Assessment of Sentinel-3A and Sentinel-3B sea state products during the tandem phase using in situ and reanalysis data

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Contribution to Sentinel-3 Tandem for Climate

Version 1.1
Submitted by Chris Banks, 15 May 2020

National Oceanography Centre

Contents

List of Figures

List of Tables

1. Introduction

The Copernicus Sentinel-3B (S3B) satellite was launched on 25th April 2018 to join the identical Sentinel-3A satellite (S3A) that had been in orbit since 16th February 2016. During the commissioning phase of S3B the two satellites were placed in a tandem orbit with S3B approximately 30 seconds ahead of S3A from 7th June 2018 to 16th October 2018.

This paper presents the findings of an investigation into the performance of significant wave height (SWH) and wind speed (WSP) as measured by the SRAL (SAR altimeter) instruments onboard both S3A and S3B. The study consists of validation assessments against two data sets one based on wind/wave buoy data (Part 1) and the other based on numerical wave model output from ERA5 (Part 2). Full details of the data used are given below in 2.

Throughout the tandem phase, S3A SRAL operated in Synthetic Aperture Radar (SAR) mode, from which altimeter data in Pseudo-Low Resolution Mode (PLRM) were also available. S3B SRAL operated in several different modes to test performance in different settings (e.g. Open Loop, Close Loop) as well as SAR/LRM. S3B SRAL operated in SAR mode for most of the tandem phase except for 1 cycle towards the beginning of the tandem phase, when S3B SRAL but was switched to Low Resolution Mode (LRM) from 14th June 2018 until 11th July 2018. This provides a unique opportunity to compare directly the sea state measured using LRM with that measured from SAR/PLRM from two instruments.

2. Data

2.1. Sentinel-3 SRAL Data

The Sentinel 3 SRAL altimeter satellite data were obtained from the dedicated platform for the Sentinel-3 Tandem for Climate project (S3TC; https://web-s3tc.dias.groupcls.com/). Early investigations indicated that the data were impacted by an offset in wind speed between S3A and S3B that was identified as being related to a known but uncorrected 0.5 dB bias in the backscatter (sigma0) for S3B. A correction to S3B wind speed data was implemented by NOC required to be made to the wind speed data using (Abdalla, 2012; T. Moreau, Pers. Comm.). The origin of this S3B sigma0 bias has since been addressed and removed from more recent reprocessings of the marine products and further details can be found at https://sentinel.esa.int/documents/247904/2753172/Sentinel-3-Product-Notice-STM-Level-2-Land.

In these analyses, only data from dates during outside the tandem period were excluded considered and only the 1 Hz records were used. Although data at 20 Hz were available, the spatial and temporal integration averaging used in these validation study negate the need for such high frequency data.

Several quality control filters were applied to the S3 data based on existing quality flags and the number of 20 Hz records used to produce the 1 Hz average (see Table 1 for full details). The QC filters were applied separately to the SAR/LRM data and the PLRM data because the latter presents its own set of QC variables.

The geographical extent of the study area (for all data not just satellite data) is limited to only those locations: between 77.5˚N and 77.5˚S; and at least 20 km from the coast.

Table 1 List of 1 Hz quality control fields and values

Description	Field for SAR/LRM	Field for PLRM	Criterion
SWH quality control flag	swh_ocean_qual_01_ku	swh_ocean_qual_01_plrm_ku	0/good
Range quality control flag	range_ocean_qual_01_ku	range_ocean_qual_01_plrm_ku	0/good
Sigma0 quality control flag	sig0_ocean_qual_01_ku	sig0_ocean_qual_01_plrm_ku	0/good
Number of valid points used to compute sigma0	sig0_ocean_numval_01_ku	sig0_ocean_numval_01_plrm_ku	> 10
Number of valid points used to compute SWH	swh_ocean_numval_01_ku	swh_ocean_numval_01_plrm_ku	> 10
Number of valid points used to compute range	range_ocean_numval_01_ku	range_ocean_numval_01_plrm_ku	> 10

2.2. Wave/Wind Buoy Data

Wave/wind buoy data were obtained from the US National Data Buoy Center online archive, downloaded from http://www.ndbc.noaa.gov. For buoys where the temporal sampling was higher than hourly, the data were averaged (median) to provide hourly values. Buoys provide estimates of wind speed and, in some cases, Significant Wave Height (SWH). Only buoy data corresponding to the S3 tandem period were included in the analyses reported here.

2.3. ERA5

Numerical wave model output from the ECMWF ERA5 reanalysis high resolution realisation (HRES) was obtained from the European Centre for Medium range Weather Forecasting online archive (apps.ecmwf.int/data-catalogues/era5). ERA5 is a global long-term climate reanalysis product that combines model data with a wide range of in situ and satellite observations. SWH and wind speed output fields were used for this activity. The HRES data have a temporal resolution of 1 hour and a spatial resolution of 0.28125˚ for the atmospheric data (i.e. wind speed) and 0.36˚ for the wave data (i.e. SWH). The ERA5 data used for this activity was a version held internally at NOC which has been re-gridded to resolutions of 0.25˚ and 0.5˚ for wind speed and SWH respectively.

3. Methodology

3.1. Part 1 – Buoy Collocations

Sentinel-3 SRAL data were collocated with data from 137 buoys for SWH and 329 buoys for wind speed (as identified by Station ID) located around the US coast. For each buoy and every time period, any Sentinel-3 data within 20 km and 30 minutes were identified. For each satellite and each mode (i.e. LRM, SAR and PLRM) the satellite data were averaged (median) to return corresponding values for SWH, sigma0 and wind speed.

In addition, the closest values of ERA5 SWH and WSP were also identified to provide additional information and support triple collocation analyses.

3.2. Part 2 – ERA5 Collocations

Buoy matchup datasets cover only small regions around the US coast. In order to extend the validation over wider geographical region, ERA5 wind speed and SWH data have been incorporated into the study. For each ERA5 grid point and timestep during the tandem phase, the Sentinel-3 data within 20 km and 30 minutes have been averaged (median unless otherwise stated). As with the buoy matchup, all data (either ERA5 or 1 Hz satellite measurement) within 20 km of the coast have been ignored. Each geographic location was assigned to an ocean basin in order to undertake regional studies as shown in Figure 1.

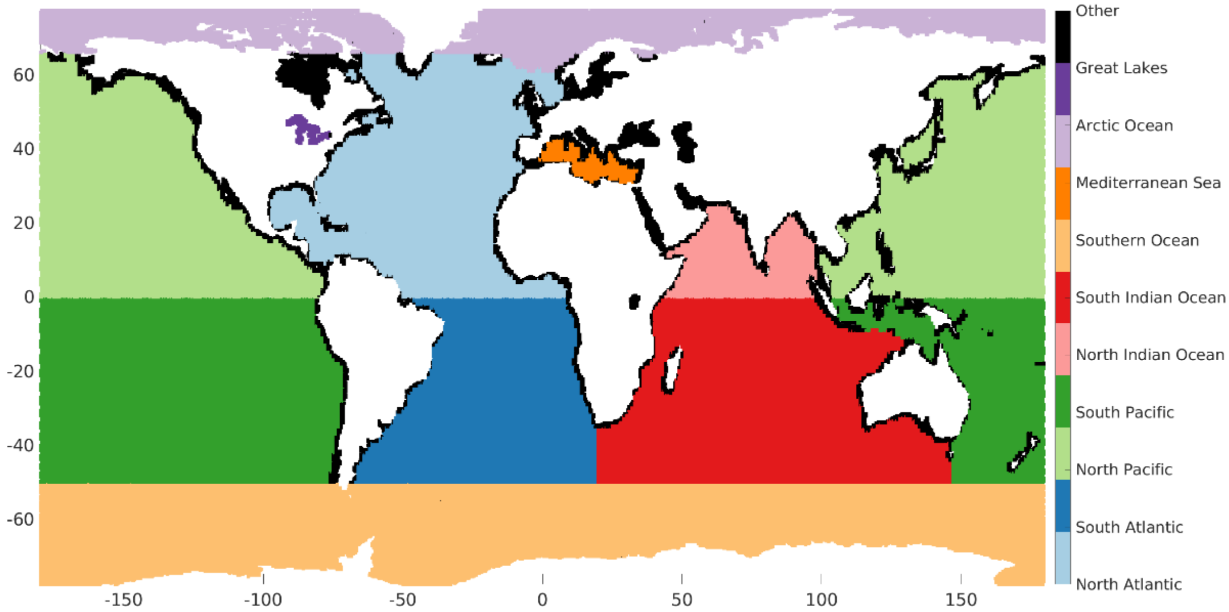

Figure 1 Part 2 study regions. The Other category includes those locations within 100 km of the coast except at high latitudes as these were defined based only on latitude.

3.3. Triple Collocation

Triple collocation is a powerful statistical method used extensively in geophysical sciences to obtain independent estimates of errors in different datasets without a-priori assumptions about data quality (i.e. no "gold-standard" assumption). A number of formulations exist in the literature. Here, triple collocations are performed as per the method proposed by (Tokmakian & Challenor, 1999; O'Carroll *et al.*, 2008). The triple collocation method uses three independent datasets to allow the estimation of the standard deviation of error (i.e. a proxy for noise and not to be confused with the standard error) in each dataset to be determined. The errors on the three datasets, σ_1, σ_2 and σ_3 are estimated as follows (for full derivations the reader is referred to the aforementioned papers):

$$\sigma_1 = \sqrt{\frac{V_{12} + V_{31} - V_{23}}{2}} \qquad (1)$$

$$\sigma_2 = \sqrt{\frac{V_{23} + V_{12} - V_{31}}{2}} \qquad (2)$$

$$\sigma_3 = \sqrt{\frac{V_{31} + V_{23} - V_{122}}{2}} \qquad (3)$$

Where σ_1, σ_2, and σ_3 are the estimated standard deviation of error in the first, second and third datasets. V_{ij} represents the variances of the differences between the pair of observation datasets i and j.

The triple collocation analyses used only data from the North Atlantic basin. Two additional quality control steps are necessary prior to triple collocation. First, data were filtered to remove any outliers greater than three standard deviations from the mean. Second, any bias between the datasets was removed by subtracting the difference in medians relative to the first dataset (ERA5 or Buoys). Both large outliers and biases between datasets have been previously shown to prevent a reliable triple collocation analysis.

For Part 1 of our analysis, the triple collocation approach is applied to the data triplet [Buoys, S3A, S3B] in each instrument mode (i.e. SAR, PLRM, and LRM). Note that $S3B_{LRM}$ was compared with $S3A_{PLRM}$ as there is no LRM on S3A. In Part 2, triple collocation was also explored using the data triplet [ERA5, S3A, S3B] in each instrument mode, which allows a much greater volume of data, the number of collocations with buoys being typically much more limited.

4. Results

4.1. Part 1: Assessment against Buoys

The relationships amongst the various measures of SWH and wind speed in the matchup dataset between S3A, S3B, buoys and ERA5 are shown in Figure 2 as an array of scatterplots. The distribution of SWH and wind speed for each dataset are also presented as histograms along the diagonal of Figure 2. The range of values of SWH and wind speed shown in Figure 2 are [0 4] m and [0 10] ms^{-1} respectively. Higher values were measured but are sparse and are consequently not shown, although the regression lines are based on all data. Figure 3 shows the same results as in Figure 2 after removing low sea state observations (where SWH < 1m or wind speed < 1 ms^{-1}, from buoy, ERA5 or satellite).

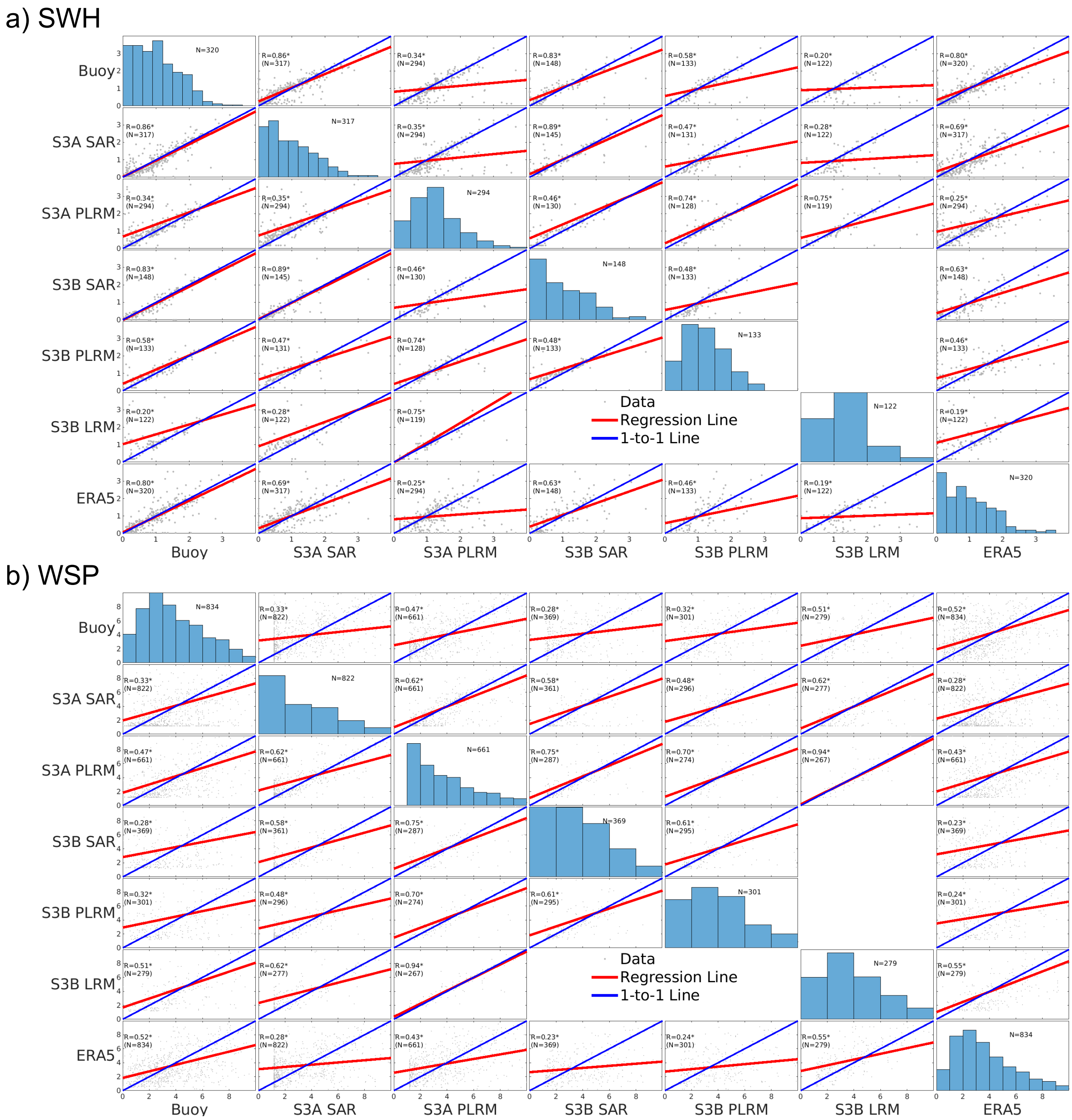

Figure 2 Buoy match-up results for a) Significant Wave Height (SWH) and b) Wind speed (WSP) for Sentinel-3 and ERA5. Labels identify variables plotted on the x-axis and y-axis. Histograms on diagonal relate to the variable identified on x-axis. Scatterplots show data as grey dots, the least-square fit line in red and the one-to-one line in blue. Each scatterplot includes the Pearson correlation coefficient (R; those that are significant at the 0.05 are marked by *) and the number of data pairs (N).

