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COMPARISON OF ATLAS AND T-FLEX MOORING DATA

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Comparison of ATLAS and T-Flex Mooring Data

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Abstract. Autonomous Temperature Line Acquisition System (ATLAS) moorings have been the predominant mooring systems deployed in tropical moored buoy arrays since 1984. The present version ATLAS was used extensively in all three tropical ocean basins beginning in 2000 and continues as a significant component of the Atlantic and Indian Ocean arrays. Obsolescence of some ATLAS components, technological advancements in commercially available instruments, and a new, more capable satellite telemetry system not available when ATLAS was designed prompted NOAA's Pacific Marine Environmental Laboratory (PMEL) to develop a new tropical mooring system, called Tropical-Flex (T-Flex). This system was designed to provide data with quality comparable to or better than that of the ATLAS system, so that multi-decadal ATLAS time series can be continued efficiently and without bias caused by changes in measurement strategy, consistent with the "Ten Climate Monitoring Principles" (Karl et al., 1996). Between 2011 and 2015 eight pairs of ATLAS and T-Flex moorings were deployed in the tropical Atlantic and Indian oceans, typically separated by a few nautical miles, to measure their relative performance in terms of real time and delayed-mode data volume, consistency, and accuracy. This report describes the design and testing of the PMEL T-Flex mooring system. We show that T-Flex meets our design criteria with both real-time and delayed-mode data being of equivalent accuracy to those of the ATLAS system. T-Flex began to replace ATLAS moorings in the Atlantic and Indian Ocean tropical mooring arrays in 2015.

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1. Introduction

The Global Tropical Moored Buoy Array (GTMBA) (**Figure 1**) provides high-quality moored time series and related data throughout the global tropics for improved description, understanding, and prediction of seasonal to decadal time scale climate variability (McPhaden et al., 2010). The program is a contribution by NOAA and its partners to the Global Ocean Observing System, the Global Climate Observing System, and the Global Earth Observing System of Systems. Components of the array occupy each of the three tropical oceans. The Tropical Atmosphere Ocean (TAO) array in the Pacific was initiated in 1984 by PMEL and transferred to the National Data Buoy Center of NOAA's National Weather Service in 2005. The Japan Agency for Marine-Earth Science and Technology (JAMSTEC) operates the Triangle Trans-Ocean Buoy Network (TRITON) of buoys in the western Pacific. The Prediction and Research Moored Array in the Atlantic (PIRATA), begun in 1997, is the Atlantic Ocean component of GTMBA (Bourlès et al., 2008). It is operated by NOAA, France's Institut de Recherche Scientifique pour le Développement en Coopération, Meteo-France, and Brazil's Instituto Nacional de Pesquisas Espaciais and Diretoria de Hidrografia e Navegacao. The Research moored Array for African-Asian-Australian Monsoon Analysis and prediction (RAMA) is the tropical Indian Ocean component of the GTMBA (McPhaden et al., 2009). It is presently maintained by NOAA, JAMSTEC, India's Ministry of Earth Sciences, Indonesia's Agency for Meteorology, Climatology and Geophysics and Agency for the Assessment and Application of Technology, and China's First Institute of Oceanography (FIO), State Oceanic Administration.

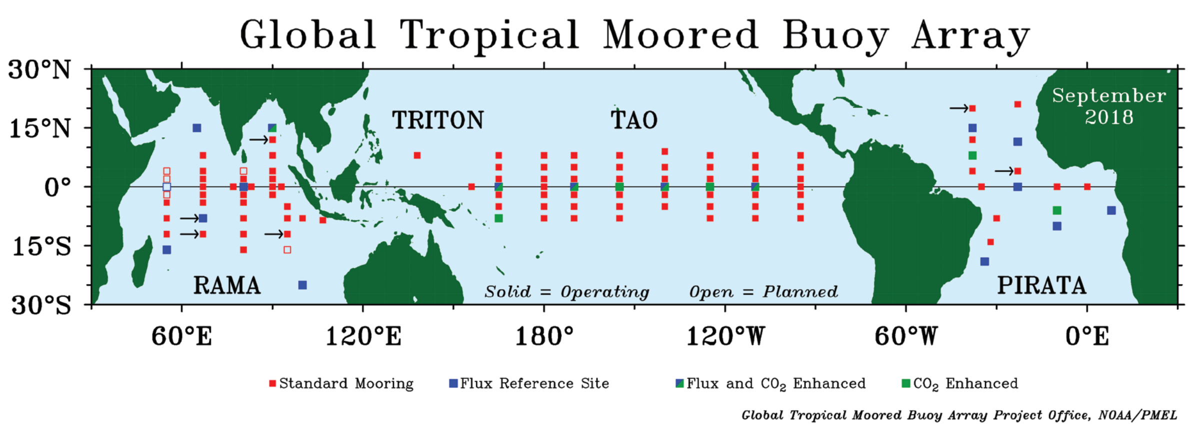

Figure 1. The Global Tropical Moored Buoy Array composed of RAMA in the Indian Ocean, TAO/TRITON in the Pacific Ocean, and PIRATA in the Atlantic Ocean. Arrows indicate sites at which T-Flex moorings were tested near ATLAS moorings.

PIRATA and RAMA were implemented using the Next-Generation version Autonomous Temperature Line Acquisition System (aka NX-ATLAS) system (Milburn et al., 1996), which also comprised most TAO/TRITON sites for two decades. PMEL has developed a replacement mooring system for ATLAS named Tropical-Flex (T-Flex), which draws upon new technologies unavailable when NX-ATLAS was developed. These include two-way telemetry via Iridium (vs. one-way via Argos), sonic anemometers (vs. propeller vane), newer model compasses and air temperature/relative humidity (ATRH) sensors, commercially available temperature/conductivity/pressure sensor packages with integrated inductive modems (IM) and pumped conductivity cells (vs. modules designed and constructed by PMEL), and current meters with integrated IM (vs. current meters coupled with PMEL modules). Sensors common to both systems include those measuring shortwave radiation (SWR), longwave radiation (LWR), precipitation (RAIN), and barometric pressure (BP) (**Table 1**). Use of Iridium for telemetry and Seabird Electronics, Inc. IM increases the resolution of real-time data from primarily daily averages for ATLAS to hourly samples for T-Flex (**Table 2**). T-Flex also has real-time communication channels for up to 8 times more subsurface sensors. The temporal resolution of internally recorded data is equal for both systems (primarily 10 min). Both ATLAS and T-Flex moorings have a design life of 12 months, with some reserve battery capacity for longer than intended deployments. The two mooring systems (Figure 2) essentially use the same buoys, wire, and rope. The main difference in buoys is that the ATLAS electronic control unit (CPU, memory, batteries, and transmitter) is mounted on the tower, while the T-Flex electronics are mounted in the buoy for better protection against vandalism and the elements. The present composition of PIRATA and RAMA is roughly half ATLAS and half T-Flex.

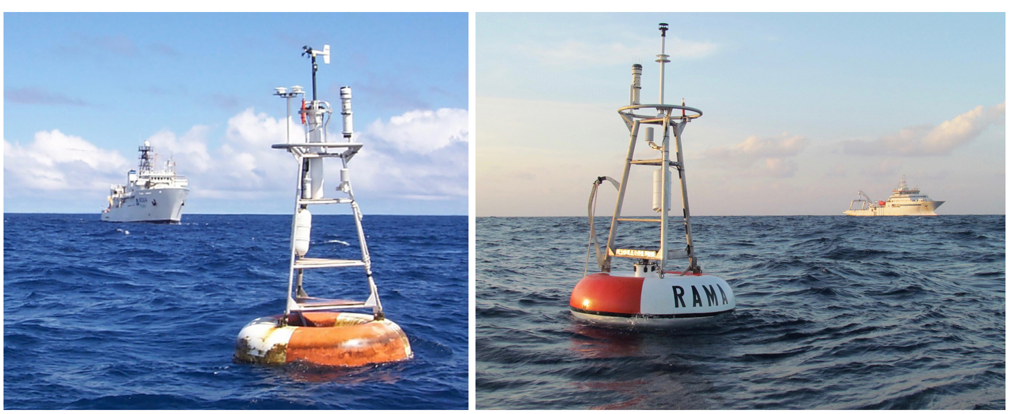

Figure 2. Buoy, tower, and meteorological sensors for ATLAS (left) and T-Flex (right) moorings.

Table 1. Sensor specifications for ATLAS and T-Flex mooring systems. The number of subsurface measurements shown are minimum standard configurations. Additional sensors are deployed at some RAMA and PIRATA sites. Most ATLAS sensor accuracies are based on calibration analysis described in the references below and may differ from those specified by the manufacturers. Manufacturers' specifications are relied on for ATLAS LWR and BP and for T-Flex sensors that differ from those used on ATLAS moorings..

		ATLAS	T-Flex
Wind Speed & Relative Direction	Manufacturer: Model	R.M. Young: 5103	Gill Inst. Ltd.: WindSonic
	Height (m)	4	4
	Resolution	0.2 ms^{-1}; 1.4°	0.1 ms^{-1}; 1°
	Accuracy	±0.3 m s^{-1} or ±3%; ±2°	±2% @ 12 m s^{-1} or ±2° @ 12 m/s
Compass	Manufacturer: Model	EG&G: 63764,KVH: LP101-5, or KVH: C100	Sparton: SP3004D
	Resolution	1.4°	0.1°
	Accuracy	±2° to 7°	±1°
Air Temperature & Relative Humidity	Manufacturer: Model	Rotronic Inst. Corp.: MP-101	Rotronic Inst. Corp: HC2 S3
	Height (m)	2.5	2.5
	Resolution	0.01°C, 0.02%RH	0.1°C, 0.1%RH
	Accuracy	±0.2°C; ±2.7%RH	±0.1°C, ±0.8%RH
Precipitation	Manufacturer: Model	R.M. Young: 50203-34	R.M. Young: 50203-34
	Height (m)	3.5	3.5
	Resolution	0.2 mm hr^{-1}	0.2 mm hr^{-1}
	Accuracy	±0.4 mm hr^{-1}	±0.4 mm hr^{-1}
Short-wave Radiation	Manufacturer: Model	Eppley Laboratory: PSP-TAO	Eppley Laboratory: PSP-TAO
	Height (m)	3.5	3.5
	Resolution	0.4 W m^{-2}	0.4 W m^{-2}
	Accuracy	±2.8%	±2.8%
Long-wave Radiation	Manufacturer: Model	Eppley Laboratory: PIR-TAO	Eppley Laboratory: PIR-TAO
	Height (m)	3.5	3.5
	Resolution	0.1 W m^{-2}	0.1 W m^{-2}
	Accuracy	±1%	±1%
Barometric Pressure	Manufacturer: Model	Paroscientific, Inc.: Met1-2	Paroscientific, Inc.: Met1-2
	Height (m)	2.5	2.5
	Resolution	0.1 hPa	0.1 hPa
	Accuracy	±0.01%	±0.01%
Water Temperature	Manufacturer: Model	PMEL: ATLAS Module	Seabird Electronics: SBE37, SBE39
	Depth (m)	1 to 500 @ $\geq$ 11 levels	1 to 500 @ $\geq$ 11 levels
	Resolution	0.001°C	0.001°C
	Accuracy	±0.02°C	±0.002°C
Salinity	Manufacturer: Model	PMEL, Seabird Electronics: ATLAS Module	Seabird Electronics: SBE37
	Depth (m)	1 to 500 @ $\geq$ 4 levels	1 to 500 @ $\geq$ 4 levels
	Resolution	0.002 S m^{-1}	0.0001 S m^{-1}
	Accuracy	±0.02 psu	±0.003 mS/cm
Current Speed & Direction	Manufacturer: Model	Sontek: Argonaut	Nortek: Aquadopp
	Height (m)	10 (others optional)	12 (others optional)
	Resolution	0.1 cm s^{-1}, 0.1°	0.1 cm s^{-1}, 0.1°
	Accuracy	±5 cm s^{-1}, ±5°	±1% of value ±0.5 cm s^{-1}, ±2°
Water Pressure	Manufacturer: Model	PMEL: ATLAS Module	Seabird Electronics: SBE39
	Depth (m)	300, 500	300, 500
	Resolution	0.02 dbar	0.002% of full range (600 m)
	Accuracy	±1.0 dbar	±0.1% of full scale (600 m)

Table 2. Standard data sampling schedules and real-time data resolution (RTR) for ATLAS and T-Flex systems.

		ATLAS	T-Flex
Wind Speed & Direction	Sample Rate	2 Hz	1 Hz
	Sample Period	2 min	2 min
	Recording Interval)	10 min	10 min
	RTR	Daily and some hourly	Hourly
Air Temperature & Relative Humidity	Sample Ratel	2 Hz	1 Hz
	Sample Period	2 min	2 min
	Recording Interval	10 min	10 min
	RTR	Daily and some hourly	Hourly
Precipitation	Sample Rate	1 Hz	1 Hz
	Sample Period	1 min	1 min
	Recording Interval	1 min	1 min
	RTR	Daily	Hourly
Short-wave Radiation	Sample Ratel	1 Hz	1 Hz
	Sample Period	2 min	1 min
	Recording Interval	2 min	1 min
	RTR	Daily	Hourly
Long-wave Radiation	Sample Rate	1 Hz	1 Hz
	Sample Period	2 min	1 min
	Recording Interval	2 min	1 min
	RTR	Daily	Hourly
Barometric Pressure	Sample Rate	2 Hz	1 Hz
	Sample Period	2 min	2 min
	Recording Interval	1 hr	1 hr
	RTR	Daily and some hourly	Hourly
Water Temperature	Sample Rate	Single sample	Single sample
	Sample Period	Instantaneous	Instantaneous
	Recording Interval	10 min	10 min
	Surface RTR	Daily and some hourly	Hourly
	Subsurface RTR	Daily	Hourly
Salinity	Sample Rate	Single sample	Single sample
	Sample Period	Instantaneous	Instantaneous
	Recording Interval	10 min	10 min
	Surface RTR	Daily and some hourly	Hourly
	Subsurface RTR	Daily	Hourly
Current	Sample Rate	1 Hz	1 Hz
	Sample Period	2 min	2 min
	Recording Interval	30 min	10 min
	RTR	Daily	Hourly
Water Pressure	Sample Rate	Single sample	Single sample
	Sample Period	Instantaneous	Instantaneous
	Recording Interval	10 min	10 min
	RTR	Daily	Hourly

Data from both ATLAS and T-Flex systems are available from PMEL's display and delivery web page (http://www.pmel.noaa.gov/gtmba/data-access/disdel). Real-time data from both systems are also available on the Global Telecommunications System (GTS). A few (8–14 per day) 2-min average data from meteorological sensors and daily mean subsurface data are distributed on the GTS from the ATLAS systems. T-Flex systems transmit both meteorological and subsurface data from the top of each hour. ATLAS and T-Flex data are submitted to the GTS by Service Argos and PMEL, respectively.

ATLAS sensor calibration procedures and accuracy estimates (**Table 1**) have been reported by Freitag et al. (1999, 2001, 2005), Serra et al. (2001), A'Hearn et al. (2002), and 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 were 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). A land-based comparison of ATLAS, T-Flex, and FIO's BaiLong meteorological sensors was documented by Freitag et al. (2016). This work provides side-by-side comparisons between ATLAS and T-Flex meteorological and ocean sensors deployed within RAMA and PIRATA.

Eight ATLAS/T-Flex test mooring pairs were deployed—four in RAMA and four in PIRATA (**Figure 1** and **Table 3**). Indian Ocean (RAMA) test locations included the southeast (Test 1) and south central (Tests 5 and 6) tropical basins and Bay of Bengal (Test 3). Atlantic Ocean (PIRATA) test locations included the north-central tropical basin (Tests 2, 4, and 7) and a near-equatorial northeastern site (Test 8). The distance between moorings was 3–7 nm. Mooring deployment lengths ranged from 291 to 806 days. Of the 16 moorings, 10 were deployed for more than the nominal design life of 1 year. Due to logistical difficulties in obtaining ship time, two T-Flex moorings were deployed for more than 2 years.

Both mooring types were recovered largely intact in five of the eight tests (Tests 1–4 and 8). Internally recorded data at the highest common sample rate were analyzed from these five tests. Of the 16 moorings deployed for these tests, five went adrift and two were not recovered (both in Test 5). Substantial instrumentation and data were lost from the other three moorings (one in Test 6 and two in Test 7).

The ATLAS buoy in Test 6 went adrift and was recovered, but nearly all instrumentation and data from this mooring were lost. Of the four moorings deployed in Tests 5 and 6, only one was recovered intact. Data analysis for these two tests was mostly limited to the daily means of real-time data. Internally recorded, high-resolution rain data on both moorings in Test 6 were recovered and included in the analysis. In Test 7, telemetry from the T-Flex mooring failed within a few hours of deployment and was found to have lost its tower and all meteorological instrumentation. The ATLAS and T-Flex buoy towers being identical, the loss did not represent a uniquely T-Flex performance issue. No meteorological data were internally recorded after the failure. Internally recorded data were recovered from the mooring's subsurface instrumentation. No subsurface instruments below 10 m were recovered from the ATLAS mooring that had gone adrift, leaving the only common data between the two Test 7 mooring systems to be delayed-mode temperature and salinity at 1 m and 10 m. Test 7 was therefore omitted from the analysis due to lack of sufficient comparable data. Additional details for each test and individual sensor statistics are available for each mooring test in Appendices A–H.

Table 3: Mooring ID, location, deployment, and recovery dates of ATLAS/T-Flex mooring comparisons in RAMA (mooring IDs beginning with R) and PIRATA (mooring IDs beginning with P). If moorings went adrift, days of deployment were computed to the date of going adrift.

Test Number	System	Mooring ID	Latitude	Longitude	Deploy Date	Recover Date	Days Deployed
1	ATLAS	RA058	11° 51.8′ S	93° 20.0′ E	3/21/2011	4/25/2012	401
1	T-Flex	RT001	11° 51.8′ S	93° 13.5′ E	3/20/2011	4/26/2012	403
2	ATLAS	PI164	20° 1.0′ N	37° 51.8′ W	7/30/2011	1/18/2013	538
2	T-Flex	PT001	20° 0.4′ N	37° 47.7′ W	7/30/2011	1/19/2013	539
3	ATLAS	RA092	12° 4.5′ N	88° 49.8′ E	9/2/2012	11/29/2013	453
3	T-Flex	RT002	12° 3.5′ N	88° 43.0′ E	12/29/2012	11/29/2013	335
4	ATLAS	PI181	20° 0.6′ N	37° 51.0′ W	1/18/2013	11/17/2013	303
4	T-Flex	PT002	20° 0.5′ N	37° 47.2′ W	1/19/2013	11/18/2013	303
5	ATLAS	RA102	12° 11.4′ S	67° 14.4′ E	7/18/2013	Lost at Sea	291
5	T-Flex	RT003	12° 16.3′ S	67° 15.0′ E	7/18/2013	Lost at Sea	806
6	ATLAS	RA103	8° 4.4′ S	66° 57.0′ E	7/20/2013	11/20/2015*	484
6	T-Flex	RT004	8° 7.3′ S	66° 55.7′ E	7/21/2013	10/31/2015	737
7**	ATLAS	PI199	20° 0.8′ N	37° 51.6′ W	11/17/2013	1/3/2015	380
7**	T-Flex	PT003	20° 1.1′ N	37° 48.8′ W	11/18/2013	1/6/2015	414
8	ATLAS	PI220	4° 6.4′ N	23° 0.6′ W	1/21/2015	12/2/2015	315
8	T-Flex	PT004	4° 2.3′ N	22° 59.4′ W	1/23/2015	12/1/2015	312

* No subsurface instrumentation or data were recovered from ATLAS mooring RA103.

