Global Southern Ocean Apex Surface Mooring (GS01SUMO) Data Quality Report
Evaluation Date: 5/22/2018

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Review Summary
This report summarizes a data quality review of the Global Southern Ocean Apex Surface Mooring (GS01SUMO). In addition to the wave data, we also use wind speeds from the METBK sensors which measure atmospheric quanities. My goal is to understand the data quality from recovered datasets. My particular interest is to know how many large events (Hs>10 m) are captured and the quality of those events. The eventual goal is to use these data as reference for calibration of different satellite technologies such as altimeters and synthetic aperture radars. In this report we also use satellite and model data as reference to understand the differences with the buoy measurements. This particular station is interesting due to its remote location and high occurrence of large sea states. We summarize recommendations regarding the data quality in the last section.

This report follows these steps
1) Data Availability - What data are available? Are they relevant to the study?
2) Metadata - What metadata are available? Are they complete? Is anything missing? What does it tell you about the dataset (for good or bad)?
3) Understand the context - Plot a large range of data. Does it look right based on what you would expect? What are the ranges, and do they make sense?
4) Focus on one or more smaller ranges to see if data look reasonable - PPlot some smaller periods (in space or time) to see if they look correct or have issues.
5) Environmental comparisons - Compare the dataset with other datasets, from the cruise/shipboard data, satellites, and models.
6) Summary and outlook – Give recommendations of the data quality

1) Data Availability

In this report, we will evaluate the surface wave buoy (specifically wave spectra) from the Global Southern Ocean Apex Surface Mooring (GS01SUMO), focusing on the recovered deployment datasets from 2015-2016. Additional instruments on the mooring are listed for reference and could be used for further evaluation.

We focus on the recovered data stream in this review because they might be more data available. There are 2 deployments I will focus on (1 & 2). This can be seen here:
http://ooi.visualocean.net/instruments/view/GS01SUMO-SBD12-05-WAVSSA000#deployments

Deployment	Cruise	Start Date	Stop Date	Mooring Asset	Node Asset	Sensor Asset	Latitude	Longitude	Deployment Depth	Water Depth
1	AT-26-29	02/18/2015	12/27/2015	CGMGS-01SUMO-00001		CGINS-WAVSSA-05971	-54.4083	-89.3575	0	4611
2	NBP-15-11	12/14/2015	12/12/2016	CGMGS-01SUMO-00002		CGINS-WAVSSA-04571	-54.4041	-89.2069	0	4588
3	NBP16-10	11/25/2016		CGMGS-01SUMO-00003		CGINS-WAVSSA-05971	-54.4076	-89.3567	0	4612

Additionally a graph of data availability is available here: http://ooi.visualocean.net/instruments/view/GS01SUMO-SBD12-05-WAVSSA000

2) Metadata

In this section, we will review some of metadata available in the system to make sure it is present and correct.

2a) First, we grab some basic vocabulary information (metadata) from the system to make sure we have the right instrument.

For wave data:

https://ooinet.oceanobservatories.org/api/m2m/12586/vocab/inv/GS01SUMO/SBD12/05-WAVSSA000

[{u'mindepth': 0.0, u'instrument': u'Surface Wave Spectra', u'tocL3': u'Surface Buoy', u'vocabId': 1237, u'tocL1': u'Global Southern Ocean', u'maxdepth': 0.0, u'tocL2': u'Apex Surface Mooring', u'model': u'TRIAXYS', u'refdes': u'GS01SUMO-SBD12-05-WAVSSA000', u'@class': u'.VocabRecord', u'manufacturer': u'Axys Technologies'}]

For wind speed data:

https://ooinet.oceanobservatories.org/api/m2m/12586/vocab/inv/GS01SUMO/SBD12/06-METBKA000

[{u'mindepth': -5.0, u'instrument': u'Bulk Meteorology Instrument Package', u'tocL3': u'Surface Buoy', u'vocabId': 1238, u'tocL1': u'Global Southern Ocean', u'maxdepth': -5.0, u'tocL2': u'Apex Surface Mooring', u'model': u'ASIMET', u'refdes': u'GS01SUMO-SBD12-06-METBKA000', u'@class': u'.VocabRecord', u'manufacturer': u'Star Engineering'}]

-Looks good and there are data in the system.

2b) Deployment Information

Next, we grab some information about the deployments for this instrument. We will grab all of the recovered deployments available in the system and then output the date ranges, latitude/longitude, asset ID, and sensor ID for each. Note that the “reference designator” specified above represents the geographical location of an instrument across all deployments (e.g. the wave buoy on the Global Southern Ocean site), the “Sensor ID” (and its Asset ID equivalent) represent the specific instrument used for a given deployment (i.e. a unique make, model, and serial numbered instrument).

	asset_id	deployment	latitude	longitude	sensor \
0	1952.0	1.0	-54.40833	-89.357500	CGINS-WAVSSA-05971
1	1266.0	2.0	-54.40408	-89.206910	CGINS-WAVSSA-04571
2	1952.0	3.0	-54.40760	-89.356733	CGINS-WAVSSA-05971

	start	stop
0	2015-02-18 21:06:00	2015-12-27 11:20:00
1	2015-12-14 20:20:00	2016-12-12 07:58:00
2	2016-11-25 01:11:00	None

2c) Annotations

Relevant annotations for the instrument:

0 Upon recovery of deployment 2, damage to some components of the surface buoy were noted (e.g., FDCHP was bent, the tops of the METBK-PRC and FleetBroadBand antenna were missing).

	id	node	sensor	site	start	stop
0	95.0	SBD12	None	GS01SUMO	2015-12-14	2016-12-12

annotation \
0 Upon recovery of deployment 2, damage to some components of the surface buoy were noted (e.g., FDCHP was bent, the tops of the METBK-PRC and FleetBroadBand antenna were missing).
1 Deployment 2: Wind speeds may be low-biased (5%) at speeds > 5 m/s, as determined by comparisons with ship measurements and measurements from the FDCHP.
2 Deployment 3: At deployment (and continuing for several months), the sea surface temperature sensor exhibited random spikes. In the beginning of the deployment, the conductivity and salinity measured by the two met sensors were offset by ~0.01 S m-1 and ~0.1 psu, respectively (SBD12 was lower). The offset decreased over time, and gradually switched to SBD12 values being slightly higher (around Nov 2017). There was also a LWR (longwave radiation) offset of ~5 W m-2.

	id	node	sensor	site	start	stop
0	95.0	SBD12	None	GS01SUMO	2015-12-14 00:00:00	2016-12-12 00:00:00
1	766.0	SBD12	06-METBKA000	GS01SUMO	2015-12-14 20:20:00	2016-12-12 07:58:00
2	768.0	SBD12	06-METBKA000	GS01SUMO	2016-11-25 01:11:00	None

-So for the wave wave spectra: there is an annotation currently in the system, and it's for deployment 2: “surface buoy was bent and the METBK-PRC sensor antenna was missing.” I am not sure how this will impact the quality of the data.

-For the wind speeds, there are 2 annotations currently in the system, but only the first is relevant for this report:
-deployment 2 wind speeds are biased low (5%) compared to ship measurements
-deployment 3: At deployment (and continuing for several months), the sea surface temperature sensor exhibited random spikes. In the beginning of the deployment, the conductivity and salinity measured by the two met sensors were offset by ~0.01 S m-1 and ~0.1 psu, respectively (SBD12 was lower). The offset decreased over time, and gradually switched to SBD12 values being slightly higher (around Nov 2017). There was also a LWR (longwave radiation) offset of ~5 W m-2.
The wind speeds will further analyzed to verify this underestimation.