a) SWH

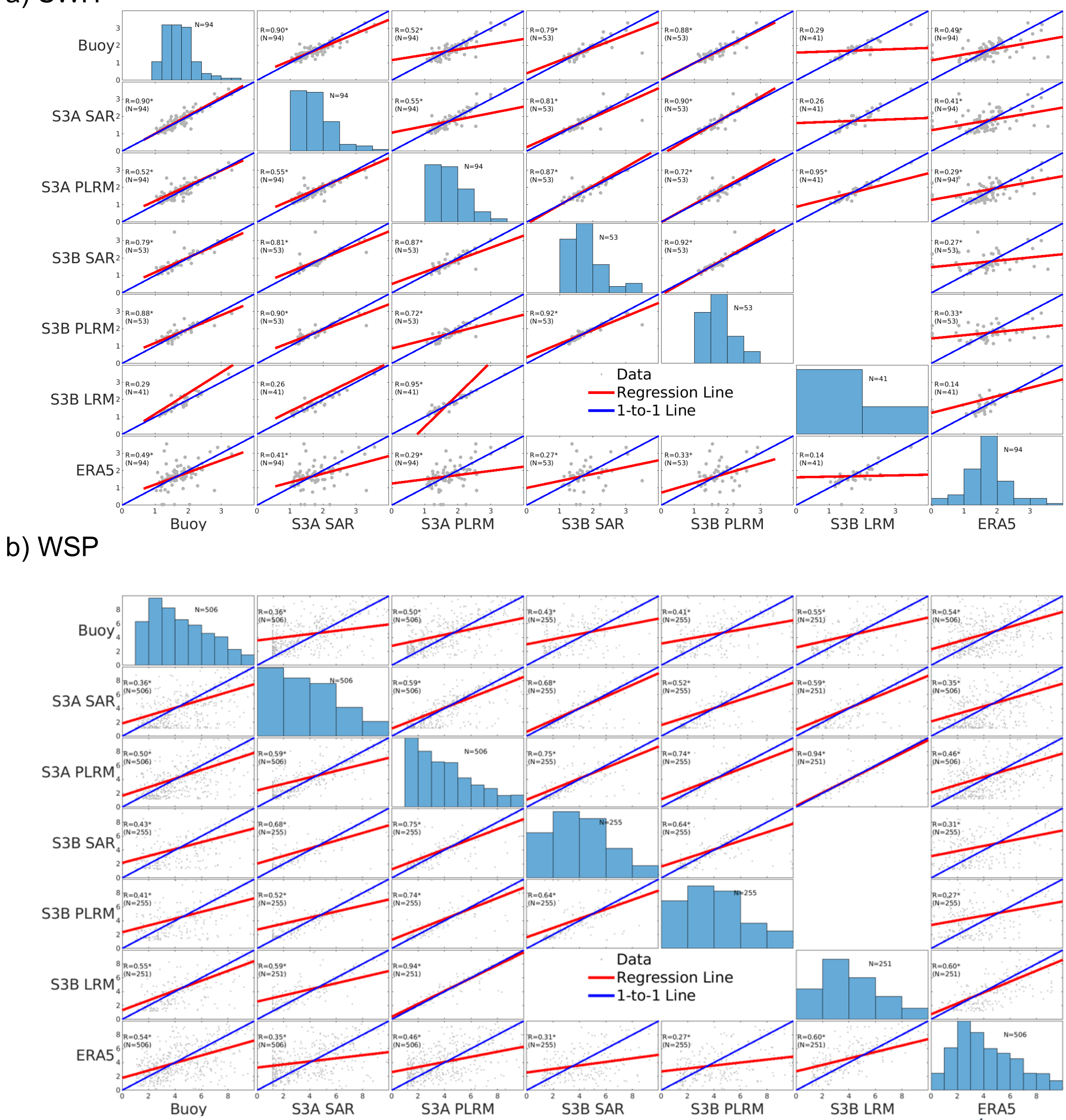

Figure 3 Same as Figure 2 but only including data with SWH>1 m and WSP>1ms^{-1}.

4.1.1. SWH

A total of 320 buoy collocations were made with SWH data from both S3A and S3B. Boxplot summaries of SWH data with and without SWH<1 m are provided in Figure 4. In addition, the mean value plus three times the standard deviation are also shown as this filtering of data is used later in the triple collocation (§3.3). It is clear from Figure 4 that the matchup data from S3B LRM are significantly more noisy (even after filtering out of data below 1 m, the magnitude of mean plus 3 SDs is much higher than the other measurements), a reflection of the significantly smaller number of data matchups for S3B LRM.

The correlation coefficients between all pairs of SWH were positive and significant at the 0.05 level. The highest correlations are those between: S3A and S3B in SAR mode (0.86); followed by the buoy values with S3A SAR (0.86) and S3B SAR (0.83); and then buoy matched with ERA5 (0.80).

The lowest correlations (but also the lowest number of data pairs) are those for when S3B was in LRM (0.19 with ERA5 and 0.20 with buoys) except for a relatively high correlation with S3A in PLRM (0.75).

For both ERA5 and buoys, the ranking of correlations with satellite data are always S3A SAR, S3B SAR, S3B PLRM, S3A PLRM and S3B LRM in decreasing order.

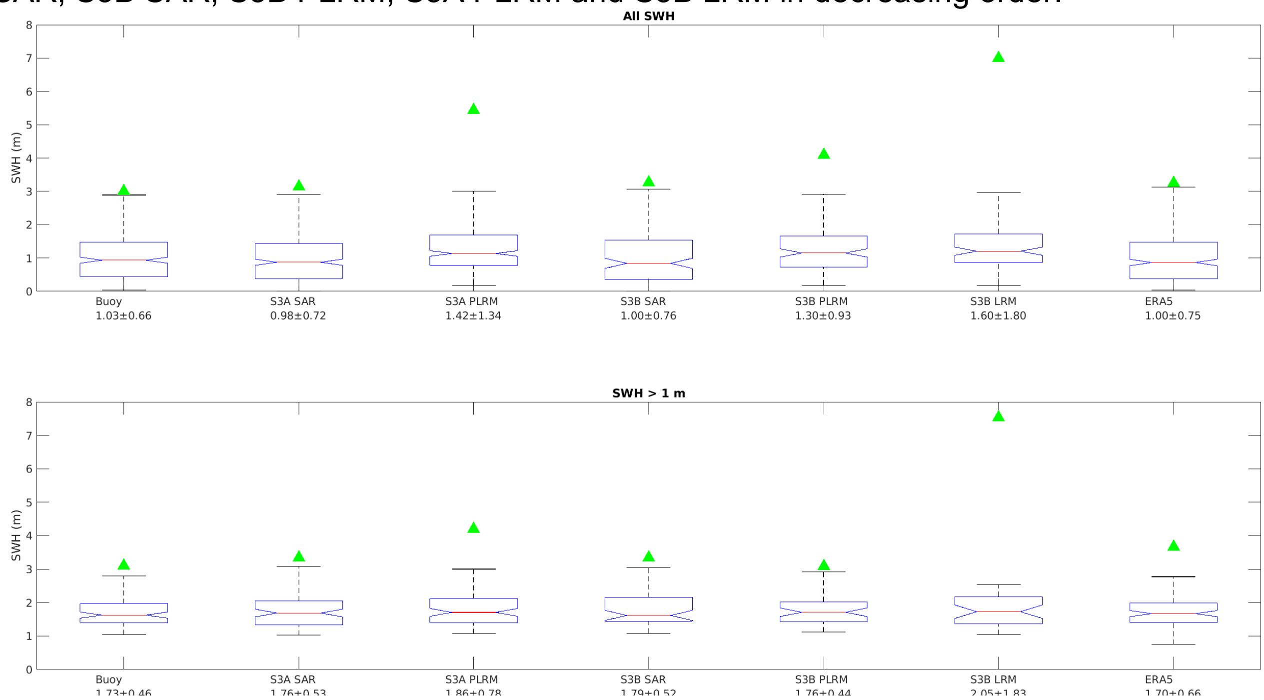

Figure 4 Boxplot of significant wave height (SWH). Top is for all data and bottom shows only where SWH> 1 m. Red line/notch in box shows median, top and bottom of the box indicate the 75th and 25th percentiles. Whiskers indicate maximum/minimum values not considered outliers[1]. Green triangle shows mean plus 3 standard deviations (used later in triple collocation section). Numbers underneath x-labels are mean ± standard deviation.

4.1.2. Wind Speed

Collocation between satellite and buoys produced significantly more matchups for wind speed (N=834) compared to SWH, as there are more buoys measuring wind speed than wind speed and SWH. Boxplot summaries for wind speed with and without values less than 1 ms^{-1} are provided in Figure 5. For wind speed, Figure 5 suggests that the matchup data for S3A SAR is the noisiest dataset.

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[1] Considered outliers if > $q_3 + 1.5 \times (q_3 - q_1)$ or < $q_1 - 1.5 \times (q_3 - q_1)$, where q_1 and q_3 are the 25th and 75th percentiles of the sample data, respectively.

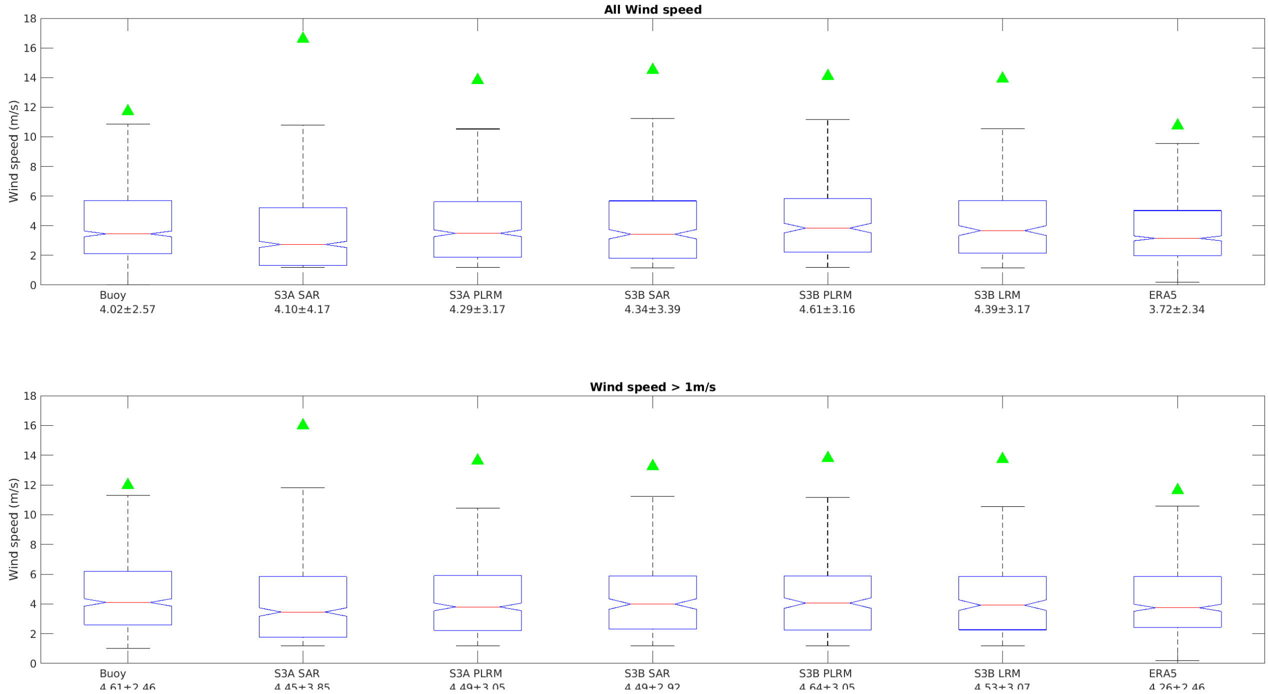


Figure 5 Boxplot of wind speed. Top is for all data and bottom shows only where Wind speed> 1 ms^{-1}. Red line/notch in box shows median, top and bottom of the box indicate the 75th and 25th percentiles. Whiskers indicate maximum/minimum values not considered outliers. Green triangle shows mean plus 3 standard deviations (used later in triple collocation section). Numbers underneath x-labels are mean ± standard deviation.

Correlations for wind speed were given in Figure 2b and were all positive and significant at the 0.05 level for all modes. Figure 2b clearly shows the inability of both S3A and S3B and all modes to measure wind speed below 1 ms^{-1}. For this reason, the analysis is repeated for only those cases where all measurements of wind speed were at least 1 ms^{-1} (Figure 3). When low winds are ignored, the correlations (Figure 3b) are higher than those in Figure 2b, although obviously also include fewer data pairs.

For wind speed, the best correlation is that achieved between S3B LRM and S3A PLRM (0.94). The next highest correlations are for S3A PLRM with: S3B SAR (0.75); and S3B PLRM (0.74). Surprisingly the correlation of S3A PLRM with S3A SAR is slightly lower at 0.59 (no winds < 1 ms^{-1}) although the number of pairs is much higher. For both ERA5 and buoys, the highest correlations with satellite data are always with S3B LRM followed by S3A PLRM in either Figure 2b or Figure 3b.

4.1.3. Triple Collocation

The results for the triple collocation analysis using buoys are discussed in this section. Figure 6 shows the first set of triple collocations invoking buoys, for SWH. The members of each triplet are indicated on the left, the number in square brackets represents the number of data points.

For the second and third triplet (I.e. Buoys/S3A$_{PLRM}$/S3B$_{PLRM}$ and Buoys/S3A$_{SAR}$/S3B$_{SAR}$), one can see that, on average, S3A and S3B have similar error levels (standard deviations of error) to the buoys, around 0.2-0.3m (0.20m for S3A and 0.24m for S3B in SAR mode; 0.27 m for S3A and 0.24 m for S3B in PLRM).

S3B in LRM shows significantly higher error than any other dataset, at 0.53 m, in line with the findings of section 4.1.1. The estimated error for Buoys is also higher in this triplet. It should be noted that the points in this grouping are mutually exclusive from those in the other two groupings, as S3B cannot operate in LRM at the same time as SAR or PLRM. Also, there are concerns about the low number of data points in each of the three groupings (varying between 122 and 143), caused by the limited number of available collocations with buoys in the tandem phase. Low number of samples will lead to large uncertainties for the triple collocation method, which is particularly dependent on large volumes of good quality unbiased data. For this reason, the triple collocation analysis was repeated using ERA5 collocations in section 4.2.4.

