National Oceanography Centre

Coastal Sea State Representation, Variability and Uncertainty from the Sentinel-6 Michael Freilich – Jason-3 Tandem Phase Experiment

Ben Timmermans[1,*], Christine Gommenginger[1] and Chris Banks[2]

[1]National Oceanography Centre, Southampton, UK
[2]National Oceanography Centre, Liverpool, UK
*ben.timmermans@gmail.com

esa

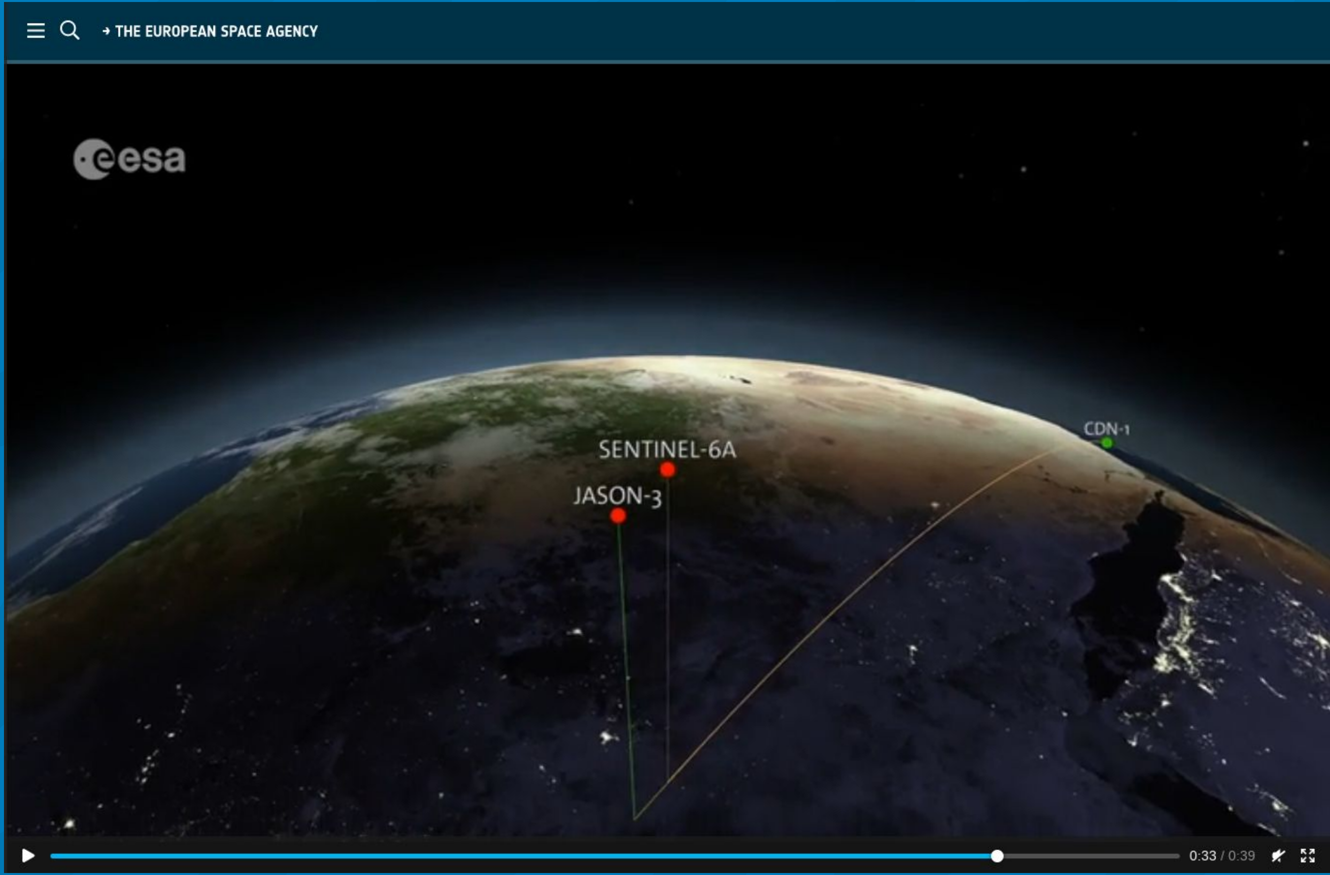
OSTST Forum
6-11 Nov 2023

Sentinel-6 / Jason-3 Tandem Experiment (S6-JTEX)

Flight details

- **Sentinel-6(A) Michael Freilich, launched November 2020**
  - Carries Poseidon 4B altimeter, capable of LRM and SARM retrieval.
  - Fulfils “Jason Continuity of Service” (Jason-CS)
- **Tandem Phase (S6-JTEX)**
  - December 2020 to April 2022 (~15 months)
  - S-6 trailed J-3 by ~30s
  - Jason-3 orbit (~10 day repeat)

Donlon et al. 2021, The Copernicus Sentinel-6 mission: Enhanced continuity of satellite sea level measurements from space, *Remote Sensing of Environment*



https://www.esa.int/ESA_Multimedia/Videos/2021/06/Sentinel-6_and_Jason-3_tandem

Sentinel-6 / Jason-3 Tandem

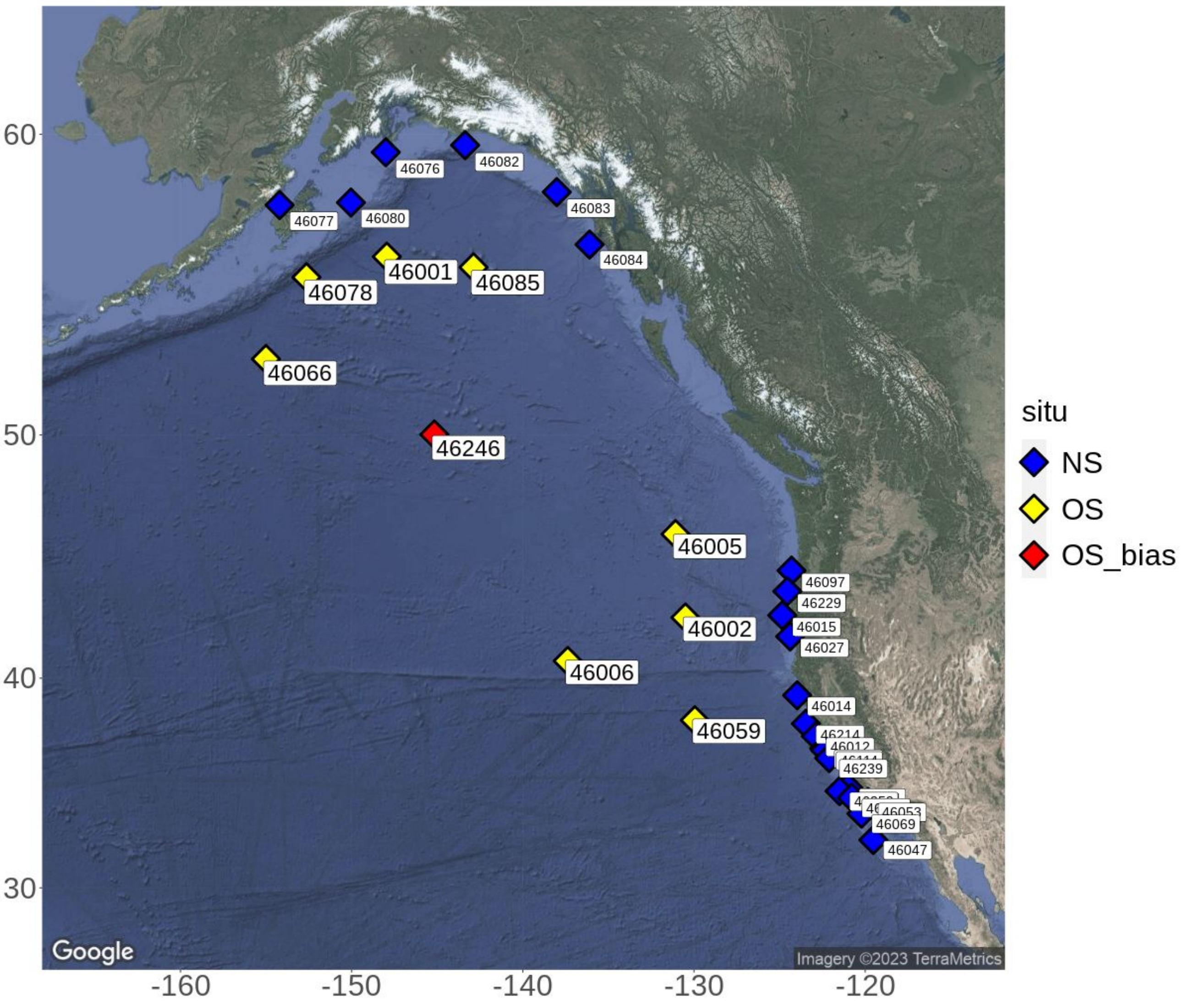
We address two questions:

1) **With a focus on *in situ* sites closer to the coast, can we use the altimetry to learn more about the spatial properties of sea state variability?**

2) **Can we use that knowledge to better exploit *in situ* records in order to better understand how uncertainties affect analyses based on multiple collocations, e.g. through different sampling approaches?**

Use of *in situ* moorings

- Analysis is limited to the north east Pacific region where sea states are relatively homogenous and moorings are fairly abundant.
- Nearshore (NS) sites (**blue diamonds**) are relatively abundant compared to offshore (OS) deep water sites (**yellow diamonds**).
- Site 46246 is marked in **red** to indicate the strong mean bias w.r.t. Jason-3 (see later slides).