** Test 7 was omitted from the analysis due to lack of sufficient data for comparison.

2. Analysis Methodology and Data Preparation

One measure of the mooring system performance is the percentage of expected data returned over a common deployment period. The amount of daily mean ATLAS data telemetered in real time was compared to the amount of daily mean T-Flex data computed from hourly T-Flex data telemetered in real time. Internally recorded high temporal resolution (10-min or less) data are available in delayed-mode only. The quantity of data returned was also compared.

High-resolution data differences were analyzed at the temporal resolution stored in internal memory when ATLAS and T-Flex sample intervals were equal. In cases where the system recording intervals differed, higher resolution data were averaged or subsampled to best match the sample rate of the lower resolution data. For example, the 1-min resolution SWR and LWR data from T-Flex systems were averaged to 2-min resolution for comparison to ATLAS data. Similarly, T-Flex current data, recorded at 10-min intervals, were subsampled to 30 min for comparison to ATLAS current data.

Quantitative analysis of high-resolution data followed initial data processing. Salinity data analysis included additional standard QC as described below.

Because wind direction is highly variable at low speed and uncorrelated at the time and space scales of this comparison, wind direction differences were computed only at times when wind speed exceeded 1 m s^{-1}. To remove the ambiguity inherent in directional computations, difference time series were rotated to be within ± 180° before computing statistics such as means and standard deviations.

Upward looking ATLAS Sontek Argonaut Doppler current meters were deployed at 12 m (head depth). The center of its 3.0 m vertical measurement cell had a nominal depth of 10 m. The upward looking T-Flex Nortek Aquadopp Doppler current meter was deployed at 12.4 m (head depth). The center of its 0.6 m vertical measurement cell had a nominal depth of 12 m. Current direction differences were computed in the same manner as wind direction.

SWR data difference statistics were computed for daytime values (i.e., excluding times when one or both sensors read zero). Sensor performance analysis of high-resolution (2-min sample rate) data was based on the daytime values. Analysis of daily mean data was based on 24-hour averages.

Three measurements are made by the LWR instrument: net LWR from the sensor thermopile, temperature of the instrument case, and temperature of the glass dome. Downwelling LWR, the measurement of interest for climate research, was computed from the three measured parameters. The sensor thermopiles are routinely calibrated by the manufacturer before each deployment. Nominal thermistor calibration coefficients were used to compute temperature.

The ATLAS system measures salinity using Sea Bird Electronics, Inc., conductivity cells integrated into ATLAS temperature modules. Freitag et al. (1999) estimated moored salinity accuracy to be 0.02 psu, primarily based on analysis of Sea Bird Seacat instrumentation used on tropical moorings at that time. The T-Flex system measures salinity using Sea Bird Microcats (SBE37). A significant difference between the instruments deployed in the present tests is that the T-Flex Microcats are pumped versions, while the ATLAS temperature/conductivity modules rely on mooring motion and currents to flush the conductivity cell. Freitag et al. (1999) noted the occurrence of salinity spiking and suggested the bias could be elevated when conductivity cell flush rates were low. PMEL adopted a standard practice of filtering all ATLAS salinity time series to hourly values to reduce spiking. To identify and reduce drift due to conductivity cell fouling or scouring, standard ATLAS salinity delayed-mode quality control also includes comparison to CTD data if available, comparison between instruments at neighboring depths on the same mooring, and comparison with ATLAS data from moorings deployed before or after at the same site. Adjustments made in these processes can be subjective. To identify possible qualitative instrumental differences (spiking and sensor drift) between ATLAS and T-Flex measurements, we initially compared 10-min salinity data as recorded from both ATLAS and T-Flex systems, i.e., prior to smoothing and other subjective quality control practices. Quantitative salinity differences were computed after standard QC procedures were performed.

Water pressure is measured at 300 m and 500 m on these taut-line moorings as an indication of differences between actual and nominal sensor depths. Pressure is measured at the two deepest sensors as these are the locations of maximum excursion from nominal depths. Because the buoy is fixed at the sea surface, subsurface instrument excursions are limited to movements toward the surface from their nominal depth. Large upward spikes in water pressure are indicators of a mooring being pulled on by vandals. Differences between the intended sensor depth and measured depth can be due a number of factors. Typically, the largest difference is due to the shape a taut-line mooring assumes in response to current- and wind-induced drag. The degree to which the mooring changes shape is affected by the amount of tension in the line under no-drag conditions, which is in turn a function of the mooring scope (i.e., the ratio of the mooring length under no tension and the water depth). Mooring scope depends on the accuracy of measuring the water depth at the intended anchor site and the ability to place the anchor in that location. Thus, pressure differences between two moorings may be due to real differences in the sensor depths in addition to instrumental error. The accuracy of the ATLAS pressure sensor is estimated to be ± 1 dbar. Uncertainty in measuring and marking the mooring line for sensor attachment (order 1 m or less) can also contribute to measurement error.

Graphical analyses included scatterplots, time series of data plotted on common axes, time series of data differences (T-Flex 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:

$$\text{ATLAS} = \textit{offset} + \textit{slope} \times \text{T-Flex}$$

Differences between T-Flex and ATLAS sensors were compared to the estimated ATLAS sensor accuracies in Freitag et al. (1999, 2001, 2005), Serra et al. (2001), A'Hearn et al. (2002), and Lake et al. (2003). Most ATLAS accuracy estimates are based on RMS differences between pre-deployment and post-recovery sensor calibrations over ensembles of order hundreds of calibration pairs. Assuming normal distribution of calibration drift, about 68% of pre/post-calibration pairs should be less than or equal to the accuracy estimate. Assuming ATLAS and T-Flex sensors have comparable accuracy, mean differences between ATLAS and T-Flex systems greater than $\sqrt{2} \times$ ATLAS sensor accuracy may indicate calibration errors, a bad sensor, or systematic differences between systems. In the analysis below we refer to $\sqrt{2} \times$ ATLAS sensor accuracy as the maximum expected mean difference for a given sensor type. Given that distances between moorings (3–7 nm) may have been larger than coherence scales for high-resolution (1 min to 1 hr) measurements, RMS differences between ATLAS and T-Flex data at these sample intervals can be expected to exceed the ATLAS accuracy several fold. The standard deviation and RMS of differences of daily mean data were computed to reduce the effect of spatial coherency scales. Regression analysis and spectral comparison were also considered as system performance indicators.

Most sensor accuracy estimates do not include environmental factors, such as solar heating of air temperature/relative humidity (Payne et al., 2002) and near-surface water temperature sensors (A'Hearn et al., 2002), wind effect on rain gauges (Serra et al., 2001) and barometers (Lanzinger and Schubotz, 2012), buoy tilt on SWR measurements (Medovaya et al., 2002), and variation in sensor depth. Thus, differences observed between ATLAS and T-Flex measurements may be due to a combination of instrumental and environmental factors.

3. Data Return

In cases where one or both moorings went adrift, data return statistics were computed up until the time that the first mooring of a given pair went adrift.

3.1 Real time

Real-time data return analysis was performed on daily mean data, which is primarily what the ATLAS system transmits. Real-time hourly values transmitted by the T-Flex systems were averaged to daily values for this analysis. Data return metrics (**Table 4**, **Figures 3** and **4**) include individual surface meteorological sensors, combined surface meteorological sensors (up to 7 sensors), combined subsurface water temperature sensors (12 depths), combined subsurface salinity sensors (6 depths), combined subsurface water pressure sensors (2 depths), the current meters (1 depth), all subsurface sensors combined, and all surface and subsurface sensors combined. Real-time data losses were due to a number of causes, including sensor failures, cable and connector failures, battery depletion, and vandalism. Real-time data metrics in **Table 4** are intended for comparison of real-time data volume and may include some data which were considered suspect or bad during quality analysis procedures.

Real-time T-Flex data return averaged over all sensors for a given test exceeded that for the ATLAS by 1% to 17% on Tests 1–4 and 8, but was lower than the ATLAS by 6% to 7% for Tests 5 and 6, respectively. Averaged over all seven tests the T-Flex systems had 83% data return versus 77% for the ATLAS.

Both moorings in Test 3 had real-time data return of < 50% for all sensor types. In the ATLAS system this was due to a failed transmitter battery. Internal recording of data continued and were available after recovery of the ATLAS mooring, thus increasing delayed-mode data return (section 3.2). Water intrusion into the T-Flex ATRH sensor cable connector caused the depletion of the T-Flex battery, resulting in the loss of all real-time data thereafter. All T-Flex meteorological sensors ceased functioning at that time but subsurface sensors continued to record data internally.

All T-Flex sensor types had real-time data return levels equal to or above the ATLAS sensors, with the exception of air temperature and relative humidity sensors. The T-Flex ATRH sensor case and connectors were prone to leakage, leading to several sensor failures. Modifications to the sensor housing deployed in Test 8 were encouraging, with 100% T-Flex data return for that deployment. Subsequent stand-alone T-Flex systems deployed in RAMA and PIRATA have also had high ATRH data return rates.

Table 4: Real-time percent data return for 7 of 8 ATLAS/T-Flex mooring pair test deployments and combined percentages over the 7 tests. Test number 7 was omitted due to lack of T-Flex data. Averages computed over all sensors are weighted by the number of sensors for water temperature (12), salinity (6) and pressure (2). Three moorings for Tests 5 and 6 went adrift and were not recovered. The end dates for these two tests have been set to the day before a mooring went adrift. NA indicates that no sensor of a given type was deployed.

		Test Deployments							
	System	**1**	**2**	**3**	**4**	**5**	**6**	**8**	**Combined**
Nominal Locations		12°S 93°E	20°N 38°W	12°N 89°E	20°N 38°W	12°S 67°E	8°S 67°E	4°N 38°W	
Mooring ID	ATLAS	RA058	PI164	RA092	PI181	RA102	RA103	PI220	—
	T-Flex	RT001	PT001	RT002	PT002	RT003	RT004	PT004	—
AT	ATLAS	100%	100%	38%	100%	100%	100%	100%	92%
	T-Flex	83%	100%	46%	80%	34%	8%	100%	65%
RH	ATLAS	100%	100%	38%	100%	100%	100%	100%	92%
	T-Flex	40%	100%	46%	80%	34%	8%	100%	58%
Wind	ATLAS	36%	100%	38%	100%	100%	67%	100%	77%
	T-Flex	68%	100%	47%	99%	100%	90%	100%	87%
BP	ATLAS	NA	100%	NA	100%	NA	NA	NA	100%
	T-Flex	NA	100%	NA	99%	NA	NA	NA	100%
SWR	ATLAS	100%	9%	38%	100%	100%	100%	100%	74%
	T-Flex	94%	100%	46%	97%	99%	98%	98%	91%
LWR	ATLAS	NA	9%	NA	100%	NA	NA	NA	42%
	T-Flex	NA	100%	NA	99%	NA	NA	NA	100%
Rain	ATLAS	91%	35%	0%	100%	91%	73%	98%	67%
	T-Flex	60%	100%	47%	99%	57%	100%	100%	82%
All Surface Met	ATLAS	85%	65%	30%	100%	98%	88%	100%	79%
	T-Flex	69%	100%	46%	94%	65%	61%	100%	77%
Water Temp	ATLAS	84%	79%	38%	100%	100%	84%	89%	81%
	T-Flex	96%	89%	47%	97%	90%	86%	100%	87%
Salinity	ATLAS	82%	58%	38%	83%	83%	85%	75%	72%
	T-Flex	96%	77%	47%	97%	82%	95%	100%	85%
Pressure	ATLAS	100%	100%	38%	54%	100%	83%	70%	80%
	T-Flex	97%	100%	47%	98%	98%	36%	100%	81%
Current	ATLAS	82%	69%	NA	100%	0%	0%	71%	53%
	T-Flex	67%	80%	47%	39%	99%	0%	100%	59%
All Subsurface	ATLAS	85%	74%	38%	91%	90%	80%	82%	77%
	T-Flex	95%	86%	47%	95%	89%	80%	95%	84%
All	ATLAS	85%	72%	36%	93%	92%	82%	86%	77%
	T-Flex	90%	89%	47%	94%	85%	76%	96%	83%
Concurrent Record Length (in days)		400	537	335	301	290	482	312	2657

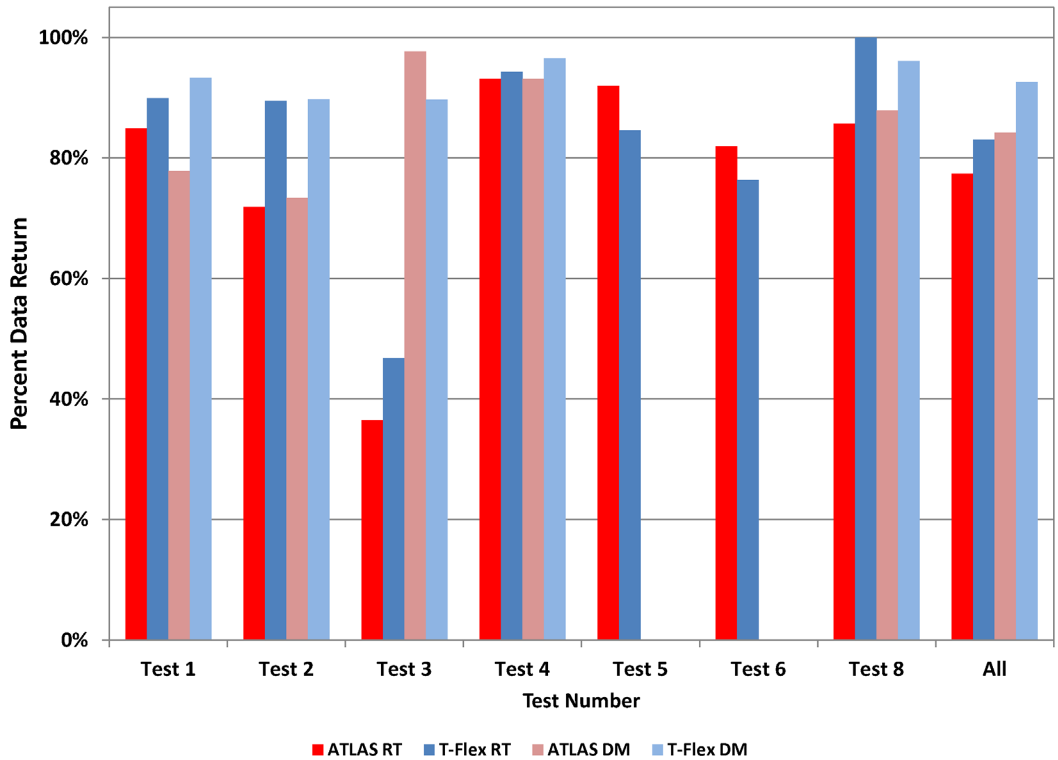

Figure 3. Real time (RT) and delayed mode (DM) data return averaged over all sensors for each of seven tests and for all tests combined.

T-Flex real-time wind data return was 10 % higher than that for ATLAS (87% vs. 77%), with loss of wind data for both systems primarily due to vandalism or mooring system failures rather than to issues specific to the anemometers.

T-Flex SWR, LWR. and RAIN real-time data return was larger than that for ATLAS: 91% vs. 74%, 100% vs. 42%, and 82% vs. 67%, respectively. Both mooring systems use identical sensors for these measurements, so we believe that these results may not predict better long-term performance by the T-Flex system. This is particularly the case for LWR, for which only two tests were performed and the ATLAS sensor on one was stolen by vandals.

T-Flex real-time water temperature data return was 6% higher than that for ATLAS (87% vs. 81%). Factors that contributed to lower ATLAS temperature data return included battery failure (the ATLAS transmitter in Test 3 and individual subsurface modules on other tests), lost sensors, and intermittent inductive modem (IM) telemetry. The largest T-Flex real-time water temperature data loss was due to a leak in the ATRH sensor that caused the entire system to shut down in Test 3 (i.e., not related to the T-Flex water temperature instruments, which continued to record data internally).

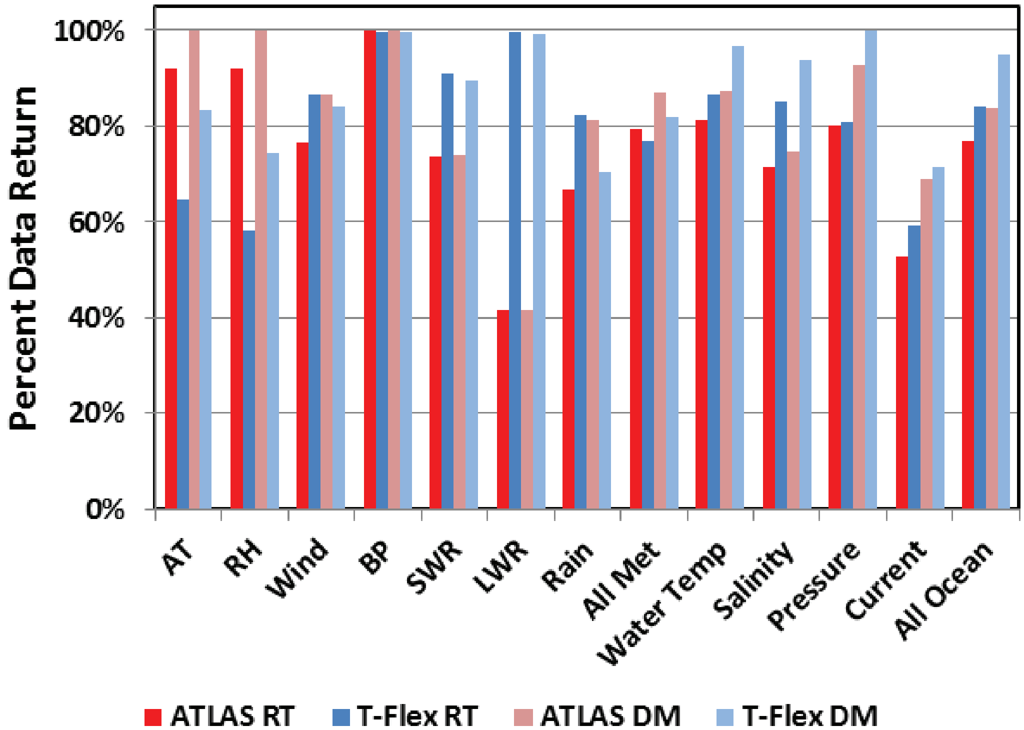

Figure 4. Real time (RT) and delayed mode (DM) data return averaged by sensor type for all tests combined.

