



NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

**THE DATA PROCESSING AND QUALITY CONTROL OF THE
MARINE ATMOSPHERIC BOUNDARY LAYER
MEASUREMENT SYSTEMS DEPLOYED BY THE NAVAL
POSTGRADUATE SCHOOL DURING THE CASPER-WEST
FIELD CAMPAIGN**

by

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March 2019

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“...[FLIP] was to be capable of staying on station for up to two weeks with a scientific party and a crew of 4 to 6.”

- Fisher & Spiess (1963) on the design capabilities of the *Floating Instrument Platform*.

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I. INTRODUCTION

A. Scope of this Document

This report provides detailed information on the data processing and quality control methods used for the various measurement systems deployed by the Naval Postgraduate School (NPS) Boundary Layer Processes research group during the CASPER-West field study. This document is the second in a two-part documentation of the instrument systems deployed by NPS during the field campaign. The first part, Yamaguchi et al. [2019], provides details on the system design and installation on the various platforms used in the field. The present report was written assuming that the reader has at least a cursory knowledge of the CASPER-West study and the major observational components. A brief overview of CASPER is provided within this section, but the reader is encouraged to review Yamaguchi et al. for background information on the field study and Wang et al. [2017] for background information on the entire CASPER project.

The descriptions and analysis presented here are primarily concerned with the NPS atmospheric and oceanographic measurements made from the Research Platform *FLIP*, Research Vessel *Sally Ride* (RVSR), and the NPS Wave Glider (glider). The bulk of this report is dedicated to describing the data processing and quality control. The final section contains major *caveats* for using these data for analysis. Where relevant, other notes and guidance on using these data are included within the report body.

B. CASPER-West Background

The Coupled Air-Sea Processes and Electromagnetic ducting Research (CASPER) is an Office of Naval Research (ONR) Multidisciplinary University Research Initiative (MURI) focused on the impacts atmospheric variability has on the propagation of electromagnetic (EM) energy within the Marine Atmospheric Boundary Layer (MABL). Specifically, the CASPER project was concerned with Radio Frequency (RF) energy propagation along a path parallel to the coastal ocean surface. EM propagation in the atmosphere is largely governed by the Modified Index of Refraction (M), which is a function of temperature, pressure, water vapor concentration, and range. Ultimately, the scientific objective of CASPER requires a critical re-evaluation of the premises and application of Monin-Obukhov Similarity Theory (MOST) (Monin & Oboukhov, 1954)

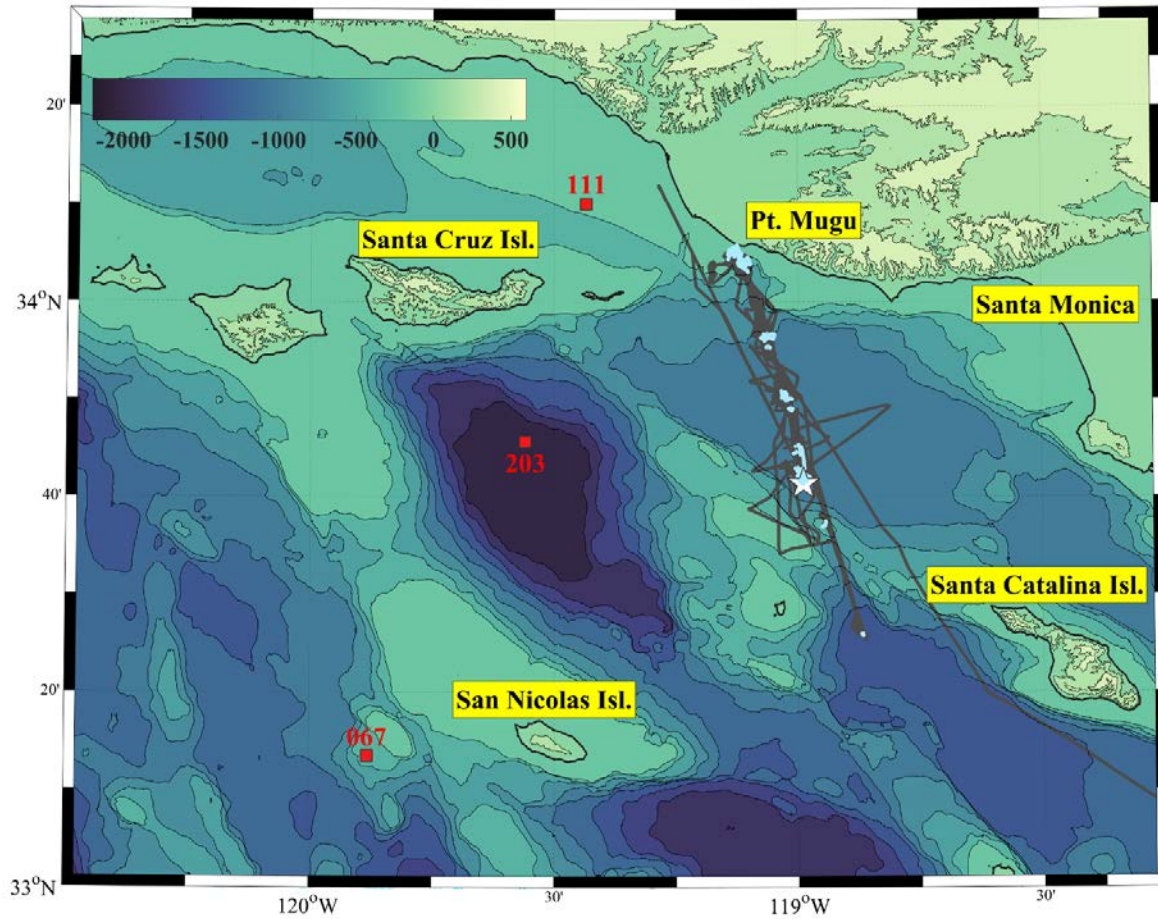


Figure 1. CASPER-West study site marking the location of *FLIP* (white star), the track line of the R/V *Sally Ride* (gray), and the locations of the small boat operations (light blue). Red squares mark nearby NDBC/CIP buoys. Topography relative to sea level is given in meters.

within the marine environment. MOST provides the basis for micrometeorological observation within the MABL and is utilized to predict the vertical gradients of wind, temperature, and water vapor in EM propagation models.

CASPER-West was the second, of two, field studies done to address the aims of CASPER and was completed from September to October, 2017 offshore of Southern California and within the Santa Monica Basin (Figure 1). The campaign involved two major ocean-going platforms: Research Vessel *Sally Ride* (RVSR) and Research Platform *FLIP*, both operated by the Scripps Institution of Oceanography and ONR. In addition, a land-based meteorological and EM station was set-up, a meteorological small boat was deployed from the RVSR, several autonomous gliders were used (surface and sub-surface, the latter deployed by NPS is discussed here, and multiple flights were conducted by the

Center for Interdisciplinary Remotely Piloted Aircraft Studies (CIRPAS) Twin Otter research airplane. The sampling strategy was to characterize the MABL from Pt. Mugu on land to nearly 70 km offshore and to understand the EM propagation variability at various range-segments along this transect. This was done using EM links on land and both major ocean platforms. As part of the sampling, a continuous battery of radiosondes was launched from both RVSR and *FLIP*, which in effect helped to build a nearly month-long time series of the entire MABL, including the upper ocean mix layer. Near the surface, sampling from the *FLIP* included a high-resolution meteorological mast (detailed below) and very near-surface to skin-depth optical and infrared measurements of the air-sea interface (measurements contributed by collaborators). Also, from *FLIP*, a temperature string and two acoustic doppler current profilers (ADCPs) were deployed to measure the variability within the upper ocean (from ~0 to 40 m depths). In general, the environmental conditions for CASPER-West exemplified a Southern California late summer, early fall season. However, an intense wind event and several Santa Ana wind events during the study provided interesting variability and useful case studies in terms of both the data quality and scientific analysis.

The remainder of this document will focus on the data quality inspection of the majority of the NPS-specific systems. This endeavor has multiple aims: to describe the data processing methods used by NPS as part of CASPER-West; (2) to provide detailed information and guidance for eventual data-users; and (3), to diagnose potential issues with certain measurements or systems.

II. DATA PROCESSING AND QUALITY ASSESSMENT

A few notes: unless specifically stated otherwise, all times are in UTC, all directions are *coming from* clock-wise (CW) from true North, and SI units will be used.

A. FLIP Motion Diagnosis

Platform motion can significantly impact the direct observation of atmospheric and oceanographic parameters and is a perpetual challenge to making reliable measurements at-sea. *FLIP* was specifically designed to be a stable, ocean-going platform and was originally engineered for making robust acoustic measurements (Fisher & Spiess, 1963). *FLIP* is essentially a large (~108 m long) floating spar buoy topped with a habitable observational platform. Since construction, *FLIP* has been modified to include three 18.3 m long booms, or catwalks, that extend radially from the above-water structure. These booms enable making measurements away from the super-structure (i.e. minimize potential flow distortion effects) and very near to the air-sea interface. For these unique capabilities, *FLIP*, after over a five decade lifespan, endures as the paragon observing platform for air-sea interaction over the ocean (Miller et al., 2008).

While *FLIP* is a stable platform, it is not *stationary*. In the original article describing the impetus and design for *FLIP*, Fisher & Spiess (1963) present the theoretical response of *FLIP* to monochromatic wave motion. They found that *FLIP*'s resonant period was 27 seconds, but the spar also exhibited a low period peak response to waves at ~15 seconds at about 10% of the wave height. (see their Figure 1). While the authors did not specifically state this, it is reasonable to assume that this theoretical response corresponds to a free *FLIP*—i.e., un-tethered. (Smith & Rieder, 1997) present a more detailed characterization of *FLIP*'s motion and develop a linear mechanical model to predict the six-degrees of platform motion. The purpose of the model was to help correct measurements made from *FLIP* and only required input of the acceleration and heading data. Smith & Rieder (1997) report a natural frequency of *FLIP* motion at 58 seconds, which is a significant increase from previous analysis and that was due to changes in the center of mass and rotation due to modifications to the platform. As a result of these changes, *FLIP*'s translational motion is stronger than its rotations (see Smith & Reider pg. 106). Also, the spectral decomposition

of the linear and rotational motions exhibited a strong wave-induced response in the surface wave gravity band and a peak was located at the frequency of the peak waves. We should note that in recent years, the advent of cheap, reliable inertial motion units (IMUs) has made the need for this mechanical model somewhat moot, since investigators can just as easily measure *FLIP*'s motion during their study.

Previous investigations into *FLIP*'s motion generally conclude that the platform motion is relatively small and that the impact on typical measurements, e.g. air-sea fluxes, is slight compared to the effect of a research vessel under-power. However, much of the previous work was limited in that it only considered a free-floating *FLIP* forced primarily by approximately monochromatic wave trains. *FLIP* is often used in a free floating mode



Figure 2. *FLIP* during the CASPER-West experiment with several features highlighted. Note that the *heading* of *FLIP* is the direction the keel points (x). The platform coordinate system is also given. Photo credit: D. Khelif, University of California at Irvine.

(e.g. Dickey et al., 2012), but it can also be deployed using a mooring system. Furthermore, depending on the location of the deployment, *FLIP* can be subject to strong hydrodynamic forcing, independent of the surface waves, that can be depth-varying. The problem of a tethered structure forced by currents is complex and leads to motion responses very different from the oscillatory forcing of waves (Williamson & Govardhan, 1997). Therefore, in order to formally develop a more generalized understanding of *FLIP*'s motion in the ocean it is necessary to explore the platform's response in more varied conditions. This may impact how previous research studies from *FLIP* are interpreted, but more importantly the intention is that this will help with planning future expeditions. To this day, *FLIP* remains the only mobile air-sea interaction platform that enables researchers to make such careful atmospheric and oceanic measurements in such a wide array of environmental conditions. However, comprehensive descriptions and analyses of *FLIP* motion during deployments are not consistently done or available in the literature. Therefore, we hope that this discussion here will be useful for posterity and help inform future work on this, and similar, platforms.

1. FLIP's Deployment for CASPER-West

FLIP was deployed at the CASPER-West study site (Figure 1) using a three-line mooring system (i.e. a tri-mooring) from September 23 through October 25, 2017. During the mooring deployment, the release of the second line was botched, which resulted in the anchor being deployed far away from the intended setting. This changed where *FLIP* was moored (by 100's of meters), its mean heading, and importantly, the orientation of the mooring lines. An ideal set-up for a tri-mooring is an equilateral triangle, but because of the placement of the starboard anchor of *FLIP*, the arrangement was closer to 90-135-135. This configuration enhanced the feedback between the platform and the lines, which even when properly set-up can significantly affect the orientation and motion of *FLIP* in certain conditions (anecdotes provided by Captain and crew). Fortunately, the NPS measurement systems included a differential GPS antenna array as well as at least seven IMU units on the port boom, which will help diagnose the scales of variability in *FLIP*'s motion during CASPER-West.

A platform coordinate system has been adopted for discussion of *FLIP* as it relates to the CASPER-West campaign. The local coordinates are x in the face-keel direction

increasing towards keel, y in the port-starboard direction increasing towards port, and z given by the right-hand rule (see Figure 2). Surge, sway, and heave motion are linear accelerations parallel to the x , y , and z axes, respectively. Roll (θ) is CW rotation about the x -axis, pitch (ϕ) is CW rotation about the y -axis, and yaw (ψ) is CW rotation about the z -axis.

2. Translation and Heading

The geospatial location of *FLIP* was recorded using a differential GPS system (see Yamaguchi et al., 2019), which is capable of providing very accurate location information at high frequency (> 1 Hz). For the duration of CASPER-West, *FLIP* occupied a roughly 100 m x 100 m area, but did experience a mean drift of about 45 m northwest (327°) from the initial mooring site. During the experiment, the maximum instantaneous *FLIP* translation was ~ 1.5 m/s, or a translation $\sim 40\%$ of the spar's diameter per second. The largest motion tended to be in the north-south direction and the variance in this direction was 14.5% higher than in the east-west directions, if only considering times before 10/12. If including all of the time series this value jumps to 45%. Given the orientation of *FLIP*, the north-south motion represents translation parallel to the starboard and port anchors. Figure 3 reveals the daily variability of *FLIP* translation and highlights the semi-regular elliptical motion of the platform.

To investigate the scales of motion further, *FLIP* displacement record was segregated into a low frequency and high frequency motion band using spectral decomposition (Figure 4). The bounds of the upper and lower cut-off periods for the low frequency band were set to 48 hours and 3 hours, respectively; while the high frequency bandwidth was set to 2 hours and 10 seconds. Before band-pass filtering, the original position record was sub-sampled to 0.5 Hz and the filter was applied to the entire record (for each band) from CASPER-West. A simple box filter was applied at the cut-off periods for each band-pass.

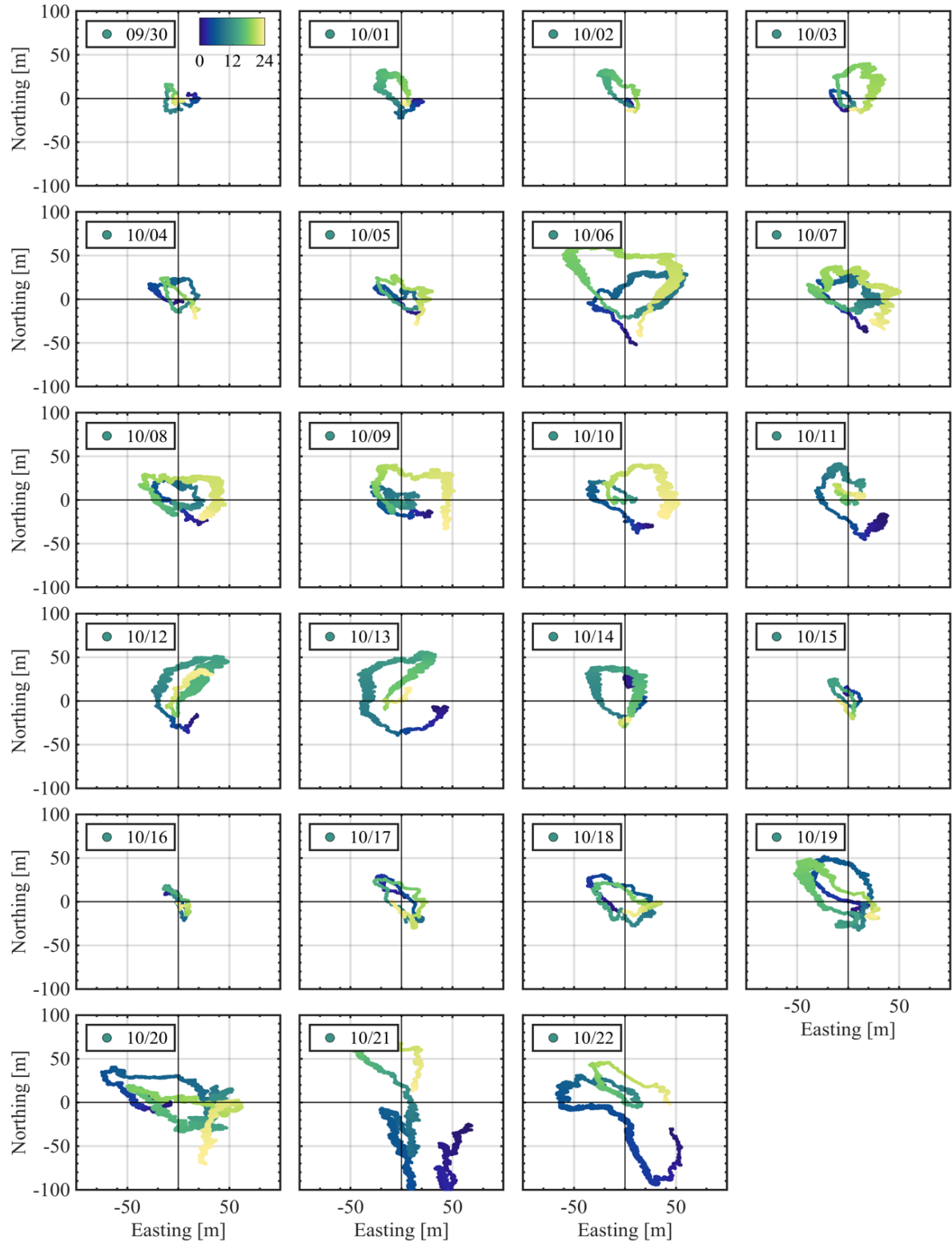


Figure 3. Daily position loops colored by the hour of day. The origin marks the geometric mean of the daily position.

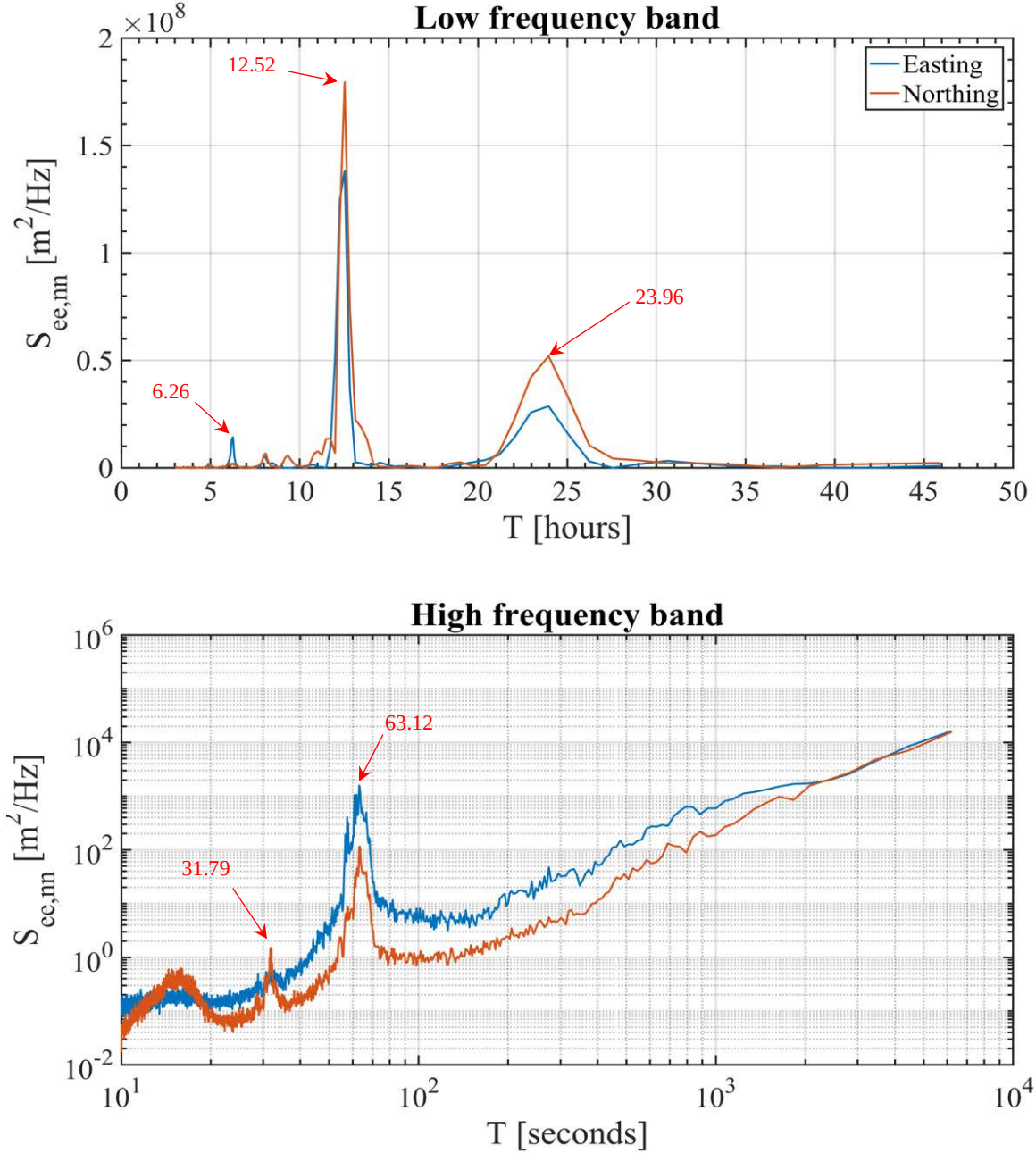


Figure 4. Autovariance spectra of the band-pass filtered position time series at low (upper) and high (lower) frequency bands. The high frequency spectra were smoothed using a 128-wide frequency bin average.

The spectral decomposition of *FLIP* translation revealed that the dominant motion scale was at the semi-diurnal period with a secondary peak at the diurnal period (see Figure 4). These periodicities correspond with the primary tidal periods, suggesting *FLIP*'s motion was mainly driven by tidal forcing. It was interesting to note that the east-west motion had a significant peak at 6.26 hours, which is the inter-tidal period, i.e. the transition between

flood and ebb. The semi-diurnal peak was not only the dominant signal (by two orders of magnitude) but was also had higher kurtosis (peakiness) than the secondary diurnal peak. This may be from the interaction between the diurnal and inertial forcing (21.57 hours), which was calculated using:

$$T_{inertial} = f^{-1} = \frac{1}{2\omega \sin \varphi} \quad (1)$$

$$\omega = 2\pi/S_D, \quad (2)$$

where S_D is one sidereal day and φ is the latitude in degrees.

The high frequency motion of *FLIP* was dominated by variability at $T = 63.12$ seconds in both translation directions (Figure 4), which is a six second increase from the natural resonant frequency reported in Smith & Rieder (1997). This was the primary signal in the east-west motion, but the north-south motion exhibited a secondary and tertiary peak at 31.79 seconds and around 15 seconds, respectively. The latter, broad peak at the lowest periods is consistent with the dominant wave periods measured throughout the experiment.

A similar spectral analysis was applied to the 0.5 Hz heading time series *FLIP*. Note that the heading gives the orientation of *FLIP*'s keel with respect to True North. The mean heading of *FLIP* during the experiment was $290.9^\circ \pm 6.3^\circ$, with an overall drift of less than 1° over the entire campaign. However, during CASPER-West *FLIP* experienced large low frequency and high frequency heading variance with mean heading changes of $>40^\circ$ within a 24 hours period (see Figure 5). The spectral decomposition for the heading, Figure 6, is very similar to Figure 4 with a dominant peak at the semi-diurnal period and a broad secondary peak spanning the diurnal band. In fact, for the heading the period at this secondary peak was 22.04 hours, which is lower than for the translational motion and just above the inertial period (see Figure 6). Furthermore, the heading variance did not exhibit any significant motion at the inter-tidal period, suggesting the azimuthal rotation of *FLIP* is confined to less overall scales of motion. The high frequency heading variance was dominated by a peak at *FLIP*'s natural period of motion with no significant signals found at other scales.

3. High Frequency Motion of *FLIP*

The air-sea interaction mast on *FLIP*'s port boom was outfitted with six IMUs, which measured the high frequency (50 Hz) linear accelerations and rotation rates of *FLIP*

at intervals along the mast. The original time records for the motion were sub-sampled to 10 Hz and then were high-pass filtered at 6 hours using the same box filtered applied to the bulk motion above. The power spectra for all six motion components for two of the IMU's on the port boom mast were compared (see Figure 7). Both the linear and rotational high frequency motions register strong peaks at the 63 second period, similar to the translational and heading variance. Upon closer inspection, it is clear that this dominant scale of motion is actually distributed across a range of periods from approximately 56-66 seconds. This was generally found for both IMUs, except for the high frequency yaw motion where the dominant peak was very kurtotic and centered on 63.38 seconds; this rotational component also had the highest overall energy. A sub-harmonic peak around 33 seconds was also captured in all degrees of motion, but the strength of this peak varied.

FLIP's motion response over the surface gravity wave band was highly variable and was strongly component-dependent. Qualitatively, the surge and sway (x and y component linear acceleration) appeared to rectify the wave-induced motion the best, with spectral distributions in this band that correspond well with previous work (see Smith & Rieder, 1997). The yaw spectra also exhibited some clear wave-like spectral distribution, though this went to noise at around 4 seconds. Interestingly, the vertical acceleration (i.e., heave) spectra did not exhibit a uniform wave-like spectral distribution in this band. Instead, *FLIP*'s vertical wave response appeared to be very scale dependent, seeming to respond comparatively better to wave periods ~14 seconds versus ~6 seconds. This behavior loosely agrees with the original motion-response model for *FLIP* (Fisher & Spiess, 1963). The spectral characteristics of the motion found here are most likely due to a combination of *FLIP* being moored (i.e. damped oscillatory motion) and the wave climate of CASPER-West. The spectra revealed that it may be possible to derive directional wave information from the inertial measurements, but deriving the absolute surface height information may be challenging given the varied response of the platform's vertical motions.

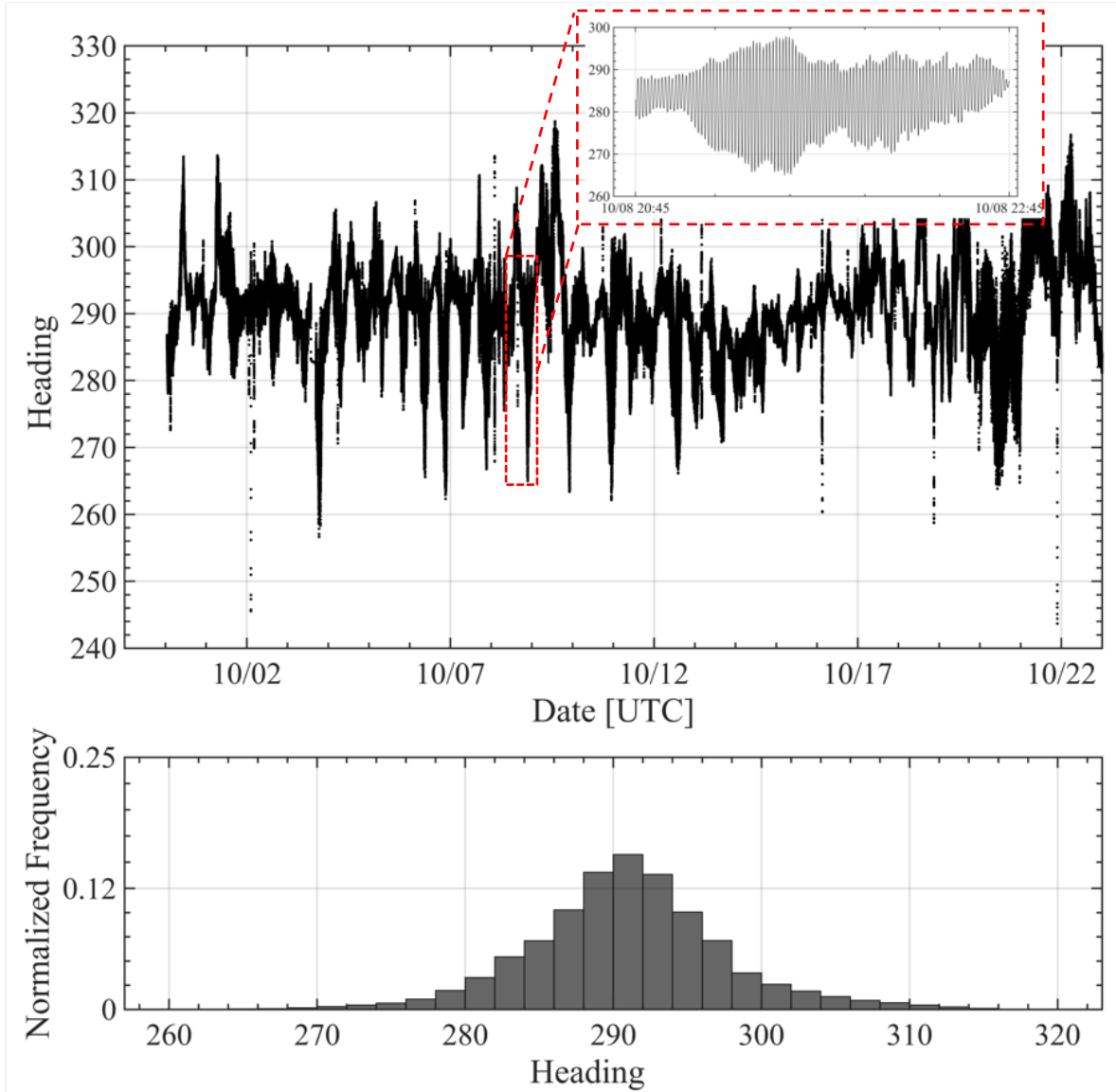


Figure 5. *FLIP* heading time series (top) and probability distribution (bottom), as derived from NPS differential GPS array on port boom. (Top) The snippet shows 2 hours of heading variability.