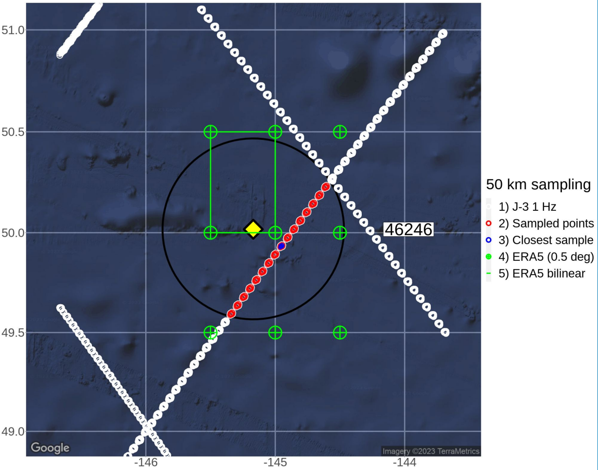


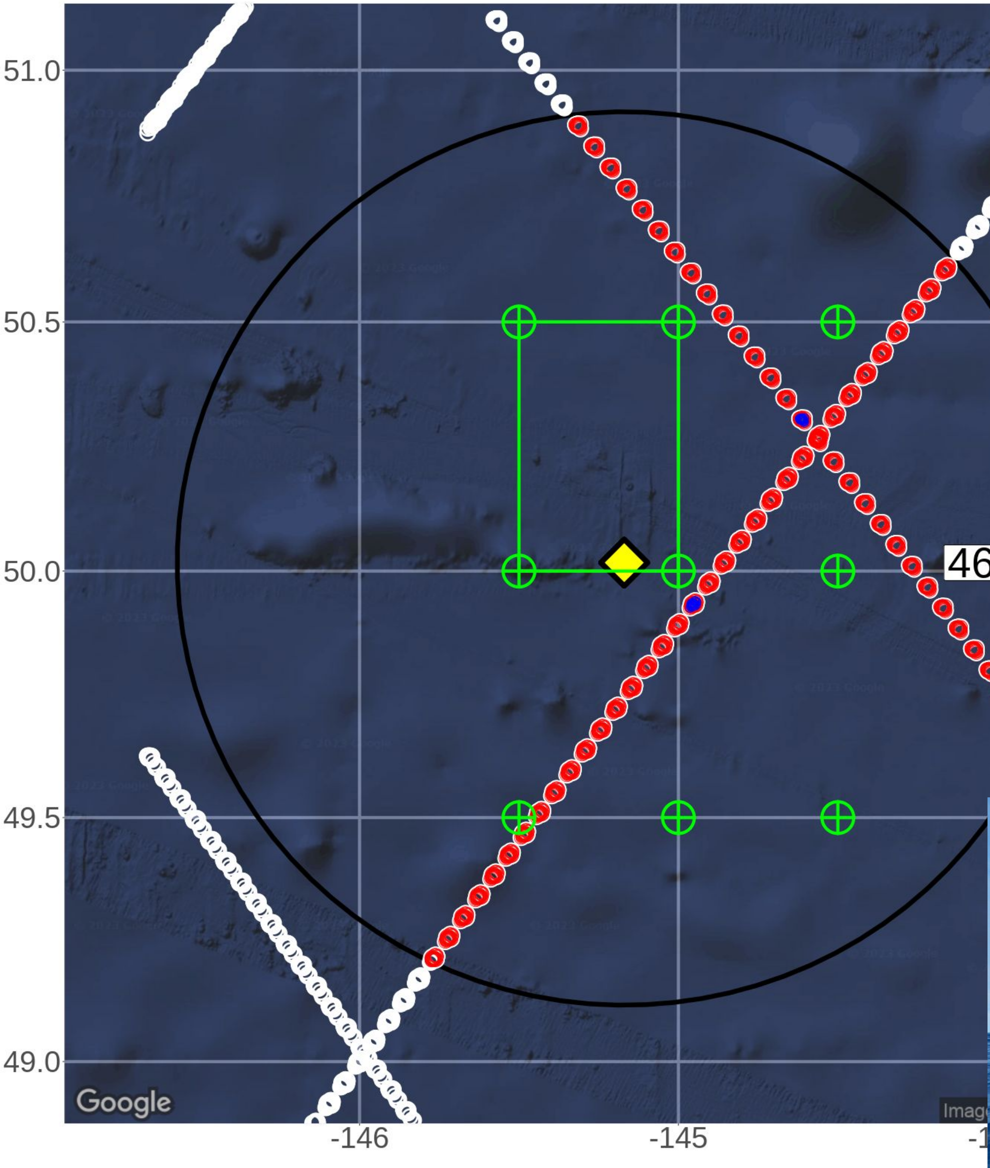
1) With a focus on *in situ* sites closer to the coast, can we use altimetry to learn more about the spatial properties of sea state variability?

We begin by looking at the collocation problem offshore.

Collocation introduces sources of uncertainty:

- Maps show collocation of three data sources; Jason-3 altimetry; in situ mooring; reanalysis grid (ERA5) at “Station Papa” 46246.
- Average of 1 Hz “**Super-observations**” (e.g. 50 km or 100 km) used for collocation (assume homogeneity of local conditions).
- Is this sampling approach effective in the presence of spatial sea state gradients?

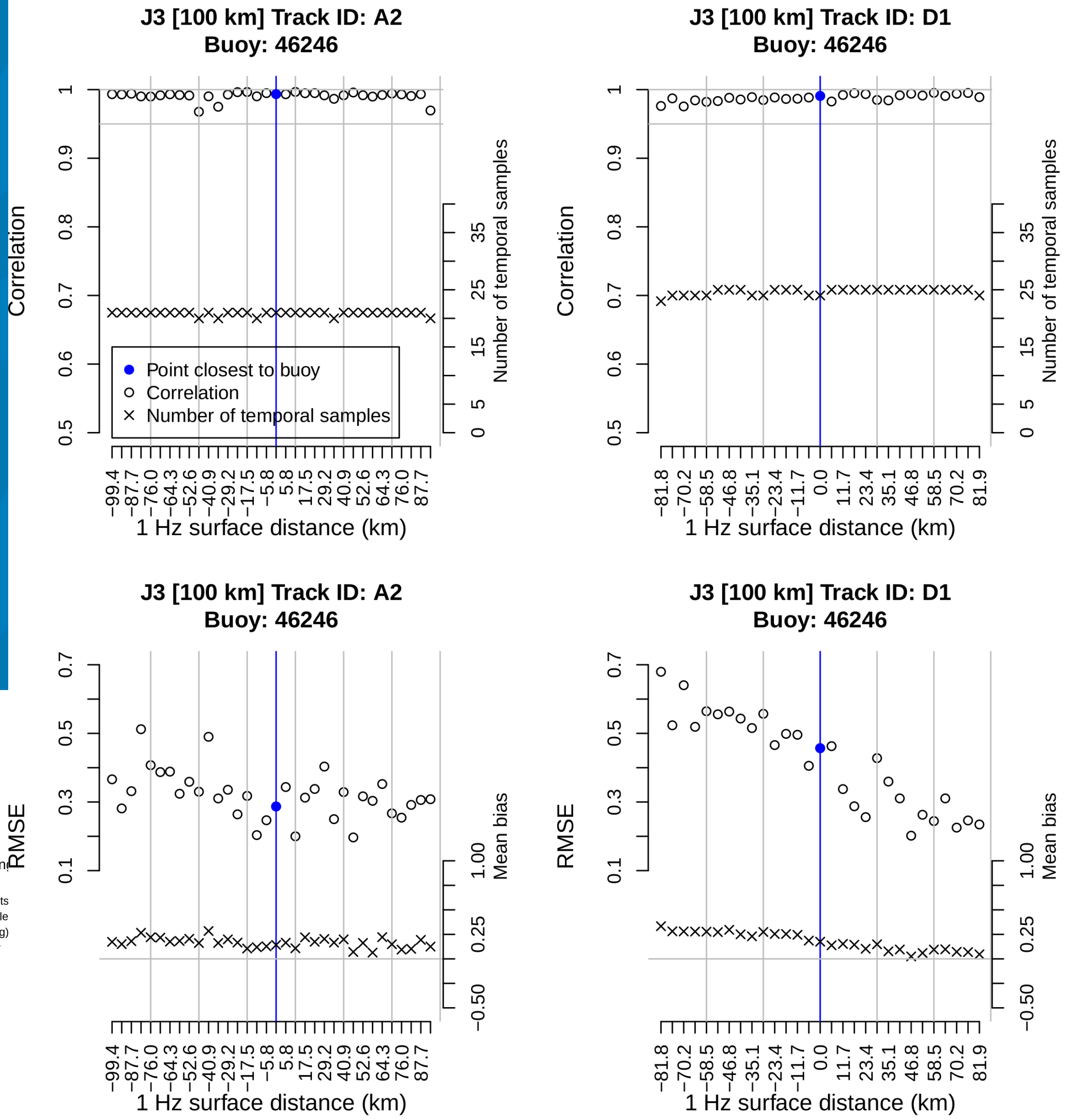


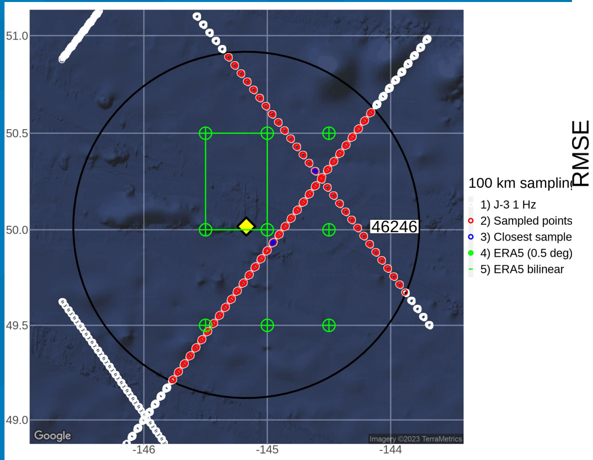


Sampling sea state at 46246

We can look explicitly at longer term statistics between "1 Hz locations" and e.g. in situ or reanalysis.

