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NOAA Technical Memorandum ERL PMEL-104

CALIBRATION PROCEDURES AND INSTRUMENTAL ACCURACY ESTIMATES OF TAO TEMPERATURE, RELATIVE HUMIDITY AND RADIATION MEASUREMENTS

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Pacific Marine Environmental Laboratory
Seattle, Washington
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Calibration Procedures and Instrumental Accuracy Estimates of TAO Temperature, Relative Humidity and Radiation Measurements

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LT Julia Neander, and Linda D. Stratton

Abstract. Calibration procedures for instruments measuring air and water temperature, humidity and shortwave radiation on Tropical Atmosphere Ocean (TAO) Array buoys are described. Initial sensor accuracy as well as drift are quantified. Improvements in calibration procedures, where necessary, are discussed.

1. INTRODUCTION

The Tropical Atmosphere Ocean (TAO) Array of moored buoys spans the tropical Pacific from longitudes 137°E to 95°W between latitudes of approximately 8°S and 8°N (Fig. 1). Moorings within the array measure surface meteorological and upper-ocean parameters and transmit most data in real time to shore via Service Argos. The array is part of the in-situ measurement portion of the Tropical Ocean-Global Atmosphere (TOGA) Program, a 10-year (1985–1994) study of climate variability on seasonal to interannual time scales, the most pronounced mode of which is the El Niño/Southern Oscillation (ENSO) phenomenon (McPhaden, 1993). The TAO array is presently supported by the United States, France, Japan, Korea and Taiwan.

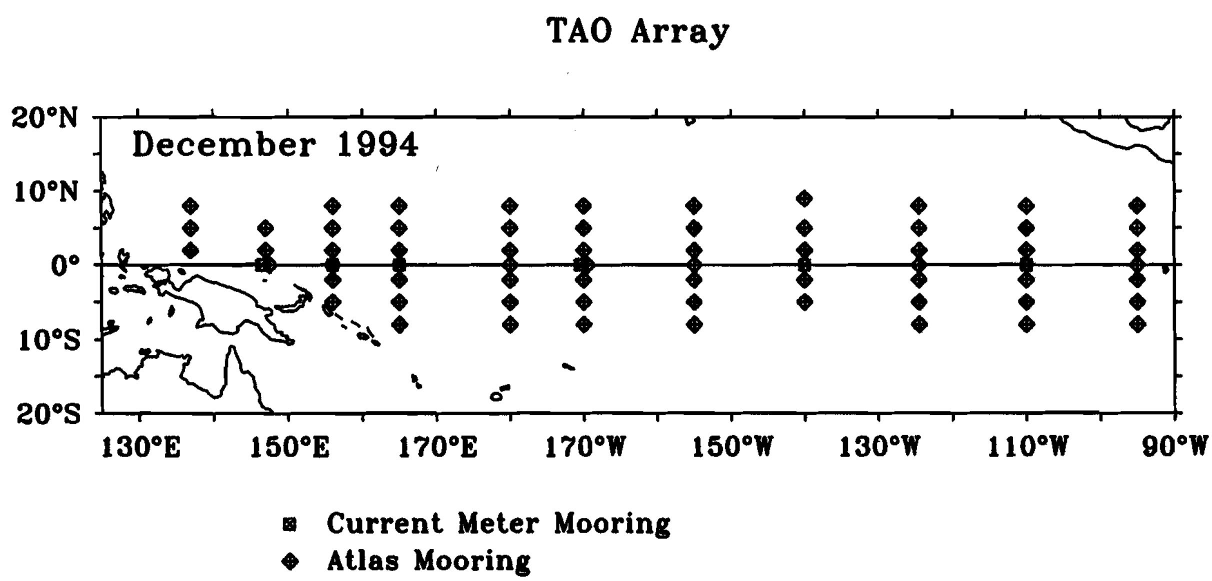

Fig. 1. Map of the tropical Pacific Ocean with location of ATLAS and PROTEUS moorings within the TAO array shown as of December 1994.

[1] Now at First Institute of Oceanography, State Oceanic Administration, P.O. Box 98, Qingdao, People's Republic of China

TAO moorings are designed, tested, calibrated and constructed at NOAA's Pacific Marine Environmental Laboratory (PMEL). TAO began in 1985 as regional-scale meridional arrays spanning the equator along 110° and 165° and has steadily expanded to its present size of approximately 70 moorings. Moorings are typically separated by 2–3 degrees of latitude and by 10–15 degrees of longitude.

The majority of TAO moorings are ATLAS moorings (Hayes *et al.*, 1991) which measure surface wind, air-temperature (AT), relative humidity (RH), sea-surface temperature (SST), subsurface temperature (SBT) and pressure (P) (Fig. 2a). ATLAS moorings are designed for a nominal 1-year deployment. At a few sites PROTEUS moorings (McPhaden *et al.*, 1990) (Fig. 2b) are deployed, which measure and transmit the same surface parameters as well as current profiles from Acoustic Doppler Current Profilers (ADCPs). Recently shortwave radiation (SWR) has been added to the real-time PROTEUS meteorological measurement suite. Surface meteorological measurements on PROTEUS moorings are made by an AMP (Argos Meteorological Package) which is similar in design to the ATLAS. In addition, internally recording temperature sensors (MTRs), temperature-conductivity sensors (Seacats; western-Pacific sites only), and mechanical current meters (MCMs) measure temperature at up to 17 depths, conductivity at up to 10 depths, and current velocity at up to 7 depths, depending on the particular mooring site. Temperature and current data from the above internally recording instruments are not available in real time. PROTEUS moorings are designed with a nominal 6-month deployment.

