Nearshore sea state variability from diverse long-term satellite observations produced by the ESA Sea State CCI consortium

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ESA CCI & S6-JTEX

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Key points

New sea state data from the ESA Sea State Climate Change Initiative consortium

— Phase 2 (on-going) has recently produced data updates ;

> Underlining the importance of the long term satellite record for analysis of environmental change

— Coastal applications ;

> Strengths and limitations of satellite altimeters

> New multi-parameters sea state data from Synthetic Aperture Radars (SAR) offer new perspective

Sea State CCI User Consultation and Science meeting

— No registration required for remote connection

— Connection details via email… (see last slide)

National Oceanography Centre

Sea State

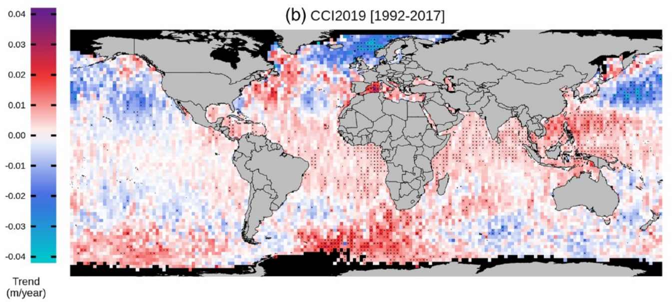
The Sea State project is developing an 18-year data set (2002-2020) capitalising on the rich satellite altimeter,

https://climate.esa.int/en/projects/sea-state/

Sea State CCI

— ESA SS CCI one of many CCI projects tasked with producing datasets of GCOS-defined “essential climate variables” (ECV) from satellite

— Sea State often implies “significant wave height” but SS CCI is moving well beyond SWH: multiparameter datasets from Synthetic Aperture Radars (SAR) on Envisat and Sentinel-1



Timmermans et al. (2020): Long term wave height trends

Earth Syst. Sci. Data, 12, 1929–1951, 2020
https://doi.org/10.5194/essd-12-1929-2020

Open Access Earth System Science Data

The Sea State CCI dataset v1: towards a sea state climate data record based on satellite observations

Guillaume Dodet[1], Jean-François Piolle[1], Yves Quilfen[1], Saleh Abdalla[2], Mickaël Accensi[1], Fabrice Ardhuin[1], Ellis Ash[3], Jean-Raymond Bidlot[2], Christine Gommenginger[4], Gwendal Marechal[1], Marcello Passaro[5], Graham Quartly[6], Justin Stopa[7], Ben Timmermans[4], Ian Young[8], Paolo Cipollini[9], and Craig Donlon[10]

Geophysical Research Letters

RESEARCH LETTER
10.1029/2022GL102348

Time of Emergence for Altimetry-Based Significant Wave Height Changes in the North Atlantic

Antoine Hochet[1], Guillaume Dodet[1], Florian Sévellec[1], Marie-Noëlle Bouin[1,2], Anindita Patra[1], and Fabrice Ardhuin[1]

[1]Laboratoire d’Océanographie Physique et Spatiale, University Brest CNRS IRD Ifremer, Brest, France, [2]CNRM, Université de Toulouse, Météo-France, CNRS, Toulouse, France

Key Points:

- Altimeter based significant wave height trends in the North Atlantic (NA) are largely dominated by internal variability
- Forced significant wave height changes in the NA will only be detectable in altimeter data after 2050

Hochet et al. (2023): Time of emergence of long term trends in North Atlantic

Coastal Wave Analysis with Satellite Data

Coastal applications with altimeters

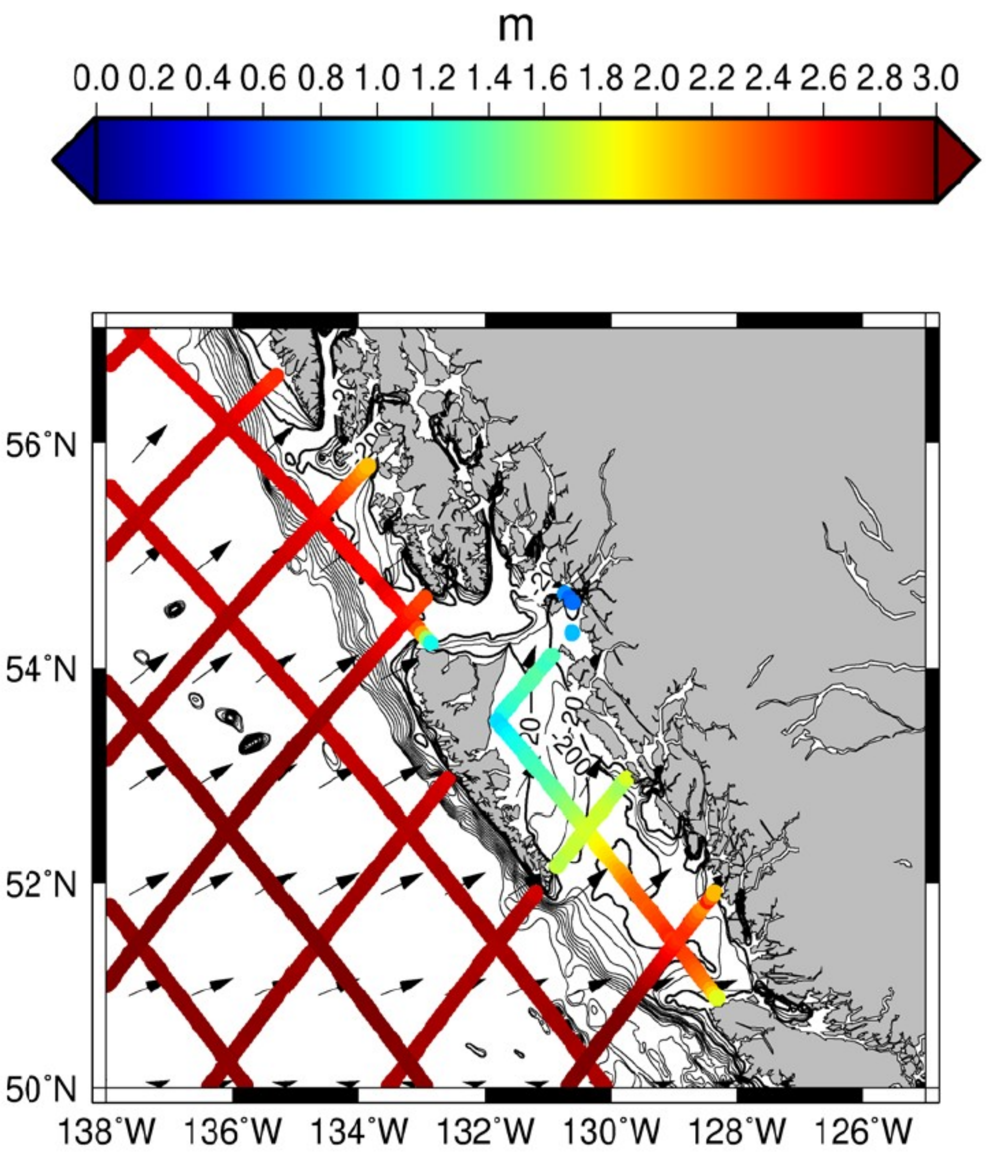
— Altimeters capture coastal sea state properties (Alaska, Jason tracks, Fig. 2a Passaro et al. 2021)

— Higher frequency re-visit leads to wide ground-track separation (up to ~300 km)

— Detailed information limited to along track information

— Along-track limited by sampling rate (1 Hz, 7 km)

— Radar altimeter footprint leads to signal contamination within ~3-4 km of land

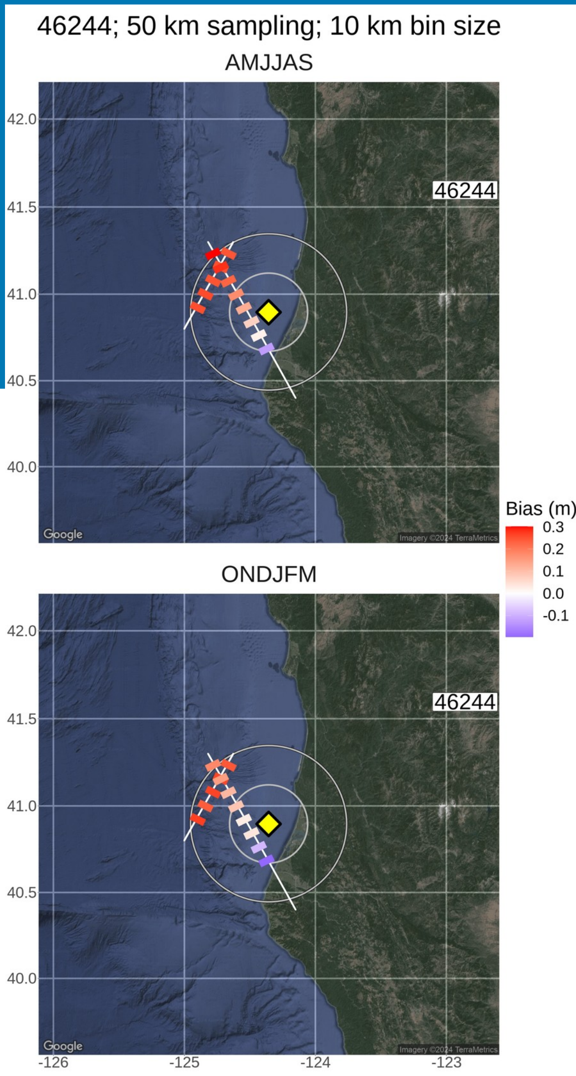


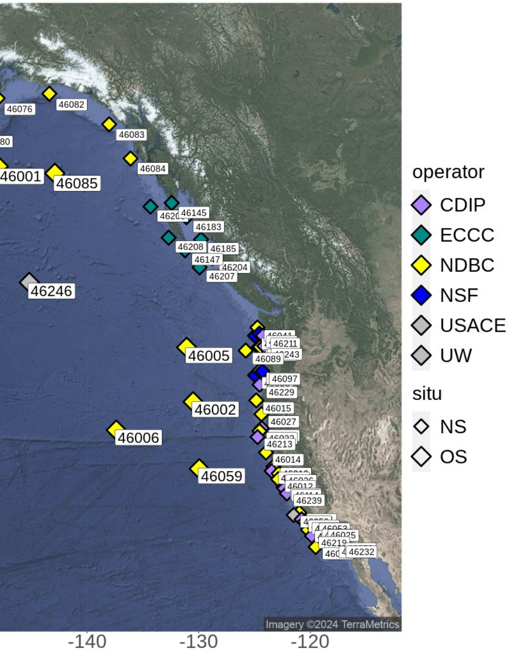
Passaro et al. (2021)

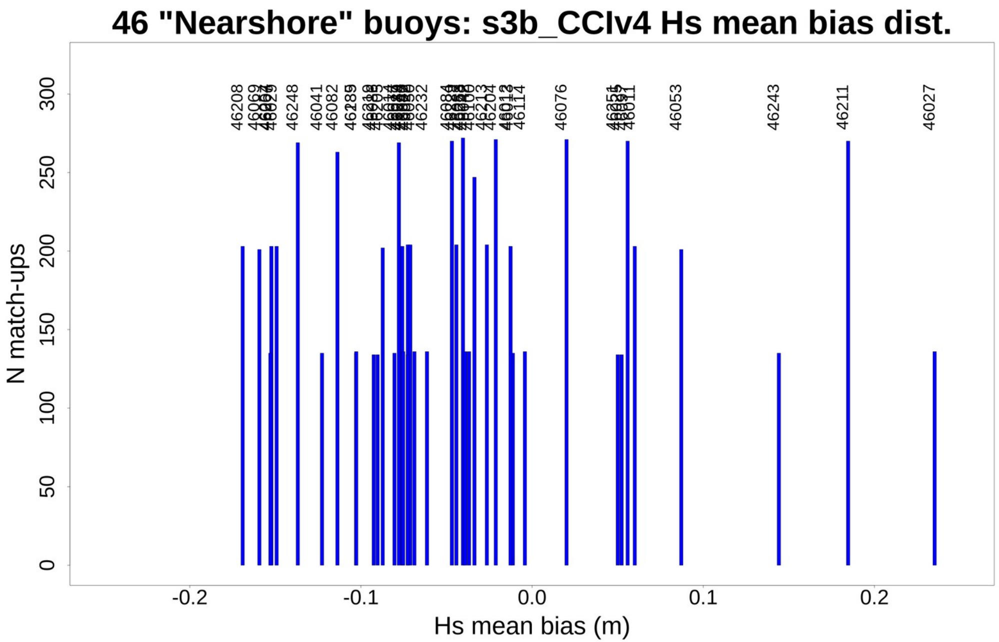
Coastal applications with altimeters

- — Validation with in situ measurements ;
- — But we also use altimeter record to verify stability of *in situ* record ;
- — Examine SWH bias characteristics ;
  - > locally (site-by-site)
  - > across numerous sites to establish a statistical "baseline"
  - > collocations have complex dependence on local morphology