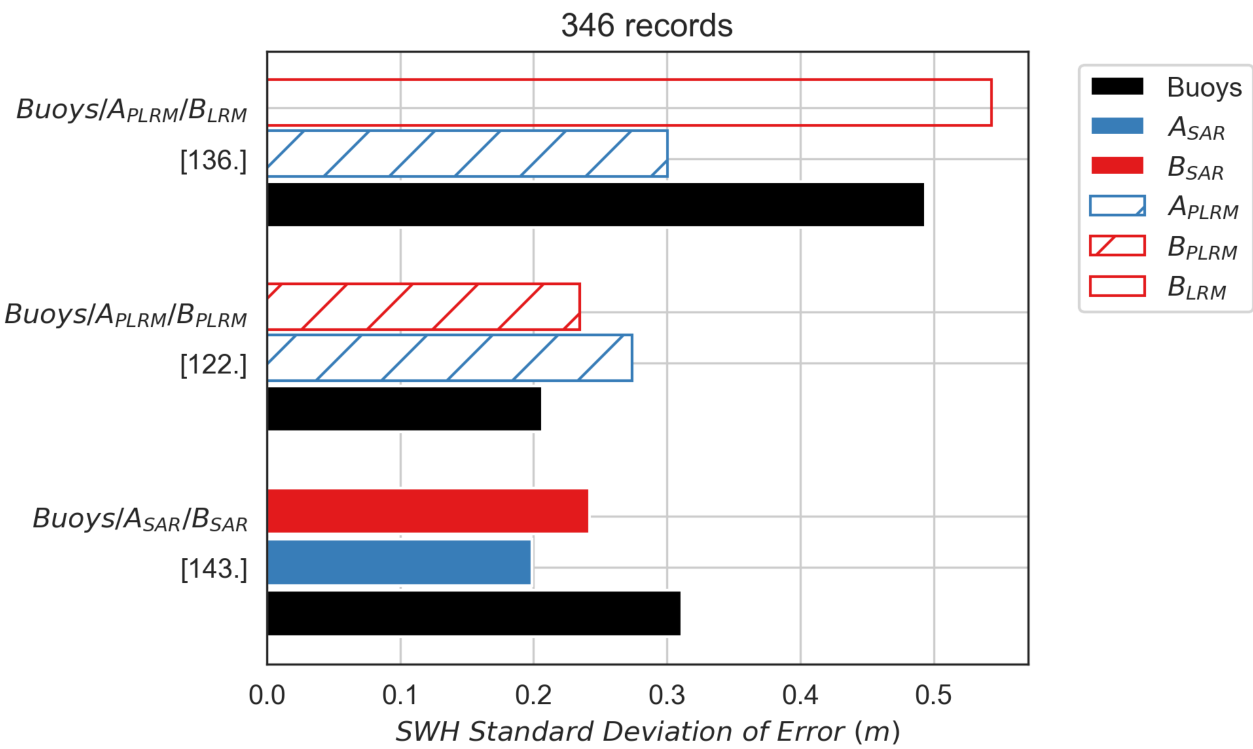


Figure 6 Triple collocation results for all 3 dataset groupings (comparing ERA-5 and the two Sentinel 3 satellites in each mode) showing the estimated standard deviation of the SWH error, a proxy for SWH noise. The numbers on the y-axis under the names of the datasets compared indicates the number of records compared in this grouping.

For wind speed, Figure 7 shows the first set of triple collocations including buoys. In this, one can see that the Sentinel-3 satellites show lower errors (standard deviations of error) than buoys. Contrary to the SWH results, errors in SAR mode (1.6 ms-1 for S3A and 1.3 ms-1 for S3B) are larger than for PLRM mode (~1.2 ms-1 for both S3A and S3B), although both error levels are consistent within mission requirements for winds (1.5 m/s). Additionally, for wind speed, the LRM data has relatively low standard deviation of error (0.9 ms-1). However, while wind speed data does have more data points than the SWH analysis (between 260 and 341) this is still relatively low for a triple collocation analysis 4.2.4.

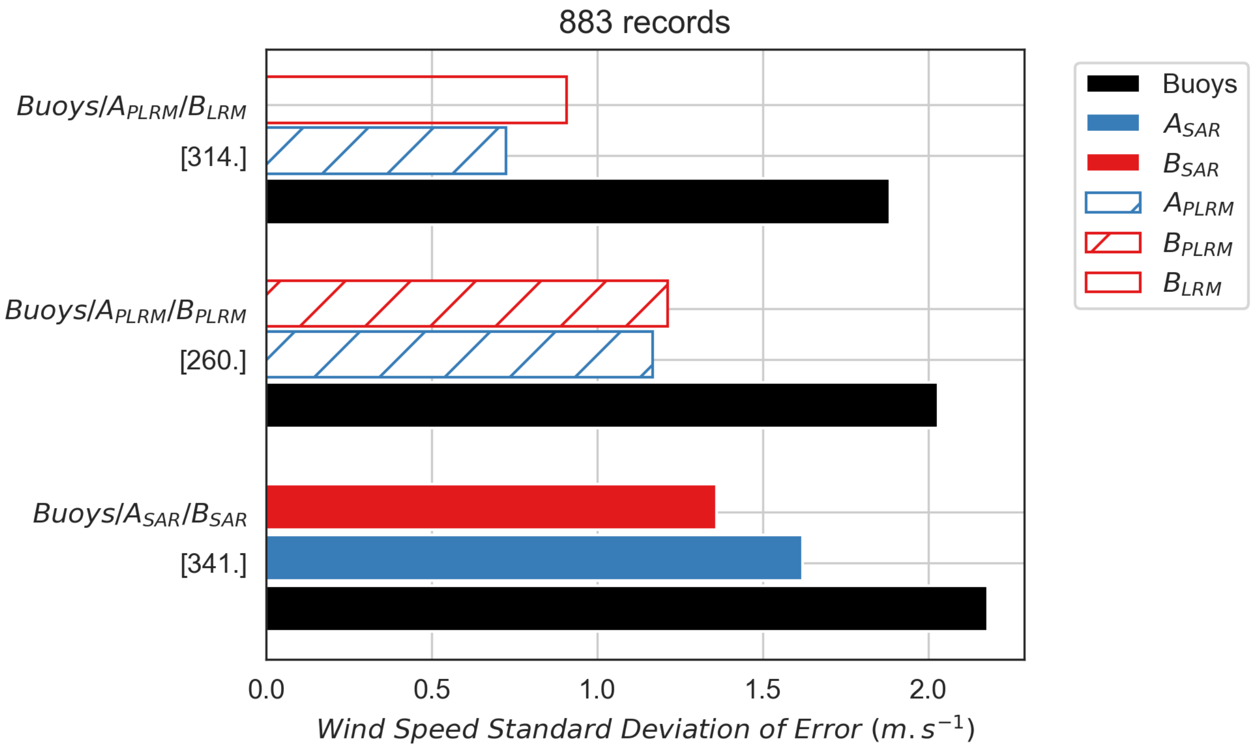


Figure 7 Triple collocation results for all 3 dataset groupings (comparing ERA-5 and the two Sentinel 3 satellites in each mode) showing the estimated standard deviation of the wind speed error, a proxy for wind speed noise. The numbers on the y-axis under the names of the datasets compared indicates the number of records compared in this grouping.

4.2. Part 2: Collocations with ERA5

4.2.1. Descriptive Statistics

The statistical distributions of SWH and WSP in the satellite matchup dataset with ERA5 are given in Figure 8 (8a all data; 8b: low sea state conditions removed). It is apparent that for SWH the distributions for ERA5, S3A SAR and S3B SAR below 1 m are problematic and very dissimilar to those shown by S3A and S3B in LRM and PLRM. When ignoring low sea state cases, the distributions for all modes and satellites are much more similar to ERA5. The differences amongst distributions with and without low wind speeds are not as clear as the case for low SWH. What is noticeable in Figure 8 for wind speed is that the LRM values are shifted towards a higher wind speed. It should be noted that the distributions in Figure 8 do not necessarily represent the same data as S3B could be in either LRM or SAR/PLRM.

Summary statistics for SWH and windspeed split by the mode of S3B are provided in Figure 9 and Figure 10 respectively. The same information but for the major ocean basins are given in Figure 11 and Figure 12.

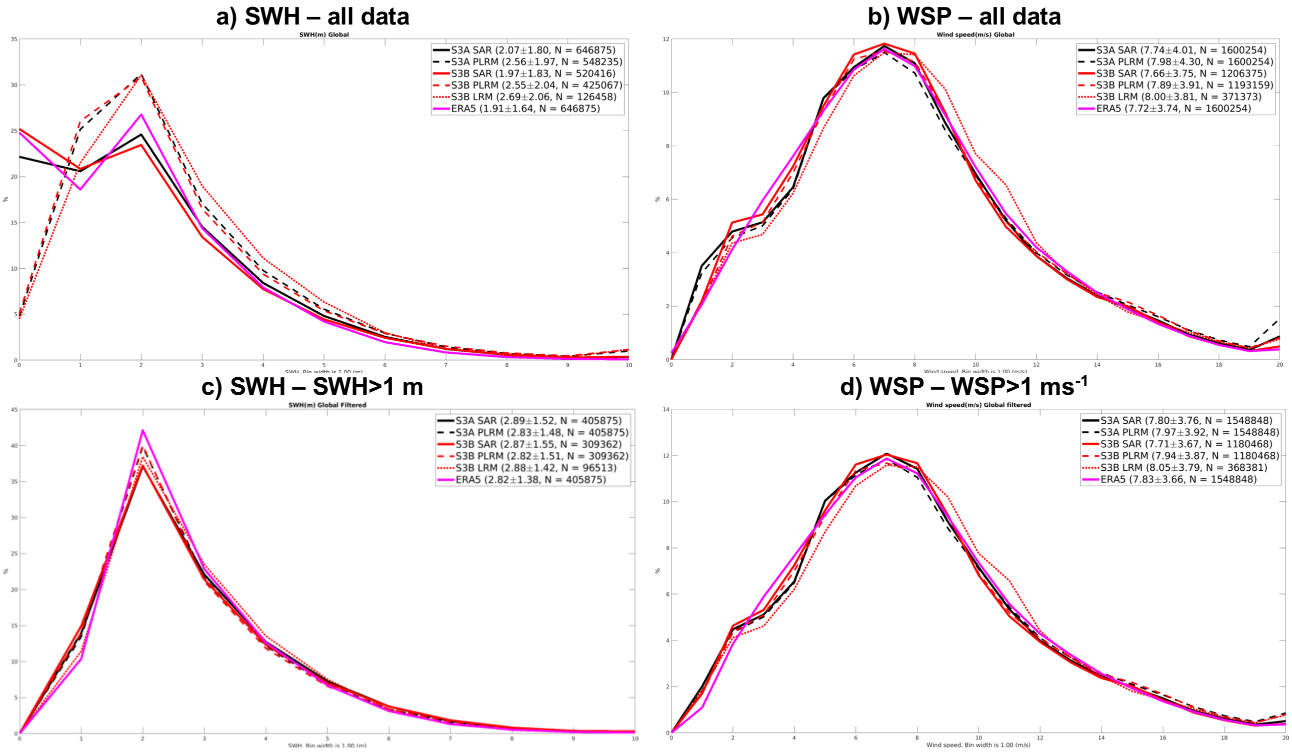


Figure 8 Distribution of a) significant wave height (SWH) and b) wind speed (WSP) throughout the study region and period, and c) and d) show the same distributions but with no data <1 m for SWH and <1 ms^{-1} for wind speed.

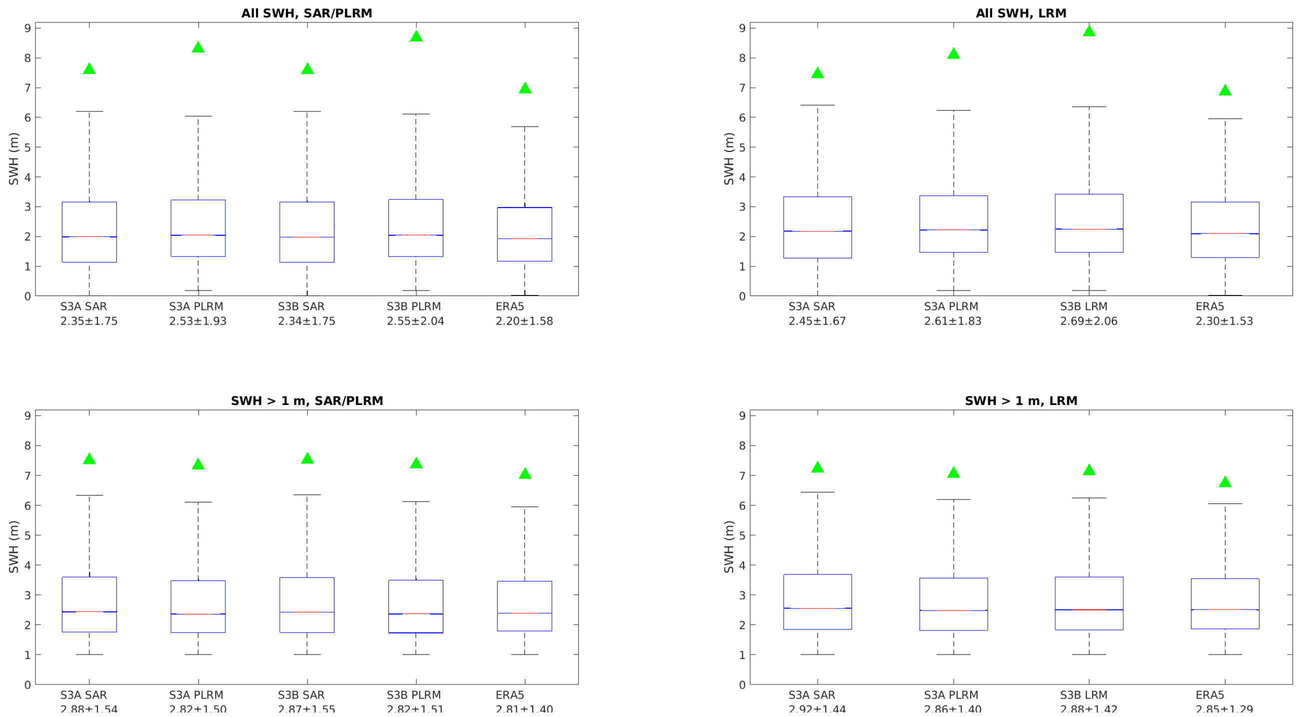


Figure 9 Box plot of significant wave height (SWH). Top is for all data and bottom shows only where SWH> 1 m, left is S3B in SAR/PLRM and right S3B in LRM. Red line in box shows median, top and bottom of the box indicate the 75th and 25th percentiles. Whiskers indicate maximum/minimum values not considered outliers. Green triangle shows mean plus 3 standard deviations (used later in triple collocation section). Numbers underneath x-labels are mean ± standard deviation.

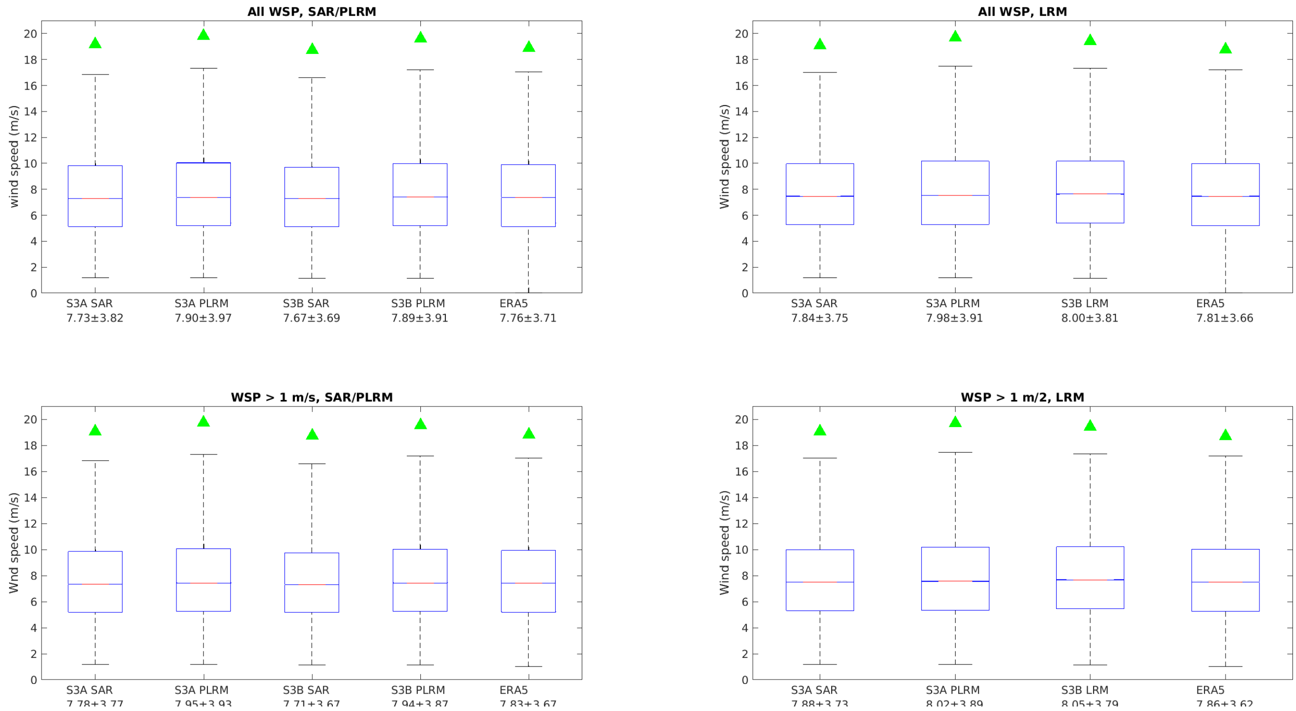


Figure 10 Box plot of wind speed (WSP). Top is for all data and bottom shows only where WSP> 1 ms-1, left is S3B in SAR/PLRM and right S3B in LRM. Red line in box shows median, top and bottom of the box indicate the 75th and 25th percentiles. Whiskers indicate maximum/minimum values not considered outliers. Green triangle shows mean plus 3 standard deviations (used later in triple collocation section). Numbers underneath x-labels are mean ± standard deviation.