3) Understand the context of the data - full time series

This is a time series of the main sea state variables of interest:

Hm0 - significant wave height

Tp - peak wave period,

Dr – average wave direction,

N – number of waves that cross the mean water level

U10 – wind speed estimated from the METBK sensor and corrected for atmospheric stability under neutral conditions and to the height of 10 m

S – non-dimension wave power spectral density as function of frequency

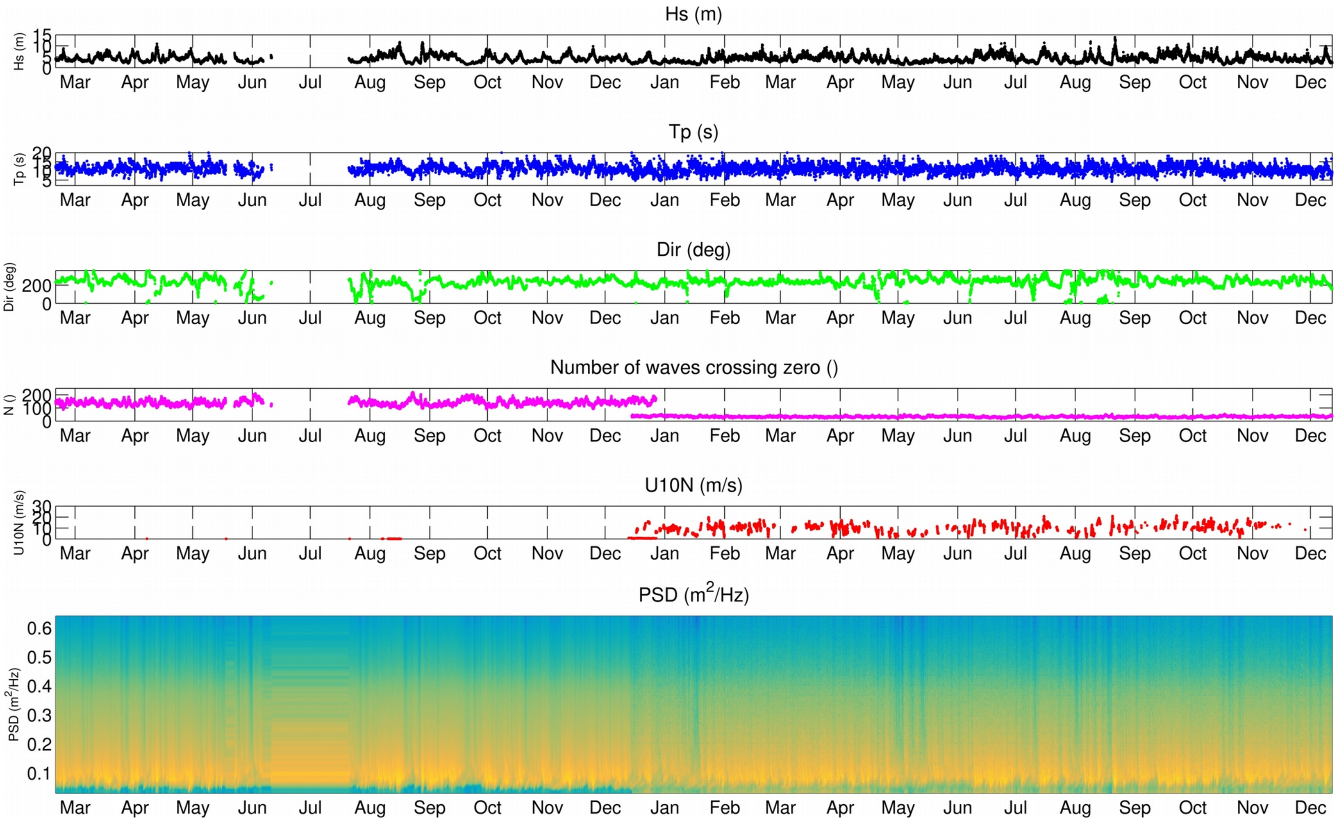

Figure 1 Time series of Hs, Tp, Dr, N (zero crossing), U10N, and wave spectra.

At a first glance the data seems reasonable and consistent with the wave climate of the region. The sea state is very active with average seas above Hs>4 m. The wave heights are large due to the fact that there is a large and presumably infinite fetch available to generate waves (i.e. the large and unimpeded expanse of ocean available in the Southern Ocean).

-There is one stretch of missing data and only a few points that drop below the lower limit (Hs>2.5 m).

-The peak period and average direction (dominantly from the WSW) seem reasonable.

-The U10N has a lot of missing data for this 2-year period. Several values are less than 2 m/s which seem odd for this location and are mostly incorrect.

-The wave spectra is very broad-band with energy in the PSD across all frequencies suggesting there are a combination of wind seas and swells throughout the year.

-Notice that the number of waves crossing zero changes between deployment 1 and deployment 2. This is concerning because it suggests that the time the buoy measurements were taken changes. The wave statistics computed using different averaging times could indeed be different.

