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Contents

List of Figures

List of Tables

ATLAS, T-Flex, BaiLong Meteorological Sensor Comparison Test Report

H. P. Freitag[1], C. Ning[2], P. L. Berk[3], D. M. Dougherty[3], R. F. Marshall[3], J. M. Strick[1], and D. K. Zimmerman[3]

Abstract. Meteorological sensors from Autonomous Temperature Line Acquisition System (ATLAS), Tropical Flex (T-Flex), and BaiLong mooring systems were run in a 6-week-long, side-by-side comparison test at the National Oceanic and Atmospheric Administration (NOAA) Pacific Marine Environmental Laboratory (PMEL) in Seattle, Washington, from 30 July to 16 September. Time series were analyzed at the highest common time interval, which was 10 min for most observations. ATLAS data were chosen to be the standard to which T-Flex and BaiLong data were compared. All three systems provided nearly complete data for the test period, all of which were highly correlated with correlation coefficients > 0.95. RMS differences in time series were generally within or near the expected accuracy of the ATLAS system. The largest differences were in wind direction, daytime air temperature, rainfall, and short-wave radiation. Rainfall was infrequent and light during the test period, limiting the comparison to a few relatively low rain events.

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1. Background

The Research Moored Array for African–Asian–Australian Monsoon Analysis and Prediction (RAMA) addresses the need to establish a system of comprehensive, long-term, high-quality, real-time measurements in the Indian Ocean suitable for climate research and forecasting (McPhaden *et al.*, 2009) and is a core component of the Indian Ocean Observing System (IndOOS). Moorings within the array are designed and maintained by China, India, Japan, and the U.S. Surface moorings within the array measure near-surface wind speed and direction, air temperature (AT), relative humidity (RH), short-wave radiation (SWR), long-wave radiation (LWR), precipitation, and barometric pressure (BP). Water temperature, salinity, and currents are measured to depths of up to 750 m below the sea surface. All mooring systems report data in near-real time via satellite (by either the Argos or Iridium networks). Measurement specifications for U.S., Japan, and Indian systems are documented in the supplement to McPhaden *et al.* (2009).

The majority of surface moorings in RAMA are the Next-Generation version ATLAS system (Milburn *et al.*, 1996), which also comprised most sites in the Tropical Ocean-Atmosphere/TRIangle Trans-Ocean buoy Network (TAO/TRITON) array in the Pacific for two decades, and is the only system used in the Prediction and Research Moored Array in the Atlantic (PIRATA). Japan's moorings occupy sites in the western Pacific portion of TAO/TRITON, and in RAMA. China's BaiLong mooring has been developed to make measurements comparable to the Autonomous Temperature Line Acquisition System (ATLAS). NOAA's Pacific Marine Environmental Laboratory (PMEL) has recently developed a replacement mooring system for ATLAS named Tropical Flex (T-Flex), the meteorological components of which were also included in this comparison test. While the intent is for all systems to make comparable observations, the sensors used may differ. Some sensors are common to multiple mooring systems (e.g., a capacitance rain gauge for precipitation), while others differ significantly between systems (e.g., analog propeller/vane anemometers versus digital sonic anemometers). There are also other differences in components such as analog-to-digital converters, CPU's, firmware, data loggers, and sampling schemes.

The ATLAS system was used as the standard for this comparison because of its long history of use in tropical arrays, with well-documented sensor calibration procedures and accuracy estimates (Freitag *et al.,* 2001, 2005; Serra *et al.*, 2001; Lake *et al.,* 2003). To ensure uniformity of measurements within multi-component moored arrays such as RAMA and TAO/TRITON, the accuracy of each system must be documented and side-by-side comparisons should be made to confirm consistency between system components and calibration procedures. ATLAS/TRITON comparisons of moorings within TAO/TRITON have been reported by Kuroda *et al.* (2001). A land-based comparison of Woods Hole Oceanographic Institution (WHOI), ATLAS, and TRITON meteorological sensors was documented by Payne *et al.* (2002). This work provides a similar land-based comparison between ATLAS, T-Flex, and BaiLong meteorological measurements.

2. Instrumentation and Test Configuration

The three sets of meteorological sensors were placed on their respective buoy towers in a relatively open area on the NOAA Sand Point campus in Seattle, Washington (**Figure 1**). The towers were oriented on a roughly east–west line, with the BaiLong tower at the western end, ATLAS tower in the middle, and T-Flex tower on the eastern end. Prevailing winds in the area were primarily toward the south. Nearby objects that potentially could have affected the measurements included an electronics van located about 8 m to the southwest of the BaiLong tower and a north–south running line of trees located about 15 m from the T-Flex tower. The tower feet were adjusted and horizontal platforms checked with a bubble level. The accuracy of this process was thought to be of order one degree of tilt. The vertical alignment of the radiometer masts on PMEL towers is expected to have about the same uncertainty, i.e., small compared to buoy tilts in response to wave motion. A more precise measure of the horizontal alignment of the radiometers was beyond the scope of this comparison test.

The sensors used were those deployed on RAMA moorings (**Table 1**); these were placed in their typical mounting locations on each tower. Most data were recorded internally by the mooring systems at 10 min intervals (**Table 2**). During the test, lower-frequency (hourly–daily) ATLAS and T-Flex data were telemetered via satellite and monitored in real time, and internally recorded data at the highest rates were manually downloaded from the systems' memory at periodic intervals.

Sample times were identical for ATLAS and T-Flex (with the exception of SWR and LWR), but differed for BaiLong. ATLAS and T-Flex sample intervals begin and end on odd-valued minutes and are given time stamps at the center of the interval. For example, averages made over time periods 00:09–00:11, 00:19–00:21, and 00:29–00:31 (hh:mm) are given time stamps of 00:10, 00:20, and 00:30. BaiLong sample intervals begin and end on even-valued minutes, which are given time stamps at the end of the interval. For example, averages made at 00:10–00:12, 00:20–00:22, and 00:30–00:32 have time stamps of 00:12, 00:22, and 00:32. There is a 1 min timing difference between BaiLong data and that of ATLAS and T-Flex that could potentially add variance to data differences at the highest sample rates but should not affect longer-term mean difference.

Sensors used in the test were either new or refurbished since last deployed at sea. ATLAS and T-Flex sensors had been calibrated within the past year. ATLAS and T-Flex anemometers (aka WND), compasses (CMP), AT, RH, BP, and precipitation (RAIN) were calibrated by PMEL as described in the references given above. SWR and LWR sensors were calibrated by the manufacturer. BaiLong sensors were new. BaiLong WND, CMP, AT, and RAIN sensor output based on nominal factory calibrations were checked using PMEL procedures and standards (see Appendix). BaiLong data based on nominal factory calibrations were used in the analysis presented here.

Figure 1: Photographs of the (left to right) BaiLong, ATLAS, and T-Flex towers taken facing northwest (top panel) and southeast (bottom panel).

The systems were initially installed on 26 June 2014. Data were monitored for a month, during which time the BaiLong firmware was evaluated for consistency with PMEL systems. Adjustments to the method of computing vector-averaged winds were necessary. The ATLAS CPU and data logger were also replaced during this period due to data recording errors. After it was confirmed that all systems were working properly, the comparison test was begun on 30 July 2014 and ended on 16 September 2014.

Table 1: Meteorological sensor specifications for ATLAS, T-Flex, and BaiLong mooring systems. ATLAS sensor resolution and accuracy are primarily those published by Freitag *et al.* (2001), Serra *et al.* (2001), and Lake *et al.* (2003), with the exception of accuracy for long-wave radiation and barometric pressure, which are those given by the manufacturer. Specifications of sensors used on both ATLAS and T-Flex are identical. Specifications for digital T-Flex sensors not used on ATLAS (WindSonic, SP3004D, HygroClip 2) are those given by the manufacturer. BaiLong sensor resolutions are those given by the manufacturer of the BaiLong DT80 data logger. BaiLong sensor accuracies combine DT80 and sensor manufacturer accuracies.

		ATLAS	T-Flex	BaiLong
Wind Speed & Relative Direction	Sensor Model	5103	WindSonic	WindSonic
	Manufacturer	R.M. Young	Gill Inst. Ltd.	Gill Inst. Ltd.
	Height[1] (m)	4	4	4
	Resolution	0.2 ms^{-1}; 1.4°	0.1 ms^{-1}; 1°	0.003 ms^{-1}; 0.02°
	Accuracy	0.3 m s^{-1} or 3%; 3.2°	2%; 3°	2%; 3°
Compass	Sensor Model	63764,LP101-5, or C100	SP3004D	C100
	Manufacturer	EG&G or KVH	Sparton	KVH
	Resolution	1.4°	0.1°	0.1°
	Accuracy	2.3° to 7.4°	1°	[3] 0.7°
Air Temperature & Relative Humidity	Sensor Model	MP-101	HygroClip 2	HMP155
	Manufacturer	Rotronic Inst. Corp.	Rotronic Inst. Corp	Vaisala
	Height[1] (m)	3	3	3
	Resolution	0.01°C, 0.4%RH	0.01°C, 0.01%RH	0.003°C, 0.003%RH
	Accuracy	0.2°C; 2.7%RH	0.1°C, 0.8%RH	0.2°C, 1.0%RH
Precipitation	Sensor Model	50203-34	50203-34	50203
	Manufacturer	R.M. Young	R.M. Young	R.M. Young
	Height[1] (m)	3.5	3.5	3.5
	Resolution	0.2 mm hr^{-1}	0.2 mm hr^{-1}	0.02 mm hr^{-1}
	Accuracy	0.4 mm hr^{-1}	0.4 mm hr^{-1}	[4] 6 mm hr^{-1}
Short-wave Radiation	Sensor Model[2]	PSP-TAO	PSP-TAO	PSP-FIO
	Manufacturer	Eppley Laboratory	Eppley Laboratory	Eppley Laboratory
	Height [1] (m)	3.5	3.5	3.5
	Resolution	0.4 W m^{-2}	0.4 W m^{-2}	0.03 W m^{-2}
	Accuracy	2%	2%	1%
Long-wave Radiation	Sensor Model[2]	PIR-TAO	PIR-TAO	PIR-FIO
	Manufacturer	Eppley Laboratory	Eppley Laboratory	Eppley Laboratory
	Height[1] (m)	3.5	3.5	3.5
	Resolution	0.1 W m^{-2}	0.1 W m^{-2}	0.08 W m^{-2}
	Accuracy	1%	1%	1%
Barometric Pressure	Sensor Model	Met1-2	Met1-2	PTB110
	Manufacturer	Paroscientific, Inc.	Paroscientific, Inc.	Vaisala
	Height[1] (m)	3	3	3
	Resolution	0.1 hPa	0.1 hPa	0.02 hPa
	Accuracy	0.01%	0.01%	0.08%

[1] Sensor height listed is that for a system deployed at sea. For the systems tested on land without buoys the sensor heights are approximately ½ m closer to the surface.