Table 2 shows the summary descriptive statistics for SWH estimated globally, by hemisphere and by region (as defined in Figure 1 except those identified as *Other*). The same statistics are repeated in Table 3 but this time only for the data where SWH>1m. A similar set of results for wind speed are provided in Table 4 (all data) and Table 5 (wind speed >1 ms-1 only).

Tables 2 to 5 are all split into two (left and right), so that the first set of numbers relate to those cases where S3B was in SAR/PLRM whereas those numbers in the righthand series relate to where S3B was in LRM. Due to insufficient data, the Great Lakes category is not included for when S3B is in LRM.

A few comments can be made about general patterns in Tables 2 to 5 but no study has been made to consider whether any of the averages are statistically different. For SWH, in Table 2, there is no clear pattern in the satellite/mode/ERA5 with the highest average except for a tendency for S3B LRM and PLRM to be highest on the global to hemispheric scale. This is not the case where SWH>1 m(Table 3) when S3A and S3B SAR tend to have the maximum means and medians. For wind speed, in both Table 4 and Table 5, there is no clear pattern for S3B in SAR/PLRM but when S3B is in LRM then the LRM tends to have the highest mean and median supporting the finding above from Figure 8.

Table 2 Summary of significant wave height (SWH) by hemisphere/region for all data. Top line is mean ± SD, middle is median ± MAD, bottom line is number of observations. The values in bold/red are the highest mean/median per region and per mode of S3B.

	S3B in SAR/PLRM					S3B in LRM			
Region	**ERA5**	**S3A_SAR**	**S3A_PLRM**	**S3B_SAR**	**S3B_PLRM**	**ERA5**	**S3A_SAR**	**S3A_PLRM**	**S3B_LRM**
Global	2.20±1.58 1.92±1.20 N=425067	2.35±1.75 1.99±1.31 N=425067	2.53±1.93 **2.04±1.33** N=418253	2.34±1.75 1.98±1.32 N=425067	**2.55±2.04** **2.04±1.38** N=425067	2.30±1.53 2.10±1.19 N=126458	2.45±1.67 2.18±1.28 N=126458	2.61±1.83 2.22±1.28 N=124128	**2.69±2.06** **2.25±1.37** N=126458
Northern Hemisphere	1.51±0.89 1.47±0.65 N=202574	1.53±1.10 1.41±0.78 N=202574	1.72±1.47 **1.48±0.80** N=200477	1.53±1.11 1.39±0.78 N=202574	**1.78±1.67** **1.48±0.87** N=202574	1.52±0.84 1.53±0.64 N=54755	1.55±1.04 1.47±0.75 N=54755	1.74±1.46 1.54±0.77 N=54128	**1.87±1.91** **1.57±0.92** N=54755
Southern Hemisphere	2.82±1.80 2.70±1.38 N=222493	3.09±1.89 2.83±1.43 N=222493	**3.26±2.01** **2.88±1.42** N=217776	3.08±1.89 2.82±1.44 N=222493	**3.26±2.09** 2.86±1.46 N=222493	2.89±1.66 2.84±1.28 N=71703	3.13±1.72 2.95±1.32 N=71703	3.29±1.80 2.98±1.28 N=70000	**3.31±1.95** **2.99±1.34** N=71703
North Atlantic	**1.76±0.85** **1.61±0.59** N=40722	1.73±1.00 1.56±0.71 N=40722	1.75±0.94 1.56±0.64 N=40696	1.71±1.00 1.55±0.71 N=40722	**1.76±0.95** 1.56±0.65 N=40722	1.65±0.66 **1.59±0.48** N=12224	1.59±0.79 1.52±0.60 N=12224	1.63±0.78 1.53±0.53 N=12211	**1.66±0.90** 1.54±0.55 N=12224
South Atlantic	2.71±1.17 2.40±0.87 N=29515	**2.76±1.31** **2.44±0.97** N=29515	2.69±1.25 2.36±0.93 N=29511	2.75±1.31 2.43±0.98 N=29515	2.69±1.26 2.36±0.93 N=29515	3.30±1.35 2.98±1.08 N=9121	**3.39±1.51** **3.05±1.19** N=9121	3.30±1.46 2.95±1.15 N=9121	3.33±1.47 2.98±1.16 N=9121
North Pacific	**1.81±0.71** **1.74±0.49** N=67135	1.77±0.87 1.68±0.60 N=67135	1.78±0.81 1.67±0.54 N=67116	1.76±0.87 1.66±0.60 N=67135	1.79±0.83 1.67±0.54 N=67135	**1.72±0.66** **1.72±0.47** N=20938	1.67±0.80 1.64±0.58 N=20938	1.69±0.75 1.64±0.51 N=20928	**1.72±0.83** 1.66±0.53 N=20938
South Pacific	2.69±1.14 **2.50±0.87** N=61724	**2.73±1.27** **2.50±0.97** N=61724	2.68±1.22 2.43±0.92 N=61702	2.72±1.27 **2.50±0.97** N=61724	2.68±1.22 2.44±0.93 N=61724	2.80±1.12 2.59±0.85 N=19429	**2.84±1.25** **2.60±0.95** N=19429	2.78±1.21 2.52±0.91 N=19421	2.80±1.23 2.55±0.92 N=19429
North Indian	2.26±0.92 2.11±0.72 N=7662	**2.31±1.09** **2.14±0.86** N=7662	2.29±1.01 2.09±0.79 N=7657	2.30±1.09 2.13±0.86 N=7662	2.29±1.02 2.09±0.79 N=7662	2.50±0.80 2.41±0.64 N=2361	**2.65±0.95** **2.55±0.77** N=2361	2.58±0.89 2.47±0.73 N=2361	2.61±0.90 2.50±0.73 N=2361
South Indian	3.56±1.54 3.20±1.19 N=41930	**3.67±1.70** **3.28±1.31** N=41930	3.58±1.67 3.17±1.29 N=41920	3.66±1.71 3.27±1.32 N=41930	3.58±1.67 3.18±1.29 N=41930	3.37±1.23 3.12±0.96 N=13052	**3.46±1.35** **3.18±1.06** N=13052	3.37±1.32 3.08±1.04 N=13049	3.40±1.33 3.11±1.04 N=13052
Southern Ocean	2.66±2.32 2.88±1.97 N=85499	3.24±2.37 3.22±1.88 N=85499	**3.80±2.58** **3.55±1.82** N=80943	3.24±2.37 3.23±1.88 N=85499	3.77±2.71 3.49±1.89 N=85499	2.66±2.10 2.97±1.76 N=28908	3.17±2.11 3.24±1.66 N=28908	**3.65±2.27** **3.45±1.56** N=27259	3.63±2.47 3.41±1.68 N=28908
Mediterranean	0.68±0.43 0.57±0.34 N=1829	0.69±0.59 0.47±0.42 N=1829	0.85±0.84 0.70±0.44 N=1820	0.70±0.75 0.46±0.45 N=1829	**0.93±1.24** **0.72±0.53** N=1829	0.79±0.54 0.62±0.42 N=562	0.83±0.89 0.50±0.57 N=562	0.99±1.04 **0.75±0.55** N=559	**1.08±1.57** 0.72±0.72 N=562
Arctic Ocean	1.20±0.86 1.07±0.63 N=68884	1.24±1.18 0.95±0.80 N=68884	1.62±1.91 1.17±1.00 N=67517	1.24±1.20 0.94±0.81 N=68884	**1.72±2.22** **1.18±1.14** N=68884	1.27±0.95 1.14±0.74 N=13978	1.34±1.23 1.03±0.89 N=13978	1.79±2.06 1.31±1.11 N=13579	**2.04±2.71** **1.34±1.44** N=13978
Great Lakes	0.35±0.39 0.23±0.29 N=482	0.66±1.22 0.32±0.58 N=482	1.65±2.67 0.72±1.57 N=450	0.70±1.24 0.33±0.63 N=482	**1.79±2.98** **0.72±1.80** N=482	0.25±0.31 0.17±0.21 N=156	0.76±1.43 0.28±0.78 N=156	2.46±4.32 0.69±2.73 N=146	**2.89±4.71** **0.71±3.22** N=156

Table 3 Summary of significant wave height (SWH) by hemisphere/region for where SWH>1 m only. Top line is mean ± SD, middle is median ± MAD, bottom line is number of observations. The values in red/bold are the highest mean/median per region and per mode of S3B.

	S3B in SAR/PLRM					S3B in LRM			
Region	**ERA5**	**S3A_SAR**	**S3A_PLRM**	**S3B_SAR**	**S3B_PLRM**	**ERA5**	**S3A_SAR**	**S3A_PLRM**	**S3B_LRM**
Global	2.81±1.40 2.39±1.07 N=309362	**2.88±1.54** **2.44±1.18** N=309362	2.82±1.50 2.36±1.14 N=309362	2.87±1.55 2.43±1.18 N=309362	2.82±1.51 2.37±1.14 N=309362	2.85±1.29 2.51±1.02 N=96513	**2.92±1.44** **2.55±1.12** N=96513	2.86±1.40 2.48±1.08 N=96513	2.88±1.42 2.50±1.09 N=96513
Northern Hemisphere	2.00±0.75 **1.81±0.52** N=124566	**2.02±0.88** 1.80±0.61 N=124566	2.00±0.87 1.78±0.58 N=124566	2.01±0.88 1.79±0.61 N=124566	2.00±0.88 1.77±0.58 N=124566	1.97±0.65 **1.84±0.46** N=35513	1.98±0.79 1.82±0.56 N=35513	1.97±0.80 1.79±0.53 N=35513	**1.99±0.83** 1.81±0.53 N=35513
Southern Hemisphere	3.36±1.47 3.03±1.14 N=184796	**3.46±1.62** **3.10±1.26** N=184796	3.37±1.59 3.00±1.22 N=184796	**3.46±1.63** **3.10±1.26** N=184796	3.38±1.60 3.01±1.23 N=184796	3.36±1.30 3.11±1.03 N=61000	**3.47±1.45** **3.18±1.14** N=61000	3.37±1.41 3.08±1.11 N=61000	3.40±1.43 3.10±1.11 N=61000
North Atlantic	2.02±0.81 **1.79±0.56** N=30805	**2.04±0.93** 1.78±0.65 N=30805	2.01±0.88 1.75±0.61 N=30805	2.03±0.93 1.77±0.65 N=30805	2.01±0.88 1.75±0.61 N=30805	**1.87±0.58** **1.73±0.42** N=9325	**1.87±0.67** 1.72±0.50 N=9325	1.85±0.65 1.70±0.46 N=9325	**1.87±0.67** 1.71±0.47 N=9325
South Atlantic	2.75±1.16 2.43±0.86 N=28829	**2.81±1.29** **2.47±0.96** N=28829	2.72±1.24 2.39±0.92 N=28829	2.80±1.29 2.46±0.96 N=28829	2.73±1.24 2.39±0.92 N=28829	3.32±1.34 3.00±1.07 N=9051	**3.40±1.49** **3.06±1.19** N=9051	3.31±1.45 2.96±1.15 N=9051	3.34±1.46 2.99±1.15 N=9051
North Pacific	**1.98±0.65** **1.84±0.43** N=56041	1.97±0.79 1.81±0.53 N=56041	1.95±0.73 1.78±0.49 N=56041	1.96±0.79 1.79±0.53 N=56041	1.95±0.75 1.78±0.49 N=56041	**1.93±0.56** **1.84±0.38** N=16684	1.91±0.68 1.80±0.47 N=16684	1.89±0.63 1.77±0.43 N=16684	1.91±0.66 1.79±0.44 N=16684
South Pacific	2.80±1.08 2.57±0.83 N=58267	**2.84±1.20** **2.58±0.92** N=58267	2.77±1.16 2.50±0.89 N=58267	**2.84±1.20** 2.57±0.92 N=58267	2.78±1.16 2.51±0.89 N=58267	2.87±1.08 2.63±0.83 N=18700	**2.92±1.20** **2.65±0.92** N=18700	2.84±1.16 2.57±0.89 N=18700	2.87±1.17 2.59±0.89 N=18700
North Indian	2.41±0.85 2.22±0.67 N=6878	**2.49±1.00** **2.27±0.79** N=6878	2.44±0.94 2.20±0.75 N=6878	2.48±1.00 2.25±0.79 N=6878	2.44±0.94 2.20±0.75 N=6878	2.55±0.76 2.45±0.61 N=2285	**2.71±0.91** **2.60±0.74** N=2285	2.63±0.86 2.51±0.70 N=2285	2.66±0.86 2.54±0.70 N=2285
South Indian	3.60±1.51 3.22±1.18 N=41348	**3.71±1.68** **3.30±1.30** N=41348	3.61±1.65 3.20±1.27 N=41348	3.70±1.68 **3.30±1.31** N=41348	3.61±1.65 3.20±1.27 N=41348	3.39±1.21 3.13±0.95 N=12936	**3.48±1.34** **3.20±1.05** N=12936	3.39±1.30 3.10±1.03 N=12936	3.41±1.30 3.12±1.03 N=12936
Southern Ocean	4.13±1.54 3.90±1.20 N=54683	**4.31±1.70** **4.06±1.32** N=54683	4.20±1.68 3.93±1.30 N=54683	**4.31±1.70** **4.06±1.32** N=54683	4.21±1.70 3.94±1.30 N=54683	3.87±1.35 3.67±1.04 N=19742	**4.03±1.50** **3.83±1.16** N=19742	3.92±1.47 3.71±1.13 N=19742	3.95±1.49 3.74±1.14 N=19742
Mediterranean	1.41±0.30 1.34±0.24 N=296	1.57±0.50 **1.48±0.33** N=296	**1.58±0.49** 1.45±0.30 N=296	1.54±0.46 1.45±0.31 N=296	**1.58±0.55** 1.46±0.31 N=296	1.64±0.40 1.56±0.34 N=126	**1.85±0.58** 1.73±0.46 N=126	1.83±0.57 1.70±0.44 N=126	1.84±0.55 **1.75±0.43** N=126
Arctic Ocean	1.96±0.80 1.73±0.57 N=27473	2.00±0.92 **1.75±0.66** N=27473	2.00±1.00 1.72±0.64 N=27473	2.00±0.92 1.74±0.66 N=27473	**2.01±1.03** 1.72±0.65 N=27473	2.08±0.78 1.86±0.58 N=6271	2.09±0.93 **1.88±0.67** N=6271	2.09±1.05 1.84±0.66 N=6271	**2.11±1.04** 1.86±0.67 N=6271

Table 4 Summary of wind speed (WSP) by hemisphere/region for all data.Top is mean ± SD, middle is median ± MAD, bottom line is number of observations. The values in red/bold are the highest mean/median per region and per mode of S3B.