Timmermans et al. (2024)







Sentinel-1(A) IW mode

Sentinel-1 A/B

— Synthetic Aperture Radars (SAR) acquisition can be post-processed to sea state parameters
— 2015 – present (S-1 B ended 2021; S1-C launched 06 Dec 2024)
— S-1 “Interferometric Wide-swath” mode (IW) Global coastal coverage, strong focus over Europe

— “Wave Mode” already processed by DLR

— “IW Mode” and “EW mode” now added to the CCI record

~745,000 imagettes comprising:

> Hs, Swell1 Hs, Swell2 Hs, Windsea Hs, Tm0, Tm1, Tm2

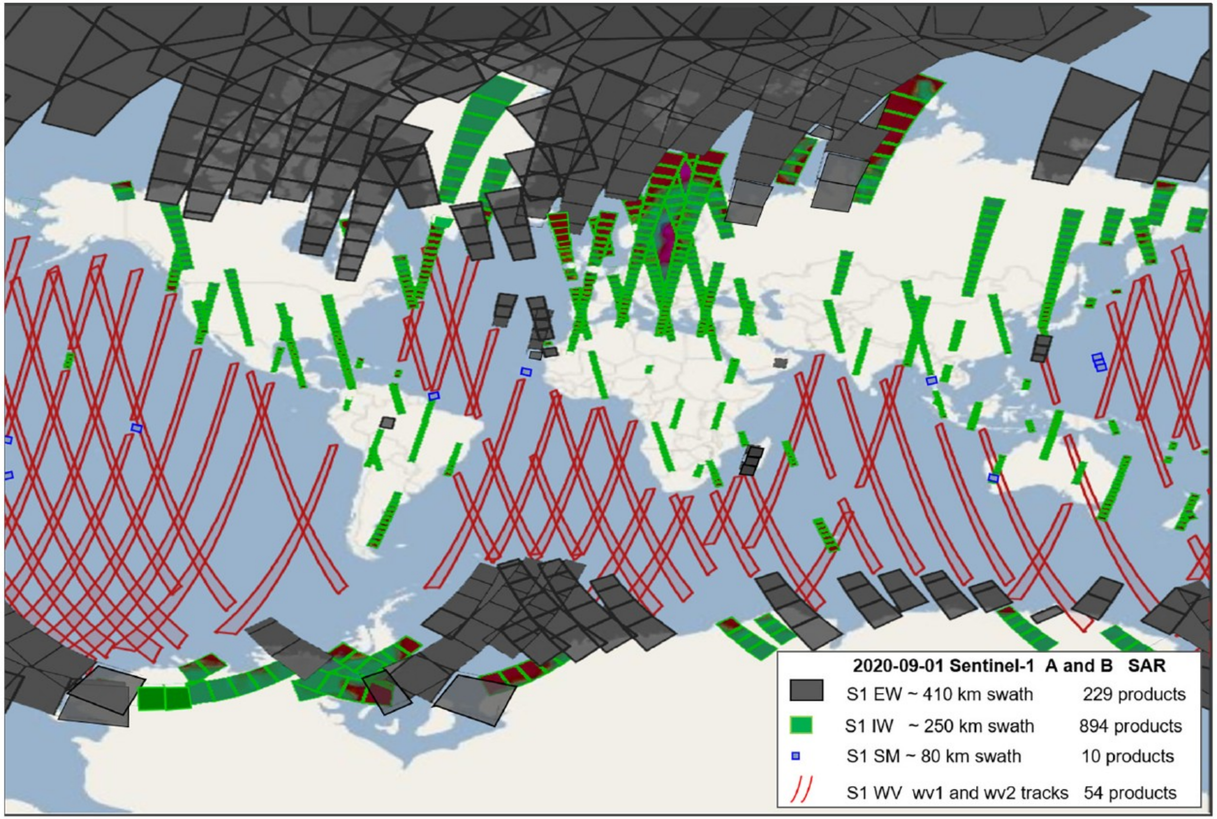
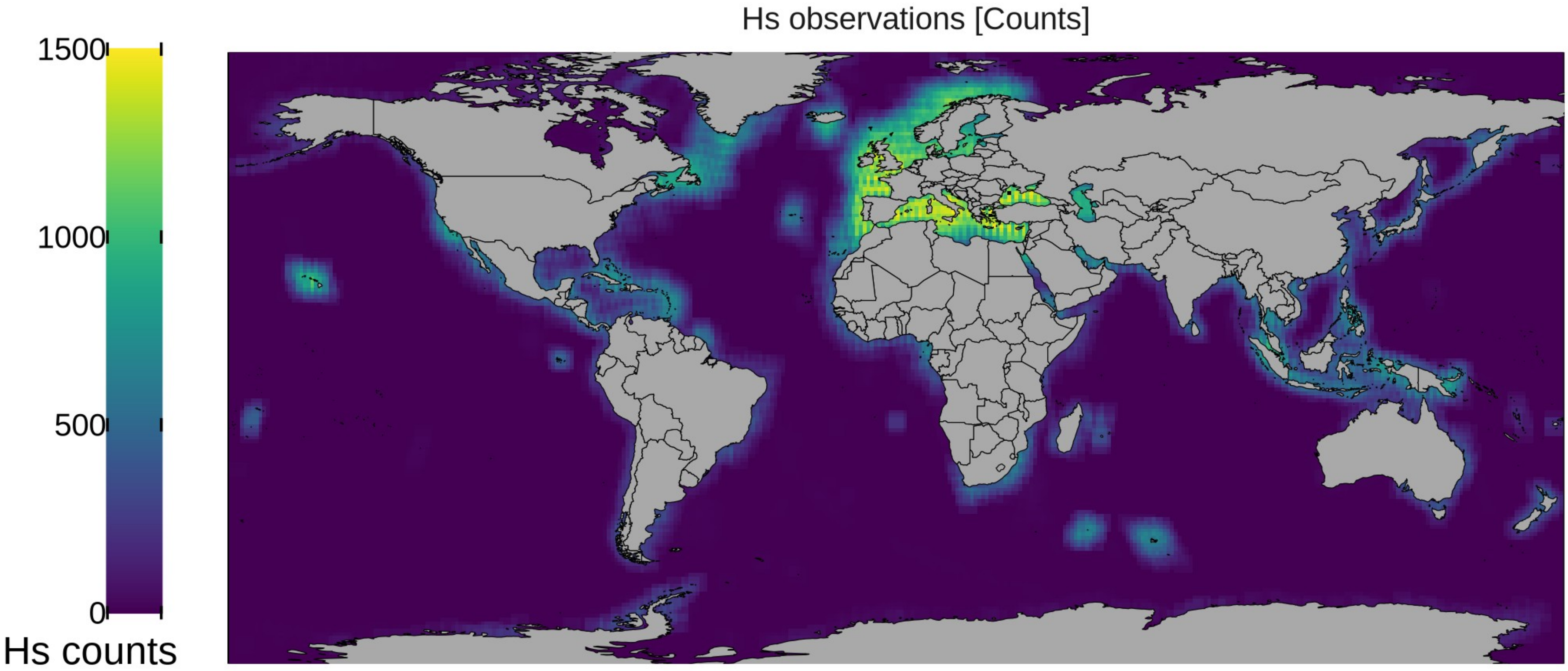


Fig. 1. An example of S1-A and S1—B worldwide acquisitions on 2020-09-01 (ESA). There are 54 S1 WV tracks (red), 894 S1 IW images (green), 229 S1 EW images (grey) and 10 StripMap images (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Pleskachevsky et al. (2022)

Sentinel-1 A coverage

- **Coastal coverage, similar resolution to 1 Hz altimetry ;**
- **Data as spatial fields, multi-parameter: Hs, Swell1 Hs, Swell2 Hs, Windsea Hs, Tm0, Tm1, Tm2**



Sentinel-1A (Descending tracks):

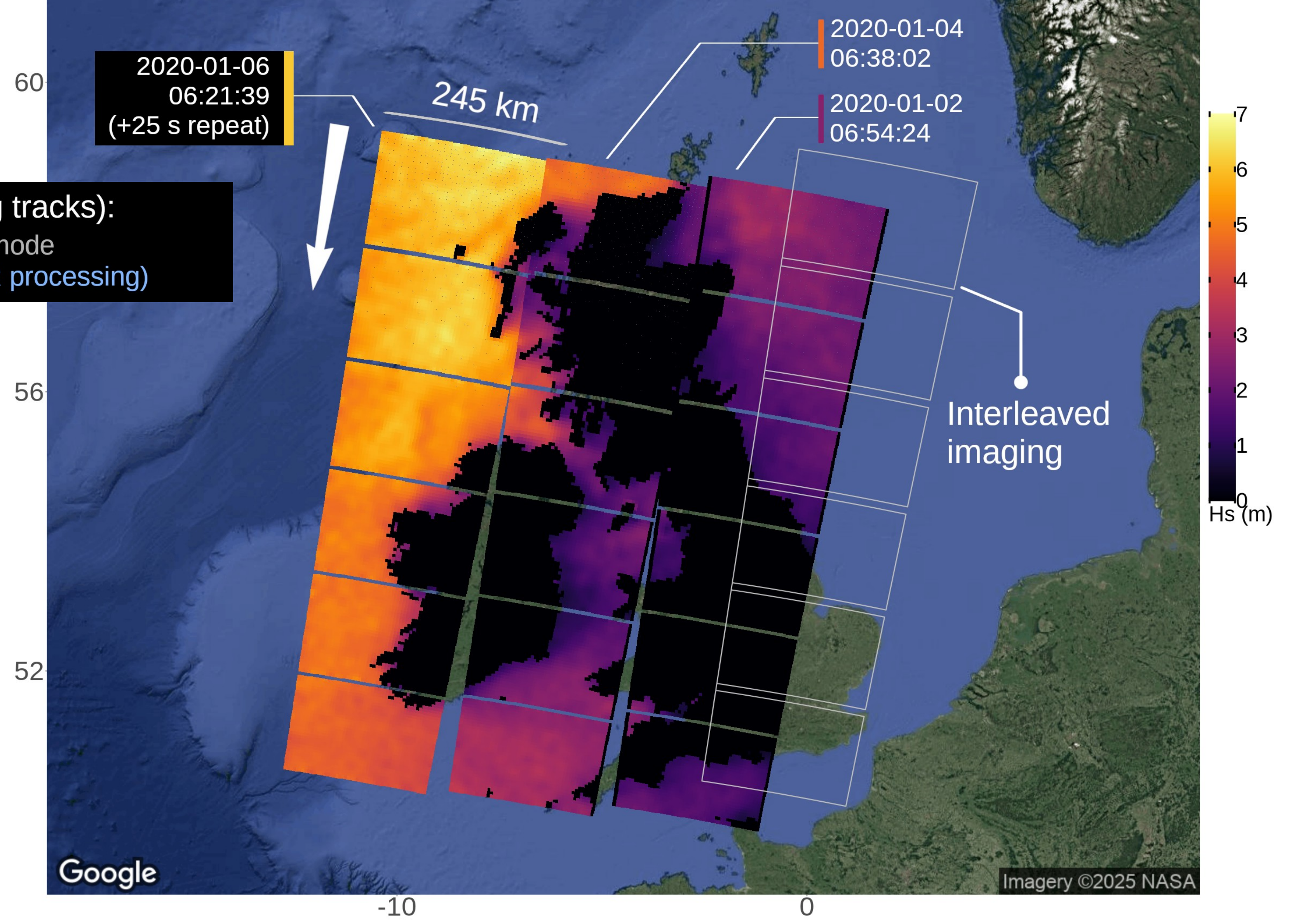
Interferometric Wide-swath mode

Hs field snapshots (CCI DLR processing)