[2] Eppley PSP and PIR radiometers deployed by PMEL and FIO use an optional plastic case offered by the manufacturer. ATLAS and T-Flex sensors include a PMEL designed PIC microcontroller A/D in the sensor case. FIO uses an A/D with their main system data logger.

[3] Manufacturer's C100 specified accuracy of 0.5° is for a compass after auto-compensation, which was not the case for the BaiLong system. No accuracy is given on the manufacturer's data sheet for a compass without auto-compensation.

[4] BaiLong rain rate accuracy was calculated by application of manufacturer's accuracy of 1 mm (water height in gauge) to rates computed from 10 min sequential data.

Table 2: Sampling schedules for internally recorded data.

		ATLAS	**T-Flex**	**BaiLong**
Wind Speed & Relative Direction	Sample Rate	2 Hz	1 Hz	2 Hz
	Sample Period	2 min	2 min	2 min
	Recording Interval	10 min	10 min	10 min
Air Temperature & Relative Humidity	Sample Rate	2 Hz	1 Hz	2 Hz
	Sample Period	2 min	2 min	2 min
	Recording Interval	10 min	10 min	10 min
Precipitation	Sample Rate	1 Hz	1 Hz	2 Hz
	Sample Period	1 min	1 min	2 min
	Recording Interval	1 min	1 min	10 min
Short-wave Radiation	Sample Rate	1 Hz	1 Hz	2 Hz
	Sample Period	2 min	1 min	2 min
	Recording Interval	2 min	1 min	10 min
Long-wave Radiation	Sample Rate	1 Hz	1 Hz	2 Hz
	Sample Period	2 min	1 min	2 min
	Recording Interval	2 min	1 min	10 min
Barometric Pressure	Sample Rate	2 Hz	1 Hz	2 Hz
	Sample Period	2 min	2 min	2 min
	Recording Interval	1 hr	1 hr	10 min

3. Data Analysis

The ATLAS system, having been used extensively in tropical moored arrays, was chosen as the comparison standard for this test. Data were analyzed at the highest common temporal resolutions available for each sensor type. The numbers of expected and available good data for each system are shown in **Tables 3a** and **3b**. The numbers of expected values are based on the start and end dates of the comparison periods and the recording interval for each system variable. The systems were each started and ended at slightly different times, so the expected values for the ATLAS data in **Tables 2** and **3** differ depending on the time period in common with either the T-Flex or BaiLong system. With the exception of T-Flex LWR, the amount of recorded good data was ≥ 99% of the expected amount. An issue in the T-Flex LWR scheduling firmware resulted in a loss of about 7% of the data. The firmware has since been revised[1]. Additional, relatively minor, data losses included a short period (4.7 hr) on 3 August during which BaiLong wind data values were unreasonably large (~30 m s^{-1}) and infrequent losses of T-Flex BP and SWR data. Each of these losses amounted to less than 1% of the expected data. Although ATLAS and T-Flex systems record precipitation at 1 min intervals, standard post-processing procedures filter the data to 10 min intervals to lower noise present in the data.

Graphical analyses included scatter plots, time series of data plotted on common axes, time series of data differences (either T-Flex minus ATLAS or BaiLong minus ATLAS), histograms of data and data differences, and spectra. Quantitative analyses included computation of mean; standard deviation; root mean square (RMS); minimum and maximum differences and linear regression analysis, including the square of the correlation coefficient (R^2); and the offset and slope of the regression equation,

$$ATLAS = offset + slope * TEST,$$

where *TEST* equals either T-Flex or BaiLong.

Statistics and plots of interest are given for each comparison in the discussion that follows.

3.1 Air temperature analysis

Air temperature during the test period ranged between 11°C and 35°C with large diurnal variability, both in measured temperature and temperature differences (**Figures 2** and **3**). The time series were highly correlated with $R^2 > 0.99$ (**Table 4**). Mean and RMS differences between all ATLAS and T-Flex AT were 0.019°C and 0.30°C, respectively. Nighttime (defined as when the ATLAS radiometer reads

1 Some loss of data remains for T-Flex sensors, which sample nearly continuously (SWR, LWR, and RAIN) but are turned off during Iridium calls to inhibit possible transmitter-induced noise in the data.

Table 3: Number of good data points (NData) recorded by the ATLAS and: (a) T-Flex systems and the number of expected data points(NExp) over a common time period; (b) BaiLong systems and the number of expected data points (NExp) over a common time period.

(a)

System	**ATLAS**			**T-Flex**		
Variable	**NData**	**NExp**	**%**	**NData**	**NExp**	**%**
AT	6944	6945	100.0	6939	6945	99.9
RH	6944	6945	100.0	6939	6945	99.9
WND	6944	6945	100.0	6939	6945	99.9
BP	1157	1157	100.0	1150	1157	99.4
SWR	34720	34724	100.0	68861	69447	99.2
LWR	34720	34724	100.0	64715	69447	93.2
RAIN	6942	6945	100.0	6936	6945	99.9

(b)

System	**ATLAS**			**BaiLong**		
Variable	**NData**	**NExp**	**%**	**NData**	**NExp**	**%**
AT	6827	6828	100.0	6823	6828	99.9
RH	6827	6828	100.0	6823	6828	99.9
WND	6827	6828	100.0	6795	6828	99.5
BP	1138	1138	100.0	6823	6828	99.9
SWR	34133	34137	100.0	6823	6828	99.9
LWR	34133	34137	100.0	6823	6828	99.9
RAIN	6826	6926	100.0	6826	6826	100.0

zero) differences were smaller (mean = 0.016°C, RMS = 0.22°C), and within the accuracy specified for ATLAS systems (0.22°C; Lake *et al.*, 2003). Air temperature differences between BaiLong and ATLAS were larger than those between the T-Flex and ATLAS (mean = 0.32°C, RMS = 0.51°C for all values; mean = 0.18°C, RMS = 0.27°C at night). The BaiLong mean nighttime difference was within the specified ATLAS accuracy but the RMS was higher by a small amount. As the ATLAS accuracy was based on RMS differences between more than 200 calibration pairs, it is to be expected that a single pair of sensors may exceed the ensemble RMS by a small amount. In addition, the laboratory-based ATLAS accuracy estimate does not include errors associated with solar heating of the sensors. The mooring systems tested here use naturally aspirated radiation shields, which are less effective in light-wind conditions. Larger daytime AT differences were also reported in the previous land-based comparison between ATLAS, TRITON, and WHOI mooring systems (Payne *et al.*, 2002).

T-Flex temperature values were typically within ±1°C of ATLAS values. BaiLong positive differences were often > 1°C and at times > 2°C, while BaiLong negative differences were smaller in magnitude, typically > –1°C. Thus, the BaiLong radiation shield appears to be less effective than the ATLAS or T-Flex shields.

Both T-Flex and BaiLong AT sensors were somewhat noisier than the ATLAS sensor. T-Flex spectral energy was higher than ATLAS energy at frequencies above about 0.6 cph (**Figure 4**). Spectra difference was significant at the 95% confidence level above 1 cph. The BaiLong AT spectral energy was also significantly higher than ATLAS, becoming larger at about 0.3 cph.

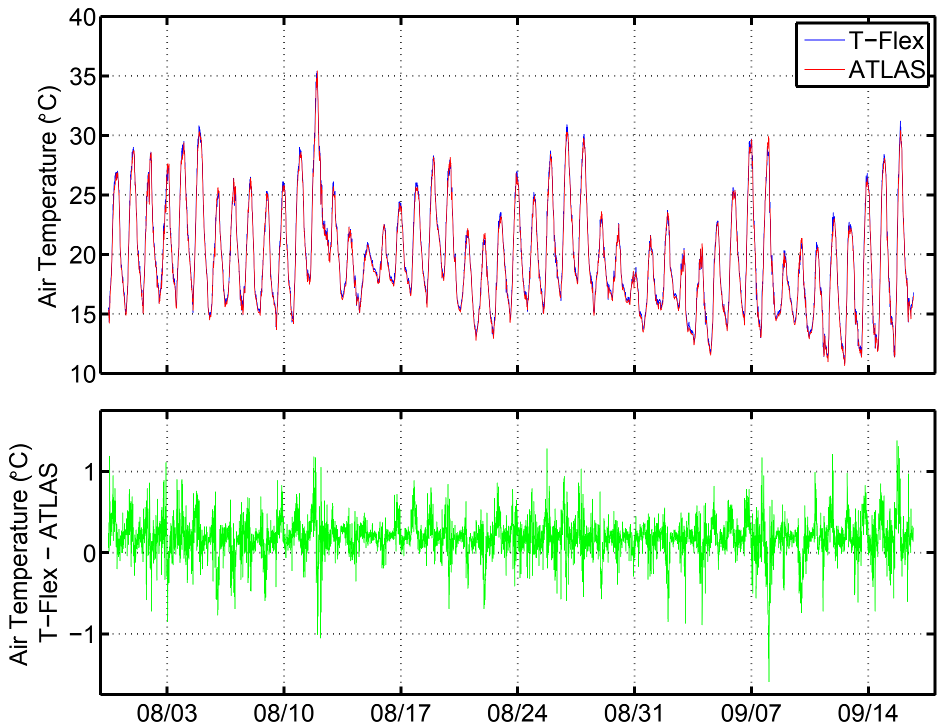

Figure 2: Time series of T-Flex (blue) and ATLAS (red) air temperature and difference (green).