	S3B on SAR/PLRM					S3B in LRM			
Region	**ERA5**	**S3A_SAR**	**S3A_PLRM**	**S3B_SAR**	**S3B_PLRM**	**ERA5**	**S3A_SAR**	**S3A_PLRM**	**S3B_LRM**
Global	7.76±3.71 7.37±2.92 N=1193158	7.73±3.82 7.30±2.96 N=1193158	**7.90±3.97** 7.37±3.08 N=1193158	7.67±3.69 7.28±2.89 N=1189906	7.89±3.91 **7.40±3.04** N=1193158	7.81±3.66 7.46±2.90 N=371372	7.84±3.75 7.46±2.93 N=371372	7.98±3.91 7.53±3.04 N=371372	**8.00±3.81** **7.64±2.96** N=371372
Northern Hemisphere	**6.40±2.96** **6.26±2.34** N=544467	6.36±3.03 6.17±2.33 N=544467	6.34±3.03 6.12±2.33 N=544467	6.31±2.91 6.16±2.27 N=543104	6.34±3.00 6.16±2.33 N=544467	**6.28±2.84** 6.17±2.27 N=157521	6.24±2.88 6.10±2.24 N=157521	6.21±2.87 6.05±2.24 N=157521	6.27±2.84 **6.19±2.24** N=157521
Southern Hemisphere	8.90±3.89 8.52±3.10 N=648691	8.88±4.03 8.47±3.17 N=648691	9.20±4.19 8.70±3.30 N=648691	8.81±3.89 8.44±3.08 N=646802	9.19±4.11 8.72±3.25 N=648691	8.93±3.79 8.62±3.02 N=213851	9.01±3.89 8.69±3.06 N=213851	**9.29±4.05** 8.89±3.18 N=213851	9.28±3.93 **8.97±3.06** N=213851
North Atlantic	**6.58±2.92** **6.41±2.27** N=129415	6.57±2.89 6.36±2.20 N=129415	6.52±2.90 6.29±2.21 N=129415	6.53±2.83 6.34±2.17 N=129261	6.52±2.88 6.32±2.20 N=129415	**6.42±2.74** 6.31±2.18 N=40546	6.38±2.66 6.26±2.09 N=40546	6.32±2.67 6.19±2.10 N=40546	6.39±2.65 **6.32±2.09** N=40546
South Atlantic	8.17±3.41 7.84±2.68 N=97932	8.22±3.31 7.87±2.59 N=97932	**8.32±3.40** 7.94±2.67 N=97932	8.17±3.26 7.85±2.55 N=97900	**8.32±3.37** **7.99±2.64** N=97932	8.73±3.79 8.16±3.05 N=31370	8.85±3.66 8.31±2.92 N=31370	9.00±3.77 8.41±3.03 N=31370	**9.02±3.67** **8.55±2.92** N=31370
North Pacific	6.23±2.82 6.18±2.20 N=226325	**6.32±2.71** **6.25±2.08** N=226325	6.25±2.69 6.17±2.08 N=226325	6.28±2.64 **6.25±2.06** N=226066	6.25±2.67 6.20±2.08 N=226325	6.02±2.65 6.00±2.11 N=73224	**6.12±2.56** 6.06±2.00 N=73224	6.05±2.54 5.99±2.00 N=73224	**6.12±2.53** **6.13±2.01** N=73224
South Pacific	7.69±3.12 7.56±2.43 N=212732	7.78±3.01 7.58±2.31 N=212732	7.85±3.09 7.62±2.38 N=212732	7.73±2.96 7.55±2.28 N=212632	**7.86±3.07** **7.67±2.36** N=212732	8.05±3.19 7.92±2.50 N=69409	8.16±3.08 7.93±2.38 N=69409	8.25±3.16 8.00±2.44 N=69409	**8.28±3.07** **8.13±2.37** N=69409
North Indian	7.49±3.33 7.47±2.73 N=25874	**7.52±3.26** **7.49±2.62** N=25874	7.45±3.25 7.39±2.63 N=25874	7.46±3.19 7.47±2.57 N=25853	7.45±3.22 7.41±2.61 N=25874	8.20±3.13 8.38±2.57 N=8553	**8.38±3.07** 8.45±2.46 N=8553	8.33±3.06 8.41±2.48 N=8553	8.35±2.98 **8.51±2.40** N=8553
South Indian	9.10±3.85 8.87±3.08 N=140700	9.22±3.69 8.88±2.93 N=140700	**9.37±3.80** **9.00±3.02** N=140700	9.14±3.62 8.83±2.87 N=140669	9.36±3.75 **9.00±2.98** N=140700	8.87±3.60 8.65±2.86 N=45645	8.98±3.44 8.72±2.71 N=45645	9.12±3.54 8.84±2.80 N=45645	**9.13±3.44** **8.93±2.69** N=45645
Southern Ocean	10.69±4.22 10.70±3.42 N=187837	10.38±4.96 10.64±3.96 N=187837	**11.22±5.02** **11.29±3.95** N=187837	10.30±4.70 10.56±3.79 N=186163	11.16±4.87 11.27±3.87 N=187837	10.16±4.13 10.16±3.35 N=64402	10.16±4.67 10.38±3.71 N=64402	**10.80±4.83** **10.85±3.78** N=64402	10.73±4.67 10.79±3.63 N=64402
Mediterranean	4.93±2.37 4.75±1.95 N=5389	**5.08±2.56** **4.95±1.93** N=5389	5.01±2.47 4.86±1.92 N=5389	5.02±2.37 4.88±1.88 N=5372	5.01±2.45 4.84±1.92 N=5389	5.17±2.26 4.90±1.81 N=1736	**5.23±2.52** 4.96±1.89 N=1736	5.16±2.37 4.95±1.85 N=1736	**5.23±2.46** **5.00±1.90** N=1736
Arctic Ocean	**6.68±3.07** **6.48±2.48** N=119681	6.33±3.38 5.96±2.66 N=119681	6.44±3.44 6.06±2.72 N=119681	6.29±3.24 5.96±2.59 N=119048	6.43±3.40 6.09±2.70 N=119681	**6.82±3.10** **6.70±2.50** N=22877	6.32±3.39 6.05±2.67 N=22877	6.40±3.44 6.12±2.73 N=22877	6.45±3.38 6.26±2.71 N=22877
Great Lakes	**5.00±2.46** **4.67±1.95** N=961	4.65±3.39 4.03±2.23 N=961	4.86±3.58 4.17±2.43 N=961	4.40±2.58 3.96±1.93 N=951	4.71±3.14 4.13±2.25 N=961	**4.88±2.45** **4.42±2.04** N=281	3.75±2.94 2.90±2.04 N=281	3.88±2.99 3.10±2.13 N=281	3.88±2.71 3.20±2.04 N=281

Table 5 Summary of wind speed (WSP) by hemisphere/region where WSP > 1 ms^{-1} only. Top is mean ± SD, middle is median ± MAD, bottom line is number of observations. The values in red/bold are the highest mean/median per region and per mode of S3B.

	S3B on SAR/PLRM					S3B in LRM			
Region	**ERA5**	**S3A_SAR**	**S3A_PLRM**	**S3B_SAR**	**S3B_PLRM**	**ERA5**	**S3A_SAR**	**S3A_PLRM**	**S3B_LRM**
Global	7.83±3.67 7.41±2.89 N=1180467	7.78±3.77 7.34±2.93 N=1180467	**7.95±3.93** 7.41±3.05 N=1180467	7.71±3.67 7.30±2.87 N=1180467	7.94±3.87 **7.43±3.02** N=1180467	7.86±3.62 7.50±2.87 N=368380	7.88±3.73 7.50±2.91 N=368380	8.02±3.89 7.56±3.03 N=368380	**8.05±3.79** **7.67±2.95** N=368380
Northern Hemisphere	**6.48±2.91** **6.31±2.30** N=536780	6.41±2.98 6.21±2.29 N=536780	6.40±2.99 6.17±2.31 N=536780	6.36±2.89 6.20±2.25 N=536780	6.39±2.96 6.20±2.30 N=536780	**6.35±2.79** 6.22±2.23 N=155578	6.29±2.85 6.14±2.22 N=155578	6.25±2.85 6.09±2.22 N=155578	6.32±2.81 **6.23±2.22** N=155578
Southern Hemisphere	8.95±3.85 8.55±3.08 N=643687	8.92±3.97 8.50±3.14 N=643687	**9.24±4.15** 8.72±3.27 N=643687	8.84±3.87 8.46±3.07 N=643687	9.22±4.07 **8.74±3.22** N=643687	8.97±3.75 8.64±3.00 N=212802	9.04±3.87 8.71±3.05 N=212802	**9.32±4.03** **8.91±3.17** N=212802	9.31±3.91 8.98±3.05 N=212802
North Atlantic	**6.63±2.88** **6.44±2.24** N=128218	6.61±2.86 6.39±2.18 N=128218	6.56±2.88 6.31±2.19 N=128218	6.57±2.81 6.37±2.15 N=128218	6.56±2.86 6.34±2.18 N=128218	**6.48±2.69** 6.34±2.15 N=40180	6.41±2.65 6.28±2.07 N=40180	6.36±2.65 6.21±2.08 N=40180	6.42±2.63 **6.35±2.07** N=40180
South Atlantic	8.21±3.37 7.87±2.66 N=97381	8.26±3.29 7.89±2.58 N=97381	**8.36±3.38** 7.96±2.66 N=97381	8.20±3.24 7.86±2.53 N=97381	**8.36±3.35** **8.00±2.62** N=97381	8.76±3.76 8.18±3.03 N=31232	8.88±3.64 8.32±2.91 N=31232	9.03±3.75 8.43±3.02 N=31232	**9.05±3.65** **8.55±2.91** N=31232
North Pacific	6.31±2.76 6.22±2.16 N=223345	**6.37±2.67** **6.29±2.06** N=223345	6.30±2.66 6.21±2.05 N=223345	6.33±2.62 **6.29±2.03** N=223345	6.31±2.64 6.25±2.05 N=223345	6.09±2.60 6.04±2.07 N=72298	6.16±2.54 6.11±1.98 N=72298	6.10±2.52 6.04±1.97 N=72298	**6.17±2.50** **6.17±1.98** N=72298
South Pacific	7.73±3.09 7.58±2.41 N=211580	7.81±2.99 7.60±2.30 N=211580	7.88±3.07 7.64±2.37 N=211580	7.75±2.94 7.57±2.26 N=211580	**7.89±3.05** **7.67±2.35** N=211580	8.08±3.16 7.94±2.48 N=69094	8.18±3.06 7.95±2.36 N=69094	8.27±3.14 8.01±2.43 N=69094	**8.31±3.05** **8.13±2.35** N=69094
North Indian	7.54±3.29 7.51±2.70 N=25683	**7.56±3.23** **7.52±2.60** N=25683	7.49±3.23 7.43±2.60 N=25683	7.50±3.16 7.48±2.56 N=25683	7.49±3.20 7.45±2.59 N=25683	8.25±3.09 8.40±2.53 N=8503	**8.42±3.04** 8.48±2.44 N=8503	8.36±3.03 8.43±2.46 N=8503	8.39±2.95 **8.53±2.38** N=8503
South Indian	9.14±3.81 8.89±3.06 N=140021	9.25±3.67 8.90±2.91 N=140021	**9.40±3.78** 9.03±3.01 N=140021	9.17±3.60 8.83±2.86 N=140021	9.39±3.72 **9.04±2.96** N=140021	8.91±3.56 8.67±2.83 N=45411	9.01±3.41 8.74±2.69 N=45411	**9.16±3.52** 8.86±2.78 N=45411	**9.16±3.41** **8.93±2.67** N=45411
Southern Ocean	10.74±4.18 10.74±3.40 N=185580	10.42±4.86 10.68±3.89 N=185580	**11.28±4.93** **11.32±3.88** N=185580	10.31±4.70 10.60±3.78 N=185580	11.22±4.80 11.31±3.80 N=185580	10.21±4.10 10.19±3.32 N=64129	10.19±4.66 10.39±3.70 N=64129	**10.83±4.82** **10.86±3.77** N=64129	10.75±4.65 10.81±3.62 N=64129
Mediterranean	5.05±2.29 4.85±1.89 N=5237	**5.16±2.52** **5.03±1.90** N=5237	5.09±2.44 4.95±1.89 N=5237	5.09±2.35 4.96±1.86 N=5237	5.09±2.42 4.92±1.89 N=5237	5.21±2.22 4.94±1.78 N=1717	5.25±2.50 4.98±1.88 N=1717	5.20±2.36 4.98±1.84 N=1717	**5.27±2.45** **5.04±1.89** N=1717
Arctic Ocean	**6.76±3.02** **6.55±2.44** N=117794	6.38±3.30 6.02±2.61 N=117794	6.49±3.38 6.12±2.68 N=117794	6.33±3.22 6.01±2.57 N=117794	6.48±3.35 6.15±2.67 N=117794	**6.90±3.05** **6.75±2.46** N=22600	6.36±3.34 6.09±2.64 N=22600	6.44±3.40 6.17±2.71 N=22600	6.49±3.34 6.29±2.68 N=22600
Great Lakes	**5.09±2.41** **4.75±1.92** N=937	4.72±3.39 4.12±2.22 N=937	4.95±3.59 4.22±2.42 N=937	4.44±2.57 4.02±1.93 N=937	4.79±3.14 4.18±2.25 N=937	**4.97±2.40** **4.57±2.01** N=275	3.79±2.95 2.99±2.05 N=275	3.93±3.00 3.19±2.14 N=275	3.94±2.72 3.24±2.04 N=275

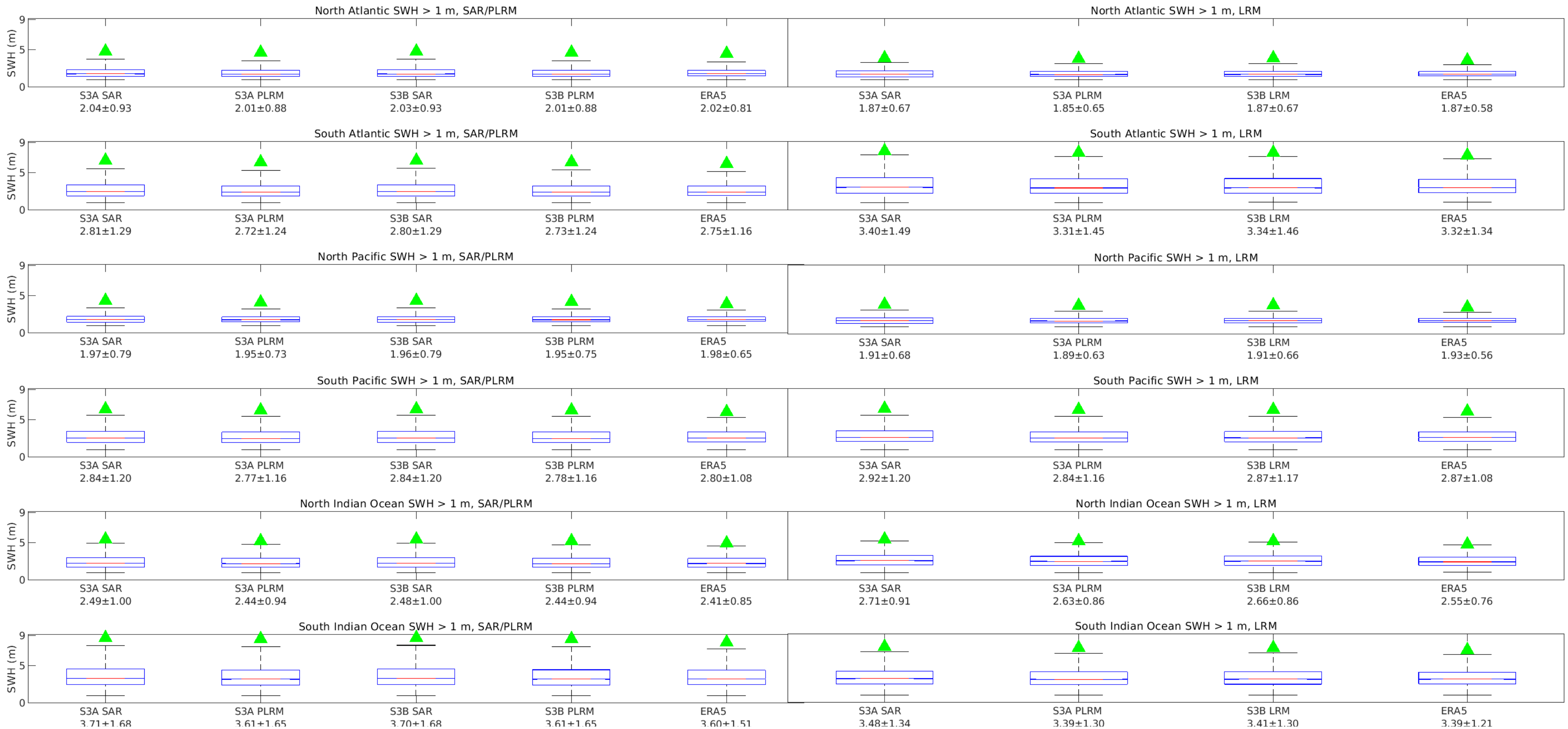


Figure 11 Box plot of significant wave height (SWH) split by ocean basin.Top is for all data and bottom shows only where SWH> 1 m, left is S3B in SAR/PLRM and right S3B in LRM. Red line in box shows median, top and bottom of the box indicate the 75th and 25th percentiles. Whiskers indicate maximum/minimum values not considered outliers. Green triangle shows mean plus 3 standard deviations (used later in triple collocation section). Numbers underneath x-labels are mean ± standard deviation.