This report covers the calibration techniques and estimated accuracies of AT, RH, SST, SWR and SBT measurements as made on presently deployed moorings. (Other measured parameters, e.g., wind speed, will be addressed in future reports.) The sensors used to make these measurements were purchased from commercial vendors. The manufacturer, model number, and manufacturer's specifications for the sensors used are listed in Table 1. The electronics hardware and software packages which digitize and record the sensor output and pass it to the Argos transmitter were designed by PMEL's Engineering Development Division (EDD) and constructed by TAO Project technicians.

Table 1. Manufacturer, model and specifications for temperature, humidity and shortwave radiation sensors used on TOGA-TAO moorings.

Sensor	Manufacturer	Model	Specifications
AT	Rotronic Instrument Corp.	MP-100	0.5°C accuracy 0.2°C drift/year 0.2°C linearity
RH	Rotronic Instrument Corp.	MP-100	2.0% RH accuracy 1.0% RH drift/year 0.7% RH linearity
SST/SBT	Yellow Springs Instrument Co., Inc.	46006	0.2°C interchangability 0.03°C drift/year
SWR	The Eppley Laboratory, Inc.	PSP	0.5% linearity 1% temperature dependance

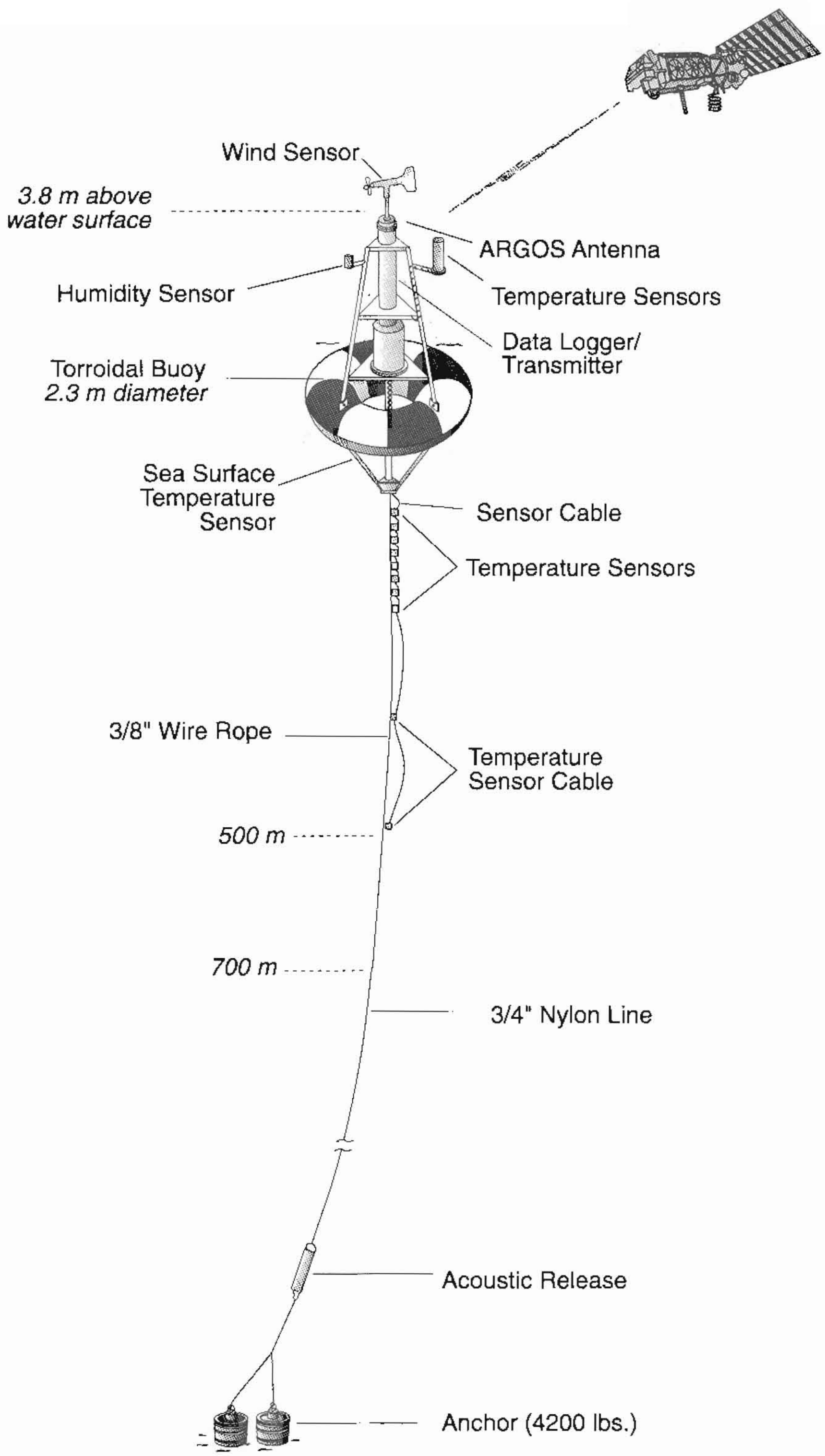

Fig. 2a. Schematic drawing of typical ATLAS mooring.