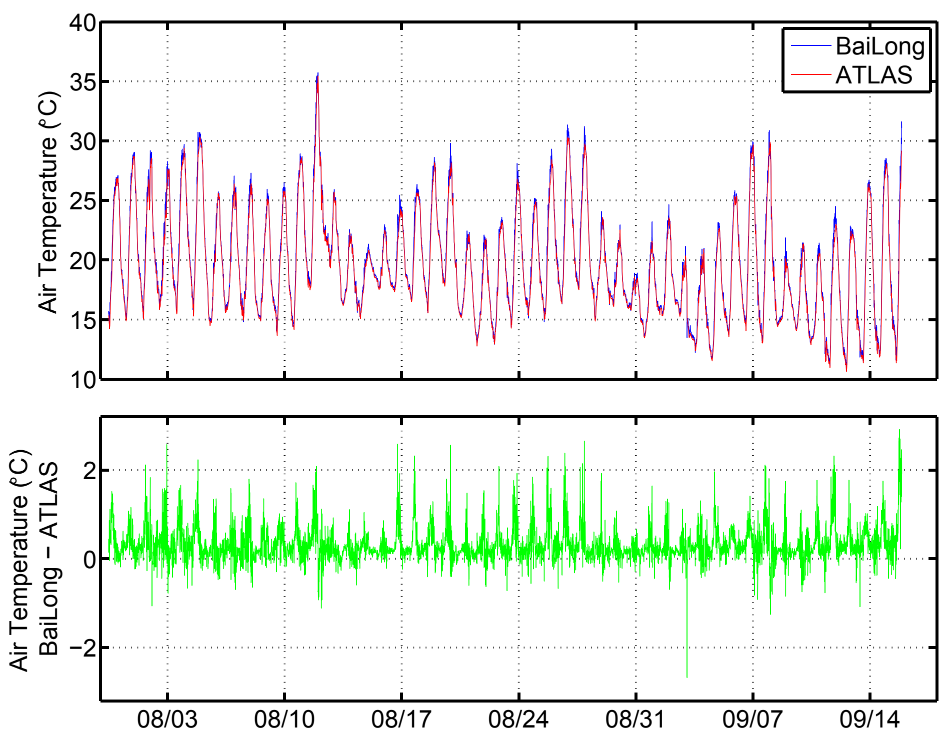

Figure 3: Time series of BaiLong (blue) and ATLAS (red) air temperature and difference (green).

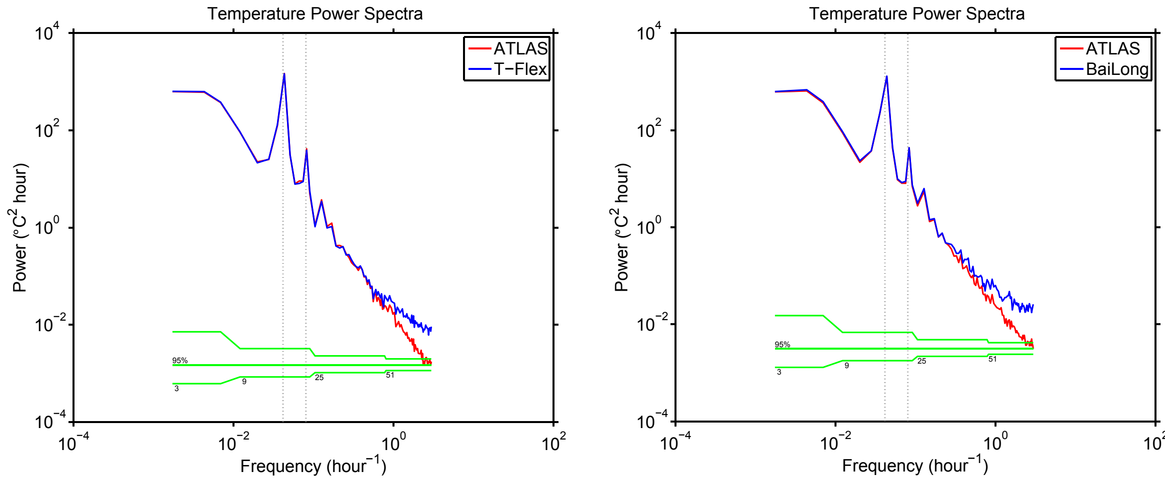

Figure 4: Air temperature spectra of ATLAS (red) and: (left panel) T-Flex (blue) time series; (right panel) BaiLong (blue) time series.

Table 4: Air temperature (°C) differences for T-Flex minus ATLAS and BaiLong minus ATLAS sensors. NCom is the number of good data points in common. Statistics for nighttime only are in shaded cells. Night is defined as periods when the ATLAS short-wave radiometer reported 0 W m^{-2}.

System	NCom	Mean	StdDev	RMS	Max	Min	R^2	Offset	Slope
T-Flex	6938	0.19	0.23	0.30	1.38	–1.59	0.997	–0.22	1.002
BaiLong	6822	0.32	0.39	0.51	2.91	–2.67	0.992	–0.01	0.984
T-Flex	2842	0.16	0.15	0.22	0.97	–1.05	0.997	–0.02	1.000
BaiLong	2772	0.18	0.20	0.27	1.18	–1.11	0.995	–0.21	1.002

3.2 Relative humidity analysis

Relative humidity (RH) during the test period ranged between 20% and 100% with diurnal variability, both in measured humidity and humidity differences (**Figures 5** and **6**). The time series were highly correlated with $R^2 > 0.99$ (**Table 5**). Mean and RMS differences were similar for T-Flex and BaiLong sensors and were less than the accuracy specified for ATLAS systems (2.73% RH; Lake *et al*., 2003). Diurnal variability of the RH differences was visually similar to temperature variability but of opposite sign. Differences were smaller for nighttime compared to full-day periods (**Table 5**). Both T-Flex and BaiLong high-frequency spectral energy were larger than ATLAS spectra, with near-zero difference at 0.2 cph, increasing to a maximum at the Nyquist frequency (3 cph) but not exceeding 95% confidence levels (not shown).

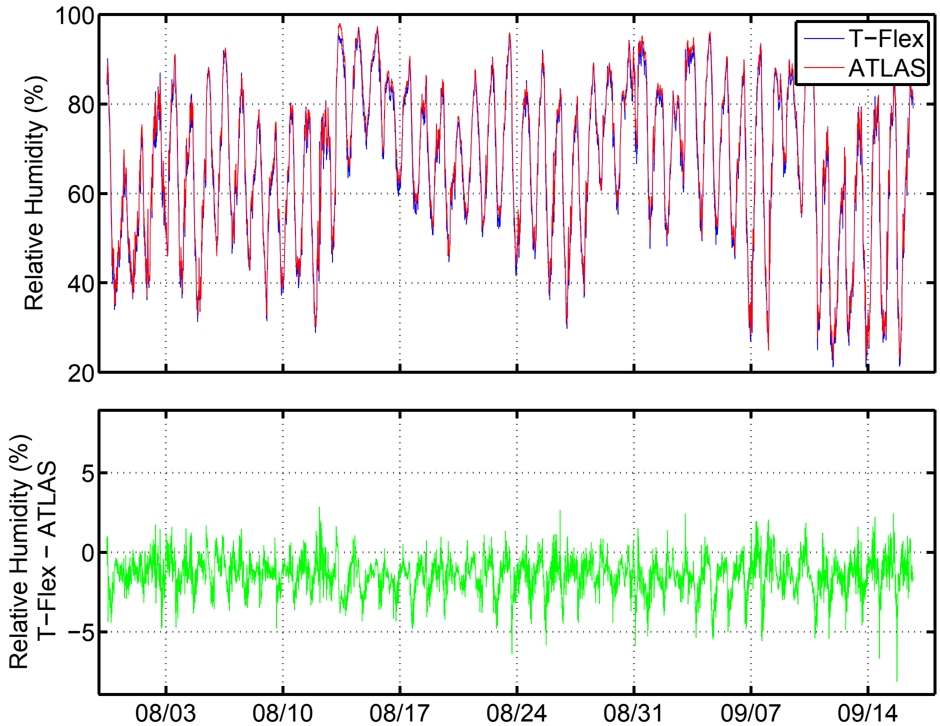

Figure 5: Time series of T-Flex (blue) and ATLAS (red) relative humidity and difference (green).

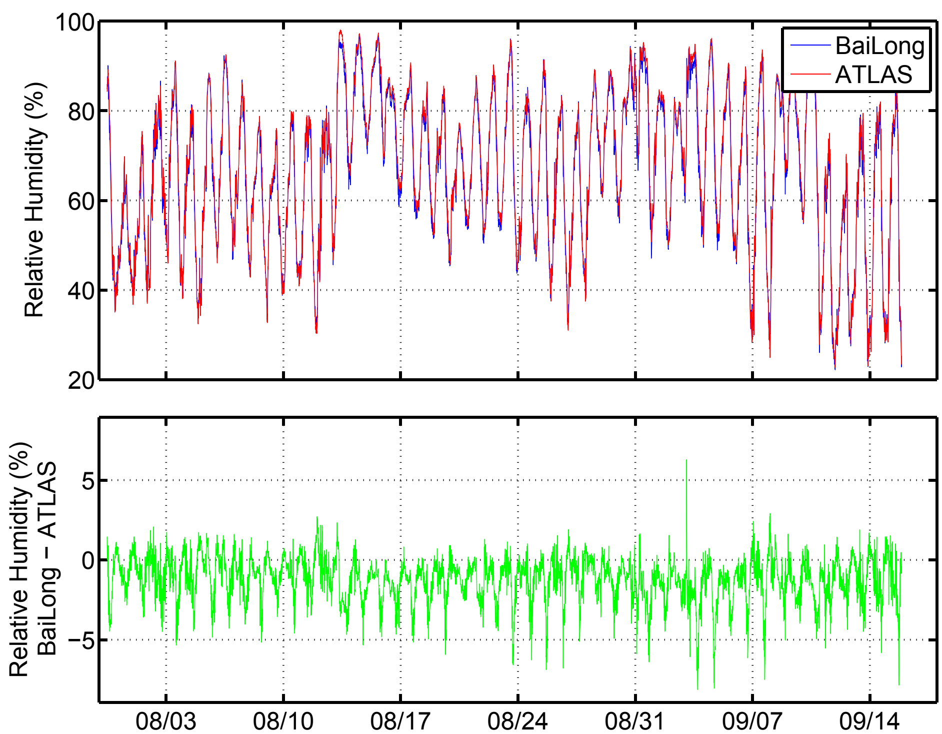

Figure 6: Time series of BaiLong (blue) and ATLAS (red) relative humidity and difference (green).

Table 5: Relative humidity (%RH) differences for T-Flex minus ATLAS and BaiLong minus ATLAS sensors. NCom is the number of good data points in common. Statistics for nighttime only are in shaded cells. Night is defined as periods when the ATLAS short-wave radiometer reported 0 W m^{-2}.

System	NCom	Mean	StdDev	RMS	Max	Min	R^2	Offset	Slope
T-Flex	6938	–1.43	1.10	1.80	2.84	–8.13	0.996	1.65	0.997
BaiLong	6822	–1.23	1.40	1.86	6.27	–8.12	0.993	–0.22	1.022
T-Flex	2842	–0.92	0.81	1.22	2.84	–3.82	0.996	1.78	0.988
BaiLong	2772	–0.81	0.85	1.17	2.33	–6.05	0.996	0.66	1.002

3.3 Wind speed and direction analysis

Winds during the test were generally light, rarely exceeding 5 m s^{-1} (**Figures 7** and **8**) and toward the south (**Figures 9** and **10**). RMS wind speed differences (**Table 6**) between T-Flex and ATLAS (0.23 ms^{-1}) and between BaiLong and ATLAS (0.24 ms^{-1}) were within the expected ATLAS accuracy (±0.3 ms^{-1} or 3%; Freitag *et al.*, 2001). Wind speed time series were well correlated, with $R^2 \geq 0.947$. Wind speed spectra (not shown) from all three systems were identical at 95% confidence levels.