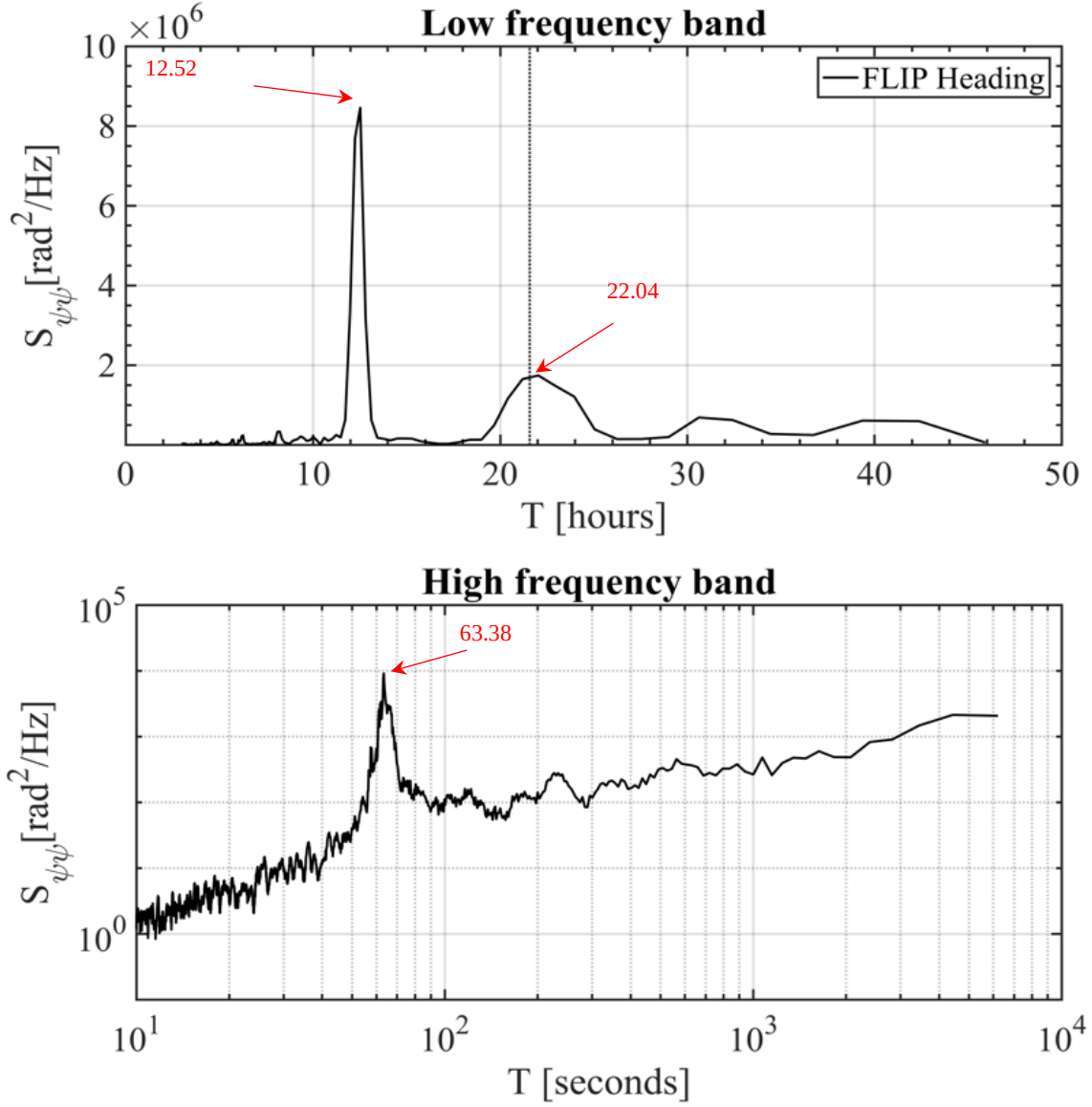


Figure 6. *FLIP* heading autovariance spectra in the low (top) and high (frequency) bands. The arrows mark the periods at the peaks in the units of the axis.

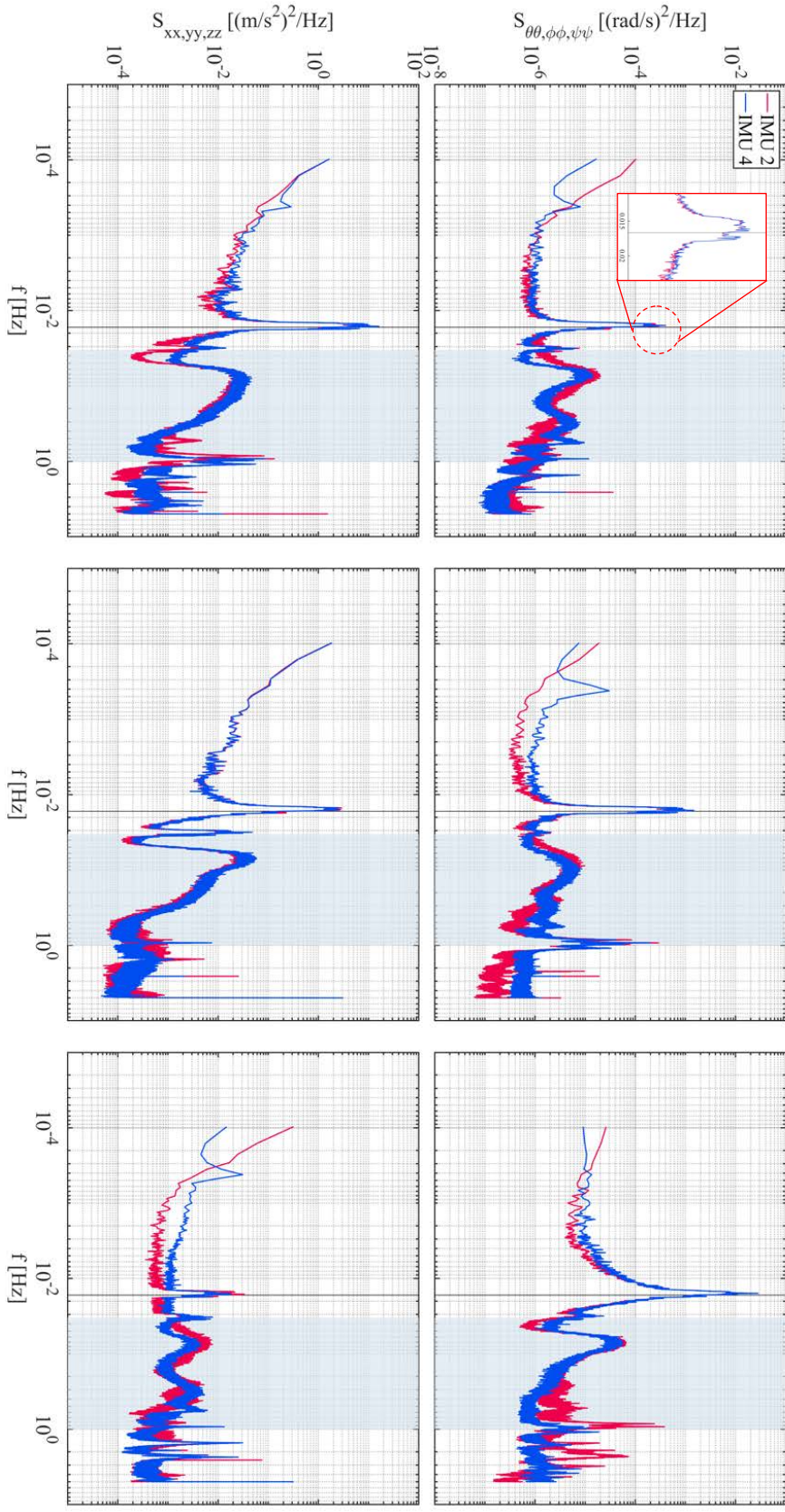


Figure 7. Top row, autovariance spectra of roll (left), pitch (middle), and yaw (right); bottom row, same surge (left), sway (middle), and heave (bottom). The surface gravity wave band is highlighted in blue.

B. Air-Sea Interaction Mast data processing

The air-sea interaction (ASI) mast on *FLIP*'s port boom was outfitted with overlapping profiles of bulk and turbulence-resolving atmospheric profiles (see Figure 8). The measurement systems deployed from the mast are detailed in the first installment of this documentation (Yamaguchi et al., 2019). Generally, the bulk profile was comprised of 10 two-dimensional sonic anemometers (2DSA) and 15 shielded temperature and relative humidity probes. The turbulence-resolving (or flux) measurement levels on the profile were comprised of three-dimensional sonic anemometers (3DSA), infrared gas analyzers (IRGA), and IMUs. Each level having an IRGA was co-located with a bulk temperature and relative humidity measurement, for inter-comparison and drift correction. The lowest flux level contained only an RM Young 3DSA. In total, 7 of the flux levels resolve the momentum and sensible heat fluxes (using sonic temperature), while 6 of the levels also directly measure the latent heat flux (using the gas analyzers). In addition, the mean air

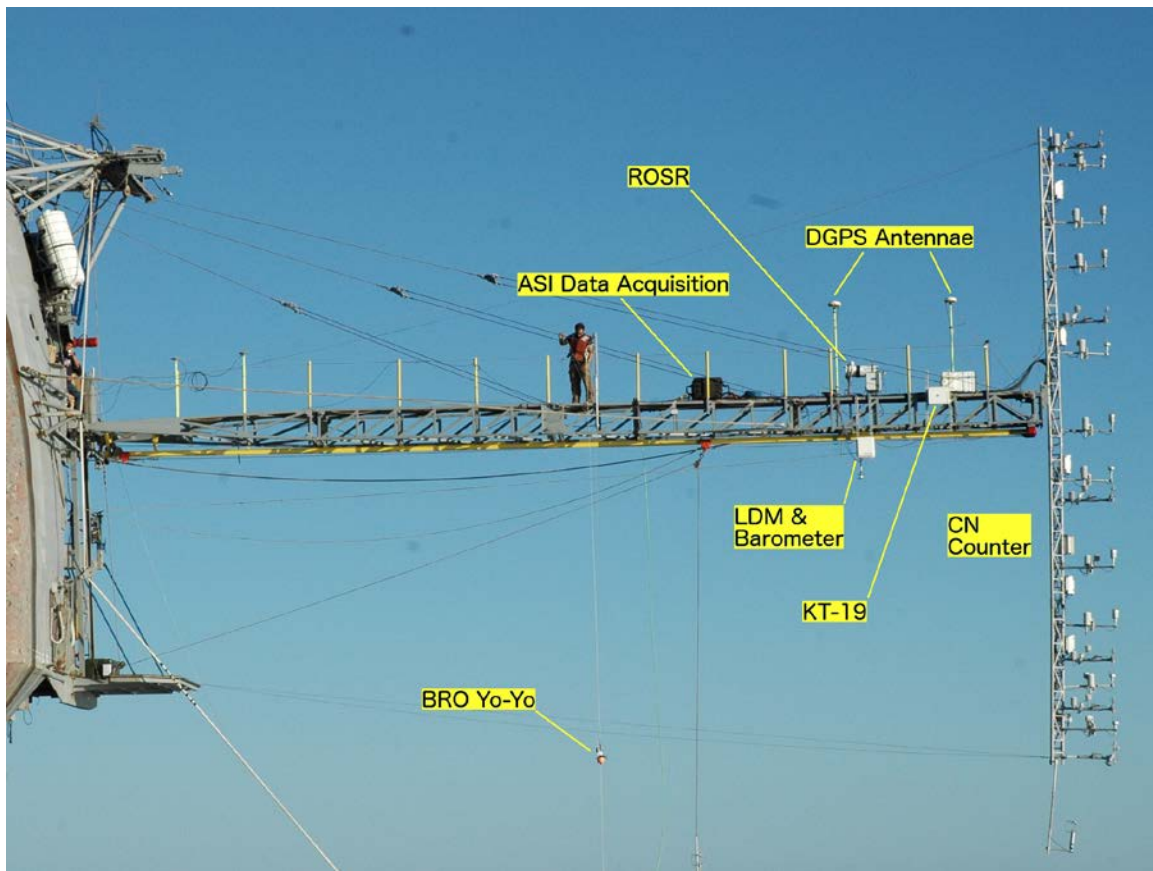


Figure 8. A view of FLIP port boom with additional NPS measurement systems highlighted.

pressure was measured at five non-uniformly spaced intervals along the mast. These measurements correspond to the data processing units of the Campbell Scientific IRGASONS, which make up 5 of the flux level measurements. In total, 17 measurement levels were deployed along the entire mast with each level containing several sensors and/or probes for atmospheric sensing. To separate the sensor from the mast latticework, the 2DSA were mounted on cross-arms oriented with the along-boom direction; while the 3DSA were mounted on similar arms, but with the sensor's sampling volume oriented parallel to the across-boom direction. This was done to have the flux levels oriented into the seasonally-adjusted prevailing wind direction.

The raw ASI mast data from the bulk and flux profile sensors were processed using a 5-minute and 20-minute moving averaging interval, respectively¹. Successive intervals were separated by 1-minute steps². The time series data were screened for outliers using a 20-sample-wide moving filter that flagged spikes as records greater than or equal to 4 times the median absolute deviation. Where possible, the specific diagnostic codes for sensors/parameters outputted as part of the raw data acquisition were used to flag bad data instead of the median filter. For example, the Campbell Scientific IRGASONS output diagnostic codes for each sample of a particular parameter, e.g. wind speed, water vapor content, etc. Any time series, for a particular averaging window, that had more than 10% of its total samples missing was rejected from the final data set. In the kept time series, residual flagged values were interpolated over using a linear polynomial.

The raw velocities from the 3DSA were motion corrected using the DGPS and IMU (for each flux level) time series. The position and acceleration/rotation data were blended to fully resolve the entire spectrum of *FLIP*'s velocity and position/attitude. Only the scales from 120 to 30 seconds from the DGPS were incorporated to the IMU time series, i.e. the DGPS was used to better resolve the low frequency motion. This blended motion record was used to correct the raw velocity time series following the procedure described in Edson et al. [1998]. The motion correction was applied on a sample-by-sample basis at 50 Hz.

¹ Other window lengths have been tested, see discussion in § II.B.2.c.

² This is done to increase temporal resolution of windowed data, however in practice it is not recommended to analyze the full resolution data. Instead remove some fraction of successive steps to remove the self-correlation between individual windows.

This differs from other eddy covariance motion correction procedures that utilize mean parameters computed over the entire averaging window (e.g. Anctil et al., 1994).

Figure 8 shows that the 3DSA at the bottom of the mast was tilted off the vertical axis of the mast. Using this picture as a reference, the anemometer was initially thought to have a 4.89° tilt to the left of the mast axis. Upon inspecting the processed data, this tilt was revised to 9.5° . Similarly, the IRGASON closest to the boom was observed to have been tilted 3.1° below the local x axis (this is not visible in Figure 8). This particular tilt was directly observed during the experiment because of the proximity of the sensor to the

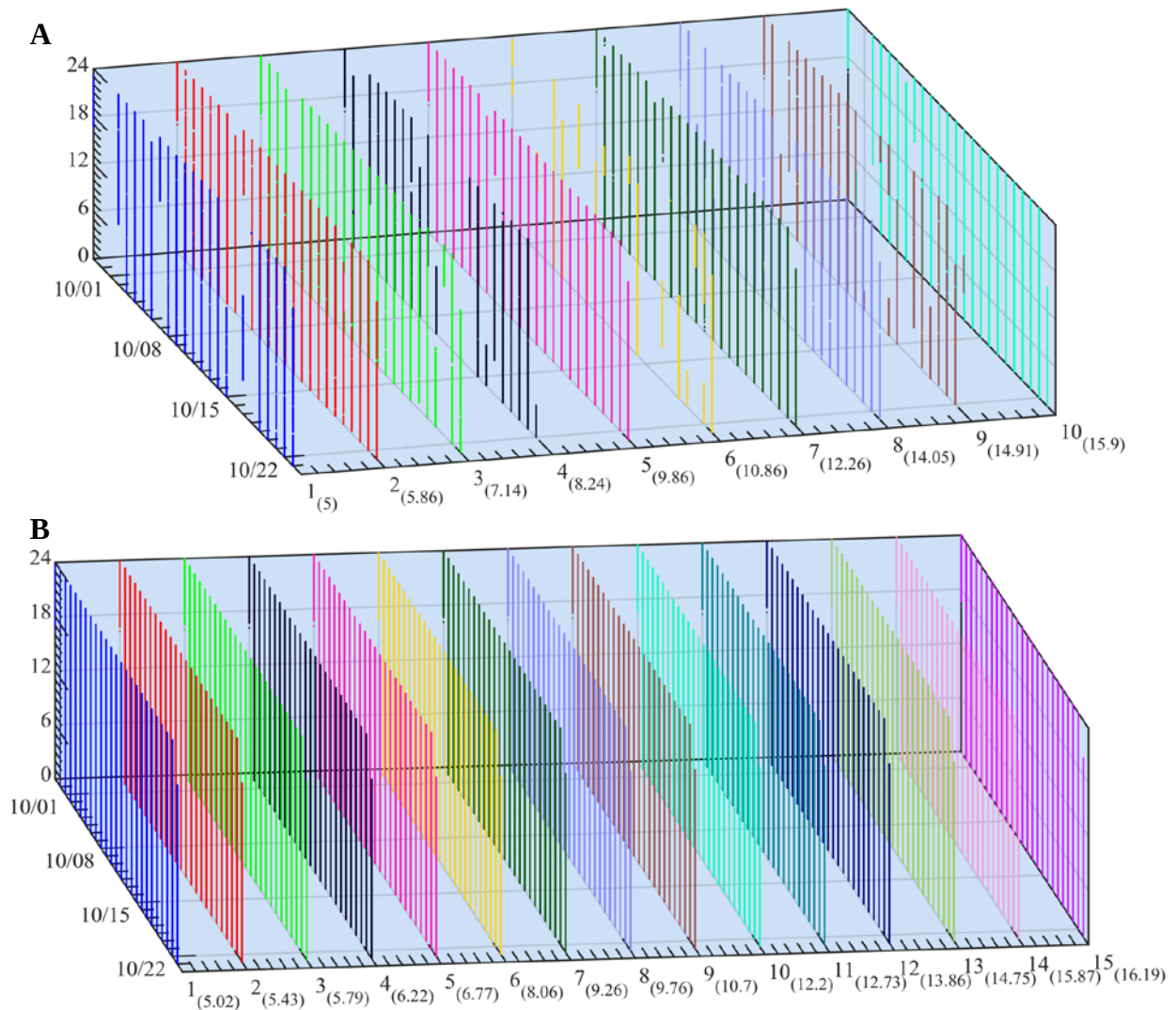


Figure 9. Data retention graphic for bulk wind (A) and state (B) sensors on ASI mast. The horizontal axes are date and level along the mast, starting at the bottom. The value in () gives the median height above sea level. The vertical axis gives hour of day. A gap in the column indicates no data retained.

boom catwalk. These mounting-related tilts were incorporated into the motion correction algorithm for these levels. The results of this static tilt correct were checked by inspecting the mean of the means of the vertical velocity component to ensure that it converged to zero.

1. Slow-varying sensors

The *slow*-varying sensors include the 2DSA, temperature, and humidity probes. These sensors are also collectively referred to as bulk measurements. For the latter, these include the Vaisala HMP155, the Rotronic HC2-S3, and the external thermistor integrated with the IRGASON measurement system. These absolute scalar measurements provide slow-response, high-fidelity mean air temperature and relative humidity along the mast. Collectively, these will be considered as *state* variables. These can also be used to diagnose the drift of the high frequency sonic temperature and water vapor content (infrared gas analyzers) measurements.

a. Data Retention

The total data retention means exactly how many 5-minute intervals of processed data were included in the final processed data set relative to the total intervals possible over the time frame. The amount of data that passes all of the quality control criteria is a function of the individual sensor's reliability, but also dependent on ancillary measurement used to generate the final processed variable. For example, if the GPS data is missing over a particular interval, no wind vector data can be outputted because this information is needed to correct the raw measurement.

The bulk observations commenced on 9/28 23:57 and ceased on 10/23 23:57. The ten 2DSA have very different retention rates and the data loss did not appear to follow a coherent pattern. Most likely, the data loss seen in Figure 9a is caused by the individual sensors, since it was confirmed that other measurements (e.g. GPS) were not missing that frequently. The maximum retention was 92.5%, which was 2DSA level 7. Excluding level 6, the mean retention rate was across the entire experiment and all levels was 79.4%. Level 6 performed the worst, 28.1%, for the duration of CASPER-West. While the source of the dropouts is assumed to be a faulty sensor, when the unit was collecting, the data agreed very well with the

other 2DSA. Compared to Level 7, the linear agreement in mean wind speed was 99.6%, with a bias and offset of 0.989 and -0.026 m/s, respectively. Therefore, when this sensor was working, the data can be trusted.

Comparatively, the state sensors were very stable throughout the entire experiment. For every level, the retention rate was 96.5%, with only data being lost at the beginning and ends of the experiment.

b. Temperature & Relative Humidity Calibrations

The temperature and humidity probes deployed by NPS for CASPER-West were pre- and post-experiment calibrated using an isolation chamber with reference measurement of state. The calibrated probes included those from Figure 9b as well as the sensors deployed on the FLOP and the wave glider (see § II.E, § II.G, respectively). The pre-calibration coefficients were used as part of the post-experiment processing algorithm to generate corrected slow-varying temperature and humidity.

Mean T/RH probes (Vaisala HMP155 and Rotronic HC2-S3) were calibrated in a Thunder Scientific 2500 Chamber³. The chamber can control both temperature and relative humidity. Temperature is regulated with a fluid jacket surrounding the chamber; while, the relative humidity can be controlled via “two-pressure” technique. The temperature and relative humidity can be changed separately, in general, one variable is fixed, while the other is varied.

Although the calibration chamber measures air and chamber temperature and relative humidity, a chilled mirror hygrometer is used as the calibration standard. The RH Systems 473 Chilled Mirror Hygrometer directly measures the dewpoint inside the chamber⁴. Also, attached to the hygrometer is an external, calibrated platinum resistance thermometer (Pt100) that is used as the temperature standard. The relative humidity is calculated from the hygrometer air and dewpoint temperatures and chamber barometric pressure.

³ https://www.thunderscientific.com/humidity_equipment/model_2500.html

⁴ http://www.rhs.com/product_473.php

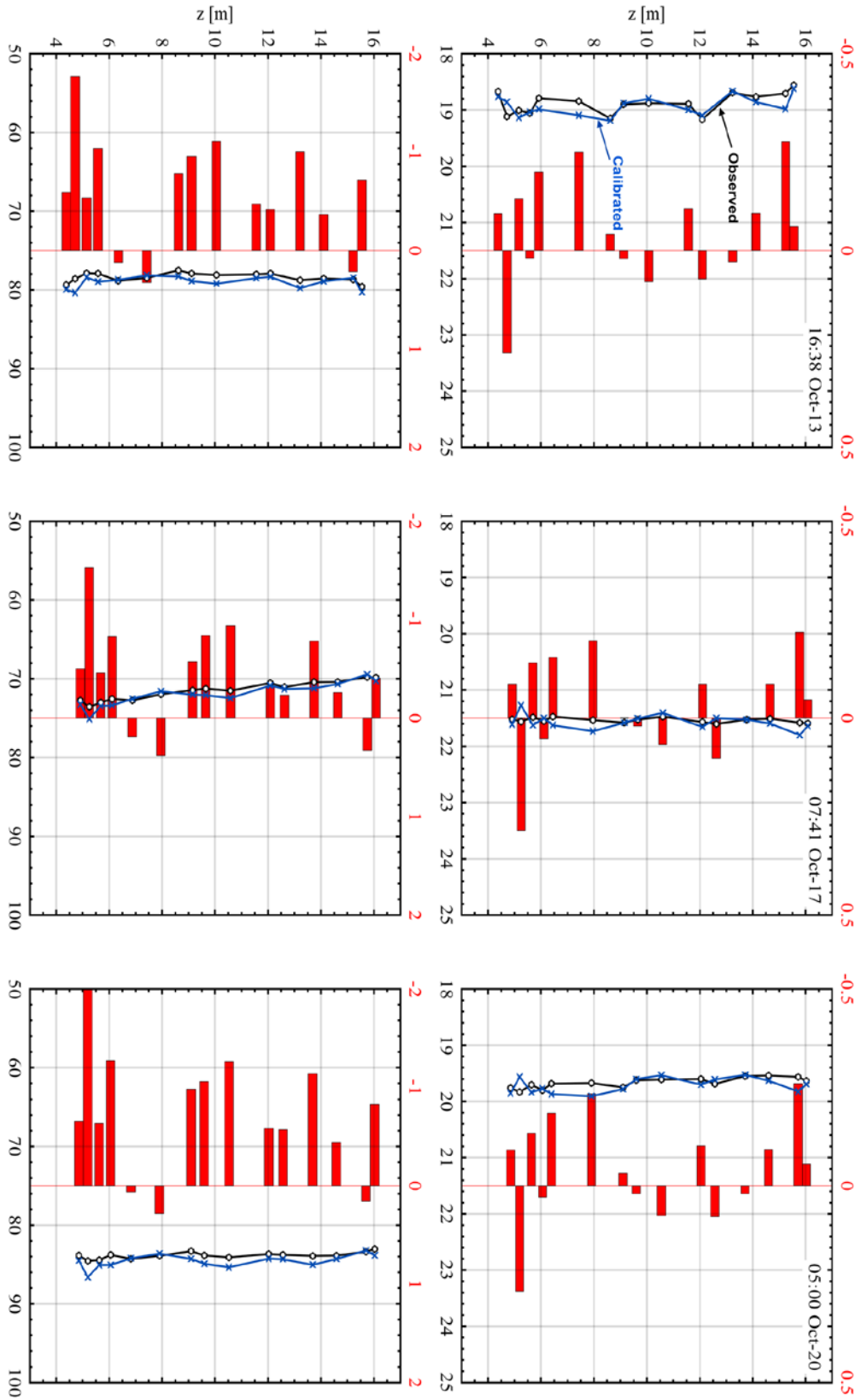


Figure 10. Three randomly selected profiles showing the observed (black, o-), calibrated (blue, x-) and residual (red, upper abscissa) data for temperature (top row) and relative humidity (bottom row).

The probes to be calibrated were sealed inside the chamber and were done in several batches, as the chamber is too small to fit more than seven probes. Two probes used in a subsequent calibration in order to ensure that there is consistency among each of the calibration. T/RH probes are connected to an external Campbell Scientific CR6 datalogger, along with the output of the calibration chamber and hygrometer.