- The ascending track (A2) and descending track (D1) exhibit different characteristics.
- Figures (top) show temporal correlations and number of temporal samples for ~12 months J-3 data (~38 orbital repeats):
  - Number of temporal samples (crosses)
  - Correlation for each 1 Hz repeat location (circles) with buoy data.
- Figures (bottom) show RMSE (circles) and mean bias (crosses).
- Note the spatial variability of RMSE and bias for track D1.





Results on the previous slide illustrate that, even at offshore deep water sites, where sea state conditions are often assumed to exhibit considerable spatial homogeneity, we should expect to find changes in summary statistics (such as mean bias) on spatial scales ~20 km.

We also find a fairly large mean bias in Hs between 46246 and Jason-3 (see lower two panels).

In the following slides, in order to better visualize the spatial structure, we project summary statistics (correlation and mean bias) from a number of buoys, onto the spatial domain.

North East Pacific

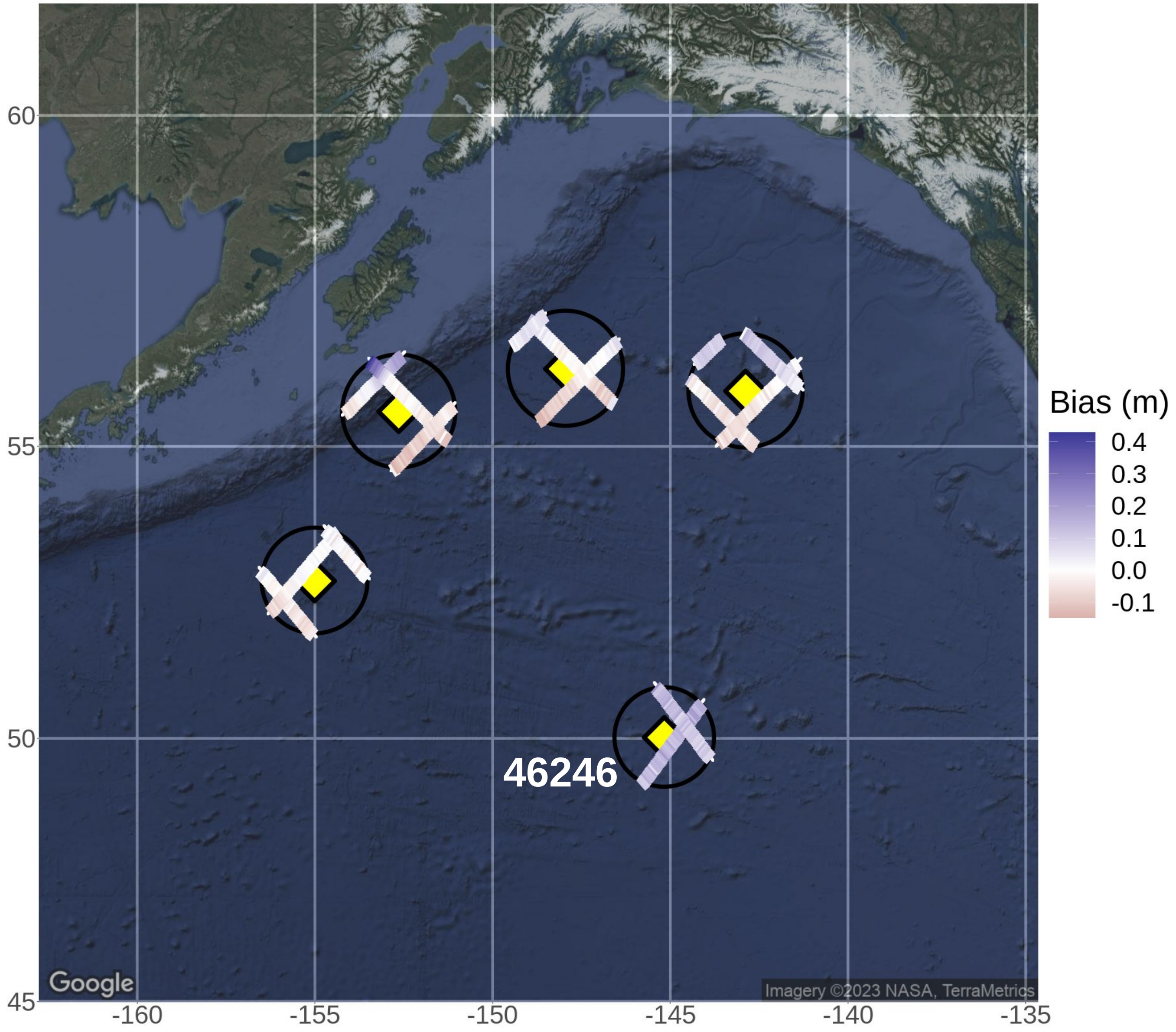
Jason-3 (2017-2021)

Sampling at 100 km radius (black circles)

Mean bias between buoys and Jason-3

Note the site dependent gradients:

- Sheltering and shelf-sea likely linked to large changes in bias.
- Anomalous bias at 46246?



North East Pacific

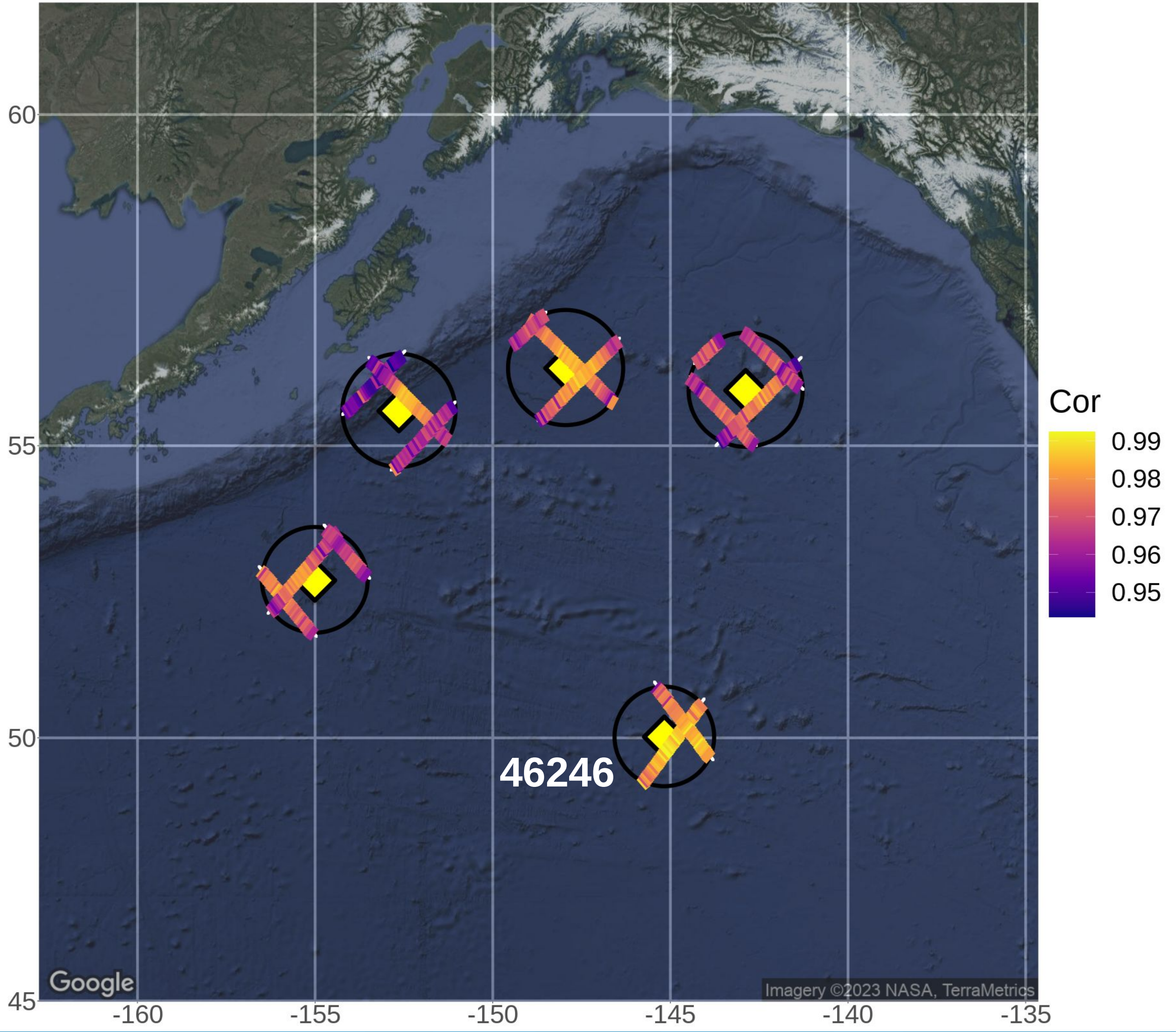
Jason-3 (2017-2021)

Sampling at 100 km radius

Correlation between buoys and Jason-3

Note the site dependent gradients:

- Highest correlations furthest offshore (46246).
- Correlation more variable closer to coast.