Because wind direction can be highly variable at low wind speed, wind direction differences were computed only when wind speed was ≥1.0 ms^{-1}. Wind direction time series were well correlated, with $R^2 > 0.99$. Wind direction difference between T-Flex and ATLAS were small (mean = 0.00°, RMS = 4.66°) and within the expected accuracy of ATLAS direction (±5°; Freitag *et al.*, 2001). Wind direction difference between BaiLong and ATLAS (mean = –8.48°, RMS = 9.47°) exceeded the expected ATLAS direction accuracy. The difference could be due to misalignment of the BaiLong compass, which was contained in an enclosure attached to the Bailong anemometer mast. The compass was held in place by foam and not solidly fixed within the enclosure. In addition, while the ATLAS and T-Flex compasses were calibrated using procedures recommended by the manufacturer, the BaiLong compass was not. Compass checks on PMEL's compass stand indicated BaiLong heading errors in the range of –2.8° to 11.9° (Appendix). During the test, the BaiLong compass consistently reported a heading in the range 60–61°, at which the compass stand check indicated it was high by 8°. This is the same magnitude difference as the mean wind direction difference from the ATLAS system, but of opposite sign. The compass may have moved within its enclosure between the time of the compass check and the beginning of the comparison test.

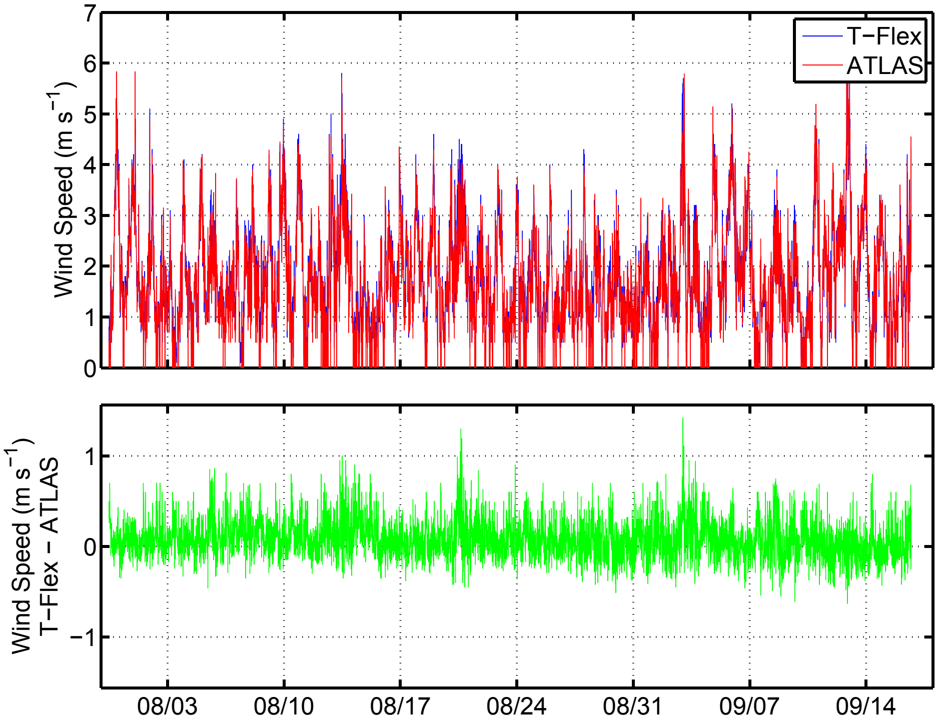

Figure 7: Time series of T-Flex (blue) and ATLAS (red) wind speed and difference (green).

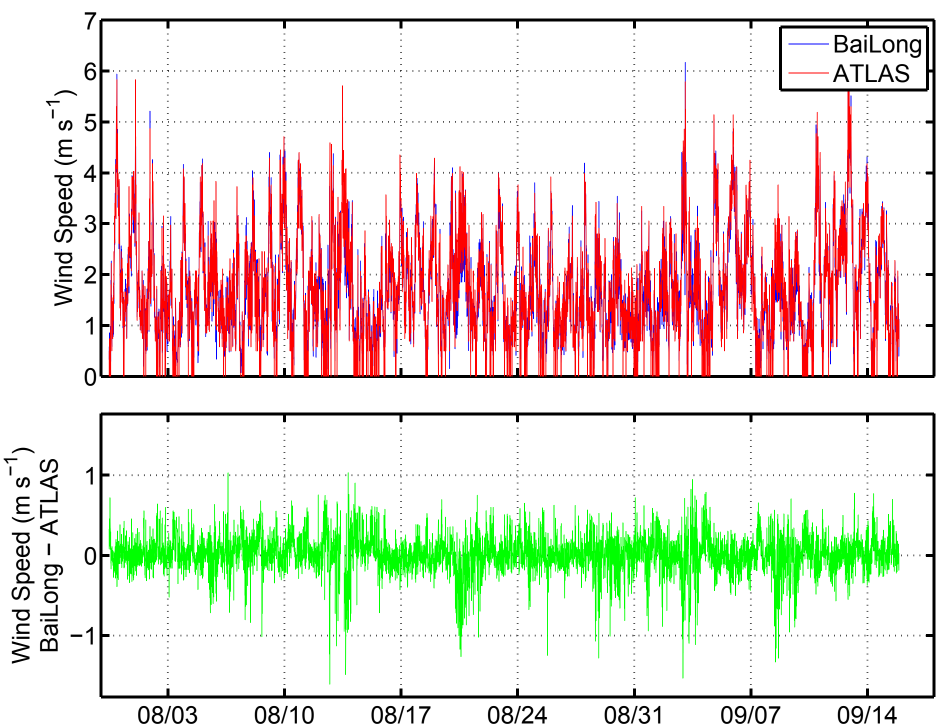

Figure 8: Time series of BaiLong (blue) and ATLAS (red) wind speed and difference (green).

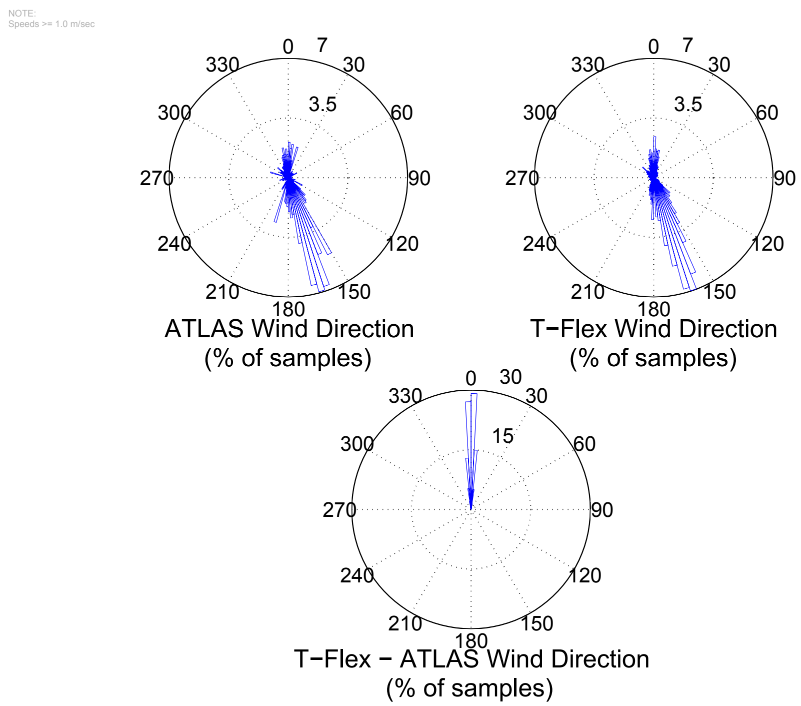

Figure 9: Histograms of T-Flex (upper right) and ATLAS (upper left) wind direction and difference (lower).

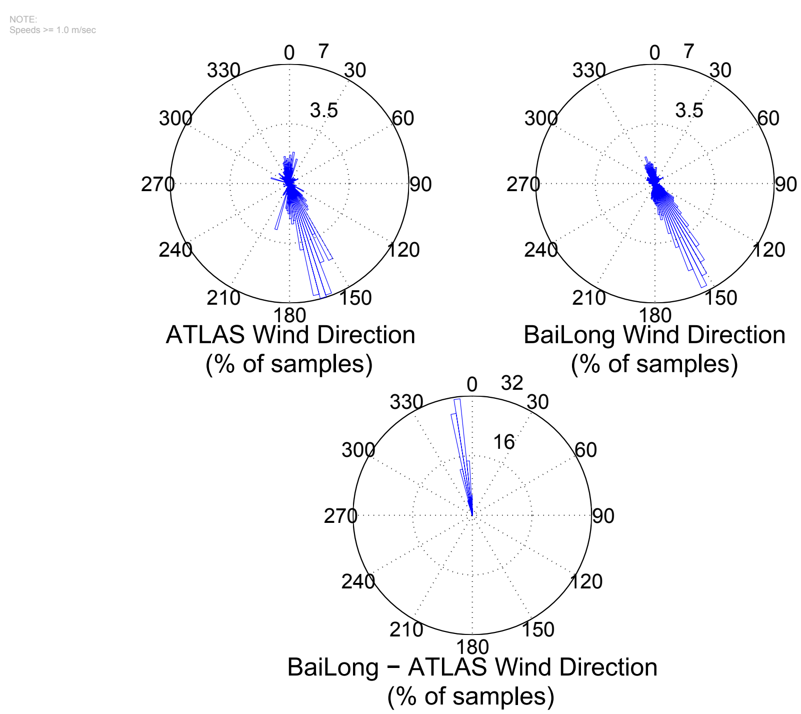

Figure 10: Histograms of BaiLong (upper right) and ATLAS (upper left) wind direction and difference (lower).

Table 6: Wind speed (m s^{-1}) and direction (°) differences for T-Flex minus ATLAS and BaiLong minus ATLAS sensors. NCom is the number of good data points in common. Wind direction statistics were computed when values of wind speed > 1.0 m s^{-1}.