T-Flex real-time salinity data return was higher than that for ATLAS for all but one individual test and was 13% higher when averaged over all tests (85% vs. 72%). The factors that lowered ATLAS temperature data mentioned above also lowered ATLAS salinity data. In addition, in five cases ATLAS salinity sensors malfunctioned, producing data out of expected range for the entire record or having a rapid and large shift to unrealistic values after deployment.

Average real-time water pressure data return was comparable between systems (ATLAS 80%, T-Flex 81%), but five of seven T-Flex deployments returned 97% to 100% of real-time pressure data. As mentioned above, Test 3 real-time data return was low (46–47%) for all instruments, thus the loss of pressure data there was not related to a failure of the pressure instruments themselves. Loss of real-time 500 m temperature and pressure data in Test 6 was presumably related to a knot in the mooring wire found when recovered. We suspect that T-Flex water pressure data return may be close to that for T-Flex temperature over a large number of deployments, since temperature and pressure are measured by the same instrument.

Historically, ATLAS Sontek current meters have consistently had low data return levels. The size and shape of the current meter and associated stabilization fin make the instrument susceptible to being fouled by fishing line and nets. A cable between the current meter and ATLAS temperature module, which provides real-time IM data telemetry to the surface, is also susceptible to damage by fishing gear.The T-Flex Nortek Aquadopp current meter is smaller than the ATLAS Sontek, has an IM integrated into its case, and is designed to shed fishing gear from below. The six ATLAS current meters deployed in the tests had 53% real-time data return. Real-time data return from seven deployed T-Flex current meters was somewhat higher than the ATLAS current meters (59%), but substantially lower data return than most other T-Flex sensors. The major causes of T-Flex real-time current data loss were improper instrument set up (Test 6), inductive modem failure (Test 4), Aquadopp battery depleton (Test 1), T-Flex system battery depletion (Test 3), and vandalism (Test 2).

Despite the relatively low data return in these tests, we expect that the T-Flex system will provide more current meter data than has ATLAS. Failures of the T-Flex inductive modem are rare, occurring only once in dozens of deployments (during and after these test deployments). T-Flex system failure due to leakage within the ATRH sensor has been eliminated by a new ATRH sensor case design. Aquadopp battery depletion has happened on other Nortek current meters. We suspect that the depletion is due to a problem with a harness which connects the two instrument batteries. PMEL is considering modifications to the Aquadopp harness to address this problem. Additional T-Flex mooring implementation within RAMA and PIRATA subsequent to the eight test deployments has confirmed that real-time current meter data telemetry rates have been higher than historical Sontek rates.

The analysis above suggests that overall real-time data return performance for T-Flex systems is at least as good as ATLAS systems and may be better for some sensor types. A large portion of data loss can be attributed to vandalism, which is presumably random, and thus may mask system performance differences over a relatively small number of tests such as here. Having the T-Flex antenna on the toroid rather than the tower, as is the case for ATLAS, could potentially decrease real-time data loss due to vandals damaging the antenna and stopping data telemetry. We do not expect data return to be significantly different for SWR, LWR, and RAIN since both systems use the same sensors. A 7% larger T-Flex data return over all subsurface sensors (84% vs 77% for ATLAS subsurface sensors) may result from the T-Flex sensors having more robust attachment mechanisms.

Table 5: Delayed-mode percent data return for 5 ATLAS/T-Flex mooring pair test deployments and combined percentages over the 5 tests. Three tests were omitted due to lack of delayed mode data from one or both systems. Averages computed over all sensors are weighted by the number of sensors for water temperature (12), salinity (6) and pressure (2). NA indicates that no sensor of a given type was deployed.

		Test Deployments					
	System	**1**	**2**	**3**	**4**	**8**	**Combined**
Nominal locations		12°S 93°E	20°N 38°W	12°N 89°E	20°N 38°W	4°N 23°W	
Mooring ID	ATLAS	RA058	PI164	RA092	PI181	PI220	—
	T-Flex	RT001	PT001	RT002	PT002	PT004	—
AT	ATLAS	100%	100%	100%	100%	100%	100%
	T-Flex	82%	100%	46%	81%	100%	83%
RH	ATLAS	100%	100%	100%	100%	100%	100%
	T-Flex	40%	100%	45%	81%	100%	74%
Wind	ATLAS	36%	100%	100%	100%	100%	86%
	T-Flex	70%	100%	47%	99%	100%	84%
BP	ATLAS	NA	100%	NA	100%	NA	100%
	T-Flex	NA	100%	NA	99%	NA	100%
SWR	ATLAS	100%	9%	100%	100%	100%	74%
	T-Flex	98%	99%	47%	99%	99%	89%
LWR	ATLAS	NA	9%	NA	100%	NA	42%
	T-Flex	NA	99%	NA	99%	NA	99%
Rain	ATLAS	100%	37%	95%	100%	100%	81%
	T-Flex	65%	99%	47%	21%	100%	70%
All Surface Met	ATLAS	87%	65%	99%	100%	100%	87%
	T-Flex	71%	100%	46%	83%	100%	81%
Water Temp	ATLAS	83%	75%	98%	100%	92%	87%
	T-Flex	100%	89%	100%	100%	100%	97%
Salinity	ATLAS	66%	67%	95%	83%	68%	75%
	T-Flex	100%	79%	100%	100%	100%	94%
Pressure	ATLAS	100%	100%	100%	54%	100%	93%
	T-Flex	100%	100%	100%	100%	100%	100%
Current	ATLAS	0%	100%	NA	100%	74%	69%
	T-Flex	71%	80%	100%	100%	0%	72%
All Subsurface	ATLAS	76%	76%	97%	91%	85%	84%
	T-Flex	99%	86%	100%	100%	95%	95%
All	ATLAS	78%	73%	98%	93%	88%	84%
	T-Flex	93%	90%	90%	96%	96%	92%
Concurrent Record Length (in days)		400	537	335	301	312	1885

3.2 Delayed mode

Data missing in real time was retrievable from instrument memory after recovery in some cases, raising delayed-mode data rates. Delayed-mode data return (**Table 5**) was higher than real-time data return for both ATLAS (+7%) and T-Flex (+9%) systems when averaged over all tests and all sensors (**Figure 3**). T-Flex sensors with lowest real-time data return (AT 65%, RH 58% and CM 59%) had substantially higher delayed-mode data return (+83%, +74% and +72%, respectively). As was the case for real-time data, ensemble T-Flex delayed-mode data return was greater than ATLAS delayed-mode data (92% and 84%, respectively).

When individual sensor types are considered (**Figure 4**), ensemble delayed-mode T-Flex data return was higher than that for ATLAS for shortwave radiation (89% vs 74%), longwave radiation (99% vs. 42%), water temperature (97% vs. 87%), salinity (94% vs. 75%), pressure (100% vs. 93%), and currents (72% vs. 69%). Barometric pressure data return was 100% for both systems. T-Flex data return was lower than for ATLAS for wind (84% vs. 86%), air temperature (83% vs. 100%), relative humidity (74% vs. 100%), and precipitation (70% vs. 81%). Lower T-Flex wind data return was due to initial sensor firmware problems which were corrected after Test 2. Lower T-Flex ATRH data return was due to hardware problems that were corrected in Test 8. Lower T-Flex rain data return was not due to an inherent problem with the system, since both employ identical rain sensors. While T-Flex delayed-mode rain data return was lower than ATLAS data return in 3 of 5 tests, the causes of T-Flex data loss in two of these were vandalism and system battery drain (due to leakage of the ATRH sensor), neither of which is related to the rain sensor itself. In the third instance the T-Flex rain gauge was noisy, which is an issue with rain sensors, but as both systems use the same sensor, this problem is equally likely to occur with either system.

A small amount of T-Flex data loss was due to the system intentionally turning continuously running sensors (SWR, LWR, and RAIN) off while making Iridium phone calls to remove the possibility of data spikes due to interference. Iridium calls were scheduled at six-hour intervals and typically lasted about 1 min. If calls did not complete they were repeated. Improvements to later versions of the T-Flex firmware lowered the number of SWR, LWR, and RAIN data losses of this kind, by reducing the amount of time sensors were turned off.

As was the case for real-time data, the analysis above suggests that overall delayed-mode data return performance for T-Flex systems is at least as good as ATLAS systems and may be better for some sensor types.

4. Data Analysis

In this section we present statistical analyses of ATLAS and T-Flex mooring data by sensor type. Key metrics—mean, standard deviation, and RMS differences; and cross correlation—are computed based on daily-averaged time series data. Rain analysis is limited to mean rain rate difference, rain accumulation, and percent time raining given the sporadic and non-uniform distribution of rainfall. Additional details for each test and individual sensor statistics based on high-resolution (typically 10 min) data are available for each mooring test in Appendices A through H.

4.1 Air temperature and relative humidity

The initial T-Flex air temperature and relative humidity sensors were prone to leakage, which caused sensors to fail or produce low-quality data. A redesigned sensor housing, first deployed in Test 8, eliminated this problem. When T-Flex ATRH sensors were functioning, mean AT and RH differences between ATLAS and T-Flex time series were less than the expected maximum difference (0.28 °C, 3.8 %RH). The largest absolute mean difference over seven tests (**Figure 5**) for AT was –0.11 °C (Test 4) and for RH was 1.16 %RH (Test 3). Mean differences for Test 8 in which the new housing was used were smaller, 0.06 °C and 0.20 %RH, respectively. The standard deviation and RMS of daily mean AT and RH differences were all less than the expected maximum difference, with the exception of AT in Test 1, for which the T-Flex sensor values drifted during the latter part of the deployment. Daily mean AT and RH were well correlated. AT correlation coefficients (R^2) were between 0.96 and 1.00, with the exception of Test 1 for which it was 0.80. R^2 for RH was 0.96 for Test 1, and 0.99 for all others.

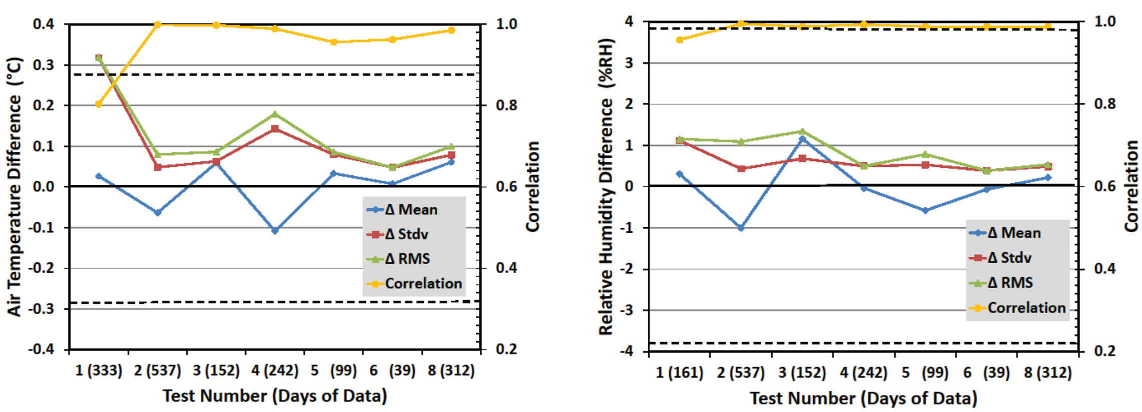

Figure 5. Mean (blue), standard deviation (red), and RMS (green) difference and correlation coefficients (R^2, yellow) between T-Flex and ATLAS daily mean air temperature (left) and relative humidity (right). Dashed lines indicate expected maximum difference under the assumption that ATLAS and T-Flex sensor accuracies are comparable. The numbers of daily mean values per test are in parenthesis on the x axis.

T-Flex air temperature spectra were consistently higher than that for ATLAS at frequencies above 1.0 cph for the five tests for which 10-min data were available. Differences between relative humidity spectra were less consistent. Relative humidity spectra differences were within the 95% confidence level for Tests 1 and 3; the ATLAS spectra exceeded the T-Flex at high frequency (>1 cph) in Test 2; and the T-Flex spectra exceeded the ATLAS above 0.8 cph in Tests 4 and 8. The inconsistency may be related to sensor leakage issues, and possibly due to a relatively longer response time for the ATLAS sensor. Note also the difference in measurement resolution (0.02 %RH for ATLAS, 0.1 %RH for T-Flex). Given the problems with sensor failure due to leakage for most tests, the spectra of the eighth test should be considered the best example of sensor performance, in which T-Flex air temperature spectra was higher than the ATLAS spectra, but differences were within or comparable to the 95% confidence level (**Figure 6**). The T-Flex relative humidity spectra exceeded the ATLAS spectra above 0.1 cph in Test 8 by more than the 95% confidence level. While the slopes of the spectra decreased near the Nyquist frequency, it should be noted that relative humidity spectra from both systems continually fall as frequency increases, rather than being flat as would be the case for white noise. This indicates that the accuracies of the 10-min data are above the sensors' noise threshold (although the spectral falloff rate is diminished at the Nyquist, indicating the noise threshold may be near).

4.2 Wind speed and direction

Wind speeds were typically moderate at all locations, with deployment means between 5 m s^{-1} and 7 m s^{-1}. High-resolution (10-min) wind speeds were rarely above 10 m s^{-1}.

T-Flex wind speed and direction firmware used in Tests 1 and 2 passed some data erroneously between the sensor and T-Flex controller that resulted in biased wind direction and possibly affected wind speed accuracy to a small degree. Corrected firmware was used beginning with Test 3.

The two sensors have different wind speed thresholds (ATLAS RM Young, 1.0 ms^{-1}; T-Flex Gill, 0.01 ms^{-1}) and resolution (ATLAS 0.2 ms^{-1}; T-Flex 0.1 ms^{-1}). The 10-min ATLAS time series typically had some wind speed values of zero while the T-Flex time series had none, suggesting that the ATLAS wind propeller may have occasionally stalled in very light wind conditions.

Mean, standard deviation, and RMS differences of daily-averaged wind speed were all less than the expected maximum difference (0.42 m s^{-1}) (**Figure 7**). Daily mean wind speed correlation coefficients (R^2) were 0.99 or 1.00. Linear regression analysis indicated that at speeds of 10 m s^{-1}, which were rare, T-Flex wind speed would exceed ATLAS wind speed by more than 3% (the ATLAS accuracy expressed as a percentage) in 3 of 7 tests, but never by more than 3.7%, and thus being less than the maximum expected difference of 4.2%. For the five tests using

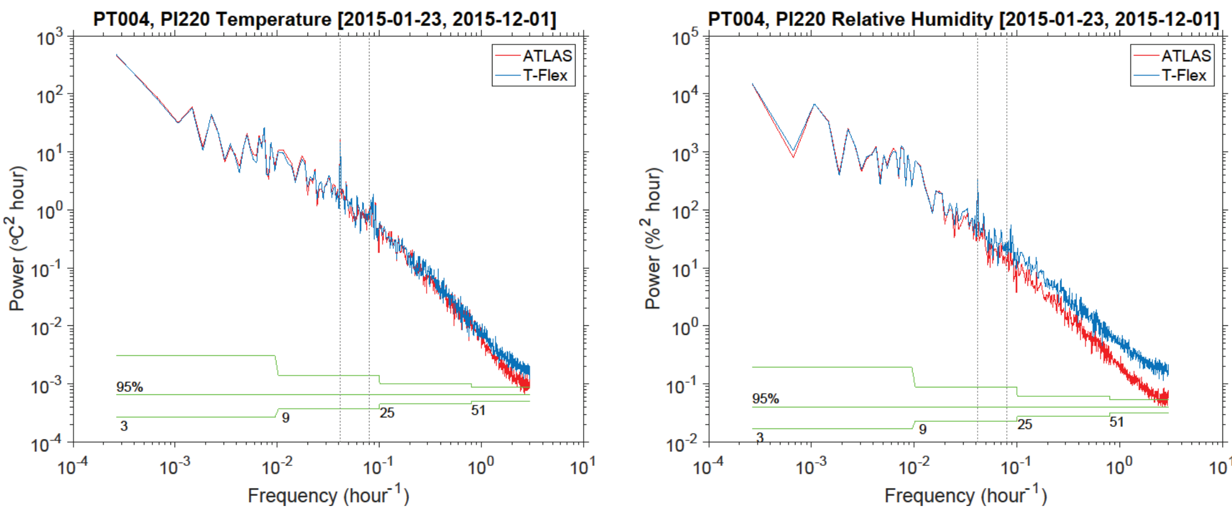

Figure 6. Left: Test 8 air temperature spectra from T-Flex PT004 (blue) and ATLAS PI220 (red) sensors. Right: Test 8 relative humidity spectra from T-Flex PT004 (blue) and ATLAS PI220 (red) sensors. Green lines indicate 95% confidence limits, with numbers below giving the number of raw periodogram points averaged for a given frequency band.

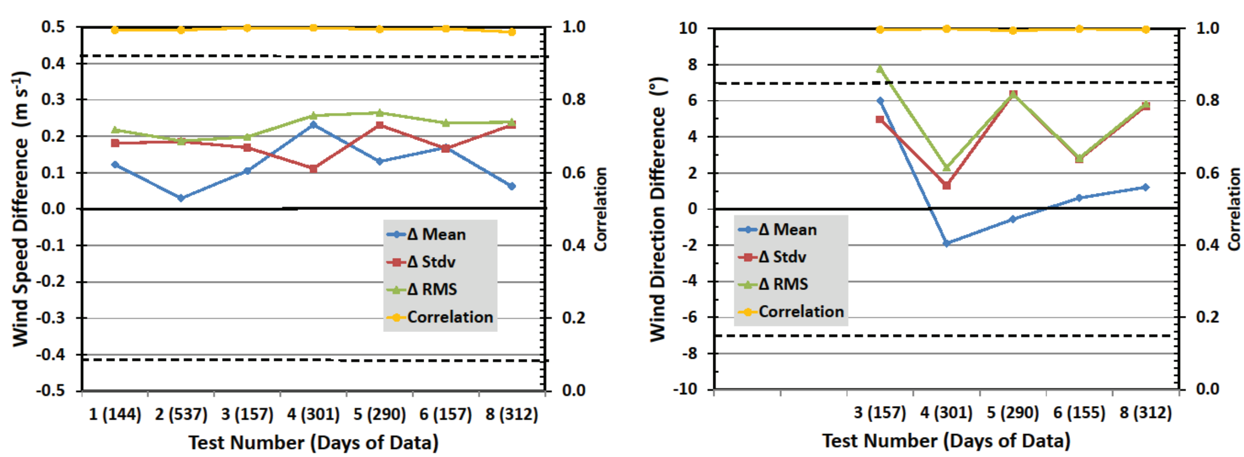

Figure 7. Mean (blue), standard deviation (red), and RMS (green) difference and correlation coefficients (R2, yellow) between T-Flex and ATLAS daily mean wind speed (left) and wind direction (right). Dashed lines indicate expected maximum difference under the assumption that ATLAS and T-Flex sensor accuracies are comparable. The numbers of daily mean values per test are in parenthesis on the x axis.

the corrected wind direction firmware, mean wind direction differences were all less than the expected maximum difference (7°) (**Figure 7**). RMS differences of daily mean wind direction exceeded 7° in Test 3, with the RMS difference being 7.7°. Given that winds were typically light to moderate, wind direction variance of this magnitude is to be expected over the distance between moorings. Daily mean wind direction correlation coefficients (R^2) were 0.99 or 1.00.