The RH inside the chamber was varied from 20% to 90% increments of 10%, with temperature fixed at 20° C. At each step, the chamber was allowed to come to equilibrium, which was defined at a certain RH variance threshold. After reaching this threshold, the probes ‘soak’ for approximately 30 minutes at a given RH step. The RH was ramped up and down in order to account for any sensor hysteresis. The same procedure was completed for the temperature, while the RH is fixed at 50%. See Figure 10 for an example showing the observed and calibrated measurements.

c. *Flow Distortion*

One of the foremost issues with respect to the post-processed data quality was determining the effects of flow distortion around FLIP superstructure,

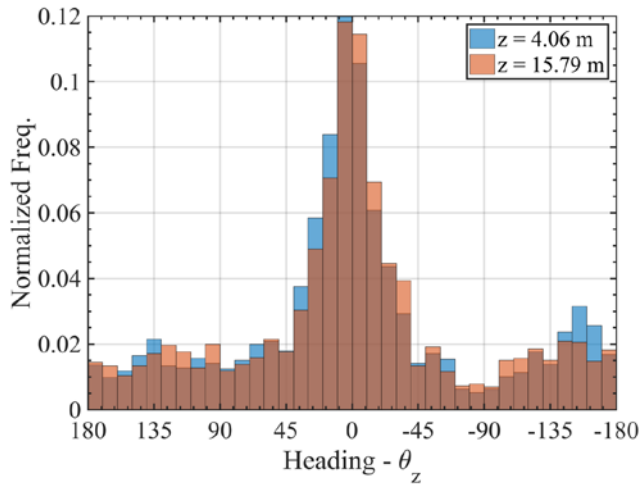


Figure 11. Distribution of wind direction relative to *FLIP* heading for 2 of the 2DSA. The distribution has been segregated into 10°-wide bins, the counts were normalized by the total number of observations.

booms, and ASI mast itself on the measurements. The issues of flow distortion have been recognized for decades (e.g. Dobson, 1980, p. 241) and continues to be an active area of discussion because of the idiosyncratic nature of the problem (Landwehr et al., 2015). To clarify a point that generally should not have to be made: objects upstream of a sensor can

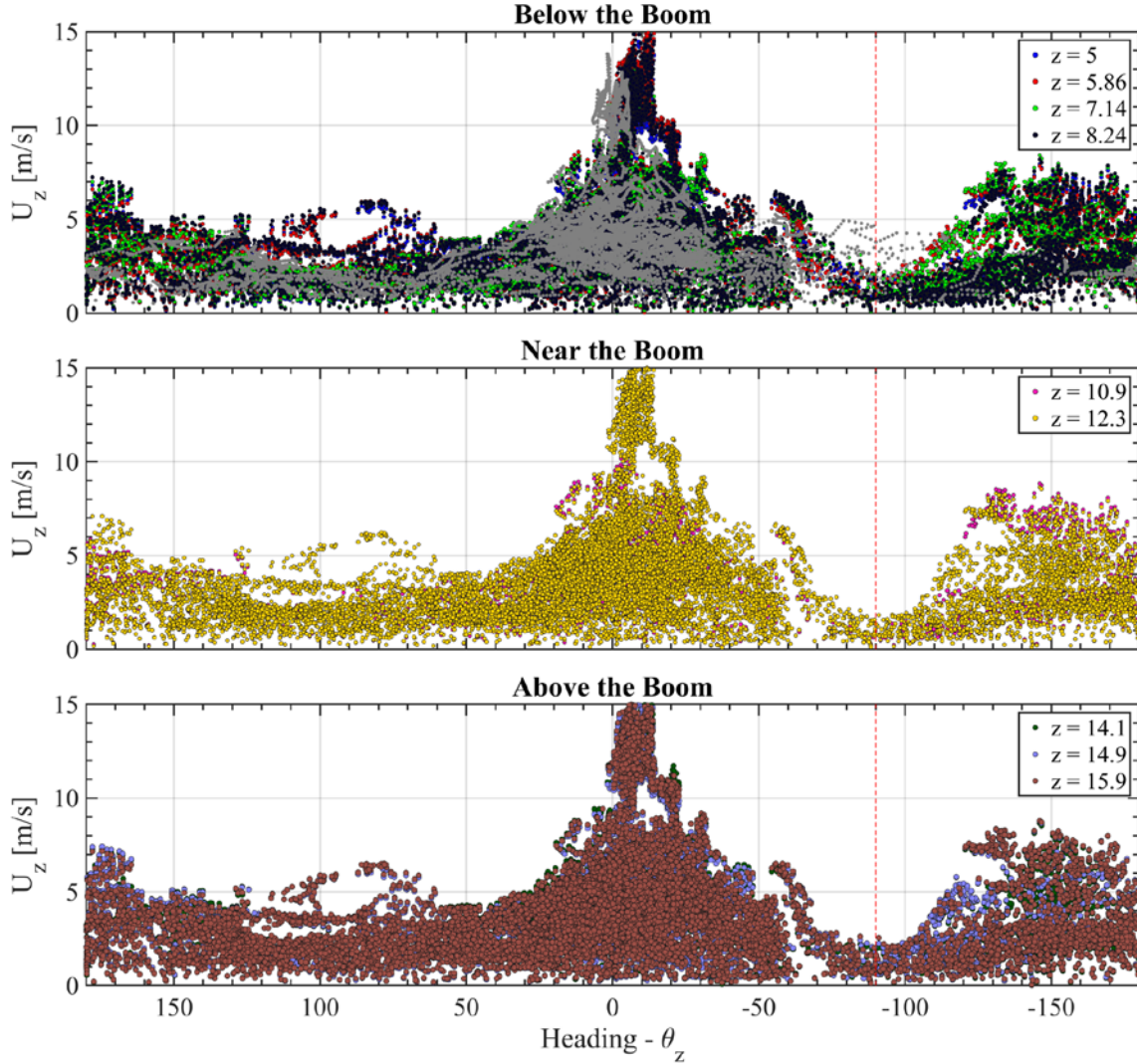


Figure 12. Distributions of mean wind speed at level z as a function of the wind direction at z relative to *FLIP*'s heading. The red dashed line gives *FLIP* platform location relative to the *ASI* mast. The gray data were measured from 2 3DSA on poles below the starboard boom, courtesy of M. Buckley, Helmholtz-Zentrum Geesthacht (HZG).

alter the characteristics of the ambient flow such that the measurement does not reflect a geophysical process. Therefore, the challenge of making real-world measurements is to balance the experimental aim of measuring a physical process with the operational considerations of the actual experiment. This poses a particular challenge to measurements made over the physical ocean because in order to accommodate the *human* equipment, large and bulky structures are necessarily employed. While a large research vessel's superstructure provides a dramatic example of an upstream object, flow distortion can corrupt

measurements simply by placing a sensor too near a 10-inch radiation shield. The platform, etc. can have other effects on the measurement quality that are not directly related to the flow around the object, i.e. ship exhaust and discharge (e.g. Lind & Shaw, 1989, p. 5). Many of the issues regarding flow distortion may be mitigated by exercising good experimental ship exhaust and discharge (e.g. Lind & Shaw, 1989, p. 5). Many of the issues regarding flow distortion may be mitigated by exercising good experimental planning and foresight. However, some issues are unavoidable and so the collected data must be inspected to determine the potential effects.

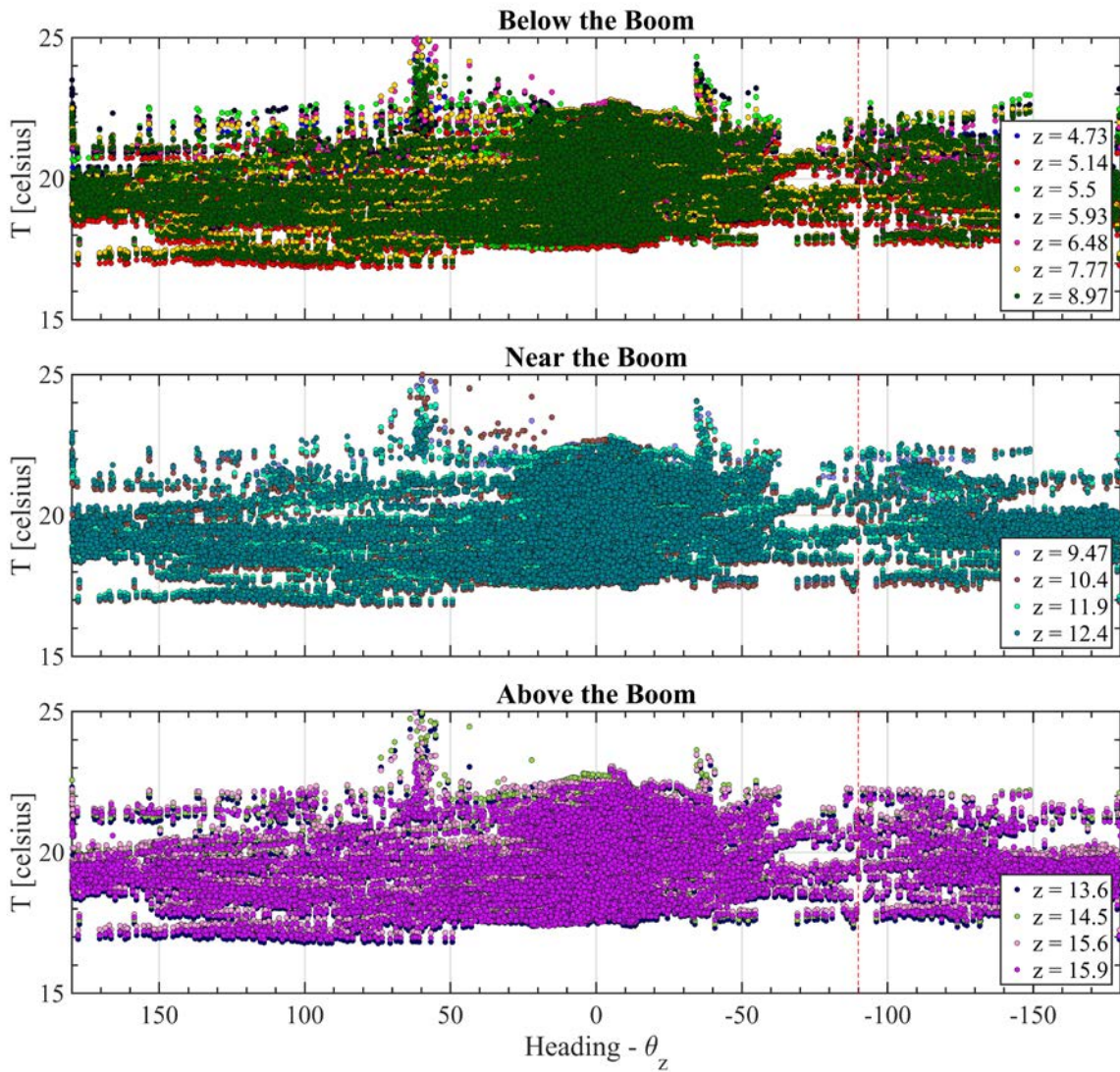


Figure 13. Same as Figure 12, but for air temperature.

FLIP is unique among ocean-going platforms in that it provides a fairly stable body, as well as the booms for making measurements far away from the superstructure. The above-water width of *FLIP*'s face (see Figure 2) is about 7.9 m and the booms extend 18.2 m radially from the edge of the main platform. While this helps to place measurements at a considerable distance from the body, *FLIP*'s structure still has a projected surface area of approximately 400 m². Therefore, prior to the analysis of the ASI mast data, we had to determine the flow (atmospheric) that was most disturbed by the platform, booms, and mast itself.

The distribution of the wind directions relative to *FLIP*'s heading during CASPER-West is given in Figure 11. In this coordinate system, positive (negative) values indicate wind coming from the left (right) of *FLIP*, 0 indicates *FLIP* is oriented into the wind; *FLIP*'s face is at -90°. In general, the wind came from a favorable sector with 55% of the total observations made between -45° and 45°. Coincidentally, only 6.7% the observations came from times when the mast was directly downstream of *FLIP*.

Figure 12 to Figure 14 give the distributions of wind speed, air temperature, and water vapor mixing ratio as a function of the wind direction relative to *FLIP* heading, respectively. The distributions in Figure 12 demonstrate that when the mast is downstream of *FLIP*, there is a dramatic effect on the mean wind speed at each level along the mast. This was evidenced by the systematic deflection of the wind speed towards zero over the sector from -55° to -120°. The minimum of this deflection occurred at about -90°, for all of the sensors. Note that the 2DSA were mounted on arms extending from the mast, but parallel to the port boom. Therefore, wind coming from *FLIP* also interacts directly with the boom, the mast, and sensors along the arm extension before reaching the measurement volume of the anemometer. The sensors located well-below the port boom were compared to wind measurements made from a pair of 3DSA mounted on poles below the *starboard* boom. The starboard sensors do not show a coherent deflection in the velocities at -90°, but rather the deflection occurs centered on 90°, which mirrors the ASI mast observations. The comparison between the port and starboard booms is somewhat limited because the latter sensors were only recording for ten days and lack the total

variance observed by the port boom. However, when there is overlap the correlation between the two sensors is 0.99 with an offset of 0.209 m/s.

The wind speed for several levels appeared to be affected beyond -120° . This was notable for $z = 8.24$, for which the wind speed behaves very oddly out to approximately -140° . Similar phenomena seemed to impact the wind speeds from the sensors near the boom and the ones at the top of the mast. This effect is characterized by an apparent segregation of the wind speed into low and high values. These two classes appear to gradually come together between -90° and -140° . There would not seem to be any plausible geophysical process that would

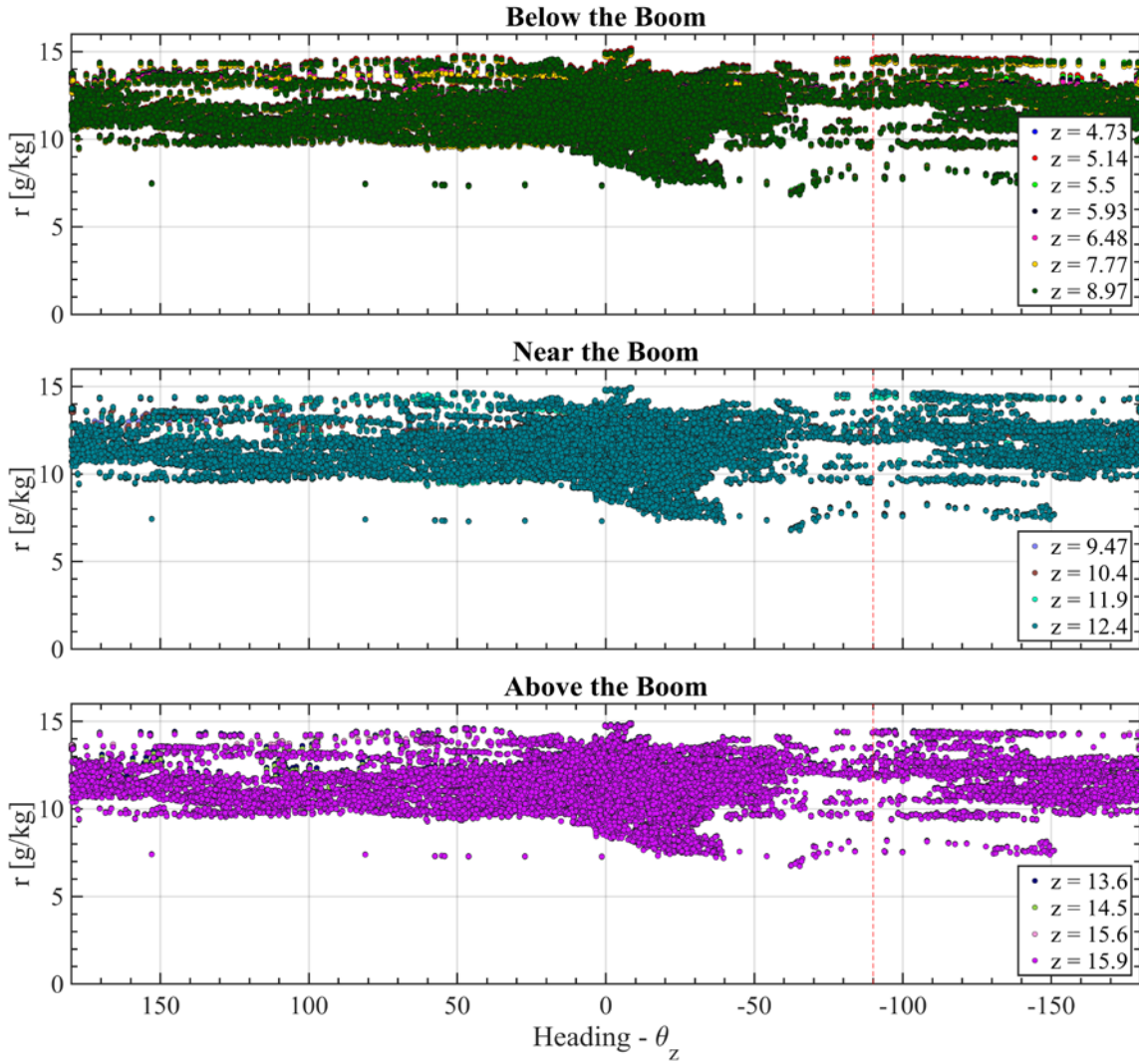


Figure 14. The same as previous, but for mixing ratio, r , derived from the relative humidity measurement.

explain this and so some obstacle in the flow may be causing this trend. Inspection of the mast (i.e. Figure 8) revealed that certain levels with 2DSA had other sensors or components of the mast directly upwind of the sensor, when the wind was coming from this sector. The deflection of the flow around these objects most likely explains this behavior within a range outside of the influence of *FLIP* itself.

Figure 12 also makes clear an interesting feature starting at -50° , where the wind speed distribution appears to detach from the main cloud of measurements. This was found for all sensors at all levels and would suggest a *FLIP*- or mast-generated disturbance. The presence of this detachment may represent the traversing of the flow separation zone. As the wind moves across *FLIP*'s keel and towards the face, the flow is accelerated around the body as the streamlines are deflected, but then at some point the sensors are sheltered by *FLIP* and the mast.

Figures Figure 13 and Figure 14 test if the flow around *FLIP* has any impact on the state variables. The results demonstrate that there is no systematic relationship between the measurement and wind direction. Both temperature and water vapor content exhibit a *thinning* of the cloud of data over an area that roughly coincides with the location of *FLIP*, relative to the mast. This sector occurs from approximately -70° to -100° . This reduction in the variance may be largely due to generally fewer observations being taken over this wind sector. Though, a portion of this behavior may be caused by the flow over *FLIP* and the mast constraining the temperature and humidity measurements via some radiative effect of the structure.

2. Flux sensors

There were seven flux packages deployed in a profile along the ASI mast and the upper most six were capable of directly measuring the latent heat flux. These packages were composed of co-located CSAT-3 and IRGA gas analyzer pairs. The uppermost five of these were IRGASONS, which have the anemometer and gas analyzer systems fully integrated—though the components are essentially the same as older, separated versions. The lowest flux package was an RM Young 3DSA and no other sensors were deployed from this level (see Figure 8). The other flux packages included IMU's as well as shielded

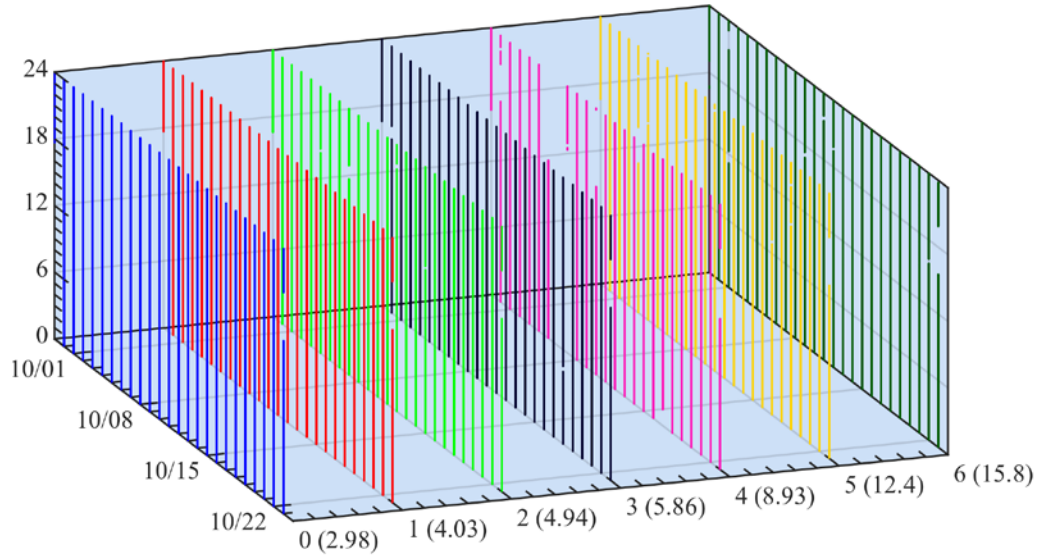


Figure 15. Similar to Figure 9, but shows the retention for the 7 flux levels starting at the RM Young 3DSA (0). The vertical axis gives hour of day and the () give the median height above sea level for the whole experiment. Gaps in the column indicate no data.

reference temperature probes. They were also co-located with bulk sensors. Similar to § II.B.1, this section will present similar analysis of data retention and flow distortion. Included is additional discussion of the motion correction processing (necessary for eddy covariance techniques) and a comparison of the fast and slow state parameters.

a. Data Retention

In general, the flux packages were fairly stable and there was very good data coverage over the entire CASPER-West experiment (see Figure 15). Excluding level 4, the total data retention was about 96%, which was substantially better than the bulk wind sensors (Figure 12). Level 4, an IRGASON, had a total data retention of 85.6%, which was just under 10% lower than the next lowest sensor (level 6). In the post-processing, it was determined that the IMU at level 4 was faulty and was one of the primary sources of data loss. Initially, only approximately 60% of the total data from this level was retained during the processing steps. Therefore, the IMU from the immediately lower flux level (level 3) was used to provide the motion correction to level 4, which greatly increased the amount of retained data.

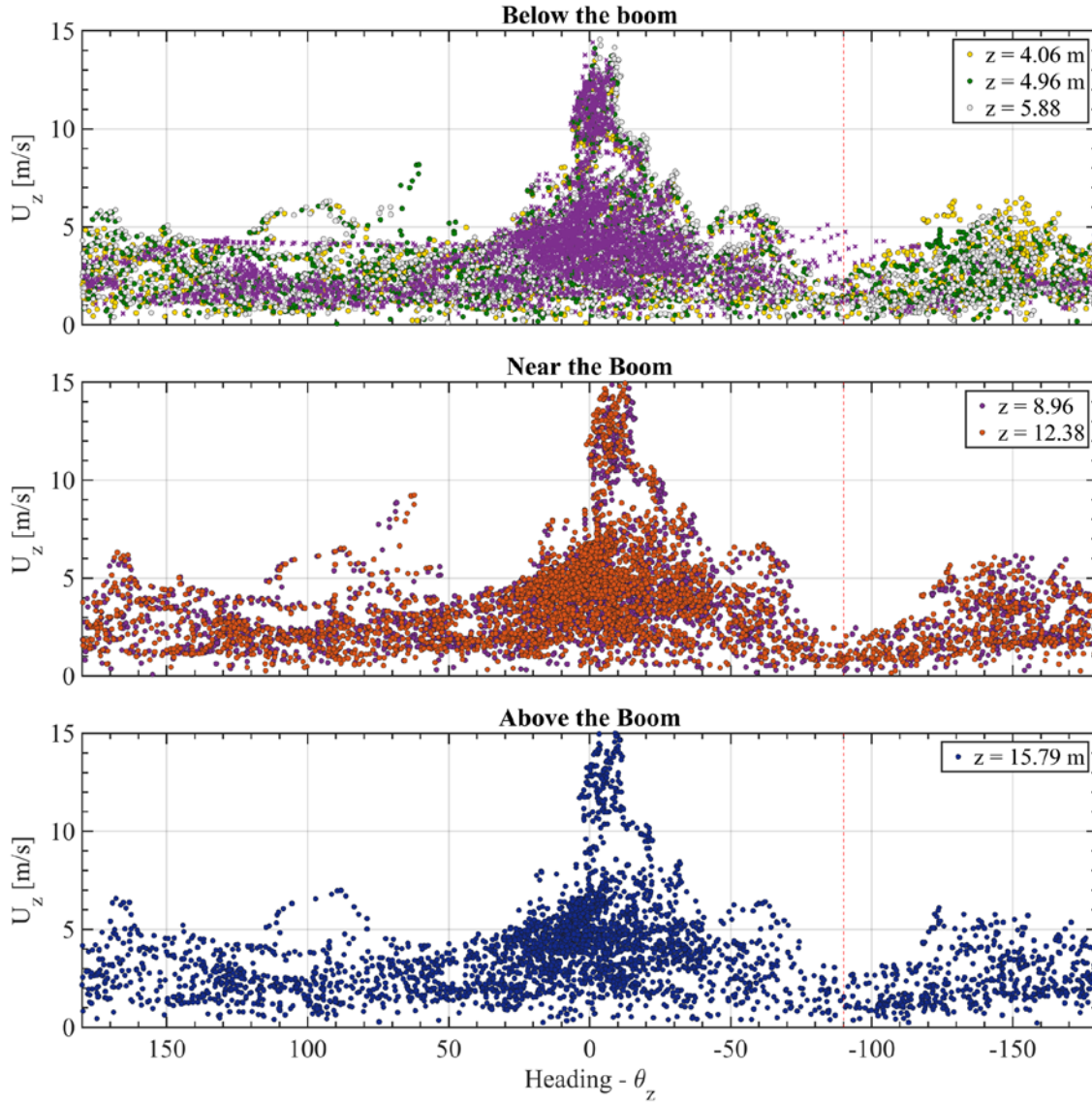


Figure 16. Flux level mean wind speed distribution as a function of wind direction relative to *FLIP* heading. Purple x 's are from the HZG sensors.

b. Flow Distortion

The primary concern with making flux measurements from at-sea platforms is correcting for the motion-induced velocity signals in the 3DSA data. A close second is considering the physical effect the platform has on the vector and scalar fields being measured. For the flux sensors, the concern is not only will the platform affect the bulk flow, but also distort the ambient turbulence in the boundary layer.

A similar procedure as described in § II.B.1.c was conducted to inspect the flux levels. The parameters inspected for each flux level were the: mean wind speed, friction velocity, sonic temperature, mixing ratio (from IRGA), and the variance of the vertical velocity.

The mean wind speed and friction velocity exhibit very different responses as the wind vector shifts to come from near *FLIP*'s superstructure (see Figure 16 and Figure 17). Similar to the 2DSA, the flux levels mean wind speed is deflected and sheltered around the sector -60° through -120° , which is centered on *FLIP*'s location relative to the mast. Comparison with the HZG starboard 3DSA data generally confirms that this is coherent dip across the mast is a sheltering of the flow. The starboard data also show a mirrored dip in the wind speed around $+90^\circ$. Unlike the 2DSA, there is less difference across the individual levels, which is primarily because the IRGASONS were less likely to be obstructed by the mast and components on their mounting arms. Sheltering from the mast does become important for wind coming from circa $\pm 180^\circ$, where a slight dip in the mean wind speed was observed at all levels. This roughly corresponds to winds coming from -170° through $+170^\circ$, or directly from the back of the sensor.

Figure 17 gives the friction velocity distribution along the mast, which depicts far more significant and wide-spread (over wind direction) effects related to the flow relative to *FLIP*. This is distinguished by an unrealistic increase in the measured momentum flux ($\tau = \rho u_*^2$). For example, at -90° all of the flux levels observe friction velocities comparable to the highest wind speed measurements at $\sim 0^\circ$, even though the mean wind speed has collapsed to < 2 m/s. Figure 17 reveals that the platform was distorting the measured turbulence for all wind directions beyond -50° and through $+160^\circ$. Comparison with the HZG data helps to confirm that these increased turbulence levels are not geophysical. Figure 17 reveals that the platform was distorting the measured turbulence for all wind directions beyond -50° and through $+160^\circ$. Comparison with the HZG data helps to confirm that these increased turbulence levels are not atmospheric.

The vertical velocity variance was also inspected to understand how different velocity components were affected (Figure 18). This helped to confirm the -50° cut-off for the distorted region but also shows that the effects from the mast itself were strongest for the horizontal components. In other words, the vertical velocity variance does not exhibit much distortion at -170° through $+160^\circ$.

