SENTINEL-6 MICHAEL FREILICH & JASON-3 TANDEM FLIGHT EXPLOITATION (S6-JTEX)

Sea state studies: Triple collocation

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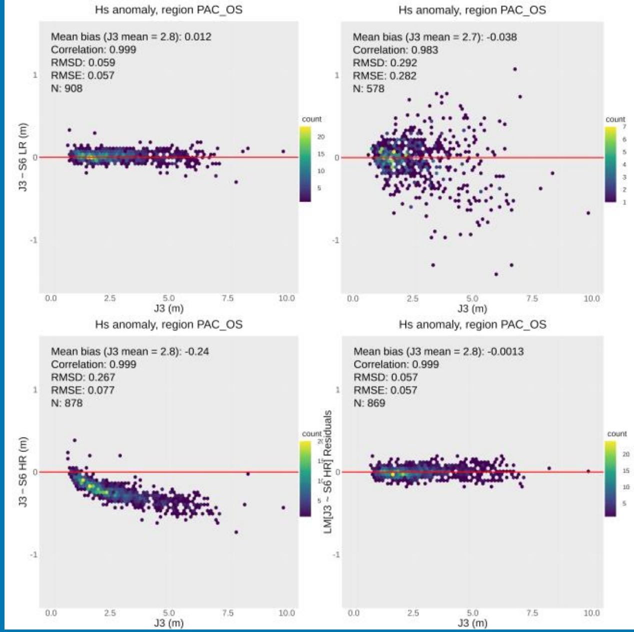
Project Summary



Highlights...

— Found tandem observations highly consistent across all analysis.

— Uncertainties in tandem data (J3, S6 LR & HR F06 reprocessing) are small (0.01 m mean bias; 0.06 m RMSD), compared with moored buoys and models (0.04 m; ~0.29 m).

— Triple Collocation *suggests* that S6-MF HR exhibits the lowest errors (0.18 m) but sampling limits the robustness of results.

— Due to challenges with the use of Triple Collocation, we focused on the use of in situ collocation methodology and how to implement this in "nearshore" regions.

> An ensemble of buoys is a collection of independent and often inconsistent observing systems;

> Those uncertainties dominate intercomparison with tandem data.

— Consequently, we have focused on "Offshore" and "Nearshore" in the eastern North Pacific:

> Identified impacts of sea state gradients on collocation sampling on a site-by-site basis;

> Identified problematic buoys (statistical outliers) and make recommendations as to their use.

Triple Collocation Analysis

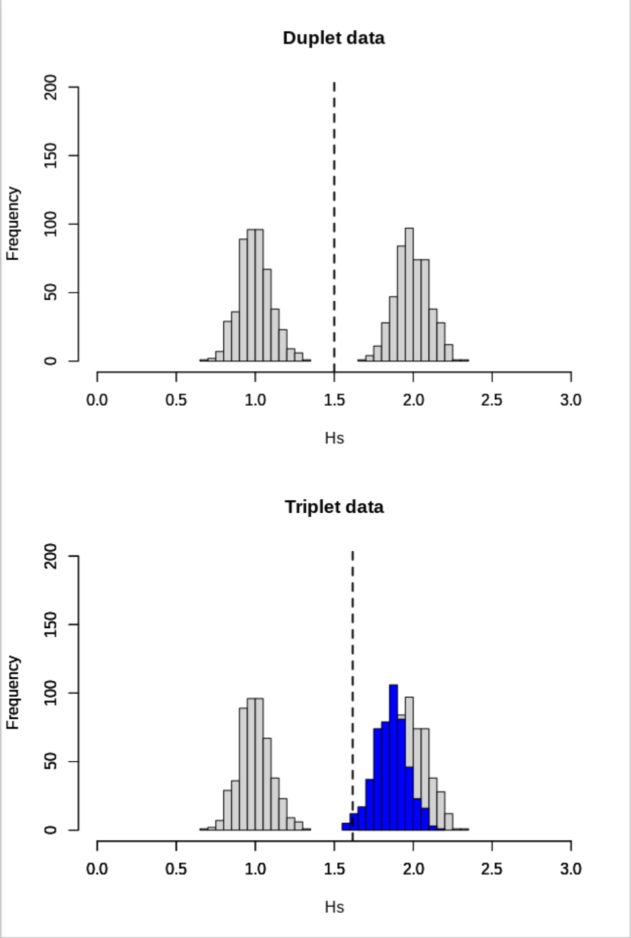
The Triple Collocation (TC) method is a powerful means of estimating systematic and random error in observations where three simultaneous observations of the same quantity can be made. See, Vogelzang & Stoffelen (2012) who, in particular, identify several key assumptions, including:

Assumptions

— Linear calibration is sufficient over the whole range of measurement values;

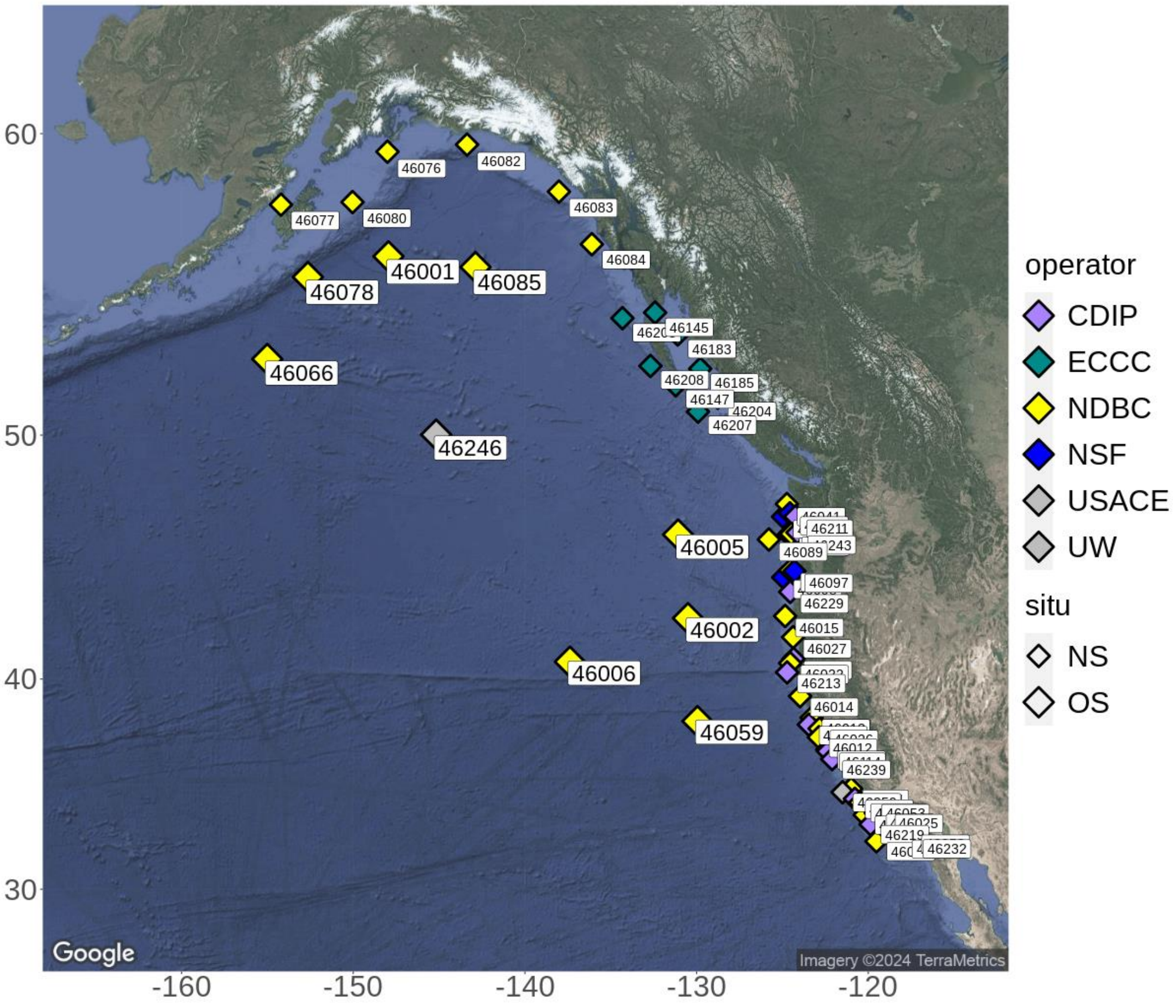
— The measurement errors are uncorrelated with each other (except for representation errors);

Meeting these requirements can be challenging, and interpretation of results from TC is fraught, or impossible, where these are violated.