Wind Speed									
System	**NCom**	**Mean**	**StdDev**	**RMS**	**Max**	**Min**	**R^2**	**Offset**	**Slope**
T-Flex	6938	0.08	0.21	0.23	1.42	–0.63	0.956	–0.14	1.03
BaiLong	6794	0.01	0.24	0.24	1.03	–1.61	0.947	–0.15	1.079

Wind Direction									
System	**NCom**	**Mean**	**StdDev**	**RMS**	**Max**	**Min**	**R^2**	**Offset**	**Slope**
T-Flex	5200	0.00	4.66	4.66	25.20	–34.40	0.997	–0.18	1.001
BaiLong	4959	–8.48	4.21	9.47	13.34	–33.76	0.998	5.59	1.016

3.4 Barometric pressure analysis

Barometric pressure during the test ranged between 1005 hPa and 1025 hPa (**Figures 11** and **12**). Differences between T-Flex and ATLAS were small (mean = –0.04 hPa, RMS = 0.08 hPa; **Table 7**), less than the sensor resolution (0.1 hPa) and within the manufacturer's accuracy specification (0.01% of reading, which equals 0.1 hPa at 1000 hPa). Differences between BaiLong and ATLAS were also small (mean = 0.02 hPa, RMS = 0.14 hPa). The RMS difference was slightly above the ATLAS/T-Flex manufacturer's specification but within the BaiLong manufacture's specification of 0.3 hPa. BaiLong differences were typically within the expected accuracy during most of the test period, with the exception of a short period near 3 September 2014, during which differences were as large as 1.3 hPa (**Figure 12**). This time period was coincident with the largest rain rate and some of the highest wind speed during the test. All time series were well correlated, with $R^2 > 0.99$. Barometric pressure spectra (not shown) from all three systems were virtually identical and well within 95% confidence levels.

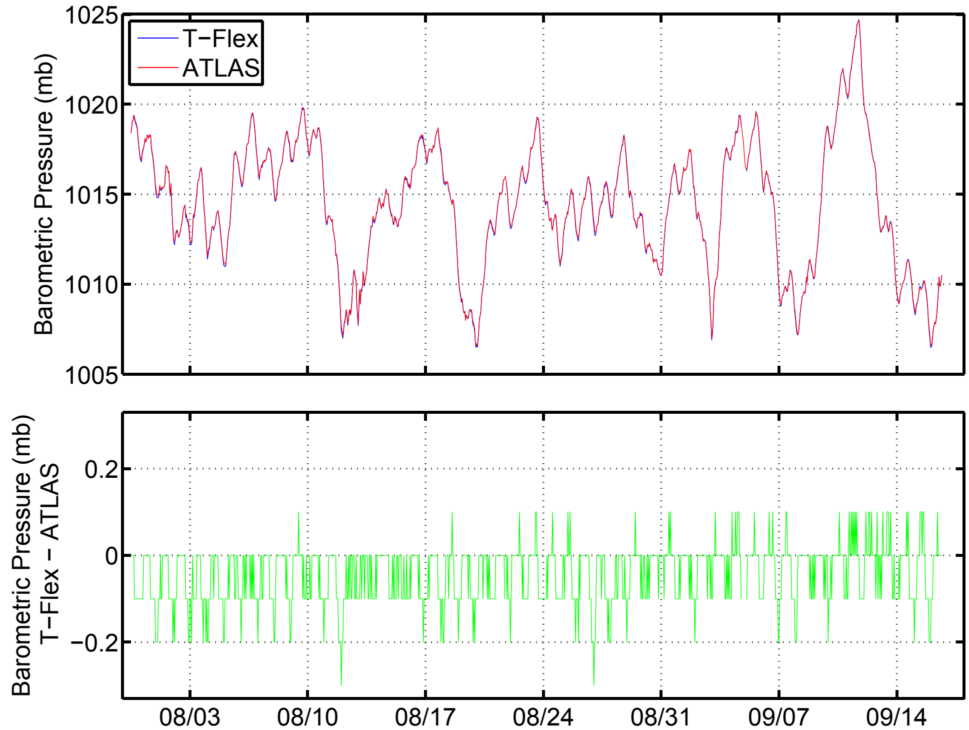

Figure 11: Time series of T-Flex (blue) and ATLAS (red) barometric pressure and difference (green).

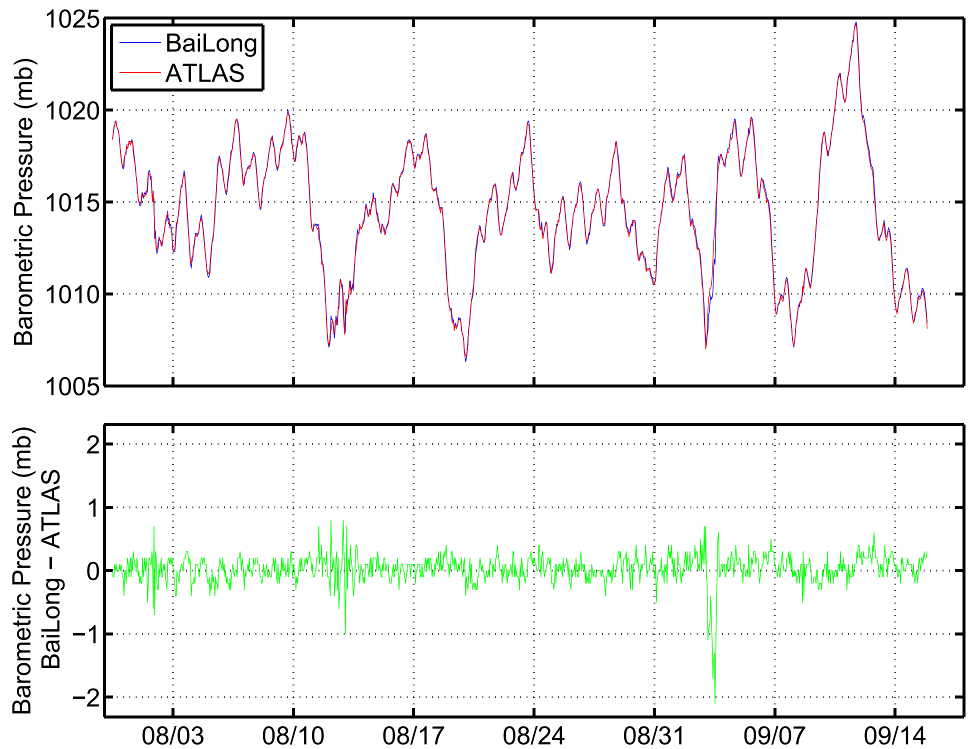

Figure 12: Time series of BaiLong (blue) and ATLAS (red) barometric pressure and difference (green).

Table 7: Barometric pressure (hPa) differences for T-Flex minus ATLAS and BaiLong minus ATLAS sensors. NCom is the number of good data points in common.

System	NCom	Mean	StdDev	RMS	Max	Min	R^2	Offset	Slope
T-Flex	1150	–0.04	0.07	0.08	0.10	–0.30	1.00	2.70	0.997
BaiLong	1138	0.02	0.14	0.14	0.80	–1.30	0.998	8.00	0.992

3.5 Short-wave radiation (SWR) analysis

Maximum SWR during the test was about 1100 W m^{-2} (**Figures 13** and **14**). Analysis of the data was complicated by the presence of shadows cast on the radiometers during morning hours by nearby trees (**Figure 1**), which were not uniformly distributed across all sensors (**Figure 15**). Due to these shadows, data recorded between 1306 GMT and 1832 GMT were omitted from the analysis, as were nighttime values (defined as SWR values of zero). One min T-Flex data were averaged to 2 min for comparison to the 2 min average ATLAS data. Continuous 2 min averaged ATLAS data were subsampled at 10 min intervals for comparison to the 2 min BaiLong data recorded at 10 min intervals. All time series were well correlated, with $R^2 > 0.99$. The T-Flex regression offset was small (–0.1 W m^{-2}) but was larger for BaiLong (6.9 W m^{-2}). The linear regression offset does not model well the sensor performance at low-light levels. ATLAS/BaiLong differences did, in fact, approach zero at the light levels < 50 W m^{-2}. Given the wide range of SWR data, differences are best measured in terms of percent difference rather than absolute values. As indicated by the slopes of linear regression (**Table 8**) T-Flex SWR was 3.9% greater than ATLAS SWR, and BaiLong SWR was about 8.3% greater (9% at 1000 W m^{-2} when the offset is included). Both differences exceed the ATLAS SWR accuracy specification of 2% (Cronin and McPhaden, 1997). The RMS of more than 300 ATLAS SWR sensor pre-deployment, post-recovery calibration differences was 2.8 W m^{-2} (unpublished analysis, PMEL).

It has been suggested that ATLAS sensors deployed in the tropical ocean may experience larger calibration drift due to more exposure to high solar radiation compared to sensors deployed elsewhere (George Kirk, personal communication, 1994). Such drift should not be a factor for the ATLAS and T-Flex sensors used in the present test as they had not been deployed since last having been calibrated in October 2013 and August 2013, respectively. These sensors were calibrated again after the test in December 2014. Differences from the 2013 calibrations were 0.3% and 1.3%, respectively. Application of the post-test calibrations would increase the difference between T-Flex and ATLAS SWR from 3.9% to 4.9%, thus the difference is not thought to be solely due to calibration error but perhaps in part to horizontal alignment differences between sensors. The BaiLong sensor was last calibrated 13 March 2012 and had not been deployed before being tested at PMEL.

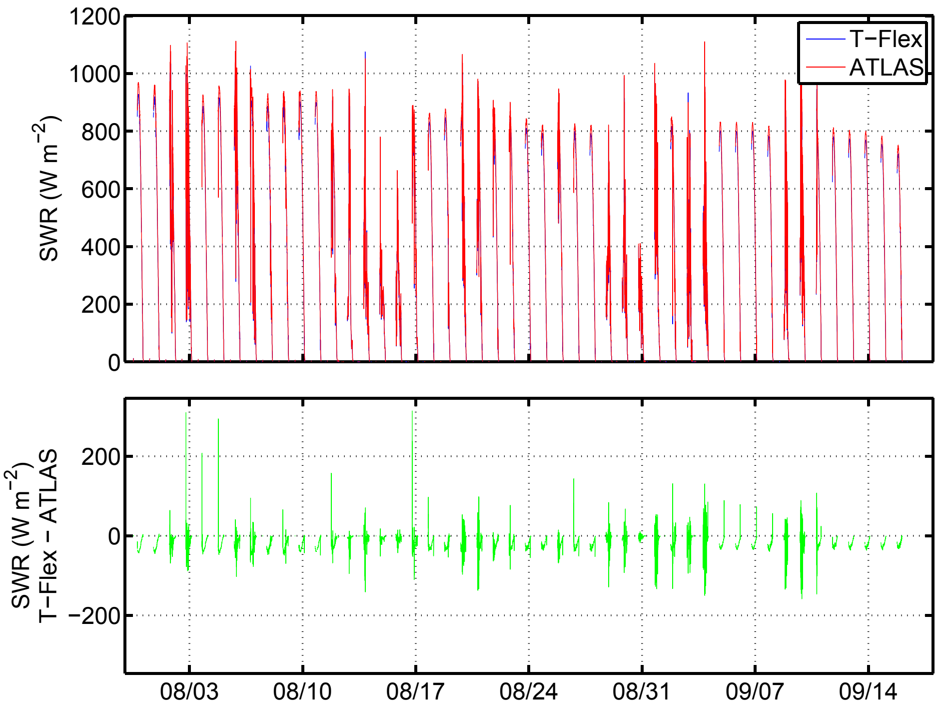

Figure 13: Time series of T-Flex (blue) and ATLAS (red) short-wave radiation and difference (green). Values between 1306 and 1832 GMT have been omitted due to shadows cast on the sensors.