Apart from the fast wind velocities and vertical velocity variance, the fast scalars were also inspected, which included the sonic temperature and the mixing ratio from the 3DSA and open-path gas analyzers, respectively (Figure 19 and

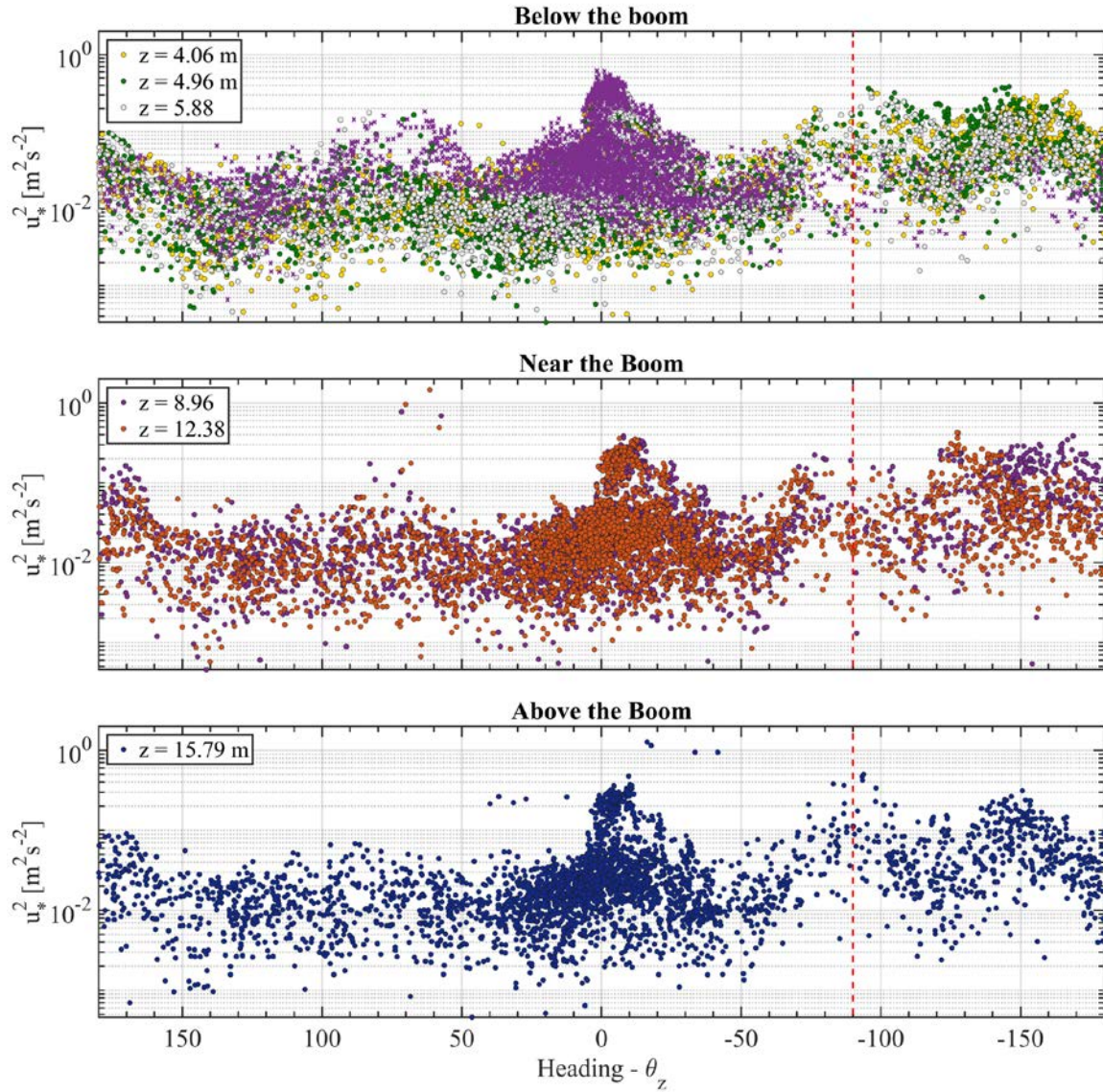


Figure 17. Same as previous, but for friction velocity.

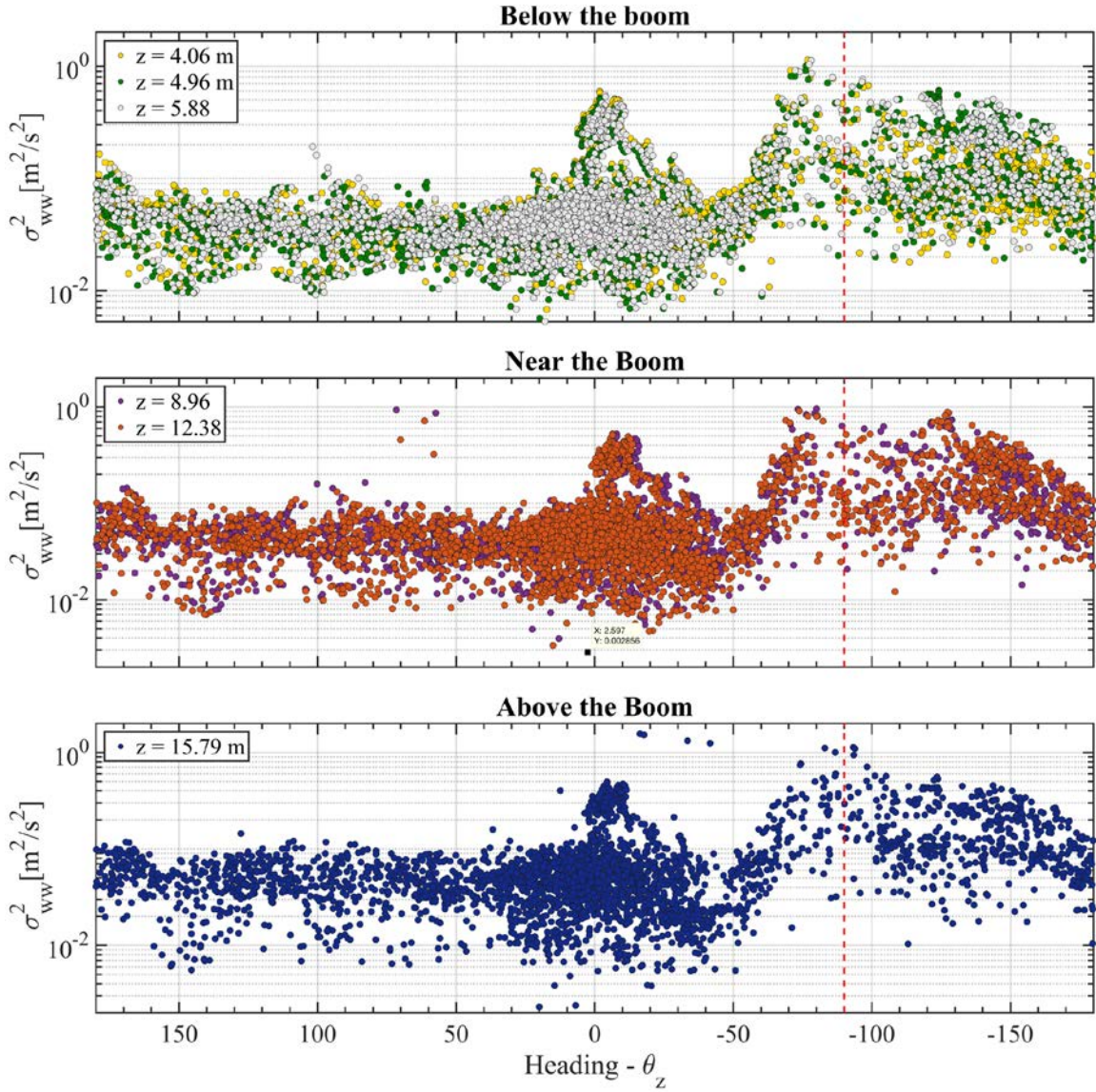


Figure 18. Same previous series, but for the vertical velocity variance. Note that the variance at *FLIP*'s location (red dashed line) is higher than at 0° , which peaks for mean wind speed > 10 m/s, even though the mean wind speed at -90° is < 2 m/s.

Figure 20). No systematic effect of *FLIP* was noted for the scalar measurements, which differs from what was found for the bulk sensors (see Figure 13). One note is that the mixing ratio at the **Above Boom** level is significantly different from the rest of the flux levels. Upon inspection, it was determined that this was due to some issue with the sensor that corrupted all of the water vapor concentration measurements beyond October 8th during the experiment.

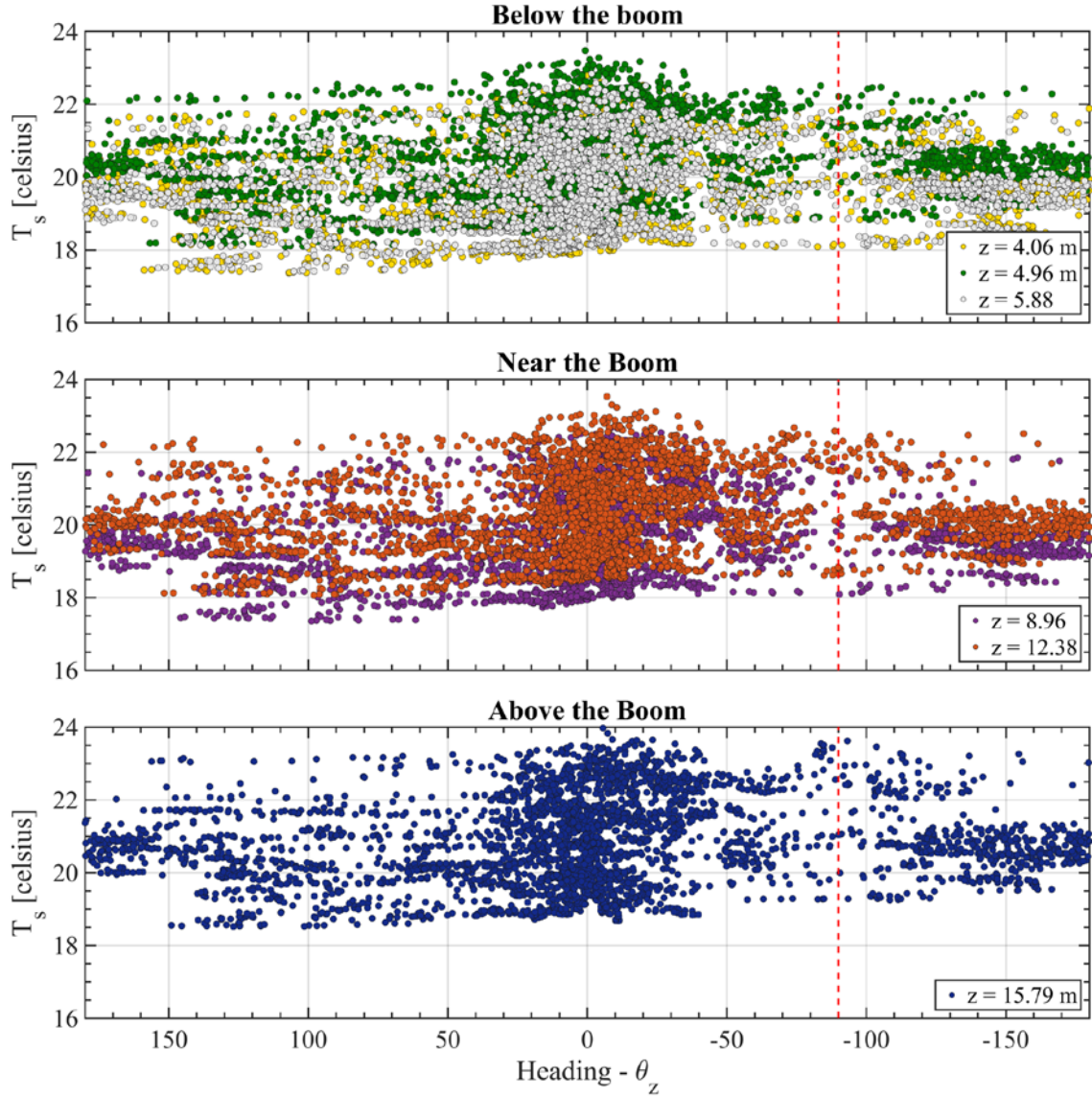


Figure 19. Sonic temperature as a function of wind direction relative to *FLIP* heading.

c. *Turbulence Measurement Quality Evaluation*

Several factors that can affect the quality of the actual turbulence measurements made from a given flux package along the ASI mast. Flow distortion around the body of *FLIP*, the boom, the mast itself, and/or nearby sensor mounts/housings must all be considered as potential sources of unexplained variance in the measurements. The potential for flow distortion effects at varying positions along the mast was considered in the previous section, which is an $O(1)$ data quality concern. Aside from this, it is important

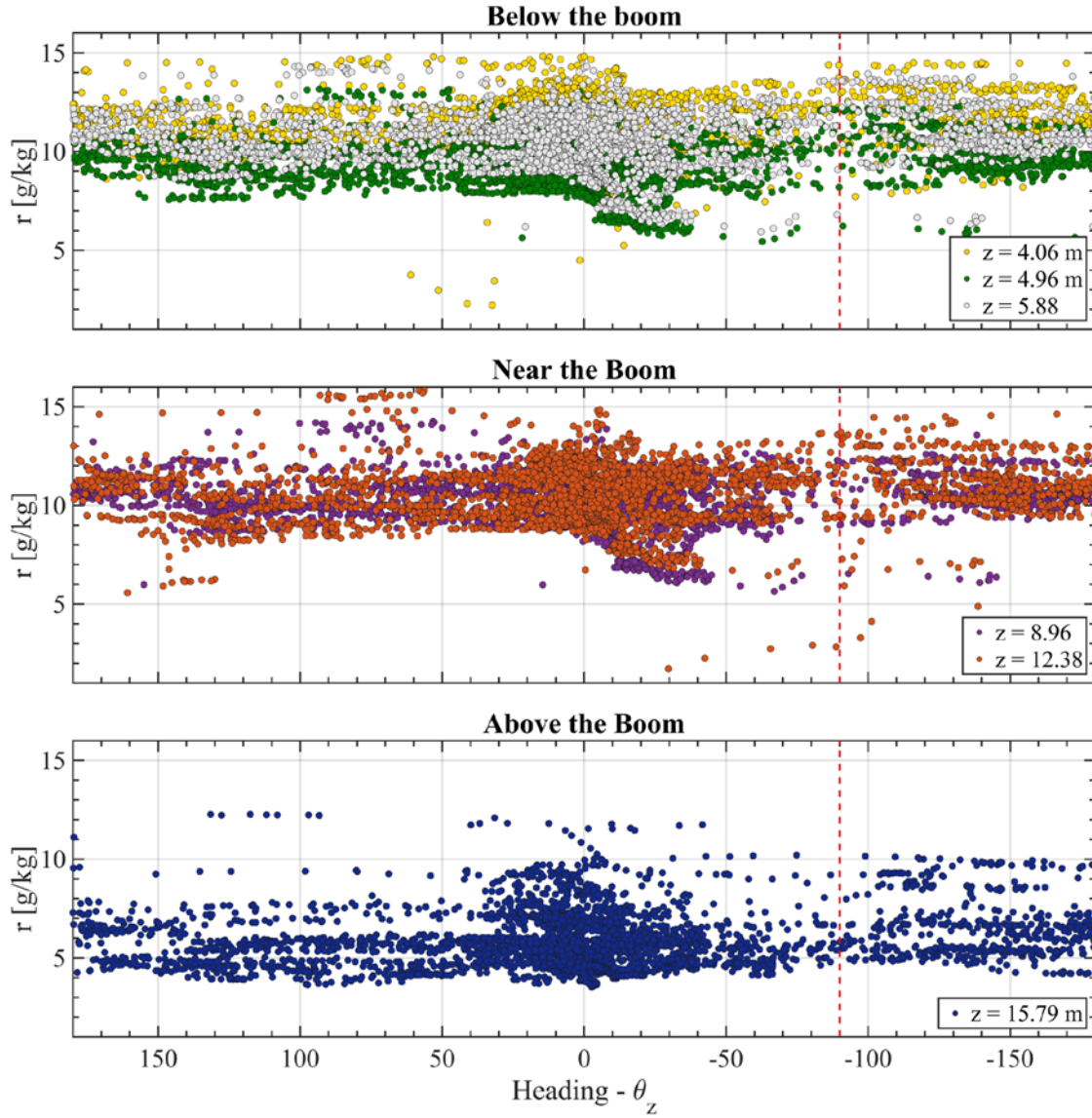


Figure 20. Same as previous, but for the mixing ratio.

to determine a proper averaging window to use for the eddy covariance method. The averaging window (or interval) can affect the scales of turbulent motion the sensor resolves, which ultimately affects the absolute values of the parameters being calculated from the 3DSA and/or gas analyzers. Determining a universally applicable averaging interval for a profile of sensors spanning several meters can be very challenging. This is because the height of the sensor above the surface determines the maximum size of an atmospheric eddy that can be resolved, which implies an interval length needed to fully capture all the relevant

variability. Also, individual averaging windows must satisfy the conditions of stationarity to be considered a valid eddy covariance measurement. While related, this may be an all-together separate requirement for the measurements from the MOST condition of homogeneity, which is significantly harder to diagnose via inspection of the measured turbulence characteristics⁵.

A subset of the ASI mast data was inspected to determine the turbulence characteristics of individual averaging intervals. This was done for levels 0, 1, 2, 5, and 6 (as in Figure 15) for the time period of 10/18 through 10/21 (inclusive). Ideally, every interval of data, for each level would be visually inspected for the entire experiment, however this is not feasible given the length of the experiment and number of sensors. For a 30-minute averaging interval, this would require visually inspecting as many as 250,000 individual time windows. The subset of data was considered representative of the CASPER conditions as well as included the relatively high wind period.

For this subset, intervals of the otherwise quality controlled 3DSA wind velocities were visually inspected for 20, 30, and 45-minute averaging windows. Subsequent windows had a 50% overlap. Intervals with averaging wind speeds below 1 m/s were not considered. Also, intervals with a mean wind direction relative to *FLIP*'s heading of $< -50^\circ$ (following results from Figure 16-Figure 18). An interval was deemed *acceptable* if it:

1. Exhibited an approximately linear normalized cumulative summation,
2. Had an Ogive that smoothly asymptotes to 1 at the minimum resolved frequency.

The normalized cumulative sum, CS, a series x of N samples is defined as,

$$CS = \frac{\sum_0^{n=j} x(n)}{\sum_0^N x}, \quad (3)$$

⁵ For MOST, homogeneity refers to the turbulence-generating elements (i.e. roughness) on the surface directly upwind of the measurement. This is a two-dimensional (surface area), statistical concept that could only be *confirmed* by observing the surface characteristics for each individual flux footprint for each level of the mast.

where $j = 1, 2, 3 \dots N$, and CS has the same number of samples as x and $CS_{j=N} = 1$. For the analysis done here, x was the covariance between the along- and vertical-wind components, $(u - U) \cdot (w - W)$. The Ogive is the spectral corollary to CS,

$$Ogive = \frac{\sum_{f=Nyq}^{f=j} S(f)}{\sum_{f=Nyq}^{min(f)} S}, \quad (4)$$

where S is the co-spectrum between u and w that is dependent on frequency, f . The Ogive is integrated from the Nyquist frequency (Nyq) to the minimum resolvable frequency band. $j = 1, 2, 3 \dots N^{\text{th}}$ frequency band, so that for $j = 1$, $S(f)$ is integrated from $f = Nyq$ to $f = Nyq - df$, where df is the uniform frequency resolution.

The cumsum is analyzed as a function of the fraction of the window length, i.e. ranging from 0 to 1. The Ogive is represented as a function of frequency. A linear CS, with a slope ~ 1 , indicates that the contribution to the total covariance is uniformly distributed across the entire averaging window. This would imply a statistically homogeneous (in time) sample, as well as provide some evidence for the stationarity of the interval. The Ogive conveys similar information, but because the frequency-dependence is preserved it can indicate how well an individual interval resolves all of the relevant scales of motion. For a stationary interval that resolves all of the turbulent motion, the Ogive should smoothly transition from an asymptote $S(f = Nyq) = 0$ to $S(f = min(f)) = 1$. In the low frequency range, this behavior indicates that less and less appreciable contributions to the net covariance are added by resolving larger and larger scales. In other words, this interval resolves all of the relevant turbulent scales of motion during that particular window. Failure of either condition #1 or #2 indicates an interval of data that does not satisfy the conditions of the eddy covariance technique and should not be included in the broad data set⁶.

⁶ Failure of #1 and/or #2 does not mean that this interval is *bad* per se, it simply indicates that the variance over this time cannot be fully accounted for by the assumptions of the eddy covariance technique. Therefore, it cannot be directly compared to a sample whose characteristics satisfy the conditions. We would note that in general practice for large data sets, rigorously testing spectra against these conditions is *not* typically done—or the results are not reported.

Table 1. Inspected windows that exhibited stationarity and appropriate averaging window length. All values are given in %, left column indicates level.

	20-MIN (<i>N</i> = 424)	30-MIN (<i>N</i> = 288)	45-MIN (<i>N</i> = 190)
ANY ⁷	49.5	46.8	51.5
ALL ⁸	10.1	12.2	20.0
0	26.4	24.7	29.5
1	40.6	40.6	45.3
2	39.6	40.3	44.7
5	19.6	23.2	35.8
6	20.0	23.6	35.8

The results from the five levels chosen for this analysis, for the three averaging windows tested, were all visually inspected (by D. G. Ortiz-Suslow) and categorized by whether or not the individuals failed either of the conditions. The results of this evaluation are given in Table 1. Note that Level 4 was specifically chosen because of its proximity to *FLIP*'s port boom. This allowed for checking if some unaccounted-for flow distortion affects this stationarity analysis.

Over these 96 hours inspected, roughly 50% of all of the intervals contained at least 1 level that could be characterized as acceptable. This did not change substantially between the three averaging intervals. However, the results of this analysis did reveal strong sensitivity to the averaging interval when considering if all the flux levels were stationary. Little difference was found for 20- and 30-minute intervals, but for the 45-minute averaging window 20% of all of the inspected samples were stationary across the entire profile. This was largely

⁷ ANY refers to *any* level satisfying both criteria.

⁸ ALL refers to *all* levels satisfying both criteria.

driven by a 12-15% increase in the number of stationary samples for levels 5 and 6. Levels 0, 1, and 2 were least effected by the averaging interval and only exhibited a small ($< 5\%$) increase between the 20/30- and 45-minute windows. Three examples of inspected data segments (30-minute interval) are provided in Figure 21 through Figure 23. Of particular interest is Figure 22, which provides an example where Level 0 (the RM Young 3DSA) was considered to have failed both conditions #1 and #2, while all other levels were considered acceptable. While this effect is attributed to *non*-stationarity, it is most likely exacerbated by some wind-wave interaction that itself may not have been stationary. This particular circumstance was very common and probably explains the relatively low success rate for this level when compared to Levels 1 and 2—as in, waves significantly and persistently impact this level. Also, this was noticed for all averaging intervals. This is suggestive of Level 0 being within the wave boundary layer (WBL) for much of the CASPER-West sampling.

This analysis intended to characterize how much of the flux measurements from the ASI mast during CASPER-West could be accepted in an eddy covariance data set. However, the other goal was to systematically determine what length of averaging window to use for the flux analysis. The results of this analysis would argue for a circa 45-minute interval in order to maximize the times when the entire flux profile could be considered stationary. However, it should be emphasized that for all intervals the ANY criteria were not very different in absolute terms; and for the ALL criteria, no interval gets near to 50%. Therefore, analysis into the fluxes should consider the potentially confounding impact stationarity and averaging interval have on the results.

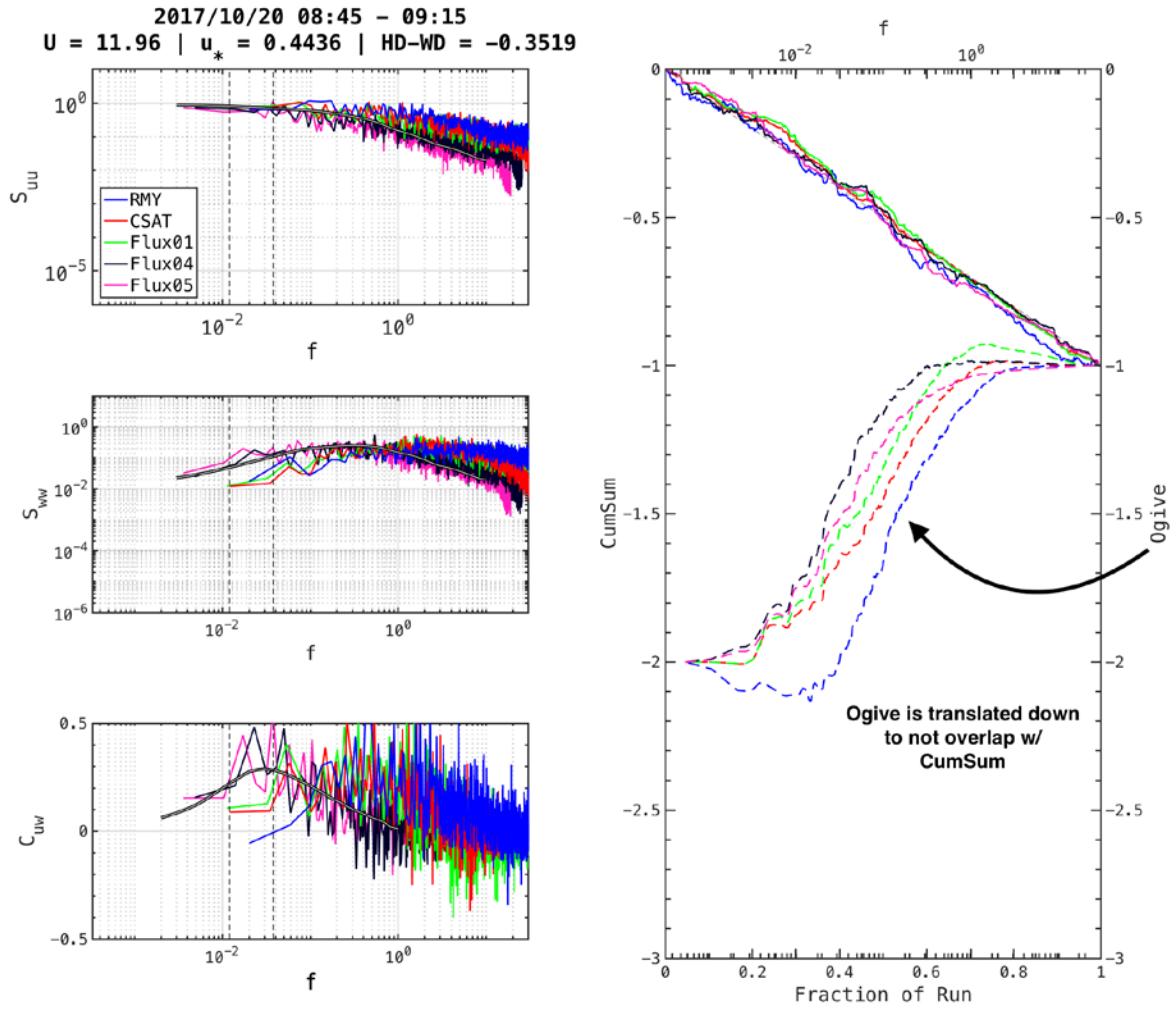


Figure 21. Example where *all* levels were considered to satisfy both conditions #1 and #2. Here, the spectra of the left column are given in surface layer coordinates (Miyake et al.,

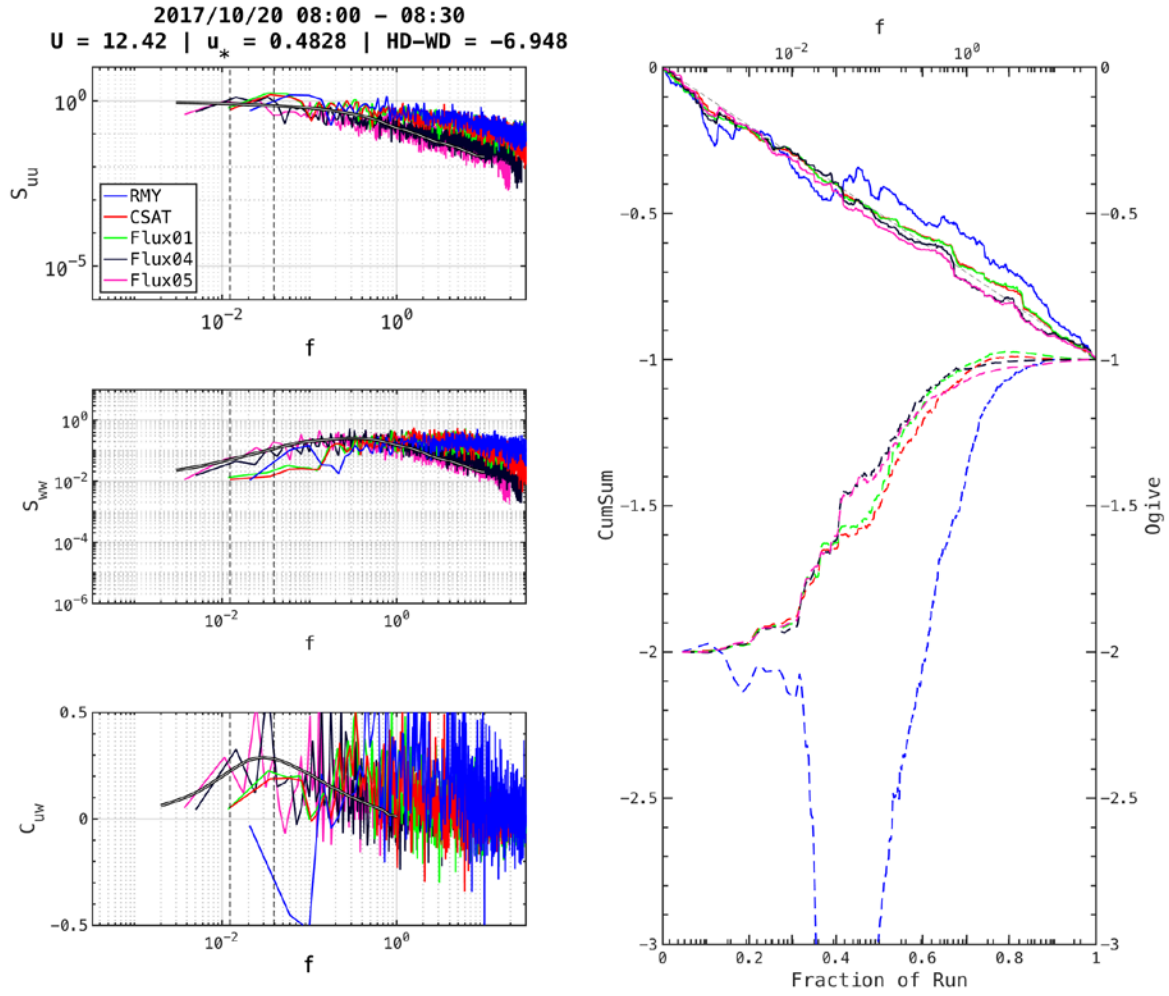


Figure 22. An example where Level 0 (RMY) fails both conditions #1 and #2, but the other levels were considered to have passed.