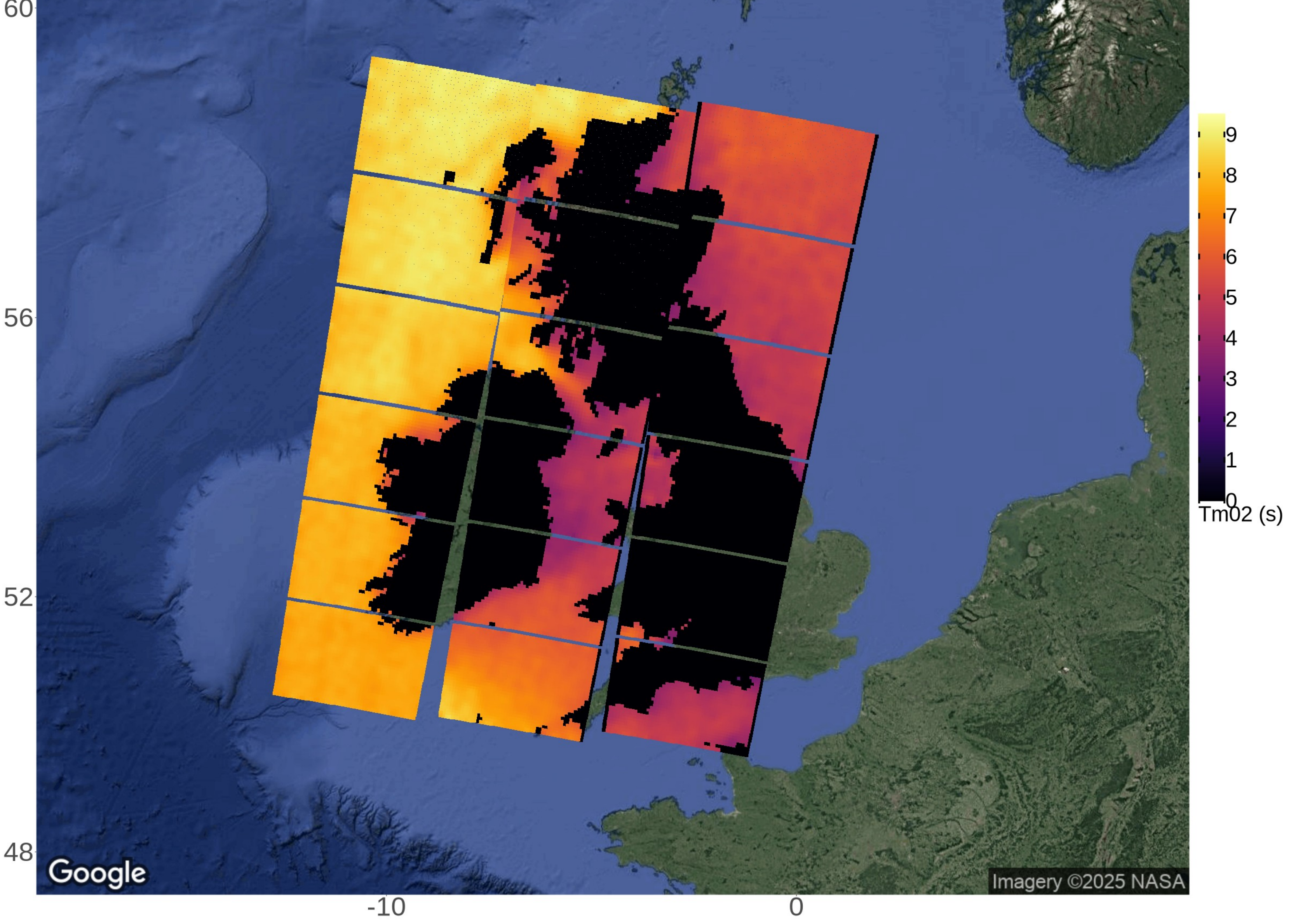
— Ascending tracks not shown ;

— S-1B not shown ;

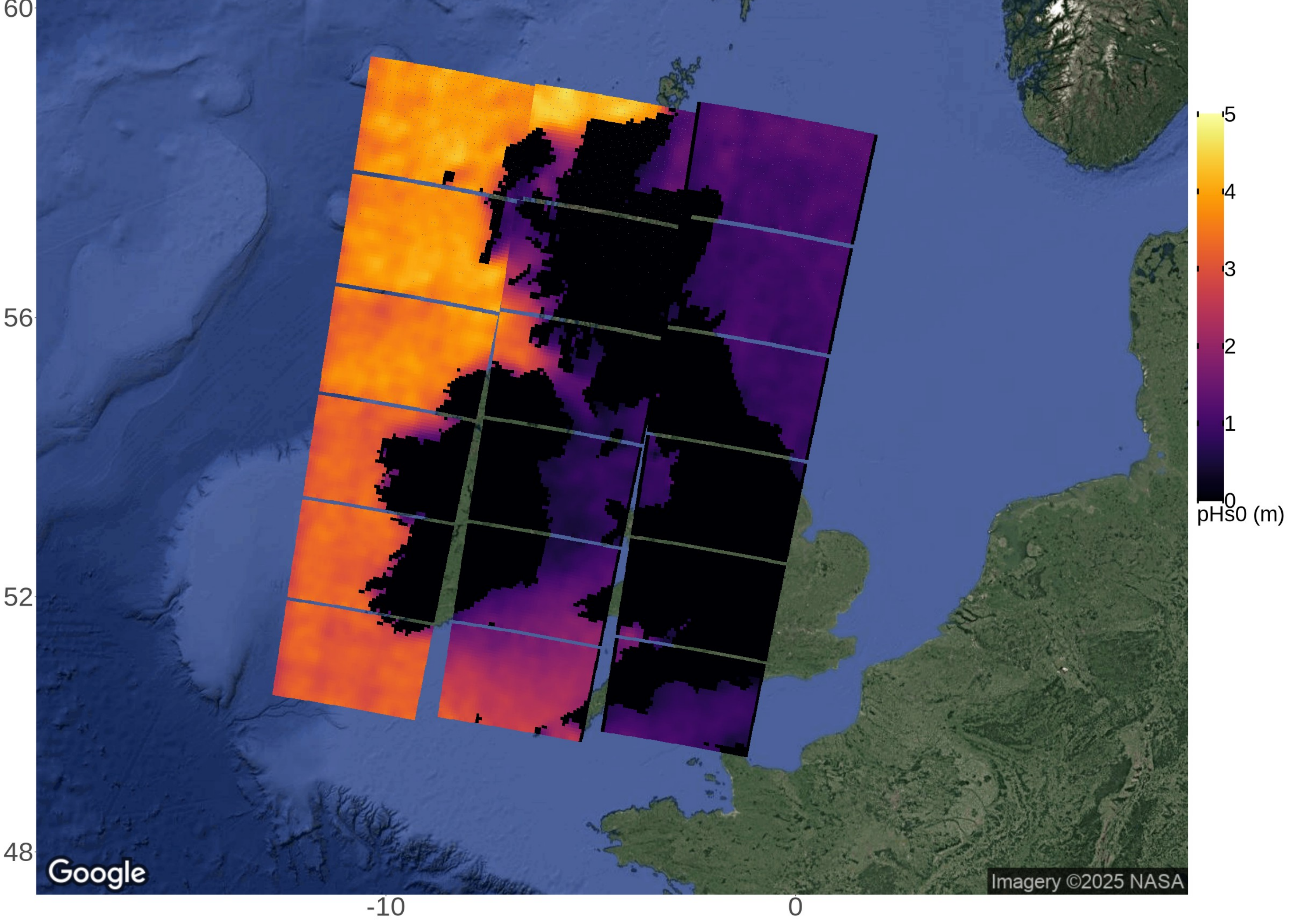
— 25 s repeat imagettes



— Fields for Tm2 (Tz)



— Fields for Partition 1 SWH

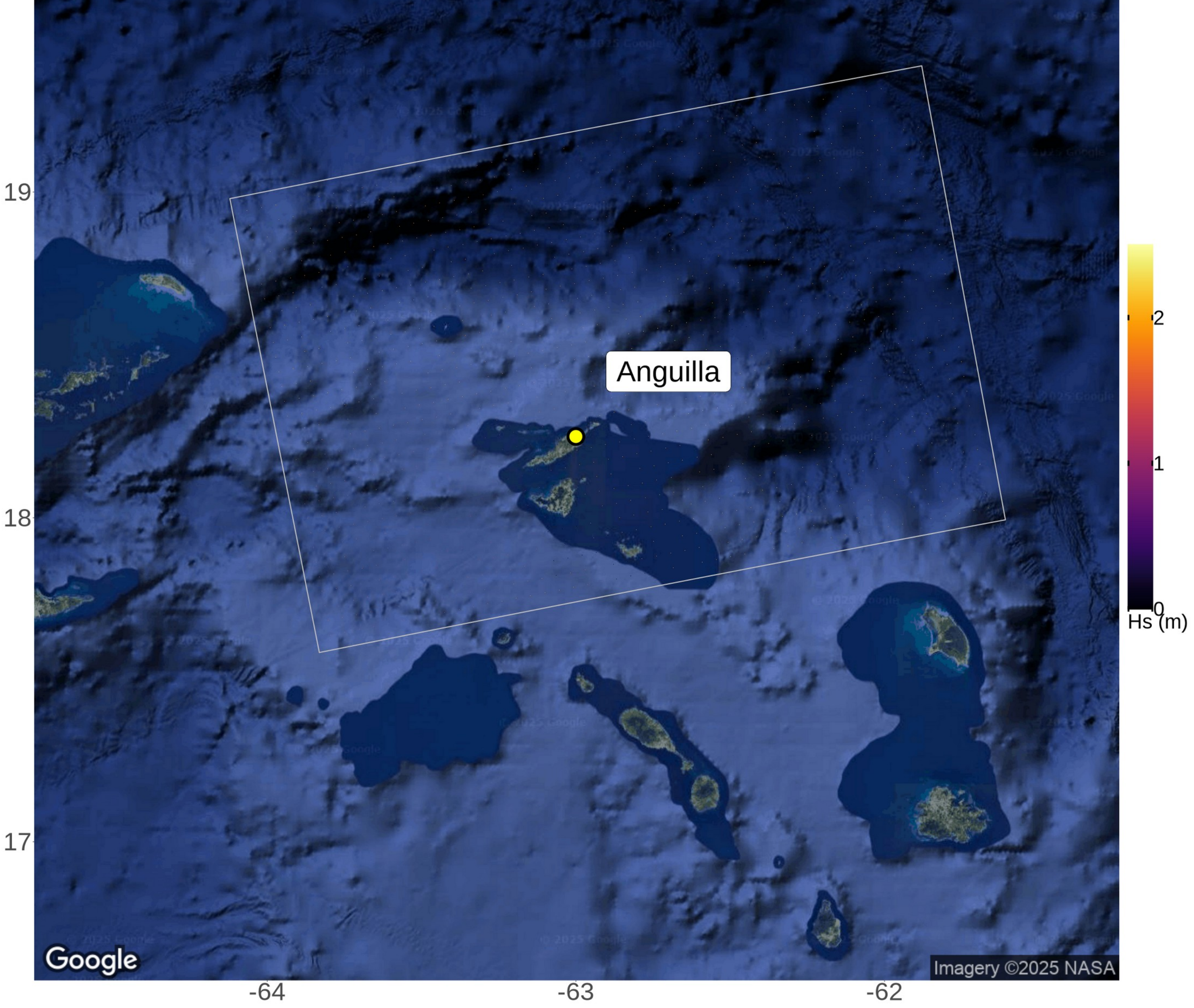


Application to remote coastlines

— Coastal change and erosion on Anguilla (British Overseas Territory)

— Spatial scale too large for coastal analysis?

— Suitable for domain validation?