Study Location

- **Offshore (OS) buoys shown by large diamonds;**
- **Nearshore (NS) buoys shown by small diamonds;**
- **Colour denotes operating agency;**



Data characteristics

— **Differences between tandem data are small!**

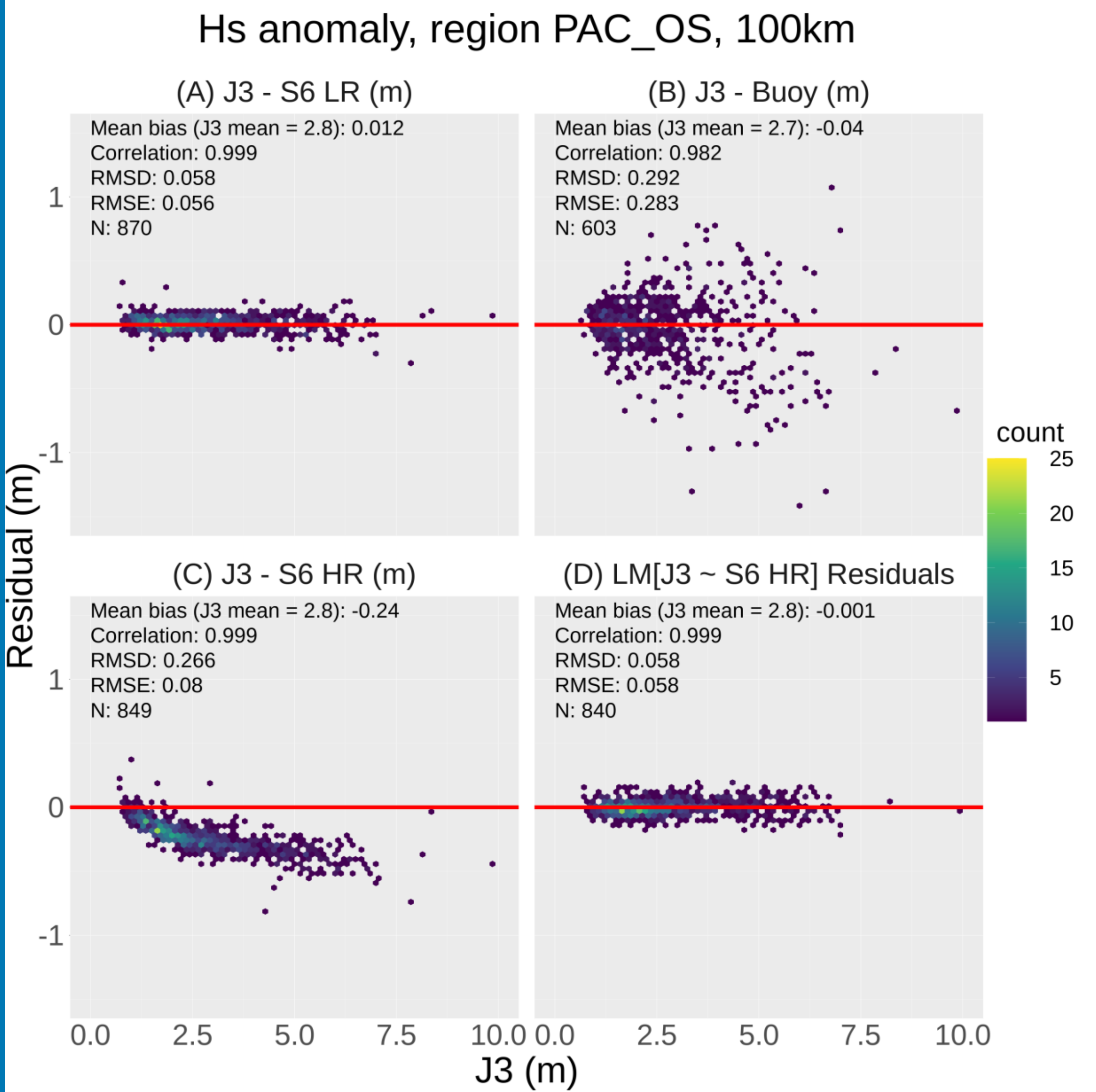
— **(0.01 m mean bias; 0.06 m RMSD), compared with moored buoys and models (0.03 m mean bias; ~0.25 m RMSD)**

— **HR bias correction via linear modelling:**

> **LR vs HR has high correlation**

> **Model of the form:**

$$\widehat{\mathbf{H}_{\mathbf{sJ3}}} \sim a\mathbf{H}_{\mathbf{sS6}}{}^{\frac{1}{2}} + b\mathbf{H}_{\mathbf{sS6}} + c$$



Triple Collocation Analysis

Assumptions

— Several assumptions required (Vogelzang & Stoffelen):

> Data must be linearly related;

> Errors must be uncorrelated;

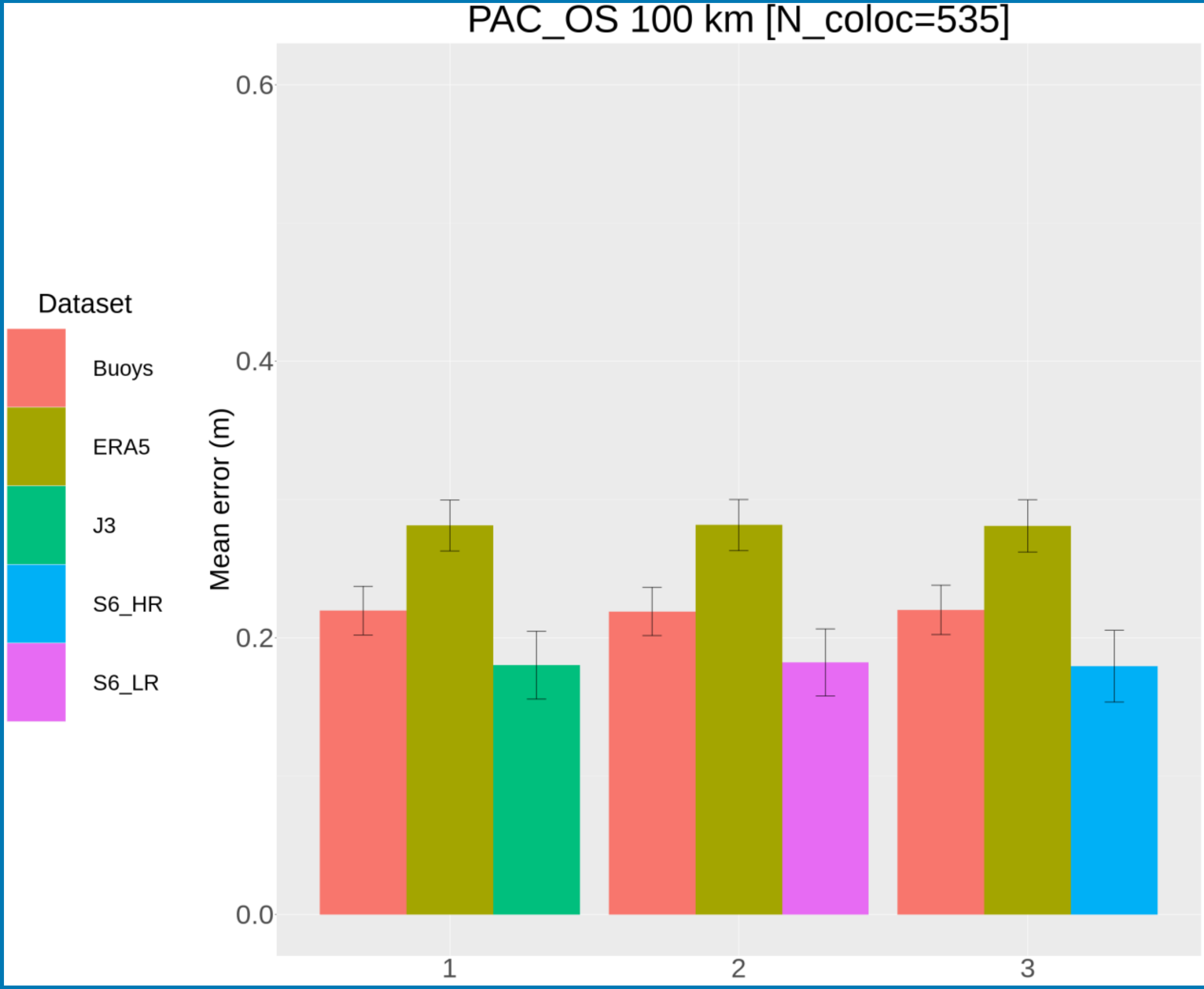
> Error variance must be constant throughout the value range.