4.3 Barometric pressure

Barometers were deployed on only two tests (2 and 4). All ATLAS and T-Flex systems returned 99–100% of expected data in real time and delayed mode. The mean difference in Test 2 (0.12 hPa) was less than the maximum expected difference (0.14 hPa). In Test 4 the mean difference (+0.27 hPa) exceeded the specified accuracy. Pre-deployment and post-recovery calibration checks at PMEL of both Test 4 sensors indicated calibration errors were responsible for half the observed difference, with the ATLAS sensor low by –0.105 hPa and the T-Flex high by +0.038 hPa. Adjustment for the cumulative calibration errors would reduce the observed difference to +0.13 hPa (less than the maximum expected difference). Both systems use identical barometers that report text data in engineering units; therefore, data differences were not due to ATLAS or T-Flex hardware or firmware. Given the small sample size (two tests) and differences of opposite sign and magnitudes near the maximum expected difference, we conclude that there was no systematic bias between ATLAS and T-Flex barometric pressure sensors.

4.4 Short-wave radiation

Both systems use identical short wave radiometers and A/D circuitry, which have an estimated accuracy of ±2.8%. Daily mean day time SWR percentage differences for all seven tests were within the maximum expected difference of 3.9% (**Figure 8**). The largest difference was –3.7%. Three mean differences were greater than zero and four less than zero. Mean test differences of both signs, with magnitudes within the maximum expected difference, indicated no inherent systematic bias between the ATLAS and T-Flex systems. Daily mean SWR time series were well correlated, with coefficients (R^2) between 0.88 and 0.97. Data comparison for Test 2 was limited due to loss of the ATLAS sensor to vandals.

4.5 Long-wave radiation

Long-wave radiometers were deployed on only two tests (2 and 4). The amount of data available for comparison in Test 2 was limited due to removal of the ATLAS sensor by vandals. Mean downwelling radiation differences for both tests were small, 0.4% and 0.2% of the mean ATLAS value, respectively, and well within the maximum expected difference of 1.4%. Daily mean LWR time series were well correlated, with coefficients (R^2) of 0.88 and 1.00, respectively.

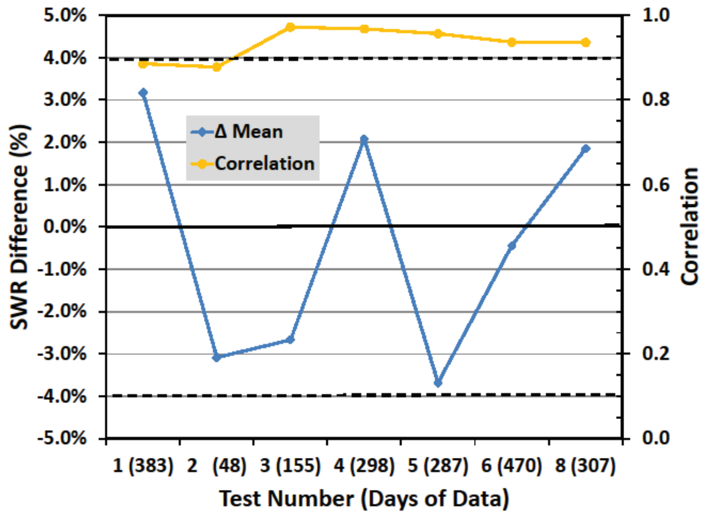

Figure 8. Mean (blue) and correlation coefficients (R^2, yellow) between T-Flex and ATLAS daily mean short-wave radiation time series. Dashed lines indicate expected accuracy of the ATLAS sensors. The numbers of daily mean values per test are in parenthesis on the x axis.

4.6 Precipitation

ATLAS and T-Flex systems use identical sensors and A/D circuitry internal to the sensor package to measure precipitation. Thus, the ATLAS and T-Flex CPUs function simply as data loggers and have no impact on rain data values themselves. Rain rate is computed from time differences in water volume captured by the instrument. These rain gauges are prone to being noisy and their data typically require manual adjustments when delayed-mode quality control is applied. Serra et al. (2001) estimated the ATLAS rain gauge accuracy for 10-min data to be ±0.4 mm hr^{-1} when raining and ±0.1mm hr^{-1} when not raining. ATLAS (and T-Flex since they are the same) rain gauges have been found to underestimate rain accumulation in low rain rate conditions (Yuter et al., 2004).

Given the episodic nature of rainfall, these time series contain substantial numbers of zero or near-zero values. Time series means computed over the entire time series are biased low by the predominately zero values. Therefore, we have analyzed the 10-min rain rate time series only during times of measurable rain, using 0.4 mm hr^{-1} as a threshold for rainfall detection. The amount of rainfall measured during Tests 2, 3, and 4 was relatively small due to sensor failures and relatively dry environmental conditions. Therefore, we have focused the rain data analysis on Tests 1, 6, and 8.

Quantitative comparison of concurrent data was complicated by rainfall events having small horizontal length scales compared to the 3–7 nm separations between moorings. Rainfall was often measured at one site but not both, and rain rates differed significantly even when raining at both mooring locations. Correlation coefficients (R^2) of 10-min data were small, ranging from 0.00 to 0.23. For example, comparing the data in Test 6 on 15–16 January 2014 (**Figure 9**), a rain event on 15 January occurred earlier and more intensely at the ATLAS site than at the T-Flex site, which was 3.2 nm away. A shorter event on 16 January was much more intense at the T-Flex site than that at the ATLAS site. The rain time series were better correlated over longer time periods, with R^2 for daily means ranging from 0.70 to 0.82. Given the non-uniformity of rainfall, we have made qualitative ensemble comparisons (such as distributions of rain rate and rain duration). Quantitative analyses are limited to ensemble percent time raining (PTR), mean rain rate, and total accumulation. Other quantitative analysis at coincident times (e.g., the standard deviation and RMS of differences) as discussed for other observation types has not been included for rainfall.

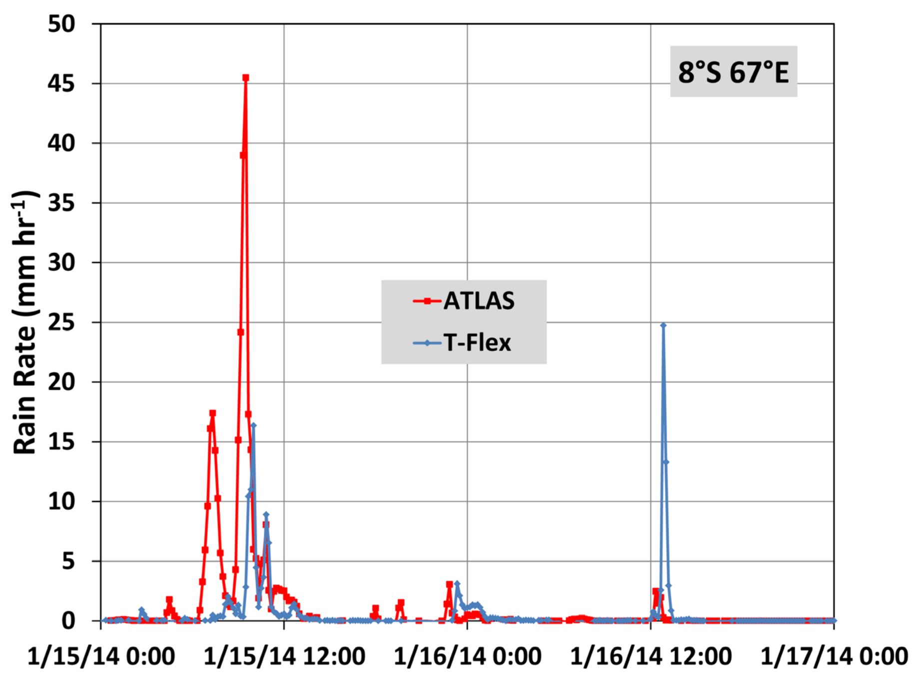

Figure 9. Test 6 10-min rain rate from ATLAS (red) and T-Flex (blue) gauges on 15–16 January 2014. The moorings were separated by 3.2 nm.

PTR for Tests 1, 6, and 8 ranged from 3.2% to 4.2%. PTR differences between ATLAS and T-Flex systems ranged from 0.2% to 0.6%. Rain rate distribution at all three test sites were similar in that most measurable rain observations were at rates of a few mm hr^{-1} and most events lasted a half hour or less. A large majority (66% to 76%) of rain rate observations had values of 5 mm hr^{-1} or less and differences between ATLAS and T-Flex percentage values were at most 3% (**Figure 10**). Rain rates >15 mm hr^{-1} comprised no more than 13% of the measurable rainfall and differences between ATLAS and T-Flex percentage values were <1%. Most rain events (defined as consecutive rain rate observations above 0.4 mm hr^{-1}) were of short duration. Single point events comprised from 29% to 39% of all events, and events of 30 min or less (1, 2, or 3 sequential points > 0.4 mm hr^{-1}) accounted for 64% to 82% of all rain events (**Figure 11**). Test 8 had the highest percentage of events longer than 2 hours comprising 8% of the ATLAS events and 6% of the T-Flex events.

Mean rain rate differences between ATLAS and T-Flex systems were less than the maximum expected difference (0.56 mm hr^{-1}) in Tests 6 and 8, but larger than expected (0.9 mm hr^{-1}) in Test 1 (**Figure 12**). The T-Flex time series in Test 1 surpassed the ATLAS in the number of values above 55 mm hr^{-1} (15 vs. 2, respectively) and maximum value (112.2 mm hr^{-1} vs. 69.8 mm hr^{-1}, respectively). When computed over values below 55 mm hr^{-1}, the mean rain rate difference between systems was less than the ATLAS expected accuracy (ATLAS mean of 4.7 mm hr^{-1}, T-Flex mean of 4.8 mm hr^{-1}). Thus, the mean difference over all events was primarily due to a few intense events at the ATLAS site not observed at the T-Flex site.

T-Flex ensemble rain accumulation differed from the ATLAS accumulation by 3.3%, –14.5%, and –5.8% for Tests 1, 6, and 8, respectively (**Figure 13**). The larger accumulation difference for Test 6 (325 mm), despite having a small overall mean rain rate difference (0.01 mm hr^{-1}), was due in part to the relatively long record length (445 days) coupled with differences in sensor sensitivity. The number of ATLAS gauge rain rate measurements above the 0.4 mm hr^{-1} threshold was greater than the T-Flex gauge by 38%. The majority (77%) of the additional ATLAS measurements were in the range of 0.4 mm hr^{-1} to 5 mm hr^{-1}. The accumulation difference in this range was 110 mm, a third the total accumulation difference. The last month of the ATLAS gauge data was omitted from this analysis due to it being extremely noisy with large numbers of negative values. There were additional short periods of noise included in the analysis earlier in the ATLAS record that may have contributed to its accumulation at low rain rates being larger than for the T-Flex. The episodic nature of large rain events also contributed to the accumulation difference. The ATLAS gauge measured rates > 50 mm hr^{-1} more often (24 values vs. 9 by the T-Flex gauge), which added 145 mm to the accumulation difference.

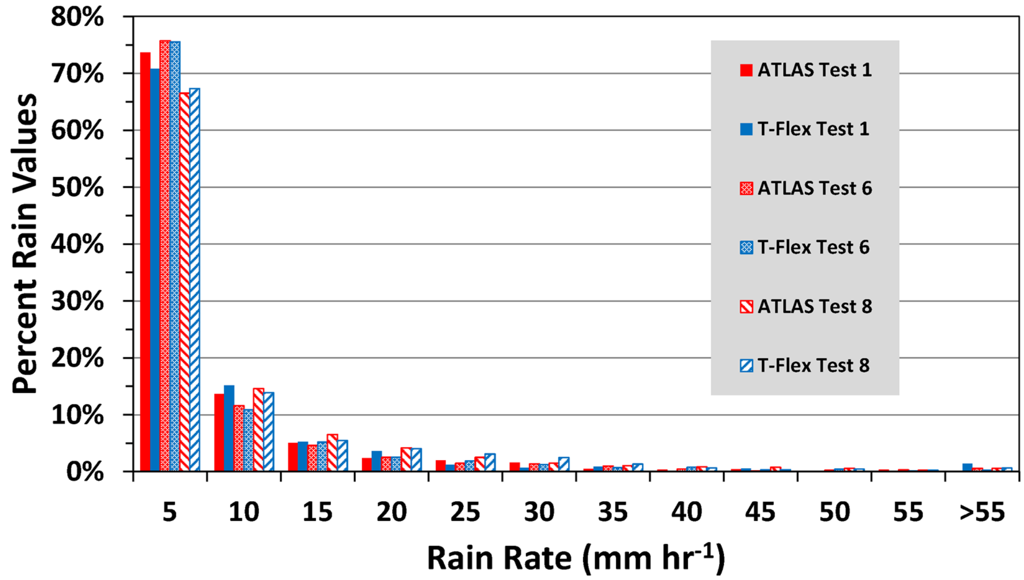

Figure 10. Percentage distribution of rain rate observations by intensity (mm hr^{-1}). Percentages are relative to the total number of rain rate observations above 0.4 mm hr^{-1}. ATLAS data are in red and T-Flex data in blue.

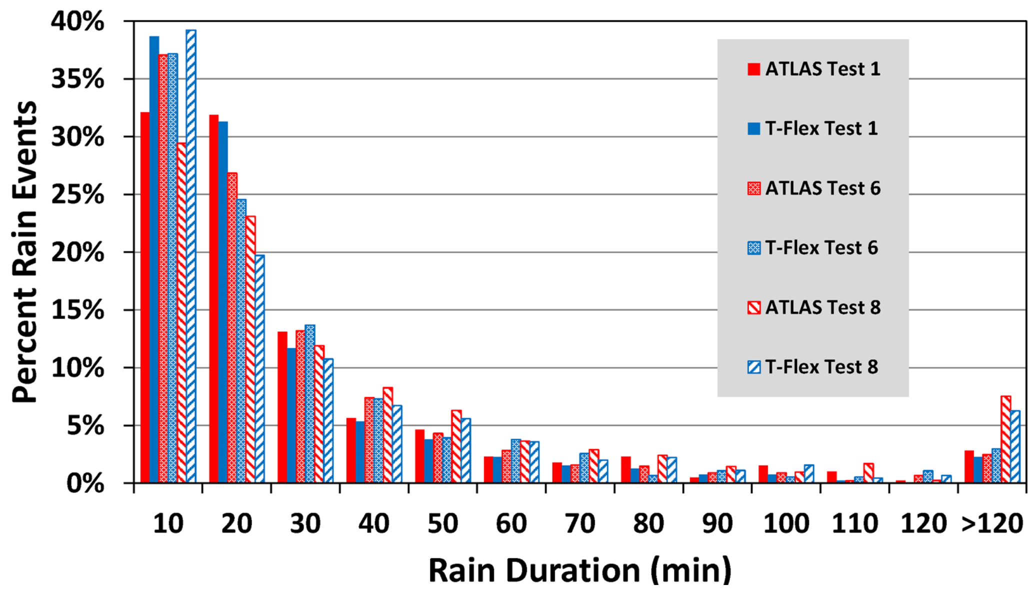

Figure 11. Percentage distribution of rain events by duration (min). Percentages are relative to the total number of rain events composed of continuous rain rates above 0.4 mm hr^{-1}. ATLAS data are in red and T-Flex data in blue.

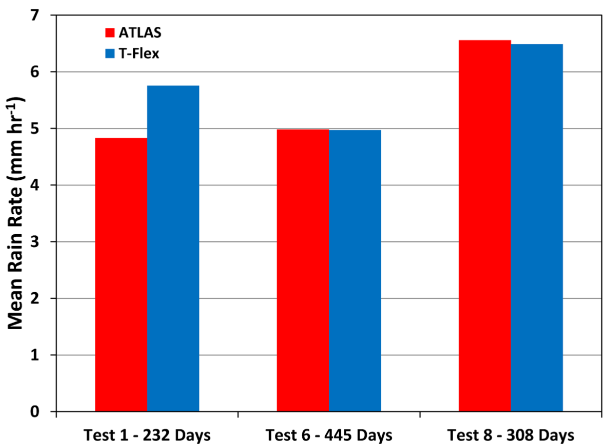

Figure 12. ATLAS (red) and T-Flex (blue) mean rain rates for Tests 1, 6, and 8.

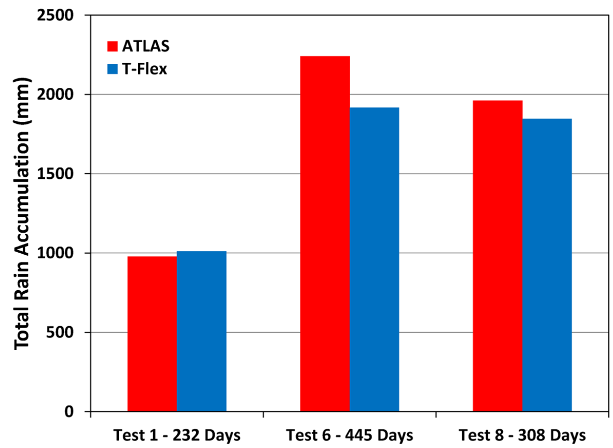

Figure 13. ATLAS (red) and T-Flex (blue) total rain accumulation for Tests 1, 6, and 8.

Rain rate time series from these gauges contain a considerable number of small negative values caused by instrumental noise and evaporation of water in the gauges during long periods without rain. Users of GTMBA rain data often ask whether negative values can be ignored (or set to zero) when analyzing the data. The analysis of these data offers an opportunity to investigate how to deal with negative rain rate values. Standard delayed mode processing at PMEL manually removes water volume data which result in rain rate values less than –3 mm hr^{-1}. This may seem a rather coarse criterion compared to the accuracy estimates of Serra et al. (2001). The accuracy should be considered an RMS estimate rather than absolute maximum error. Given that the manufacturer's error estimate for water height in the gauge is 1 mm, a 2 mm difference (if one gauge were high and the other low) over a 10-min interval would produce a rain rate difference of 12 mm hr^{-1}. Negative rain rate values less than –3 mm hr^{-1} are (in most time series) relatively rare and are manually eliminated during the delayed-mode processing. Simply removing all negative rain rate values (i.e., including those between –3 mm hr^{-1} and zero) would potentially bias estimates of mean rain rate and total accumulation high, as positive values of noise would remain in the time series (assuming that the noise has a mean of zero). Conversely, using all data values (positive and negative) would potentially bias estimates low, as periods of evaporation would be included.