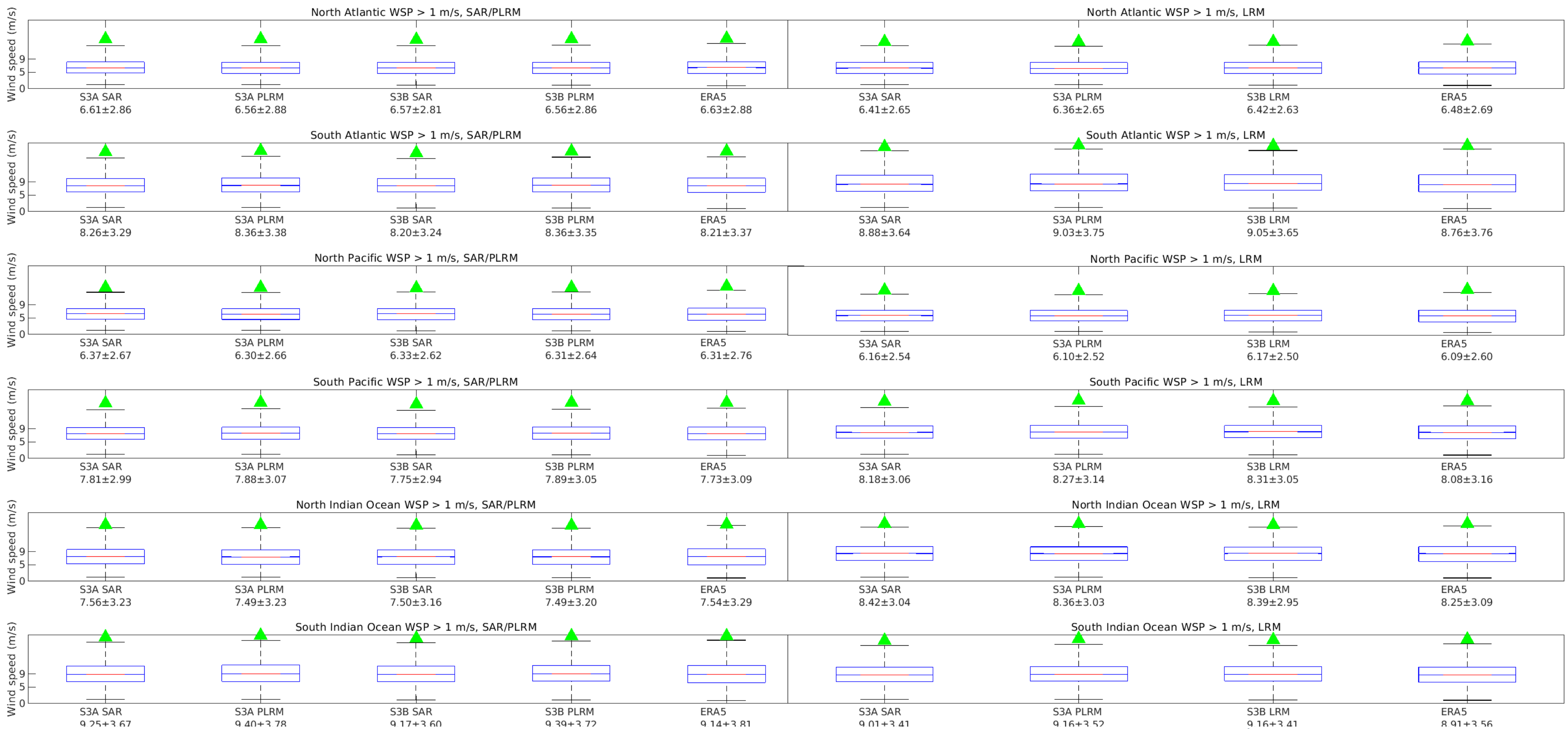


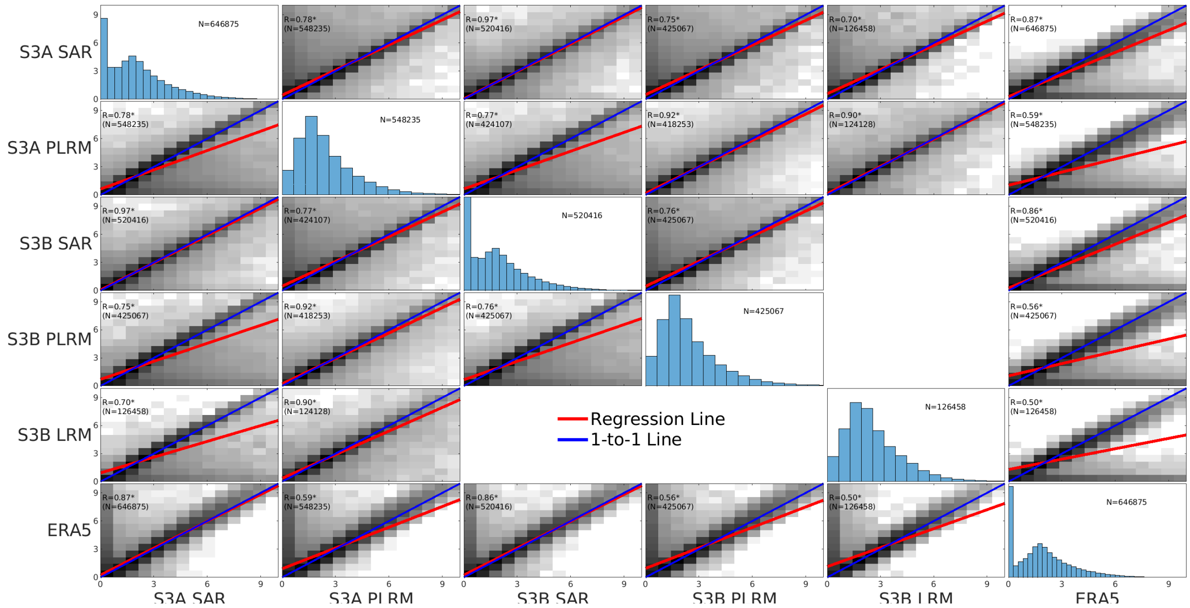
Figure 12 Box plot of wind speed(WSP) split by ocean basin.Top is for all data and bottom shows only where WSP> 1 ms^{-1}, left is S3B in SAR/PLRM and right S3B in LRM. Red line in box shows median, top and bottom of the box indicate the 75th and 25th percentiles. Whiskers indicate maximum/minimum values not considered outliers. Green triangle shows mean plus 3 standard deviations (used later in triple collocation section). Numbers underneath x-labels are mean ± standard deviation.

4.2.2. Correlations

The relationships between the S3A, S3B and ERA5 values of SWH and wind speed are given below in Figure 13. The contents of Figure 13 are repeated in Figure 14 after removing low SWH (<1 m) and wind speed (<1 ms^{-1}). Figures 13 and 14 reflect the data irrespective of the operating mode of S3B. In order to look further at the impact of the S3B mode, the correlation coefficients of the satellite data with ERA5 are given on a regional basis in Table 6 and Table 7 for SWH and wind speed respectively, for the observations where low sea state conditions are ignored. Care must be taken in concluding too much from the correlation values as there are not the same number of pairs of observations in all cases.

In all cases, in both Figure 13 and Figure 14, most of the data clusters around the one-to-one line suggesting good agreement between the different datasets for both SWH and wind speed. This is particularly the case for where low SWH and wind speed values have been removed (Figure 14). There is apparently more spread in wind speed compared to SWH but conversely there is clearer evidence of biases in SWH. For example, in the bottom line of both Figure 13a and Figure 14a (relationship of satellite data with ERA5) there are more data above the one-to-one line than below suggesting that ERA5 has higher values of SWH compared to either S3A or S3B.. For wind speed, there is excellent agreement with the one-to-one lines fitting closely to the regression lines in both Figure 13 and Figure 14. The alignment of one-to-one lines with regression lines for LRM and PLRM against ERA5 SWH is markedly better where SWH> 1 m suggesting again there is an issue with the satellite data in low wind conditions.

a) SWH



b) Wind speed

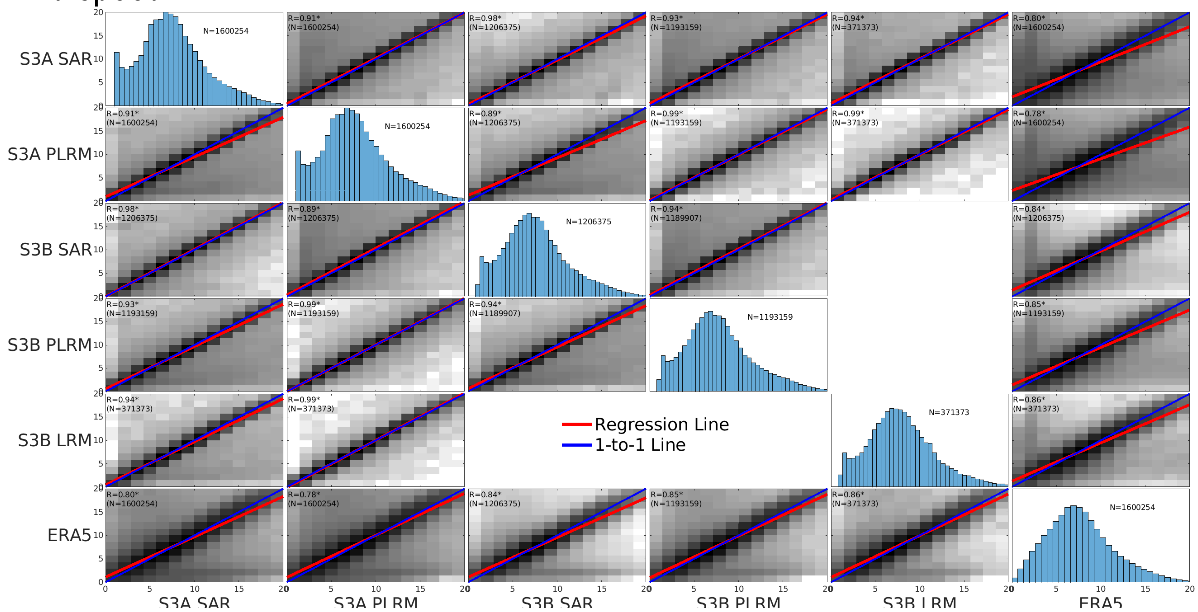


Figure 13 Results for a) Significant Wave Height (SWH) and b) Wind speed from match-up of Sentinel-3A SAR/PLRM, Sentinel-3B SAR/PLRM/LRM with ERA5 data.
Labels underneath show the variable given on the x-axis. Histograms on diagonal relate to the variable identified on x-axis. The density of the colour scale in the scatter-plots shows the intensity of data points with the labels on the left-hand side showing the variable on the y-axis and those underneath the variable on the x-axis. The least-square fit line is red and the one-to-one line is blue. Each scatter-plot includes the Pearson correlation coefficient (R; those that are significant at the 0.05 are marked by *) and the number of data pairs (N).

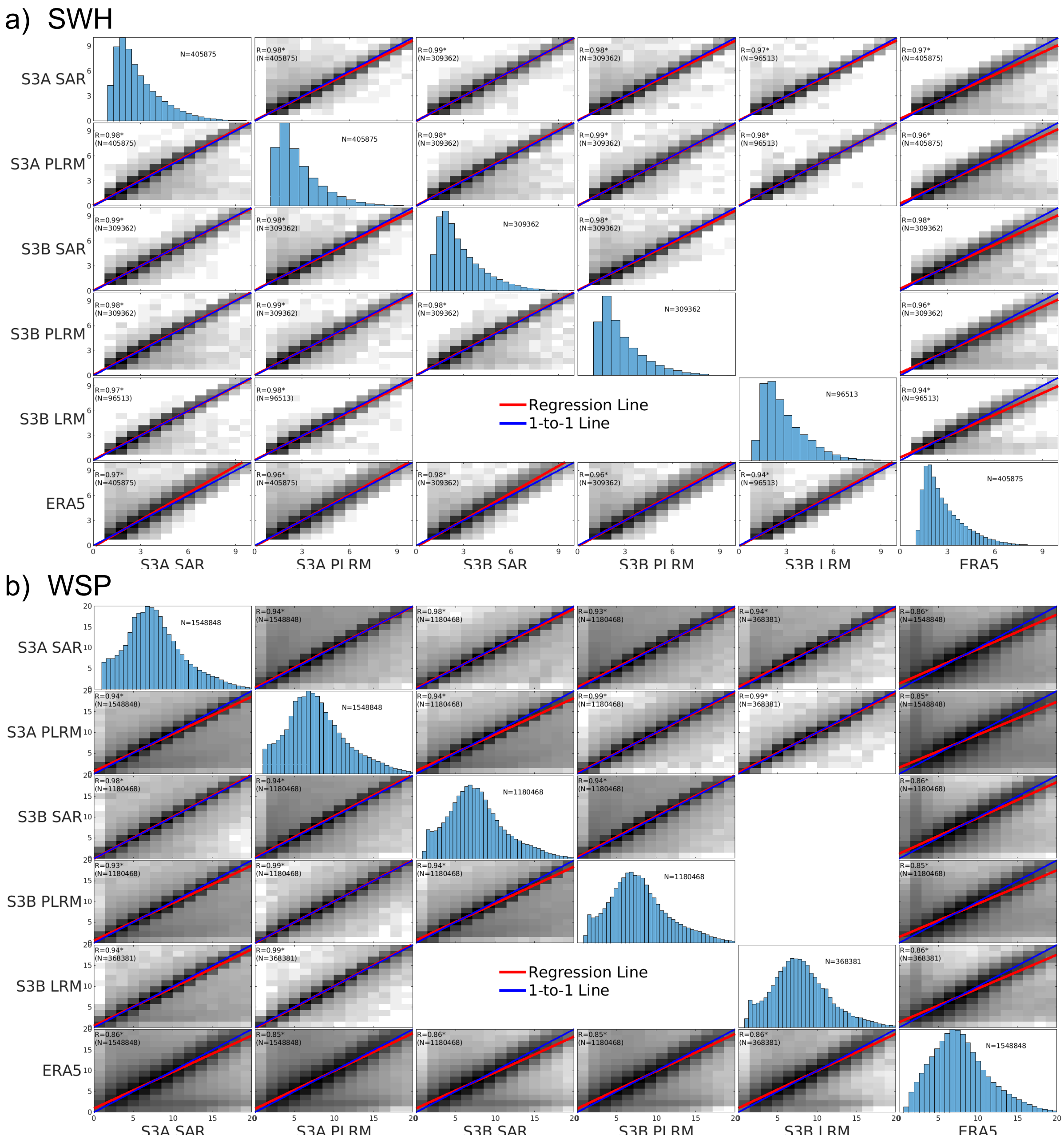


Figure 14 Results for a) Significant Wave Height (SWH) and b) Wind Speed from match-up of Sentinel-3A SAR/PLRM, Sentinel-3B SAR/PLRM/LRM with ERA5 data, where SWH>1 m and WSP>1 ms-1. Labels underneath show the variable given on the x-axis. Histograms on diagonal relate to the variable identified on x-axis. The density of the colour scale in the scatter-plots shows the intensity of data points with the labels on the left-hand side showing the variable on the y-axis and those underneath the variable on the x-axis. The least-square fit line is red and the one-to-one line is blue. Each scatter-plot includes the Pearson correlation coefficient (R; those that are significant at the 0.05 are marked by *) and the number of data pairs (N).