Results

— Altimeters all the same!

— Buoy uncertainty and ERA5 uncertainty affected by collocation error.

Is this the right "tool for the job"?



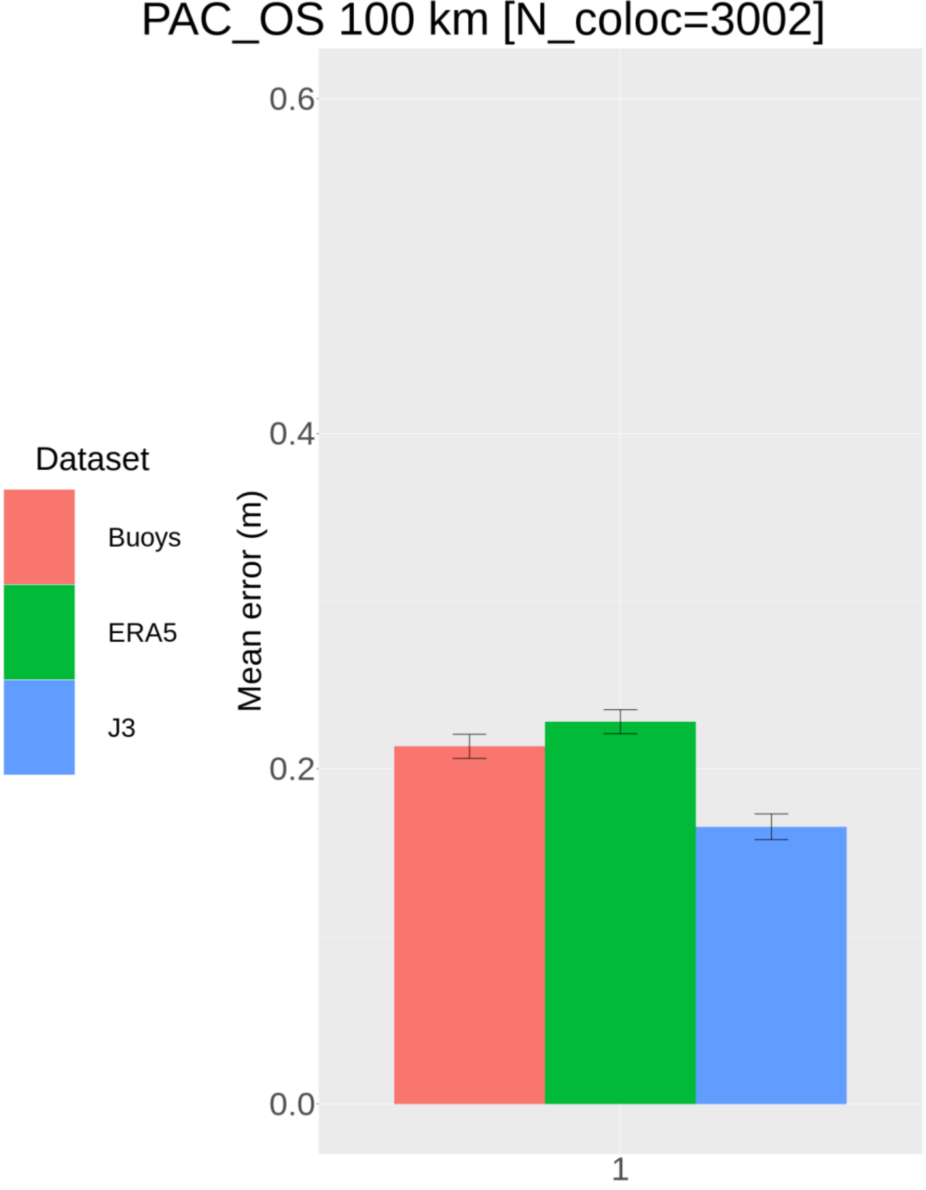
Triple Collocation Analysis

Jason-3 (2017-2021)

— **Uncertainty reduction due to increased sampling:**

> 535 (tandem phase)

> 3002 (Jason-3)



TCA Summary

Results suggest that S6-MF HR shows small improvement in TCA error...

- **May be more evident closer to the coast?**

Sampling uncertainty is always going to be challenging for tandem experiments

- **What options are there to increase collocations / sampling?**
- **Can we dispense with using buoys entirely?**

Can we perform analysis closer to the coast?

- **Requires a more refined collocation methodology...**

Can we better understand the sources of error that contribute to TCA?

- **Probably requires a site-by-site analysis.**

Can we say that the consistency of the Jason-3 and Sentinel-6 data motivates a more refined approach?

Assess buoy reliability by Hs mean bias

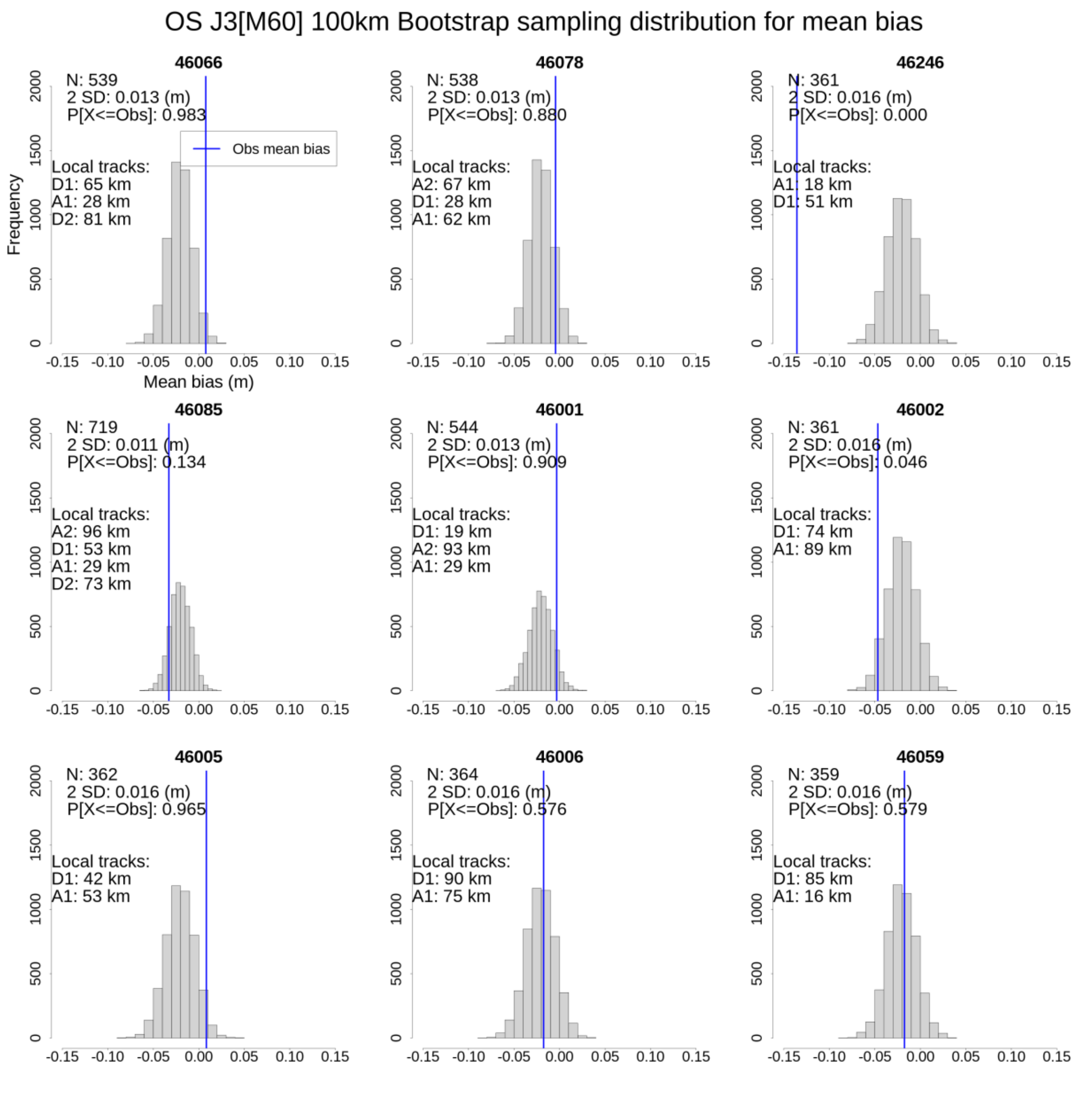
Jason-3 (2017-2021)

— 100 km sampling;

— Notice that 46246 is an extreme outlier;

— Notice that sampling distribution is offset from zero;

— Notice other buoys are statistically questionable (4002, 46085).