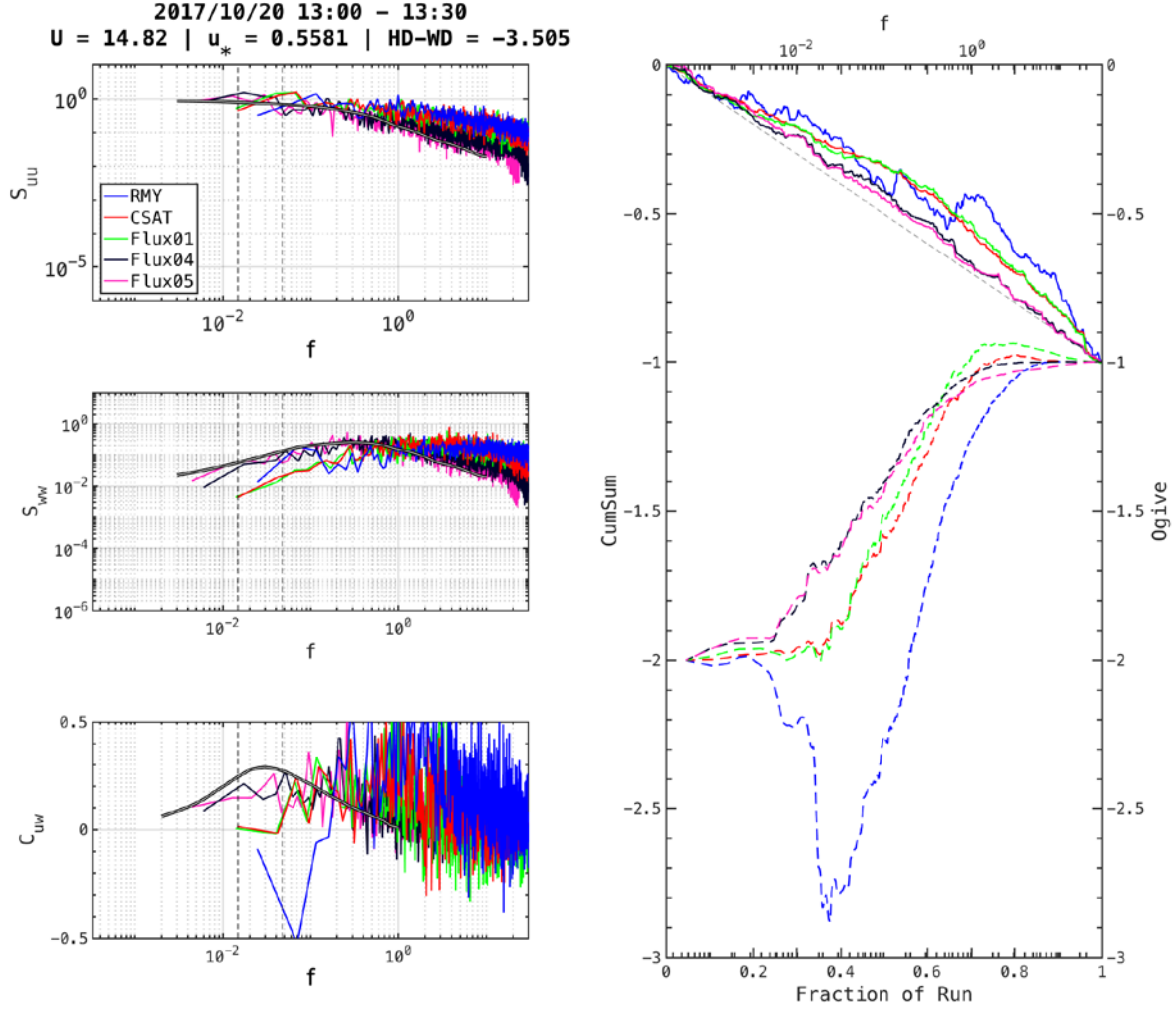


Figure 23. An example where Level 1 (CSAT) and 2 (Flux01) did not satisfy condition #1 and Level 0 failed both conditions.

d. *Fast-Slow State Variable Comparison*

A comparison between the state variables from the slow- and fast-response sensors was done. The combined 3DSA/IRGA flux levels simulatenously measured mean air temperature and water vapor specific humidity. The sonic temperature was converted to actual air temperature using the water vapor specific humidity measurement. These parameters were also measured directly or derived from the co-located (same height) bulk temperature and relative humidity probes. The bulk sensors have been calibrated in a calibration chamber (§ 1b). However, the flux sensors cannot be calibrated in a calibration chamber. The mean state values of the fast-response sensors are not useful because the

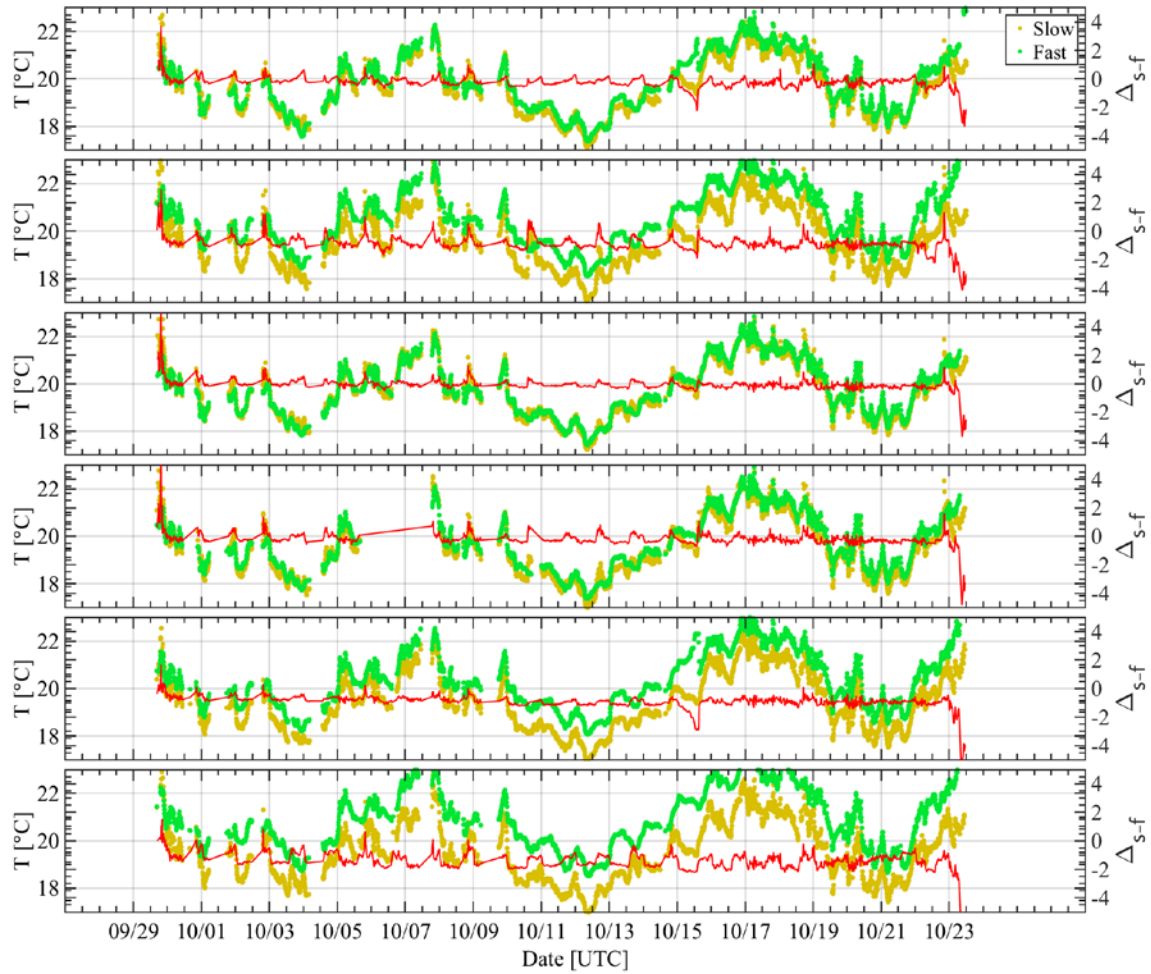


Figure 24. Time series of slow- and fast-varying air temperature, T , from Levels 1 (top) to 6 (bottom). Residuals given on right vertical axis.

bulk sensors give accurate measurements of them at the same levels. But, even though the covariance (eddy correlation estimation of turbulent fluxes) will remove the mean from the time record, there is interest in determining if the fast measurements respond similarly as the slow equivalent, i.e. if the bias (slope) coefficient of fast sensors is close to unity.

Figure 24 and Figure 25 show that in general there may be significant differences in mean values between the fast and the slow sensors. The differences are larger for specific humidity in some levels (like level 6 on *FLIP* mast), most likely due to contamination on the optics of the open-path gas analyzers. However, as it was noted above the calibration bias of fast sensors is of interest for turbulent estimation (fluxes or variances). Thus, in

order to diagnose any drift in the perturbation sensor mean and check the calibration of the measured variations, the low frequency part of the time series of fast sensors measurements have to be removed before making the comparison with the corresponding bulk parameter. The fast-slow sensor inspection was done using 20-minute averages in order to compensate for the differences in sensor response and additionally these time series were high-pass filtered at 24 hours. Thus, the very low frequency, diurnal variability was removed before comparing. These filter values were compared and a best linear fit was made of each pair of sensors (Figure 26, Figure 27, and Figure 28).

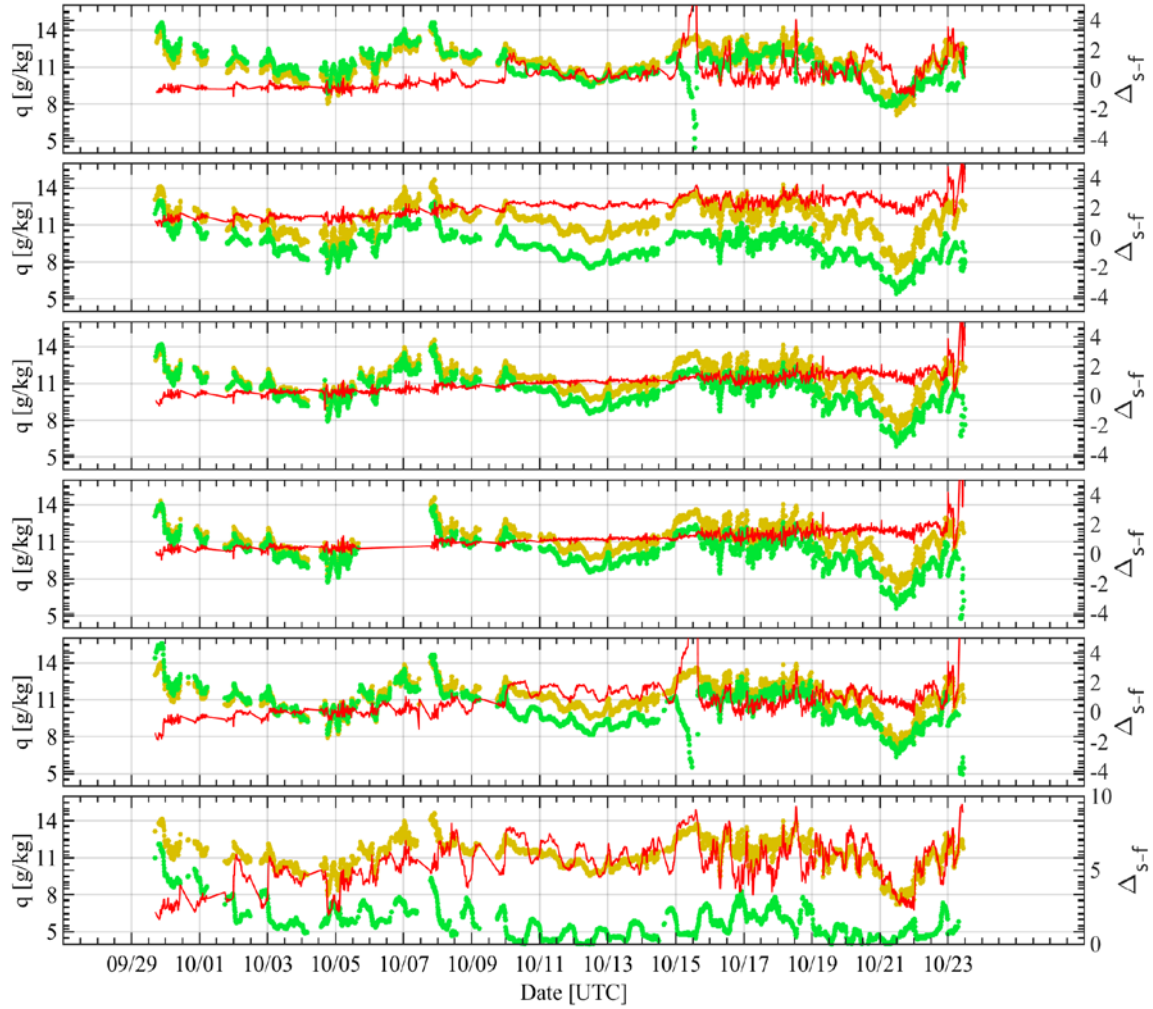
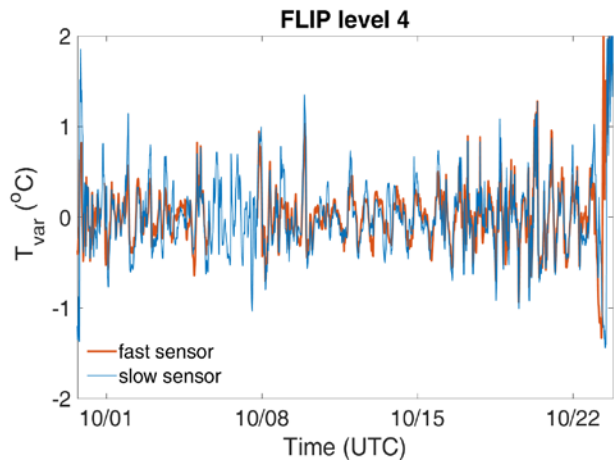
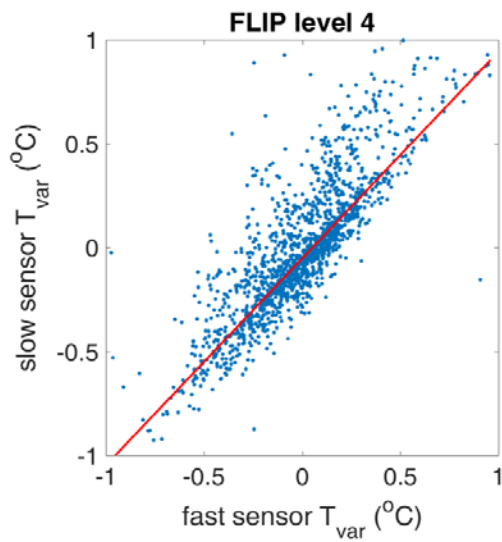
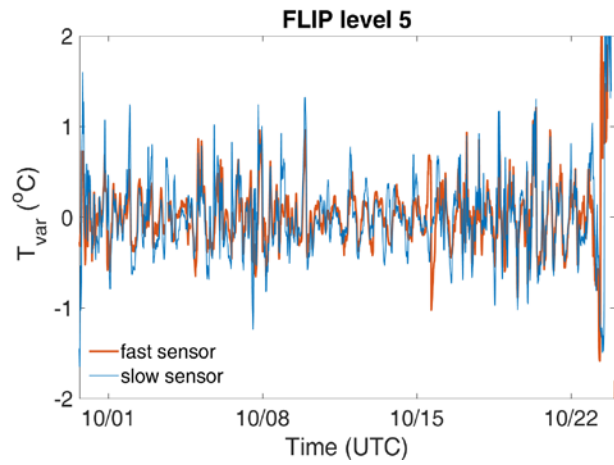
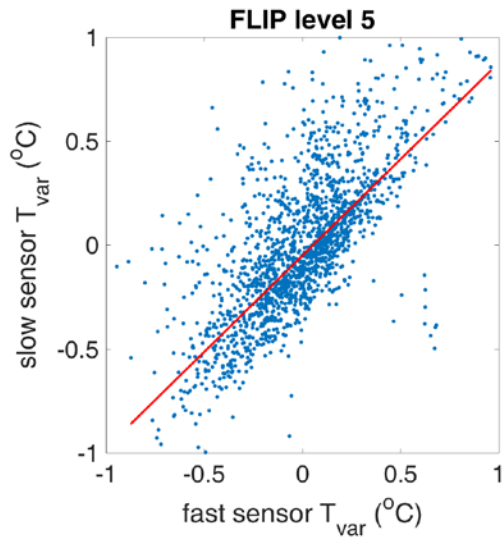
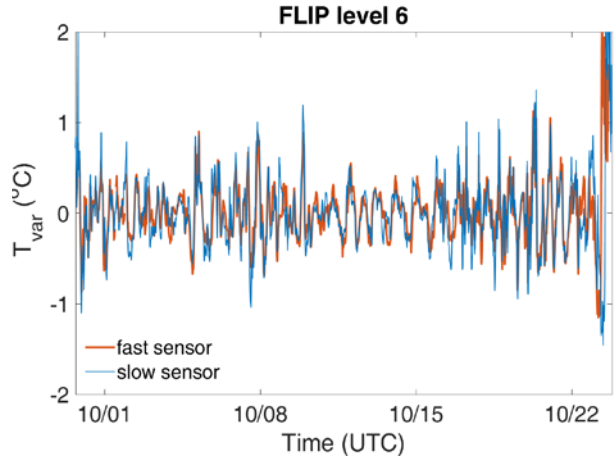
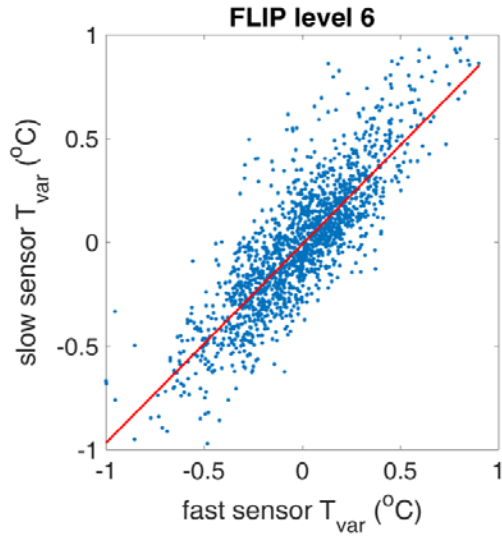


Figure 25. Same as previous for specific humidity, q .



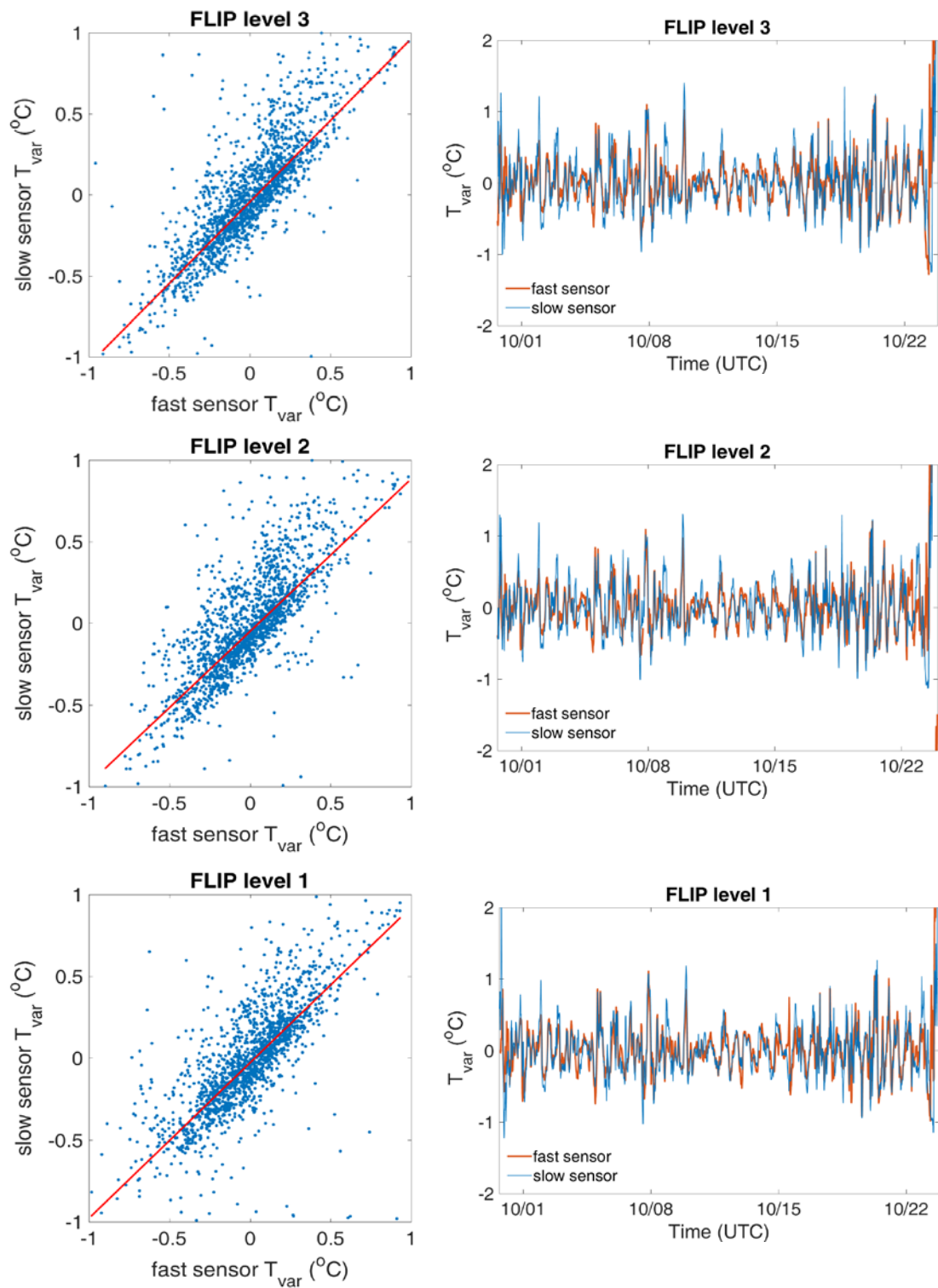


Figure 26. Scatter plots (the red line is the best fit) and time series of filtered variations of temperature from fast and slow measurements at each level on *FLIP* mast.

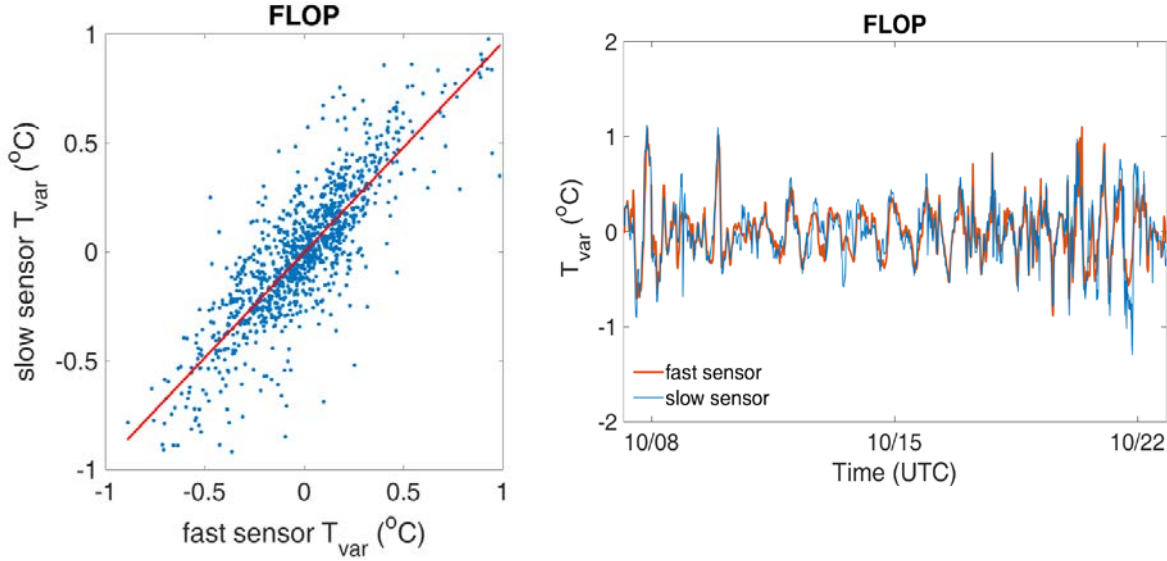


Figure 27. Scatter plot (the red line is the best fit) and time series of filtered variations of temperature from fast and slow measurements from the FLOP mast (see § II.E).

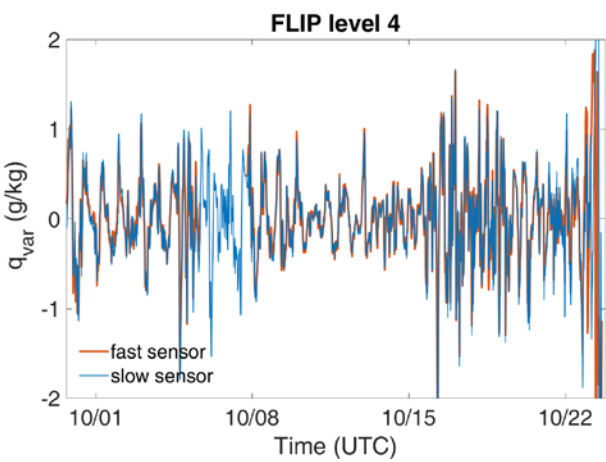
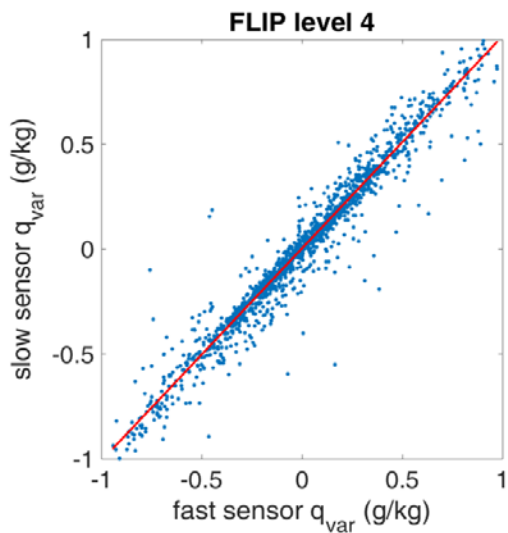
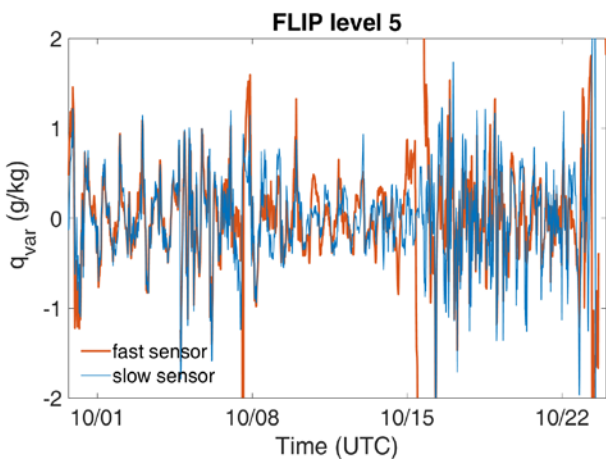
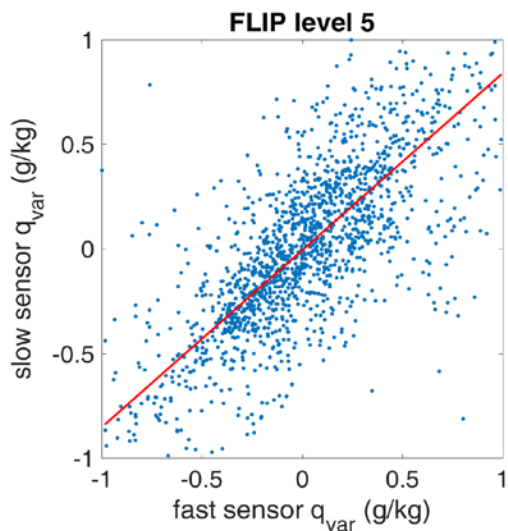
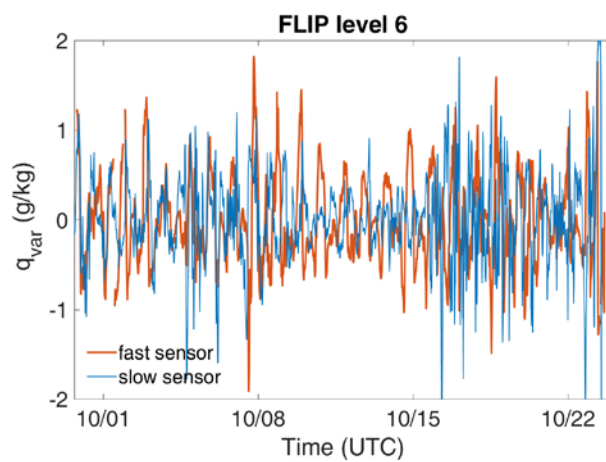
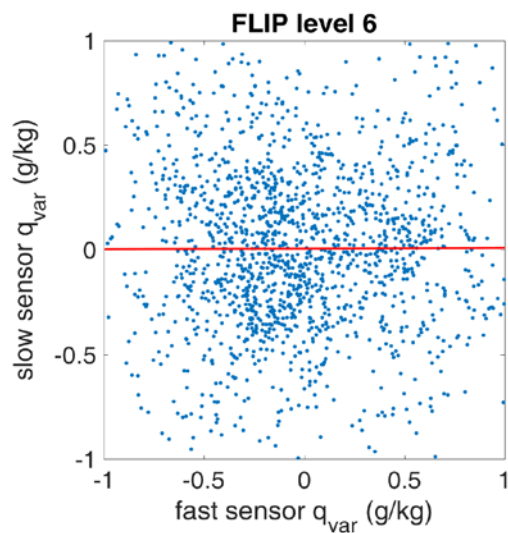
Table 2 presents the estimated bias (slope) and offset coefficients and fit statistics (root mean square error (RMSE) and Pearson's correlation coefficient). The offset values are practically zero, which is expected because the data of the comparison represent variations instead of absolute values. The bias values for fast temperature sensors are close to unity within 7%, which indicates that the calibration of the fast sensors is quite good at least for the high frequency (variations) part, which is of interest for turbulence measurements. However, there is significant scatter especially for higher variation values, where an underestimation from fast sensors can be seen, as compared to the slow sensors ($r^2 < 0.9$). This scatter may be due to noise problems of the sonic temperatures in the marine atmospheric environment close to the sea surface, where the variations of temperature are generally small. The time series of variations show that this behavior is not changing with time and appears to be systematic for all fast temperature sensors (sonic anemometers) compared to the slow sensors.

