Sea state uncertainty from a triple collocation analysis of observations during the Sentinel-6 Michael Freilich – Jason-3 tandem phase

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1 – Introduction

The growing satellite record of sea state observations is becoming increasingly important for climate change research, to improve ocean and weather forecasts and to inform climate change mitigation and investment strategies. The Copernicus Sentinel-6 Michael Freilich (S6-MF) mission was launched in November 2020 by the European Space Agency to succeed Jason-3 (J3) as the long term satellite altimetry reference mission. S6-MF commissioning involved a unique 12-month Tandem Experiment during which S6-MF flew approximately 30 seconds behind J3 on the same ground tracks, resulting in an unprecedented global dataset of quasi-simultaneous collocated altimeter sea state measurements in Low-Resolution (LRM) and Synthetic Aperture Radar (SAR) modes.

In this work, this unique dataset is examined to evaluate uncertainties in altimeter significant wave height (Hs) observations from the two missions in different operating modes and different sea state conditions. S6-MF and J3 data are compared with *in situ* buoy measurements and reanalysis data using, amongst other methods, triple collocation (TC) analysis. Initial results indicate that, at locations offshore and nearshore in the Pacific Ocean [Fig 2.1], J3 and S6-MF Low-Resolution Hs are almost identical, with near-zero bias (<0.002), low RMS difference (0.04) and very high correlation (>0.999). Comparing S6-MF SAR with J3 LRM and buoys confirms the positive sea-state dependent bias in SAR Hs. High correlation in the Tandem Data appears to violate the error independence assumption for the TC method and motivates a broader examination utilising a variety of datasets where error independence can be argued. Nonetheless, the abundant collocated altimetry data permits highly detailed analyses of uncertainty in concurrent missions together with other climate quality data sea state datasets.

2 – In situ locations

Data from the Jason-3 Sentinel-6 MF Tandem Phase Experiment were collocated with in-situ observations from NDBC (https://www.ndbc.noaa.gov) moored buoys both nearshore and offshore. Initially, collocations have been limited to 63 sites in the North Pacific. Locations are shown in Figure 2.1. Buoys marked in yellow and blue are considered to be "offshore" (OS) and "nearshore" (NS, within approx. 100 km from the shore) respectively. Separation of sites based upon coastal proximity provides a means of separating increased variability due to coastal effects. Sea state variability is anticipated to be subject to strong spatial gradients at some coastal locations. In this work, a collocation radius of between 100 and 150 km is used to maximise satellite sampling, however, smaller sampling radius can reduce error variance where strong sea state spatial gradients are present (see Figure 4.1).