Rain accumulations computed using all data compared to data with rain rates >0.4 mm hr^{-1} were smaller by 2.5% to 7.6% (**Table 6**). Assuming that noise in the data range ±0.4 mm hr^{-1} had zero mean, the decrease in accumulation was due to evaporation. Expressed as evaporation rates, values ranged from –0.14 mm day^{-1} to –0.26 day^{-1}, which are comparable to the evaporation estimate of Serra et al. (2001) of up to 0.2 mm day^{-1}. Averaged over all six time series, the loss of accumulation due to evaporation and noise amounted to about 5% or the total accumulation, with 4% due to evaporation and 1% due to noise in the –0.4 mm hr^{-1} to –3 mm hr^{-1} range. Assuming that noise in rain rate over the range 0.4 mm hr^{-1} to 3 mm hr^{-1} is comparable to that in the range –0.4 mm hr^{-1} to –3 mm hr^{-1}, it can be estimated that accumulation (and mean rain rate since they scale) computed from rates >0.4 mm hr^{-1} as done in this investigation may be biased high by 1%.

4.7 Water temperature

The depth of subsurface sensors may differ from nominal depths due to being raised when a mooring responds to wind and/or current drag. Although not directly measured, vertical excursions near the surface are expected to be ≤1 m (comparable to the accuracy of the pressure gauges deployed at 300 and 500 m. Drag-induced excursions measured at 300 m (500 m) are typically ≤10 m (≤ 20 m). Thus, observed temperature difference between moorings can be in part due to the sensors being at different depths. Temperature differences caused by sensor depth differences are larger where vertical gradients are larger, most notably in the thermocline (**Figure 14**). Hence, we have focused the temperature difference analysis to sensors within the surface mixed layer (ML[1], which we define here as 40 m and above), in order to lessen the impact of sensor depth difference.

In Test 3, many of the ATLAS sensors were found to have calibration drifts of order 0.04°C, exceeding the expected sensor accuracy of ±0.02°C. Temperature adjustments were made by applying a linear combination of pre-deployment and post-recovery calibrations to these time series. Such adjustments are rarely necessary. We suspect that the pre-deployment calibrations for the sensors had small (but larger than normal) errors. Many of the sensors were newly built so the pre-deployment calibrations were their first.

1 The upper 4 sensors (1 m, 10 m, 20 m, and 40 m) were generally, but not always, in the ML. Of 28 sensor pairs deployed at these depths, 25 pairs were included in the analysis. No data were available for comparison at 40 m in Test 2. The T-Flex SST sensor in Test 6 had failed electronics. The ML was above 40 m for half of the deployment in Test 5, so these data were not included in the analysis. The ML was above 40 m for the first 3 of the 10 month-long Test 8, but the 40 m data were included in the analysis.

Table 6. Rain accumulation (mm) computed from (1) all rain rate data, (2) rain rate > 0.4 mm hr^{-1}, (3) rain rate in the range ± 0.4 mm hr^{-1}, and (4) rain rate < –0.4 mm hr^{-1}. Evaporation rate (mm day^{-1}) was computed from the accumulation in (3) and the equivalent number of data days in that rain rate band.

	System	Test 1: 232 days	Test 6: 445 days	Test 8: 308 days
(1) All Data	ATLAS	914	2122	1913
	T-Flex	945	1794	1750
(2) Rain Rate >0.4	ATLAS	979	2242	1961
	T-Flex	1001	1917	1847
(3) Rain Rate ± 0.4	ATLAS	–51	–96	–41
	T-Flex	–43	–78	–77
(4) Rain Rate <–0.4	ATLAS	–13	–24	–8
	T-Flex	–23	–45	–20
Evaporation Rate	ATLAS	–0.23	–0.23	–0.14
	T-Flex	–0.19	–0.18	–0.26

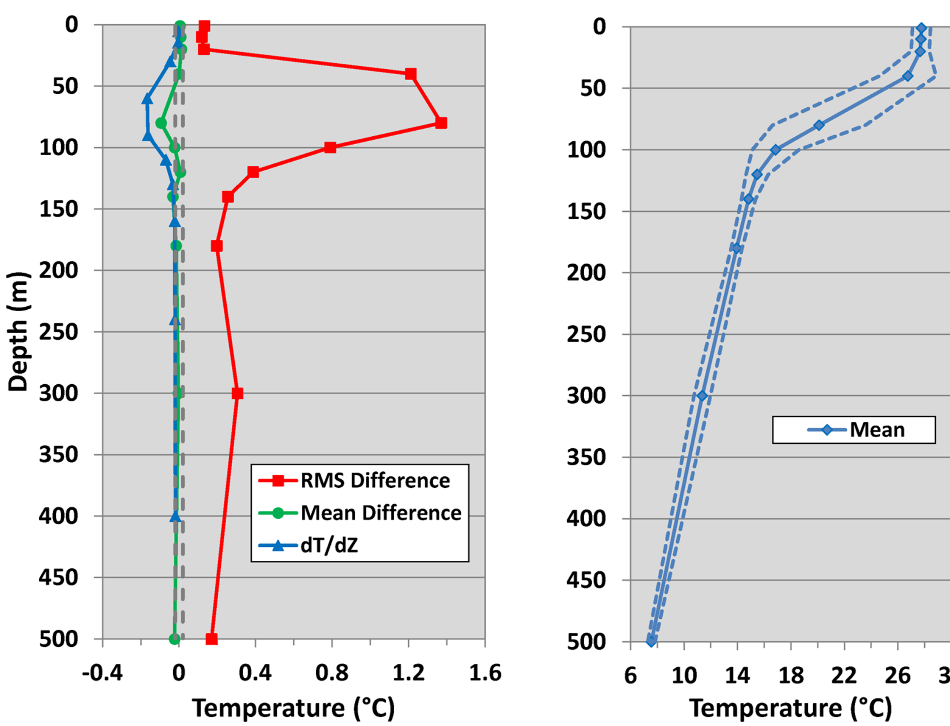

Figure 14. Left: Test 8 T-Flex PT004 minus ATLAS PI220 mean (green) and RMS (red) temperature difference. Mean ATLAS dT/dZ (blue). Right: ATLAS mean temperature profile (solid blue), and mean ± standard deviation (dashed blue).

Mean ML temperature differences were within the expected maximum difference (0.028°C) for all tests (**Figure 15**). Standard deviation and RMS differences of daily mean ML temperature were larger, with the largest being 0.14°C in Test 3, which may indicate residual ATLAS calibration error in the time series. Test 8 also had relatively large standard deviation and RMS difference, which was due to the 40 m sensors in Test 8 being below the ML for a portion of the time series. The standard deviations of differences were small compared to those of the time series themselves, e.g., the standard deviations of the ATLAS sensors in the ML in Test 8 were between 0.66°C and 0.68°C at 1 m, 10 m, and 20 m, and 1.89°C at 40 m. Daily mean ML temperature time series were well correlated, with R^2 between 0.98 and 1.00.

Spectra of 10-min temperature from ATLAS and T-Flex systems were equal at 95% confidence limits for nearly all comparisons. Exceptions were a T-Flex sensor (1 m, Test 2) that sustained damage due to vandalism and an ATLAS sensor (20 m, Test 1), which was found nearly fully encased in fishing net. We speculate that the net may have reduced the high-frequency temperature variability at this instrument.

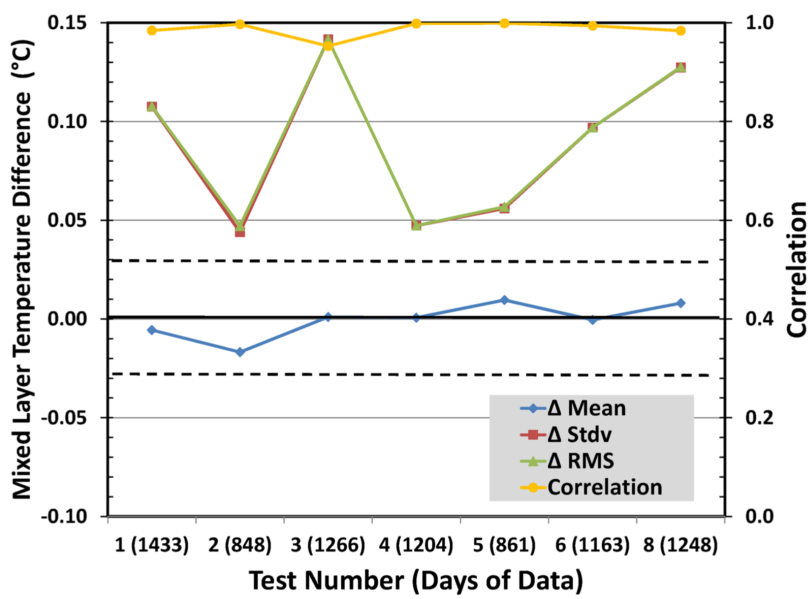

Figure 15. Mean (blue), standard deviation (red), and RMS (green) difference and correlation coefficients (R^2, yellow) between T-Flex and ATLAS daily mixed layer temperature. Dashed lines indicate expected accuracy of the ATLAS sensors. The numbers of daily mean values per test are in parentheses on the x axis.

4.8 Salinity

Delayed-mode salinity quality control procedures (described in section 2) were completed on these data before quantitative analysis of salinity differences was made. Observed sensor drifts, which can be nonlinear and non-monotonic, typically require piecewise adjustments during delayed-mode QC. During the QC procedure it was found that the T-Flex salinity time series adjustments required fewer adjustment pieces than did the ATLAS, reducing the complexity of the QC process. The reduction in drift complexity may be due to the T-Flex sensors having pumps. It was not possible to QC the salinity data in Tests 6 and 7 due to loss of moorings.

For the five tests in which both ATLAS and T-Flex moorings were recovered (Tests 1–4 and 8), 22 of 30 sensor pairs returned good high-resolution data. Cases for which high-resolution data were not available for comparison included three ATLAS sensors that were not recovered, three ATLAS sensors with erroneous data (e.g., large data shifts, possibly caused by foreign objects caught in the conductivity cells or by cracked cells), and two ATLAS sensors with no data recorded.

Quality control for the salinity sensors in Test 3 was complicated by the fact that many of the ATLAS sensors on this mooring experienced higher than expected temperature drift during the deployment (as mentioned in section 4.7). ATLAS salinity data for this mooring were recomputed using adjusted temperature and the measured conductivity. In addition, the ATLAS mooring in this test was deployed about 4 months earlier than the T-Flex mooring, the conductivity cells thus being potentially fouled at the beginning of the test.

Mean salinity differences between T-Flex and ATLAS systems were less than or equal to the maximum expected difference (0.028 psu) in 16 of 22 cases (**Table 7**). The largest mean difference (0.041 psu) and most of those exceeding expectations (4 of 6) were from Test 3. This may have been due to the ATLAS temperature calibration error noted above.

Salinity spectra of 10-min data from ATLAS and T-Flex systems were equal at the 95% level for 14 of 22 sensor pairs analyzed. Larger differences were limited to high frequency (>~0.8 cph), and in 7 of 8 cases the spectra of the ATLAS time series was higher than that of the T-Flex (**Figure 16**). In most cases, the frequency at which elevated high-frequency ATLAS salinity spectra began was also where the temperature spectra for both ATLAS and T-Flex time series flattened or fell off less rapidly. The T-Flex system was less prone to elevated high-frequency salinity variance (**Figures 16** and **17**), presumably due to the sensor pump providing more equally matched temporal response for temperature and conductivity samples.

Table 7. Mean salinity difference (psu) between T-Flex and ATLAS moorings for 5 test deployments. Shaded data are those exceeding the maximum expected difference of 0.028 psu.

Depth	Test 1	Test 2	Test 3	Test 4	Test 8
1 m	0.025	—	0.034	—	–0.012
10 m	—	—	0.039	–0.015	0.024
20 m	0.016	—	0.041	–0.009	0.032
40 m	0.032	—	0.032	–0.015	0.010
60 m	—	–0.002	–0.005	–0.009	—
100 / 120 m	–0.007	–0.028	–0.007	–0.007	–0.014

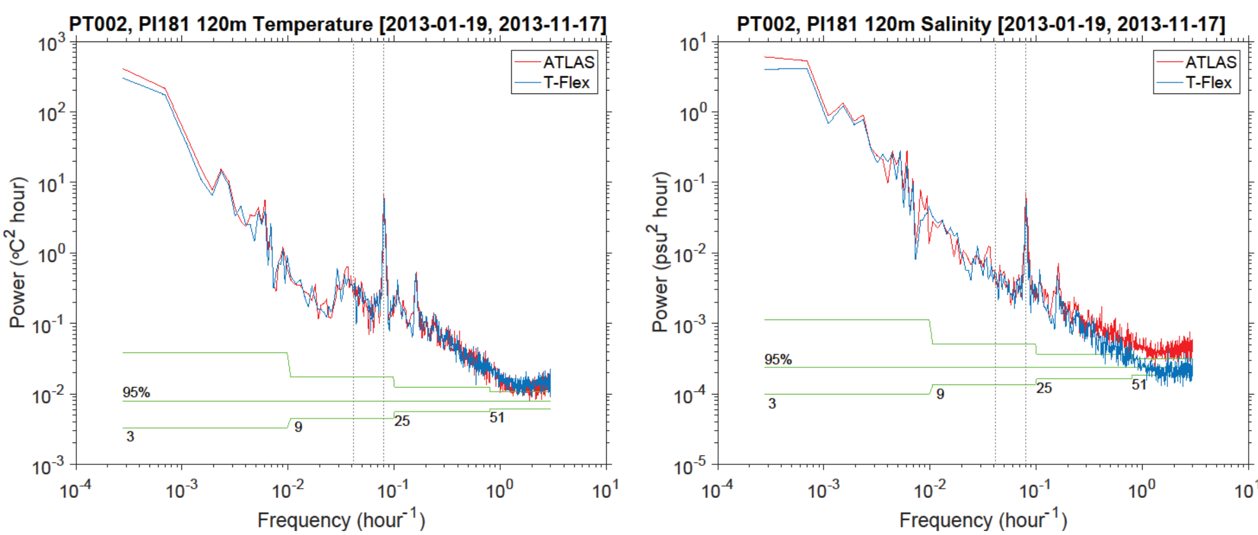

Figure 16. Left: Test 4 temperature spectra from 120 m ATLAS PI181 (red) and T-Flex PT002 (blue) sensors. Right: Salinity spectra from 100 m ATLAS PI181 (red) and T-Flex PT002 (blue) sensors. Green lines indicate 95% confidence limits, with numbers below giving the number of raw periodogram points averaged for a given frequency band.

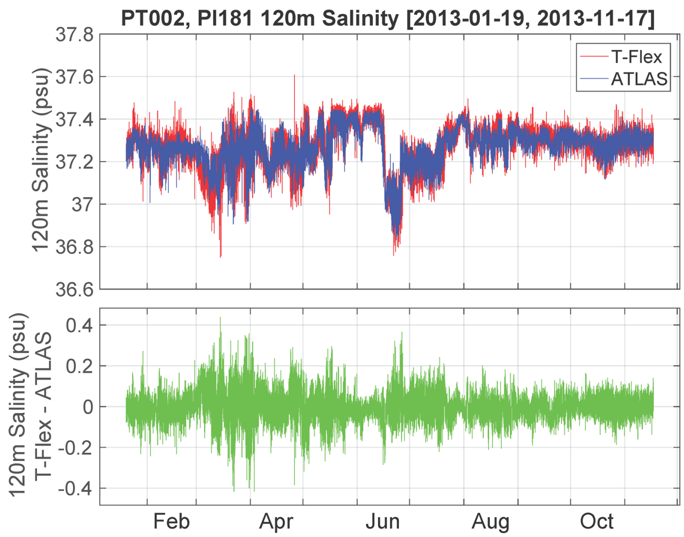

Figure 17. Test 4 10-min salinity (PSU) from 120 m T-Flex PT002 (blue) and ATLAS PI181 (red) sensors and difference (green).

4.9 Water pressure

ATLAS and T-Flex mooring systems measure water pressure at 300 m and 500 m depth as an indicator of differences between nominal and actual subsurface instrument depth. Upward (toward the surface) spikes in pressure also indicate when moorings are pulled upon by vandals. All moorings tested had mean pressures within normal ranges, with the exception of the 500 m sensor on the T-Flex mooring of Test 5, which had been raised by 10 m due to a knot in the mooring wire. Observed pressure difference between moorings can be due to both instrumental error and actual depth differences caused by differences in the shapes of the mooring lines, the latter potentially being the larger of the two. For example, T-Flex mean 300 m pressure over the seven tests ranged from 299.8 dbar to 302.4 dbar, a difference of 2.6 dbar, and at 500 m ranged from 499.6 dbar to 504.2 dbar, a difference of 4.6 dbar. Thus, the range of T-Flex mean pressure between tests was larger than the maximum mean difference between T-Flex and ATLAS mooring pairs (1.6 dbar at 300 m, 1.8 dbar at 500 m). Mean water pressure differences between systems were within the expected difference of ±1.4 dbar in 11 of 13 cases. ATLAS sensor calibration drift was evident in Test 2, which caused the largest difference (see Appendix B).

4.10 Current speed and direction

As detailed in section 3 above, both ATLAS and T-Flex current meters had relatively low data return. Loss of these data limited high-resolution comparisons to two instances (Tests 2 and 4). Real-time daily mean current data were also available from Test 1. Mean current speed and direction difference for these three tests were all less than the expected maximum velocity differences (7 cm s^{-1}, 7°). Mean differences computed from high-resolution (30-min) data for the longest time series available for comparison (Test 2, >14 months) were 0.1 cm s^{-1} for current speed and –1.2° for current direction (**Figure 18**). Spectra from the two systems were also equivalent.

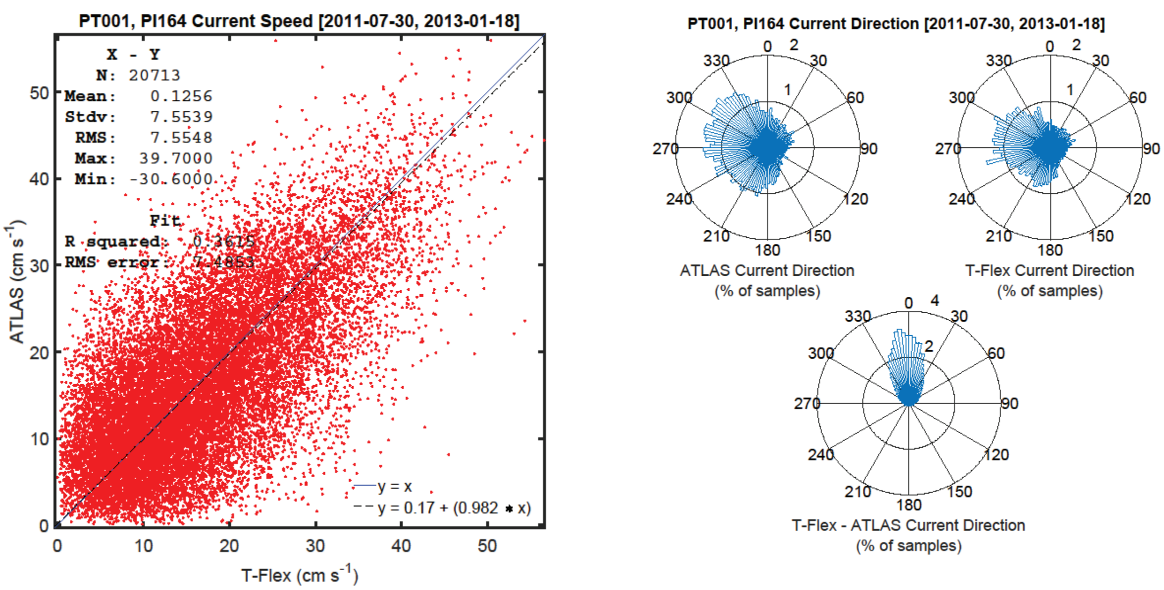

Figure 18. Test 2 current speed scatter plot (left) and current direction histogram (right) for T-Flex PT001 and ATLAS PI164.