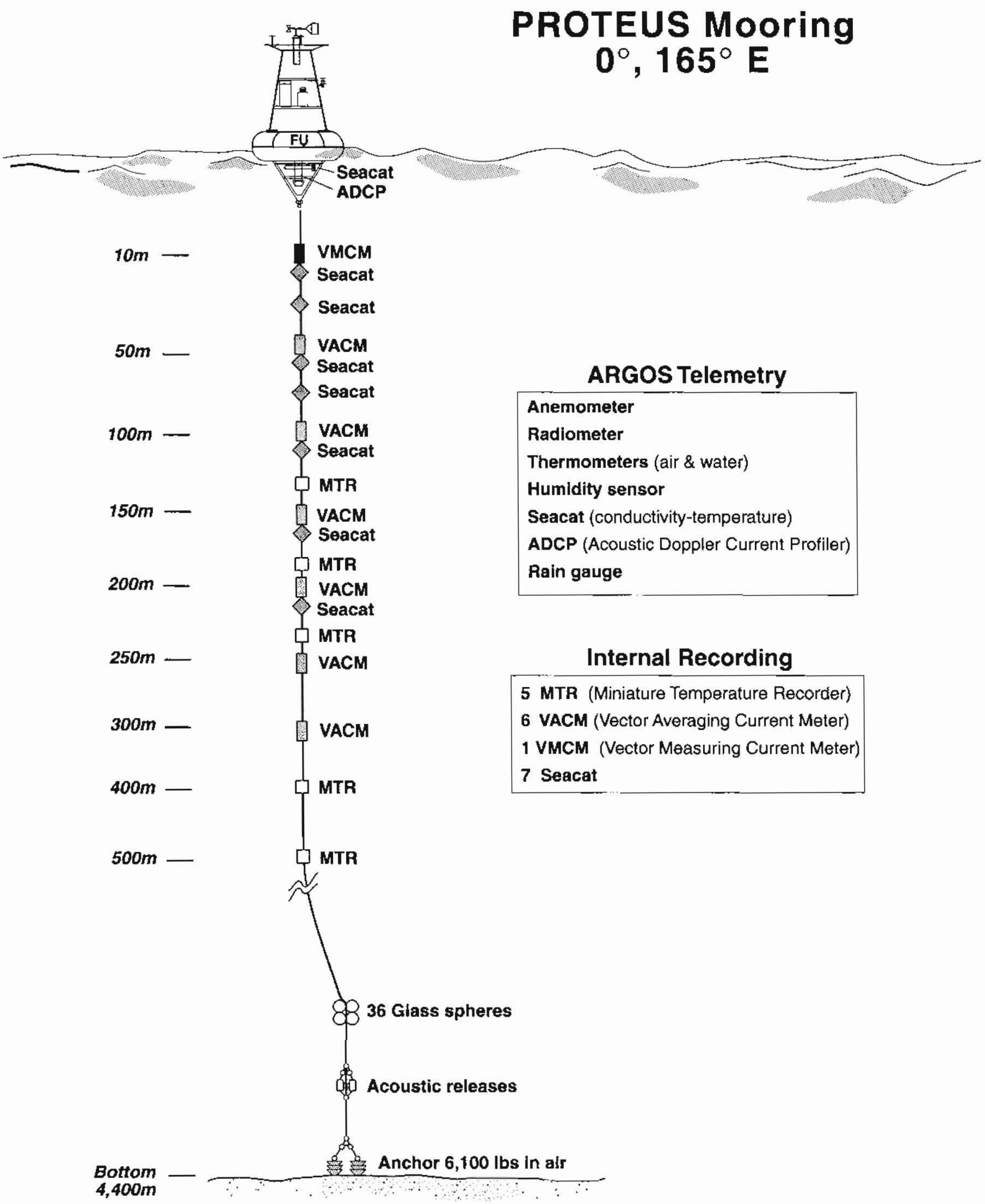

Fig. 2b. Schematic drawing of typical PROTEUS mooring.

Measurements were typically a two stage process (Fig. 3). The environment was sampled by the sensor and output as an analog signal (voltage, V, or resistance, R). The sensor output was converted and stored in digital memory by input/output (I/O) boards employing either analog to digital (A/D) or voltage to frequency (V/F) converters. Most calibrations were performed separately upon the sensor and electronics portions of the measuring systems. An exception was the SBT cable for which sensors and electronics were constructed as one and calibrated as a whole. Sensors and electronics were calibrated at PMEL with the exception of SWR sensors which were calibrated by the manufacturer.