Results on the previous slides illustrate the changes in spatial variability in sea state summary statistics between mooring sites.

Sampling over these gradients will introduce uncertainty into any aggregated intercomparison where multiple sites are used.

In the following slides, we examine this issue when performing analysis closer to the coast.

Nearshore sites

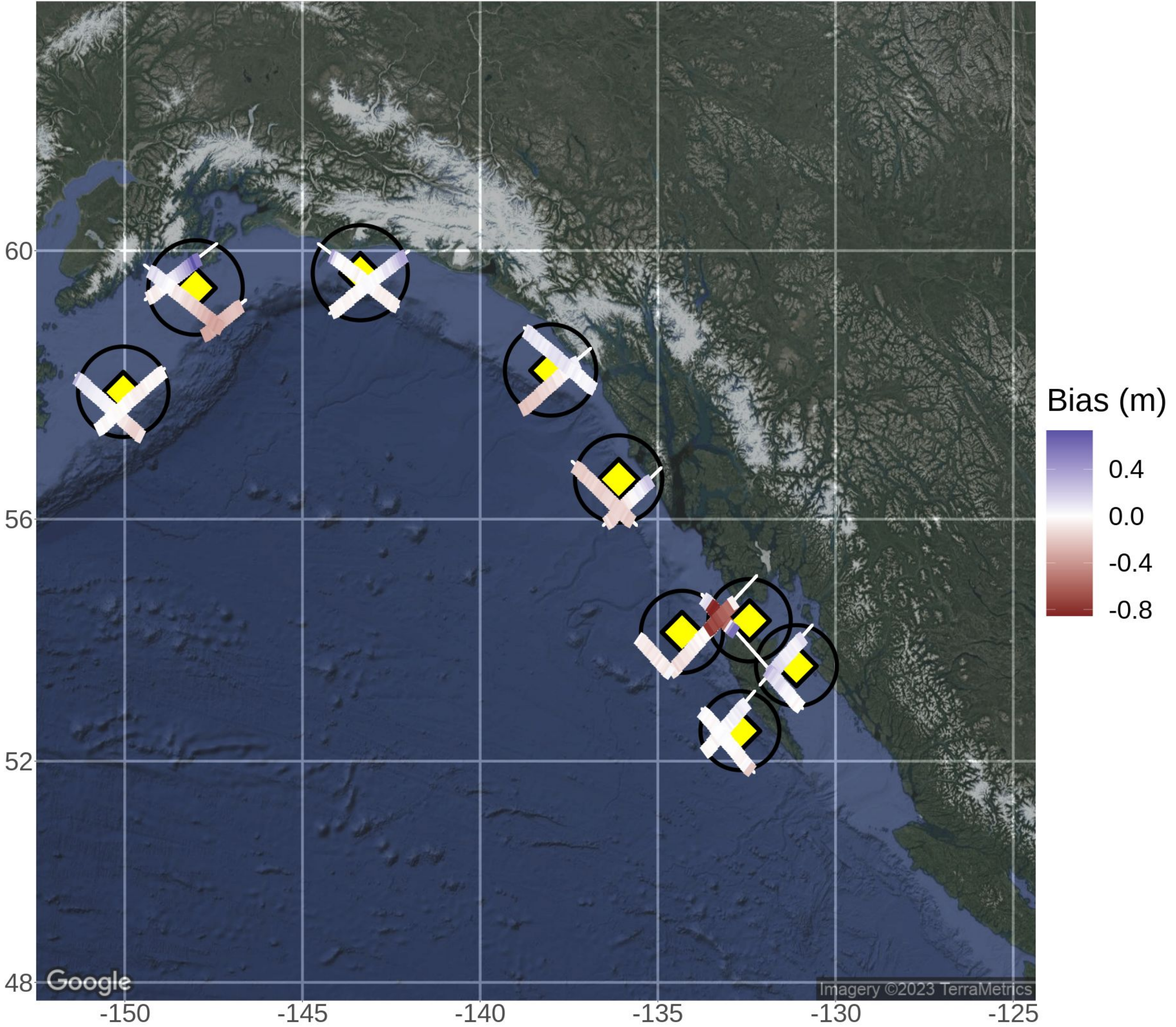
Jason-3 (2017-2021)

Sampling at 75 km radius

Mean bias between buoys and Jason-3

Note the site dependent gradients:

- Stronger gradients than seen offshore (increased range of bias).
- Increased variability between sites.

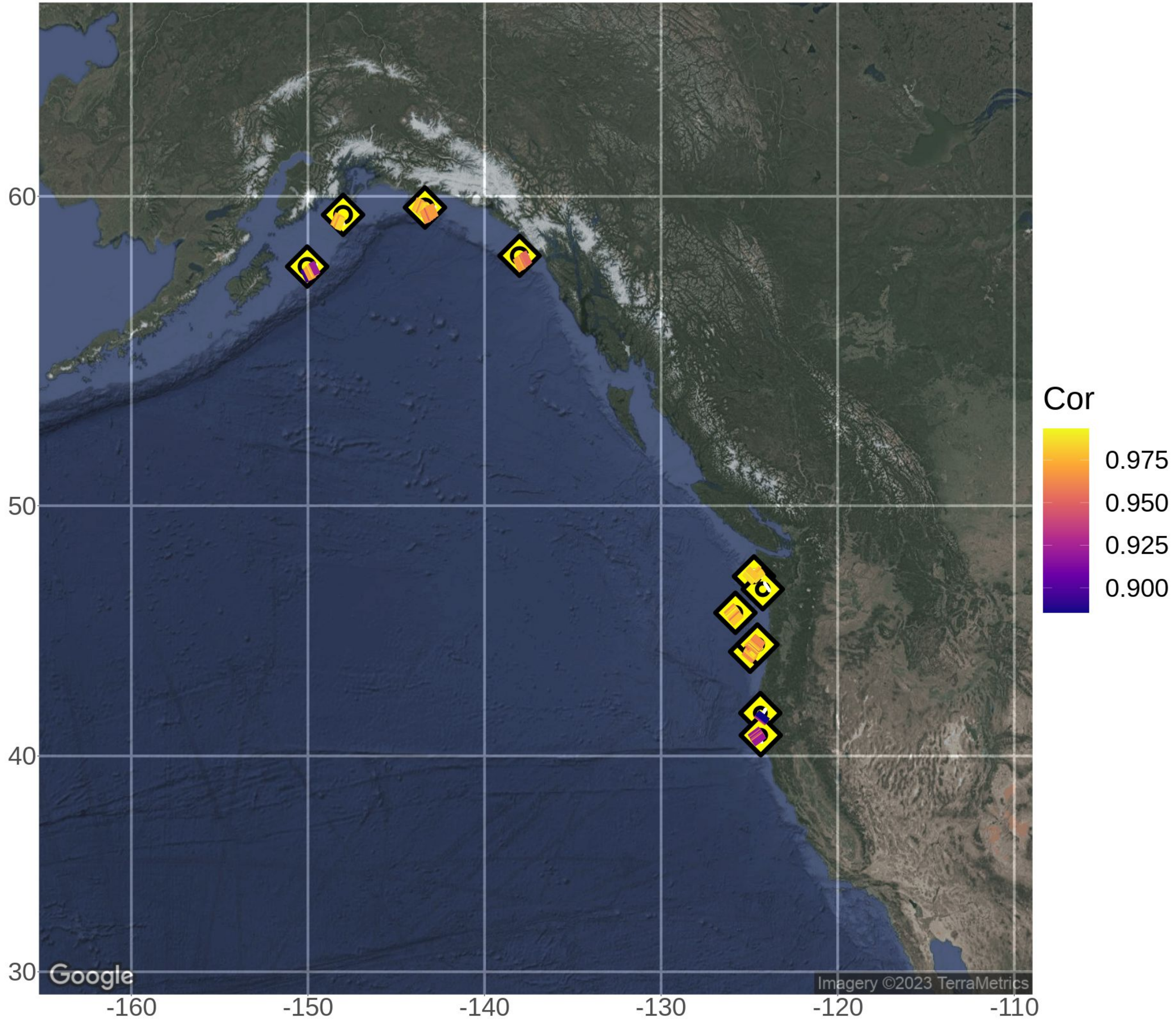


To perform an analysis across many sites, the impact of representativity errors from sea state gradients can be mitigated by constraining collocations:

25 km sampling

11 buoys

For a single mission like Jason-3, with fairly wide ground-track separation, samples become very limited!