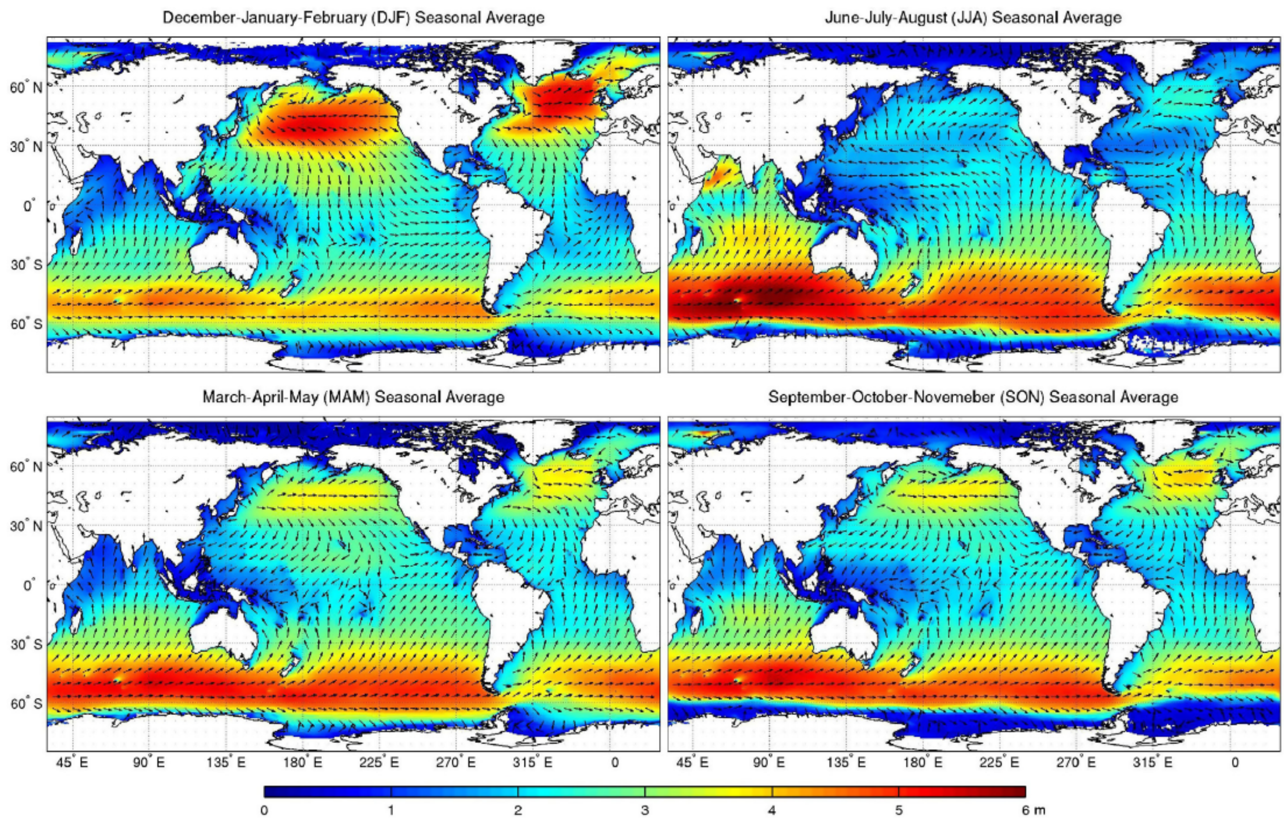

Figure 2 showing average Hs (color) and average wave direction (Dr) from a wave hindcast forced by the Climate Forecast System Reanalysis wind speeds and ice concentrations. Reproduced from Stopa et al., 2013 OCEMOD, their Figure 3.

To deepen the context. I included a plot (Fig. 2) from Stopa et al., 2013 OCEMOD showing the average wave height (Hs) and average wave direction from a wave hindcast using 30 years of data (1980-2009). This shows on average our location (lon=-89.20691W, lat=-54.40408) or approximately (270E,55S) typically has wave heights of at least 5 m throughout the year. Also notice that wave direction of WSW is consistent with the average wave direction plotted above.

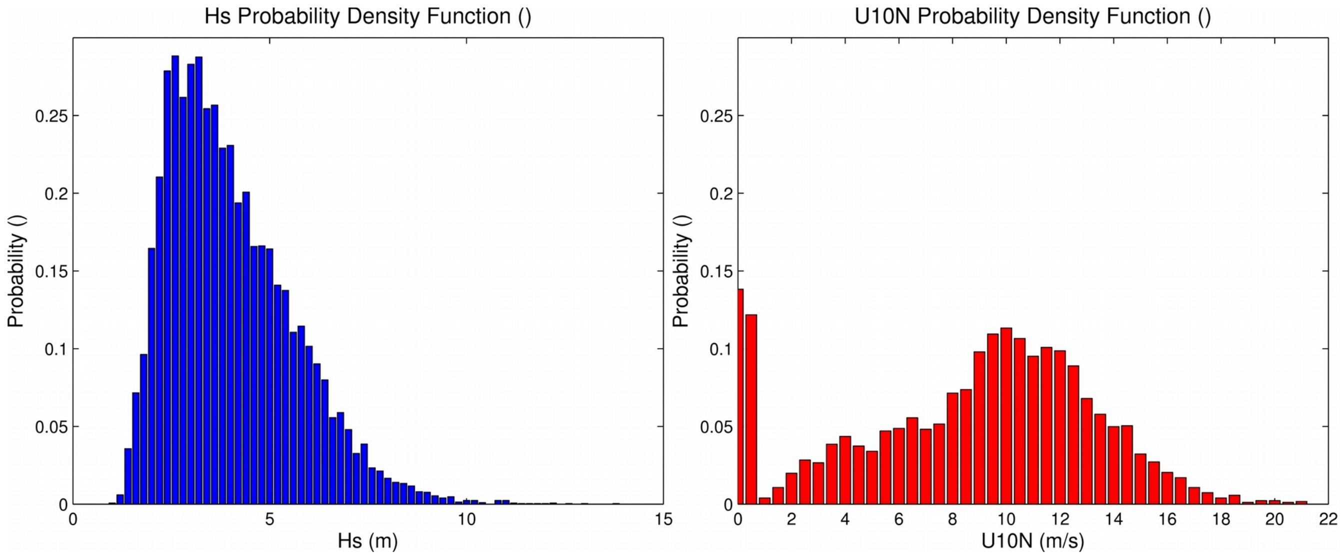

Figure 3: Probability density functions (PDFs) of Hs and U10N.

Here are some histograms to understand the range of data. The histogram of Hs should follow a Rayleigh distribution. It should be relatively easy to pick out the suspected 'bad' values less than Hs of 2 m seen in the time series plots. It seems there are only 2 'bad' values (will confirm later).

We made a similar plot the the wind speed (U10N) this should follow a Weibull distribution. This should also be relatively easy to pick out outliers or wrong data values. The annotation file states that the wind speeds were biased low by 5% for deployment 2 and will be evaluated in section 5.