The ATLAS and PROTEUS mooring projects were originally headed by separate principle investigators with separate support teams of technicians and programmers. Although the projects have since merged, calibrations are still performed independently and calibration data bases remain separate. (For example, ATLAS I/O board calibration coefficients are routinely scaled to be of order zero (for bias) and 1 (for gain), but have not been normalized in this report to simplify comparison with PROTEUS I/O boards.) Because of this separation and because of the different mooring design lifetimes, this report will make a distinction between like sensors (AT, SST, RH) which are used on both types of mooring. More unified and standardized procedures for calibrating ATLAS and PROTEUS moorings are presently being instituted, however, to insure a uniform quality to all TAO measurements.

This report has been organized into two major sections with each section subdivided by sensor or I/O board type. The first section defines calibration equations and describes calibration methods for each sensor or I/O board type. For each calibration the maximum residual (the largest difference between the known input and the sensor or I/O board output as calculated using the calibration coefficients) is computed. Focus is on the root-mean-square (RMS) of maximum residuals from the calibration equation computed over all calibrations of a sensor or I/O board type, which may be interpreted as an estimate of the initial sensor or board accuracy as they were deployed. The second section deals with sensor or board drift as indicated by the difference between multiple calibrations of the same sensor or board as it was used and reused on multiple deployments.

2. INDIVIDUAL SENSOR AND I/O BOARD CALIBRATIONS

2.1 Air Temperature Sensor

Air temperature measurements were made by model MP-100 humidity-temperature probes manufactured by Rotronic Instrument Corporation of Huntington, New York. Specifications pertaining to sensor accuracy given by the manufacturer are listed in Table 1. Sensors were calibrated at PMEL by immersing them in a controlled water bath and measuring their output voltage at seven temperatures over a range of 14°C to 32°C. The resultant temperature-voltage pairs were fit to a least squares linear equation. A sample calibration is included in Appendix A. Statistics from the calibration of 31 PROTEUS and 154 ATLAS AT sensors were quite similar (Table 2). The RMS maximum residual for both groups of sensors was an order of magnitude smaller than the