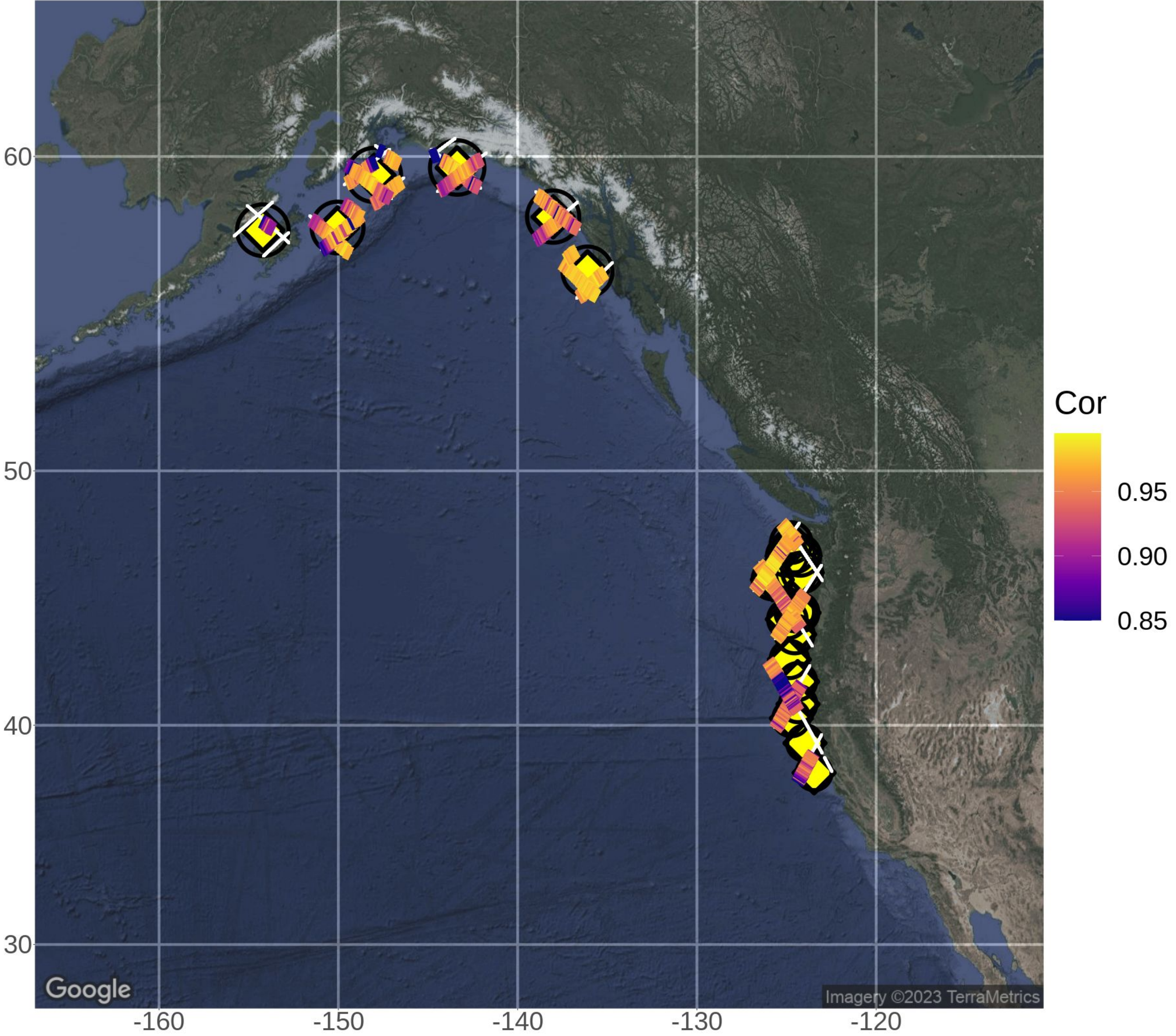


Perhaps we can sample over larger area but “adaptively” filter by matching the long term variability (e.g. using a threshold based on temporal correlation?):

75 km sampling

21 buoys

Sites increased by ~100%!

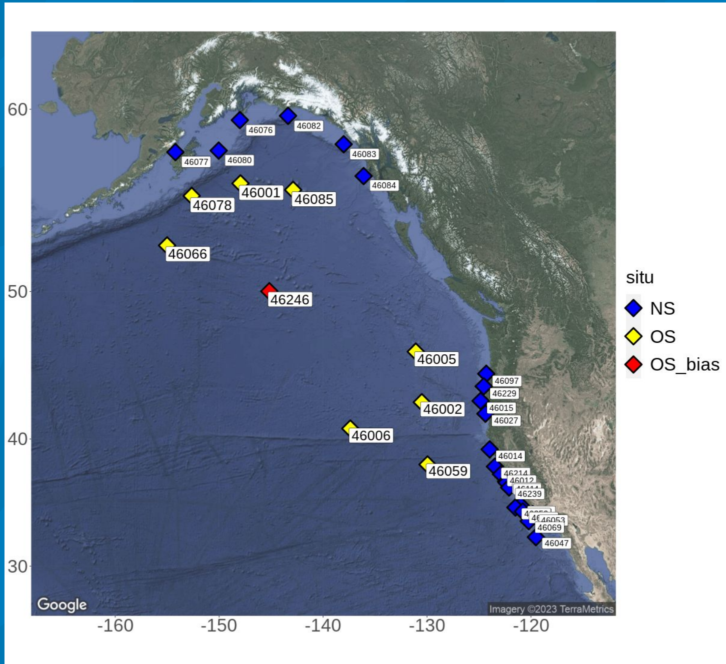


Results on the previous slides demonstrate, particularly at nearshore locations, that the sampling approach is linked to uncertainties and also strongly governs the number of locations and samples available for intercomparison.

We therefore examine different sampling approaches at nearshore locations to assess the impact on performance for the S6-JTEX tandem-phase data.

2) Can we use knowledge of local sea state variability to better exploit in situ records and better understand how uncertainties affect analyses based on multiple collocations, e.g. through different sampling approaches?

We begin by considering four different sampling approaches at nearshore locations (**blue diamonds**).

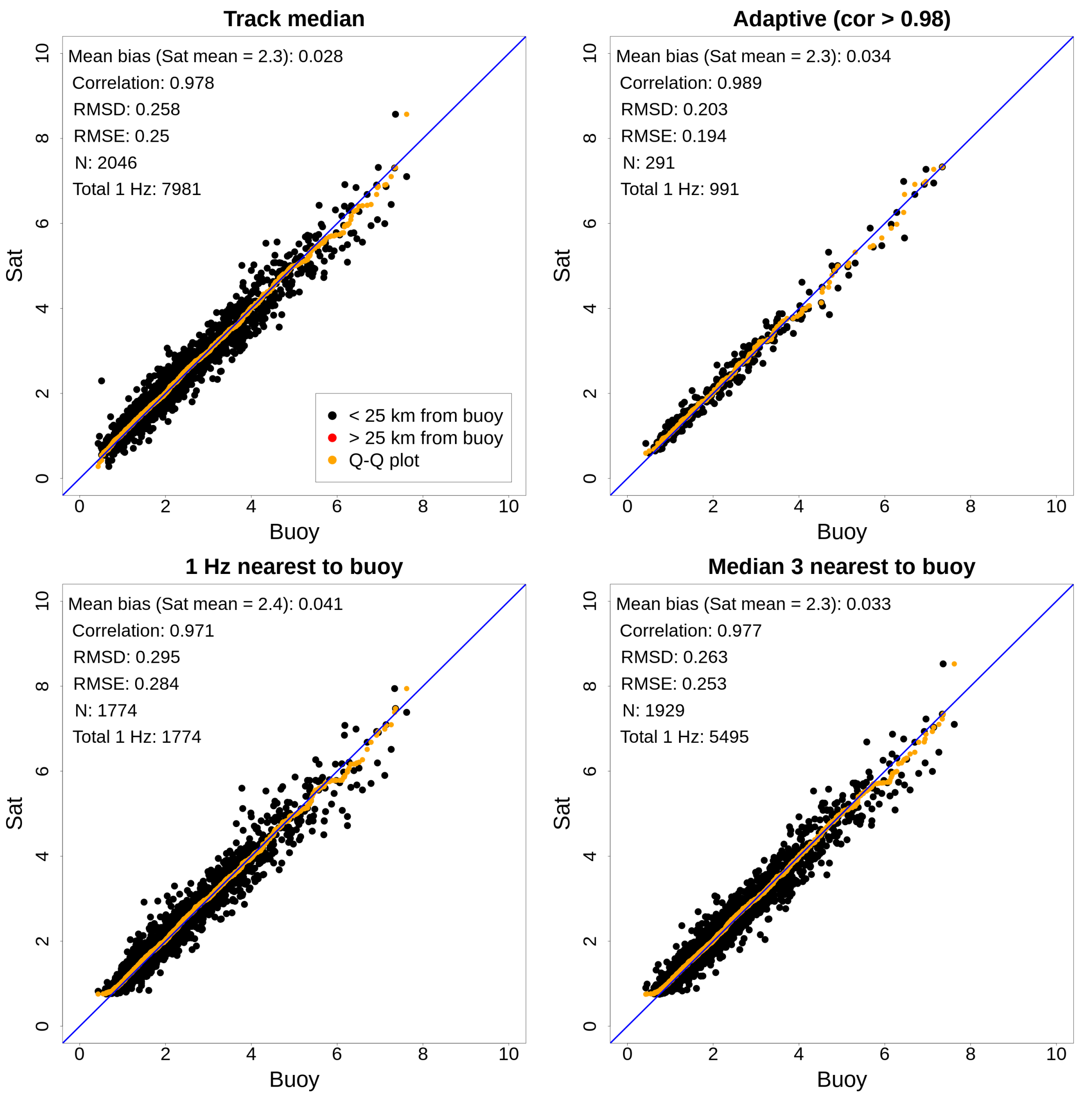


Performance statistics for Jason-3 (2017-2021) at 25 km sampling.