The fast humidity sensors (Fig. 29) show quite different behavior between levels. Their variations at middle levels (2, 3 and 4) show very small scatter and high correlation compared to the slow sensors, but very high scatter at the lower and upper most levels. From the time series of variation, it can be seen that at these levels with large scatter, at the beginning of the experiment the fast sensors

follow very well the slow sensors. However, after the first week they start to lose their correlation with the slow sensors, which is probably due to contamination on the optics of IRGA. Especially for Level 6, the variations of the fast humidity sensor do not correlate with the slow reference sensor from the beginning of the experiment and no best fit calibration could be estimated. Thus, high caution is needed on the use of the fast humidity data and the corresponding flux on this level and less for levels 1 and 5 after the first week of the experiment.

Table 2. Results of comparison between slow and fast sensors variations. Using 20-minute average data.

	T [° C]				q [g/kg]			
	<i>bias</i>	<i>offset</i>	<i>RMSE</i>	<i>r</i> ²	<i>bias</i>	<i>offset</i>	<i>RMSE</i>	<i>r</i> ²
<i>FLOP</i>	0.966	-0.01	0.162	0.848	-	-	-	-
1	0.950	-0.02	0.169	0.832	0.938	-0.02	0.216	0.795
2	0.933	-0.05	0.177	0.823	1.131	0.01	0.133	0.939
3	1.005	-0.04	0.167	0.861	1.006	0.01	0.089	0.973
4	0.995	-0.05	0.159	0.864	1.012	0.00	0.082	0.976
5	0.927	-0.05	0.196	0.801	0.846	-0.01	0.227	0.790
6	0.957	-0.01	0.160	0.854	-	-	-	-



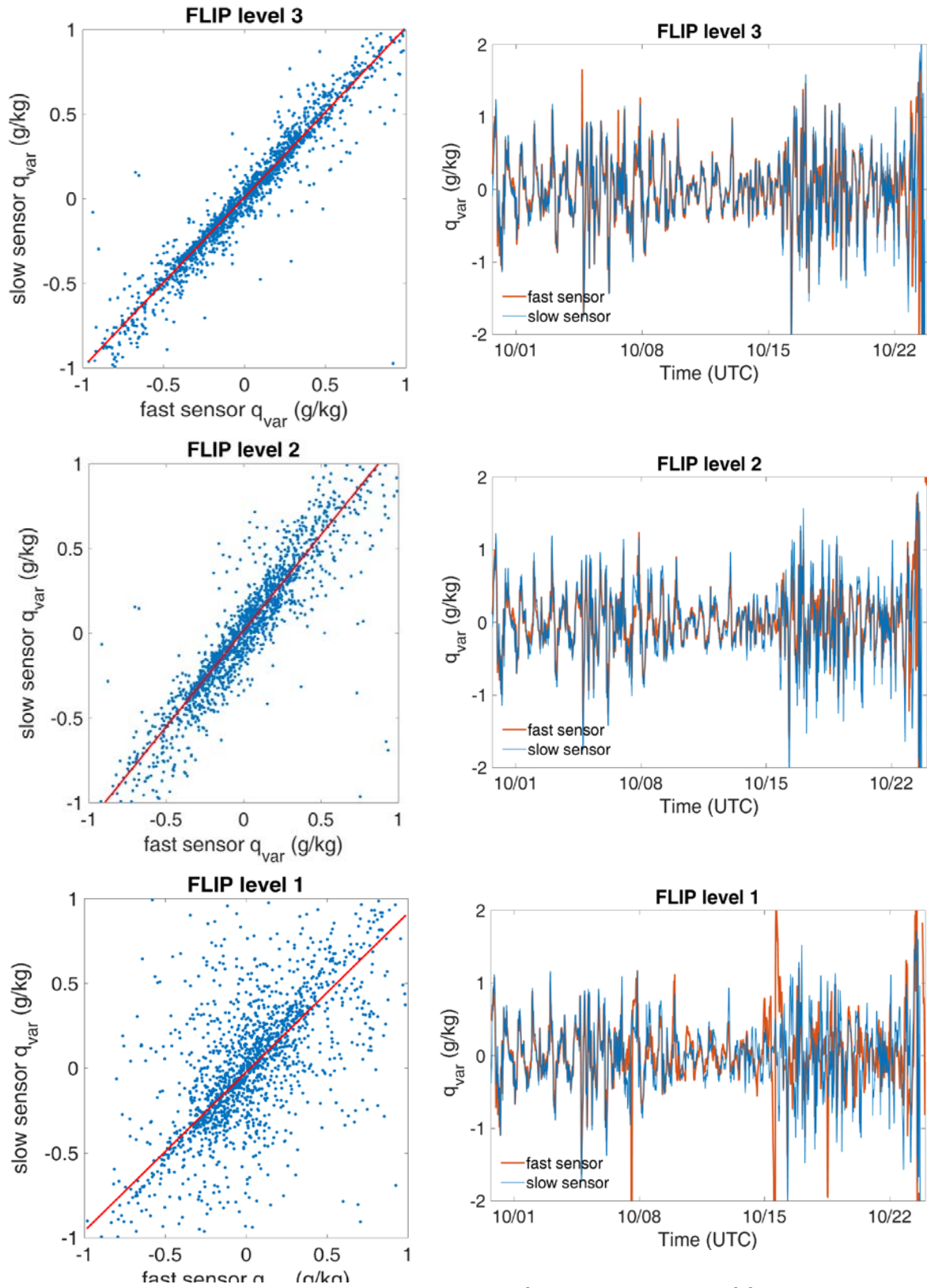


Figure 28. Scatter plots (the red line is the best fit) and time series of filtered variations of specific humidity from fast and slow measurements at each level on *FLIP* mast.

C. Radiometers

NPS deployed two types of radiometric sensing systems from *FLIP*. First, two different sea surface temperature (SST) sensors were deployed from the port boom; and second, a broadband radiometer (Kipp-Zonen CNR4 Net Radiometer, hereinafter CNR4) was deployed from the upper deck of *FLIP*. The focus here will be on the processing and quality control of the SST sensors.

A RMRCO Remote Ocean Surface Radiometer (ROSR⁹) and a Heitronics KT-19.85 infrared (IR) narrowband pyrometer were deployed from the port boom of *FLIP* from 9/30 through 10/23. The ROSR is a stand-alone measurement system that incorporates a Heitronics KT-15.85, tilt motor and gyor, 2 blackbodies for calibration, GPS, and rain gauge. The ROSR provides a very precise measure of temperature (± 0.1 C), that over one measurement cycle accounts for the downwelling longwave radiation reflected from the ocean surface and calibrates the radiometer against two blackbodies at two different temperatures. These measurement steps are done automatically and enable a single measurement of the calibrate sea surface skin temperature (SSST) every 5 minutes. The reflected irradiance is measured via sky view at the same incidence angle for the ocean surface reading ($\sim 45^\circ$). The KT-19.85 (herein KT19), is an IR pyrometer with a fast

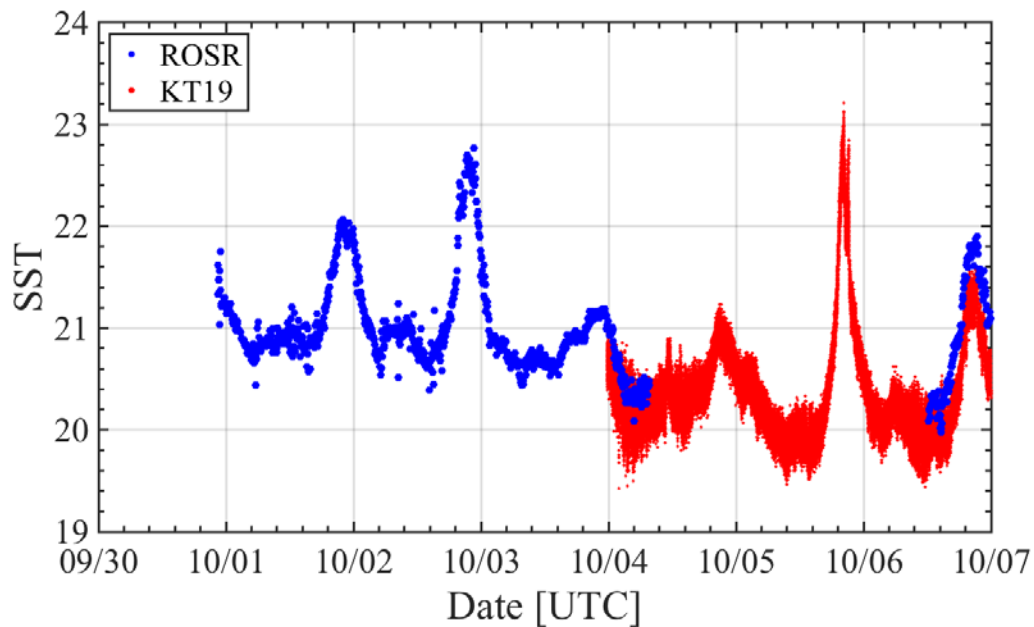


Figure 29. Portion of SST time series when ROSR and KT19 overlap.

⁹ <http://www.rmrco.com/prod/rosr/index.html>

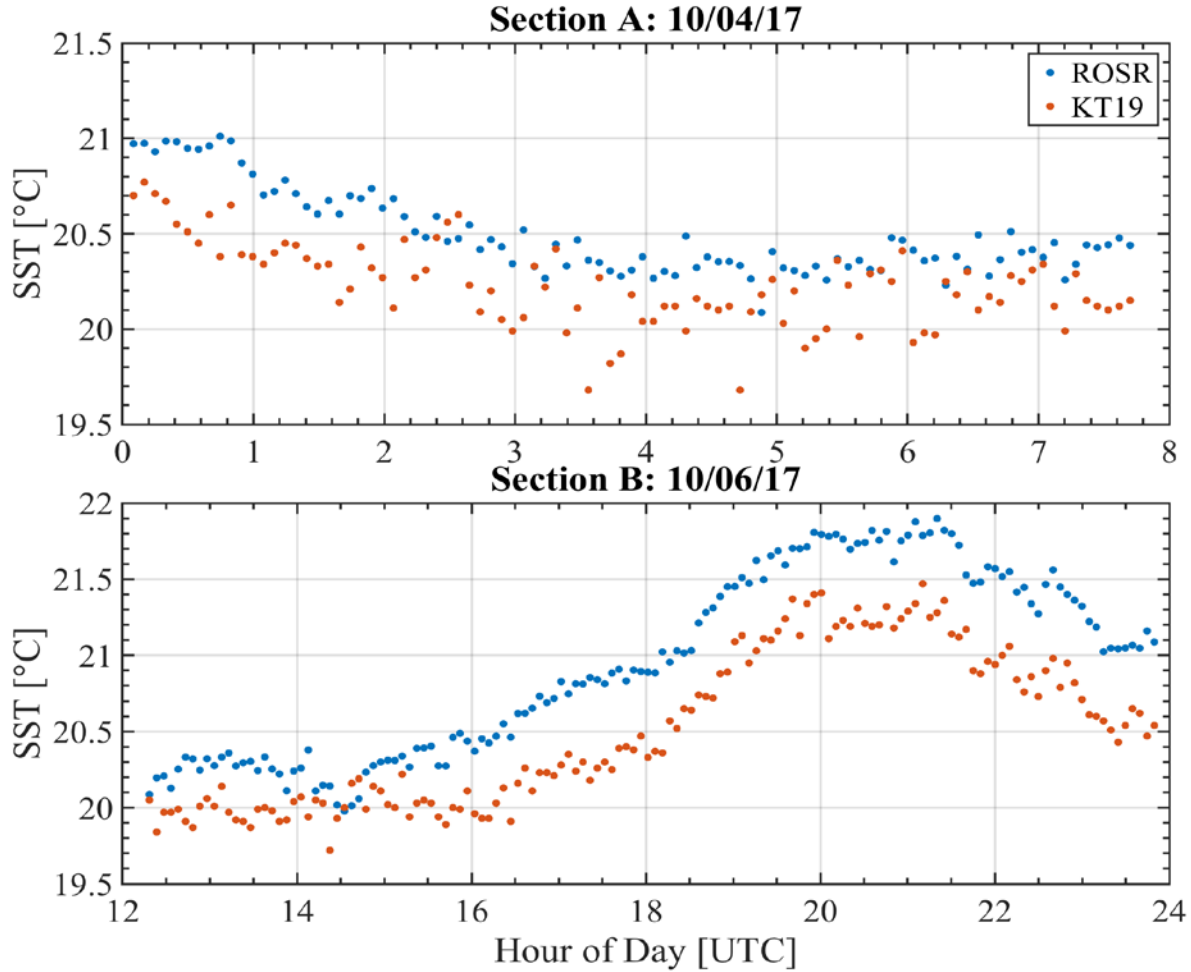


Figure 30. Radiometer data sections used in post-calibration and sky correction of KT19.

response (5 ms) that was sampled at 10 Hz. The measurement from the KT19 is not *in situ* calibrated or corrected for reflected irradiance. The KT19 was co-located with the ROSR and sampled the water surface directly below the boom, which was ~7.78 m upstream of the ROSR-sampled surface.

Just before 10/07 at 00:00 UTC, the ROSR experienced a catastrophic system failure that caused the acquisition system to overwrite saved data every hour. This error in the data logging was not discovered until after the experiment when the ROSR was sent back to the manufacturer for routine post-experiment inspection. Fortunately, the KT19 was deployed from *FLIP*, and so a record of SST was measured during the majority of the experiment.

The KT19 is a fast-response system, but does not make as robust a measurement as the ROSR. In particular, the KT19 does not *in situ* correct for the reflected, longwave irradiance from the ocean surface. Generally, this effect causes an $O(-0.5^\circ)$ bias in the SST measurement. Due to the ROSR system failure, an effort was made to develop a physically-based (as opposed to *statistically*-based) correction to the KT19, reproduce a ROSR-equivalent measure of SSST. Unfortunately, due to an unaccounted-for system failure before 00:00 10/07, the ROSR and KT19 records only overlap for a total of ~20 hours. While this is not an ideal situation, it does provide some opportunity for comparing the success of the KT19 correction with ROSR measurements.

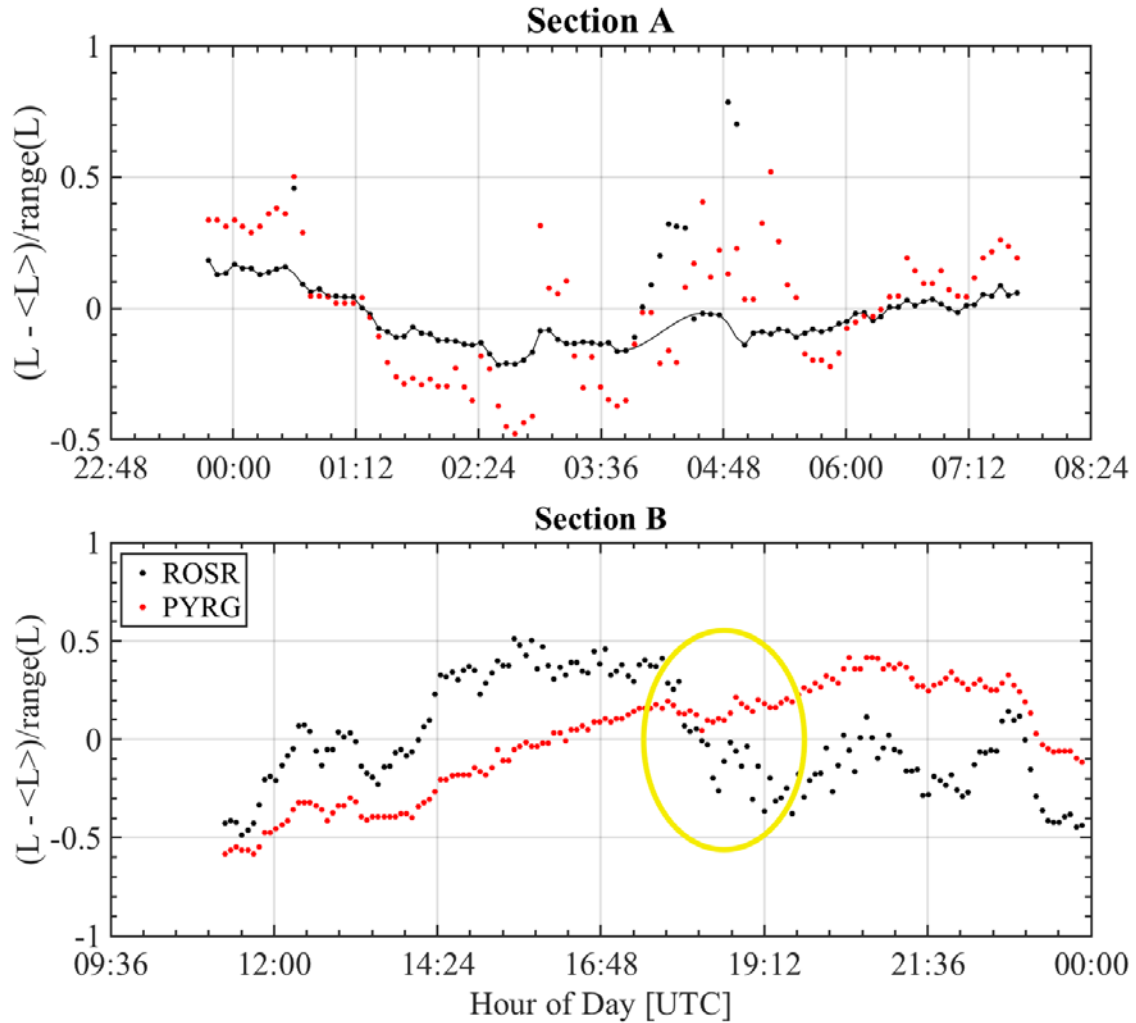


Figure 31. Sections A (top) and B (bottom) comparing the measured downwelling irradiance from the ROSR and PYRGeometer. The solid line in A represents a polynomial interpolation through ROSR observations rejected from the post-calibration analysis. The circled period in B was not included and Section B was split into subsections before and after this ~1-hour period.

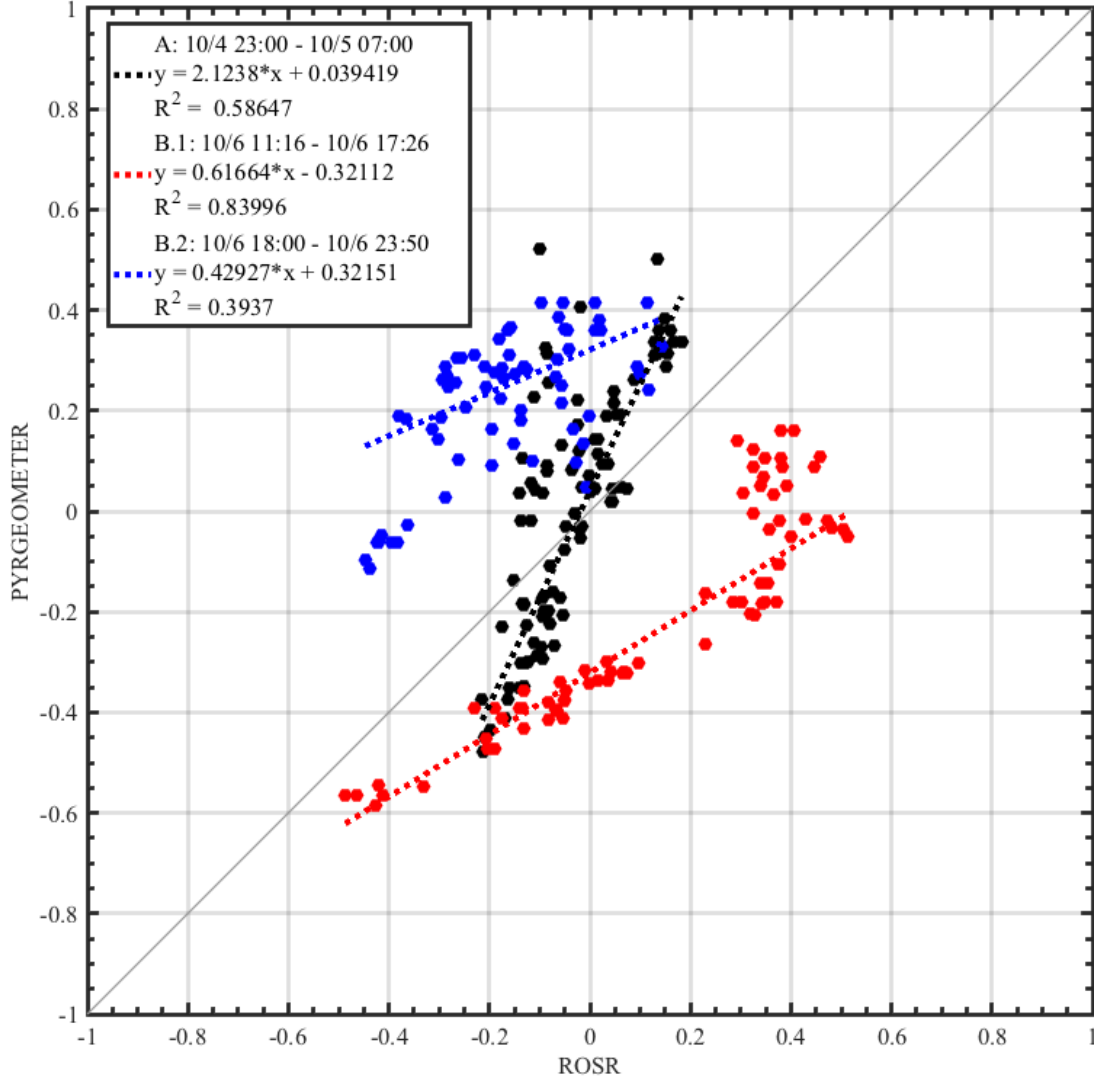


Figure 32. Comparison between ROSR and Pyrgeometer measured L.

The observed SST, SST_{obs} , can be corrected for the reflected irradiance using the sky temperature, T_{sky} (see Lind & Shaw, 1989),

$$SSST = \frac{1}{\epsilon} (SST_{obs}^4 + \alpha T_{sky}^4)^{1/4}, \quad (5)$$

where ϵ is the ocean surface emissivity at the look angle θ and $\alpha = 1 - \epsilon$. The value for emissivity used for all CASPER-West was 0.9927, which was determined via polynomial interpolation of the relationship between the emissivity and look angle used by the ROSR—the KT19 was assumed to have a look angle near-nadir. T_{sky} is derived from the downwelling long-wave irradiance, L ,

$$T_{sky} = \left(\frac{1}{\sigma}L\right)^{1/4}, \quad (6)$$

here σ is the Stefan-Boltzmann constant, $5.670367 \times 10^{-8} \text{ W}/(\text{m}^2\text{K}^4)$. For the ROSR, L is determined using a sky-view: the radiometer is pivoted upward at $-\theta$ (i.e. same emissivity) to get a direct T_{sky} reading from the same ocean-viewing sensor. For the KT19, the CNR4, which integrates 4 broadband up-/down-welling solar and infrared radiometers, must be used to derive a sky temperature. T_{sky} derived from the broadband radiometer is not equivalent to the one derived from the ROSR pyrometer (a narrowband sensor). Therefore, a post-calibration was done to determine the coefficients needed to make a ROSR-equivalent, L_{ROSR} , from the output of the CNR4's pyrgeometer, L_{pyrg} . While this approach is favorable to using either L_{pyrg} or a brute-force statistical correction between $SSST_{ROSR}$ and $SSST_{obs}$, only ~ 20 hours of data was available for the sky-view comparison.

Figure 30 and Figure 31 provide the details of the two sections (A & B) used to develop a post-calibration for the KT19. Section B was split into sub-sections B.1 and B.2 due to a ~ 1 -hour period where the ROSR response was atypical and did not track with the variability in the pyrgeometer. The L measured from each sensor was nondimensionalized to account for the difference in response of the narrow- versus broadbanded sensor. This non-dimensionalizing should not affect the outcome of the post-calibration. The results of the comparison between the ROSR and the pyrgeometer are given in Figure 32. The linear regression lines were derived using the Theil-Sen method, which uses the median and is thus less susceptible to outliers or influential samples. Firstly, the results demonstrate that samples B.1 and B.2 exhibit similar ROSR-pyrgeometer response, but with differing offsets (see Figure 31). Secondly, we can see that Sections A and B exhibit all-together differing relationships. The bias between the ROSR and pyrgeometer were $>$ and $<$ 1 for sections A and B, respectively. From these results, it was decided to merge the findings from B.1 and B.2 and compare them with the results from A. For both sections the ROSR-equivalent irradiance, $\bar{L}$, become:

$$\bar{L}_A = 0.47086 * L_A + 0.018561 \quad (7)$$

$$\bar{L}_B = 1.9122 * L_B + 0.0003812. \quad (8)$$

Figure 30 with the corrections based on the analysis described above is given in Figure 33. The KT19-derived SSST estimates for *both* sections A and B were determined by linear

regression (*Statistical*), the uncalibrated pyrgeometer measurement of L (*PYRG uncorrected*), $\overline{L}_A$ (*PYRG v1*), and $\overline{L}_B$ (*PYRG v2*). The first set of corrections provides a control test because we expect this to be the best ROSR-equivalent SSST. The linear regression was applied, per section, directly between the measured ROSR and KT19 SST. The uncalibrated L based correction to the KT19 SST provides a direct test of the calibration coefficients. The performance of the various corrections was judged by the mean squared error (MSE) between the corrected SSST and the ROSR measurement. The results demonstrated that $\overline{L}_A$ and those set of coefficients (equation 7) performed best for both Sections A and B when compared to the brute-force linear regression (x's in Figure 33). Therefore, a bias of 0.47086 and an offset of 0.018561 were applied to the measured L from the pyrgeometer before using the correction for T_{sky} (equation 5).

A RMRCO radiometer system (ISAR) was deployed from the port bow deck on the RVSR. The viewing angle was oblique to the ship path and such that the ocean reading was outside the bow wake. Alongside the ISAR was a co-located, co-viewing KT19, similar to FLIP system. There were no system interruptions with either of the RVSR radiometers, but when the data was sent back to the manufacturer for post-calibration and inspection, a saturation in the sky reading was observed (Figure 34). This occurred in clear sky conditions. In spite of this, the manufacturer's $\pm 0.1^\circ\text{C}$ precision was maintained over the course of the entire cruise.