5. Summary and Conclusion

PMEL designed and tested a new tropical mooring system named T-Flex to replace legacy ATLAS moorings. The system update was motivated by the obsolescence of some ATLAS components, technological advancements in instrumentation, and the availability of new and more capable satellite telemetry systems since the ATLAS system was originally designed. New sensors include: sonic anemometers (vs. propeller vane), newer model compasses and air temperature /relative humidity sensors, commercially available temperature /conductivity/ pressure sensor packages with integrated inductive modems and pumped conductivity cells (vs. ATLAS modules designed and constructed by PMEL), and current meters with integrated inductive modems (vs. current meters coupled with PMEL modules).

The T-Flex system incorporates two-way telemetry via Iridium (vs. one-way via Argos). ATLAS systems primarily transmit daily mean meteorological and oceanographic data (with some hourly meteorological data, limited to the times of satellite over-passes). T-Flex systems transmit hourly values of both meteorological and oceanographic data. Both systems internally record higher-resolution data (10 min for most sensors) that are available in delayed-mode after recovery of the moorings.

ATLAS and T-Flex moorings were deployed at co-located sites on eight occasions between March 2011 and December 2015. Four tests were conducted in RAMA and four in PIRATA. Loss of entire moorings, due to longer than intended deployment periods and vandalism, caused the loss of internally recorded high-resolution data and limited comparison for Tests 5 and 6 to daily mean real-time data (with the exception of Test 6 rainfall). The T-Flex mooring in Test 7 lost nearly all meteorological data due to failure of a buoy tower, and the ATLAS mooring lost nearly all high-resolution subsurface data due to mooring line failure, preventing any substantive data comparison for this test. The record lengths of comparable time series ranged from 290 to 537 days. Three test periods exceeded the one-year design lifetime of the moorings.

To summarize our results, mean differences for the various ATLAS and T-Flex sensors were converted to a single metric by referencing each sensor difference to their respective expected ATLAS accuracy. A value of $\sqrt{2}$ or less for this metric indicated that differences were within the expected sensor accuracies, assuming that the accuracies for ATLAS and T-Flex are equivalent. The mean and RMS differences met this criterion for all sensor types (**Figure 19**). The largest mean difference for a given test for most sensors also met the criterion. Exceptions were rain rate (metric = 2.3), mixed layer temperature (1.5), salinity (2.1), and water pressure (1.8). The largest mean rain rate difference was in Test 1 and was due to a few intense rainfall events that were not uniform between the ATLAS and

T-Flex sites. The largest mixed layer mean temperature difference ratio was for SST sensors in Test 5 for which the sensors were not recovered, so they could not be checked for proper function or calibration. The largest salinity differences were in Test 3, in which the ATLAS temperature sensors experienced temperature calibration drift that could have also increased the error of ATLAS salinity measurements. Large water pressure ratios were likely due to differences in sensor depths, rather than sensor measurement bias.

We conclude that T-Flex mooring systems provide:

- Real-time and delayed-mode data of equivalent accuracy as ATLAS systems
- Equal or better percentage of expected data in both real time and delayed mode
- Higher temporal resolution data in real time (hourly vs. daily)
- High resolution salinity data less prone to spiking and with simpler sensor drift characteristics.

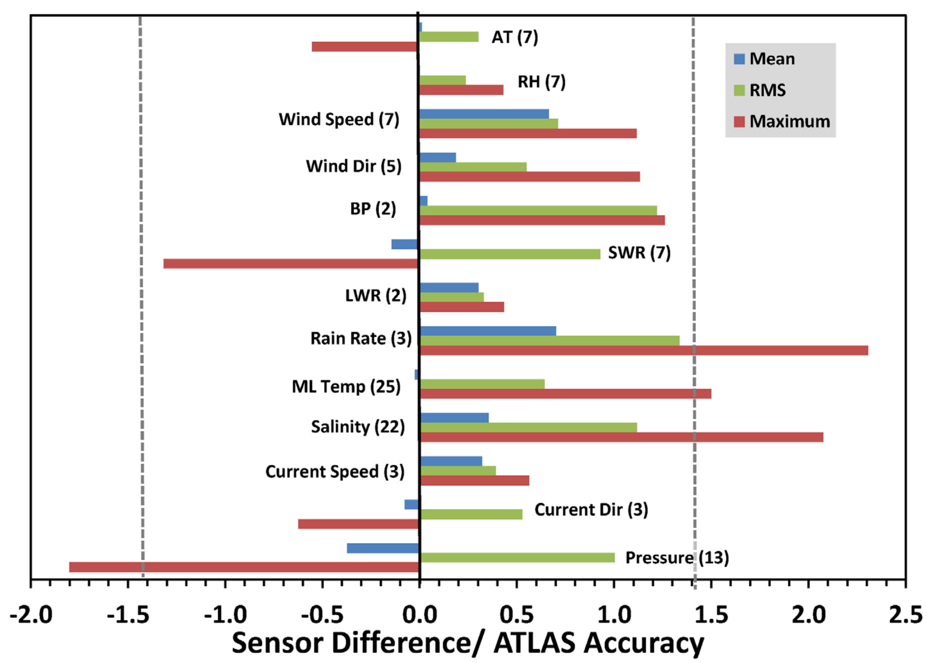

Figure 19. Ratio of mean, RMS, and maximum difference of T-Flex and ATLAS sensors divided by the expected ATLAS accuracy. The number of sensor pairs for each sensor type is indicated in parentheses. The RMS and maximum were computed from each test mean difference. Vertical dashed lines indicate the expected standard deviation for normalized ATLAS minus T-Flex mean differences assuming that sensors for the two mooring systems have comparable accuracy and that errors are normally distributed.

Therefore, replacement of ATLAS mooring systems by T-Flex systems in the PIRATA and RAMA arrays will provide consistency in long-term, sustained observations from these arrays, as advocated in NOAA's "Ten Climate Monitoring Principles" (Karl et al., 1996).

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Appendix A. Test 1—ATLAS RA058, T-Flex RT001 Delayed Mode Data Analysis

Nominal Site: 12°S, 93°E

Common Test Period: 21 March 2011 to 25 April 2012 (400.4 days)

The moorings were separated by about 6.5 nm in the zonal and 1.8 nm in the meridional direction (**Figure A1**). Both moorings were heavily vandalized causing damage to anemometers and SWR sensors, loss of some subsurface sensors, and fouling of the mooring line and subsurface instruments with fishing line and net. Research Vessel *Roger Revelle* visited the area on 5–6 September 2011 and replaced damaged surface sensors. Several upward (toward the surface) pressure spikes of up to 60 dbar occurred on both moorings, indicating the moorings were pulled on by vandals.

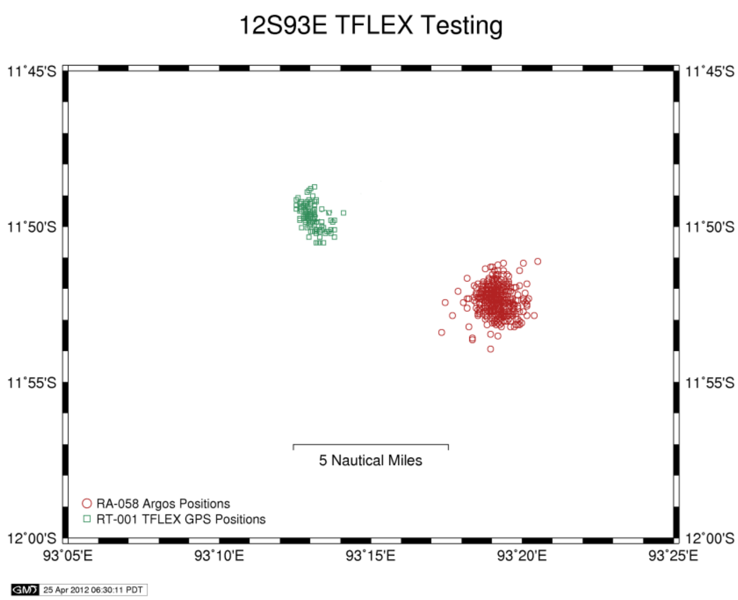

Figure A1. Mooring locations reported by Argos (ATLAS RA058) and GPS (T-Flex RT001).

Table A1. Test 1 summary of damaged, lost, or failed instruments and hardware.

Issue	Description
Damaged ATLAS Sensors	Anemometer, SWR (shield bent)
Damaged T-Flex Sensors	SWR (shield and mast bent), RAIN
Lost ATLAS Sensors	10 m and 60 m TC modules, 12 m Sontek Current Meter
Failed T-Flex Sensors	ATRH (water intrusion, replaced by RV *Roger Revelle*)
T-Flex Firmware Errors	The firmware for compass data in Tests 1 and 2 had an error that produced erroneous wind direction in a random manner. This affected not only direction accuracy, but also vector components and vector wind speed.

Table A2. Test 1 data difference statistics (T-Flex RT001 minus ATLAS RA058) over the common time period from high temporal-resolution (2–60 m) data. SWR metrics were computed for daytime values. Rain metrics were computed over all data (rain and no rain conditions). Rain metrics computed only when raining are presented in section 4 above. Salinity data differences were computed after data QC was performed.

	N	Δ Mean	Δ Stdv	Δ RMS	Δ Min	Δ Max	R^2	Slopes	Intercept
AT (°C)	47537	0.02	0.44	0.44	−3.70	3.14	0.740	1.103	−2.85
RH (%RH)	23145	0.34	2.25	2.27	−12.92	16.85	0.864	0.955	3.23
Wind Spd (m s^{-1})	20880	0.33	0.89	0.95	−6.08	10.96	0.800	0.920	0.23
U (m s^{-1})	20880	−0.78	1.21	1.45	−9.14	9.13	0.715	0.993	0.74
V (m s^{-1})	20880	−1.59	1.34	2.08	−11.19	10.62	0.699	0.889	1.78
Wind Dir (°)	20820	−16.6	14.0	21.7	−170.3	177.0	0.830	0.990	19.5
SWR (w m^{-2})	146580	13.6	184.3	184.8	−1255.5	1221.0	0.715	0.971	−0.3
Rain (mm hr^{-1})	37428	0.009	2.198	2.198	−65.5	91.3	0.025	0.561	0.069
Temp 1 m (°C)	57683	−0.003	0.097	0.097	−1.240	1.453	0.983	0.998	0.066
Temp 10 m (°C)	0	NA	NA	NA	NA	NA	NA	NA	NA
Temp 20 m (°C)	57075	−0.006	0.197	0.197	−4.080	3.250	0.923	0.978	0.619
Temp 40 m (°C)	57075	−0.009	0.481	0.481	−4.964	4.225	0.795	0.982	0.486
Temp 60 m (°C)	0	NA	NA	NA	NA	NA	NA	NA	NA
Temp 80 m (°C)	57075	−0.068	0.622	0.626	−4.350	4.075	0.945	0.992	0.252
Temp 100 m (°C)	57075	−0.009	0.612	0.612	−3.791	3.605	0.956	1.004	−0.080
Temp 120 m (°C)	57075	−0.039	0.608	0.610	−2.629	3.381	0.958	0.998	0.082
Temp 140 m (°C)	57075	−0.057	0.597	0.600	−2.345	3.164	0.956	0.999	0.068
Temp 180 m (°C)	57075	−0.023	0.483	0.483	−2.550	2.671	0.950	1.005	−0.056
Temp 300 m (°C)	57075	−0.018	0.256	0.256	−1.450	1.160	0.837	0.991	0.126
Temp 500 m (°C)	57075	−0.007	0.142	0.142	−0.700	0.709	0.844	0.974	0.235
Pres 300 m (dbar)	57683	−0.07	2.61	2.61	−39.07	23.97	0.012	0.777	67.00
Pres 500 m (dbar)	57683	−0.84	4.51	4.59	−63.93	39.60	0.139	0.823	89.39
Sal 1 m (psu)	9611	0.025	0.088	0.092	−0.802	1.201	0.891	0.955	1.498
Sal 10 m (psu)	0	NA	NA	NA	NA	NA	NA	NA	NA
Sal 20 m (psu)	9324	0.017	0.071	0.073	−0.506	0.508	0.916	0.981	0.635
Sal 40 m (psu)	9324	0.032	0.089	0.094	−0.709	0.625	0.884	0.999	0.020
Sal 60 m (psu)	0	NA	NA	NA	NA	NA	NA	NA	NA
Sal 100 m (psu)	9324	−0.007	0.116	0.116	−0.643	0.730	0.864	0.929	2.451

Appendix B. Test 2—ATLAS PI164, T-Flex PT001 Delayed Mode Data Analysis

Nominal Site: 20°N, 38°W

Common Test Period: 31 July 2011 to 18 January 2013 (537.2 days)

The moorings were separated by about 4.1 nm in the zonal and 0.6 nm in the meridional direction (**Figure B1**). Deployment of more than 17 months resulted in battery depletion and incomplete time series for some sensors. Vandals tied up to the ATLAS mooring, removing and/or damaging some meteorological sensors as well as the tower and buoy, and leaving fishing line entangled in the mooring. The T-Flex mooring did not sustain damage, but fishing line was found in the mooring line.

Mean pressure differences between T-Flex and ATLAS sensors of –1.2 dbar and –1.8 dbar at 300 m and 500 m, respectively (**Table B2**), the latter exceeding the expected difference (1.4 dbar). The pressure difference increased with time (300 m shown in **Figure B2**. 500 m data had similar characteristics). A linear trend fit to each pressure time series and to the pressure difference time series indicated that while all four pressure time series increased with time, the ATLAS sensors' increase was larger (1.4 dbar at 300 m, 1.1 dbar at 500 m) than the T-Flex difference (0.2 and 0.1 dbar, respectively). Post-recovery calibration of the ATLAS sensors indicated calibration drift of 0.9 and 0.5 dbar, respectively.

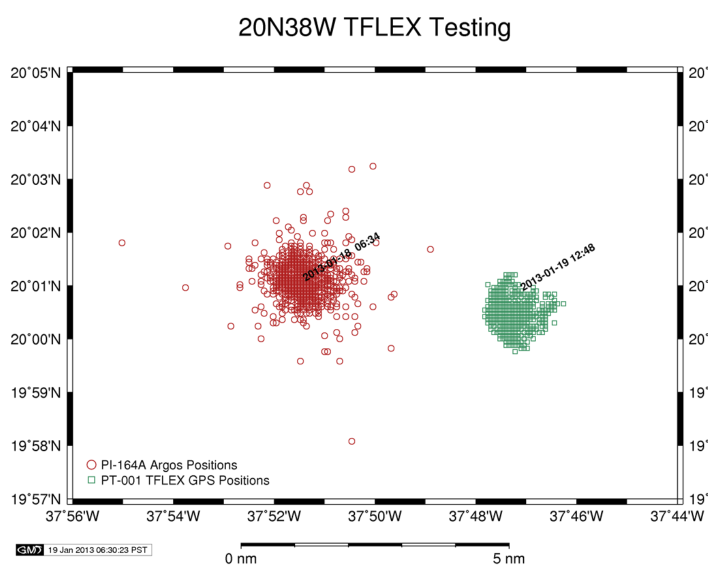

Figure B1. Mooring locations reported by Argos (ATLAS PI164) and GPS (T-Flex PT001).

Table B1. Test 2 summary of damaged, lost, or failed instruments and hardware.

Issue	Description
Damaged ATLAS Sensor	RAIN. Sontek fin missing
Damaged T-Flex Sensors	SST/SSC module connector
Lost ATLAS Sensors	SWR, LWR
Failed ATLAS Sensors	1 m and 10 m ATLAS salinity data shifted by large amounts (~ 2 psu at 1 m and 0.5 psu at 10 m) within weeks of deployment. 20 m, 40 m, and 80 m modules returned no data.
T-Flex Firmware Errors	The firmware for compass data in Tests 1 and 2 had an error that produced erroneous wind direction in a random manner. This affected not only direction accuracy, but also vector components and vector wind speed.

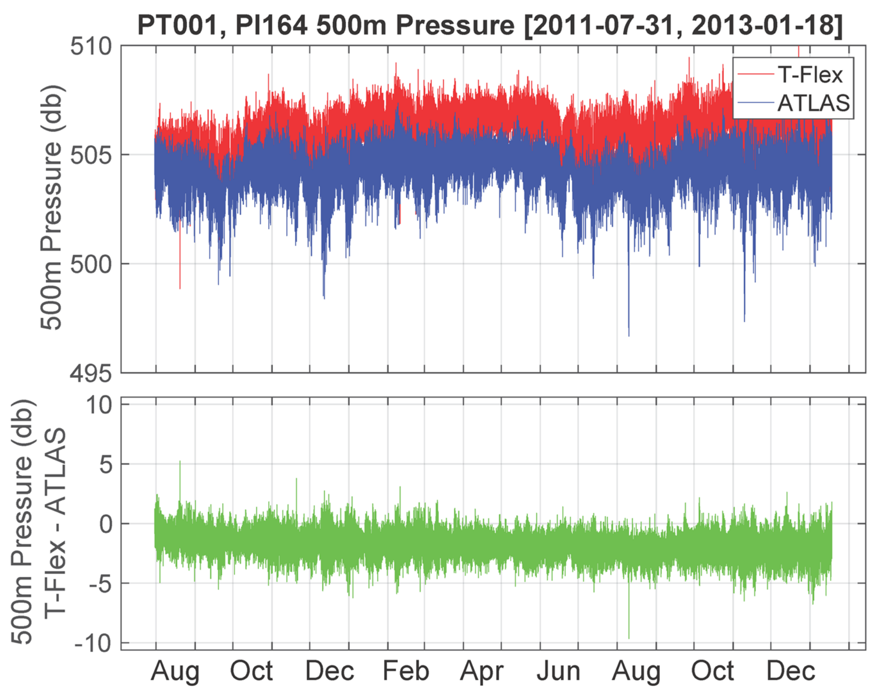

Figure B2. Water pressure (dbar) at 500 m from T-Flex PT001 (blue) and ATLAS PI164 (red) sensors and difference (green).

Table B2. Test 2 data difference statistics (T-Flex PT001 minus ATLAS PI164) over the common time period from high temporal-resolution (2–60 m) data. SWR metrics were computed for daytime values. Rain metrics were computed over all data (rain and no rain conditions). Rain metrics computed only when raining are presented in section 4 above. Salinity data differences were computed after data QC was performed.