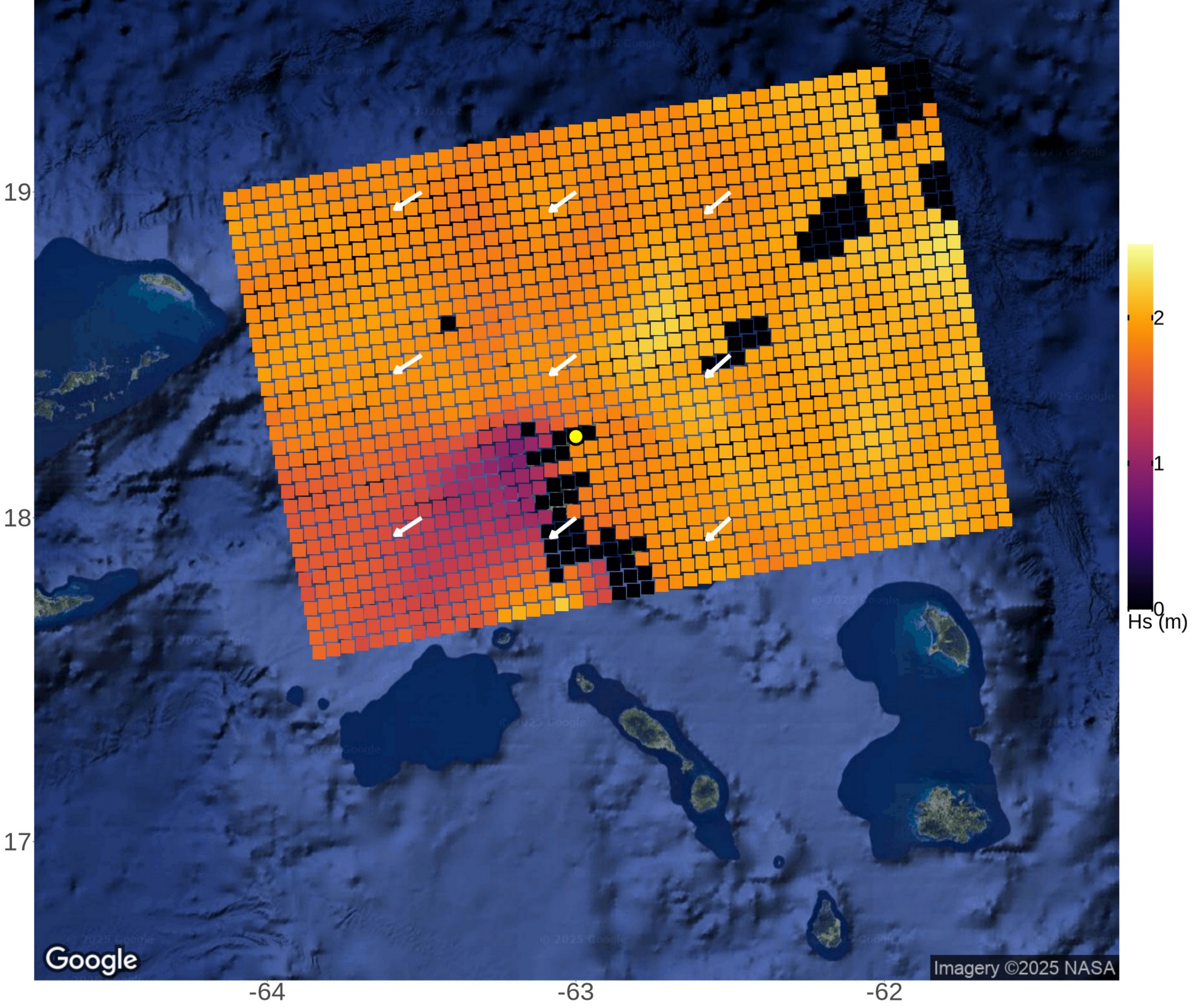


Application to remote coastlines

— Sentinel-1A (ascending) SWH field

— **white arrows** show ERA5 mean wave direction

— SWH data shows island sheltering

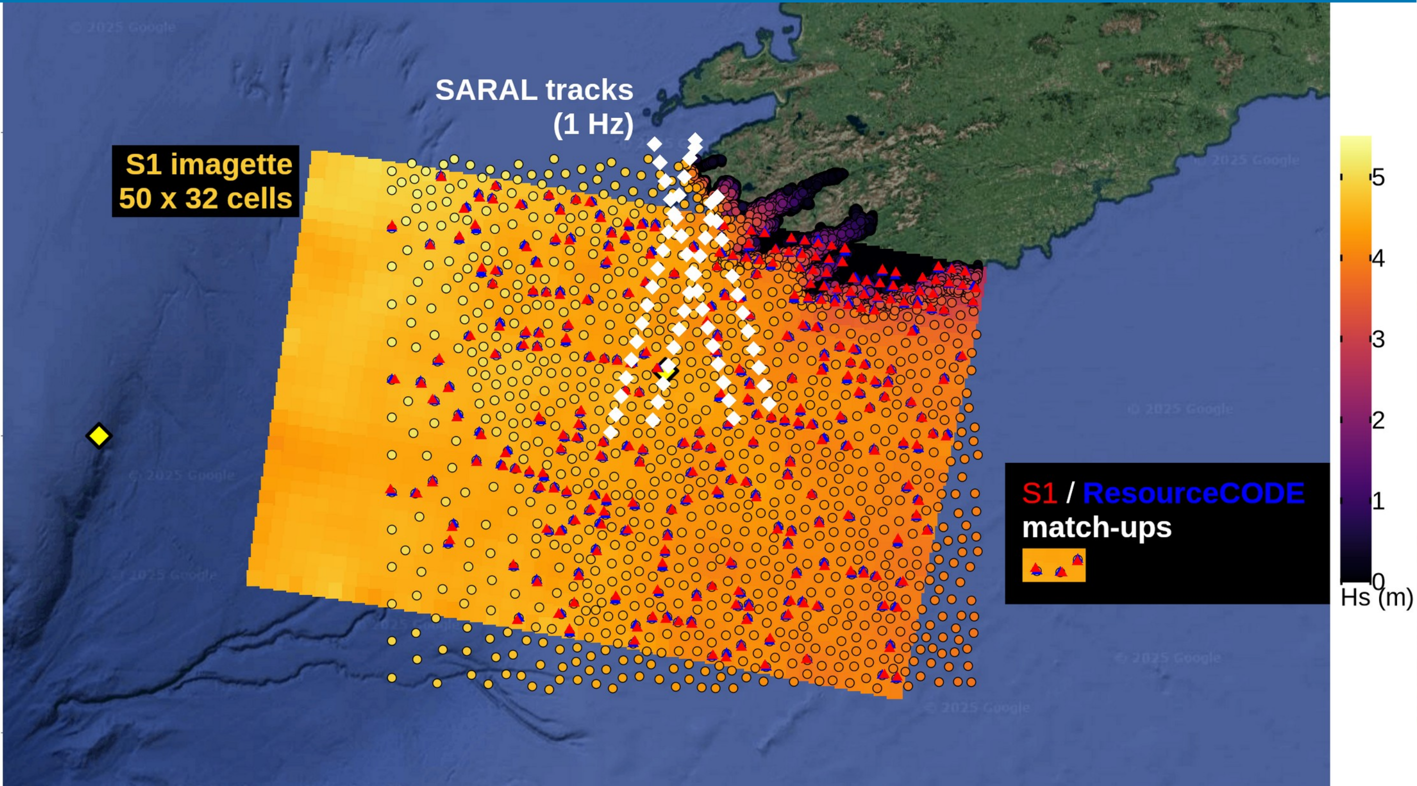


Sentinel-1(A) IW mode

Validation

Comparison with "ResourceCode" Hindcast (Accensi et al., 2021)

— Wave / current / tidal WW3 hindcast for European shelf (1993-2024) ;
— Unstructured grid to high resolution < 1 km close to coast ;
— Various collocation schemes possible (single image match-up) ;



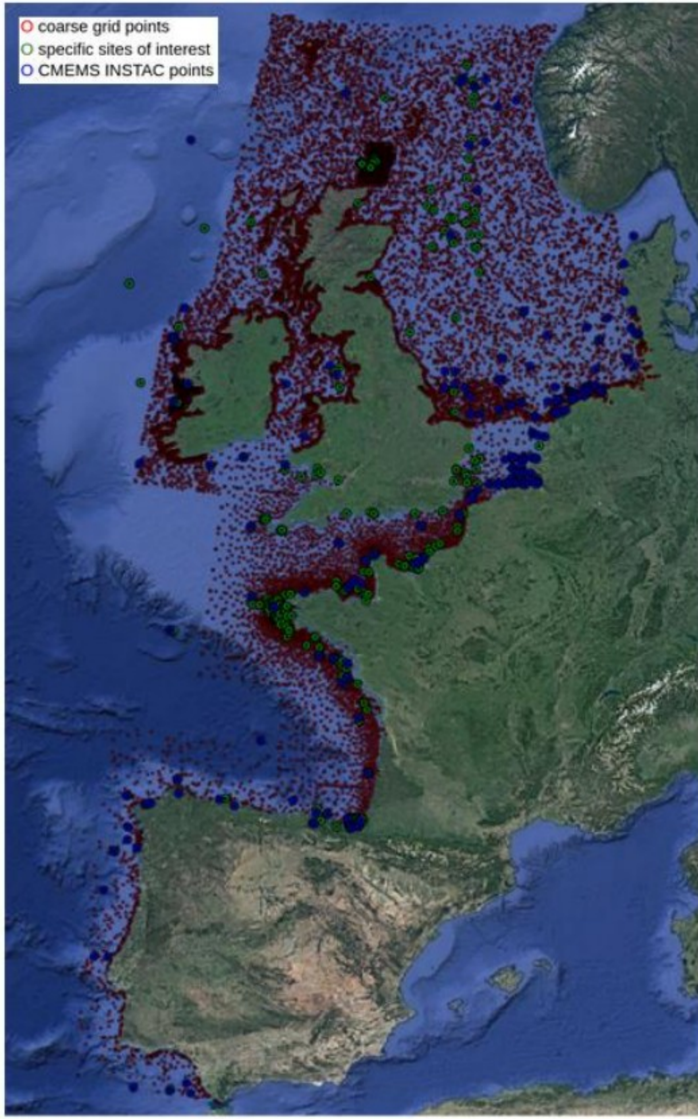


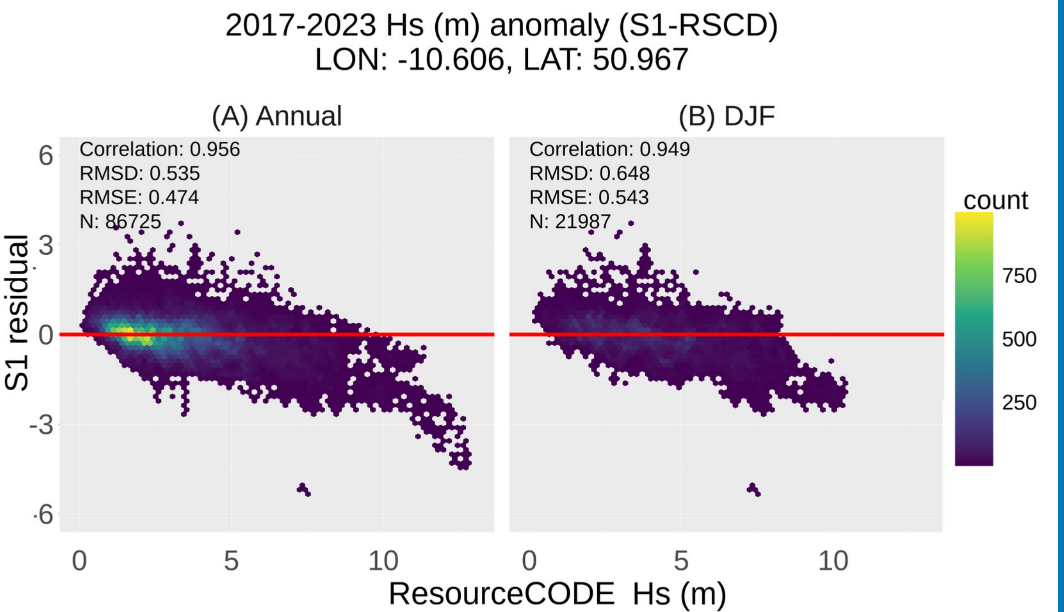
Fig. 3. Directional spectra output locations