Table 3. MSE from various estimates of KT19-derived SSST. SST_{obs} is the uncorrected KT19 measurement.

	SST_{obs}	<i>Statistical</i>	L	$\overline{L}_A$	$\overline{L}_B$
A	0.315	0.215	0.214	0.188	0.531
B	0.462	0.146	0.345	0.184	0.699

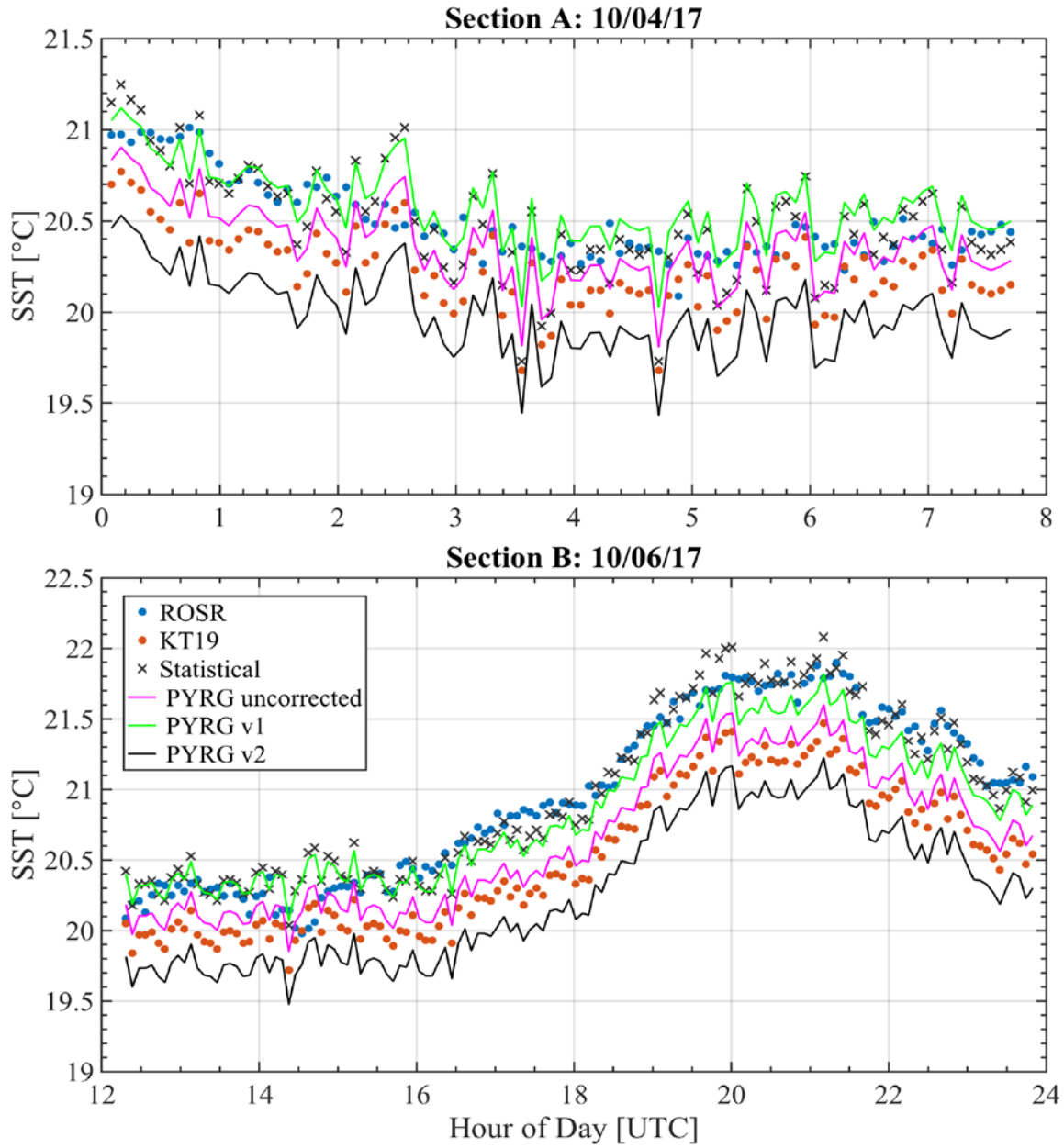


Figure 33. Sections A and B with various corrections to KT19-measured SST. v1 and v2 refer to corrections derived from Sections A and B, respectively.

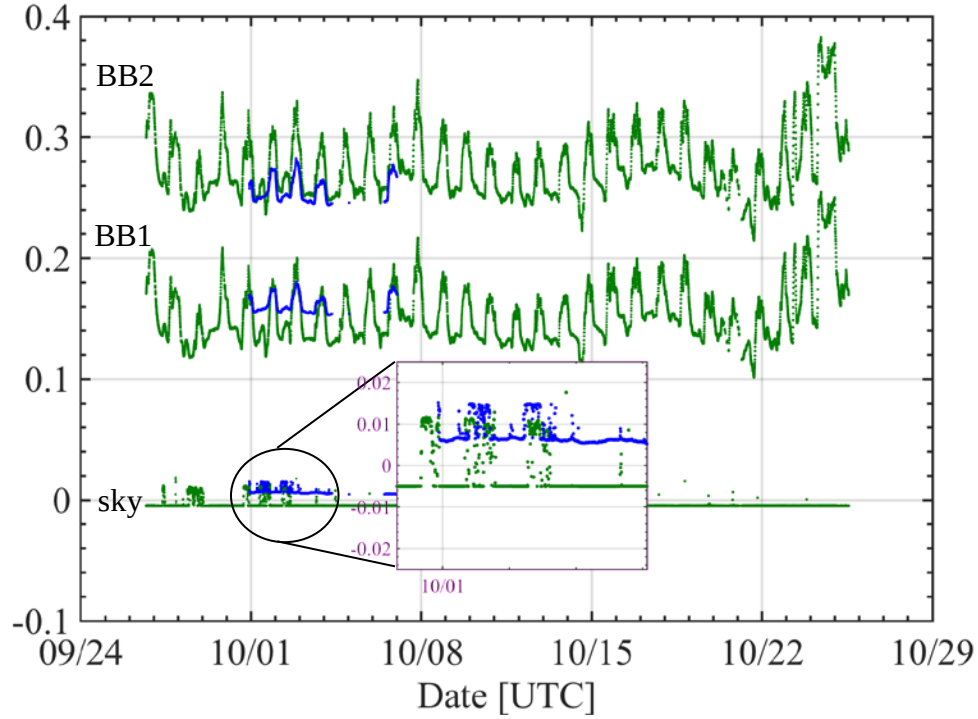


Figure 34. Raw voltages for the ROSR (blue) and ISAR (green) internal blackbody readings (BB1/2) and the sky view. The various readings have been scaled to all appear on the same axis.

D. Laser Distance Meter/Laser Wave Gauge

A Riegel Laser Distance Meter (LDM) was deployed in a downward-looking mode from FLIP port boom, approximately 1.19 m below the deck and a few meters from the ASI mast (see Figure 8). The laser was oriented such that it sensed the distance between the sensor and the instantaneous ocean surface (at 50 Hz). In this mode, the laser can be considered a Laser Wave Gauge (LWG), similar to the analog capacitance wave gauges (or wires) used in the literature.

The LDM operates by emitting a known pulse of near-infrared energy and using the time-of-flight of the backscattered pulse to calculate the distance from the sensor to the scattering surface, at a precision $O(20 \text{ mm})$. At these wavelengths, the ocean is a fairly good scattering surface, especially if the surface is roughened with short gravity and capillary waves. However, during CASPER, given the mean distance to the water ($\sim 10 \text{ m}$) and the relatively mild wind/wave condition, there was a high rate of data loss. The data loss was defined as the fraction of missed samples divided by the total number of samples

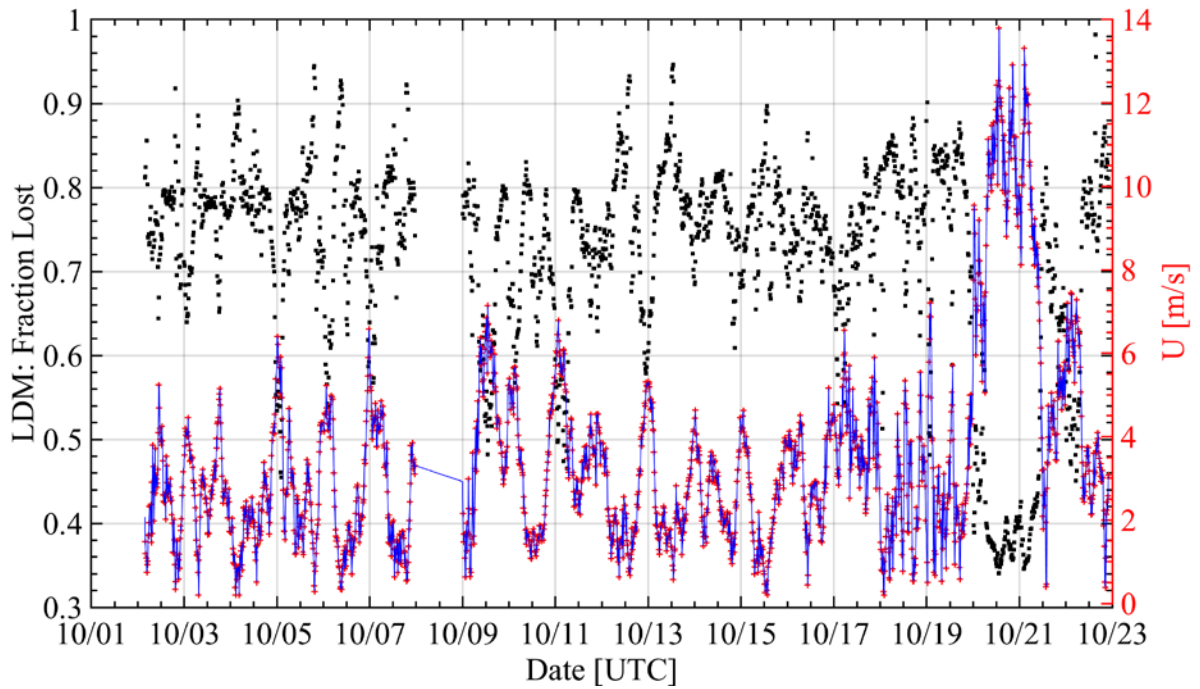


Figure 35. Time record of fraction data loss for LDM (left axis, black squares) alongside vertically-averaged wind speed from the 2DSA profile (right axis, red x's). The blue line is a linear interpolation of the gaps in the U record.

in a 30-minute window. The record of loss for 10/02 through 10/22 is given in Figure 35, which represents a moving average of 30-minute data loss with each window separated by 15 minutes. From this, it is evident that the absolute loss rate is $> 50\%$ for the majority of the CASPER observation period. The global mean fraction of data loss was 0.72 ± 0.12 (1 standard deviation). A relationship between U and loss can be inferred from Figure 35, where loss drops to 0.40 ± 0.056 during the relatively higher wind period of 10/20-10/21. For the time period before 10/20, the mean rate was 0.74 ± 0.080 . A note: individual samples are lost when the LDM does not register a returned pulse. This can result from oblique scattering of the emitted pulse, which may be caused by the smoothness of the surface. Another challenge to the LDM is the nominal distance between sensor and surface is ~ 9 m.

The relationships between data loss and several potential environmental factors controlling the LDM data retention are given in Figure 36. Decreasing loss rate was associated (p -value < 0.001) with the local hour of day, which was most likely caused by the diurnal sea breeze. This relationship was not found for the higher period of 10/20-10/21, during which the loss was consistently < 0.5 . Some relationship between loss and wave steepness was noted, but better collapse of the data was achieved by comparing with wave

age, U/C . From Figure 36, it seems that using the average wave celerity, C_a , resulted in better collapse of the variance. Interestingly, the response of the LDM to the wave age was highly nonlinear, which could make predicting the sensor's functionality in different conditions challenging. This could not be fully assessed because measurements were only made from one nominal distance from the surface. The data loss relationship with *FLIP*'s heading variance was not intuitive and exhibited multiple regimes.

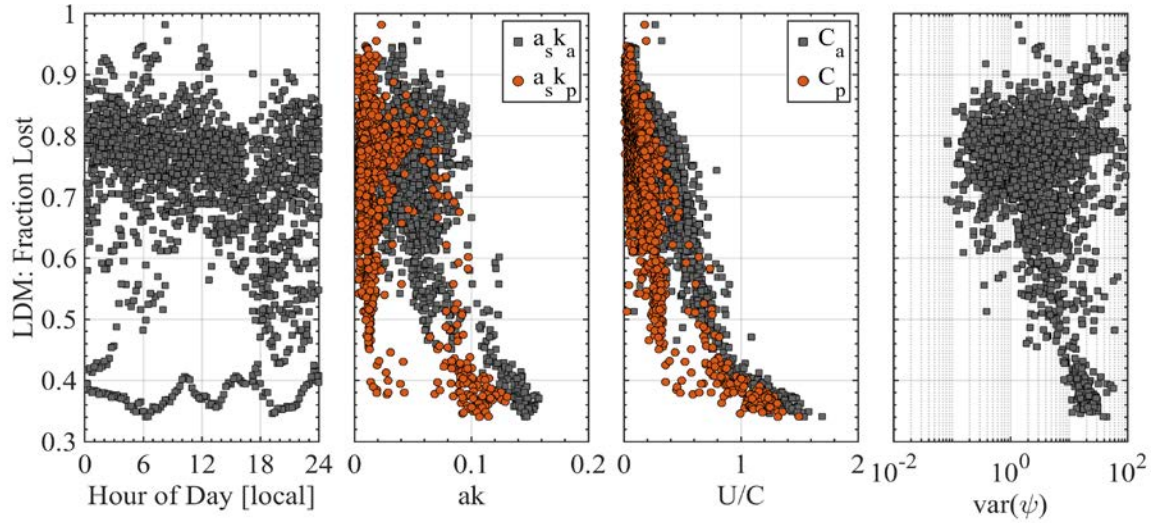


Figure 37. Fraction of loss versus several environmental factors: local hour of day, wave steepness, ak , wave age, U/C , and heading, ψ , variance. a_s is the significant wave amplitude and “a” and “p” refer to average and peak waves. The wave data used here came from the Santa Barbara wave buoy (CDIP #234), which was ~ 2.1 km away from *FLIP*.

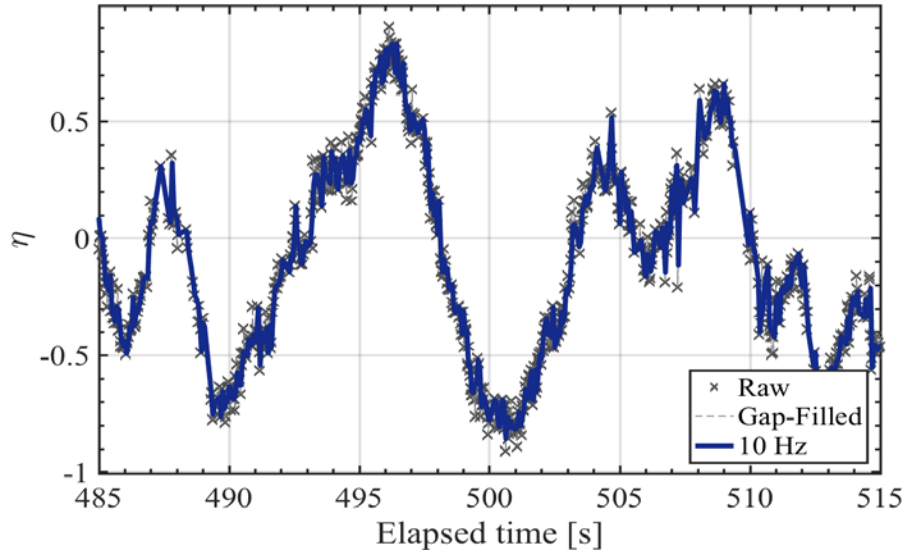


Figure 36. Snippet of water surface elevation showing gap-filling and smoothing steps.

While the LDM tended to lose a substantial amount of data per 30-minute window, sampling at 50 Hz helped to preserve measurement of all but the shortest surface gravity waves. Gaps in raw data samples were filled using a linear interpolation, then the gap-filled record was sub-sampled to 10 Hz to smooth out high frequency noise. An example of these steps on a snippet of data from 10/20 00:00 UTC is given in Figure 37. This section of data demonstrates that although many data points are missed along a particular wave, the LDM sampling was fast enough to reconstruct the dominant variability of the water surface. The motion correction algorithm described in Drennan et al. [1994] was used to process the gap-filled, observed surface elevation from the LWG¹⁰. An example of a motion-corrected 30-minute window of data is given in Figure 38. Over the majority of surface gravity wave band (0.0333 to 1 Hz) the LWG performs reasonably well. A transition in the spectral slope occurs at ~ 0.5 Hz (magenta line), which is most likely resulting from the LWG losing resolution of the shortest gravity waves. The spectral slope for frequencies between 0.1 and 0.5 Hz was $-7/3$ ($r^2 = 0.801$), which increases to -1.44 ($r^2 = 0.663$) for frequencies above 0.5 Hz. Therefore, all of the wave spectra from the LWG were band-pass filtered at cutoff frequencies 0.0333 and 0.5 Hz. The large peak in $S_{\eta\eta}$ centered on $O(0.01$ Hz), is associated with *FLIP* motion variability. This motion is being introduced into the corrected data by the motion correction algorithm. Operationally, this is not a serious issue because this signal is outside the surface gravity wave band and easily identifiable.

The motion-corrected omnidirectional wave statistics compare fairly well with nearby CDIP buoy observations (Figure 39). Apart from spurious measurements on 10/04, the H_s from the LWG traces the nearby buoy (#234) observation very well. This was generally observed for average (T_a) and peak (T_p). This provides some validation for the measurement of the dominant wave characteristics by the LWG at *FLIP*'s location. These measurements from directly under the port boom will be necessary to do analysis of the wave-phase dependent variability observed from the profiles along the ASI mast.

¹⁰ The LWG is the LDM used for measuring surface gravity waves. The LDM was also used to measure the absolute distance from the boom to the water surface.

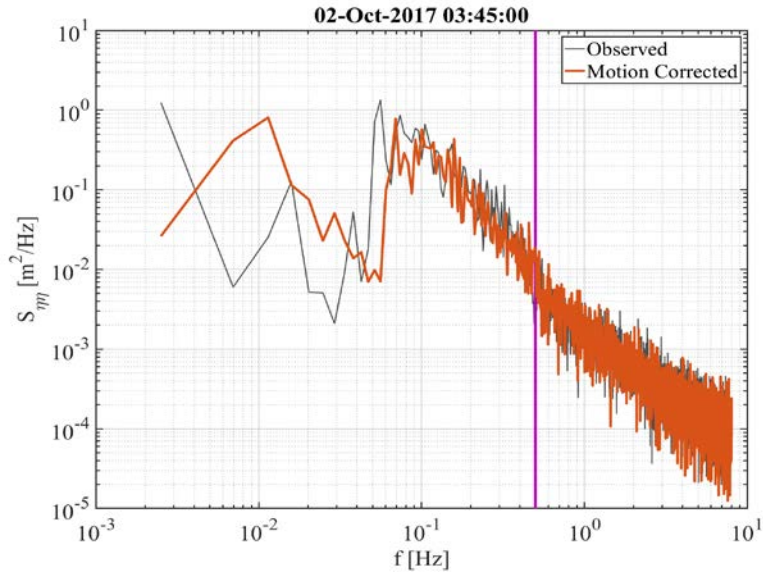


Figure 38. Example comparing observed and motion-corrected LWG output over a 30-minute window. The magenta line marks 0.5 Hz, which coincides with a transition in the elevation variance spectrum.

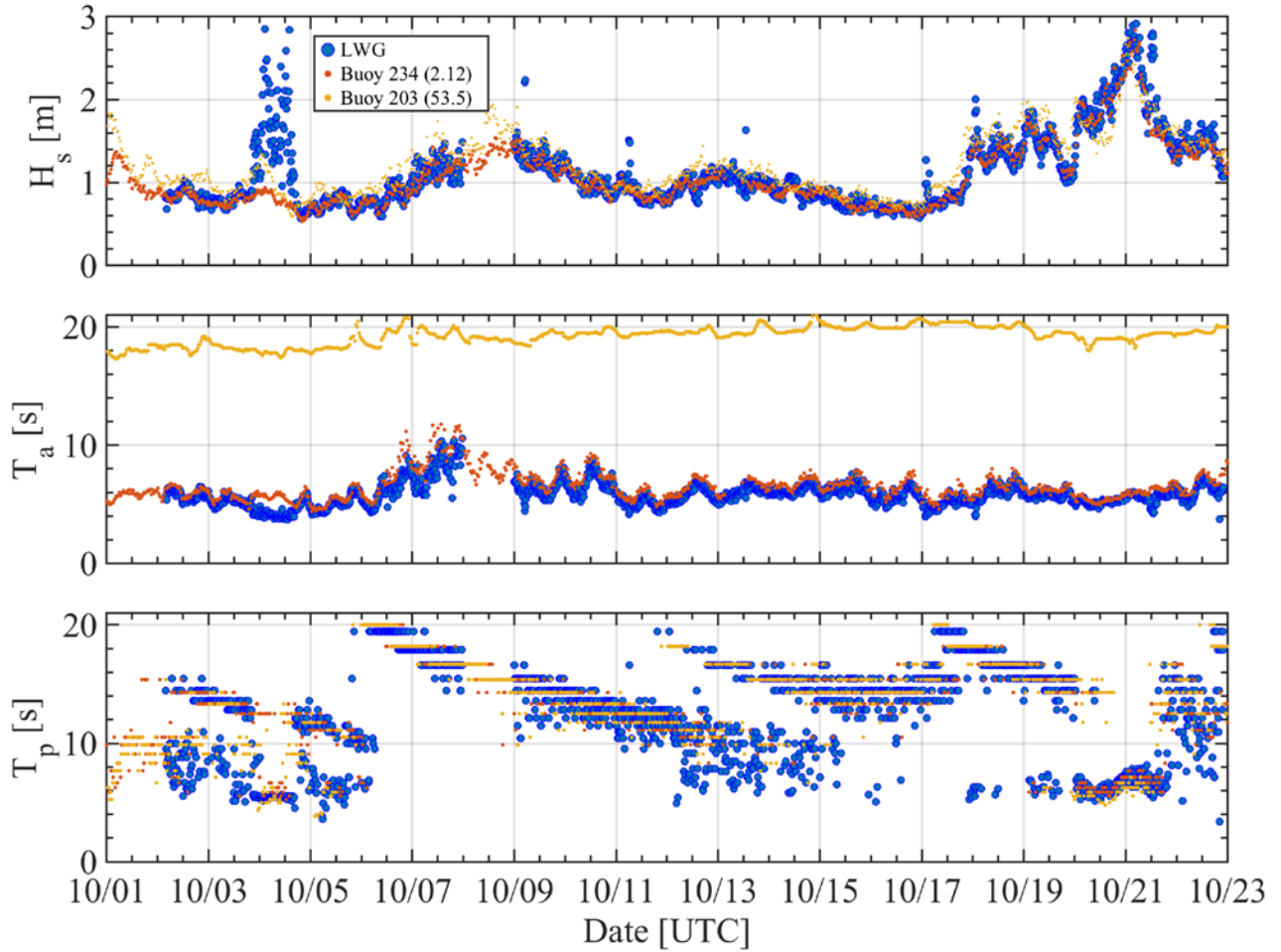


Figure 39. Time series of bulk wave statistics from LWG compared to 2 nearby CDIP buoys.

E. FLIP's Lowest Observing Platform (FLOP)

The FLOP was a re-engineered MASflux buoy that was outfitted with a profile of slow state variables (RH & T), a motion package (VN-100), and topped with a 3DSA (RM Young 81000). The FLOP (see Figure 40) was comprised of an outer instrumented pipe (Delrin® plastic) with a surface buoy (red PolyForm float in image) pressure-fitted to the base that could freely slide along an inner aluminum pipe, 6 m long. The tether line passed through the inner aluminum and attached directly to a lead weight that was in the water below the end of the instrumented pipe. The tether/inner-pipe system was designed to maintain a roughly vertical orientation and allow the instrumented pipe to follow the

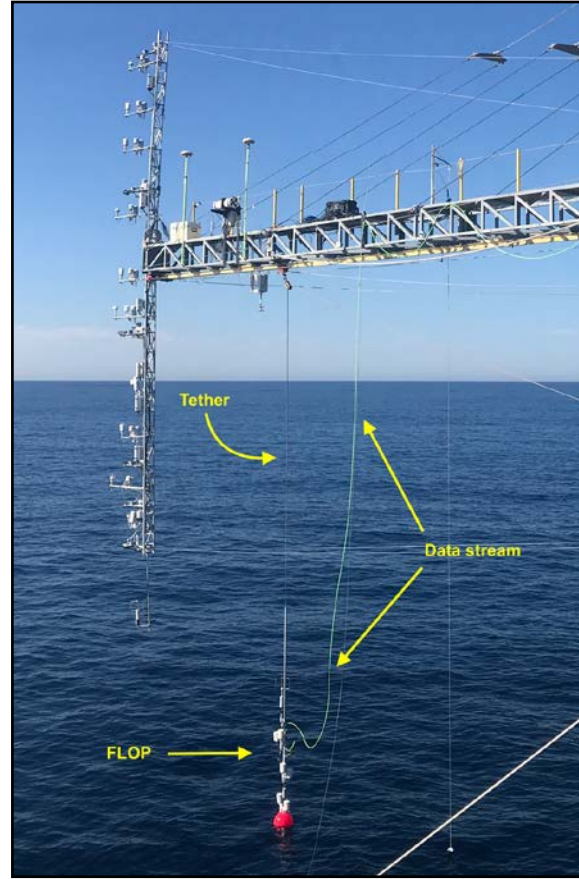


Figure 40. FLOP tethered to *FLIP* port boom during CASPER-West. Image taken October 16, 2017 10:30 PDT.

surface variability. FLOP measurement data was streamed continuously to the main lab on *FLIP*.

The FLOP is essentially a wave-following air-sea interaction spar buoy. In this capacity FLOP can operate as a wave buoy as well as a meteorological platform. Therefore, the data quality assessment will be divided into these two broad domains of operability. Due to operational safety considerations, FLOP was occasionally lifted out of the water. These time periods were rejected from the processed data set via inspection (e.g. heave signal) after CASPER-West (see Figure 41)

1. FLOP: waves

The motion unit on FLOP can be used to rectify the three-dimensional wave field by using the tilt-corrected three components of linear acceleration, and heading. The surface float acts as a low-pass filter with a wavelength cut-off $D/2$, where D is the buoy diameter (~ 1

m). As a first step, we will examine the omnidirectional surface elevation, η , determined from FLOP's motion. If FLOP were oriented perfectly vertical for all sampling, η would simply be derived as the double integration of the heave, or vertical acceleration, sampled at 20 Hz. However, Collins et al. [2014] argue, and demonstrate, that tilt-correcting the heave signal more realistically reconstructs individual wave curvature and height. In that case, they argued that this was necessary in the case of buoys in large and steep waves, where buoy tilts could exceed 10° . For CASPER-West, we never saw waves as large as Collins et al., however because of the design of FLOP, the buoy could potentially tilt significantly in relatively small waves. Therefore, the omnidirectional surface elevation was determined from the double integrated and tilt-corrected heave signal:

$$H_c = -S_u \sin(p) + S_w \cos(p) \sin(r) + H \cos(p) \cos(r) - g, \quad (9)$$

where $S_{u,w}$ are the surge and sway, H is the raw heave, p is pitch, and r is roll. Also, g is the gravitational acceleration constant, 9.8 m/s^2 . Using (9), we can get the surface elevation:

$$\eta = \int_{-\infty}^{\infty} \frac{1}{(2\pi if)^2} \widehat{H}_c df = \iint H_c dt dt, \quad (10)$$

where the double integration was carried out in Fourier space. A high-pass filter, with hard edge box cut-off, was applied to the signal before inverse Fourier transform.