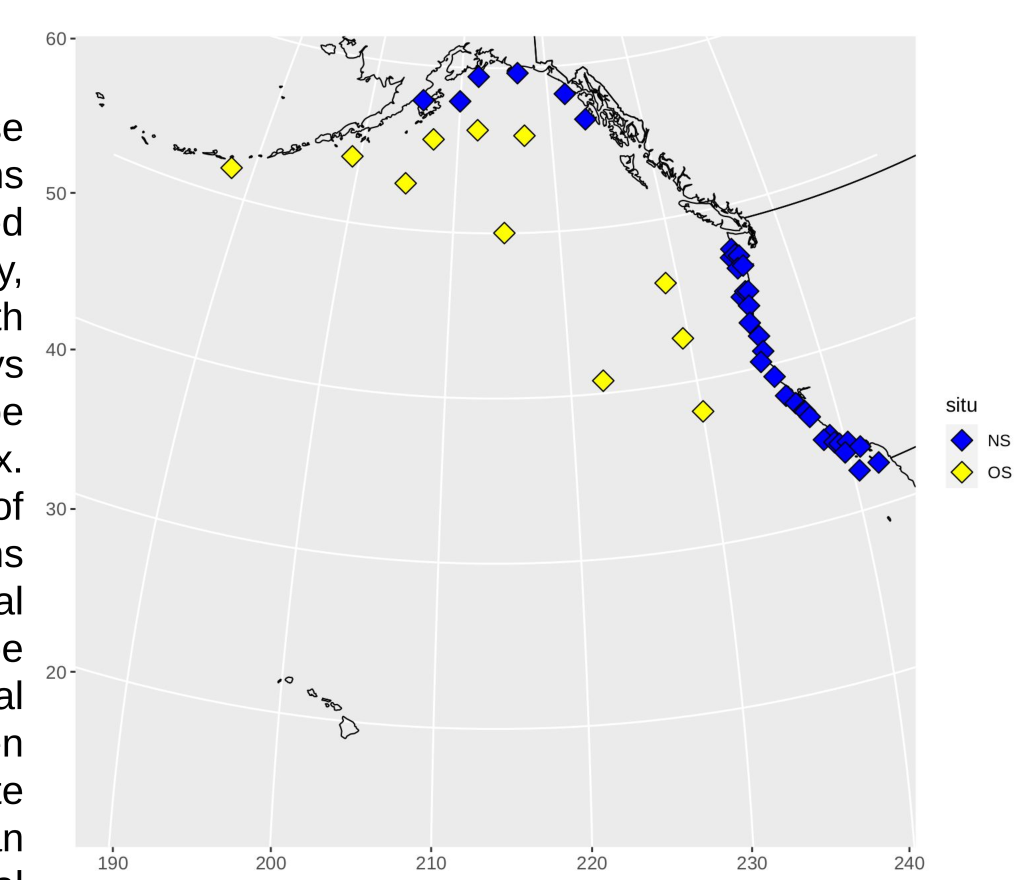
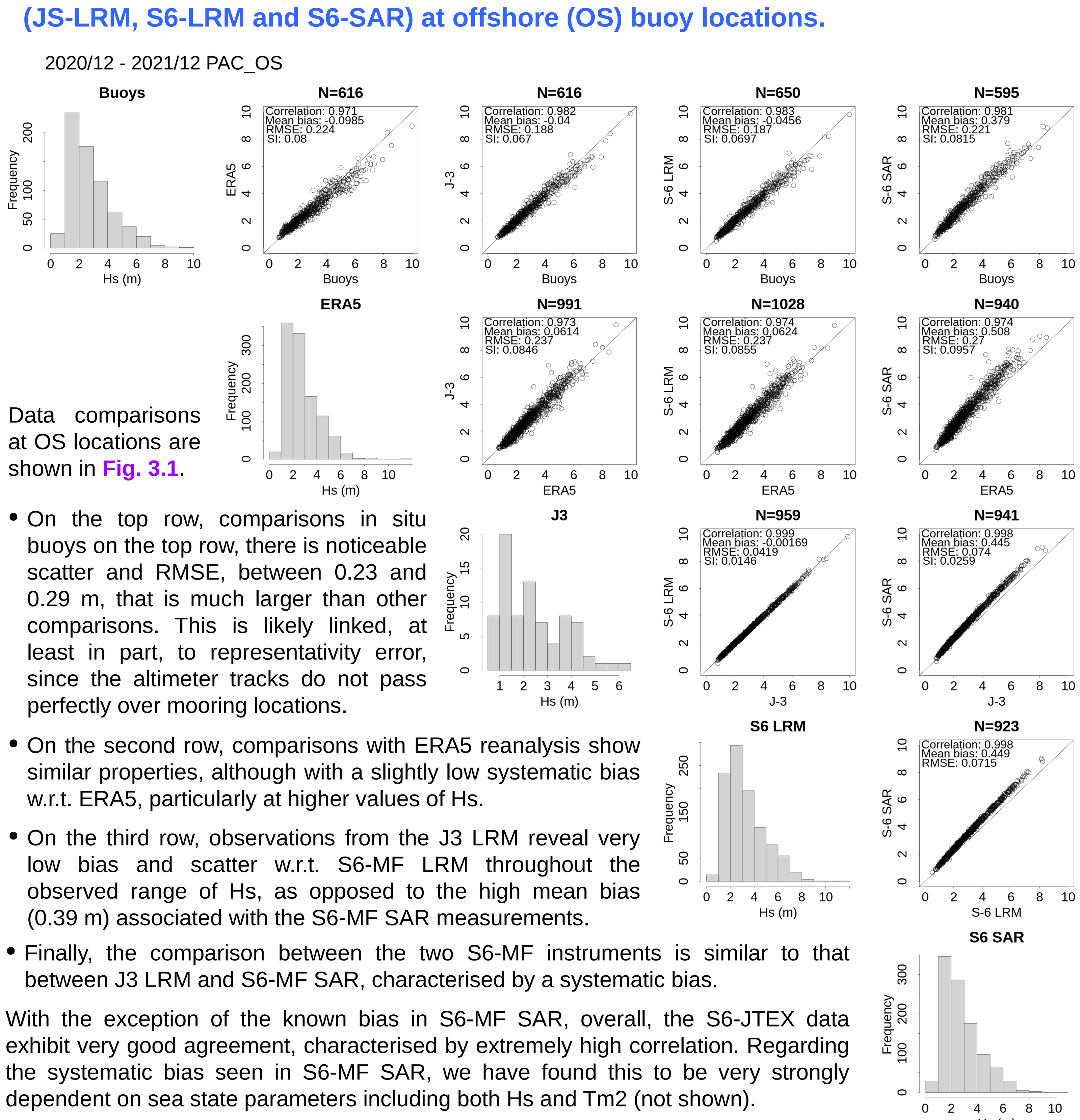