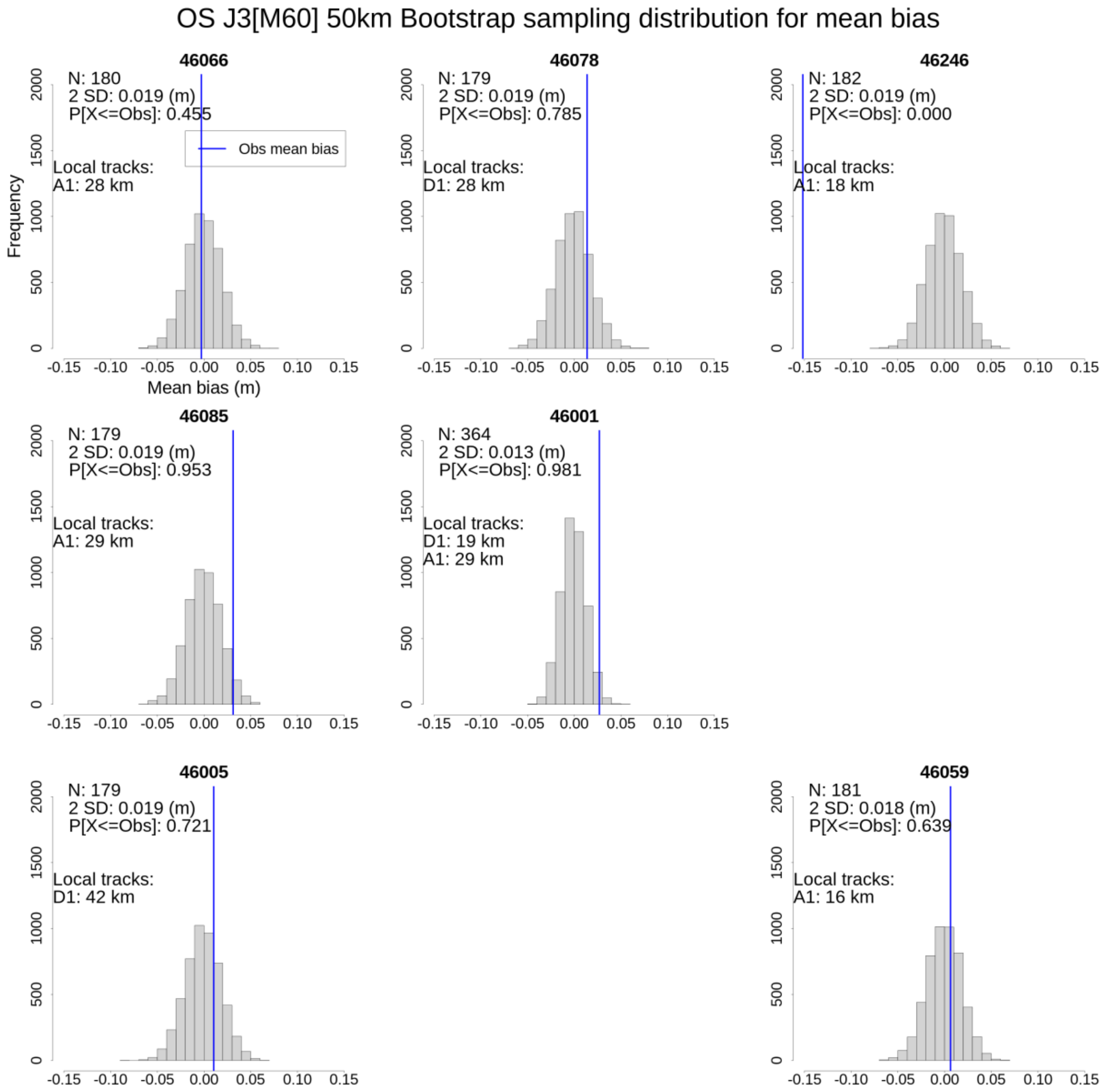
Assess buoy reliability by Hs mean bias

Jason-3 (2017-2021)

— 50 km sampling;

— Notice that 46246 is *still* an extreme outlier;

— Notice that sampling distribution is close to zero;



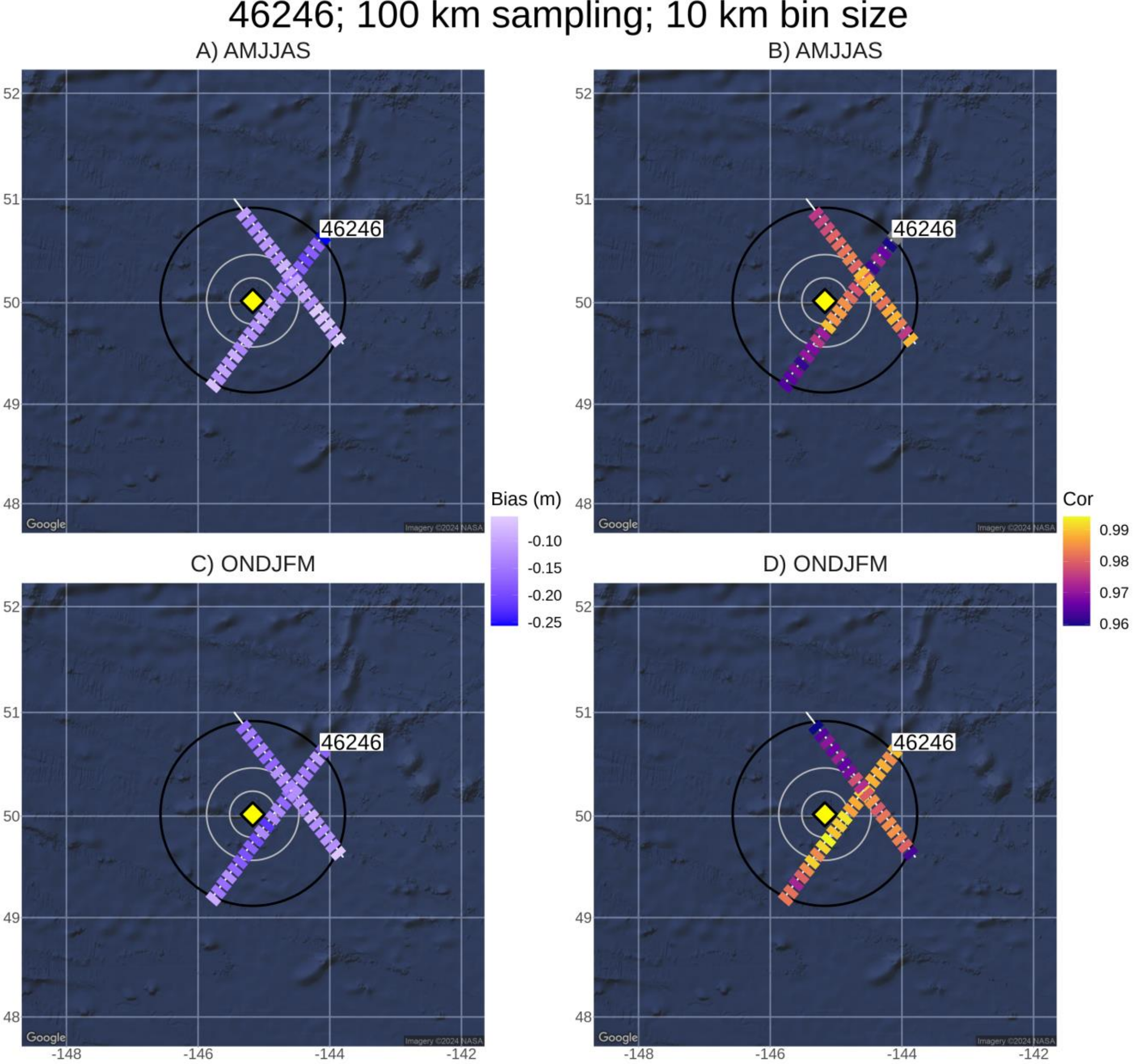
Assess buoy reliability by spatial analysis 46246

Jason-3 (2017-2021)

— Along-track statistics 10 km bin size;