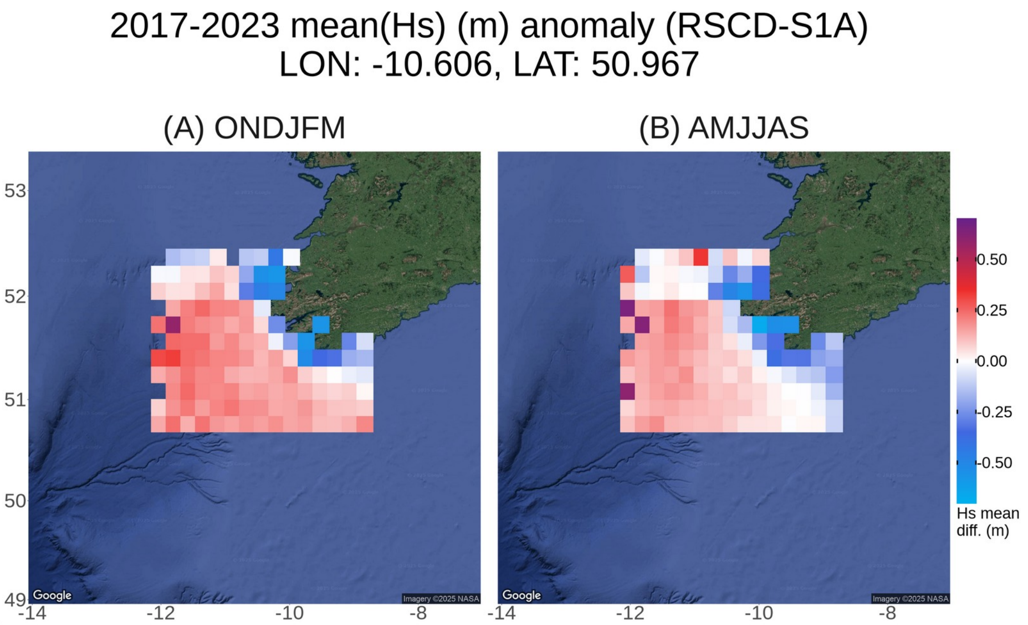
Comparison with “ResourceCode” Hindcast (Accensi et al., 2021)

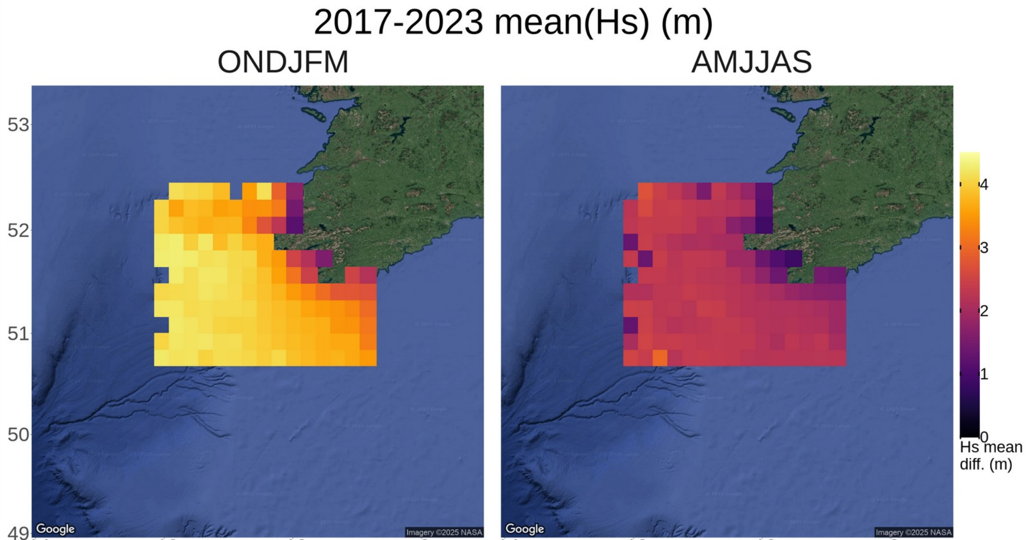
— Scatter for S-1A based on point-to-point match-ups ;

— Overall, good agreement in mean, possible bias at larger SWH ;

— Need “spatial” analysis to understand geographic structure ;







Conclusions

— ESA Sea State CCI version 4 data is available for exploration...

> Long term altimetry data remains crucial for analyses of long term change ;

> Sea State CCI is now augmented by numerous SAR-derived datasets ;

> Sentinel-1A/B “IW” mode dataset covers global coastal oceans ;

> Altimetry and SAR useful for coastal study in different ways ;

> *Community feedback welcome!*

Sea State CCI User Consultation, Science and Applications meeting

— Wide range of speakers and participants, to discuss and feedback on the present and future of sea state observations from satellite ...

> Online participation available: **Please contact me for details** ...

References

— Passaro, M. *et al.* Global coastal attenuation of wind-waves observed with radar altimetry, *NATURE COMMUNICATIONS (2021) 12:3812 https://doi.org/10.1038/s41467-021-23982-4*

— Timmermans, B; Gommenginger, C. G.; Donlon, C.; Uncertainty in Sea State Observations from Satellite Altimeters and Buoys during the Jason-3/Sentinel-6 MF Tandem Experiment *Remote Sensing, 2024, 16, 2395 https://doi.org/10.3390/rs16132395*

— Pleskachevsky, A.; Tings, B.; Wiehle, S.; Imber, J.; Jacobsen, S.; Multiparametric sea state fields from synthetic aperture radar for maritime situational awareness, *Remote Sensing of Environment 280 (2022) https://doi.org/10.1016/j.rse.2022.113200*

— Accensi, M. *et al.* Resourcecode framework: A high-resolution wave parameter dataset for the European shelf and analysis toolbox *Proceedings of the European Wave and Tidal Energy Conference: 14th EWTEC 5-9th September 2021 Plymouth, UK. EWTEC, pp. 2182-1-2182-9*

Additional Slides

Coastal applications

— Many reasons to learn about nearshore wave climate!

— However, complicated by coastal morphology...

— Satellite data can be useful but also complicated by:

> low sampling frequency

> spatial heterogeneity

— “Naive” spatial aggregation is inappropriate...

Timmermans et al. (2020): Reliability of Extreme Significant Wave Height Estimation from Satellite Altimetry and In Situ Measurements in the Coastal Zone

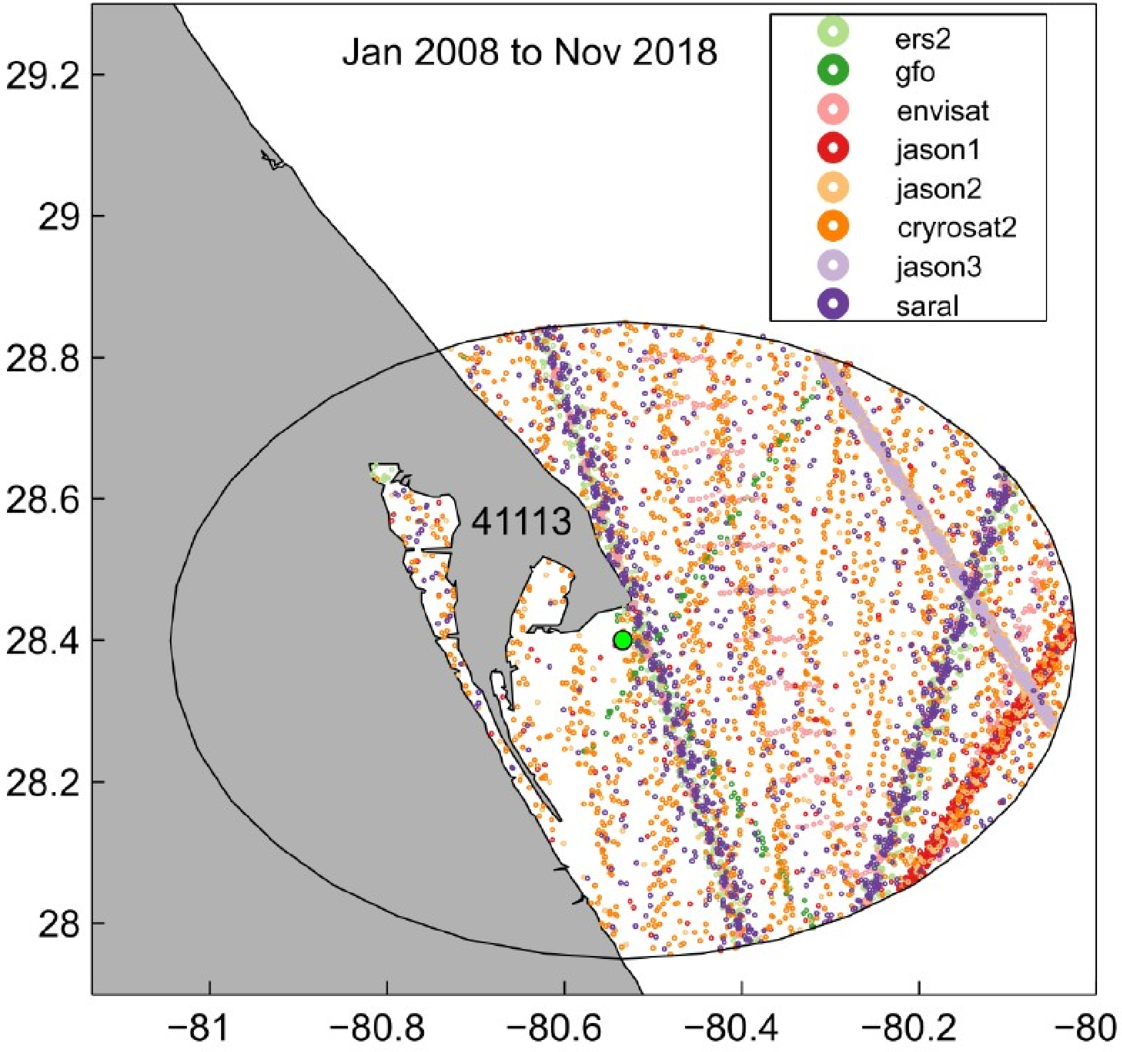


Figure 4. Spatial distribution of satellite tracks contributing to Hs measurements within a 50 km radius of buoy 41113 (region #3).

Buoy-Sat along-track gradients

— **Buoy 46027, Oregon coast**

— **Buoy provides ~hourly measurements of Hs (~20 minutes time integration)**

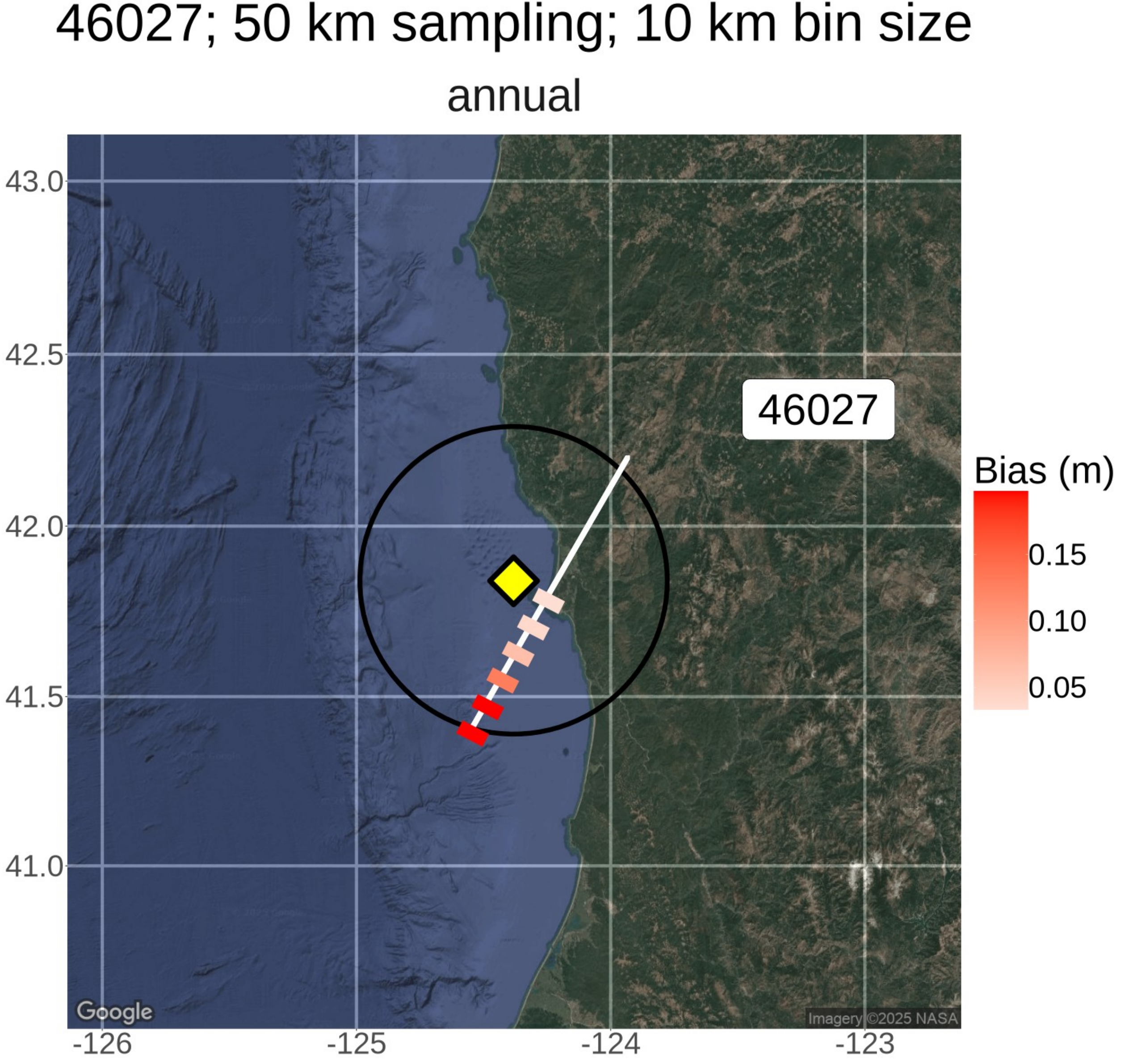
— **Jason 3 (CCI v3) 2017-2020 (~10 day repeat)**