Figure 2.1: Map of NDBC data buoy locations.

3a – Dataset properties offshore

Properties of the collocated S6-JTEX data, together with moored buoys in the Pacific Ocean [Figure 2.1], are shown using scatterplot projections for pairwise comparison.

Figure 3.1: Pairwise scatterplot projections of collocations between S6-JTEX data (JS-LRM, S6-LRM and S6-SAR) at offshore (OS) buoy locations.



Data comparisons at OS locations are shown in Fig. 3.1.

- On the top row, comparisons in situ buoys on the top row, there is noticeable scatter and RMSE, between 0.23 and 0.29 m, that is much larger than other comparisons. This is likely linked, at least in part, to representativity error, since the altimeter tracks do not pass perfectly over mooring locations.
- On the second row, comparisons with ERA5 reanalysis show similar properties, although with a slightly low systematic bias w.r.t. ERA5, particularly at higher values of Hs.
- On the third row, observations from the J3 LRM reveal very low bias and scatter w.r.t. S6-MF LRM throughout the observed range of Hs, as opposed to the high mean bias (0.39 m) associated with the S6-MF SAR measurements.
- Finally, the comparison between the two S6-MF instruments is similar to that between J3 LRM and S6-MF SAR, characterised by a systematic bias.

With the exception of the known bias in S6-MF SAR, overall, the S6-JTEX data exhibit very good agreement, characterised by extremely high correlation. Regarding the systematic bias seen in S6-MF SAR, we have found this to be very strongly dependent on sea state parameters including both Hs and Tm2 (not shown).

3b Data properties nearshore

Scatterplot projections for observations of Hs in nearshore locations (see Fig. 2.1), similar to those seen in Figure 3.1, can be seen in Figure 3.2. We note that, in spite of the possibility of more spatially varied sea states owing to coastal morphology, the comparisons are very similar to those at offshore locations. In particular, the LRM measurements from J3 and S6-MF remain extremely highly correlated with low scatter and almost zero bias. Observations from S6-MF SAR continue to show positive systematic bias. Note that larger numbers of moored buoys nearshore give rise to more abundant collocations, although overall this is lower than might be expected due to rejection of lower quality data. Addition of sites in the Atlantic may increase collocations further.