— Notice that mean bias is not a function of local sea state gradient;

— Notice that correlation behaves as expected;



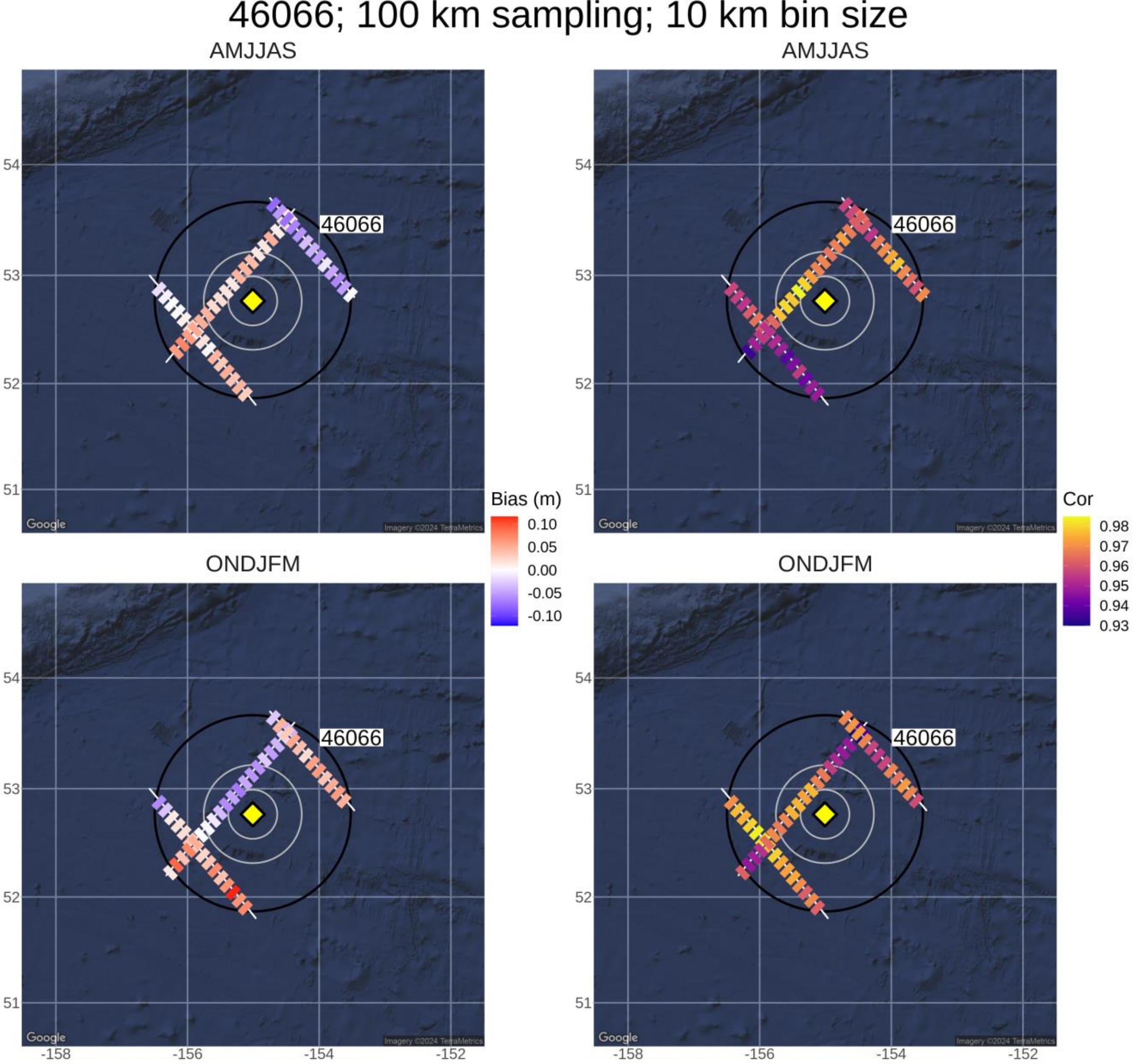
Assess buoy reliability by spatial analysis 46246

Jason-3 (2017-2021)

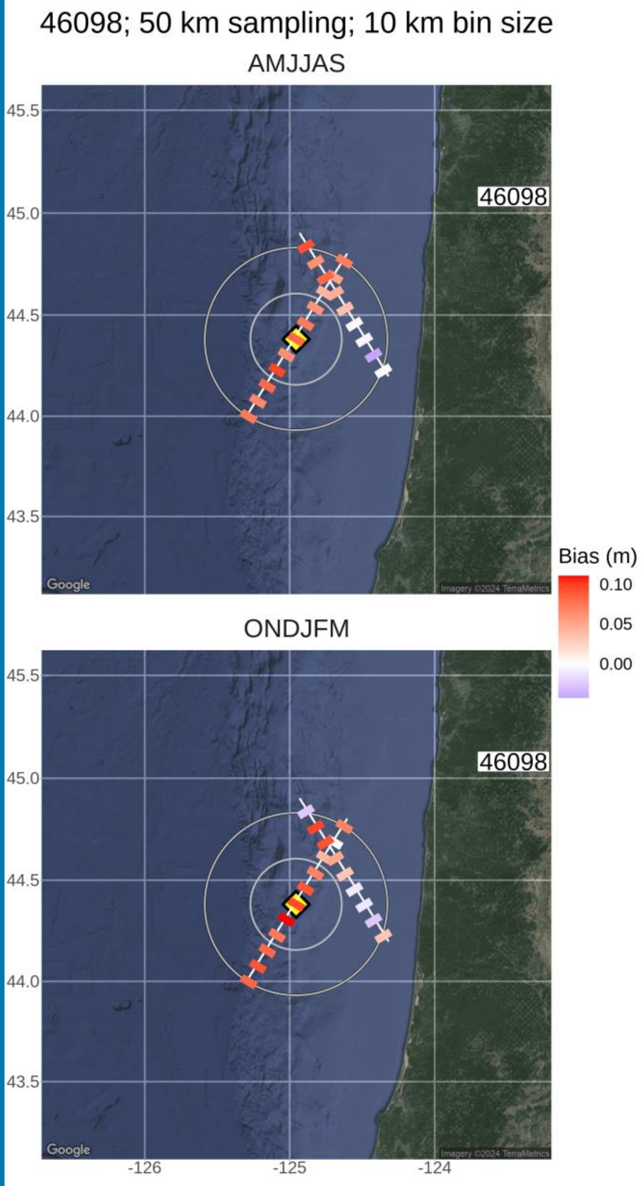
— Along-track statistics 10 km bin size;

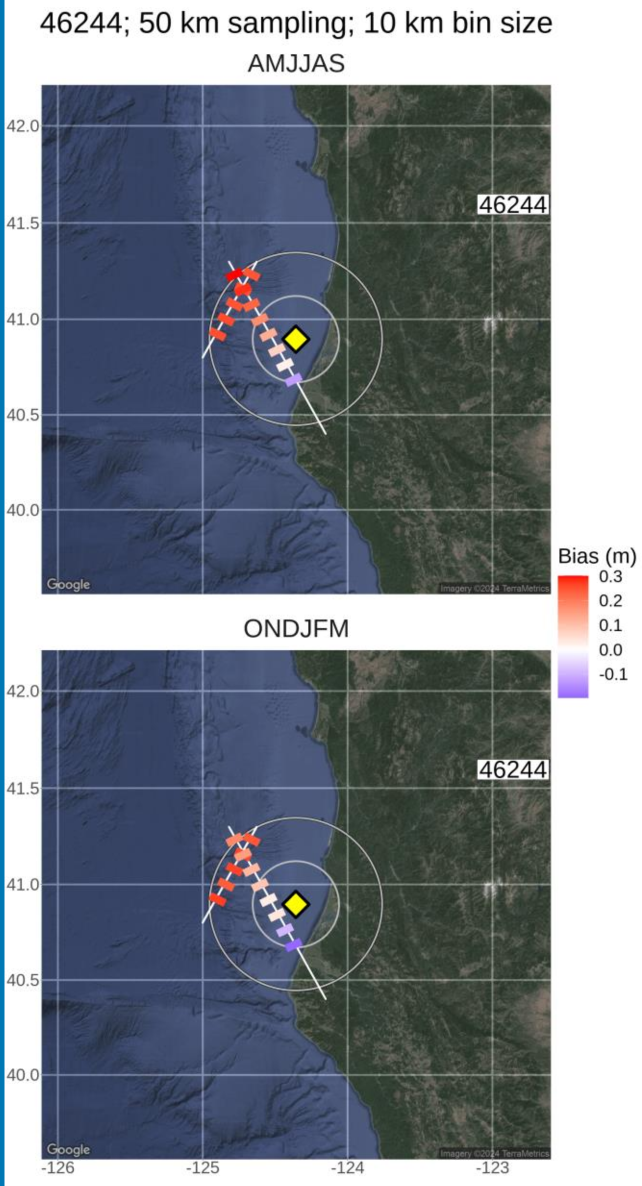
— Notice that mean bias changes sign with season!;

— Correlation behaves approximately as expected;



Assess buoy reliability by spatial analysis
46098 (left)
46244 (right)





Project Summary: Publications

Paper #1: **Remote Sensing**

Title:

Uncertainties in sea state observations from satellite altimeters and buoys during the Jason-3/Sentinel-6 MF Tandem Experiment

Key points:

1. In the north east Pacific, on scales of 10 - 100 km, we find that discrepancies between J3 and S6-MF LR collocated Hs are small compared to differences with moored buoys. Stability of the long term record appears to be maintained.