4) A closer look

Look at data near the maximum wave height

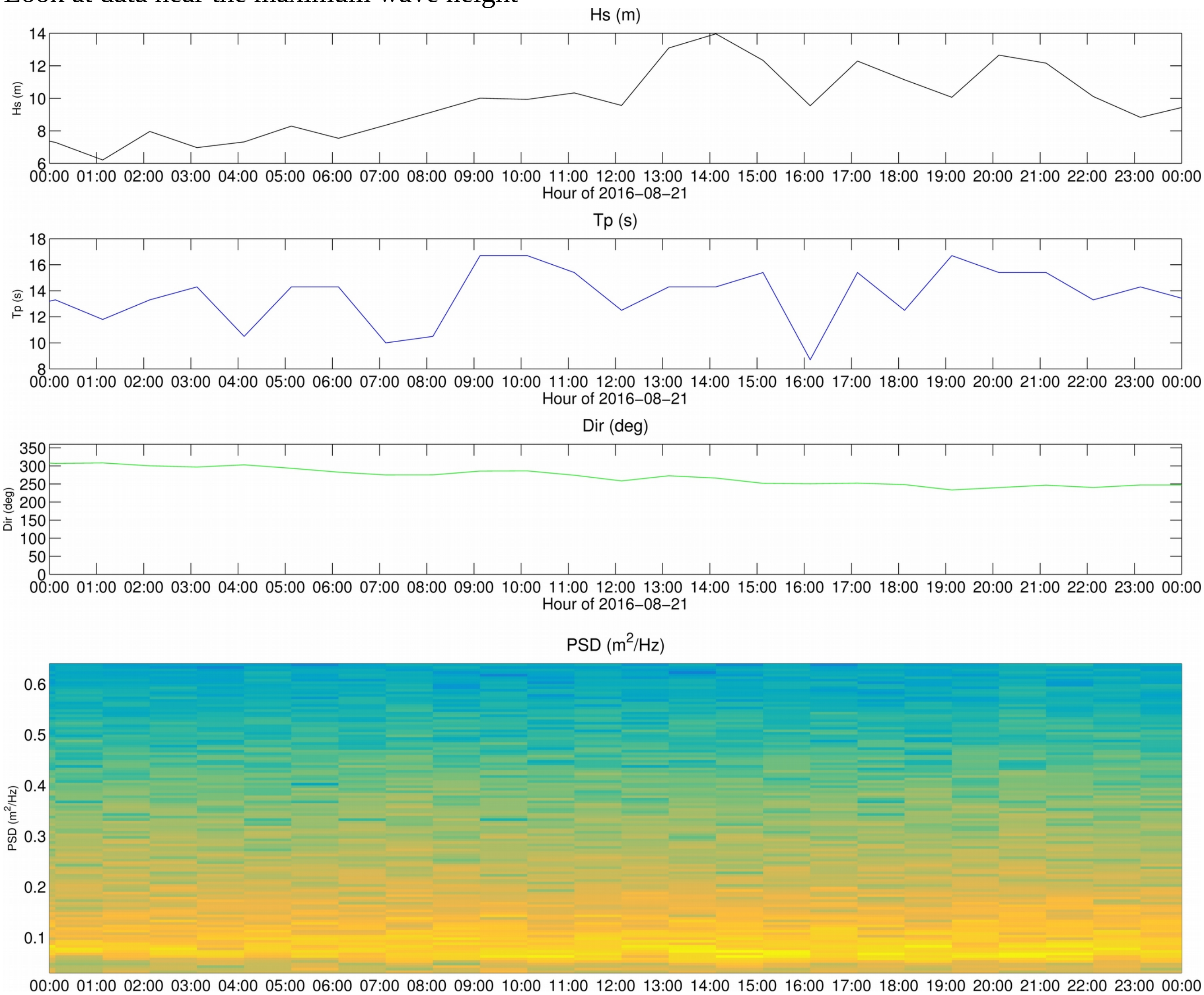

Figure 4: Time series near the day of the maximum wave height.

The data seems reasonable.

Next we explore the transition between deployment 1 and deployment 2 during December 2015.

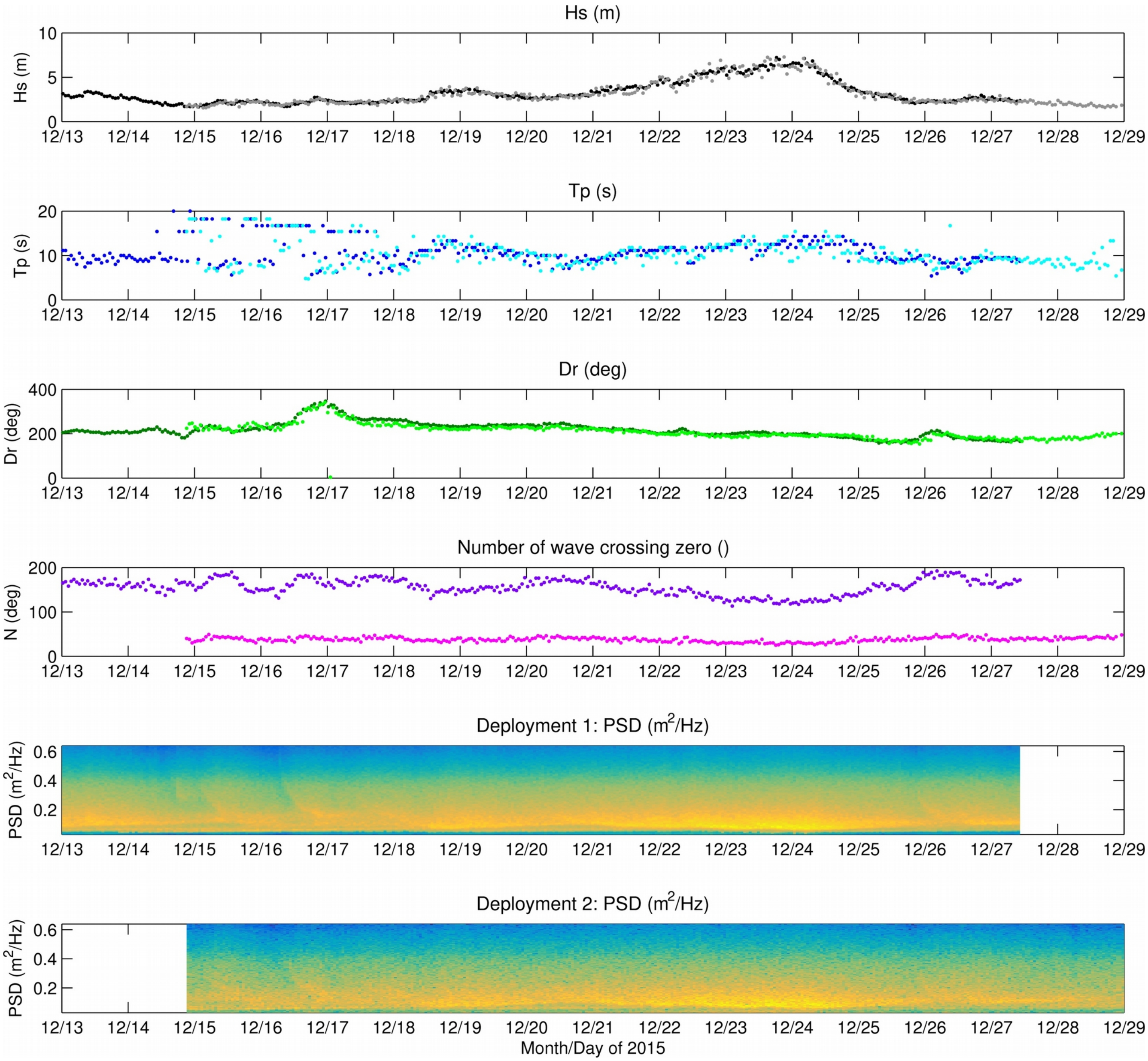

Figure 5: Time series of wave parameters during the transition from deployment 1 and deployment 2. The darker color represents deployment 1 and the lighter color represents deployment 2 on subplots 1-4. Panels 5 and 6 represent the wave spectra for deployment 1 and deployment 2.

From this depiction, it is likely that the time interval of the measurements is changing from deployment 1 and 2. For the deployment 1 it is probable that the wave statistics are computed from a longer time series compared to deployment 2. This is consistent with the fact that the wave parameters (Hs, Tp, Dr) have less variability, there are nearly 100 more waves that cross the mean sea level, and the PSD is less noisy for deployment 1 compared to deployment 2.

Next we look at the relationship between different sea state variables to understand the relationships.