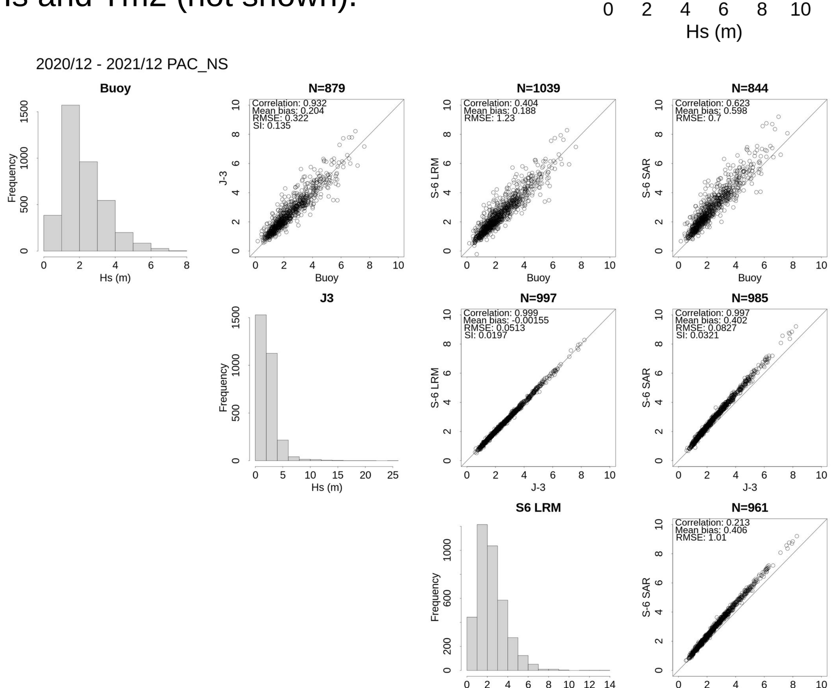


Figure 3.2: Pairwise scatterplot projections as per Fig. 3.1 at nearshore locations, with the exception of ERA5.

4a – Triple collocation method

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. Numerous examples of its application to geophysical variables such as wind speed and wave height can be found in the literature. A detailed exposition of the method is provided by Vogelzang and Stoffelen (2012) [1] who, in particular, identify several key assumptions:

- Linear calibration is sufficient over the whole range of measurement values;
- The reference measurement values are unbiased and calibrated;
- The random measurement errors have constant variance over the whole range of calibrated measurement values;
- The measurement errors are uncorrelated with each other (except for representation errors);
- The random measurement errors are uncorrelated with the geophysical signal.

Meeting these requirements can be challenging, and interpretation of results from TC is fraught where these are violated. In the context of sea state, independence of errors is often argued where triplets of data comprise observations from; 1) moored buoys; 2) satellite altimetry; 3) reanalysis or numerical hindcast. Here, we perform TC analyses using collocated data triplets formed from moored buoys, ERA5 reanalysis and successive members of the S6-JTEX altimetry data.

4b – Initial results from TC analyses

Sensitivity to altimetry sampling area

- Considerable variability in estimated error contribution can be seen with change in altimetry sampling radius around the buoy [Figure 4.1].
- A reduced sampling area results in a reduction in error contribution from all altimetry datasets.
- Note, however, that the number of collocations is substantially reduced because altimeter tracks passing >100 km from any buoy are discarded.
- Changes in error contribution therefore result from the substantial changes in collocation dataset, hampering interpretation.
- While the error attributable to S6-MF SAR appears to be substantially larger than the LRM acquisition, TC analysis is impacted by the known positive systematic bias associated with the SAR processing.

