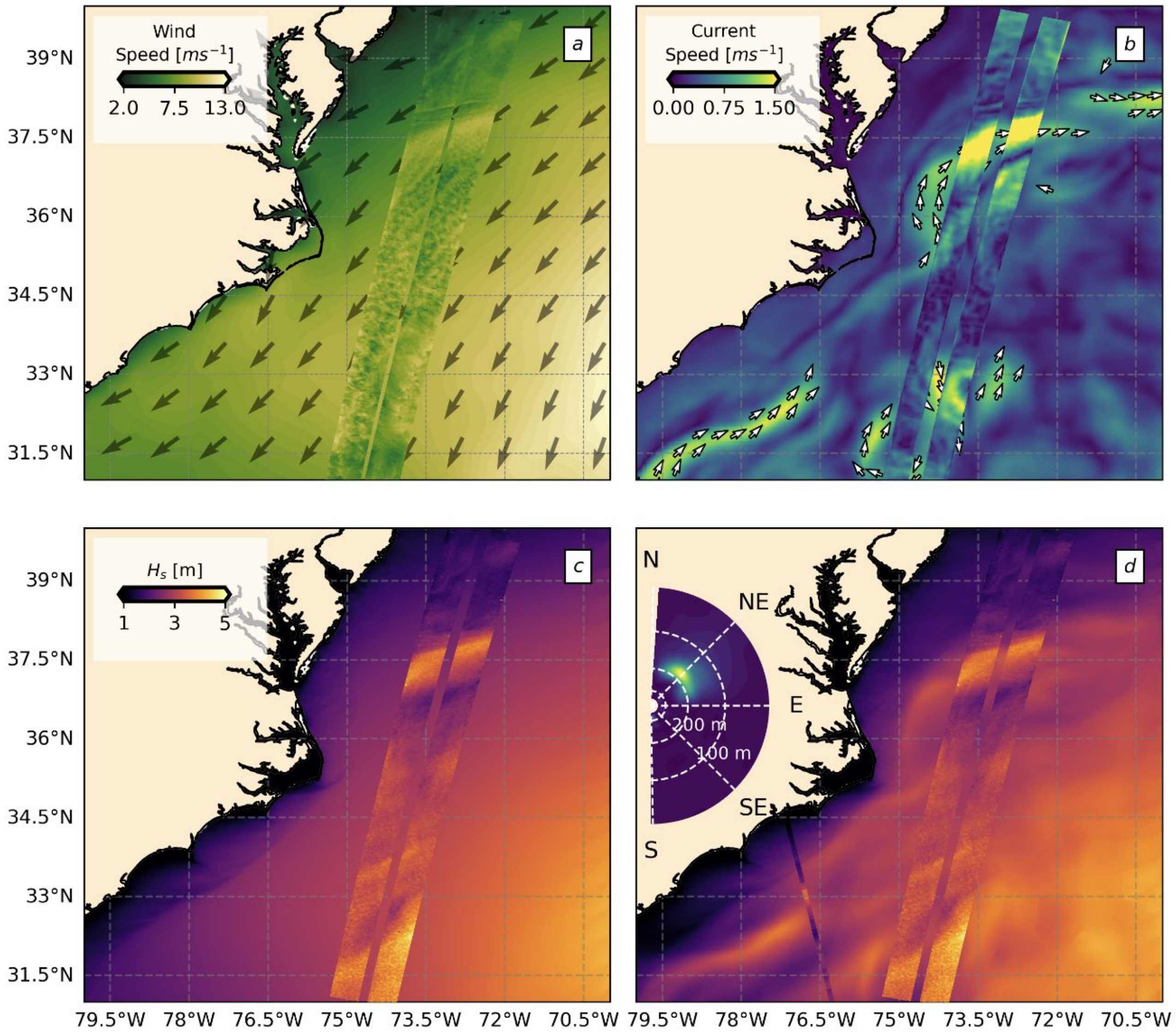


Fig. 1 | The advance of SWOT beyond conventional altimetry. An example in the east Indian Ocean at the Mascarene Plateau on 8 May 2023. **a**, Globe inset shows ocean bathymetry from ETOPO1 data; the black box denotes the Mascarene Plateau region. The main panel shows a background map of DUACS SSHA generated by AVISO+ using conventional altimetry data, superimposed with a swath from SWOT L2 unsmoothed SSHA. DUACS provides mapped spatial coverage at low resolution (about 150 km in space and about 15 days in time). SWOT provides a swath, limited in space, at high resolution (about 1 km in space and near-instantaneous in time). **b**, Zoom-in of the swath reveals the very high resolution of SWOT, beyond conventional altimetry: nonlinear internal waves and surface swell waves are captured in the SWOT SSHA measurements.

Surface Water Ocean Topography (SWOT)



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Observing Interactions Between Waves, Winds, and Currents from SWOT

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Wave height measureents from « phase noise »

Bohé, Alejandro, et al. "Measuring Significant Wave Height fields in two dimensions at kilometric scales with SWOT." *IEEE Transactions on Geoscience and Remote Sensing* (2025).