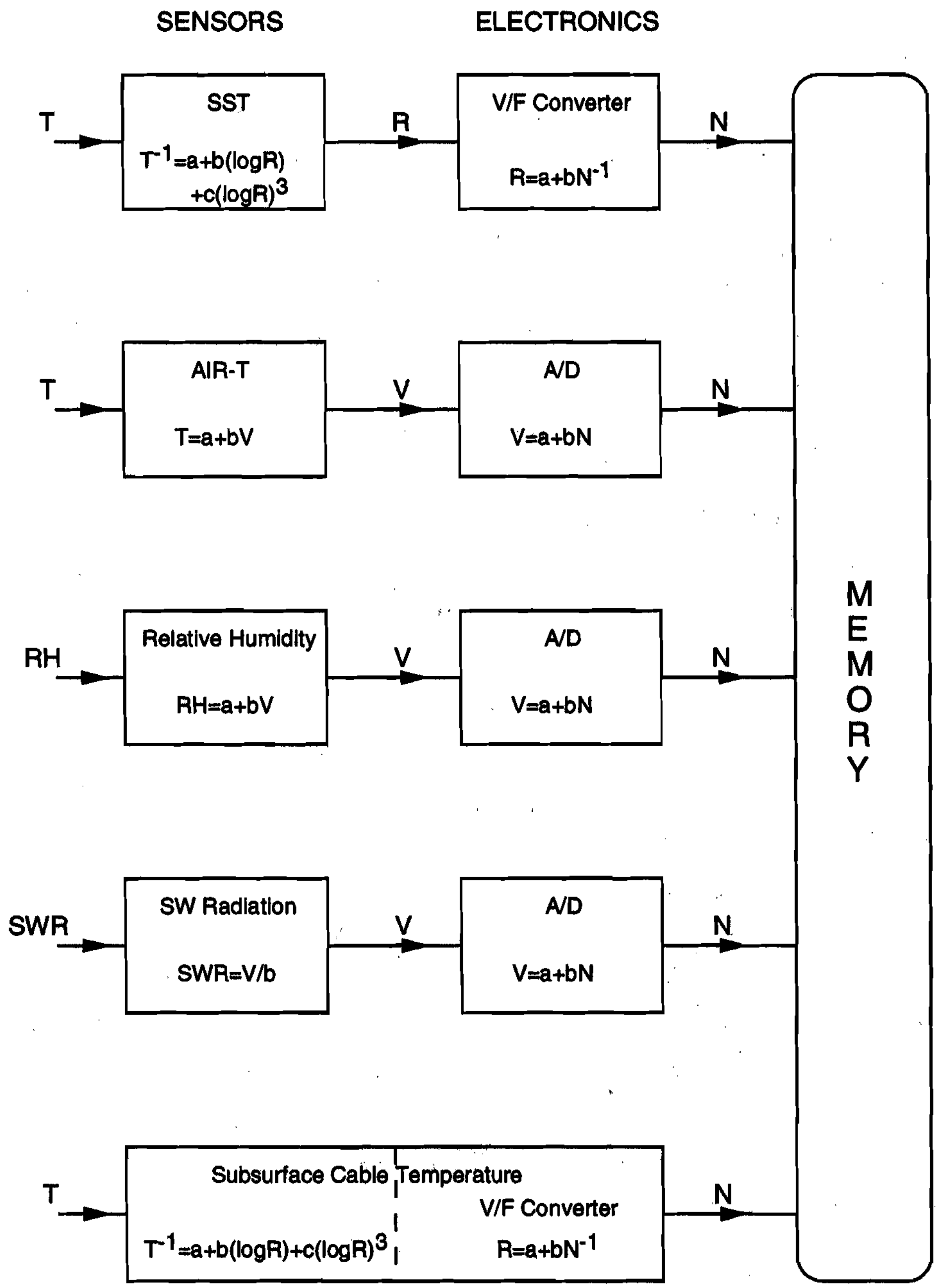

Fig. 3. Flow diagram of ATLAS/AMP operation. Boxes on left contain calibration equations relating environmental parameter (T = temperature; RH = relative humidity; SWR = shortwave radiation) to engineering units (V = voltage; R = resistance) output by sensors. Boxes in center contain calibration equations relating engineering units to number (N) stored in memory by electronic I/O boards. Calibration coefficients are denoted by a, b and c.

Table 2. Statistics for sensor calibrations. M is the number of sensors calibrated. Calibration equations are shown in Figure 3. Coefficient percent deviation is the standard deviation divided by the mean expressed as a percent.

Sensor	Mooring	M	RMS Max Residual	Coef a Mean	Coef a % Dev.	Coef b Mean	Coef b. % Dev.	Coef c Mean	Coef c % Dev.
AT	PROTEUS	31	0.038°C	0.236	174.6	98.61	1.3	—	—
	ATLAS	154	0.028°C	0.323	102.8	98.80	1.2	—	—
SST	PROTEUS	38	0.003°C	1.028×10^{-3}	1.9	5.516×10^{-4}	1.3	1.871×10^{-6}	8.0
	ATLAS	269	0.003°C	1.024×10^{-3}	3.0	5.527×10^{-4}	2.0	1.868×10^{-6}	11.3
RH	PROTEUS	33	0.70% RH	−2.79	112.5	103.2	3.6	—	—
	ATLAS	40	2.61% RH	−2.94	78.4	106.3	4.0	—	—
SWR	PROTEUS	23	—	—	—	8.63×10^{-6}	4.9	—	—
SBT	ATLAS	3666	0.002°C	1.038×10^{-3}	2.7	5.506×10^{-4}	1.7	1.925×10^{-6}	11.8

Table 3. Statistics for board calibrations. M is the number of boards calibrated. Calibration equations are shown in Figure 3. Coefficient percent deviation is the standard deviation divided by the mean expressed as a percent. Residuals have been scaled to have same units as sensors.

Board	Mooring	M	Calib. Range	1-bit Resol.	RMS Max Residual	Coef a Mean	Coef a % Dev.	Coef b Mean	Coef b % Dev.
AT	PROTEUS	34	5–40°C	0.040°C	0.019°C	4.784×10^{-4}	98.9	3.979×10^{-4}	0.3
	ATLAS	186	0–35°C	0.040°C	0.136°C	1.470×10^{-4}	325.4	3.983×10^{-4}	0.5
SST	PROTEUS	34	14–32°C	<0.001°C	0.002°C	-1.160×10^{1}	39.8	3.837×10^{8}	5.0
	ATLAS	196	14–32°C	<0.001°C	0.004°C	-1.236×10^{1}	157.1	3.813×10^{8}	4.5
RH	PROTEUS	34	10–90% RH	0.39% RH	0.17% RH	2.432×10^{-3}	62.4	3.901×10^{-3}	0.4
	ATLAS	190	0–90% RH	0.39% RH	0.26% RH	1.814×10^{-3}	78.4	3.922×10^{-3}	0.5
SWR	PROTEUS	23	115–1150 W m^{-2}	1.3 W m^{-2}	1.8 W m^{-2}	-9.110×10^{-6}	197.6	1.127×10^{-5}	1.2

manufacturer's stated accuracy of 0.5 °C and linearity of 0.2 °C. The sensor gain (coefficient b) was essentially equal for both PROTEUS and ATLAS groups and was within 1.4% of the manufacturer's nominal gain of 100. Sensor to sensor differences were small with the standard deviation of the gain being only 1% of the mean. Sensor bias (coefficient a) of 0.2 °C (PROTEUS) to 0.3 °C (ATLAS) is near the manufacturer's nominal bias of 0. The standard deviation as a percentage of the mean for coefficient a is large (>100%) for both ATLAS and PROTEUS moorings because the coefficient itself is so small.

2.2 Air Temperature I/O Board

Air temperature I/O boards have 10-bit A/D converters and were calibrated at PMEL by applying a known voltage and recording the digital output. These data were then fit to a least squares linear equation. A sample calibration is included in Appendix A. Statistics from the calibration of 34 PROTEUS and 186 ATLAS AT boards are shown in Table 3. The RMS maximum residual for the PROTEUS boards (expressed in temperature units) was 0.019 °C or half the single-bit resolution of the boards and thus as small as possible for the given resolution. This value was half the RMS maximum residual for the AT sensor. The RMS maximum residual for the ATLAS boards was significantly higher at 0.136 °C. The difference was due to the range of voltages over which the calibration was performed. Originally both groups of boards were calibrated down to 0 °C (0 volts) and both groups had comparable maximum residuals. It was noticed that the maximum residual occurred almost entirely at the 0 v value. Since this was a value that would never be experienced in the tropics the calibrations were recomputed for the PROTEUS boards after omitting this calibration point and the maximum residuals decreased to the level shown in Table 3.