Table 6 provides the correlation coefficients for satellite SWH (>1 m only) with ERA5 globally, by hemisphere and by region. All the correlations are statistically significant at 0.05 level except for S3B LRM in the *Great Lakes* (there are only 2 collocations). The highest and lowest correlations for each region are identified in Table 6. Although care must be taken when comparing the correlations (as there are different numbers of pairs) for SWH, the highest correlation is always with either S3B SAR or S3A SAR. In all but a few cases the lowest correlation of ERA5 SWH is with S3B LRM.

The same information is provided for wind speed in Table 7 where all correlations are significant at the 0.05 level. Unlike SWH, there is little evidence of a pattern as to which satellite wind speed data has the highest correlation with ERA5, although there is a tendency for higher correlations with S3B SAR or PLRM. However, as stated above, the differences in the number of matchup pairs limits further interpretation (whilst S3A is always SAR/PLRM, S3B is split between SAR/PLRM and LRM, and open loop/closed loop).

Table 6 Correlations of satellite significant wave height (SWH) measurements with ERA5. Only the top row includes any measurements where SWH < 1 m. * indicates significant at the 0.05 level. For each region the highest correlation(s) are shaded, conversely the lowest correlations are shown by the light, diagonal hatching.

Region	S3A-SAR	S3A-PLRM	S3B-SAR	S3B-PLRM	S3B-LRM
Global	0.866 * (N=646875)	0.587 * (N=548235)	0.861 * (N=520416)	0.564 * (N=425067)	0.500 * (N=126458)
Filtered	0.975 * (N=405875)	0.961 * (N=405875)	0.975 * (N=309362)	0.958 * (N=309362)	0.945 * (N=96513)
Northern Hemisphere	0.925 * (N=160079)	0.862 * (N=160079)	0.929 * (N=124566)	0.860 * (N=124566)	0.797 * (N=35513)
Southern Hemisphere	0.976 * (N=245796)	0.967 * (N=245796)	0.977 * (N=184796)	0.964 * (N=184796)	0.951 * (N=61000)
North Atlantic	0.956 * (N=40130)	0.944 * (N=40130)	0.962 * (N=30805)	0.954 * (N=30805)	0.866 * (N=9325)
South Atlantic	0.981 * (N=37880)	0.980 * (N=37880)	0.981 * (N=28829)	0.978 * (N=28829)	0.978 * (N=9051)
North Pacific	0.919 * (N=72725)	0.918 * (N=72725)	0.913 * (N=56041)	0.904 * (N=56041)	0.882 * (N=16684)
South Pacific	0.980 * (N=76967)	0.976 * (N=76967)	0.981 * (N=58267)	0.978 * (N=58267)	0.972 * (N=18700)
North Indian Ocean	0.951 * (N=9163)	0.949 * (N=9163)	0.955 * (N=6878)	0.950 * (N=6878)	0.933 * (N=2285)
South Indian Ocean	0.984 * (N=54284)	0.982 * (N=54284)	0.985 * (N=41348)	0.983 * (N=41348)	0.975 * (N=12936)
Southern Ocean	0.959 * (N=74425)	0.945 * (N=74425)	0.959 * (N=54683)	0.933 * (N=54683)	0.923 * (N=19742)
Mediterranean Sea	0.664 * (N=422)	0.621 * (N=422)	0.576 * (N=296)	0.478 * (N=296)	0.751 * (N=126)
Arctic Ocean	0.917 * (N=33744)	0.775 * (N=33744)	0.919 * (N=27473)	0.755 * (N=27473)	0.761 * (N=6271)
Great Lakes	0.700 * (N=21)	0.724 * (N=21)	0.794 * (N=19)	0.786 * (N=19)	1.000 (N=2)
Other	0.725 * (N=6114)	0.507 * (N=6114)	0.776 * (N=4723)	0.554 * (N=4723)	0.313 * (N=1391)

Table 7 Correlations of satellite wind speed (WSP) measurements with ERA5. Only the top row includes any measurements where WSP < 1 ms^{-1}. * indicates significant at the 0.05 level. For each region the highest correlation(s) are shaded, conversely the lowest correlations are shown by the light, diagonal hatching.

Region	S3A-SAR	S3A-PLRM	S3B-SAR	S3B-PLRM	S3B-LRM
Global	0.805 * (N=1600254)	0.781 * (N=1600254)	0.841 * (N=1206375)	0.849 * (N=1193159)	0.855 * (N=371373)
Filtered	0.855 * (N=1548848)	0.850 * (N=1548848)	0.864 * (N=1180468)	0.853 * (N=1180468)	0.855 * (N=368381)
Northern Hemisphere	0.865 * (N=692359)	0.877 * (N=692359)	0.888 * (N=536781)	0.883 * (N=536781)	0.872 * (N=155579)
Southern Hemisphere	0.823 * (N=856489)	0.808 * (N=856489)	0.827 * (N=643687)	0.810 * (N=643687)	0.817 * (N=212802)
North Atlantic	0.913 * (N=168398)	0.922 * (N=168398)	0.923 * (N=128218)	0.926 * (N=128218)	0.910 * (N=40180)
South Atlantic	0.948 * (N=128613)	0.949 * (N=128613)	0.949 * (N=97381)	0.949 * (N=97381)	0.946 * (N=31232)
North Pacific	0.895 * (N=295643)	0.910 * (N=295643)	0.906 * (N=223345)	0.912 * (N=223345)	0.901 * (N=72298)
South Pacific	0.934 * (N=280674)	0.939 * (N=280674)	0.939 * (N=211580)	0.940 * (N=211580)	0.936 * (N=69094)
North Indian Ocean	0.924 * (N=34186)	0.932 * (N=34186)	0.933 * (N=25683)	0.936 * (N=25683)	0.920 * (N=8503)
South Indian	0.950 * (N=185432)	0.951 * (N=185432)	0.953 * (N=140021)	0.953 * (N=140021)	0.945 * (N=45411)
Southern Ocean	0.641 * (N=249709)	0.584 * (N=249709)	0.636 * (N=185580)	0.575 * (N=185580)	0.630 * (N=64129)
Mediterranean Sea	0.771 * (N=6955)	0.805 * (N=6955)	0.826 * (N=5238)	0.807 * (N=5238)	0.791 * (N=1718)
Arctic Ocean	0.849 * (N=140394)	0.845 * (N=140394)	0.867 * (N=117794)	0.852 * (N=117794)	0.844 * (N=22600)
Great Lakes	0.523 * (N=1212)	0.492 * (N=1212)	0.709 * (N=937)	0.567 * (N=937)	0.571 * (N=275)
Other	0.618 * (N=57632)	0.656 * (N=57632)	0.733 * (N=44691)	0.692 * (N=44691)	0.625 * (N=12941)

4.2.3. Global and Regional Differences from ERA5

The distribution of differences between satellite and ERA5 (satellite minus ERA5) are given, globally and by hemisphere in Figure 15 and Figure 16 for SWH and WSP respectively. The data in Figures 15 and 16 are divided into the mode of S3B in order that the distributions represent the same times/locations, but only show those data where SWH or wind speed is above 1 m or 1 ms^{-1}. Similar plots for the major ocean basins are given in Figure 17 and Figure 18 but for brevity they are not further divided by S3B operating mode.

Globally, ERA5 SWH tends to be higher (negative values) than the satellite values, it is not possible to say whether this is due to overestimation in ERA5 or underestimation by the satellites. The distribution of S3B LRM minus ERA5 appears to be similar over all geographic regions, except in the North Indian Ocean where the signal is noisy (probably as a result of the low number of data, N= 2285). Both S3A and S3B in SAR mode tend, on average, to be lower than ERA5 in the Northern Hemisphere whereas in general the differences are reduced in the Southern hemisphere even swapping sign in the Southern Ocean. PLRM has a similar pattern to SAR mode but with a larger global offset (i.e. PLRM minus ERA5 has a lower mode than that for SAR).

For wind speed at the global and hemispheric scale there are no major departures from zero, suggesting that there are no offsets amongst ERA5 and any satellite measurements. At the basin scale, the only offsets in wind speed are in the Arctic and Southern Oceans with negative offsets (ERA5 high compared to satellite) and positive offsets (ERA5 low compared to satellite) respectively.

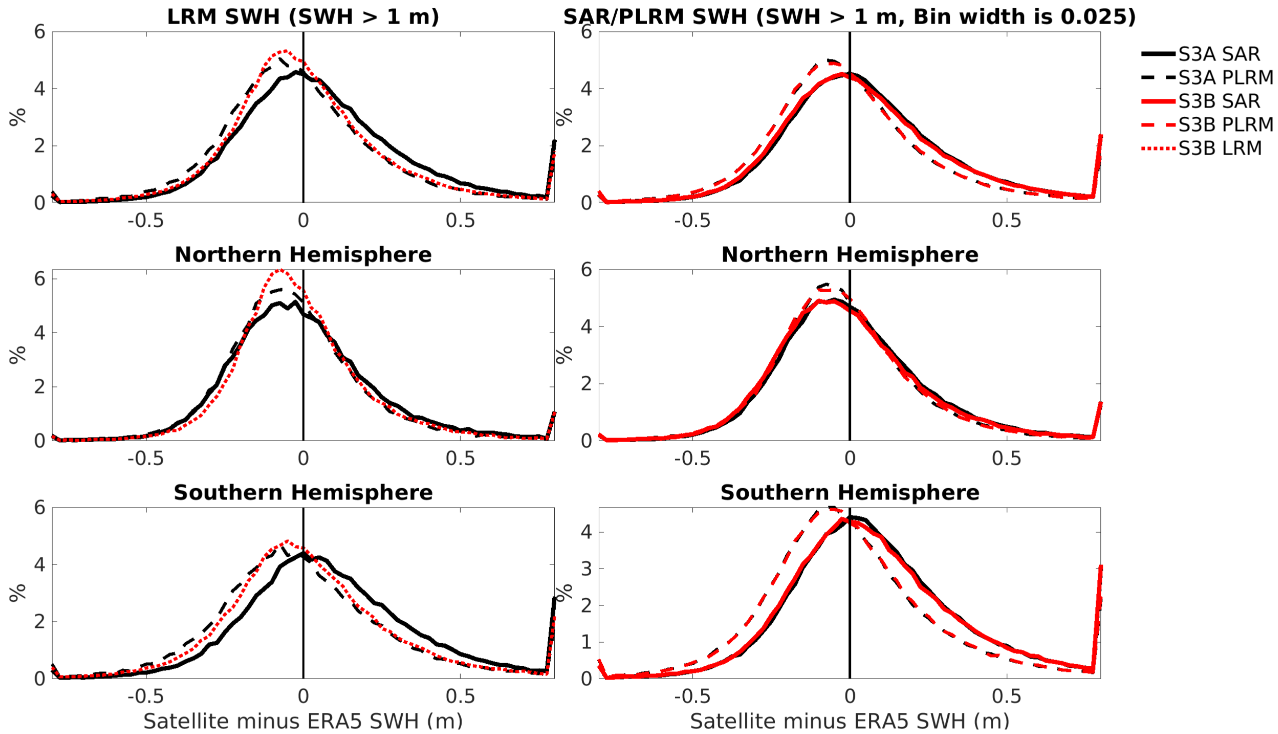


Figure 15 Distributions of ERA5 minus satellite significant wave height (SWH) globally (top) and by hemisphere.Results are split by S3B mode between LRM (left) and SAR/PLRM (right).

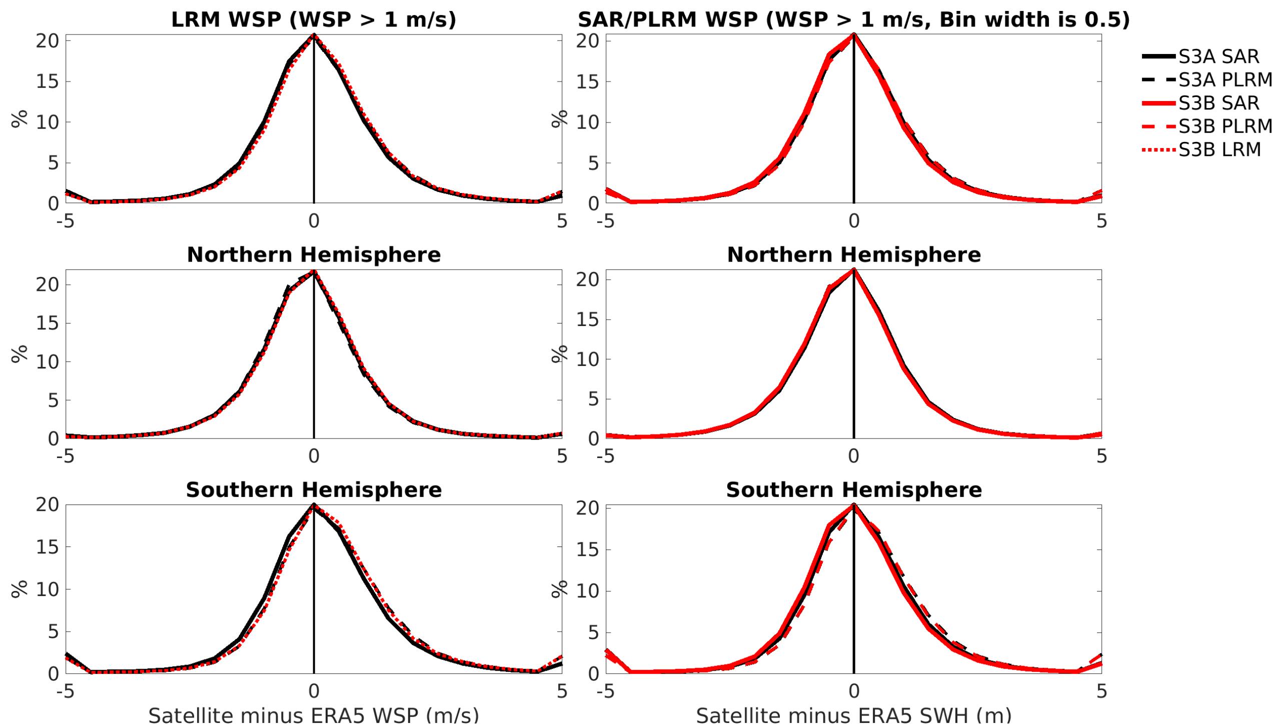


Figure 16 Distributions of ERA5 minus satellite wind speed globally (top) and by hemisphere. Results are split by S3B mode between LRM (left) and SAR/PLRM (right).