2. S6-MF HR data is found to be affected by a strong sea state dependent bias, that can be explained robustly through regression modelling based on wave height.

3. Making use of detailed along-track altimetry information, we evaluate local spatial gradients in sea state variability and show how this introduces uncertainty into collocation methodology.

4. We identify specific buoys that exhibit the largest uncertainties w.r.t. altimeters, and show how these are likely linked to both buoy-specific issues and local sea state gradients.

5. We make recommendations about the use of specific buoys as reference data, which has important consequences for validation of observations and the study of sea state variability.

Status:

Submitted

MDPI

Article

Uncertainties in sea state observations from buoys and satellite altimeters during the Jason-3/Sentinel-6 MF Tandem Experiment

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Abstract: Commissioning of the Copernicus Sentinel-6 Michael Freilich (S6-MF) mission involved a unique 15-month Tandem Experiment during which S6-MF flew approximately 30 seconds behind Jason-3 (J3) on the same ground tracks, resulting in an unprecedented global dataset of quasi-simultaneous collocated altimeter sea state measurements in "Low-Resolution" (LR) mode and synthetic aperture radar "High Resolution" (HR) mode. Given the imperative for S6-MF to reliably maintain the long term altimetry record, and it's enormous value to our understanding of long term sea state variability, consistency and uncertainties associated with measurements of sea state during the tandem phase are examined. In a region of the north east Pacific, well observed by moored buoys, both in deep water and closer to the coast, we find that discrepancies (~0.01 m) in mean Hs and root-mean-square deviation (~0.06 m) between J3 and S6-MF LR collocated observations are small compared to differences with the moored buoys. S6-MF HR data is found to be affected by a strong sea state dependent bias, that can be explained robustly through regression modelling based on wave height. However, we go on to show how uncertainties introduced by collocation with buoys are affected by altimeter sampling over local spatial gradients in sea state variability. This has important consequences for methods of evaluating sea state uncertainty, that exploit a large collection of independent buoys, such as the widely used "triple collocation" method. Sea state gradients are shown to bias results both in deep water, and, importantly, closer to the coast. For mean bias in Hs between buoys and altimeters, we go on to show that some buoys that are commonly used for intercomparison, are statistical outliers, due to both collocation methodology and platform operation bias, and we make recommendations as to which buoys in this area should generally be excluded. S6-JTEX tandem phase data are found to be highly consistent across all analyses, both offshore and close to the coast.

Keywords: Sea state; satellite altimetry; uncertainty; moored buoys; Sentinel-6 Michael Freilich; Tandem experiment; significant wave height; triple collocation

Citation: Timmermans, B. W., C. P. Gommenginger and C. J. Donlon Uncertainties in sea state observations from buoys and satellite altimeters during the Jason-3/Sentinel-6 MF Tandem Experiment. *Remote Sens.* **2022**, *1*, 0. https://doi.org/

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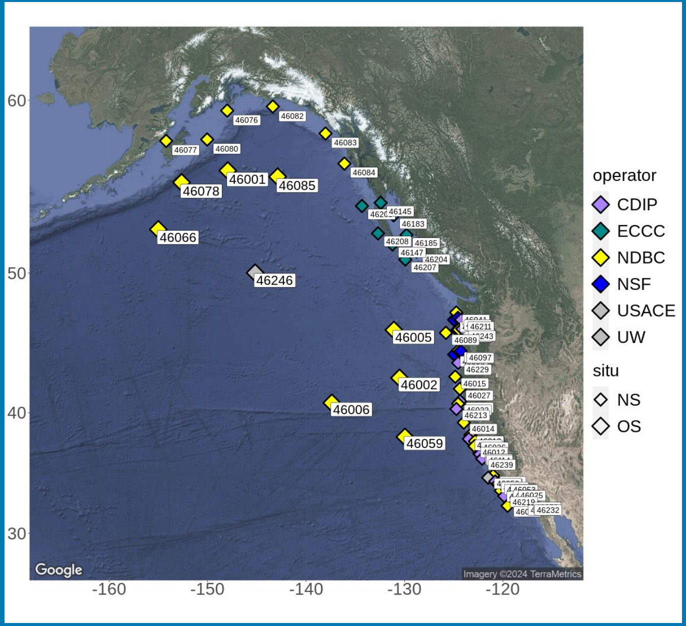
1. Introduction

Sea state observations from satellites are increasing in duration, abundance, variety and applications. The long term continuous altimetry record, is particularly significant in this context, having begun in 1992 and affording us the capability to investigate long term variability on a global scale from indirect observations (refs). The continuity and stability of this record, therefore, is of great importance, and to that end, since the TOPEX/Poseidon mission launched in August 1992 (e.g. Fu et al., 1994) the Jason series of satellites have maintained the same orbit and ensured a consistency of measurement to the present day. A growing abundance of sea state observations from other missions, spanning a variety of platforms with heterogeneity in spatiotemporal coverage, further motivates the continuation and maintenance of a long term high quality reference record. For example, relying heavily on the reference record, the European Space Agency (ESA) Sea State Climate Change Initiative (CCI) has produced Climate Data Records (CDR) of Essential Climate

Project Summary: Publications



Paper #2: **JTech(?)**

Title:

Uncertainties in nearshore sea state observations and collocations of buoys and satellite altimeters during the Jason-3/Sentinel-6 MF Tandem Experiment

Key points:

1. For ~50 sites along the North American Pacific coast, we evaluate local spatial gradients in sea state variability and explain how this introduces uncertainty into collocations with models and moored buoys.

2. We intercompare different sampling methods for altimeter 1 Hz data, to illustrate the impact of inappropriate sampling in nearshore regions, when performing observation intercomparisons.

3. Based on considerations of random error and bias between datasets, we select the most appropriate sampling method and conduct aggregate analysis using an ensemble of ~25 buoys on the full nearshore domain to evaluate the properties of the tandem data.

4. Based upon spectral buoy data, we partition results by sea state, in order to determine whether there exist sensitivities in the altimetry to local sea state conditions.

5. Using statistical methods, we identify buoys that exhibit the largest uncertainties w.r.t. altimeters, and show how these are likely linked to both buoy-specific issues and local sea state gradients.

Status:

Analysis underway, submission mid-2024.

Follow-on studies

Reseach Topic #1: **Global ocean collocation study to evaluate sea state uncertainty for tandem and model / reanalysis data.**

Description:

A direct extension of our triple collocation study, potentially quite “low-hanging fruit”, consisting of a modified collocation analysis based upon a large-scale global analysis of S6-JTEX data. Development of this method was reported during PM5 & 6 but could be progressed due to lack of resources.

The method proposes to obtain the same uncertainty measures as a TC approach but by using only two datasets, thus without the need for moored buoys, and leveraging abundant tandem observations over global oceans to improve statistical robustness. A synthetic "proof of concept" case was examined (PM5 & 6) and appeared fruitful. May be related to the method of Jiang (2023). Removing the limitation of buoys, and use of reanalysis, may provide a better opportunity to examine the sea state dependence of altimeter observations.

Depending on level of funding, an extension to this could involve the use of drifting buoys (e.g. Sofar ocean “Spotter” buoys).

Key objectives:

1. Test methodological approach (validation, statistical robustness, etc);
2. Partition global oceans by dependence / climatology, e.g. by latitude, Southern Ocean etc (good reference literature, e.g. Lobeto et al. 2022);
3. Quantify uncertainties by region using tandem and reanalysis;
4. Assess results w.r.t. sea state dependence (readily available from reanalysis, e.g. ERA5);
[5. Optional, at cost: Compare results against drifting buoys?]