Air temperature data from both PROTEUS and ATLAS moorings archived before 1994 were computed using calibration coefficients which used the 0 v value, but were surely more accurate than what the 0.136 °C residual implies since at tropical air temperatures (18–32 °C) calibration residuals were typically much lower. Data archived in 1994 and after will use calibration coefficients based on typical tropical ocean values. AT board gain (coefficient b in Table 3) was essentially equal for both PROTEUS and ATLAS groups, despite the fact that the PROTEUS calibrations omitted the 0 v data. This implies that the true accuracy of the ATLAS board was comparable to the PROTEUS.

2.3 Sea Surface Temperature Sensor

Sea surface temperature measurements were made by model 46006 thermistors manufactured by Yellow Springs Instrument Co., Inc. (YSI) of Yellow Springs, Ohio. Specifications pertaining to sensor accuracy given by the manufacturer are listed in Table 1. Sensors were calibrated at PMEL by immersing them in a controlled water bath and measuring their output resistance at seven temperatures over a range of 14 °C to 32 °C. The resultant temperature-resistance pairs were fit to a non-linear equation (Fig. 3). A sample calibration is included in Appendix A. Statistics from the calibration of 38 PROTEUS and 269 ATLAS SST sensors were quite similar (Table 2). The RMS maximum residual for both groups of sensors was nearly two orders of magnitude smaller than the manufacturer's stated interchangeability of 0.2°C. Differences between the PROTEUS and ATLAS sensors appear to be insignificant.

2.4 Sea Surface Temperature I/O Board

Sea surface temperature I/O boards converted thermistor resistance to voltage, which in turn was converted to a frequency proportional to the voltage. This frequency was then counted for 4 seconds and recorded. The boards were calibrated at PMEL by placing precision Vishay resistors on the boards and recording the output counts. This procedure was repeated at seven levels which corresponded to a temperature range of 14°C to 32°C. These data were then fit to a least squares linear equation. A sample calibration is included in Appendix A. Statistics from the calibration of 34 PROTEUS and 196 ATLAS SST boards are shown in Table 3. The RMS maximum residuals (expressed in temperature units) were 0.002°C (PROTEUS) and 0.004°C (ATLAS) and were of the same magnitude as the SST sensor residuals. SST board gain (coefficient b in Table 3) was essentially equal for both PROTEUS and ATLAS groups.

2.5 Relative Humidity Sensors

Relative humidity was measured by the same sensor (Rotronic model MP-100) used to measure AT. Specifications pertaining to sensor accuracy given by the manufacturer are listed in Table 1. Sensors were calibrated at PMEL in a manner recommended by the manufacturer. The sensors were attached to a calibration chamber into which a humidity standard was introduced. Both the calibration chamber and humidity standards were supplied by the manufacturer. The humidity standards were precisely titrated saturated-salt solutions with stated accuracies of better than 0.5% RH. Sensors were calibrated between 20% RH and 95% RH (presently modified to 50% RH to 95% RH) at 15% RH increments. A sample calibration is included in Appendix A. Calibration chambers used on the PROTEUS and ATLAS sensors differed in that the PROTEUS sensors were calibrated with the filter cap removed while ATLAS sensors are calibrated with the filter cap installed. Rotronic cautions that while a clogged filter may not produce an erroneous reading, it may significantly increase the sensor response time.

Statistics from the calibration of 33 PROTEUS and 40 ATLAS RH sensors differed more than the AT calibrations from the same sensors (Table 2). The RMS maximum residual for PROTEUS sensors was 0.07% RH, or about half the nominal accuracy of 2% RH, but the residual for ATLAS sensors was 2.6% RH which exceeded the nominal accuracy by about 30%. ATLAS sensor gain (coefficient b) was 6% higher than the nominal value of 100 while the PROTEUS gain was 3% higher than the nominal value. One explanation for this difference would be that the ATLAS sensors did not come to equilibrium (due to increased response time caused by clogged filters) before the calibration values were recorded. In any case, both of the calibration residuals were large in a relative sense when compared to those for AT and SST which were smaller than manufacturers' specifications by at least an order of magnitude.

2.6 Relative Humidity I/O Board

Relative humidity I/O boards have 10-bit A/D converters and were calibrated at PMEL by applying a known voltage and recording the digital output. These data were then fit to a least squares linear equation. A sample calibration is included in Appendix A. Statistics from the calibration of 34 PROTEUS and 190 ATLAS RH boards are shown in Table 3. The RMS maximum residuals (expressed in humidity units) were 0.17% RH (PROTEUS) and 0.26% RH (ATLAS). Both were less than the single-bit resolution of the boards. As with the AT boards it was found that maximum residuals tended to be found at the 0% RH (0 volts) calibration point. This point was omitted from the PROTEUS calibration data which may account for it being smaller than the ATLAS value. For both ATLAS and PROTEUS the RH I/O board residuals were about an order of magnitude smaller than the sensor residuals. RH board gain (coefficient b in Table 3) was about equal for both PROTEUS and ATLAS groups.