Four sampling methods:
1) Top left: full track median
2) Top right: “adaptive”, cor > 0.98
3) Bottom left: single nearest 1 Hz
4) Bottom right: median of 3 nearest 1 Hz

11 buoys available

Note: RMSD denotes absolute deviation, whereas RMSE is error derived from a fitted linear model.



Four different sampling methods are compared, and show the impact of changes to the number of samples and 1 Hz points.

At 25 km radius, there is little difference between the full track median (top left), and the nearest 3 1 Hz points to the buoy (bottom right). Highest RMSD and RMSE are associated with single 1 Hz sample (bottom left).

At higher values of Hs, Jason-3 appears to underestimate in all cases. This may serve to reduce the mean bias.

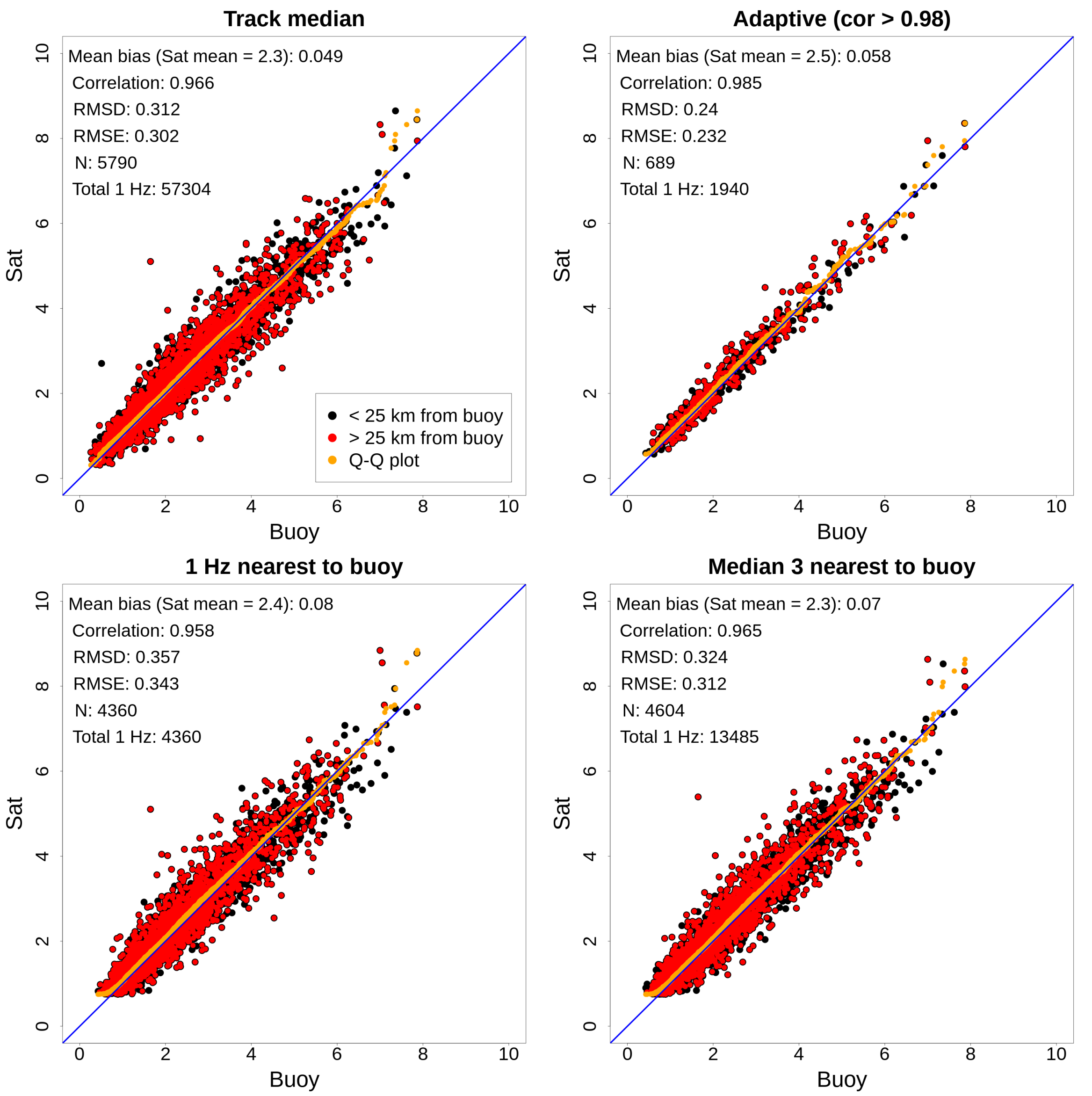
Filtering the along-track sampling (top right) by high correlation (cor > 0.98) reveals that the highest correlation (and lowest RMSD, RMSE) are associated with increased mean bias, although the number of samples is much reduced (291 vs 2046). This large reduction is indicative of strong spatial sea sate gradients that reduce correlation length scales.

Performance statistics for Jason-3 (2017-2021) at 75 km sampling.

Four sampling methods:
1) Top left: full track median
2) Top right: “adaptive”, cor > 0.98
3) Bottom left: single nearest 1 Hz
4) Bottom right: median of 3 nearest 1 Hz

21 buoys available

Red dots: > 25 km
Black dots: < 25 km



An increased sampling radius, from 25 km to 75 km, greatly increases RMSD, RMSE and correlation.

However, filtering the along-track sampling by high correlation (corr > 0.98) subsantially reduces scatter (RMSD, RMSE) while retaining many points that lie beyond 25 km sampling radius (red points).

As before, mean bias appears to be increased in this case, suggesting that higher sea states, possibly located further offshore, are being preferentially sampled by this approach.

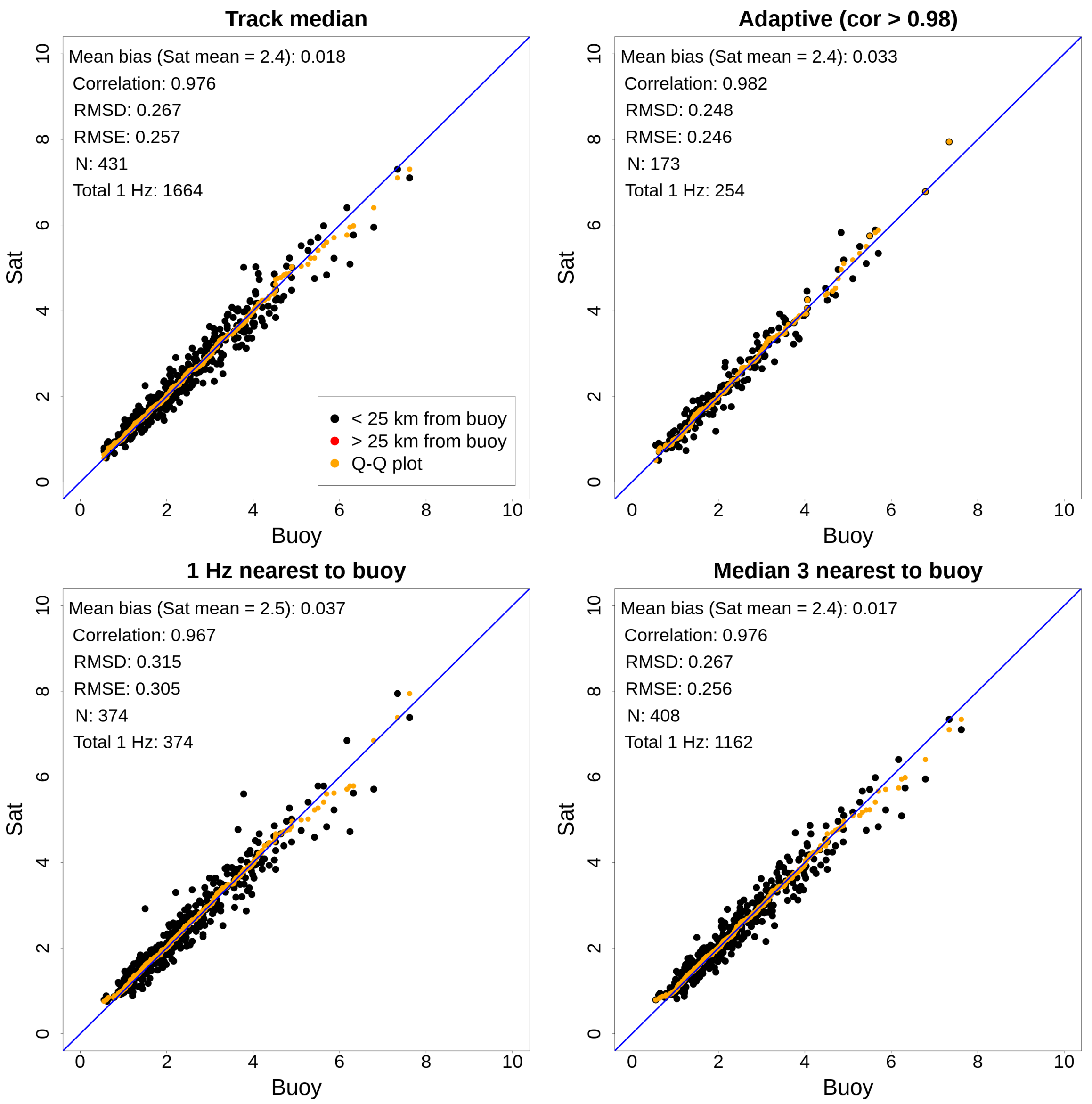
Finally we consider some results from Sentinel-6 MF from the tandem phase experiment. The ~13 month duration used here, leads to fewer samples, compared with the 5 year record of Jason-3 shown previously.