— **Paired time series (< 30 minutes)**

— **Hs mean bias, from time series**

— **1 Hz along-track data, 10 km bin size**

— **Compute along-track gradient**

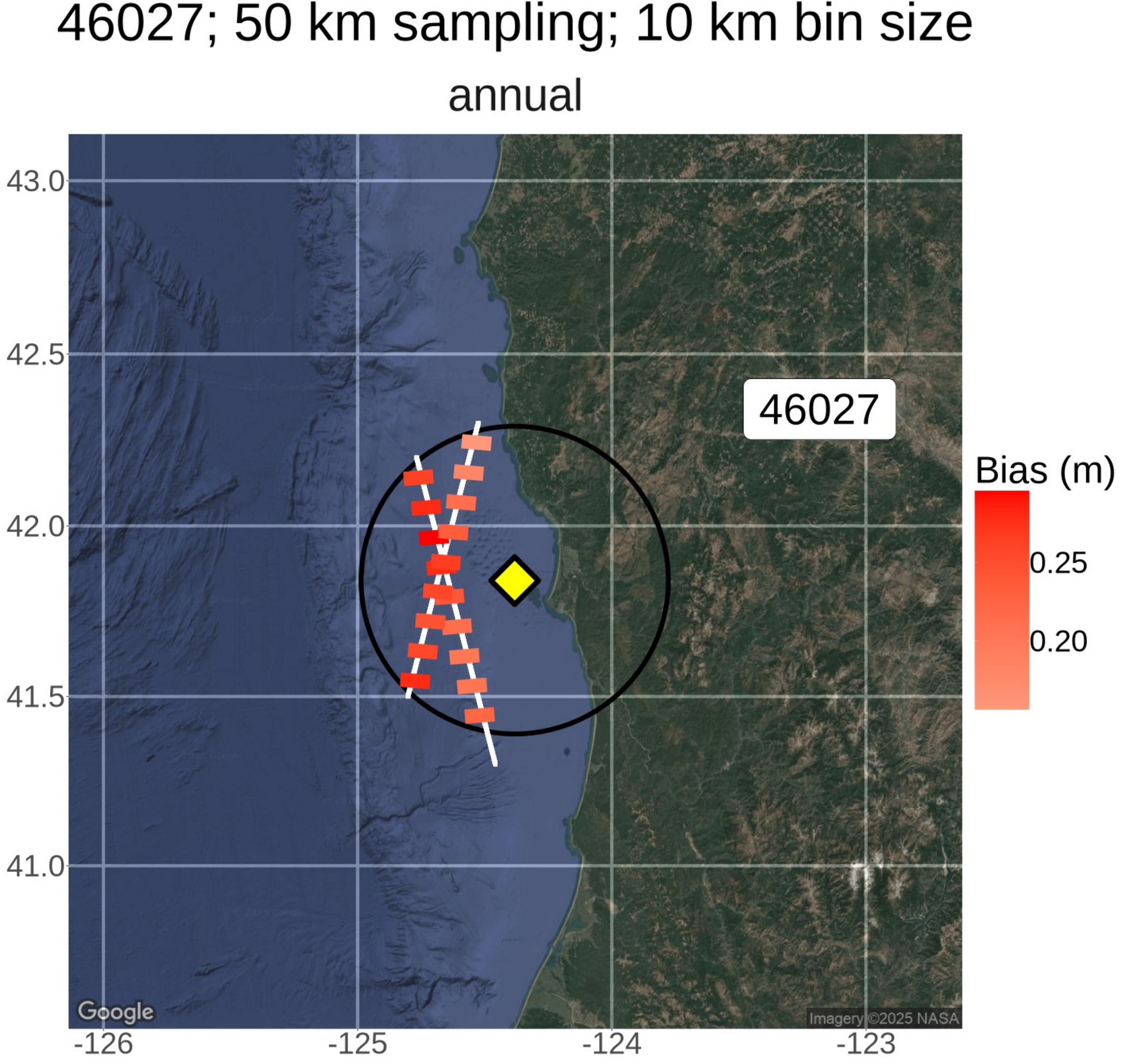


Buoy-Sat along-track gradients

— **Sentinel-3B (CCI v4) 2018-2023**

— **Hs mean bias**

— **1 Hz data, 10 km bin size**



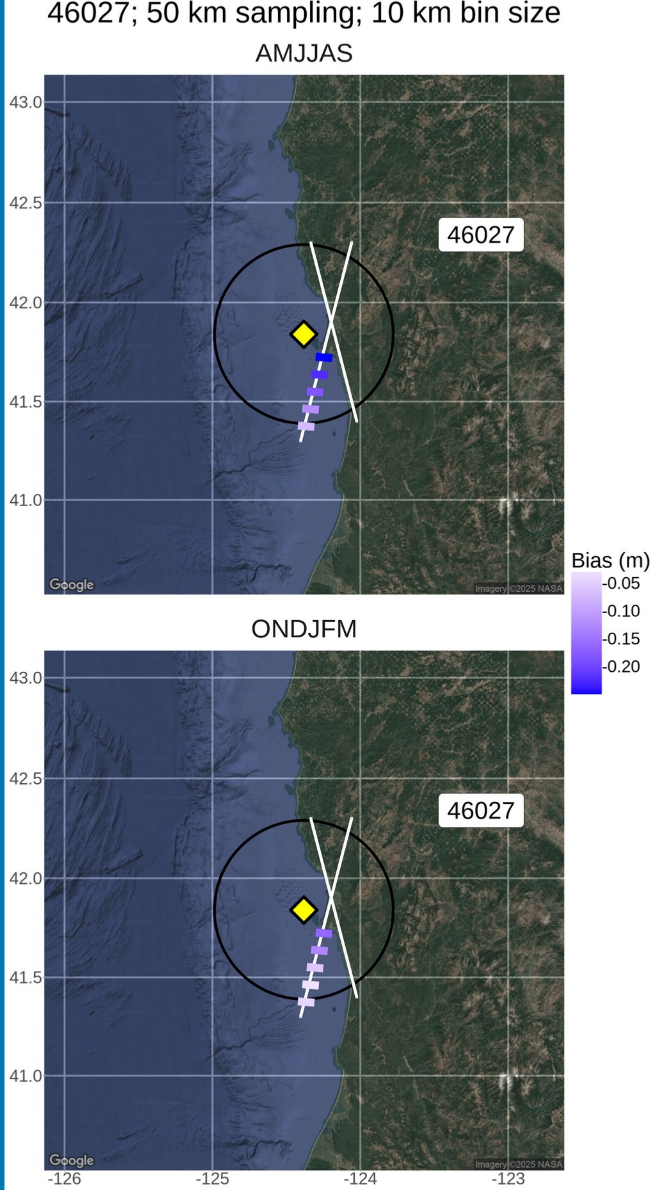
Buoy-Altimeter along-track gradients

— Sentinel-3A (CCI v4) 2016-2023

— Hs mean bias

— 1 Hz data, 10 km bin size

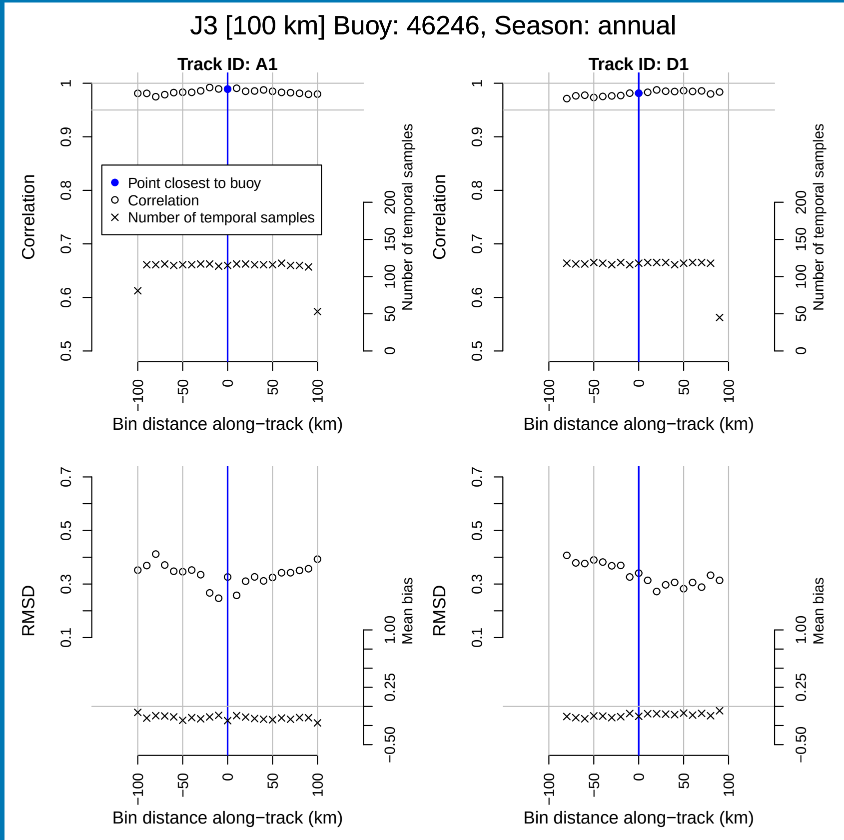
— Gradient reversal: closer to the coast and affected by local morphology?



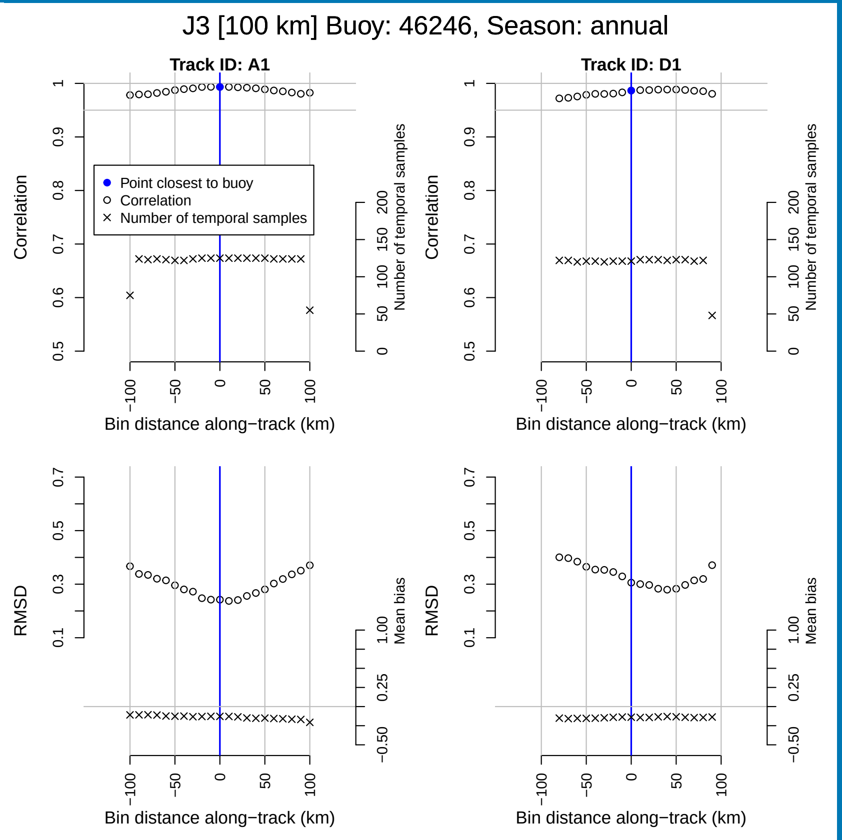
Uncertainty validation (L2)

- **De-noised data not examined in Phase 1 ;**
  - > Contains information on uncertainty
- **Impact of de-noised data on estimation of spatial gradients (collocation process).**

Jason-3 GDR



Jason-3 CCI denoised



Assessment of data conflict...