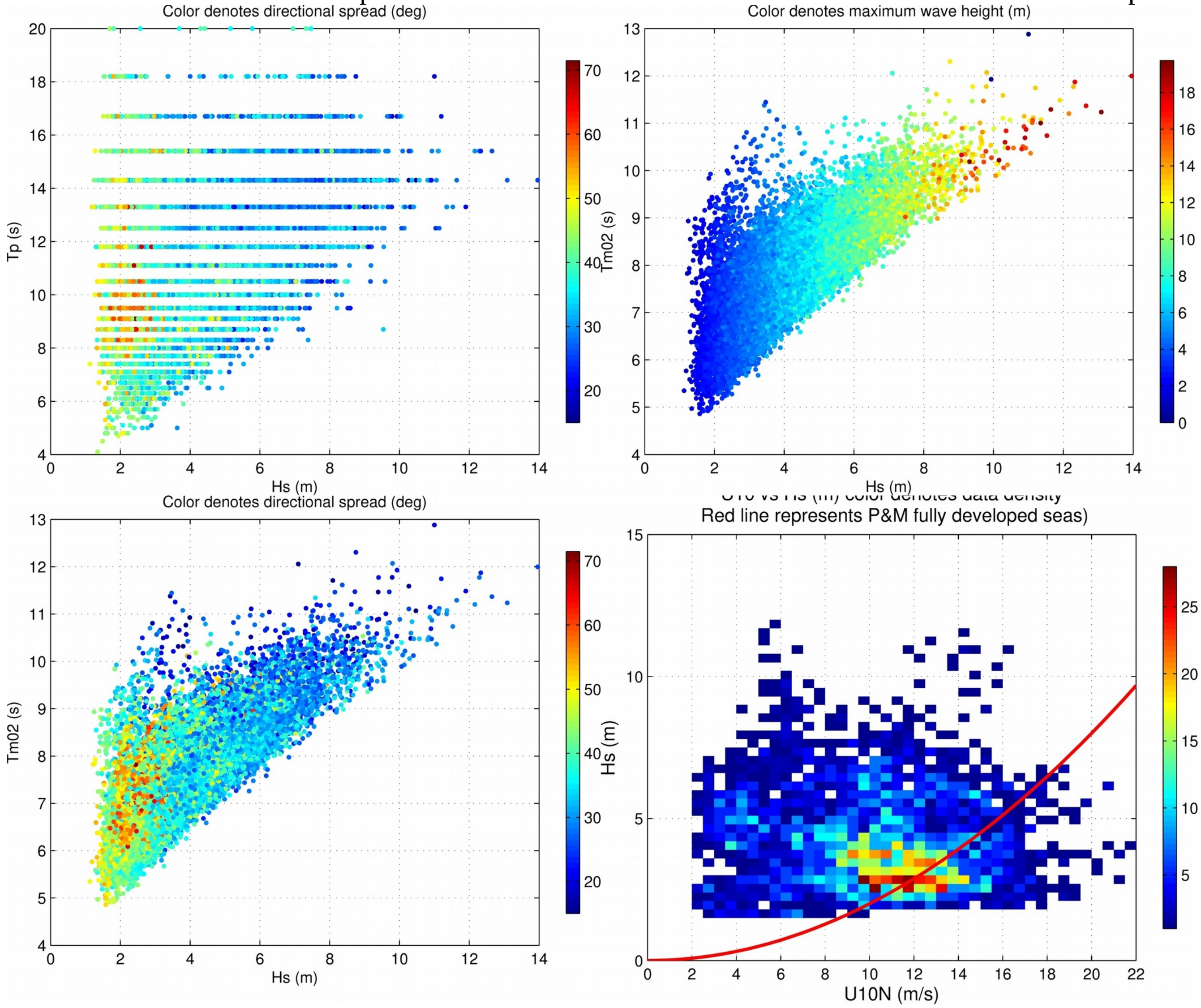

Figure 6: Scatter plots showing the relationship between various sea state parameters. The top left shows the Hs vs Tp vs directional spread (color). The top right shows the Hs vs the average wave period (Tm02) vs the maximum wave height (color). The bottom left shows the Hs vs Tm02 vs the direction wave spread (color). The bottom right shows U10 vs Hs vs occurrence (color). The red line represents the Pierson-Moskowitz fully developed seas.

All datasets seems reasonable. There are few points worth noting:
-The Hmax is most likely inconsistent between deployments 1 & 2 due to the change in averaging time
-The longest waves (large Tp) do not have the tallest seas.
-The largest sea states (large Hs and Tm02) have typical a small directional spread
-There is a mix of wind seas and swell with a higher occurrence of swell (bottom right panel). If a data point lies above the red line it is considered swell.

5.) Comparison with external data sources

5a) Buoy – ship comparison: U10

First we compare the wind speeds from the ship anemometer to the buoy. The wind speeds were recorded from the Nathaniel Palmer during December 2015. The height of the anemometer is nearly 10 m and should be comparable to the wind speeds in the flux product derived from the METBK observations.

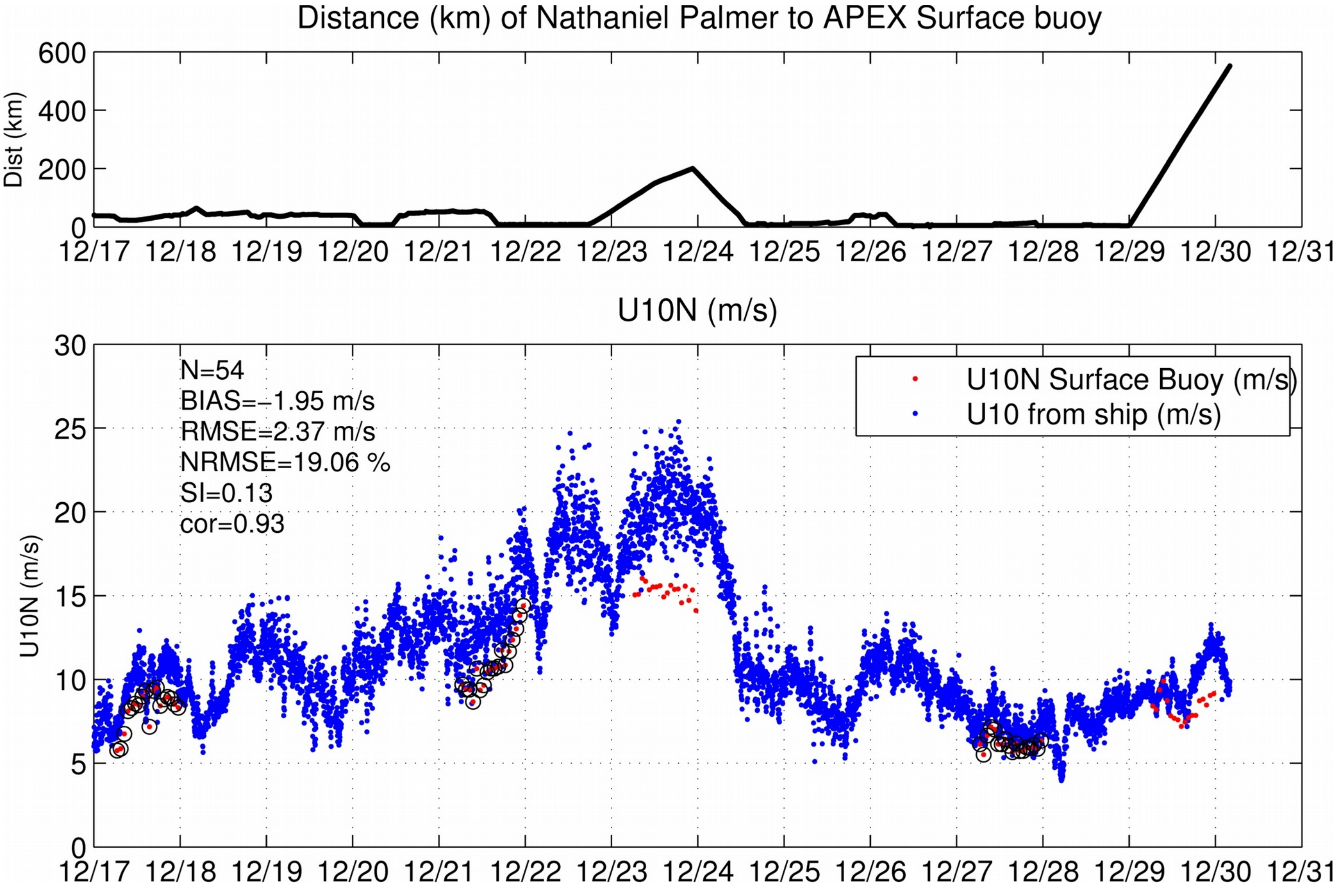

Figure 7: Time series of the distance in km of the ship to the APEX surface mooring (top). The time series of the wind speeds from the ship and buoy. The points with a black circle had distances less than 50 km and are deemed close enough to be used to calculate the error statistics shown in the top left corner of the panel (bottom).