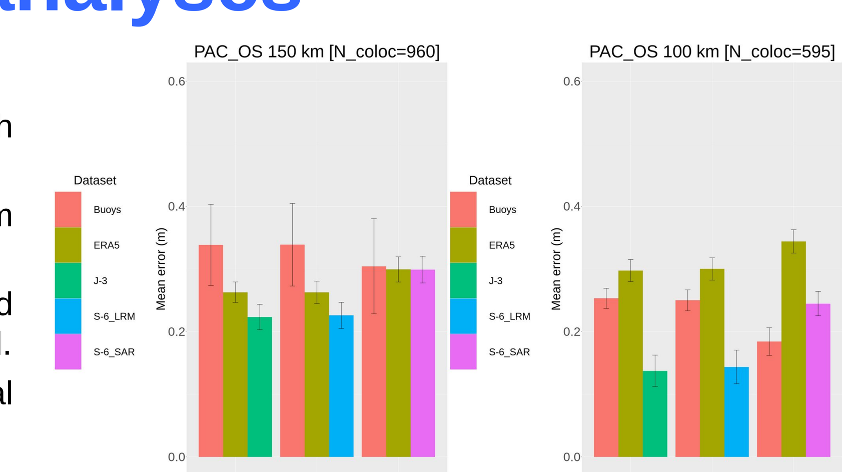


Figure 4.1: Sensitivity of estimated error variance to altimetry sampling. (left) 150 km, (right) 100 km.

Errors in "offshore" vs "nearshore" locations

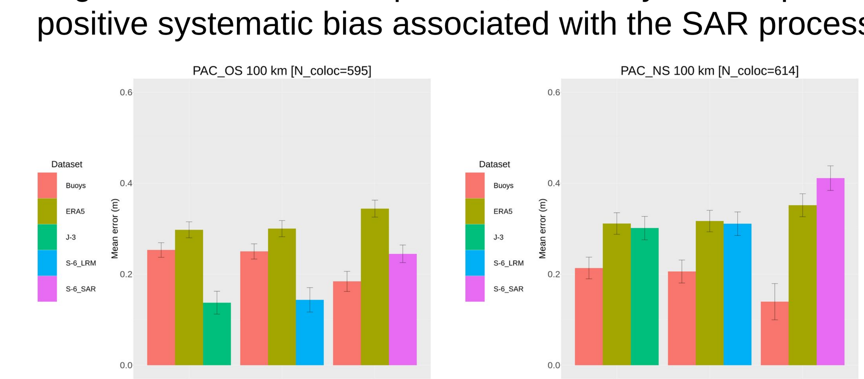


Figure 4.2: Change in estimated error variance (left) offshore vs (right) nearshore for 100 km sampling radius.

- Results are compared (left) offshore and (right) nearshore in Figure 4.2. (See also Figure 2.1).
- Tandem altimetry data all show increased error contribution nearshore, while moored buoys tend to be more accurate.
- Near the coast it is likely that the 100 km sampling radius captures stronger sea state spatial gradients and poorer quality altimetry data.

Sensitivity of estimated error to sea state

- Using observations of average wave period (Tm2) from moored buoys, observations of Hs corresponding to Tm2 > 8 s, and Tm2 < 8 s, that represent more closely long period swell waves and windsea respectively, were used to subsample the collocation data [Fig. 4.3].
- Results reveal that uncertainty increases for all datasets under more developed sea states, although the subsampling process leaves only a limited number (N=141) of collocations, considerably reducing statistical robustness of the results.