… if the collocation is reasonable!

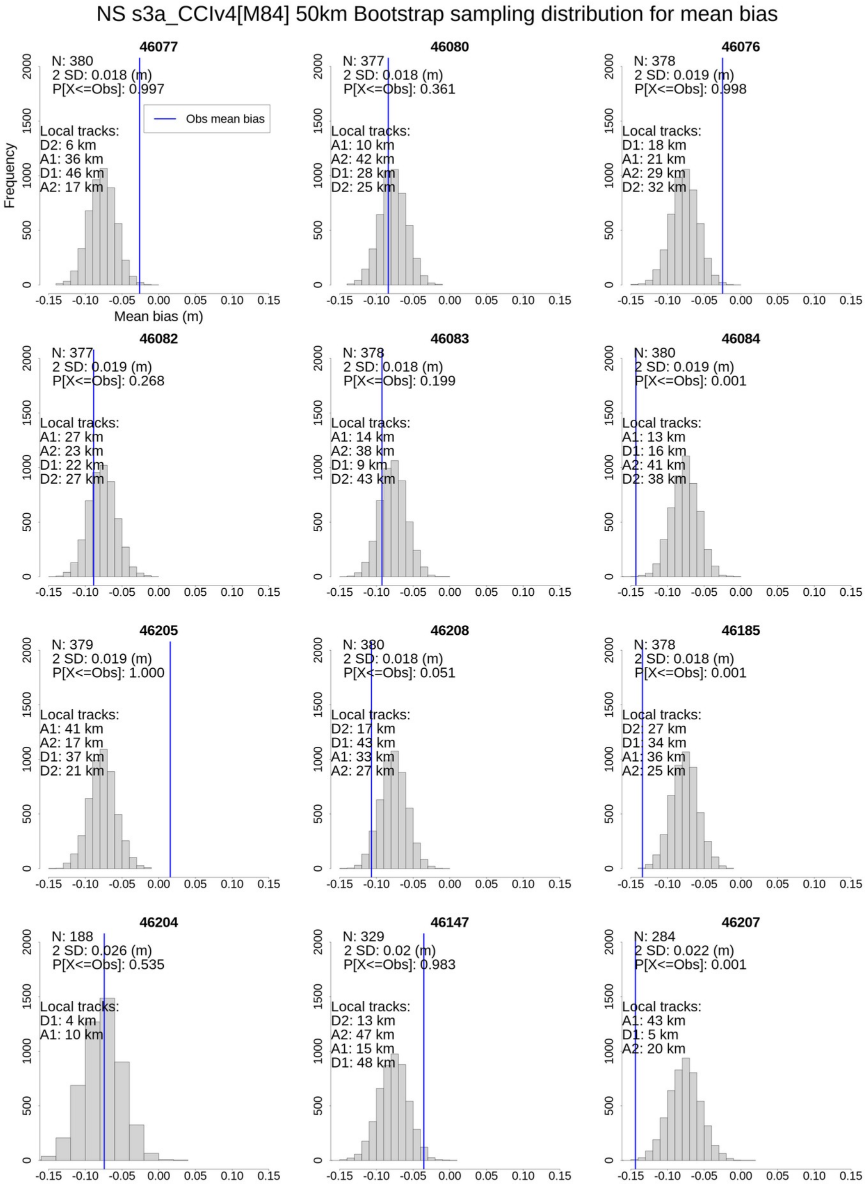
— Evaluate the "likelihood" of Hs mean bias from the "population" of biases from all buoys.

— Bootstrap probability distribution should be centred on zero (it's not!).

— Outliers (blue line) indicate conflict (for some reason).

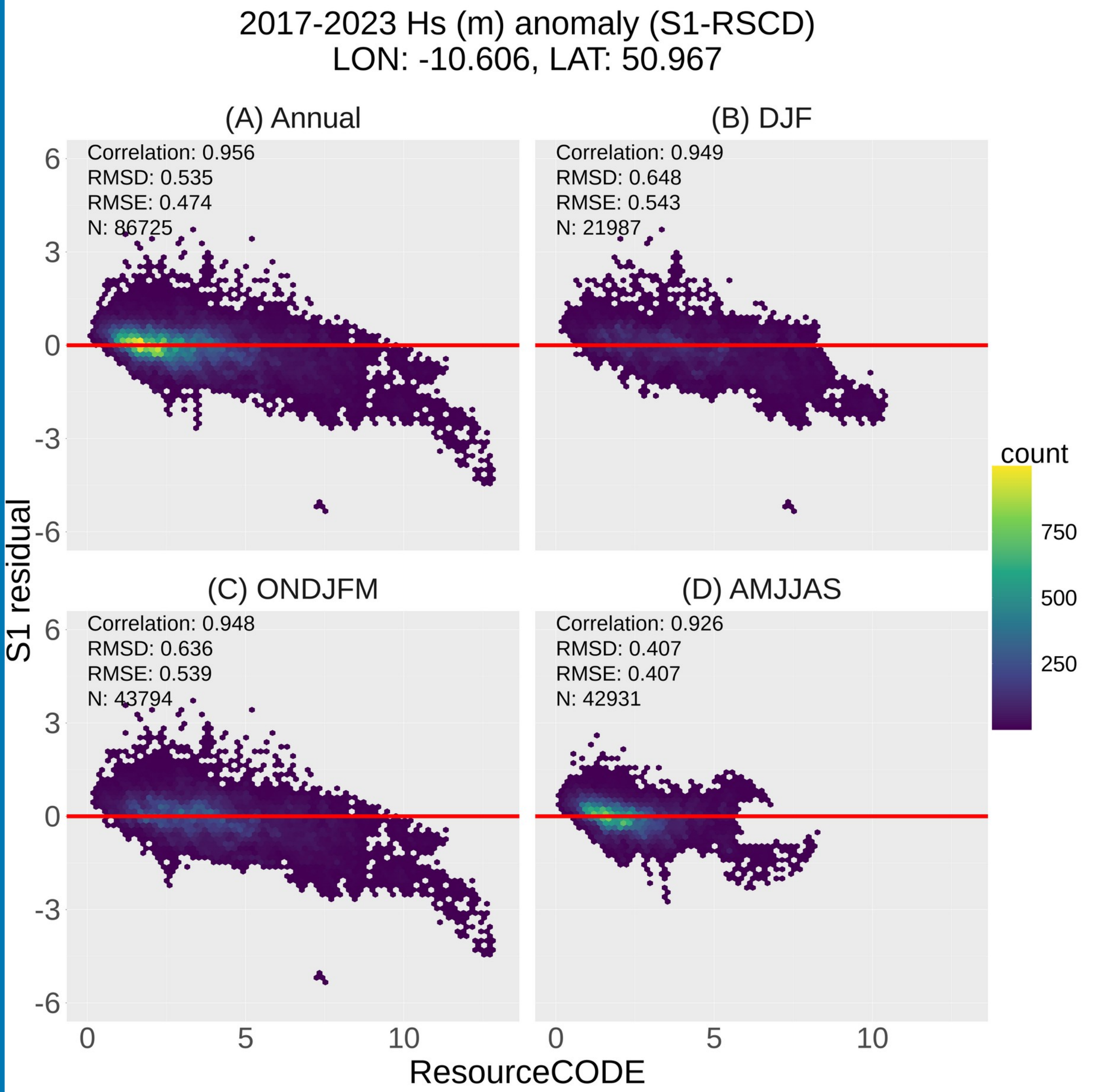
— Can be applied to other comparison statistics, such as correlation, RMSE, scatter index, ...

— Can an error model can be developed to explain disagreement?



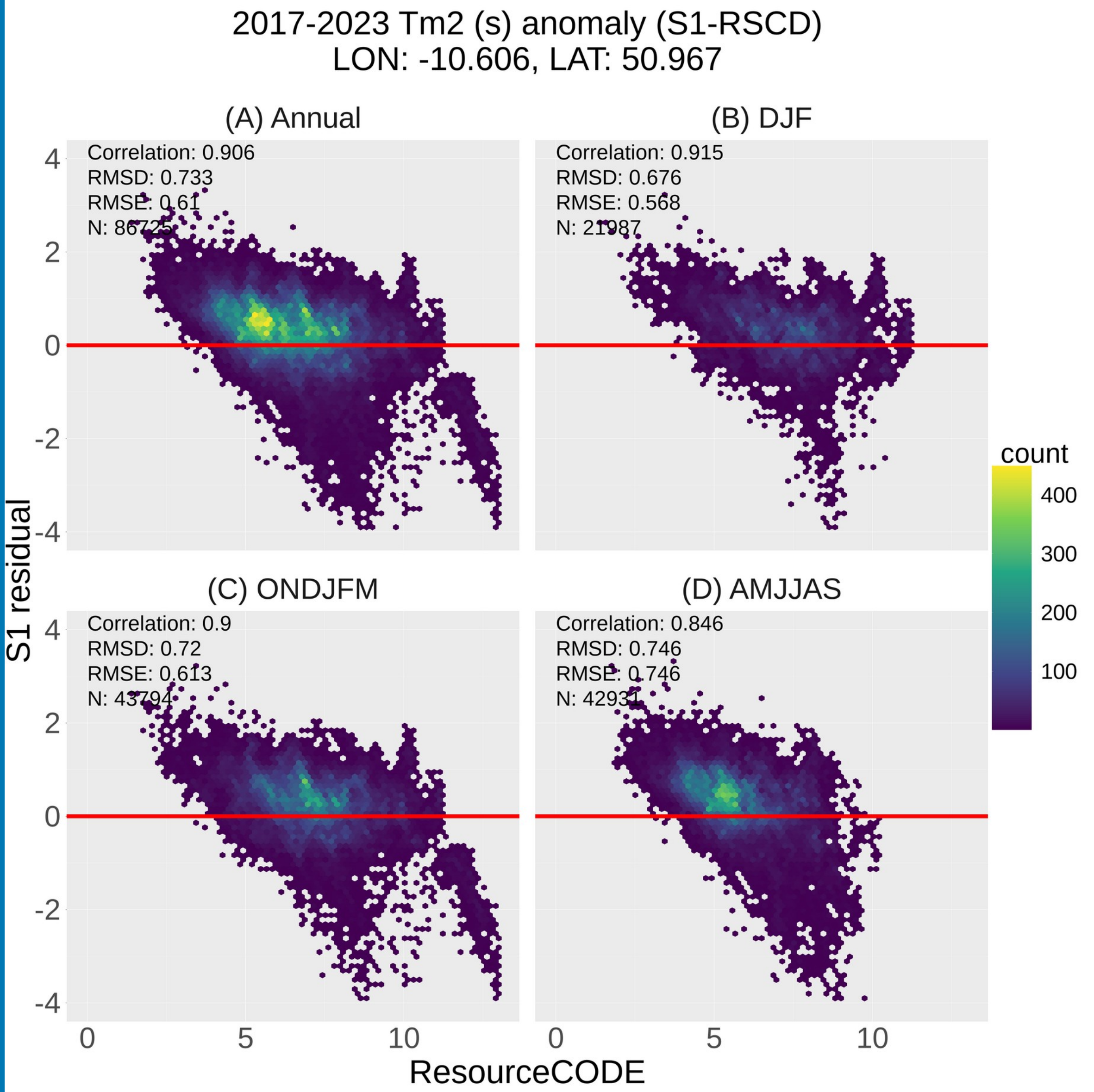
S1A / ResourceCODE comparisons (Hs)

- **Large collocation set (86725) ;**
- **“GOOD” data flag applied ;**
- **Low Hs mean bias ;**
- **Best performance for NH summer ;**
- **Sea state dependent bias at high Hs ;**