There are many missing data during this period. Note that we are using the flux data meaning the wind speed is already corrected for atmospheric stability and estimated at 10 m from the surface. There might be more data available during this period than shown but perhaps any of the other sensors besides the buoy anemometer might have poor quality data.

-The buoy is typically 2 m/s less than the ship observations which equates to a normalized root mean square error of 19%.

-The scatter is generally low and the data are well correlated (0.93).

Therefore we can corroborate the annotation that the buoy wind speed is underestimated. We find the underestimation might be larger than the reported 5%; however this is only for a relatively small sample size of 54.

5b) Buoy – altimeter comparison: Hs, U10, mean square acceleration

There are 3 mission available during this time period: 1) CRYOSAT 2) JASON2 3) SARAL. We co-located these three mission to the buoy observations with distances less than 100 km and time differences less than 1.5 h. A single altimeter track is then averaged across its track and used as a single match-up between the buoy measurement.

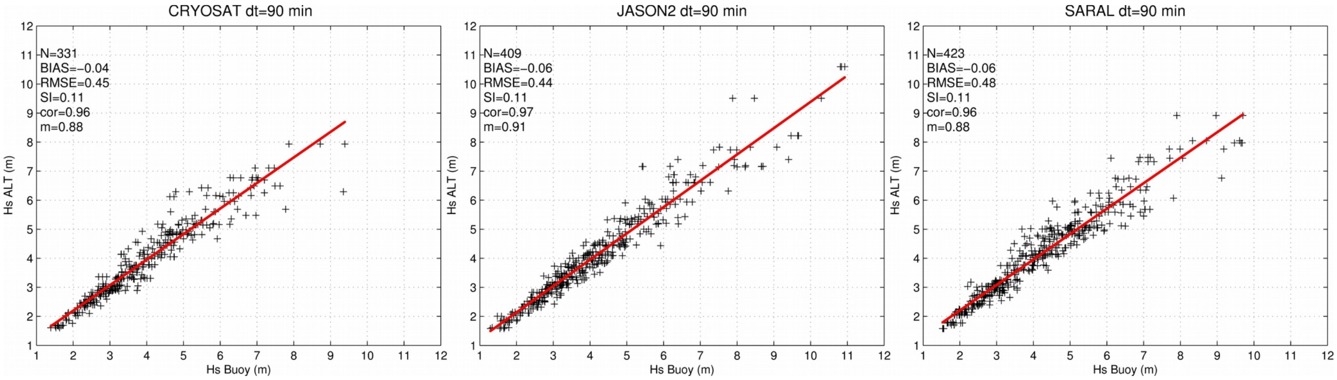

Figure 8: Buoy Hs observations versus Hs from CRYOSAT (left), JASON2 (middle), and SARAL (right) for all co-locations for deployment 1 and 2 (Feb 2015 – Dec 2016). The error metrics give the number of observations (N), bias, root mean square error (RMSE), scatter index (SI), correlation (cor), and slope of a linear regression (m).

Most of the data points reasonably match. However at high sea states (Hs>6 m) there seems to be larger discrepancies between the buoy and altimeter. All datasets are highly correlated with R>0.96. The altimeters seems to underestimate the Hs using the buoy as reference. Each altimeter has different configurations (polarization, altitude, etc) and these sensitives could be further explored.

High sea states are volatile, thus some of the differences could be explained by not having a precise match in time. Therefore we reduce the time constraint (or space) for co-location to understand the impact.

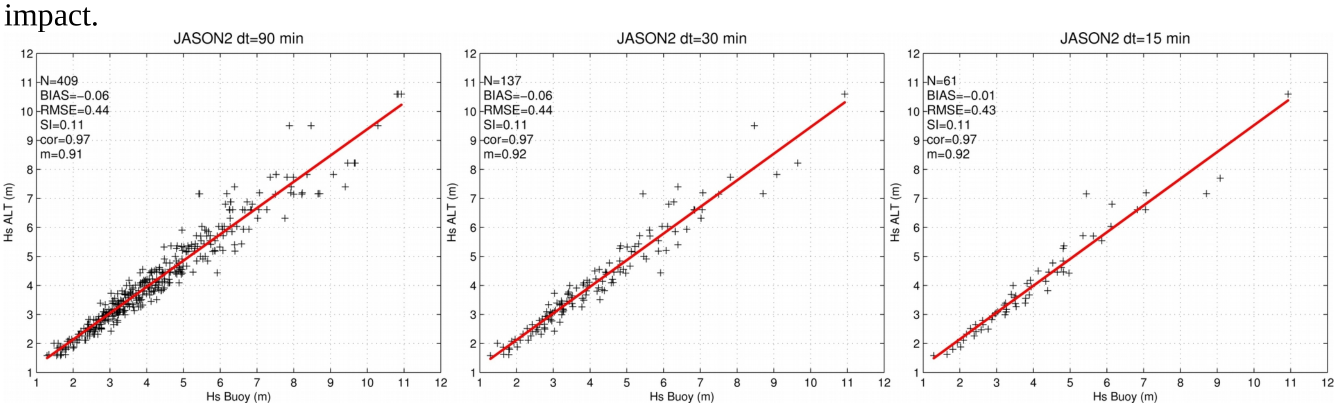

Figure 9: Same as Figure 8 except here we focus only on JASON2. The left panel shows the co-locations with dt<90 min. The middle panel shows the co-locations with dt<30 min. The right panels shows the co-locations with dt<15 min.

It is surprising the error metrics do not change considerably when the time constraint is reduced. There are still considerable differences in Hs of 1-2.5 m when dt<15 min.

Next we compare the wind speeds from the buoy to the altimeters. We took a similar approach and co-locate the satellites in space and time to the buoy measurements.

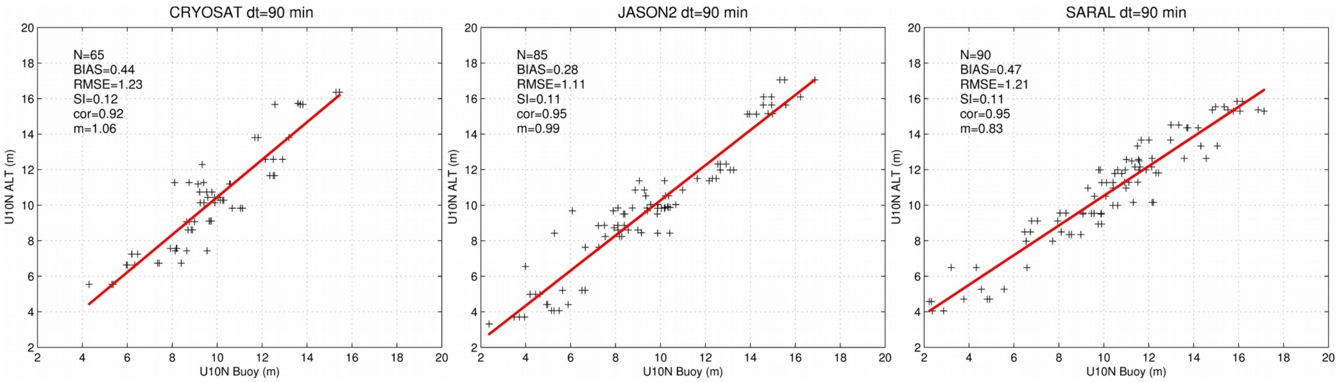

Figure 10: Same as Figure 8 but for U10. Buoy U10N observations versus U10N from CRYOSAT (left), JASON2 (middle), and SARAL (right) for all co-locations for deployment 1 and 2 (Feb 2015 – Dec 2016).