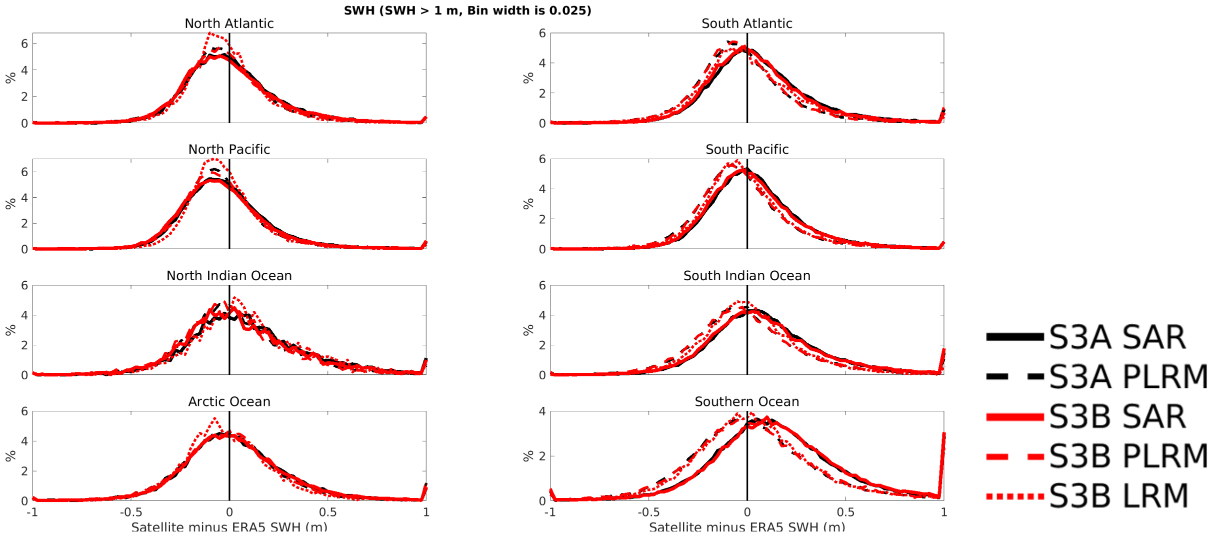


Figure 17 Distributions of ERA5 minus satellite significant wave height (SWH) by basin.

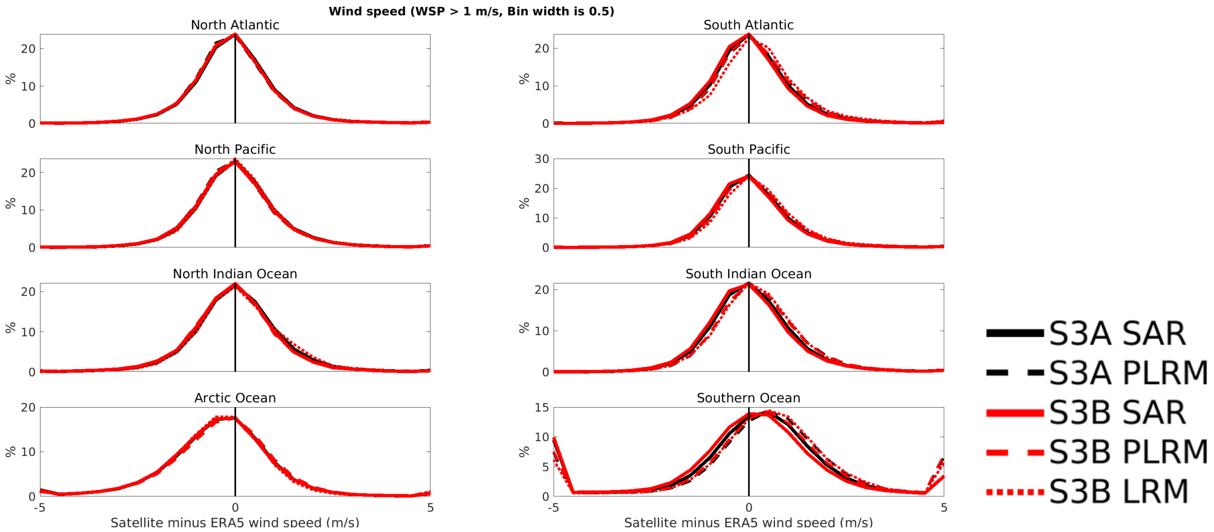


Figure 18 Distributions of ERA5 minus satellite wind speed by basin.

4.2.4. Triple Collocation Invoking ERA5

In this section, triple collocation is applied, not with buoys, but instead with ERA5 collocations with the S3A and S3B satellites, allowing an ~100-fold increase in data volume.

Figure 19 shows the first set of triple collocations done this way for SWH. Here, one can see that there is very similar performance between the two satellites, for both SAR and PLRM mode (having a standard deviation of the error ~0.05 m and ~0.10 m respectively). As for the earlier analysis, SAR mode is shown to have better performance than PLRM for SWH. Here S3B in LRM is seen to have performance in between the two other modes (i.e. higher standard deviation of error compared to SAR but lower than PLRM). ERA5 is shown here to have the highest standard deviation of error (in the range 0.18 m to 0.23 m), possibly linked to different space-time sampling in the gridded data.) this may make the ERA5 estimate unreliably high.

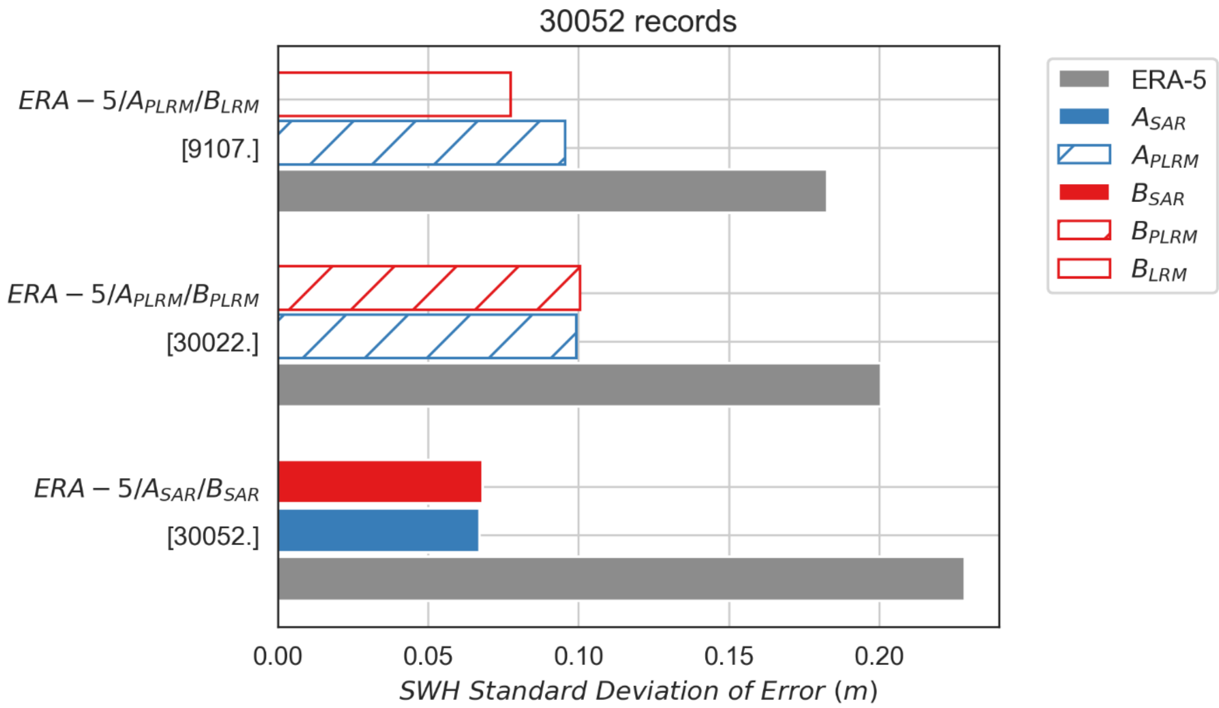


Figure 19 Triple collocation results for all 3 dataset groupings (comparing ERA-5 and the two Sentinel 3 satellites in each mode) showing the estimated standard deviation of the SWH error, a proxy for SWH noise.The numbers on the y-axis under the names of the datasets compared indicates the number of records compared in each grouping.

Figure 20 shows the triple collocations with ERA5 for wind speed. Here one can see good agreement between the two satellites in PLRM (at approximately 0.15 ms-1). For SAR mode, S3A has higher standard deviation of error compared to S3B (0.18 ms-1 versus 0.12 ms-1) consistent with the previous set of analysis. Here S3B in LRM mode is seen to have similar performance to the PLRM modes. ERA5 is again shown here to have the highest standard deviation of error (~1.1 ms-1).

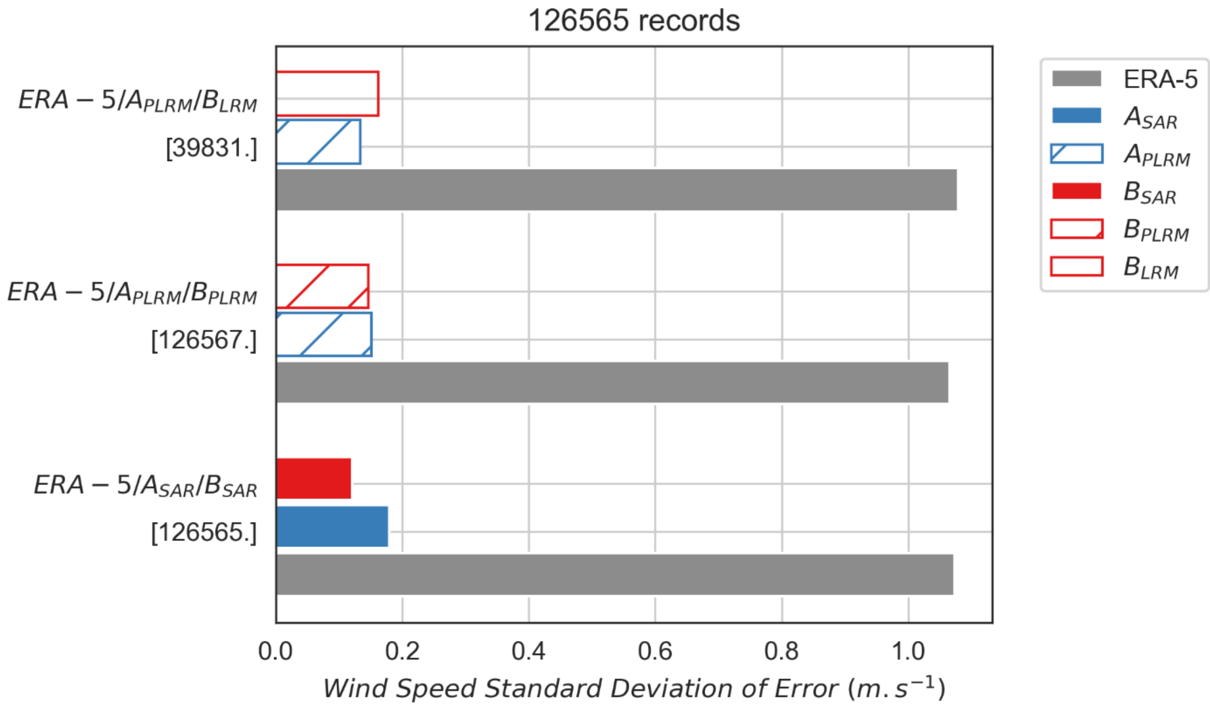


Figure 20 Triple collocation results for all 3 dataset groupings (comparing ERA-5 and the two Sentinel 3 satellites in each mode) showing the estimated standard deviation of the wind speed error, a proxy for wind speed noise. The numbers on the y-axis under the names of the datasets compared indicates the number of records compared in each grouping.

5. Conclusions

In this report, we have presented the results of a two-part assessment study of sea state (Significant Wave height and Wind Speed) during the tandem phase of S3A and S3B. It has not been possible to look at inter-seasonal performance of Sentinel-3 as the S3A/S3B tandem phase (June–October 2018) was not long enough. This is particularly the case for the comparisons of S3A SAR with S3B LRM (less than a month of data) where the tandem provided an unprecedented, but too short, opportunity to compare directly LRM with SAR/PLRM data. Even so, from our results, several conclusions can be drawn and are detailed below.

5.1. Part 1: Comparisons with Buoys

The matchup with buoys produced a relatively low numbers of collocations, particularly for S3B LRM, but still made it possible to make some general remarks about the relationship between S3A, S3B, buoys and ERA5 data.

In general, the correlations observed between S3 and buoys are higher than the correlations between S3 and ERA5. This is likely to originate from differences in the space-time sampling of buoys, satellites and ERA5, where buoys and satellites are better able to capture small scale variability that cannot be resolved by gridded model data.

For SWH, of all pairs of data, highest correlation is obtained between SAR mode data from S3A and S3B. S3B LRM appears to be more noisy (Figure 4 and Figure 6).

Conversely, for wind speed, S3B LRM consistently correlates best with buoys and ERA5 (followed by S3A PLRM). In fact, for wind speed the correlations of LRM with ERA5 and buoys is higher than between ERA5 and buoys.

Triple collocation results support the findings above that SAR performs better for SWH (for noise), and LRM (or PLRM) better for wind speed. However, there are concerns over the reliability of the estimates due to the small number of collocations with buoys. Triple collocation analysis is highly sensitive and its robustness requires large volumes of good quality data.

5.2. Part 2: Comparisons with ERA5

Collocations between S3A, S3B and ERA5 produced significantly more matchup data. However, it should be remembered that the ERA5 dataset also contains uncertainties and should not be considered perfect.

On average, ERA5 SWH is lower than any satellite estimate when all data are considered (Figure 9 or Table 2). When low sea state conditions are removed, then S3A and S3B values are much more consistent with ERA5. Investigations in §4.2.2 indicate high level of agreement between all SWH datasets, which increases further when low sea state conditions are excluded. 4.2.3 S3B LRM SWH correlates highly with S3A PLRM but less well with S3A SAR and even less so with ERA5 (Figure 13 and Figure 14).

For wind speed, Figure 8, and to a lesser extent Figure 10 and Tables 4–5, suggest that LRM wind speed is slightly overestimated compared to ERA5 and other S3 modes. In most regions, except high latitudes, LRM wind speed is highest. All correlations between the various wind speed estimates are positive although the spread is higher than for SWH (i.e. noisier).

Triple collocation results with ERA5 show that S3 SAR mode has the least noise when analysing SWH, and that S3A and S3B have almost identical noise levels in both SAR and PLRM. For wind speed, all modes show similar noise levels, however S3A has noticeably more noise than S3B in SAR mode.

6. References

Abdalla, S. (2012). Ku-Band Radar Altimeter Surface Wind Speed Algorithm. *Marine Geodesy, 35*, 276-298

O'Carroll, A.G., Eyre, J.R., & Saunders, R.W. (2008). Three-Way Error Analysis between AATSR, AMSR-E, and In Situ Sea Surface Temperature Observations. *Journal of Atmospheric and Oceanic Technology, 25*, 1197-1207

Tokmakian, R., & Challenor, P.G. (1999). On the joint estimation of model and satellite sea surface height anomaly errors. *Ocean Modelling, 1*, 39-52