Performance statistics for Jason-3 (13 months) at 25 km sampling.

Four sampling methods:
1) Top left: full track median
2) Top right: “adaptive”, cor > 0.98
3) Bottom left: single nearest 1 Hz
4) Bottom right: median of 3 nearest 1 Hz

Results here are similar to those shown earlier for the 5 year period.

Mean bias is reduced, although sampling is also much reduced (e.g. 431 vs 2046)

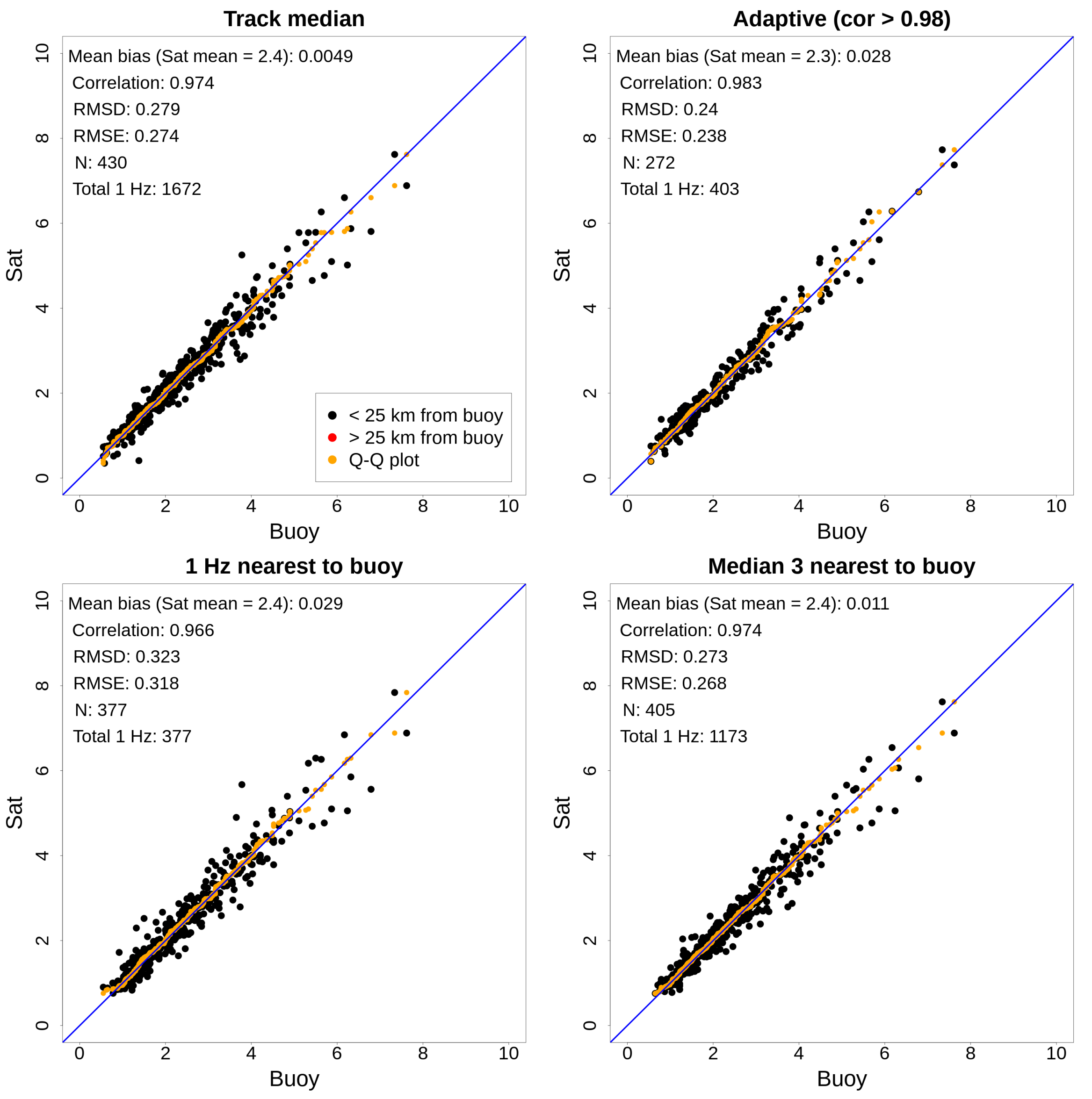


Performance statistics for S-6 LR (13 months) at 25 km sampling.

Four sampling methods:
1) Top left: full track median
2) Top right: “adaptive”, cor > 0.98
3) Bottom left: single nearest 1 Hz
4) Bottom right: median of 3 nearest 1 Hz

Very little difference between Jason-3 and Sentinel-6 LR.

Mean bias appears to be slightly lower that Jason-3: 0.005 vs 0.018 (statistical robustness not verified)



S-6 MF LR results are very simlar to Jason-3 both offshore (not shown) and nearshore. Both datasets show strong agreement with nearshore located buoys.

Mean bias is found to be ~25 cm although changes in RMSD of up to ~15% are associated with different sampling methodologies. **However, over a limited number of buoy locations, a site-by-site sensitivity analysis is recommended in order to better understand how each buoy is contributing to the overall aggregate result.**

Finally, we consider S-6 HR (SARM) data.

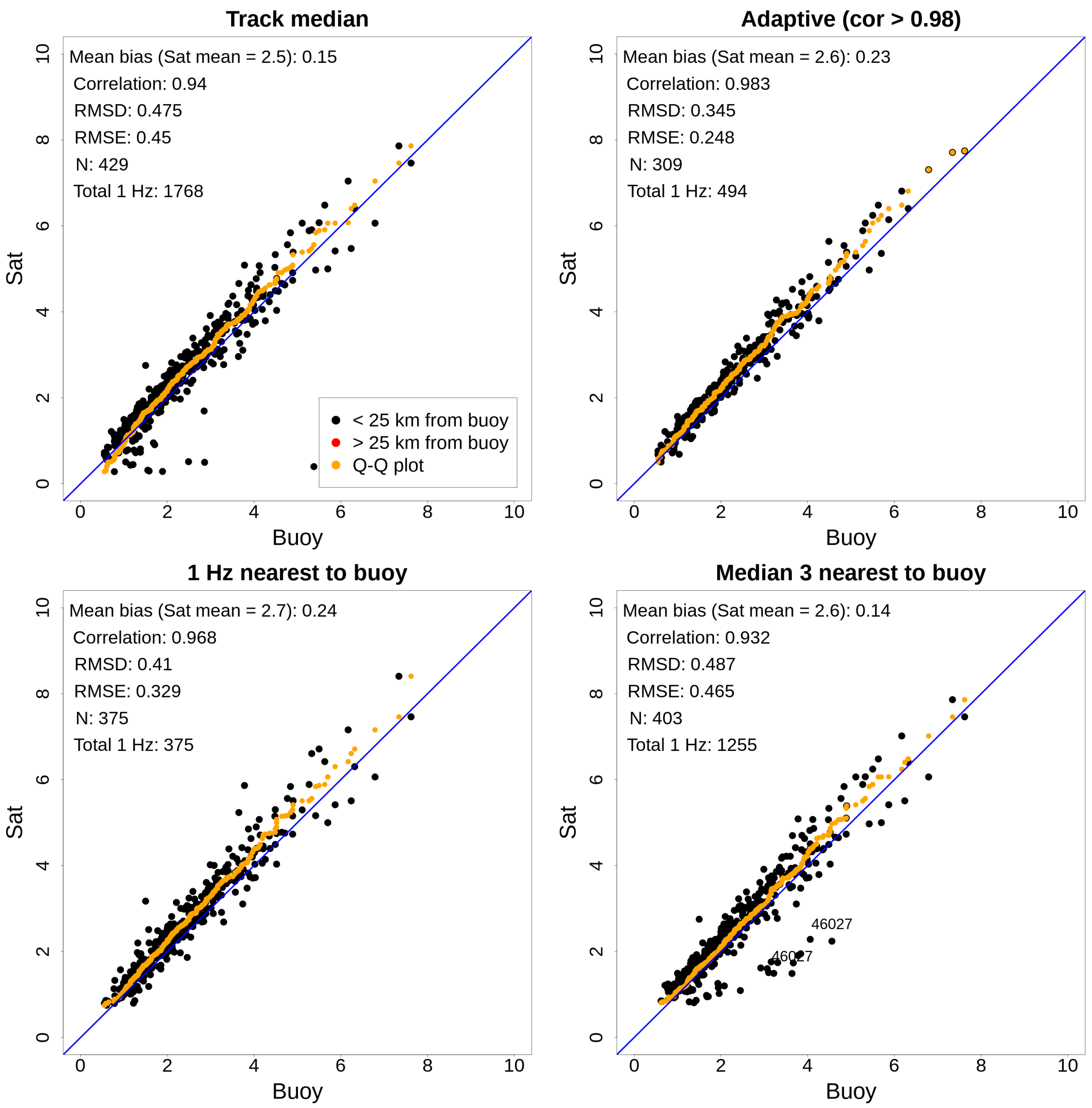
Nearshore (NS): Performance statistics for S-6 HR (13 months) at 25 km sampling (F06 rev).