Figure 42 provides a sample of FLOP's wave record and the corresponding omnidirectional wave spectrum. In general, the FLOP surface elevation measurements compare very well with the LWG, and in fact due to measurement issues noted previously

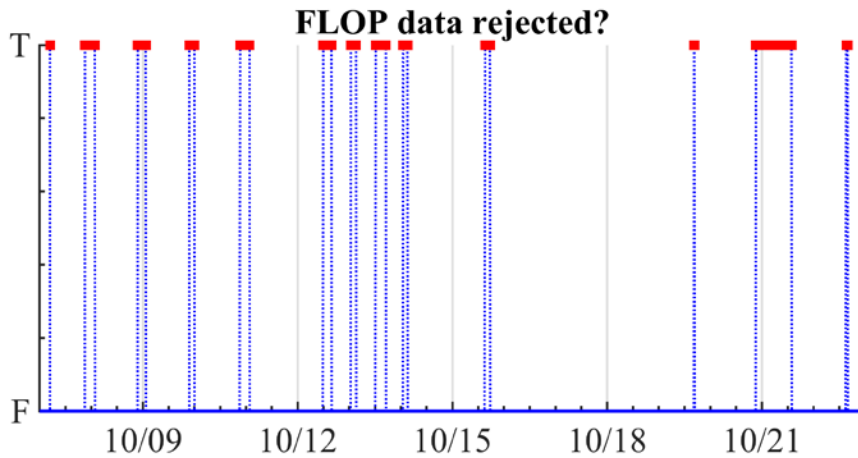


Figure 41. FLOP data rejected true (T) or false (f).

for LWG, we may expect FLOP to perform better than the laser in some circumstances. Inspection of the wave spectrum reveals signification energy at periods 25-30

seconds, which was consistently observed during FLOP's operation. This signal appears to be the nonlinear response of the buoy to *FLIP* motion, which is translated through the tether to the buoy. This motion-related signal cannot be removed using standard techniques, e.g. as was done for the LWG, because it is the result of non-rigid body mechanics. At higher frequencies, FLOP rectifies the wavy motion of the surface up through the wind sea band. Of course, if the nonlinear motion signal shifted up in frequency, this would contaminate the observed ocean wave spectrum. We are unaware of any available method for modeling this motion and removing it from the observed H , given the measurements made from FLOP. Therefore, the contaminated signal remains in the processed data and the user will have to take precautions when analyzing the FLOP wave data.

2. FLOP: meteorological sensors

The meteorological data from FLOP was processed in the same manner as the ASI mast sensors. FLOP is a unique platform and quality controlling the mean and turbulent parameters is not as straight-forward as might be done for the mast measurements. Further investigation is needed to determine the potential data quality issues arising from this unique

platform and this work will be incorporated into the formal analysis looking into the variability observed from FLOP.

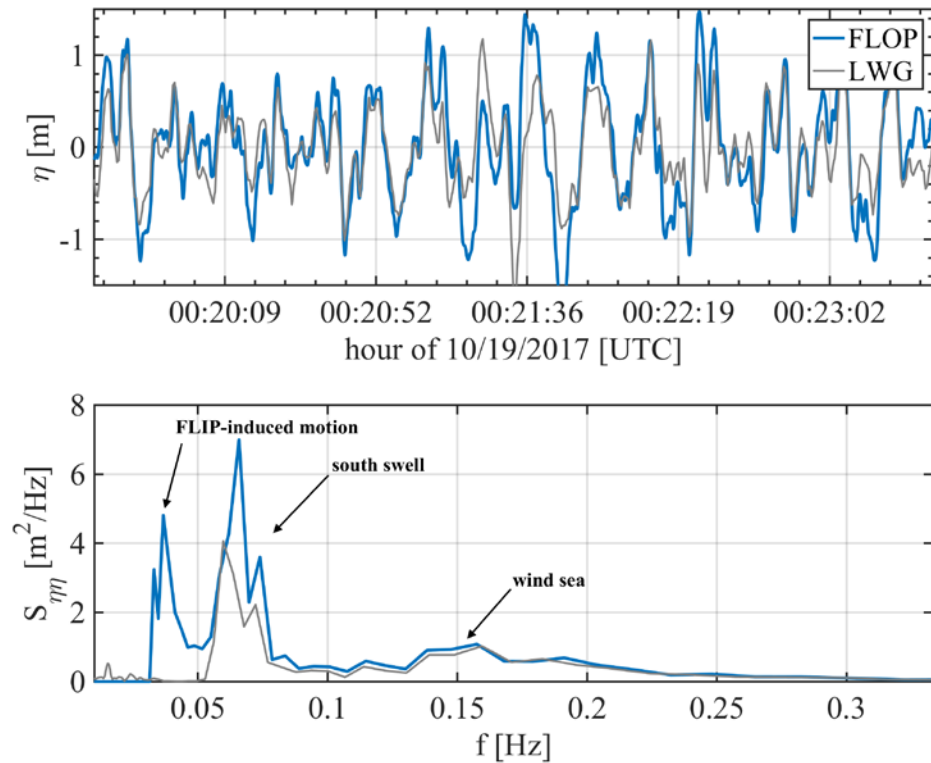


Figure 42. Sample of FLOP wave record (top) and omnidirectional spectrum (bottom), compared to the LWG.

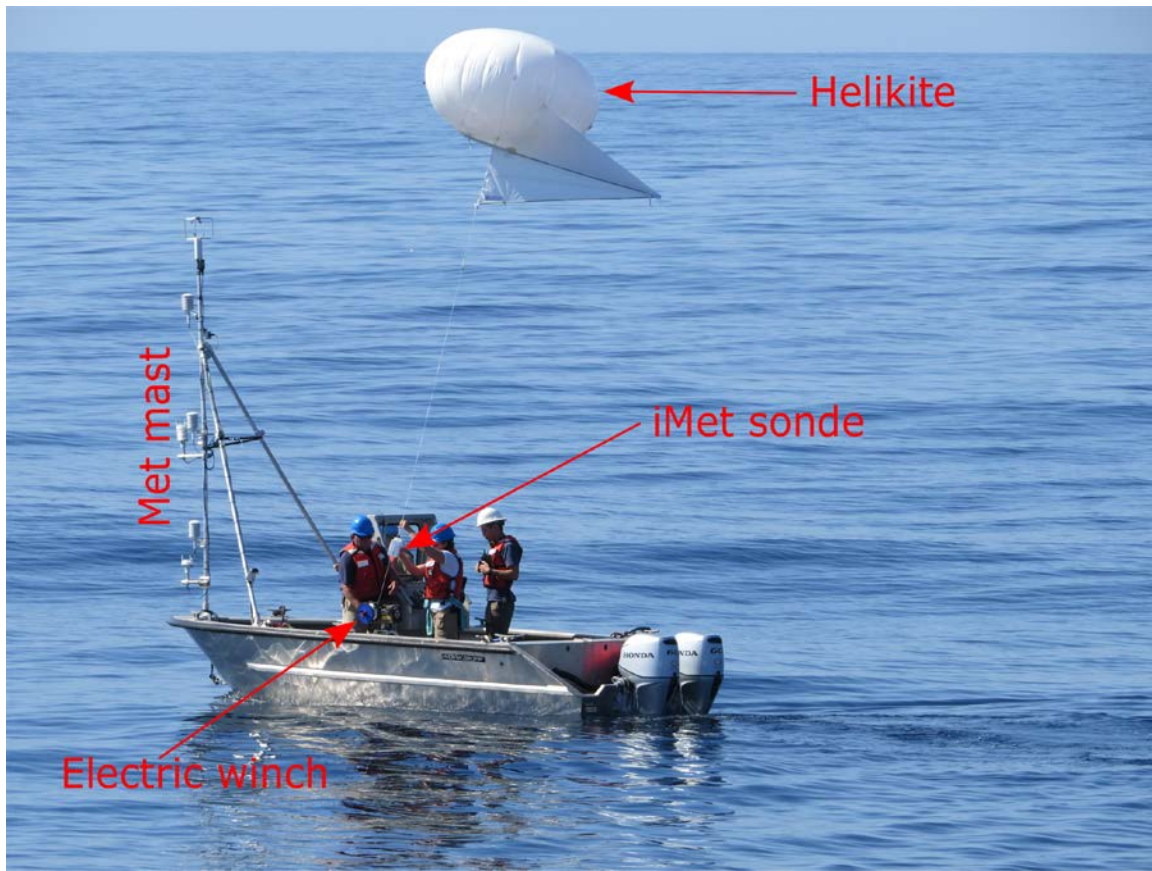


Figure 43. Components used in the air-sea interaction sampling from the R/V Sally Ride small boat.

F. SMALL BOAT DEPLOYMENTS FROM R/V SALLY RIDE

We made repeated soundings of the lowest ~50 m of the marine atmospheric surface layer (MASL) from a small boat launched from the *R/V Sally Ride* (see Figure 43). We used an InterMet iMet-1-RSB radiosonde attached to a Allsopp SkyHook Helikite to quantify the near-surface vertical profiles of pressure, temperature, and humidity. An electric winch is used to ensure the uniform ascent/descent rate of the radiosonde. The small boat (~ 6 m) is used to minimize the flow distortion resulted from the platform. For each sounding set at a given location, about 10-15 profiles were made to obtain sufficient statistics for an individual profile estimate. Apart from this, measurements of temperature, humidity, wind speed and direction were also made from multiple levels using an instrumented mast installed on the workboat bow. Bulk sea surface temperature (i.e. a “bucket” temperature) was also recorded. Figure 1 depicts the setup used for the surface layer profiling.

Our initial processing of the dataset from the tethered balloon-based surface profiling measurements from a workboat identified two main issues: a) the presence of random spikes that are clearly spurious data points in pressure, temperature and relative humidity profiles; b) Inaccurate altitude information using the GPS height, particularly near the surface. The following data quality control procedures were applied to address each of the above issues.

Level-I: Each profile set contains nominally seven ascent and descent measurements that correspond to 14 profiles. In the post-processed level-I data, we removed all data points before and after the actual measurement period. The removed data points include those before the small boat deployment, during the transits, and during the launch preparation period before the up-and-down sampling.

Level-II: The dataset went through two additional post-processing procedures described below:

- a. Spikes from the pressure, temperature and relative humidity data were removed by applying an eleven-point *Hampel* filter (this filter is similar to one used to process

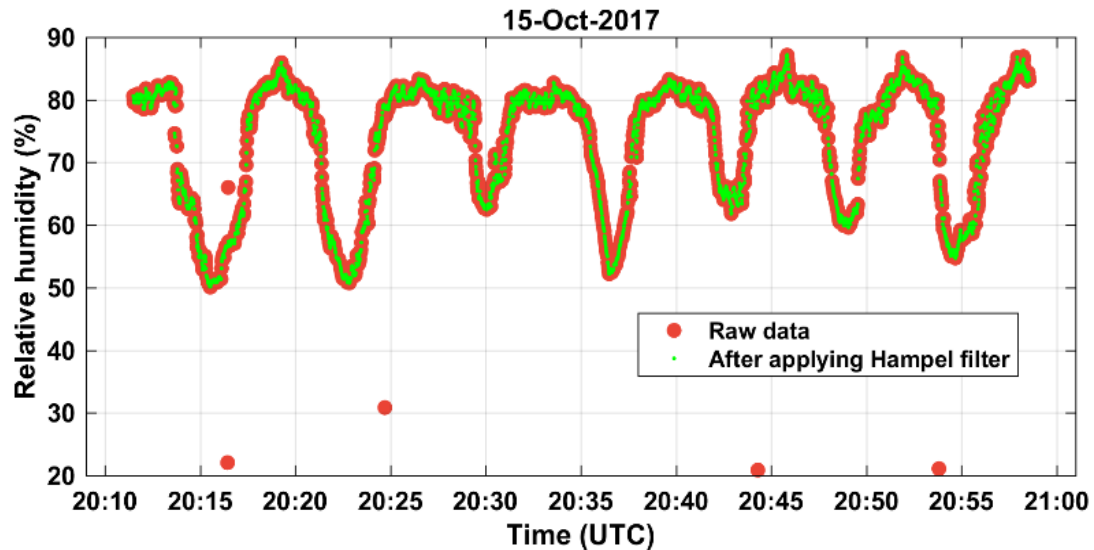


Figure 44: An example of spurious data removal using an eleven-point Hampel filter on Relative humidity soundings.

all of FLIP ASI variables described above). Figure 44 shows an example of spurious data removal using this method using the relative humidity soundings made on 15 October 2017. The spikes in the raw data are evident in this figure. The green dots in Figure 2 shows the results after applying the *Hampel* filter. Our tests

have shown that an eleven-point *Hampel* filter efficiently removes the spikes without affecting the characteristics of the profile.

- b. We calculated the pressure altitude and used this quantity as the altitude instead of the GPS altitude. To obtain the pressure altitude, the pressure measurements (after de-spiking procedure above) from one set of profiling samples were sorted in descending order. The highest pressure value from the sorted profiles was then taken as the base value for calculating the pressure altitude for each pressure value. The pressure altitudes for each up or down profile were then recovered using the time information.

Level-III: Obvious spurious data points remained in the data set after the level-II correction. These data points are mainly the result of non-uniform ascent/descent rate of the sensor or due to the sudden change in the speed and course of the workboat. These were removed manually.

Polynomial fit: A seventh order polynomial fit is then applied to the level-III data to obtain the mean profile (see Figure 45). Selection of the order of polynomial was based on the observation that the seventh order polynomial well preserves the general vertical structure and characteristics of the measured profiles and also agrees well with the bin-averaged profile. Figure 3 shows an example of measured profiles (blue circles) and fitted profile (red curve). Estimated duct height is also shown (red square).

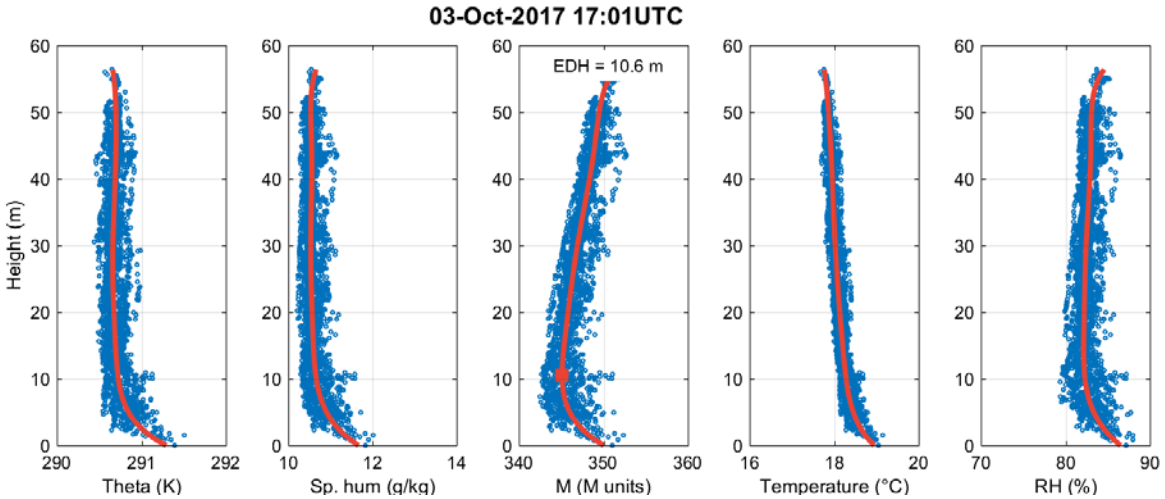


Figure 45: Example of measured profiles (blue circles) of potential temperature, specific humidity, modified refractivity, temperature and relative humidity. Corresponding fitted profiles (red curve) are also. Evaporation duct height is shown by red square in the modified refractivity profile.

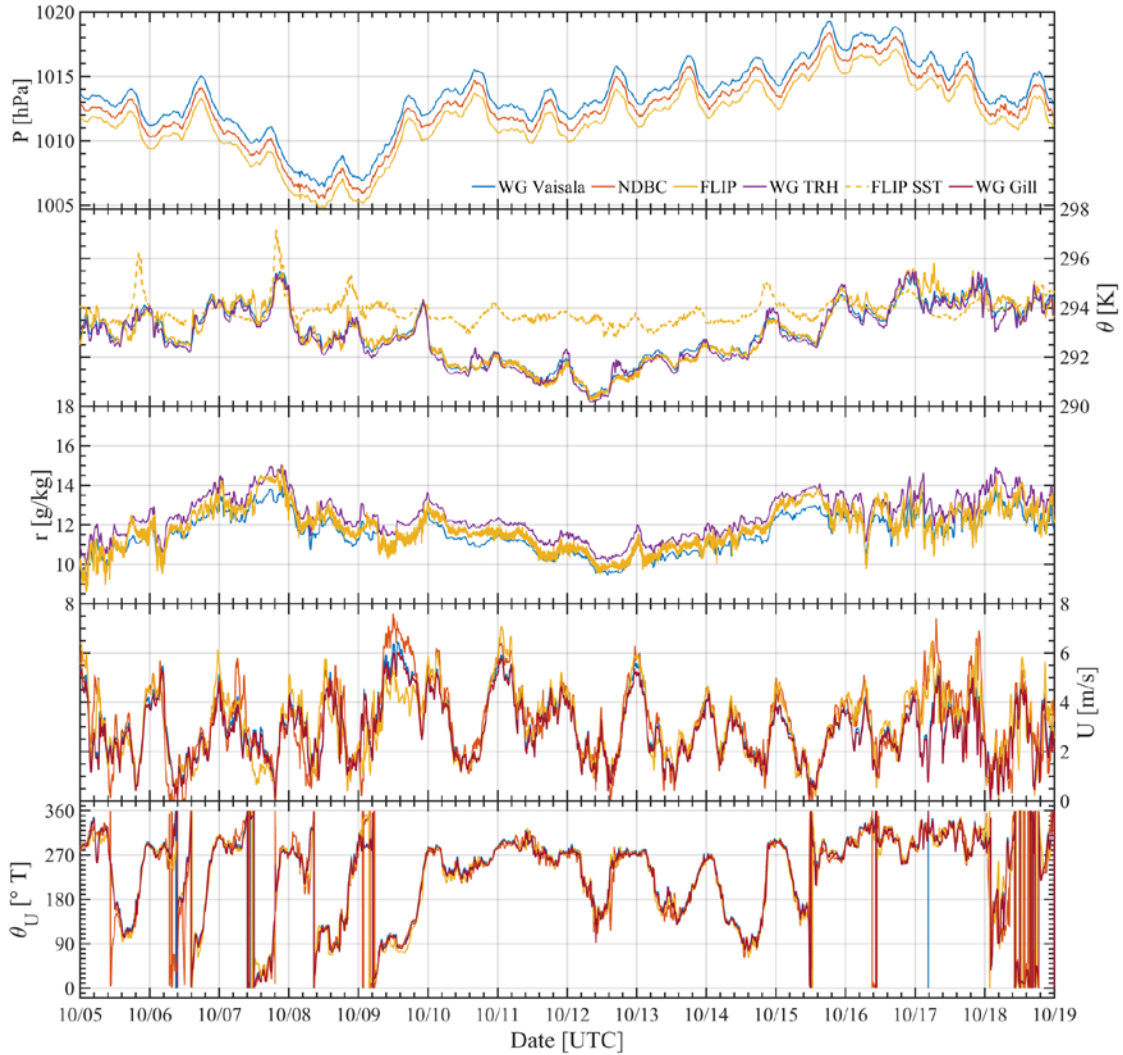


Figure 46. Comparison of mean WG parameters with nearby platforms (NDBC buoys and *FLIP*). From top-to-bottom: static air pressure, temperature (air and SST from *FLIP*), mixing ratio, mean wind speed, and wind direction. All *FLIP* atmospheric quantities correspond to flux Level 2 (see Figure 15).

G. NPS Wave Glider

The meteorological data from the NPS Wave Glider (WG) was processed in the same general method laid out above for all the NPS measurements. The glider is a unique platform and making these types of micrometeorological measurements from so close to the water surface requires extra levels of quality control beyond standard methods. Further investigation is needed to determine the potential data quality issues arising from this unique platform and this work will be incorporated into the formal analysis looking into

the variability observed from glider. Below, we discuss first order data quality inspections and comparisons with nearby platforms.

WG measurements of bulk and flux atmospheric, as well as wave parameters were compared to *FLIP* measurements and the data from the nearby NDBC buoy (CDIP #234, not visible in Figure 1). These platforms were approximately 7 km and 5 km, respectively, from the mean WG location. In general, fairly good agreement was found between WG and these platforms from an initial inspection of the timeseries. The IMU data (housed in WG hull) was used to rectify the surface gravity wave motion. While the WG is not an ideal hull design and is forced by a two-body propulsion system, an initial comparison revealed that the WG was able to reproduce the general trends in wave climate at the CASPER-West location for the duration of its deployment (see Figure 47). For H_s , there was fairly good correlation between the buoy and WG ($r^2 = 0.754$), but the relationship was non-linear. In particular, the WG became less sensitive to waves with increasing H_s above

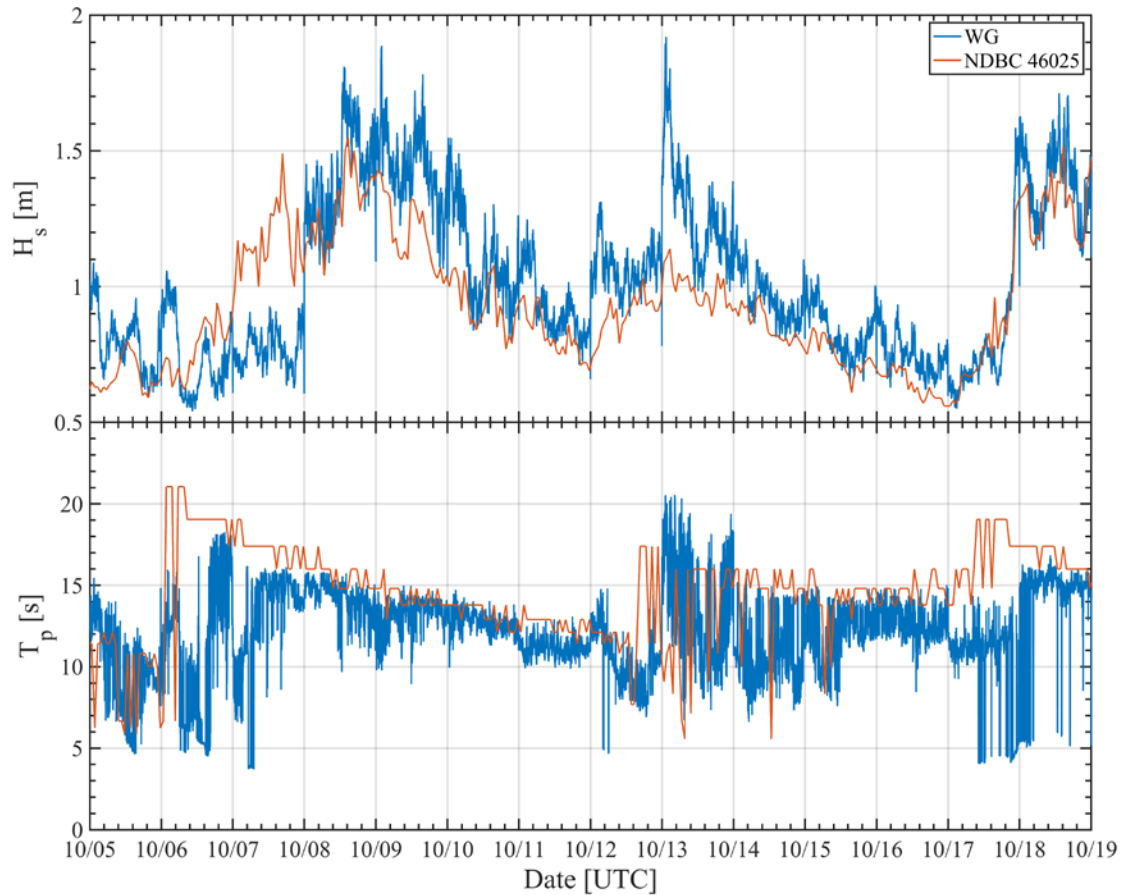


Figure 47. Comparison of significant wave height (top) and peak wave period (bottom) for WG and nearby NDBC wave buoy.

~ 1.2 m. For T_p , the WG reproduces the mean trend, but with considerably more noise ($r^2 = 0.127$) and tended to bias the dominant waves to higher frequencies. This may be related to the translation of the WG and/or accounting for the Doppler shifting due to traveling into versus against the dominant waves. Further investigation is needed if the WG is going to be used as a wave platform.

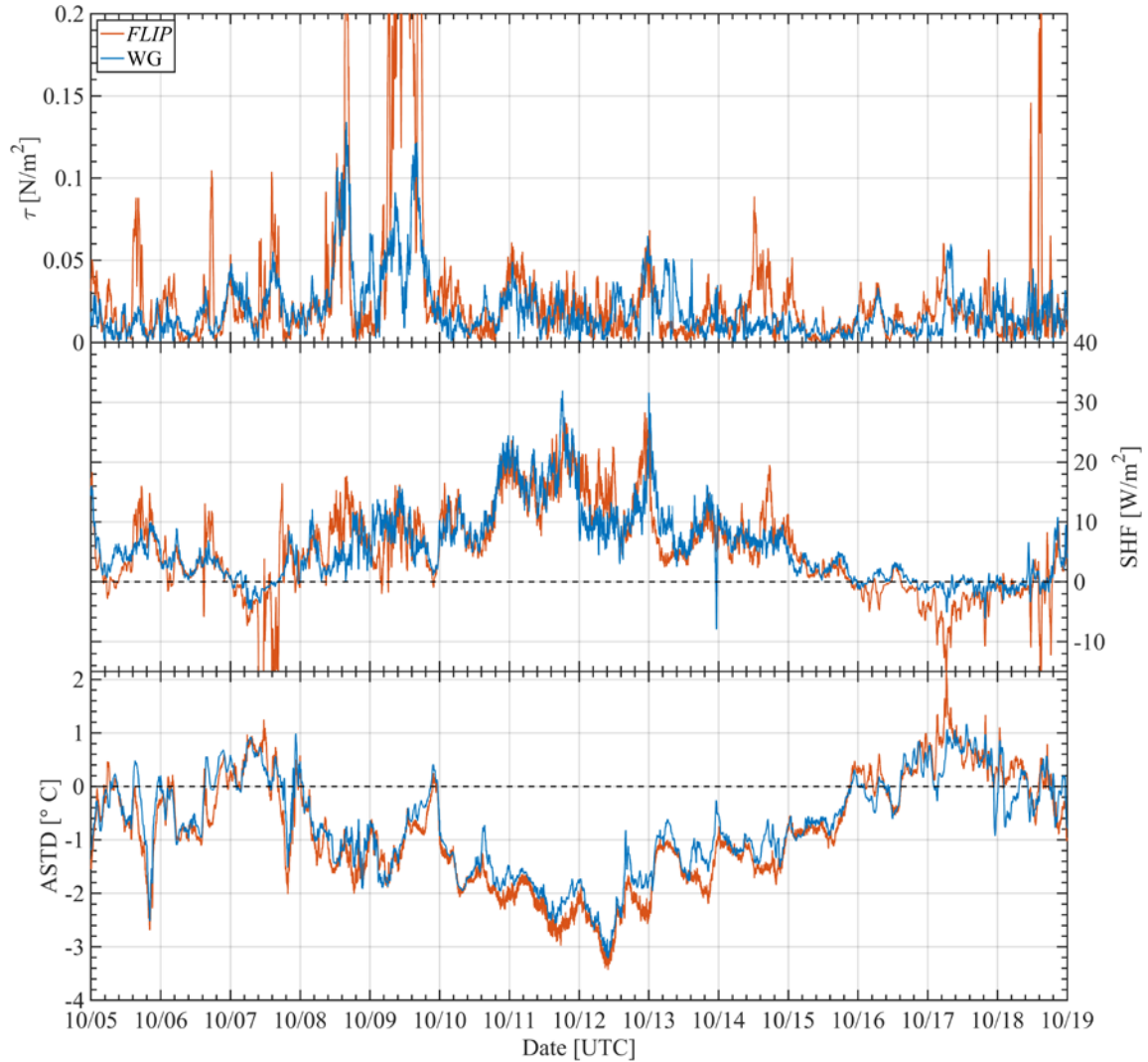


Figure 48. Comparison of momentum (top) and sensible heat flux (SHF, middle) from WG and FLIP (Level 2), as well as ASTD (bottom). For FLIP, ASTD was calculated using the SSST from the narrow-banded radiometers.

In Figure 48, a comparison is shown between the momentum and sensible heat flux from the WG 3DSA and FLIP (Level 2). The flux time series generally agree between WG and FLIP, but some clear differences are evident. The FLIP data were not screened for

unfavorable wind directions (see § II.B.2.b) and therefore the largest differences can be attributed to flow distortion about *FLIP*'s superstructure. A comparison of sensible heat flux and air-sea temperature difference (ASTD) reveal fairly good agreement between the WG and *FLIP*. Some differences are expected since WG ASTD was calculated using a bulk near-surface temperature, whereas *FLIP*'s was done using the calibrated SSST.

III. CAVEATS

Listed here are major caveats or considerations for using the CASPER-West data described in this document. These notes derive from the quality assessment done on the various measurement systems.

- I. All data inquiries should be directed to Professor Qing Wang, of the Department of Meteorology at the Naval Postgraduate School.
- II. Standard data output will be processed using 5-minute and 30-minute averaging intervals for bulk and flux parameters, respectively.
- III. At the time of writing, the sea surface skin temperature (SSST) time series from *FLIP* is a blended record of the ROSR and post-calibrated KT-19 observations. The blend is done by keeping ROSR measurements when available and using KT-19 when necessary.
- IV. *FLIP* ASI data should not be analyzed without accounting for unfavorable wind directions, which may disparately impact bulk and flux parameters and depend on the location along the ASI mast. See § II.B.1.c and II.B.2.b.
- V. Significant caution should be exercised when analyzing the water vapor *flux* from the uppermost level on the ASI mast (here reported as Level 6), especially after Oct. 9th 00:00 UTC.

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