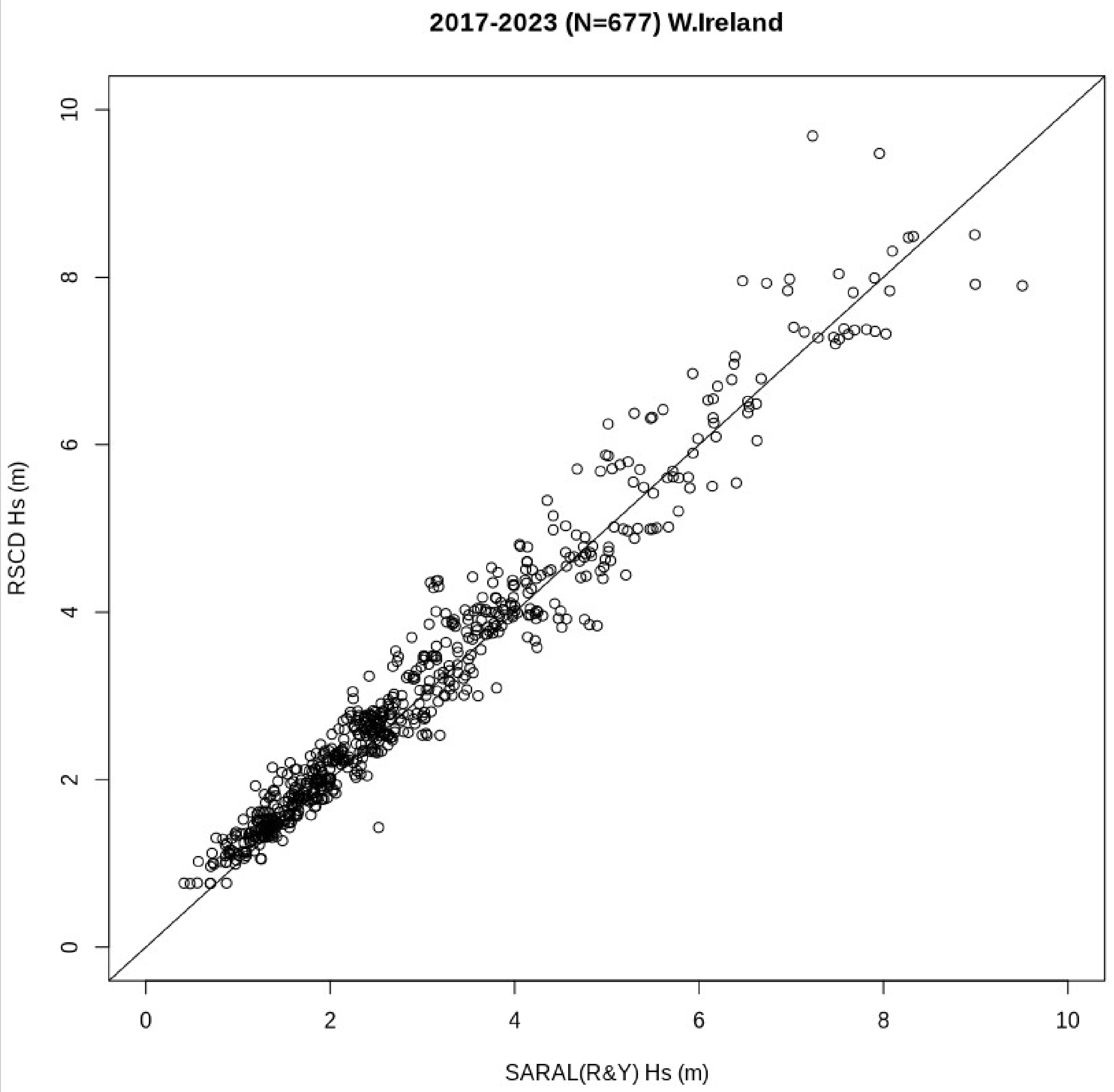
S1A / ResourceCODE comparisons (Tm2)

- **Reasonable performance ;**
- **Slight bias ;**



SARAL / ResourceCODE comparisons (Hs)

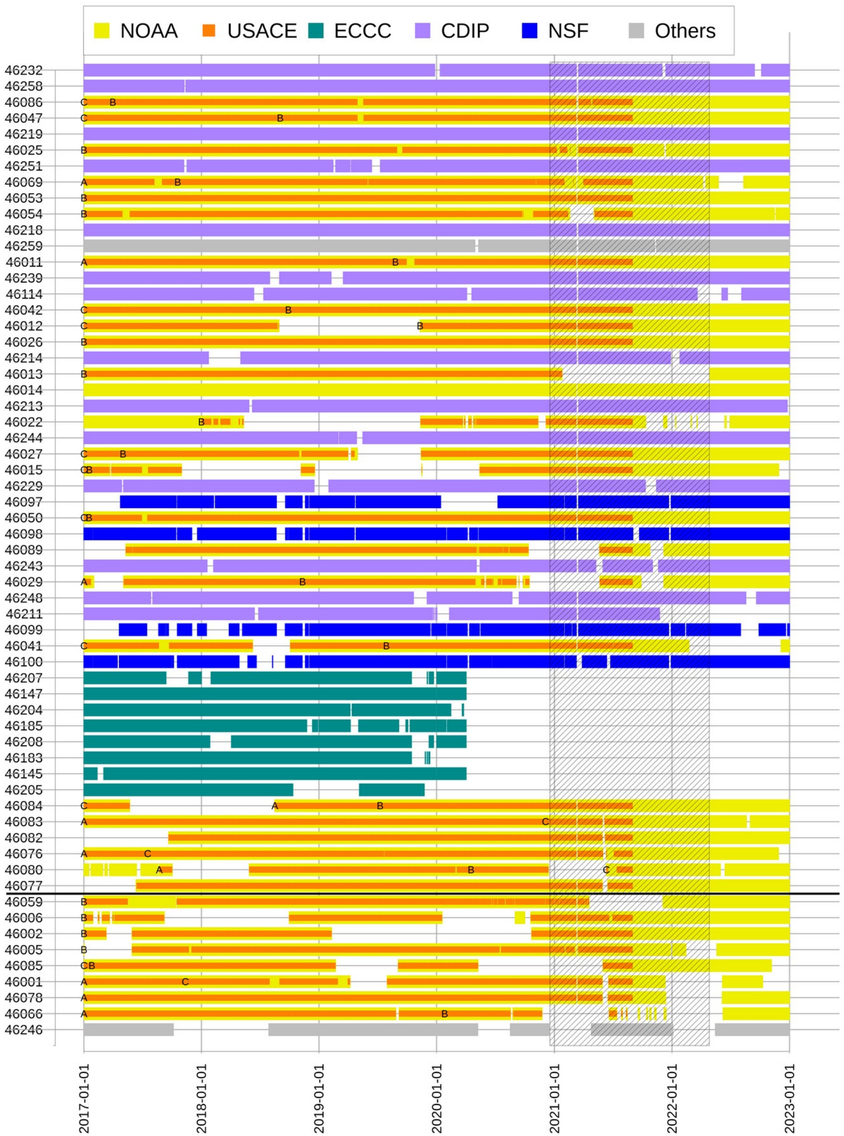
— RSCD good agreement with altimeter Hs



Variability across platforms

— Comparison of coverage and platform variability for Northeast Pacific *in situ* data

— Note, payload denoted by (small!) black letters



Coastal models for energy resource assessment:

— **U.S. coast (Yang et al., 2023) ;**

— **ResourceCode framework for European shelf (Accensi et al., 2021) ;**

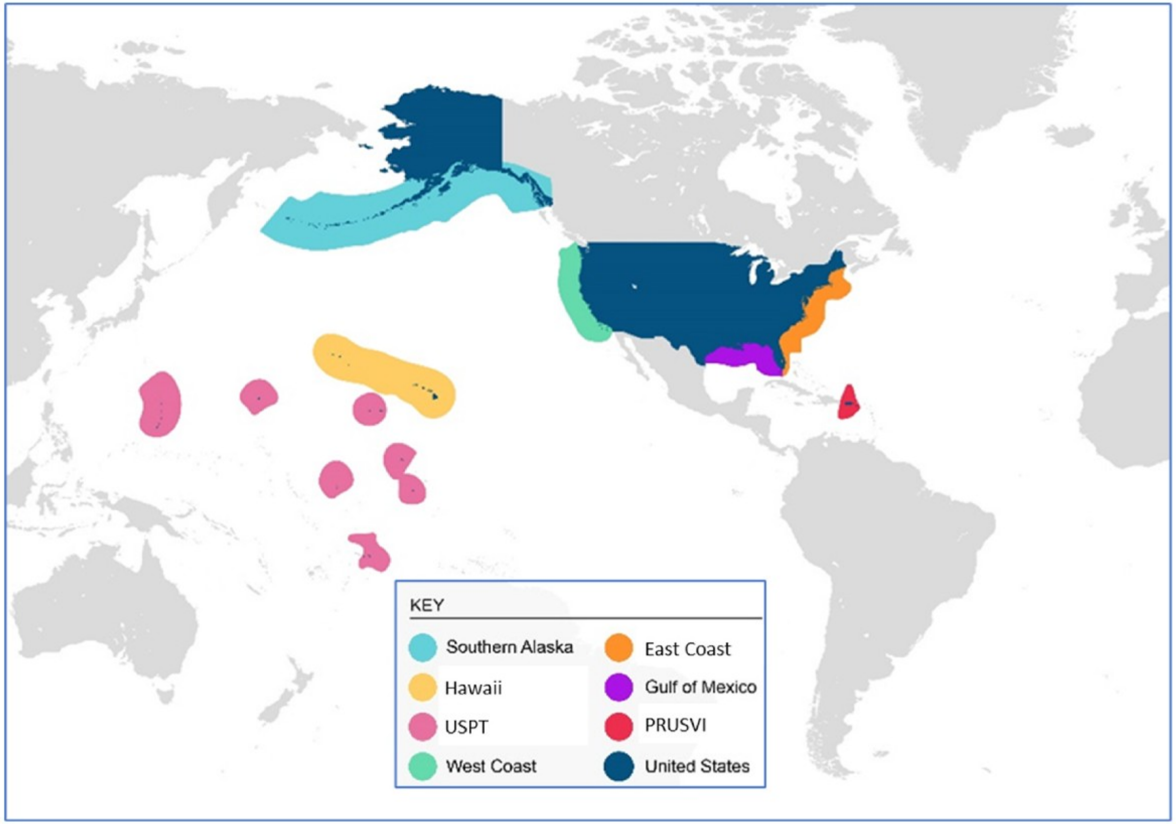


Fig. 1. U.S. EEZ regions corresponding to Table 1 for wave resource assessment.

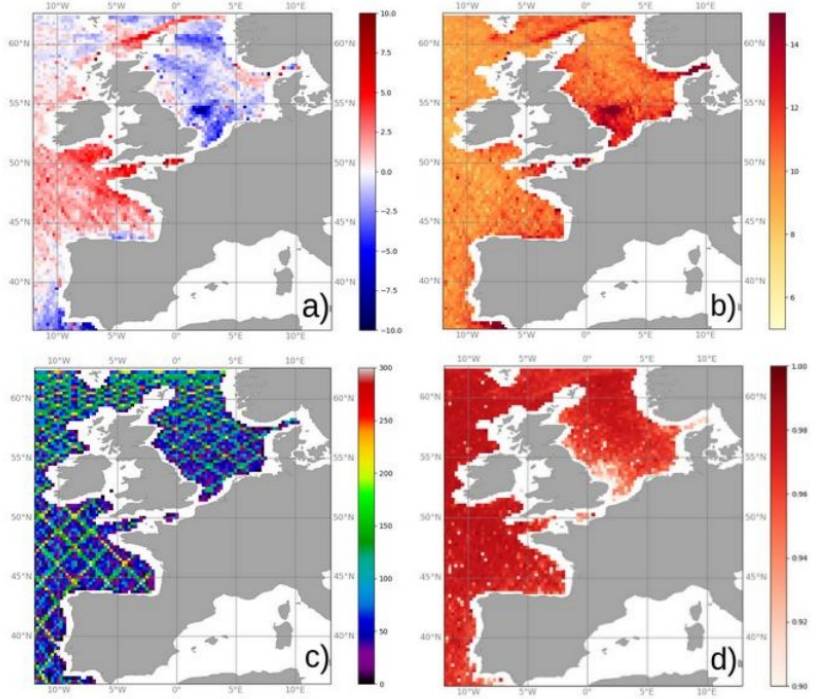


Fig. 5. yearly estimates averaged over 1993-2018.
a) NB; b) NRMSE; c) matches-up; d) R