	N	Δ Mean	Δ Stdv	Δ RMS	Δ Min	Δ Max	R^2	Slopes	Intercept
AT (°C)	77192	–0.06	0.20	0.21	–2.28	2.62	0.983	1.001	0.045
RH (%RH)	77192	–1.00	1.54	1.84	–21.71	15.34	0.938	0.982	2.380
Wind Spd (m s^{-1})	77185	0.23	0.77	0.81	–6.49	11.15	0.864	0.923	0.299
U (m s^{-1})	77185	0.52	1.15	1.27	–15.75	12.70	0.804	1.083	–0.097
V (m s^{-1})	77185	–1.53	1.26	1.99	–12.04	11.67	0.795	0.896	1.248
Wind Dir (°)	76699	–15.6	11.7	19.5	–177.2	172.9	0.913	1.010	13.185
BP (hPa)	12865	–0.12	0.10	0.16	–0.90	2.00	0.998	1.007	–7.358
SWR (w m^{-2})	18864	–15.7	153.4	154.2	–1010.2	933.4	0.800	1.046	–6.252
LWR–net (w m^{-2})	34829	–0.7	13.0	13.0	–74.6	55.5	0.558	0.965	–0.852
LWR–dwn (w m^{-2})	34829	1.8	12.7	12.8	–54.7	57.4	0.539	0.962	13.960
Case Temp (°C)	34829	0.11	0.38	0.40	–4.84	6.77	0.876	0.936	1.572
Dome Temp (°C)	34829	0.02	0.40	0.41	–5.22	6.95	0.880	0.931	1.796
Rain (mm hr^{-1})	28477	0.008	0.862	0.862	–38.0	42.1	0.042	0.636	0.004
Temp 1 m (°C)	17521	–0.015	0.068	0.070	–0.626	1.457	0.979	0.983	0.460
Temp 10 m (°C)	70080	–0.020	0.062	0.065	–0.690	0.705	0.998	0.995	0.139
Temp 20 m (°C)	0	NA	NA	NA	NA	NA	NA	NA	NA
Temp 40 m (°C)	0	NA	NA	NA	NA	NA	NA	NA	NA
Temp 60 m (°C)	67534	–0.029	0.463	0.464	–3.535	2.719	0.815	0.996	0.124
Temp 80 m (°C)	0	NA	NA	NA	NA	NA	NA	NA	NA
Temp 100 m (°C)	77397	–0.030	0.350	0.351	–2.308	2.119	0.752	0.979	0.513
Temp 120 m (°C)	60732	–0.027	0.380	0.381	–2.265	1.919	0.608	0.966	0.795
Temp 140 m (°C)	77397	–0.013	0.456	0.456	–2.587	2.858	0.694	0.973	0.592
Temp 180 m (°C)	77397	–0.020	0.544	0.544	–2.672	2.395	0.651	0.992	0.172
Temp 300 m (°C)	77397	–0.018	0.301	0.302	–1.867	1.881	0.674	1.010	–0.144
Temp 500 m (°C)	77397	–0.008	0.227	0.227	–1.057	1.088	0.457	0.976	0.300
Pres 300 m (dbar)	77397	–1.23	0.89	1.52	–6.38	3.15	0.000	2.144	–344.590
Pres 500 m (dbar)	77397	–1.80	0.92	2.02	–9.59	5.24	0.001	1.103	–50.236
Sal 1 m (psu)	0	NA	NA	NA	NA	NA	NA	NA	NA
Sal 10 m (psu)	0	NA	NA	NA	NA	NA	NA	NA	NA
Sal 20 m (psu)	0	NA	NA	NA	NA	NA	NA	NA	NA
Sal 40 m (psu)	0	NA	NA	NA	NA	NA	NA	NA	NA
Sal 60 m (psu)	11276	–0.002	0.075	0.075	–0.458	0.323	0.583	0.761	8.910
Sal 120 m (psu)	10130	–0.028	0.064	0.070	–0.474	0.270	0.670	0.794	7.709
Curr Spd (cm s^{-1})	20713	0.1	7.6	7.6	–30.6	39.7	0.361	0.982	0.172
Curr U (cm s^{-1})	20713	–1.1	7.3	7.4	–42.4	28.4	0.671	0.993	1.065
Curr V (cm s^{-1})	20713	–1.0	8.9	9.0	–40.9	46.0	0.521	1.024	0.987
Curr Dir (°)	20713	–1.2	52.9	52.9	–179.7	180.0	0.718	1.046	–9.185

Appendix C. Test 3—ATLAS RA092B, T-Flex RT002 Delayed Mode Data Analysis

Nominal Site: 12°N, 90°E

Common Test Period: 29 December 2012 to 29 November 2013 (334.7 days)

The moorings were separated by about 6.8 nm in the zonal and 1.0 nm in the meridional direction (**Figure C1**). The ATLAS system was deployed in early September 2012, about 4 months before the T-Flex was deployed. The ATLAS sensors used for comparison to T-Flex were deployed in September, with the exception of a damaged rain gauge, which was replaced when the T-Flex was deployed. Nearly half (5 of 12) of the ATLAS temperature sensors had calibration drifts of order 0.04°C, exceeding the expected sensor accuracy of ±0.02 °C. Temperature adjustments were made by applying a linear combination of pre-deployment and post-recovery calibrations to these time series. Such adjustments are rarely necessary. The ATLAS mooring was deployed without a current meter. This was the first deployment of a T-Flex system with firmware corrected for wind direction processing errors.

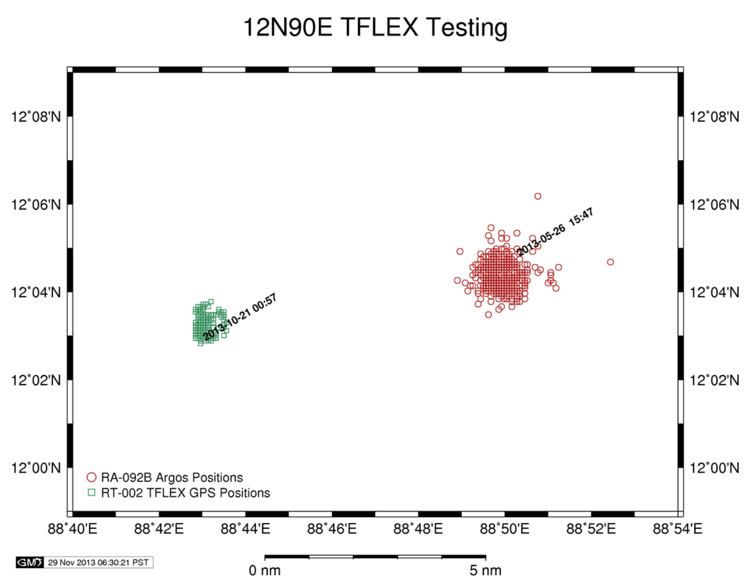

Figure C1. Mooring locations reported by Argos (ATLAS RA092) and GPS (T-Flex RT002).

Table C1. Test 3 summary of failed instruments and hardware.

Issue	Description
Failed ATLAS Component	Transmitter battery, RAIN (replaced before comparison began)
Failed T-Flex Sensors	ATRH cable connector leaked

Table C2. Test 3 data difference statistics (T-Flex RT002 minus ATLAS RA092) over the common time period from high temporal-resolution (2–60 m) data. SWR metrics were computed for daytime values. Rain metrics were computed over all data (rain and no rain conditions). Rain metrics computed only when raining are presented in Section 4 above. Salinity data differences were computed after data QC was performed.

	N	Δ Mean	Δ Stdv	Δ RMS	Δ Min	Δ Max	R^2	Slopes	Intercept
AT (°C)	21938	0.06	0.18	0.19	–3.19	6.83	0.982	0.996	0.056
RH (%RH)	21922	1.16	1.52	1.91	–11.47	12.01	0.944	0.954	2.412
Wind Spd (m s^{-1})	22597	0.14	0.61	0.63	–6.81	7.58	0.944	0.955	0.096
U (m s^{-1})	22597	–0.38	0.86	0.94	–13.45	7.25	0.942	0.934	0.284
V (m s^{-1})	22597	0.24	0.70	0.74	–6.72	11.07	0.970	1.011	–0.221
Wind Dir (°)	21654	5.7	13.2	14.3	–175.6	155.3	0.975	0.978	–1.428
SWR (w m^{-2})	56927	–13.0	116.4	117.1	–1106.6	924.2	0.870	1.038	–4.806
Rain (mm hr^{-1})	20570	0.023	0.973	0.973	–34.2	57.9	0.008	0.310	0.003
Temp 1 m (°C)	48193	–0.002	0.125	0.125	–1.771	1.600	0.979	0.992	0.234
Temp 10 m (°C)	37548	–0.004	0.129	0.129	–1.412	1.175	0.980	0.987	0.388
Temp 20 m (°C)	48193	–0.021	0.211	0.212	–2.170	1.682	0.923	0.971	0.852
Temp 40 m (°C)	48193	0.029	0.358	0.359	–2.211	2.463	0.659	0.800	5.690
Temp 60 m (°C)	43568	–0.020	0.417	0.418	–3.028	3.376	0.717	0.838	4.527
Temp 80 m (°C)	48193	–0.072	0.677	0.680	–3.058	3.363	0.745	0.848	4.033
Temp 100 m (°C)	48193	–0.077	0.674	0.678	–3.277	3.581	0.765	0.861	3.339
Temp 120 m (°C)	48193	–0.076	0.566	0.571	–2.773	2.700	0.805	0.885	2.515
Temp 140 m (°C)	48193	–0.077	0.505	0.511	–2.385	2.441	0.824	0.903	1.924
Temp 180 m (°C)	48193	–0.048	0.388	0.391	–2.168	1.705	0.829	0.908	1.483
Temp 300 m (°C)	48193	–0.022	0.123	0.125	–0.583	0.580	0.673	0.796	2.408
Temp 500 m (°C)	48193	–0.013	0.083	0.084	–0.354	0.319	0.686	0.829	1.704
Pres 300 m (dbar)	48203	1.23	0.72	1.43	–3.19	5.33	0.473	0.832	49.255
Pres 500 m (dbar)	48203	1.26	1.12	1.68	–10.93	7.40	0.670	0.953	22.561
Sal 1 m (psu)	8032	0.034	0.147	0.151	–0.853	1.152	0.917	0.953	1.513
Sal 10 m (psu)	6258	0.039	0.149	0.154	–1.071	1.359	0.907	0.930	2.282
Sal 20 m (psu)	8032	0.042	0.145	0.151	–0.944	1.058	0.897	0.945	1.795
Sal 40 m (psu)	8032	0.032	0.204	0.206	–0.986	1.400	0.764	0.869	4.358
Sal 60 m (psu)	7260	–0.005	0.250	0.250	–1.233	1.314	0.635	0.890	3.754
Sal 100 m (psu)	8032	–0.007	0.114	0.115	–0.579	0.744	0.643	0.779	7.676

Appendix D. Test 4—ATLAS PI181, T-Flex PT002 Delayed Mode Data Analysis

Nominal Site: 20°N, 38°W

Common Test Period: 19 January 2013 to 17 November 2013 (301.5 days)

The moorings were separated by about 3.8 nm in the zonal and 0.1 nm in the meridional direction (**Figure D1**).

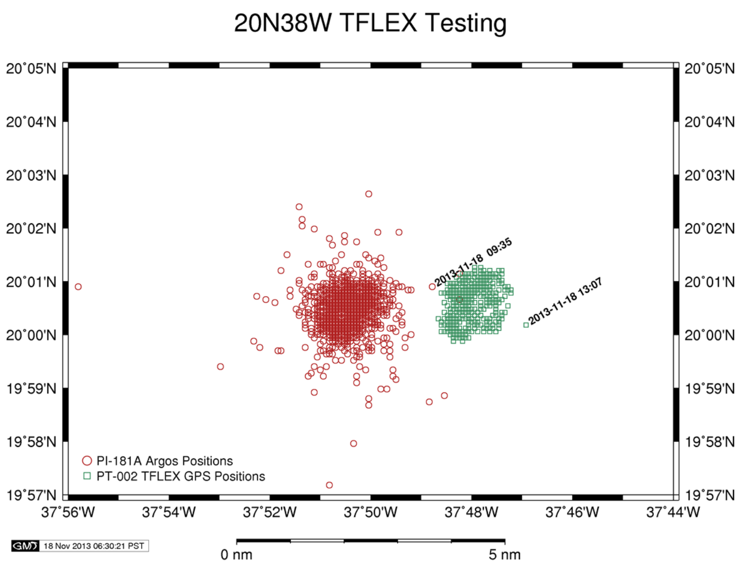

Figure D1. Mooring locations reported by Argos (ATLAS PI181) and GPS (T-Flex PT002).

Table D1. Test 4 summary of damaged or failed instruments and hardware.

Issue	Description
Damaged ATLAS Sensor	Sontek CM fin broken
Failed ATLAS Sensors	1 m salinity, 500 m pressure
Failed T-Flex Sensors	ATRH (temperature calibration drift followed by complete sensor failure, water intrusion, replaced after 8 months); RAIN (noisy); Nortek CM (IM circuitry caused RT data loss)

Table D2. Test 4 data difference statistics (T-Flex PT002 minus ATLAS PI181) over the common time period from high temporal-resolution (2–60 m) data. SWR metrics were computed for daytime values. Rain metrics were computed over all data (rain and no rain conditions). Rain metrics computed only when raining are presented in section 4 above. Salinity data differences were computed after data QC was performed.

	N	Δ Mean	Δ Stdv	Δ RMS	Δ Min	Δ Max	R^2	Slopes	Intercept
AT (°C)	35050	–0.11	0.20	0.23	–2.07	2.15	0.978	1.035	–0.747
RH (%RH)	35050	–0.04	1.58	1.58	–18.92	10.98	0.923	0.929	5.395
Wind Spd (m s^{-1})	43185	0.28	0.62	0.68	–4.59	6.31	0.912	0.968	–0.066
U (m s^{-1})	43185	–0.12	0.67	0.69	–7.19	7.34	0.943	0.970	–0.039
V (m s^{-1})	43185	–0.27	0.71	0.75	–6.55	6.06	0.911	0.960	0.175
Wind Dir (°)	42776	–2.0	8.2	8.4	–133.7	118.9	0.967	1.004	1.120
BP (hPa)	7200	0.27	0.08	0.28	–0.10	0.50	0.999	0.996	3.385
SWR (w m^{-2})	111860	10.0	137.0	137.3	–1053.4	1034.7	0.840	0.991	–5.460
LWR–net (w m^{-2})	214280	4.5	10.0	11.0	–57.5	66.4	0.796	1.066	–1.041
LWR–dwn (w m^{-2})	214280	0.7	9.9	9.9	–59.0	62.6	0.838	1.041	–16.705
Case Temp (°C)	214280	–0.1	0.2	0.2	–4.1	3.9	0.982	0.987	0.398
Dome Temp (°C)	214280	0.1	0.3	0.3	–4.3	4.3	0.977	0.966	0.786
Rain (mm hr^{-1})	19562	–0.003	0.248	0.248	–10.0	10.4	0.000	3.067	0.003
Temp 1 m (°C)	43422	–0.004	0.067	0.067	–1.288	0.967	0.996	0.997	0.073
Temp 10 m (°C)	43422	–0.004	0.059	0.059	–0.542	0.661	0.997	0.998	0.062
Temp 20 m (°C)	43422	0.000	0.090	0.090	–0.950	1.051	0.994	1.000	0.001
Temp 40 m (°C)	43422	0.009	0.167	0.167	–1.258	1.208	0.979	1.000	–0.005
Temp 60 m (°C)	43422	0.015	0.319	0.320	–2.122	1.976	0.890	1.015	–0.388
Temp 80 m (°C)	43422	0.023	0.358	0.359	–1.864	2.090	0.671	1.049	–1.197
Temp 100 m (°C)	43422	0.039	0.402	0.404	–2.012	1.998	0.515	1.114	–2.658
Temp 120 m (°C)	43422	0.041	0.396	0.398	–1.952	2.099	0.601	1.123	–2.758
Temp 140 m (°C)	43422	0.034	0.394	0.396	–2.024	2.079	0.601	1.084	–1.816
Temp 180 m (°C)	43422	–0.016	0.366	0.366	–1.863	1.786	0.487	1.026	–0.492
Temp 300 m (°C)	43422	0.014	0.265	0.265	–1.234	1.449	0.596	1.046	–0.745
Temp 500 m (°C)	43422	0.005	0.194	0.194	–0.883	0.974	0.600	1.031	–0.378
Pres 300 m (dbar)	43422	–1.6	0.8	1.8	–5.6	3.5	0.000	0.965	12.037
Pres 500 m (dbar)	3474	–0.9	1.0	1.3	–4.7	3.2	0.493	0.855	73.797
Sal 1 m (psu)	0	NA	NA	NA	NA	NA	NA	NA	NA
Sal 10 m (psu)	7235	–0.015	0.043	0.045	–0.459	0.305	0.942	0.951	1.811
Sal 20 m (psu)	7235	–0.009	0.049	0.050	–0.412	0.418	0.921	0.939	2.253
Sal 40 m (psu)	7235	–0.015	0.064	0.066	–0.527	0.312	0.858	0.909	3.376
Sal 60 m (psu)	7235	–0.009	0.062	0.063	–0.391	0.474	0.760	0.846	5.746
Sal 120 m (psu)	7235	–0.007	0.045	0.045	–0.255	0.296	0.759	0.993	0.272
Curr Spd (cm s^{-1})	14472	1.9	6.1	6.4	–30.7	31.1	0.645	0.916	–0.400
Curr U (cm s^{-1})	14472	–1.2	6.0	6.1	–36.5	24.5	0.743	0.868	0.482
Curr V (cm s^{-1})	14472	–0.6	6.9	6.9	–27.7	49.9	0.776	0.890	1.198
Curr Dir (°)	14472	–3.1	43.3	43.4	–179.6	180.0	0.859	1.034	–4.584

Appendix E. Test 5—ATLAS RA102, T-Flex RT003 Real Time Data Analysis

Nominal Site: 12°S, 67°E

Common Test Period: 19 July 2013 to 4 May 2014 (290 days)

While anchored, the moorings were separated by about 0.6 nm in the zonal and 4.9 nm in the meridional direction (**Figure E1**). This mooring site was not revisited for more than 2 years after these moorings were deployed. ATLAS mooring RA102 went adrift on 5 May 2014 (9+ months after deployment) and went ashore in the Comoros Islands. No instrumentation or internally recorded high-resolution data were recovered. T-Flex mooring RT003 stopped transmitting on 2 October 2015, more than 2 years after deployment. The mooring site was visited on 28 October 2015 in preparation for a mooring recovery, but the T-Flex mooring was not found. Interrogation of the acoustic release indicated that it was no longer attached to the mooring line. A single complete phone call from the T-Flex system was received in December 2015 from a location about 350 nm west of the deployment site, confirming that the mooring line had parted and the mooring was adrift. As there are no high-resolution data available from either mooring, real-time daily averaged data are compared for this test. Daily mean data are the primary ATLAS data telemetered in real time and are computed from high-resolution data (10-min resolution for most data types) by the mooring electronics. T-Flex systems telemeter real-time data with hourly resolution. These hourly data have been averaged to daily after reception for comparison to ATLAS daily data. Thus, the daily mean data compared here were not computed from the same number of samples: 144 for ATLAS and 24 for T-Flex.