2.7 Shortwave Radiation Sensors

Shortwave radiation measurements (PROTEUS moorings only) were made with model PSP precision pyranometers manufactured by the Eppley Laboratory, Inc. of Newport, Rhode Island. Specifications pertaining to sensor accuracy given by the manufacturer are listed in Table 1. The sensors were calibrated by the manufacturer when new and were returned for recalibration after mooring recovery. The calibration procedure entailed comparing the sensor output at 700 W m^{-2} to a standard sensor. Quoting from Eppley's calibration report, these calibrations are "traceable to standard self-calibrating cavity pyrheliometers in terms of the Systems Internationale des Unites (SI units), which participated in the Seventh International Pyrheliometric Comparisons (IPCVII) at Davos, Switzerland in October 1990." Eppley specifies that the sensors are linear to 0.5% at radiation intensities up to 1400 W m^{-2}. The mean and standard deviation of calibration coefficients from 23 calibrations performed by Eppley are given in Table 2.

2.8 Shortwave Radiation I/O Board

Shortwave radiation I/O boards have 10-bit A/D converters and were calibrated at PMEL by applying a known voltage and recording the digital output. These data were then fit to a least squares linear equation. A sample calibration is included in Appendix A. Statistics from the calibration of 23 PROTEUS SWR boards are shown in Table 3. The RMS maximum residuals (expressed in radiation units) was 1.8 W m^{-2}, which is only slightly larger than the resolution of the board. By comparison, the SWR sensor's manufacturer specification of 0.5% linearity and 1% temperature dependance imply uncertainties of 5 W m^{-2} and 10 W m^{-2}, respectively, for insolation values of 1000 W m^{-2} (typical of cloudless, mid-day values in the tropics.)

2.9 Subsurface Temperature Sensors

Subsurface temperature measurements were made by the same YSI 46006 thermistor that was used for SST. Calibration procedures differed from those for SST in that SBT was calibrated as a total system, i.e., the thermistor and V/F counter were calibrated as one at 10 temperatures over a range of 6°C to 32°C. The calibration data were fit to the same non-linear equation as the SST sensor after applying a nominal gain factor to the V/F output. A sample calibration is included in Appendix A. The RMS maximum residual from the calibration of 3666 ATLAS SBT sensors of 0.002°C was smaller than the RMS residual for SST sensors (Table 2). One reason for the lower SBT residual may be that the number of SBT sensors calibrated was an order of magnitude larger than that for SST sensors and therefore less weight was given to outliers.

3. SENSOR AND I/O BOARD DRIFT

When instrumentation was recovered in working condition it was returned to PMEL for post-deployment calibration before being reused on a future deployment. Damage to some instruments by electronic component failure, vandalism, harsh environmental conditions, loss of mooring or seal failures prevented post-deployment calibrations in some cases. When post-deployment calibrations were made, the resultant coefficients were compared to the pre-deployment coefficients in the following manner. A set of output values were computed by application of the calibration equation using pre-deployment coefficients to a set of input values. Input values were chosen so that the output values would range over normal environmental conditions. A second set of output values were generated by application of the calibration equation using post-deployment coefficients to the same set of input values. The first output values were then subtracted from the second output values. Mean and RMS differences over the full output range and for all calibration pairs are given in Table 4. Similar statistics for I/O boards are given in Table 5. Plots of individual sensor or I/O board calibration differences are in Appendix B.

3.1 Air Temperature Sensor

RMS AT sensor calibration differences (Table 4) were similar for both PROTEUS and ATLAS groups with values of 0.154°C (PROTEUS) and 0.168°C (ATLAS). These values were roughly four times larger than the RMS maximum residual for AT sensors (Table 2), indicating that the differences were significant. Mean differences were roughly 4 times smaller than RMS differences and of different sign for the two groups, indicating that there was no preferred direction for sensor drift.

3.2 Air Temperature I/O Board

PROTEUS AT I/O boards had a RMS difference between calibration pairs of 0.046°C (Table 5), about 2.4 times the RMS maximum residual of single calibrations (Table 3), indicating that the boards drifted measurably over time. The mean drift of –0.021°C was smaller than the

Table 4. Differences between pre- and post-deployment sensor calibrations.

Sensor	Mooring	Units	Calibration Pairs	Mean days between calib.	Deployments	Deployment Days	Range	Mean Difference	RMS Difference
AT	PROTEUS	°C	12	330	9	168	15–30	–0.032	0.154
	ATLAS	°C	40	463	19	293	15–30	0.041	0.168
SST	PROTEUS	°C	21	335	10	179	15–30	0.002	0.014
	ATLAS	°C	99	479	84	308	15–30	0.009	0.030
RH	PROTEUS	% RH	13	405	12	181	60–100	–0.32	1.77
	ATLAS	% RH	12	531	12	335	60–100	0.94	4.04
SWR	PROTEUS	$W\ m^{-2}$	8	451	7	157	700	11.8	13.7
SBT	ATLAS	°C	826	454	156	312	5–30	–0.033	0.094

Table 5. Differences between pre- and post-deployment I/O board calibrations.