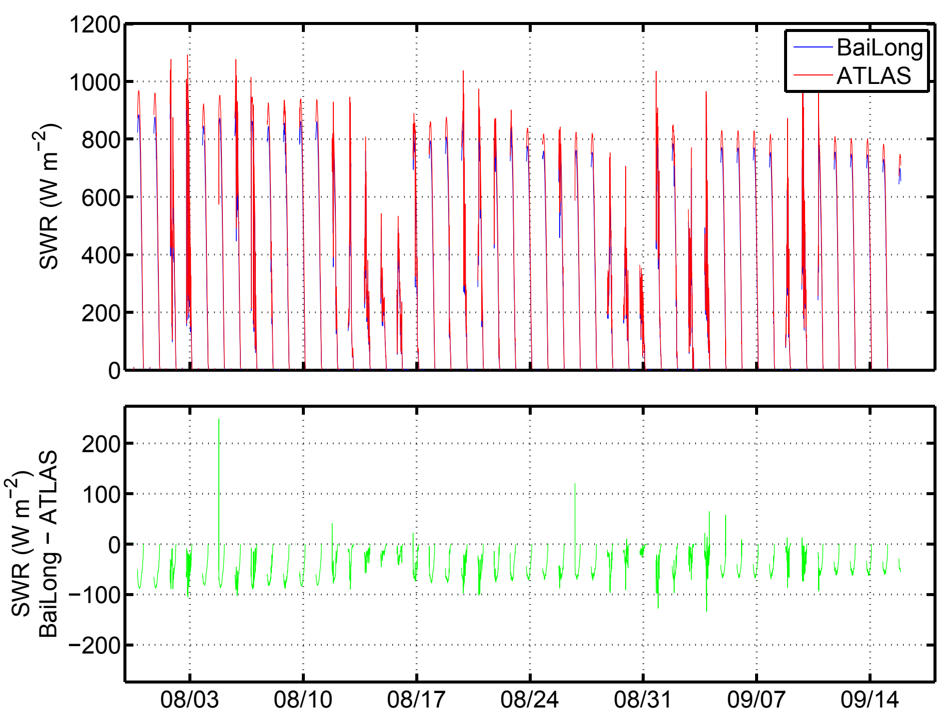

Figure 14: Time series of BaiLong (blue) and ATLAS (red) short-wave radiation and difference (green). Values between 1306 and 1832 GMT have been omitted due to shadows cast on the sensors.

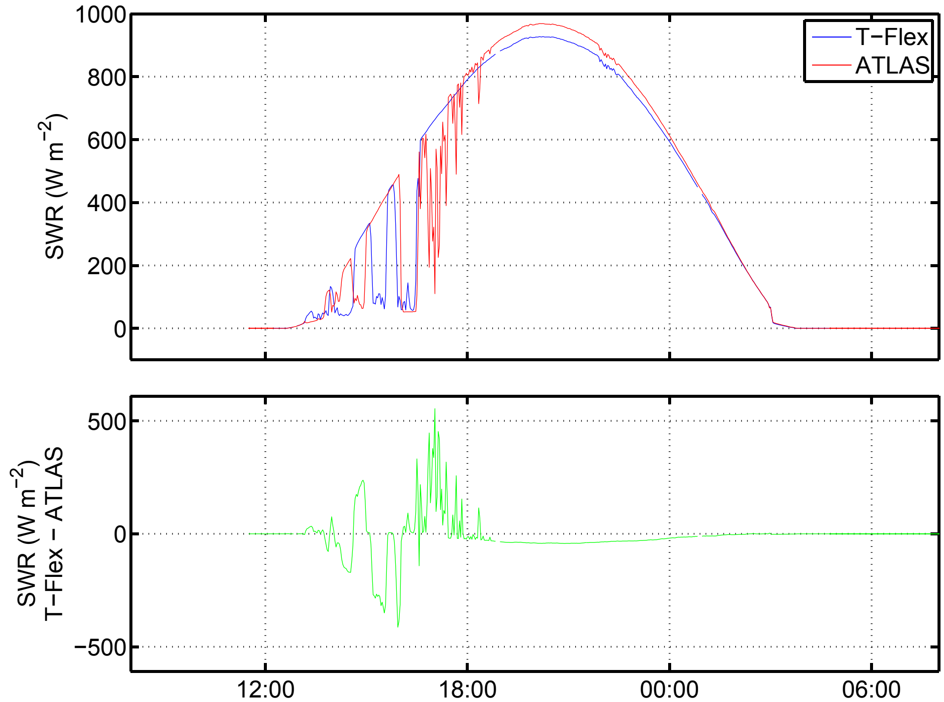

Figure 15: Time series of T-Flex (blue) and ATLAS (red) short-wave radiation and difference (green) on 30–31 July 2014. Time axis is GMT hour.

Table 8: Short-wave radiation (W m^{-2}) differences for T-Flex minus ATLAS and BaiLong minus ATLAS sensors. NCom is the number of good data points in common. Data recorded between 1306 and 1832 GMT and nighttime values were omitted from the analysis.

System	NCom	Mean	StdDev	RMS	Max	Min	R^2	Offset	Slope
T-Flex	12637	–17.2	19.1	25.7	314.4	–158.1	0.998	–0.1	1.039
BaiLong	2518	–41.8	27.9	50.3	248.7	–133.6	0.998	6.9	1.083

3.6 Downwelling long-wave radiation (LWR) analysis

Downwelling LWR during the test ranged between 275 W m^{-2} and 425 W m^{-2} (**Figures 16** and **17**). One-min T-Flex data were averaged to 2 min for comparison to the 2 min average ATLAS data. Continuous 2 min averaged ATLAS data were subsampled at 10 min intervals for comparison to the 2 min average BaiLong data recorded at 10 min intervals. Differences between T-Flex and ATLAS (**Table 9**) were small (mean = 1.8 W m^{-2}, RMS = 2.4 W m^{-2}), and within the manufacturer's accuracy specification (1% of reading, which equals 3.0 W m^{-2} at 300 W m^{-2}). Differences between BaiLong and ATLAS were smaller still (mean = 1.5 W m^{-2}, RMS = 2.2 W m^{-2}). All time series were well correlated, with $R^2 > 0.99$.

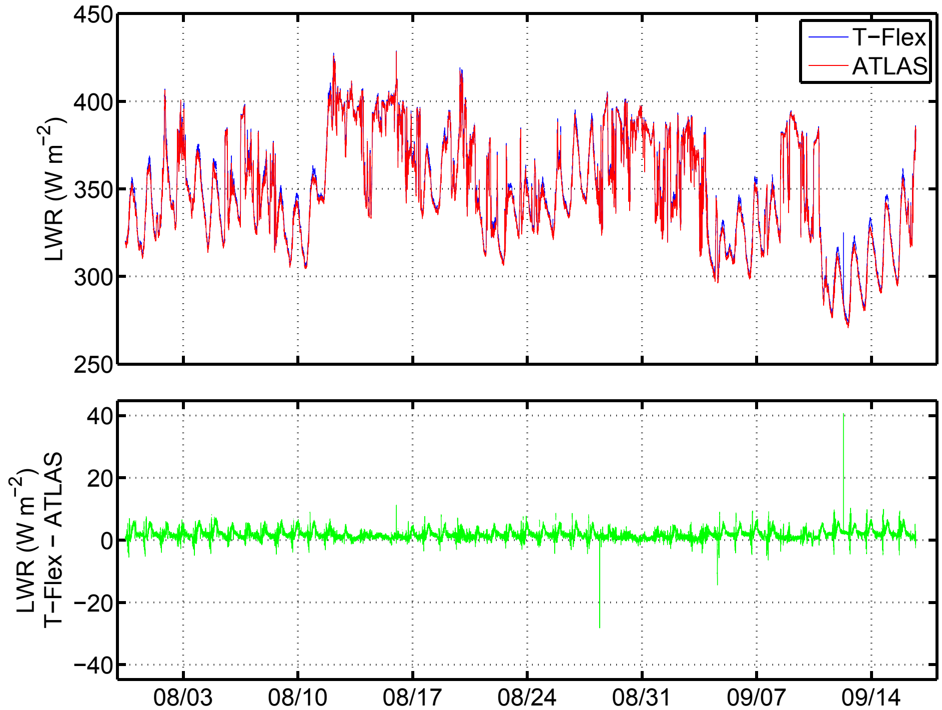

Figure 16: Time series of T-Flex (blue) and ATLAS (red) downwelling longwave radiation and difference (green). Values between 1306 and 1832 GMT have been omitted due to shadows cast on the sensors.