Cost / Timeline:

30k EUR, 12 months (~50 % Phase 1 commitment)

Follow-on studies

Reseach Topic #2: **Uncertainty in wave height measurements due to short timescale sea state variability (wave groups)**

Description:

Short timescale sea state variability is a topic of recent interest, is poorly understood and contributes to uncertainty in sea state observations. Recently, De Carlo et al. (2023) have shown that "wave groups", arising from certain sea state conditions, where spectral spreading occurs, can account for up to ~25% of observed sea state variability over spatial scales of 20 to 100 km. Due to their propagation, wave groups can manifest on timescales of ~30 s to ~few minutes. If signatures of wave groups can be identified in along-track Hs variability, then the 30 s lag in the tandem data may provide a sufficient time for those signatures to vary (or disappear). Therefore, analysis of along-track Hs variability in the concurrent tandem data may detect this phenomenon. This would be an important step in estimating and reducing uncertainty in Hs measurements – potentially applicable to the study already conducted. This investigation could be conducted using both 1 Hz and 20 Hz data, and be applicable to both S6 LR and HR observations.

Key objectives:

1. Use reanalysis wind / wave data and spectral wave data to identify suitable regions (e.g. North Atlantic) and wave events of interest during the tandem phase (e.g. storms);
2. Evaluate and analyse along-track variability for S6 LR/HR data (1 Hz or 20 Hz);
3. Search and identify variations (using statistical clustering or machine learning methods).
4. Assess contribution of Hs variance to overall uncertainty estimates previously established (e.g. though collocations).

Cost / Timeline:

30k EUR, 12 months (~50 % Phase 1 commitment)

References

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

> Jiang, H. (2023) Random, Environmental, and Representativeness Errors in Ocean Remote Sensing Versus In Situ Data: An Example of Wave Heights From Altimeters, *IEEE Transactions on Geoscience and Remote Sensing*, doi:10.1109/TGRS.2023.3285348

> Lobeto et al. (2022) The effect of climate change on wind-wave directional spectra. *Global and Planetary Change 213*

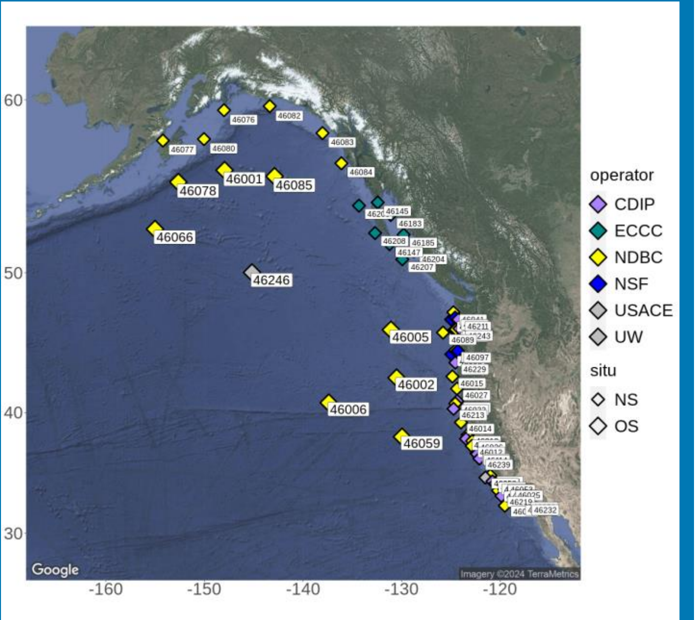
> De Carlo et al. (2023) Wave groups and small scale variability of wave heights observed by altimeters. *JGR Oceans 128* doi:10.1029/2023JC019740