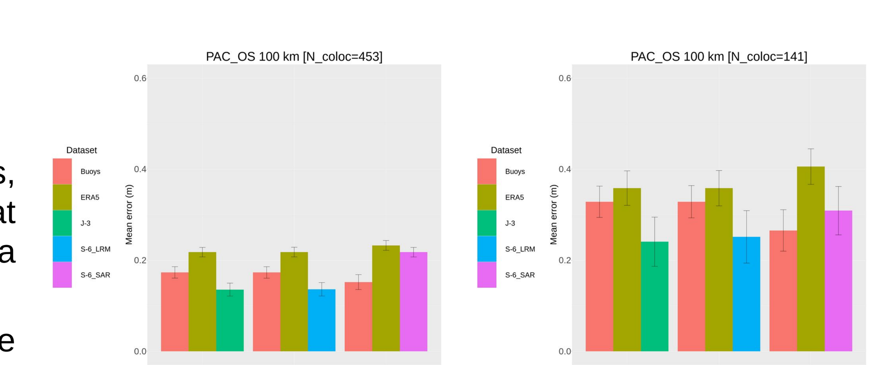
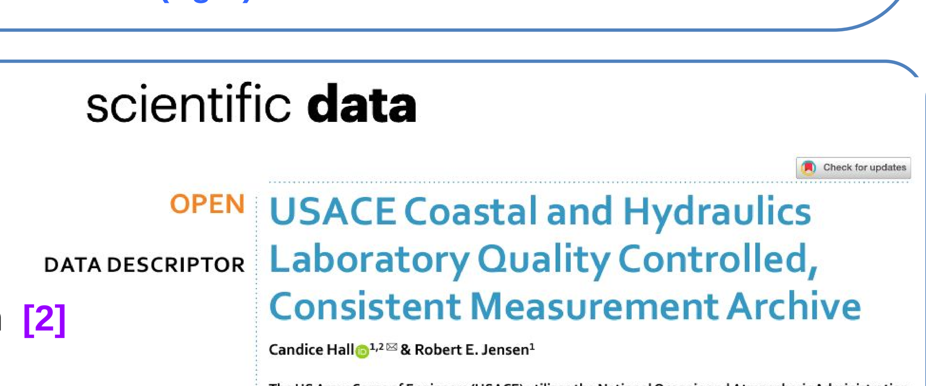


Figure 4.3: Estimated error variance for (left) Tm2 < 8 s and (right) Tm2 > 8 s.

5 – Future Work

Dataset development

- Collocations over entire tandem phase (~18 months)
- Improved quality control for NDBC buoys (recent publication [2] and data release from USACE [Figure 5.1])
- Consistent sampling scale across datasets (interpolation of ERA5)
- Additional datasets: Drifting buoys from Sofar Ocean [Figure 5.2]


scientific data

OPEN

DATA DESCRIPTOR

USACE Coastal and Hydraulics Laboratory Quality Controlled, Consistent Measurement Archive

Candice Hall & Robert E. Jensen

Figure 5.1

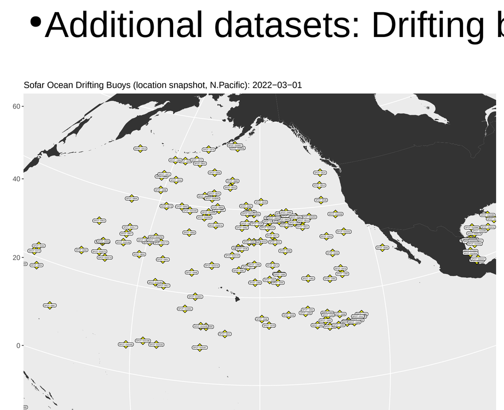


Figure 5.2 Snapshot (2022) of Pacific "Spotter" buoys

Sea state identification and subsampling

Our analysis to date has included a preliminary assessment of the sensitivity of estimated errors to sea state, achieved using observations of average wave period (Tm2) from moored buoys [Figs 2.1 & 4.3]. Observations of Hs corresponding to Tm2 > 8 s represent more closely long period swell waves. However, this approximate approach does not isolate swell explicitly. Alternative, more effective methods, could include use of the recently completed processing of Sentinel-1 SAR wave mode by DLR [3] under the ESA Sea State Climate Change Initiative (CCI) [4]. This dataset includes global observations of swell wave height and can, for example, be used in conjunction with ERA5 reanalysis to accurately identify the presence of swell during the S6-JTEX.

Acknowledgements

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