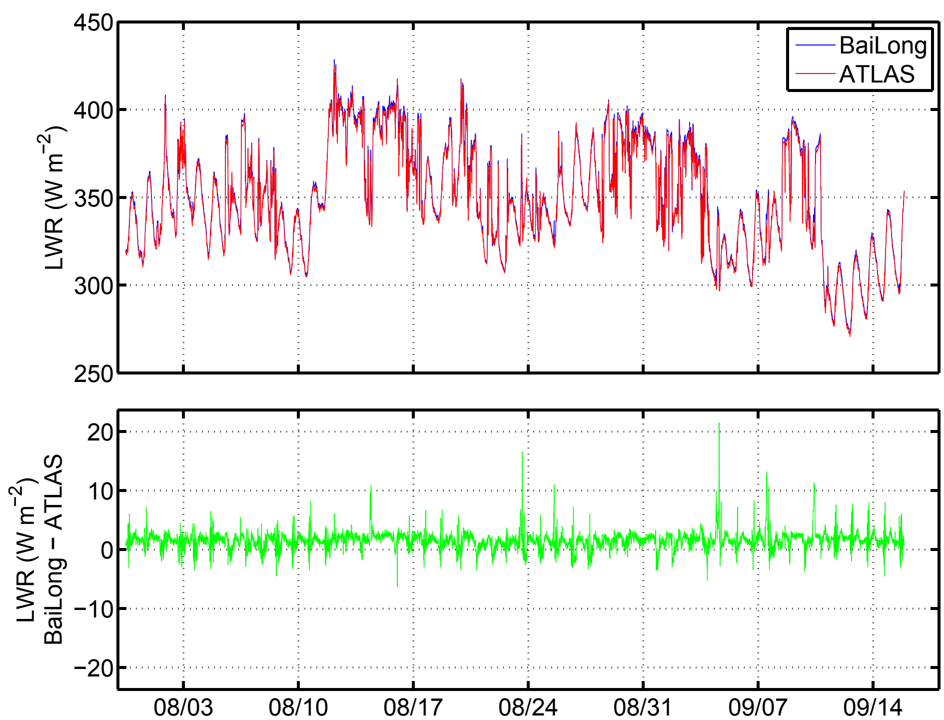

Figure 17: Time series of BaiLong (blue) and ATLAS (red) downwelling longwave radiation and difference (green). Values between 1306 and 1832 GMT have been omitted due to shadows cast on the sensors.

Table 9: Downwelling long-wave radiation (W m^{-2}) differences for T-Flex minus ATLAS and BaiLong minus ATLAS sensors. NCom is the number of good data points in common.

System	NCom	Mean	StdDev	RMS	Max	Min	R^2	Offset	Slope
T-Flex	30926	1.8	1.6	2.4	40.6	–28.2	0.997	–4.5	1.008
BaiLong	6822	1.5	1.5	2.2	21.5	–6.3	0.998	–0.5	0.997

3.7 Precipitation analysis

July and August are climatologically the driest months of the year in Seattle. The test period in 2014 was no exception, with few rain events, most of which had limited duration and accumulation (**Figures 18** and **19**). The largest rain rate was on 3 September 2014, with a peak 10 min rain rate of about 50 mm hr^{-1}. ATLAS and T-Flex sensors differed by 5 mm hr^{-1} for this single point, which is much larger than the ATLAS accuracy of 0.4 mm hr^{-1} specified by Serra *et al.* (2001). Ensemble T-Flex minus ATLAS differences computed during seven rain event periods (mean = -0.02 mm hr^{-1}, RMS = 0.47 mm hr-$^{-1}$, **Table 10**) were comparable to the specified accuracy. Mean rates during the events ranged from 0.15 mm hr^{-1} to 2.13 mm hr^{-1}. Measureable rainfall was sporadic within some of these event periods. Average ATLAS and T-Flex percent-time-raining estimates over these events were between 29% and 98%, and the time series analyzed contained some zero values. Rain accumulation over the seven rain events ranged from 1 to 20 mm, and was < 5 mm for five of the seven events. Accumulation differences between T-Flex and ATLAS for the seven events were -0.14 mm in the mean and RMS of 0.28 mm.

ATLAS and T-Flex systems record continuous time series of 1 min water volume in the gauges. Rain rates are computed by smoothing the 1 min data with a 16-point Hanning filter and computing differences at 10 min intervals centered at times of 00:00, 00:10, 00:20, etc. The BaiLong system records 2 min averages of water volume at 10 min intervals, centered at times 1 min later than those for ATLAS and T-Flex.

For comparison to ATLAS rain rates, 10 min BaiLong rain rates were computed as water level differences centered near 00:06, 00:16, 00:26, etc., which resulted in 10 min BaiLong rain rates being out of phase with ATLAS and T-Flex rain rates. This sample time difference contributed to larger RMS differences for the BaiLong system than for the T-Flex system when compared with 10 min ATLAS rain rates (**Table 10**). The timing offset is evident in rain rate differences during the 3 September 2014 rain event (**Figure 19**), during which there was a large positive difference followed by a large negative difference. The difference in rain rate sample time was also consistently apparent during a rain event on 13 August, which was the longest duration event (**Figure 20**).

Accumulation differences between BaiLong and ATLAS (mean = –0.76 mm hr^{-1}, RMS = 1.06 mm hr^{-1}, **Table 10**) were larger than accumulation differences between T-Flex and ATLAS by factors of 4 or 5. Unlike rain rate estimates, rain accumulation over events lasting many sample intervals should not be impacted by the difference in sample times. Close examination of the data suggests that the difference between the BaiLong and ATLAS accumulation was in part related to

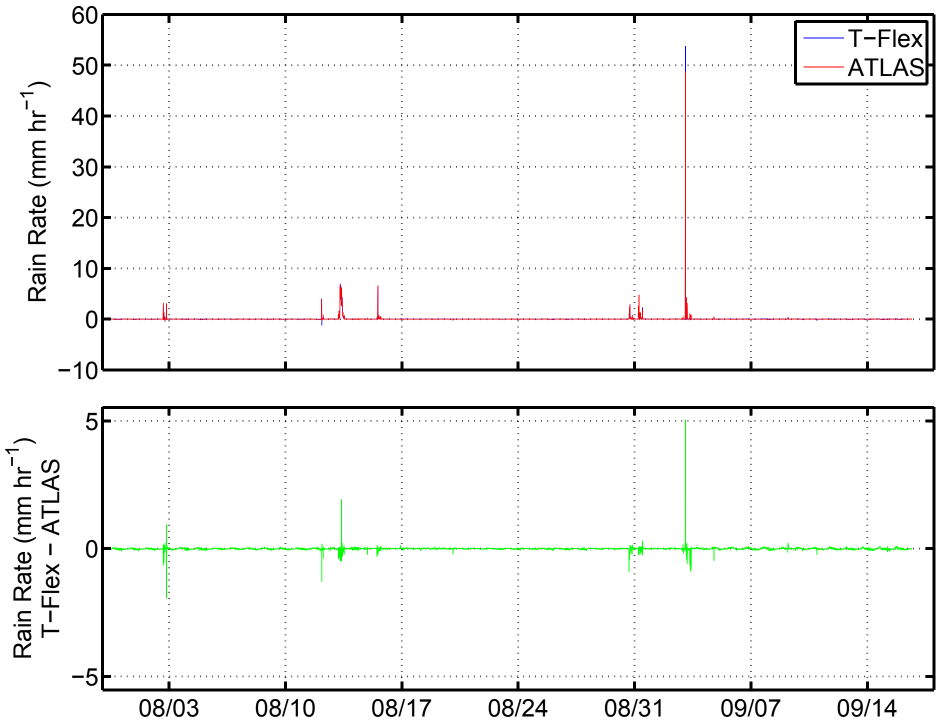

Figure 18: Time series of T-Flex (blue) and ATLAS (red) precipitation and difference (green).

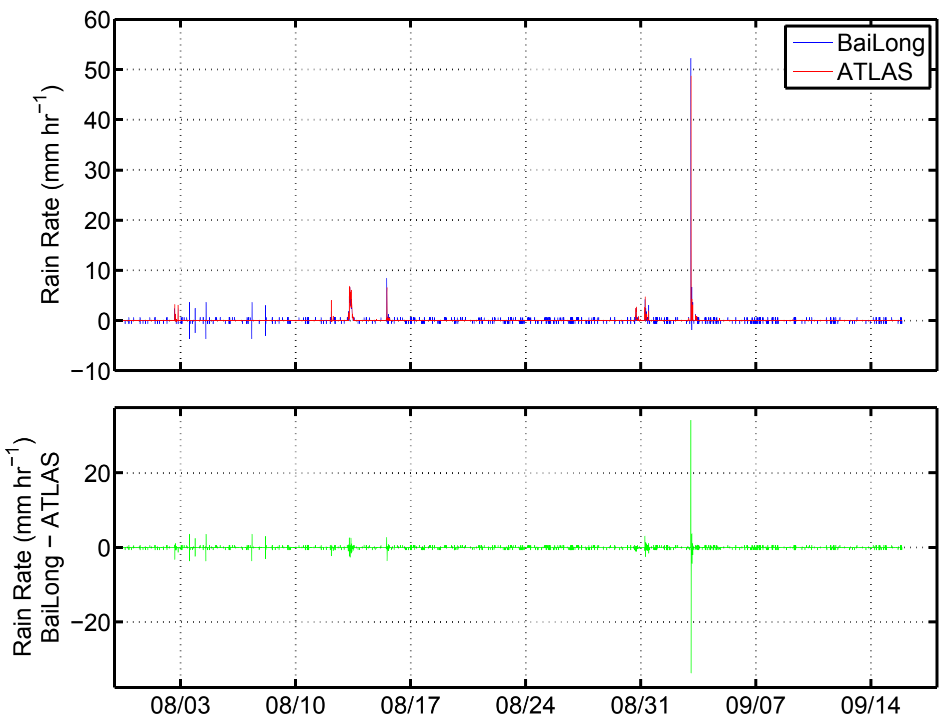

Figure 19: Time series of BaiLong (blue) and ATLAS (red) precipitation and difference (green).

Table 10: Ten-minute rain rate (mm hr⁻¹) differences for T-Flex minus ATLAS and BaiLong minus ATLAS sensors during seven rain events. NCom is the number of data points in common. Also, rain accumulation differences (mm) during these seven events.