The performance is considerably worse than Hs with a larger dispersion. The biases are positive (we assume the buoy is the reference: ALT-buoy) which is consistent with the underestimation found by comparing the ship to the buoy observations. RMSEs are typically 1.2 m/s for all platforms. The U10N discrepancies can be as large as 5 m/s but are typically within 2 m/s.

Next we compare the mean squared acceleration (mss) which is defined as

$$M_p = \int_0^\infty (2\pi f)^p E(f) df.$$

where E is the wave spectrum, f is the wave frequency and p=4. This quantity is strongly related to the high frequency content of the wave spectrum and should be related to the sea surface roughness (sigma0) measured by the altimeters.

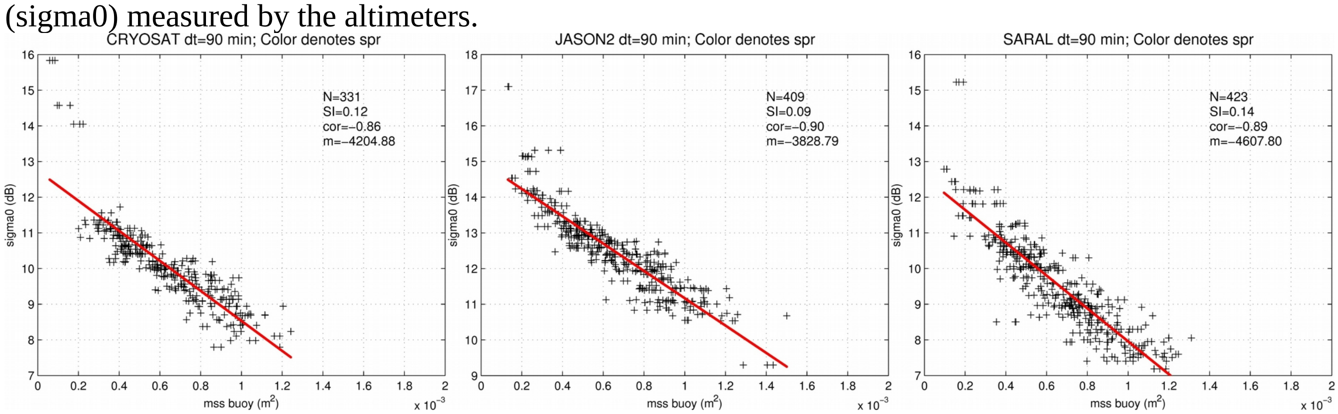

Figure 10: Same as Figure 8 but for mss and sigma0. Buoy mss observations versus sigma0 from CRYOSAT (left), JASON2 (middle), and SARAL (right) for all co-locations for deployment 1 and 2 (Feb 2015 – Dec 2016).

Note that the altimeter is “nadir-looking” so high wind speeds have a lower sigma0. The match is generally good but there is a larger dispersion than the Hs comparison. The correlations have reduced to 0.86. The buoy hull is large (4 m) and it is expected it cannot resolve high frequencies waves (e.g. >0.4 Hz). The size of the buoy will limit the science of the small scale waves.

5c) Buoy – model comparison: Hs, Tm02, Dr, and U10

In this section we compare data from a wave hindcast forced by NCEP's climate forecast system. The wave model data is linearly interpolated in time and space to match the buoy measurements for the duration of deployments 1 and 2.

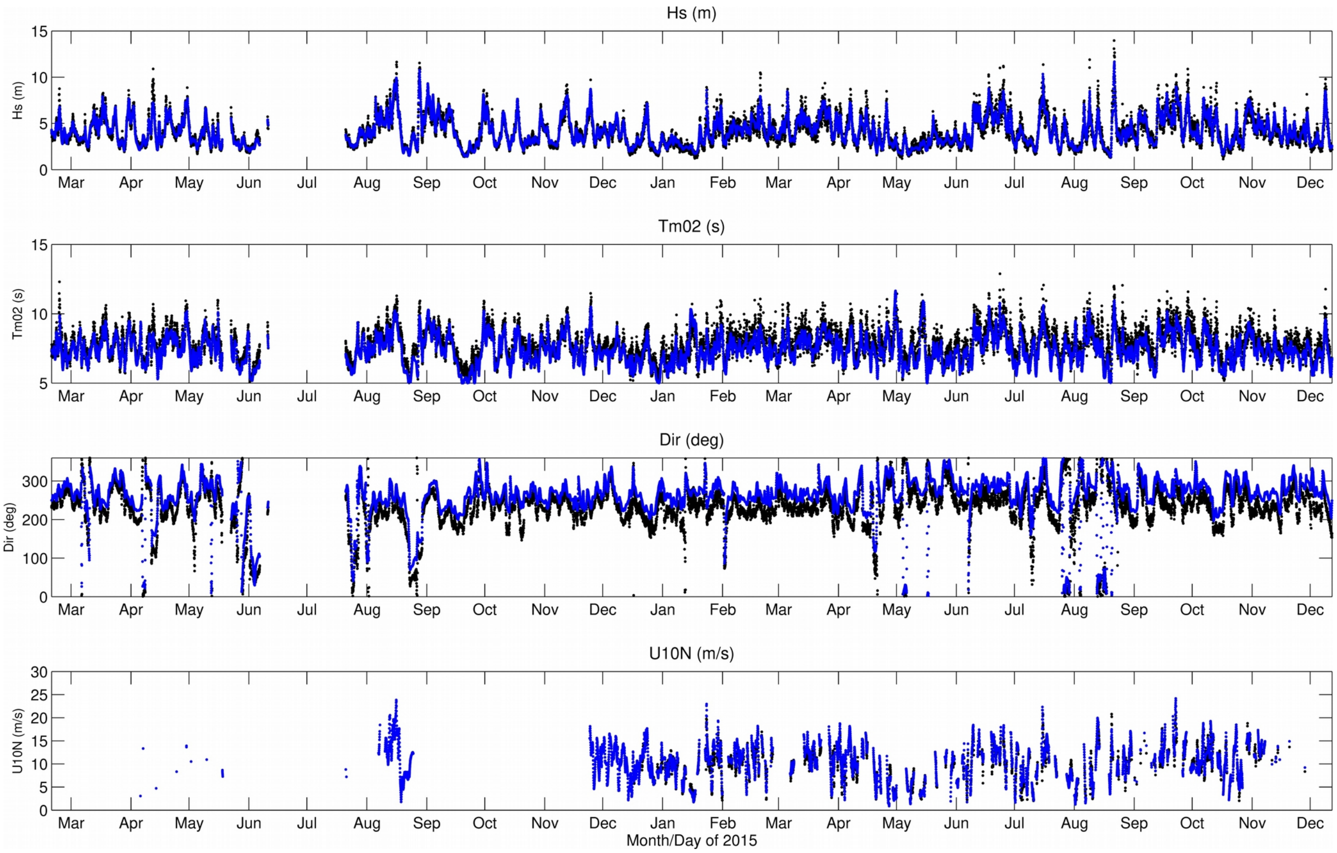

Figure 11: Time series plots comparing the buoy observations versus wave hindcast. The comparisons for Hs, (top panel), average wave period (2nd panel from the top), average wave direction (3rd panel from the top), and wind speed (bottom panel) give the buoy observations in black and the model in blue.