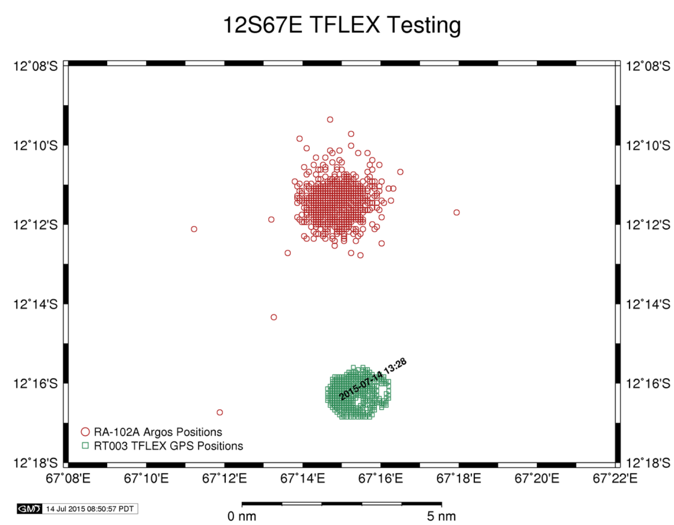

Figure E1. Mooring locations reported by Argos (ATLAS RA102) and GPS (T-Flex RT003).

Table E1. Test 5 summary of lost or failed instruments and hardware.

Issue	Description
Failed ATLAS Sensors	Sontek CM (no data), 20 m salinity (data biased low)
Failed T-Flex Sensors	ATRH, RAIN, 60 m temperature/salinity
Lost ATLAS Sensors	All
Lost T-Flex Sensors	All

Table E2. Test 5 real-time daily data difference statistics (T-Flex RT003 minus ATLAS RA102) over the common time period. Statistics were computed from daily mean data. Rain metrics were computed over all data (rain and no rain conditions). Rain metrics computed only when raining are presented in section 4 above. Post-recovery salinity QC was not performed due to loss of instruments.

	N	Δ Mean	Δ Stdv	Δ RMS	Δ Min	Δ Max	R^2	Slopes	Intercept
AT (°C)	99	0.03	0.08	0.09	–0.20	0.20	0.956	1.008	–0.236
RH (%RH)	99	–0.58	0.53	0.78	–2.10	0.80	0.988	0.976	2.500
Wind Spd (m s^{-1})	290	0.13	0.23	0.26	–0.95	1.06	0.994	0.951	0.181
U (m s^{-1})	290	–0.21	0.34	0.39	–1.34	1.22	0.994	0.968	0.065
V (m s^{-1})	290	–0.24	0.54	0.59	–3.43	0.87	0.953	0.957	0.330
Wind Dir (°)	290	0.2	11.6	11.5	–20.3	157.4	0.977	1.053	–14.380
SWR (w m^{-2})	287	–9.8	15.0	17.9	–61.1	54.8	0.956	1.055	–4.228
Rain (mm hr^{-1})	150	0.031	0.139	0.142	–0.720	0.990	0.787	0.999	–0.030
Temp 1 m (°C)	290	0.030	0.058	0.065	–0.230	0.320	0.999	0.990	0.235
Temp 10 m (°C)	286	0.000	0.052	0.052	–0.240	0.300	0.999	0.998	0.058
Temp 20 m (°C)	285	–0.001	0.052	0.052	–0.250	0.310	0.999	0.997	0.071
Temp 40 m (°C)	286	0.054	0.159	0.168	–0.600	0.740	0.983	0.977	0.557
Temp 60 m (°C)	0	NA	NA	NA	NA	NA	NA	NA	NA
Temp 80 m (°C)	286	–0.003	0.218	0.217	–0.780	0.760	0.985	1.014	–0.313
Temp 100 m (°C)	286	0.111	0.209	0.237	–0.480	0.730	0.983	0.988	0.140
Temp 120 m (°C)	286	0.067	0.182	0.194	–0.750	0.600	0.978	1.012	–0.286
Temp 140 m (°C)	285	0.061	0.208	0.216	–0.470	0.910	0.967	0.999	–0.050
Temp 180 m (°C)	286	0.083	0.205	0.221	–0.550	1.130	0.946	0.983	0.178
Temp 300 m (°C)	285	0.010	0.095	0.095	–0.250	0.290	0.938	0.979	0.244
Temp 500 m (°C)	285	–0.092	0.069	0.115	–0.320	0.250	0.936	1.057	–0.402
Pres 300 m (dbar)	285	0.2	0.2	0.3	–0.6	1.2	0.901	1.204	–61.6
Pres 500 m (dbar)	285	–1.0	0.5	1.1	–2.7	1.0	0.921	1.234	–116.8
Sal 1 m (psu)	290	–0.004	0.040	0.040	–0.227	0.138	0.977	0.965	1.225
Sal 10 m (psu)	286	0.018	0.039	0.043	–0.208	0.162	0.978	0.971	0.987
Sal 20 m (psu)	0	NA	NA	NA	NA	NA	NA	NA	NA
Sal 40 m (psu)	285	0.026	0.049	0.055	–0.148	0.634	0.956	1.004	–0.151
Sal 60 m (psu)	0	NA	NA	NA	NA	NA	NA	NA	NA
Sal 100 m (psu)	286	0.005	0.035	0.036	–0.196	0.140	0.916	0.926	2.595

Appendix F. Test 6—ATLAS RA103, T-Flex RT004 Real Time Data Analysis

Nominal Site: 8°S, 67°E

Common Test Period: 22 July 2013 to 15 November 2014 (482 days)

While anchored, the moorings were separated by about 1.3 nm in the zonal and 2.9 nm in the meridional direction (**Figure F1**). This mooring site was not revisited for more than 2 years after these moorings were deployed. ATLAS mooring RA103 went adrift on 16 November 2014 (16 months after deployment) and eventually went ashore in the Seychelles. Its buoy, ATLAS CPU electronics and sea surface module were recovered in November 2015. All meteorological and subsurface sensors were missing. T-Flex mooring RT004 went adrift on 28 July 2015 (2 years after deployment). The T-Flex mooring was recovered on 31 October 2015, at which time a knot in the mooring wire near the 500 m TP sensor was found. The wire was damaged and broken at this point. The knot caused the 500 m instrument to be elevated about 10 m, as indicated by the recorded pressure data.

As there are no high-resolution subsurface data available from the ATLAS mooring, real-time daily averaged data are compared for this test. Daily mean data are the primary ATLAS data telemetered in real time and are computed from high-resolution data (10-min resolution for most data types) by the mooring electronics. T-Flex systems telemeter real-time data with hourly resolution. These hourly data have been averaged to daily after reception for comparison to ATLAS daily data. Thus, the daily mean data compared here were not computed from the same number of samples: 144 for ATLAS and 24 for T-Flex. High-resolution (10-min) ATLAS and T-Flex data were used in the rain analysis in section 4 above.

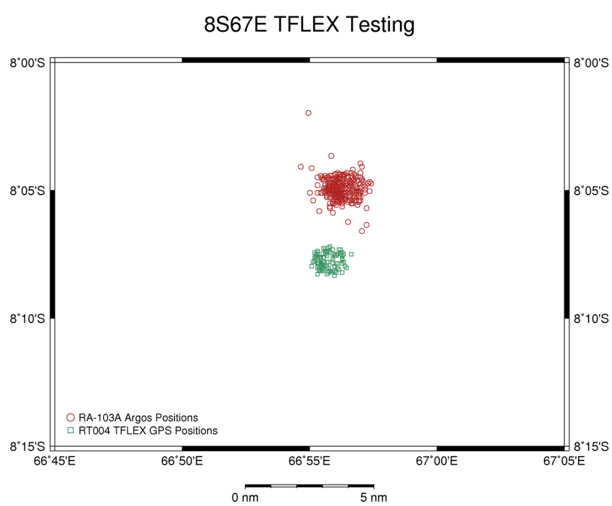

Figure F1. Mooring locations reported by Argos (ATLAS RA103) and GPS (T-Flex RT004).

Table F1. Test 6 summary of damaged, lost, or failed instruments and hardware. Subsurface sensors that failed due to battery depletion after 1 year of deployment are not considered failed.

Issue	Description
Failed ATLAS Sensor	Wind, RAIN, Sontek CM
Failed T-Flex Sensors	ATRH (water intrusion), Nortek CM, 300 m TP, 500 m TP
Lost ATLAS Sensors	All except SST/SSC and ATLAS CPU/Meteorological data logger
Damaged T-Flex Sensors	SST/SSC

Table F2. Test 6 real-time daily data difference statistics (T-Flex RT004 minus ATLAS RA103) over the common time period. Statistics were computed from daily mean data. Rain metrics were computed over all data (rain and no rain conditions). Rain metrics computed only when raining (from 10 min data) are presented in section 4 above. Post-recovery salinity QC was not performed due to loss of instruments.

	N	Δ Mean	Δ Stdv	Δ RMS	Δ Min	Δ Max	R^2	Slopes	Intercept
AT (°C)	39	0.01	0.05	0.05	–0.10	0.10	0.963	1.006	–0.166
RH (%RH)	39	–0.07	0.39	0.39	–1.10	1.00	0.988	0.981	1.549
Wind Spd (m s^{-1})	321	0.44	0.41	0.61	–0.38	2.39	0.975	1.002	–0.453
U (m s^{-1})	321	0.01	0.53	0.53	–1.21	2.04	0.992	0.922	–0.173
V (m s^{-1})	321	0.07	0.39	0.40	–1.43	1.01	0.986	0.915	0.058
Wind Dir (°)	321	0.6	13.3	13.3	–48.5	172.5	0.981	1.000	–0.572
SWR (w m^{-2})	470	–1.0	16.6	16.7	–78.3	104.9	0.936	1.012	–1.849
Rain (mm hr^{-1})	353	–0.05	0.47	0.47	–6.65	1.96	0.054	1.573	–0.047
Temp 1 m (°C)	437	0.037	0.057	0.068	–0.310	0.470	0.998	0.984	0.416
Temp 10 m (°C)	359	–0.012	0.037	0.039	–0.200	0.200	0.999	0.995	0.155
Temp 20 m (°C)	403	–0.011	0.058	0.059	–0.380	0.280	0.997	0.986	0.388
Temp 40 m (°C)	401	0.020	0.148	0.150	–0.550	0.660	0.986	1.002	–0.081
Temp 60 m (°C)	396	0.121	0.237	0.266	–0.650	1.180	0.987	0.996	–0.029
Temp 80 m (°C)	393	0.109	0.198	0.226	–0.500	0.740	0.989	0.991	0.066
Temp 100 m (°C)	391	0.031	0.132	0.136	–0.300	0.520	0.993	0.998	–0.001
Temp 120 m (°C)	391	0.036	0.125	0.130	–0.560	0.380	0.989	0.994	0.060
Temp 140 m (°C)	389	0.024	0.106	0.109	–0.530	0.360	0.988	0.982	0.252
Temp 180 m (°C)	392	0.018	0.091	0.093	–0.380	0.490	0.981	0.977	0.307
Temp 300 m (°C)	60	–0.054	0.071	0.088	–0.210	0.150	0.752	0.943	0.699
Temp 500 m (°C)	259	–0.017	0.055	0.057	–0.280	0.130	0.953	0.941	0.553
Pres 300 m (dbar)	60	–0.4	0.3	0.5	–1.0	0.4	0.918	1.137	–40.7
Pres 500 m (dbar)	258	–9.8	0.8	9.8	–11.6	–3.7	0.944	1.169	–73.0
Sal 1 m (psu)	437	–0.048	0.052	0.070	–0.359	0.100	0.990	0.992	0.334
Sal 10 m (psu)	359	0.017	0.029	0.033	–0.101	0.155	0.997	1.011	–0.398
Sal 20 m (psu)	403	0.060	0.053	0.080	–0.047	0.226	0.989	1.006	–0.285
Sal 40 m (psu)	401	0.092	0.137	0.165	–0.144	0.413	0.882	0.970	0.972
Sal 60 m (psu)	396	0.011	0.079	0.080	–0.178	0.215	0.882	1.036	–1.270
Sal 100 m (psu)	391	–0.028	0.024	0.037	–0.134	0.087	0.997	1.016	–0.525

Appendix G. Test 7—ATLAS PI199, T-Flex PT003 Limited Delayed Mode Data Analysis

Nominal Site: 20°N, 38°W

Common Test Period: 18 November 2013 to 2 December 2014 (378.1 days)

Real-time data stopped within a day of deployment from the T-Flex system. When the mooring was recovered the buoy tower was missing and little or no surface meteorological data were recorded. The ATLAS mooring line broke just below 10 m and went adrift on 2 December 2014. All instruments below 10 m and their internally recorded high-resolution data were lost. The only delayed-mode data recovered in common from both systems was water temperature and salinity at 1 m and 10 m. Test 7 was omitted from the analysis due to lack of sufficient comparable data.

Table G1. Test 7 summary of lost instruments. Subsurface sensors that failed due to battery depletion after 1 year of deployment are not considered failed.

Issue	Description
Lost ATLAS Sensors	All subsurface sensors below 10 m
Lost T-Flex Sensors	All surface meteorological sensors

Appendix H. Test 8—ATLAS PI220, T-Flex PT004 Delayed Mode Data Analysis

Nominal Site: 4°N, 23°W

Common Test Period: 23 January 2015 to 1 December 2015 (312 days)

The moorings were separated by about 1.2 nm in the zonal and 4.1 nm in the meridional direction (**Figure H1**). Both moorings were heavily fouled with long line when recovered. The 60 m ATLAS TC was missing from the mooring line. Real-time telemetered data from this instrument stopped about halfway through the deployment, presumably when the instrument was pulled from the mooring by long line.

The T-Flex mooring had an additional 10 Nortek Aquadopp current meters attached between 7 and 87 m as upper ocean current profile experiment conducted by NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML).

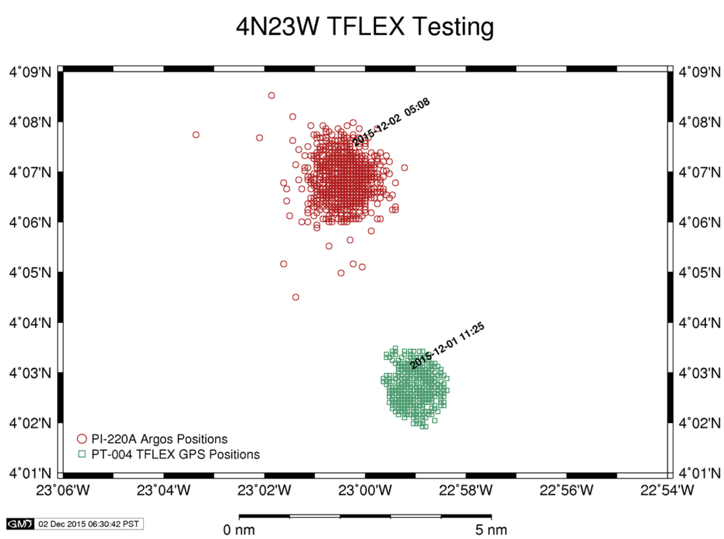

Figure H1. Mooring locations reported by Argos (ATLAS PI220) and GPS (T-Flex PT004).

Table H1. Test 8 summary of lost or failed instruments.

Issue	Description
Failed ATLAS Component	Transmitter battery, RAIN (replaced before comparison began)
Failed T-Flex Sensors	ATRH cable connector leaked
Lost ATLAS Sensors	60 m TC

Table H2. Test 8 data difference statistics (T-Flex PT004 minus ATLAS PI220) over the common time period from high temporal-resolution (2–60 m) data. SWR metrics were computed for daytime values. Rain metrics were computed over all data (rain and no rain conditions). Rain metrics computed only when raining are presented in section 4 above. Salinity data differences were computed after data QC was performed.

	N	Δ Mean	Δ Stdv	Δ RMS	Δ Min	Δ Max	R^2	Slopes	Intercept
AT (°C)	44907	0.06	0.27	0.27	–3.51	3.03	0.884	0.998	–0.001
RH (%RH)	44907	0.20	1.78	1.79	–21.87	14.49	0.878	0.949	3.949
Wind Spd (m s^{-1})	44865	0.12	0.79	0.80	–7.08	7.80	0.840	0.962	0.094
U (m s^{-1})	44865	–0.11	0.89	0.90	–7.98	8.03	0.822	1.001	0.114
V (m s^{-1})	44865	0.11	1.01	1.01	–9.73	13.57	0.958	0.991	–0.090
Wind Dir (°)	43989	1.0	18.9	19.0	–179.7	178.7	0.971	1.004	–1.886
SWR (w m^{-2})	11330	7.7	165.5	165.7	–1152.1	1168.1	0.744	0.981	0.438
Rain (mm hr^{-1})	44852	–0.025	2.693	2.693	–113.4	76.8	0.000	1.249	–0.033
Temp 1 m (°C)	44925	0.005	0.132	0.132	–0.952	1.189	0.962	1.005	–0.135
Temp 10 m (°C)	44925	0.009	0.118	0.119	–0.762	1.154	0.968	1.008	–0.233
Temp 20 m (°C)	44925	0.012	0.130	0.130	–1.899	3.256	0.965	0.993	0.181
Temp 40 m (°C)	44925	0.001	1.212	1.212	–9.465	8.857	0.669	1.007	–0.176
Temp 60 m (°C)	0	NA	NA	NA	NA	NA	NA	NA	NA
Temp 80 m (°C)	44925	–0.093	1.367	1.371	–9.689	8.509	0.844	1.007	–0.044
Temp 100 m (°C)	44925	–0.023	0.790	0.790	–6.627	7.463	0.792	1.015	–0.231
Temp 120 m (°C)	44925	0.007	0.388	0.388	–4.090	4.578	0.779	1.014	–0.216
Temp 140 m (°C)	44925	–0.032	0.254	0.256	–1.697	3..169	0.764	1.013	–0.166
Temp 180 m (°C)	44925	–0.015	0.197	0.197	–1.233	0.864	0.765	1.008	–0.094
Temp 300 m (°C)	44925	–0.003	0.306	0.306	–1.363	1.584	0.759	0.980	0.234
Temp 500 m (°C)	44925	–0.023	0.168	0.170	–0.707	0.787	0.624	0.974	0.217
Pres 300 m (dbar)	44925	0.0	0.8	0.8	–6.0	8.7	0.756	0.941	17.882
Pres 500 m (dbar)	44925	0.2	1.1	1.1	–11.0	14.9	0.866	0.934	33.068
Sal 1 m (psu)	819	–0.012	0.048	0.050	0.190	–0.281	0.817	0.882	4.204
Sal 10 m (psu)	7488	0.024	0.071	0.075	0.516	–0.622	0.944	0.970	1.048
Sal 20 m (psu)	7488	0.032	0.068	0.075	0.597	–0.422	0.943	0.978	0.753
Sal 40 m (psu)	7488	0.010	0.091	0.092	0.596	–0.670	0.878	0.981	0.675
Sal 60 m (psu)	0	NA	NA	NA	NA	NA	NA	NA	NA
Sal 100 m (psu)	7488	–0.0141	0.0263	0.0298	0.118	–0.196	0.8464	0.9341	2.358