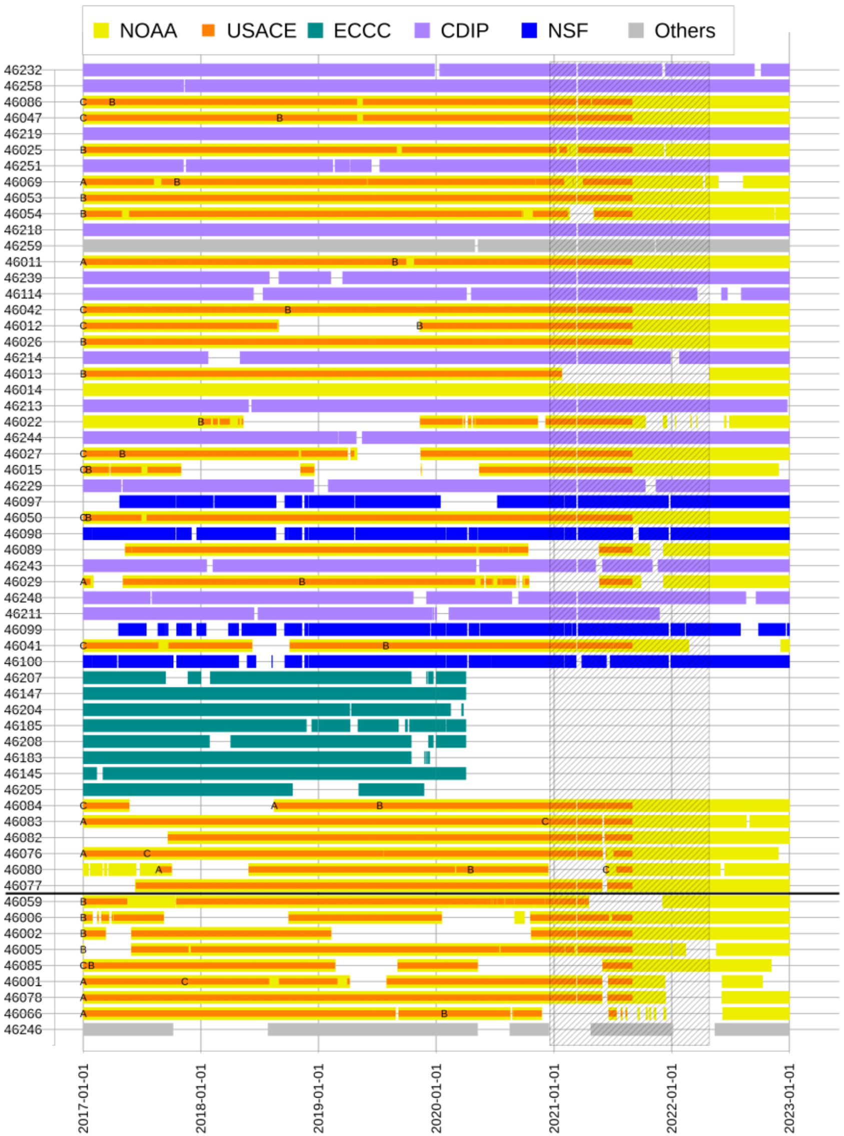
Validation updates: *In situ* data

Variability across platforms

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

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

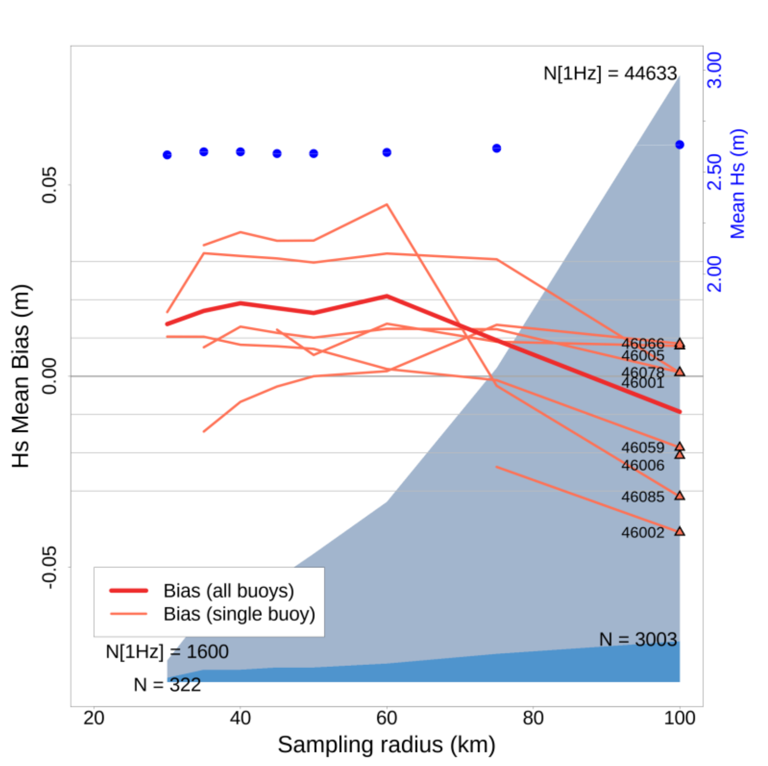


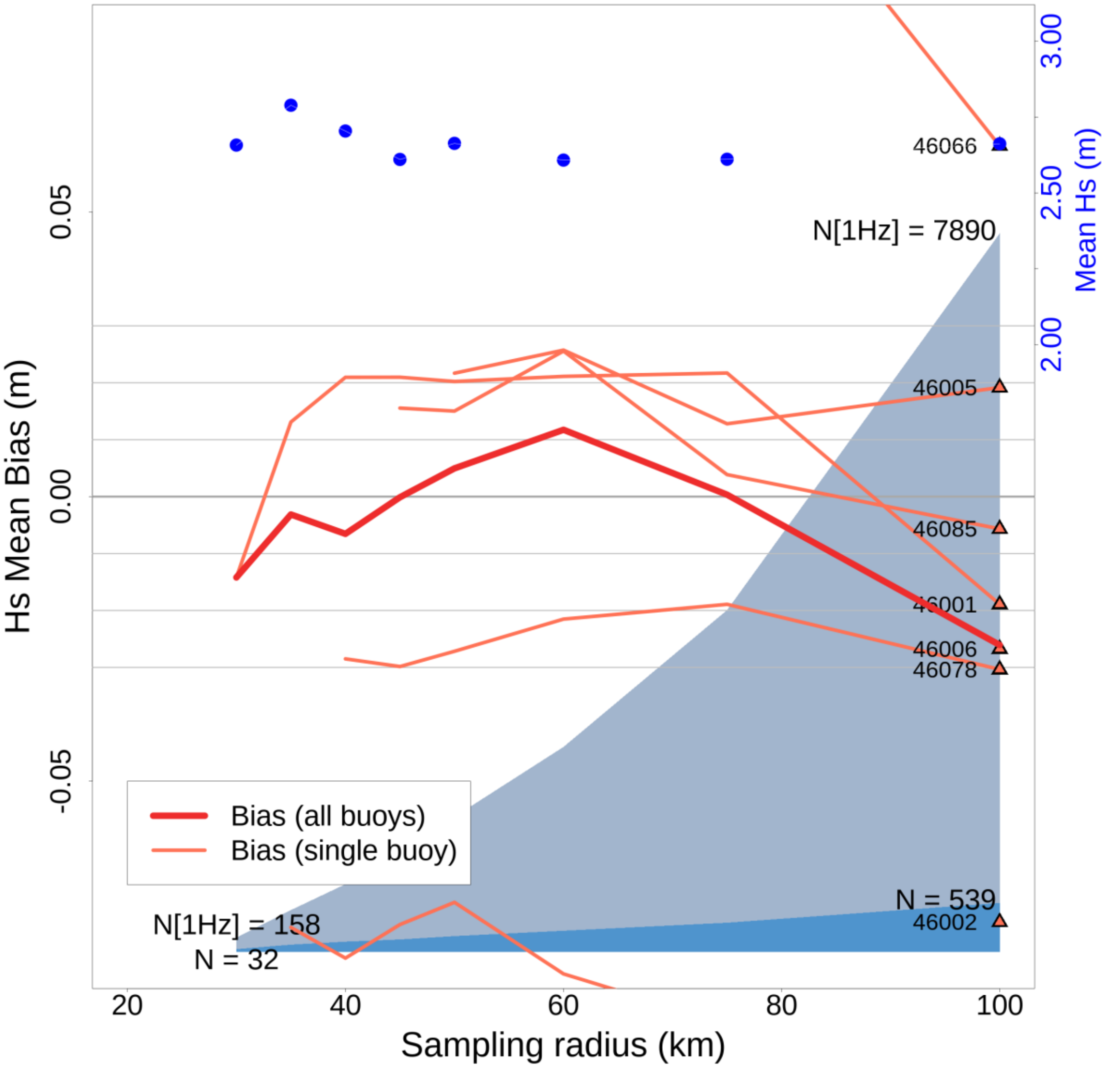


Detailed look at Hs mean bias with sampling radius.

Jason-3 (tandem, right)

Jason-3 (2017-2021, left)

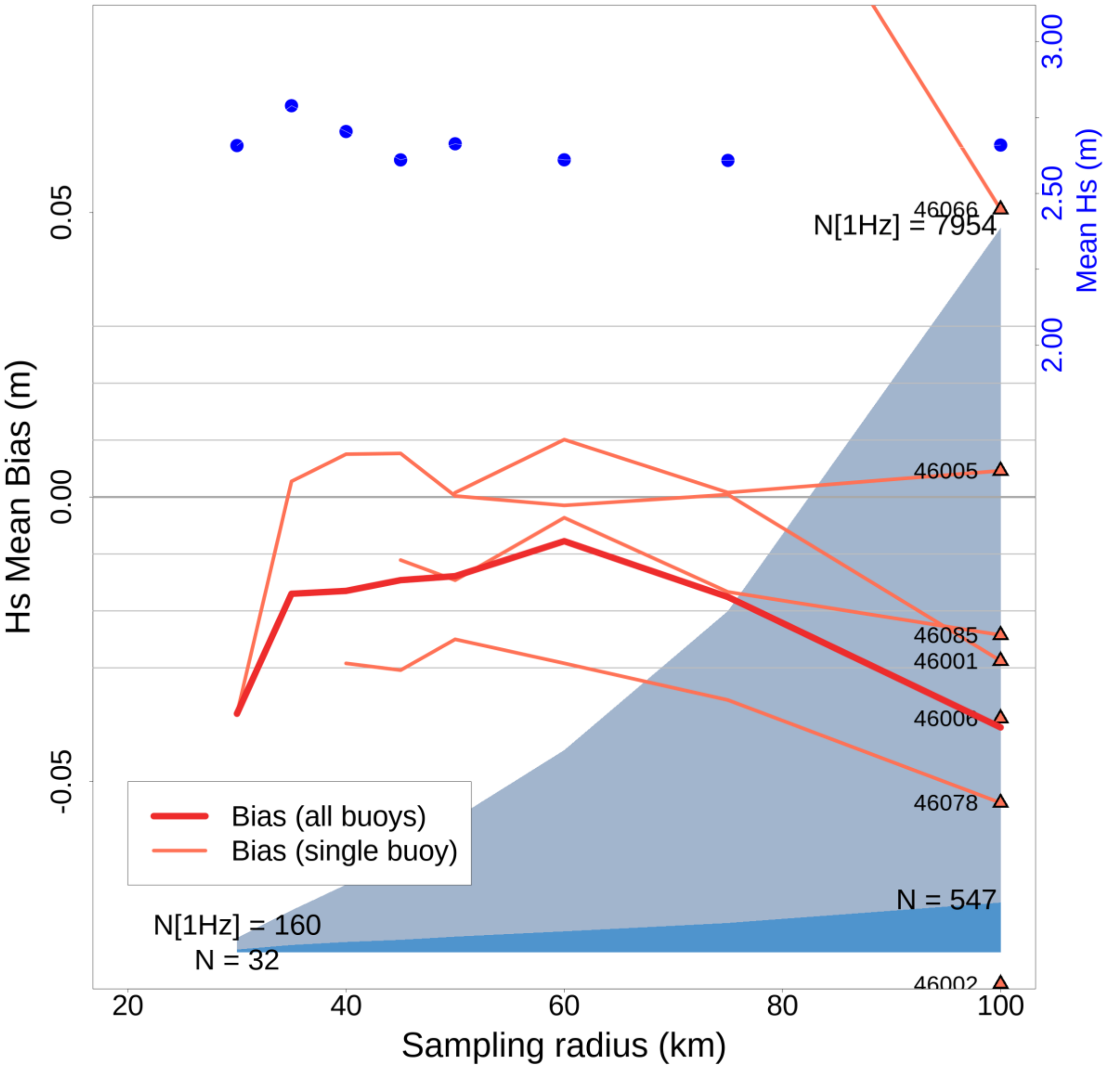




Detailed look at Hs mean bias with sampling radius.

S6-MF LR

— **Slightly lower bias than Jason-3.**



Detailed look at Hs mean bias with sampling radius.

S6-MF HR

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