Some of the notable features:

-Hs and Tm02 from the model typically underestimates the largest events.

-The model typically has the wave direction from a more Northerly direction than observations.

-U10 is well matched in this depiction.

Next we compare the buoy and model more rigorously in scatter plots and compute error metrics to give a quantitative measure of the model (and/or the buoy) performance.

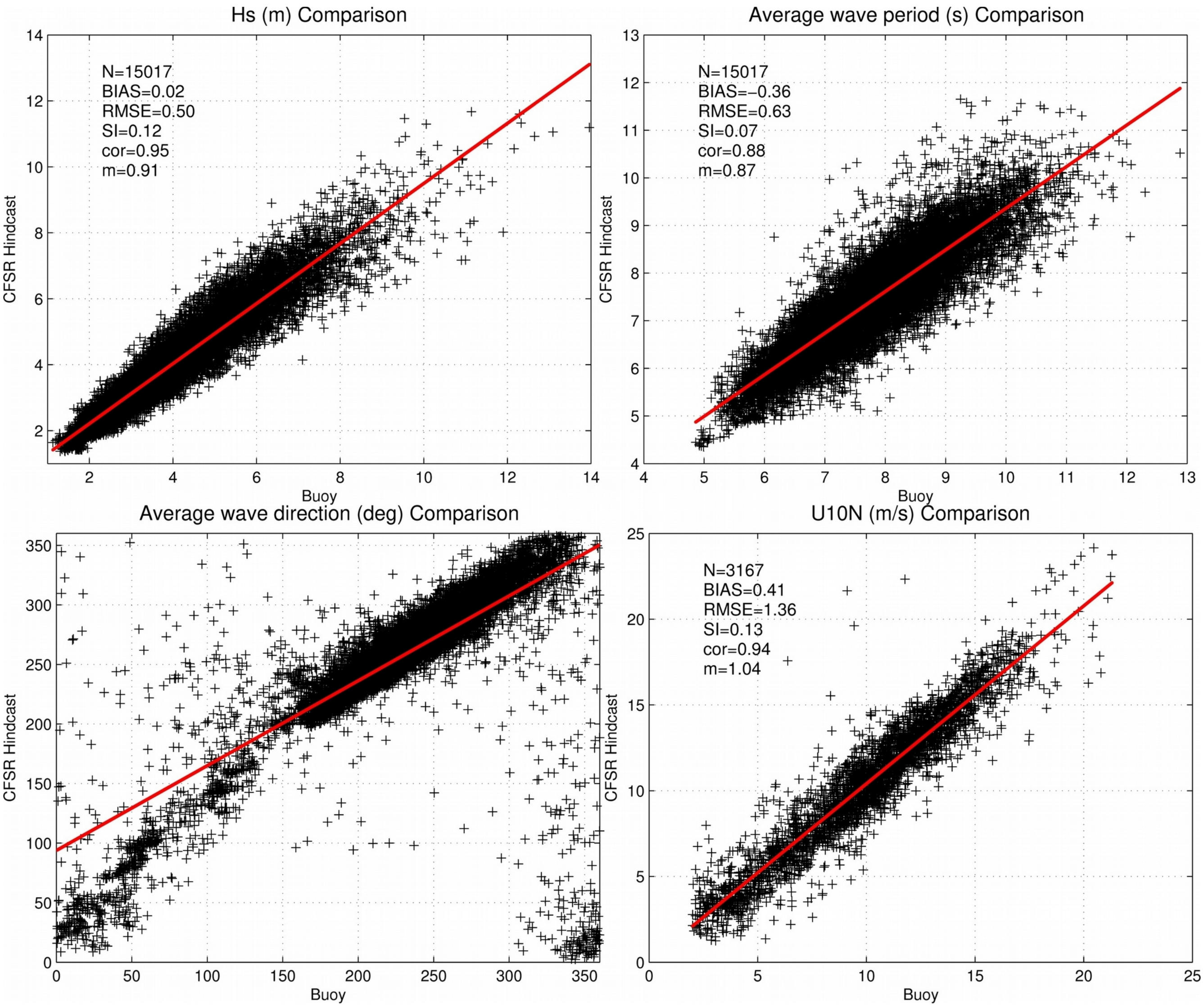

Figure 12: Scatter plots comparing buoy observations to model data. The top left panels compares Hs, the top right compares Tm02, the bottom left compares the average wave direction, and the bottom right compares U10N.

All model data seem to reasonably match the buoy observations given there are uncertainties in the model.

-Hs comparison is good and the error metrics are similar to what we see in other locations; there is nearly no bias and RMSE of 0.5 m.

-The Tm02 has more scatter and the model underestimates by 0.3 s.

-The majority of the wave directions are from the W to WNW; the model typically is slightly North of the buoy observations.

-The U10 from the model has a 0.4 m/s bias. However the buoy could be underestimating U10 explaining some of this bias consistent with comparison with the ship and altimeter observations.

6) Summary and Outlook

Summary

Based on this analysis of the Global Southern Ocean surface wave buoy, we can summarize that the buoy measurements are of good quality. Here we summarize the findings:

* The underestimation of the U10 was confirmed comparing the ship during December 2015. Our analysis shows that the underestimation could be has high as 20%, but this was based only on 50 data points.
* The comparison between the altimeters shows: Hs, U10, and mean squared acceleration (mss) are all within a reasonable range of the buoy observations. However some larger discrepancies exist and Hs residuals of up 2 m are probable. At this stage it is not clear whether the buoy or altimeter or a combination of both contribute to these discrepancies. The residuals were largest under high sea states. The U10 from altimeter had a positive bias compared to the buoy consistent with the idea that the buoy might be underestimating U10. The mss had the largest differences which could be reflective of buoy not being capable of capturing high frequency waves (due to its large size).
* The comparison between the model and buoy shows that the all buoy sea state parameters are within an acceptable range. In other words there were no obvious outliers. The U10 CFSR bias using the buoy as reference was only 0.4 m/s which is consistent that the buoy is underestimating U10.
* The time period the buoy recorded data and statistics were computed was not specified in any metadata. However it is likely the period was longer for deployment 1 compared to deployment 2. This was clearly demonstrated by jump in the number of waves crossing zero.
* It is not clear how the damage to the buoy and antenna denoted in the annotation affect the quality of the observations.

Outlook

One of the purposes was to use this site to compare satellite observations. It seems the buoy data are of good quality and no strong biases were seen with respect to altimeters or models. So it is likely this data could be used to more rigorously develop techniques to improve satellite estimation at high sea states.

When the sea state is particular large the buoy can be tilted and a bias (presumably underestimation) of the Hs can occur. This was first demonstrated when Hurricane Katrina traveled directly over a buoy from the NDBC network. This was described in the paper by Bender et al., JTECH 2010 and will be further explored for some of the extreme events. An additional motion package was mounted on the buoy and could be used a cross reference.

This remote location is of high interest to have a continued time series available since there are often high sea states.