Four sampling methods:
1) Top left: full track median
2) Top right: “adaptive”, cor > 0.98
3) Bottom left: single nearest 1 Hz
4) Bottom right: median of 3 nearest 1 Hz

Sampling is affected by data quality that is not so easily controlled (see top left, bottom right).

Spurious results impact evaluation but are removed by correlation-based “adaptive” sampling (top right).

Nearshore, bias may be stronger in higher sea states compared to offshore.

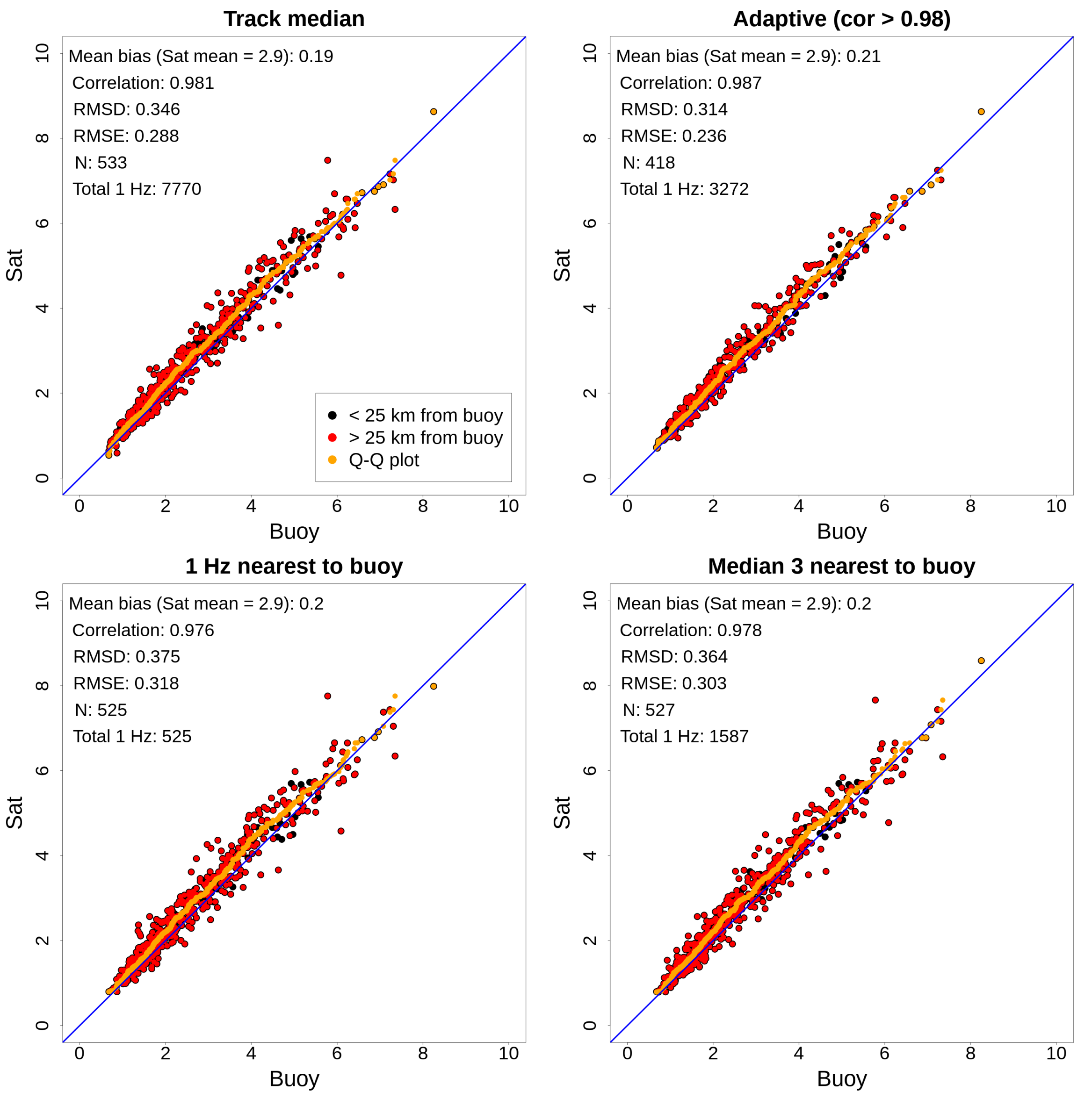


Offshore (OS): Performance statistics for S-6 HR (13 months) at 25 km sampling.

Four sampling methods:
1) Top left: full track median
2) Top right: “adaptive”, cor > 0.98
3) Bottom left: single nearest 1 Hz
4) Bottom right: median of 3 nearest 1 Hz

Unlike nearshore, offshore sampling appears unaffected by data quality.

Sea state dependent bias (~0.2 m) remains problematic although appears to be smaller than at nearshore locations, particularly for higher sea states.



S-6 MF HR (SARM) data (F06 reprocessing) exhibit a notable sea state dependent bias, which is clear from the results shown.

The bias manifests both offshore and nearshore. It may be stronger nearshore, although the results are:

1) **affected by some quality control issues nearshore, that need a resolution (see top left and bottom right panels);**
2) **not yet evaluated for statistical robustness.**

Further investigation is required.

Summary

- **The Jason-3 Sentinel-6 Michael Freilich tandem experiment offers a unique experimental setup to explore uncertainty in SWH observations from altimetry.**
  - Stability of long-term SWH LR record appears to be maintained at sites both offshore and closer to the coast. At coastal locations, Jason-3 and S-6 MF LR show close agreement with moored buoys (mean bias ~2 cm; RMSD ~27 cm).
  - S-6 MF HR (SARM) altimetry suffers sea state dependent bias that may be stronger nearshore, but requires further investigation.
  - Along-track analysis provides a deeper understanding of local sea state climatology. Filtering 1 Hz samples by (high) long-term correlation reveals an apparent positive correlation-bias dependence at nearshore sites, likely linked to more energetic sea states further from the shore.
- **Paper in prep.**

National Oceanography Centre

ESA Sea State CCI ***Phase 2*** is forthcoming...

Look out for:

- *Periodic community calls,*
- *User Consultation Meeting (NOC, Southampton) ~end 2025...!*

References

Donlon, C. et al., 2021, The Copernicus Sentinel-6 mission: Enhanced continuity of satellite sea level measurements from space, *Remote Sensing of Environment, 258, https://doi.org/10.1016/j.rse.2021.112395*

D. Kahle and H. Wickham. ggmap: Spatial Visualization with ggplot2. The R Journal, 5(1), 144-161. http://journal.r-project.org/archive/2013-1/kahle-wickham.pdf

Hall, C.; Jensen, R.E. USACE Coastal and Hydraulics Laboratory Quality Controlled, Consistent Measurement Archive. *Scientific Data 2022, 9, DOI:10.1038/s41597-022-01344-z*

Zhaoqing, Y. et al, 2023, Multi-decade high-resolution regional hindcasts for wave energy resource characterization in U.S. coastal waters *Renewable Energy, https://doi.org/10.1016/j.renene.2023.03.100*

Dodet, G. et al. 2022, Error Characterization of Significant Wave Heights in Multidecadal Satellite Altimeter Product, Model Hindcast, and In Situ Measurements Using the Triple Collocation Technique, *J.Tech, 39, https://doi.org/10.1175/JTECH-D-21-0179.s1*

Ribal, A. & Young, I. 2019, 33 years of globally calibrated wave height and wind speed data based on altimeter observations, *Sci. Dat., 6, https://doi.org/10.1038/s41597-019-0083-9*

Vogelzang, J.; Stoffelen, A. Triple collocation. Technical Report NWPSAF-KN-TR-021 Version 1.0, Date: 06/07/2012 KNMI, de Bilt, the Netherlands.

Dodet et al. 2020, The Sea State CCI dataset v1: towards a sea state climate data record based on satellite observations, *Earth Syst. Sci. Data, 12, 1929–1951, https://doi.org/10.5194/essd-12-1929-2020*