10 min Rain Rate (mm hr^{-1})									
System	**NCom**	**Mean**	**StdDev**	**RMS**	**Max**	**Min**	**R^2**	**Offset**	**Slope**
T-Flex	299	–0.02	0.47	0.47	5.03	–1.93	0.990	0.11	0.911
BaiLong	299	–0.11	2.91	2.91	34.12	–33.69	0.264	0.16	0.945

Rain Event Accumulation (mm)									
System	**NCom**	**Mean**	**StdDev**	**RMS**	**Max**	**Min**	**R^2**	**Offset**	**Slope**
T-Flex	7	–0.14	0.26	0.28	0.43	–0.37	0.999	0.27	0.982
BaiLong	7	–0.76	0.79	1.06	0.06	–2.41	0.994	0.33	1.067

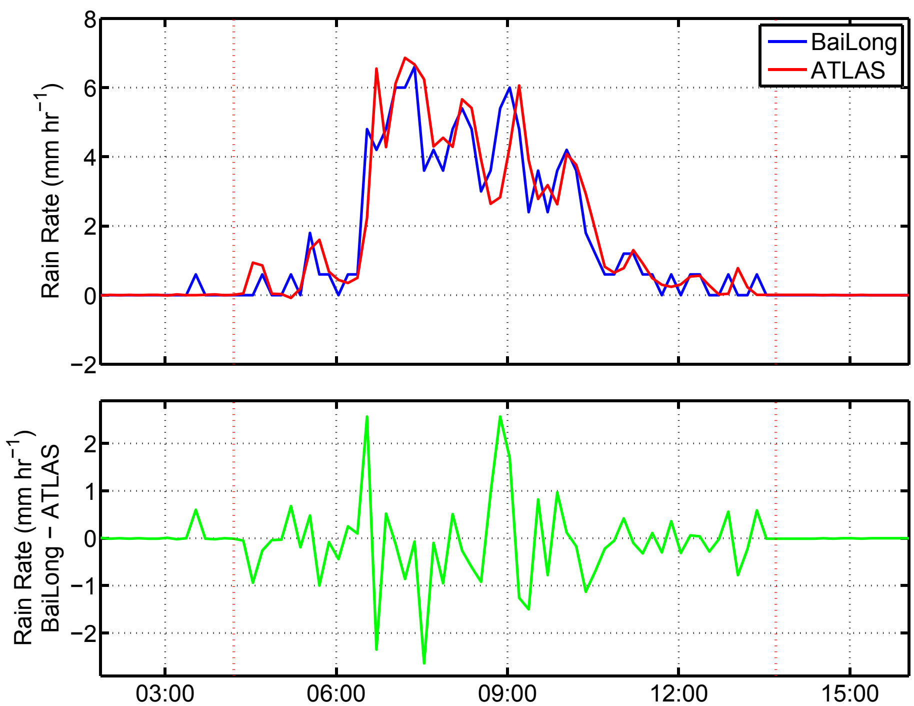

Figure 20: Time series of BaiLong (blue) and ATLAS (red) precipitation and difference (green) during rain event on 13 August 2014.

the BaiLong 10 min sampling interval's impact on rain gauge siphon processing. The largest contribution to the BaiLong mean accumulation difference (–2.41 mm) was from the rain event on 3 September, which also had the largest accumulation (16.61 mm measured by the ATLAS). This event was characterized by a short burst (order 10 min) of intense rainfall (48.69 mm hr⁻¹ measured by the ATLAS). The BaiLong gauge filled and siphoned during this burst. The siphon was processed in a manner similar (but not exactly equal) to that for ATLAS and T-Flex rain data. For the BaiLong data, values of water level after the siphon were increased by the amount in the gauge immediately before the siphon event. A siphon event takes about 30 sec to complete. Given the BaiLong sampling of 2 min averages recorded at 10 min intervals, it cannot be determined whether the siphon event was included in either the last data point before the drop in water level was detected, or in the first point after detection, or completely in the intervening 8 min period between sampling periods. The last BaiLong water level before the siphon was 47.6 mm and the first point after was 2.5 mm (**Figure 21**). The method used to process the BaiLong siphon event could have missed an accumulation of 2.4 mm, assuming the gauge reached 50 mm before the siphon began. The processing did assume the gauge drained to 0 before increasing to 2.5 mm.

The T-Flex gauge siphoned about 7 hr after the BaiLong gauge (**Figure 21**). The 1 min continuous T-Flex data reached 49.5 mm before siphoning and dropped to 0.3 mm immediately after. The continuous 1 min resolution T-Flex data allow for more precision in processing siphon events, compared to the 10 min interval BaiLong data. PMEL's processing does not assume that the ATLAS or T-Flex gauges fill to 50 mm or drain to 0 mm. Empirical data indicate differences in siphon points between gauges and events. Given the lower precision of the BaiLong sampling, assumptions about gauge level before and after a siphon may improve data accuracy. As this test period only included one siphon each for the three gauges involved, further experiments would be necessary to develop a best method of BaiLong siphon processing.

Note that the BaiLong water level continued to decrease for an hour after the siphon until a small rain event (also indicated in both the ATLAS and T-Flex time series) caused it to rise. Suspicious performance before and after siphon events has also been observed in ATLAS and T-Flex gauges and is not unique to the BaiLong gauge. The BaiLong time series also had small (order 1 mm) diurnal variations in water height during times of no rain, possibly due to ambient temperature changes, which have also been observed previously in ATLAS and T-Flex gauges.

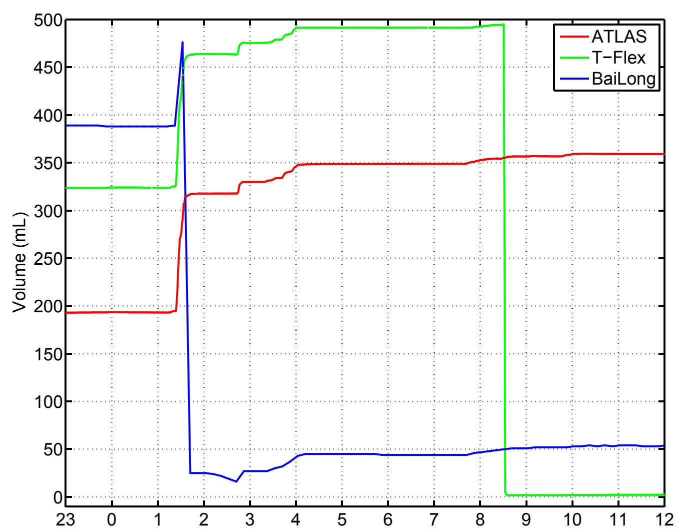

Figure 21: Water volume in ATLAS (red), T-Flex (green) and BaiLong (blue) rain gauges on 3 September 2014. Water height in gauge (mm) = water volume (ml)/10. The x axis is GMT hour.

4. Conclusion

Meteorological sensors from three mooring systems were compared at PMEL in summer 2014. For this land-based test, the sensors were installed on buoy towers, which are also used when deployed at sea. T-Flex and BaiLong data differences relative to ATLAS data are summarized in **Table 11**. Air temperature, relative humidity, wind speed, barometric pressure, and long-wave radiation differences for both systems tested were within or near the expected accuracy of the ATLAS system. Air temperature and relative humidity differences were smaller at night than during daylight hours. Day/night air temperature differences were greater for BaiLong data than for T-Flex data, suggesting differences in the sensor's radiation shield performance in reducing solar heating bias.

T-Flex differences for wind direction were within the ATLAS expected accuracy. Larger than expected wind direction difference for the BaiLong system is thought to be due to the method of installation of the compass, which did not provide a fixed orientation. The BaiLong compass was also not calibrated using the manufacturer's procedure.

Short-wave radiation differences for both systems tested exceeded the ATLAS expected accuracy, presumably due in part to differences in the leveling of each system.

T-Flex differences for precipitation were within the expected accuracy of the ATLAS system, as were mean BaiLong rain rate differences. BaiLong RMS differences, which exceeded the expected accuracy, were due in part to the BaiLong data being asynchronous with the ATLAS by half the sample rate. The 10-min BaiLong rain data resolution also lowers precision in processing siphon events which in turn increases uncertainty in rain estimates at times of siphoning.

All systems collected good data for >99% of the test period, with the exception of the T-Flex LWR for which 7% of the data were missing. The data loss was caused by a firmware timing issue which has since been corrected. Within the limitations of this test the overall result was that the T-Flex and BaiLong systems are capable of making meteorological observations comparable to the ATLAS. Improvements to BaiLong rain gauge siphon processing algorithms should be investigated, or continuous sampling should be considered. To improve wind direction accuracy, the BaiLong compass enclosure should be modified to fix the compass orientation relative to the anemometer. As is the standard procedure for ATLAS and T-Flex systems, all sensors (including the compass) should be calibrated both before and after deployment at sea.

Table 11: Mean and RMS differences for all T-Flex and BaiLong meteorological sensors compared to ATLAS sensors.

Sensor Type	System	Mean	RMS
Air Temperature (°C)	T-Flex	0.19	0.30
	BaiLong	0.32	0.51
Relative Humidity (%RH)	T-Flex	–1.43	1.80
	BaiLong	–1.23	1.86
Wind Speed ($m\ s^{-1}$)	T-Flex	0.08	0.23
	BaiLong	0.01	0.24
Wind Direction (°)	T-Flex	0.00	4.66
	BaiLong	–8.48	9.47
Barometric Pressure (hPa)	T-Flex	–0.04	0.08
	BaiLong	0.02	0.14
Short-wave Radiation (W m)	T-Flex	–17.20	25.70
	BaiLong	–41.80	50.30
Long-wave Radiation (W m)	T-Flex	1.80	2.40
	BaiLong	1.50	2.20
Precipitation ($mm\ hr^{-1}$)	T-Flex	–0.02	0.47
	BaiLong	–0.11	2.91

5. Acknowledgments

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Appendix

Summary of calibration tests performed on BaiLong sensors at PMEL.

Air Temperature (°C)		
Standard	**BaiLong**	**Difference**
14.205	14.211	0.006
17.139	17.146	0.007
20.062	20.067	0.005
22.980	22.980	–0.001
25.907	25.901	–0.006
28.850	28.837	–0.013
31.808	31.791	–0.017
	Mean	–0.003
	RMS	0.009
	Max	0.007
	Min	–0.017

Wind Speed (m s^{-1})		
Standard	**BaiLong**	**Difference**
1.43	1.23	–0.20
2.47	2.23	–0.24
4.18	3.96	–0.23
6.27	5.96	–0.31
7.95	7.63	–0.32
10.13	9.75	–0.38
13.80	13.56	–0.23
	Mean	–0.28
	RMS	0.29
	Max	–0.20
	Min	–0.38

Precipitation (mm)		
Standard	**BaiLong**	**Difference**
0	0.98	0.98
7	7.90	0.90
14	14.59	0.59
21	21.40	0.40
28	28.24	0.24
35	35.21	0.21
42	42.18	0.18
49	49.30	0.30
	Mean	0.48
	RMS	0.56
	Max	0.98
	Min	0.18

Compass Heading (°)		
Standard	**BaiLong**	**Difference**
0	360	0.0
15	16.9	1.9
30	34	4.0
45	50.9	5.9
60	68	8.0
75	84.8	9.8
90	100.9	10.9
105	116.9	11.9
120	131.8	11.8
135	146.6	11.6
150	161.2	11.2
165	175.1	10.1
180	188.8	8.8
195	202.5	7.5
210	215.9	5.9
225	229.4	4.4
240	242.6	2.6
255	256.1	1.1
270	269.7	–0.3
285	283.6	–1.4
300	297.7	–2.3
315	312.2	–2.8
330	327.3	–2.7
345	343.1	–1.9
0	359.5	–0.5
	Mean	4.8
	RMS	7.1
	Max	11.9
	Min	–2.8