Board	Mooring	Units	Calibration pairs	Mean days between calib.	Range	Mean Difference	RMS Difference
AT	PROTEUS	°C	14	328	15–30	–0.021	0.046
	ATLAS	°C	71	404	15–30	–0.041	0.113
SST	PROTEUS	°C	14	328	14–33	0.001	0.003
	ATLAS	°C	62	400	14–33	0.001	0.005
RH	PROTEUS	% RH	14	329	60–100	–0.01	0.07
	ATLAS	% RH	68	448	60–100	0.27	0.48
SWR	PROTEUS	$W\ m^{-2}$	8	353	64–1035	–4.6	7.7

single bit resolution, thus it cannot be said that the boards had a preferred drift direction. Statistics for ATLAS I/O boards were larger than for PROTEUS boards presumably because of the inclusion of the 0 v calibration point in their calibration procedure (see discussion in the AT board individual calibration section above). In fact, the RMS difference between calibration pairs, 0.113 °C, was smaller than the RMS maximum residual of single calibrations, 0.136 °C, indicating no significant change between calibrations. However, PROTEUS calibrations (which do not include the 0 v calibration point) should be regarded as a more accurate indication of board performance.

3.3 Sea Surface Temperature Sensor

RMS SST sensor calibration differences (Table 4) were significantly larger than the individual calibration residuals, indicating that measurable drift occurred between calibrations. RMS PROTEUS SST sensor differences (0.014 °C) were almost 5 times larger than the RMS maximum residual (Table 2), while ATLAS sensor differences (0.030 °C) were 10 times larger than RMS maximum residual. Although ATLAS RMS calibration differences were twice as large as those for PROTEUS sensors, they equaled the manufacturer's specified drift of 0.03 °C per year. Mean differences were roughly 4 to 7 times smaller than RMS differences indicating that there was little or no preferred direction for sensor drift. The larger differences for ATLAS sensors may be in part due to the fact that they are deployed 1.7 times longer than PROTEUS sensors, which is roughly the same as the ratio between ATLAS and PROTEUS RMS difference. There was a significant, yet small, correlation ($r = 0.27$) between the absolute drift and the time between calibration for ATLAS SST sensors (Fig. 4). Application of the regression slope to the mean difference in deployment days would account for about one third of the 0.016 °C difference. Other sources for the larger drift for ATLAS SST sensors could be errors in the calibration coefficient data base. The large number of sensors involved may increase the likelihood of a sensor ID number being entered in error, or a sensor being modified without being noted in the data base.

3.4 Sea Surface Temperature I/O Board

RMS SST I/O board calibration differences were relatively small and only 0.001 °C larger than the RMS maximum residual of the individual calibrations, indicating that SST board drift, if present, was small relative to calibration uncertainty. SST board drifts were likewise small compared to SST sensor drifts.

3.5 Relative Humidity Sensor

RMS RH sensor calibration differences (Table 4) for both PROTEUS and ATLAS sensors were twice as large as their respective individual calibration residuals, indicating that measurable differences occurred between calibrations. ATLAS sensor RMS differences (4.04% RH) were about

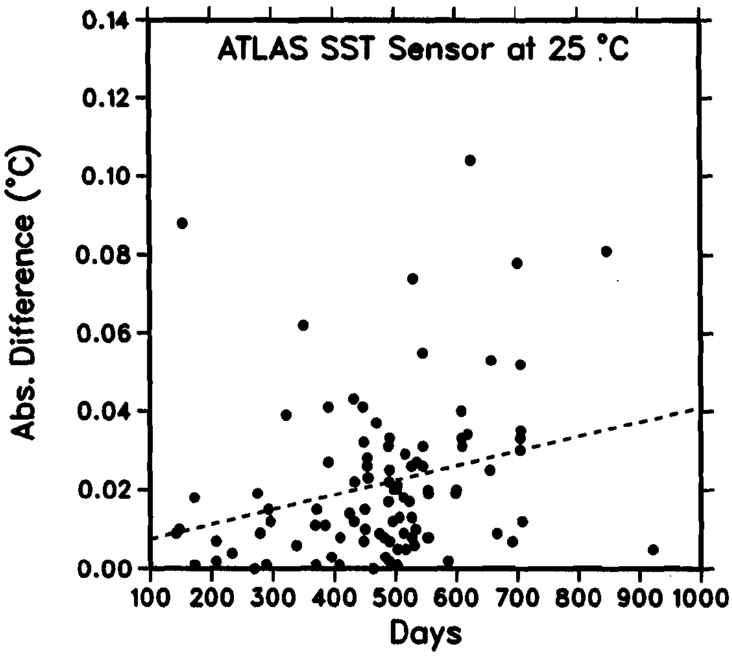

Fig. 4. Absolute value of ATLAS SST sensor calibration differences at 25°C vs. the number of days between calibrations. The dashed line is a least squares fit to the data. The correlation coefficient for the fit is 0.27.

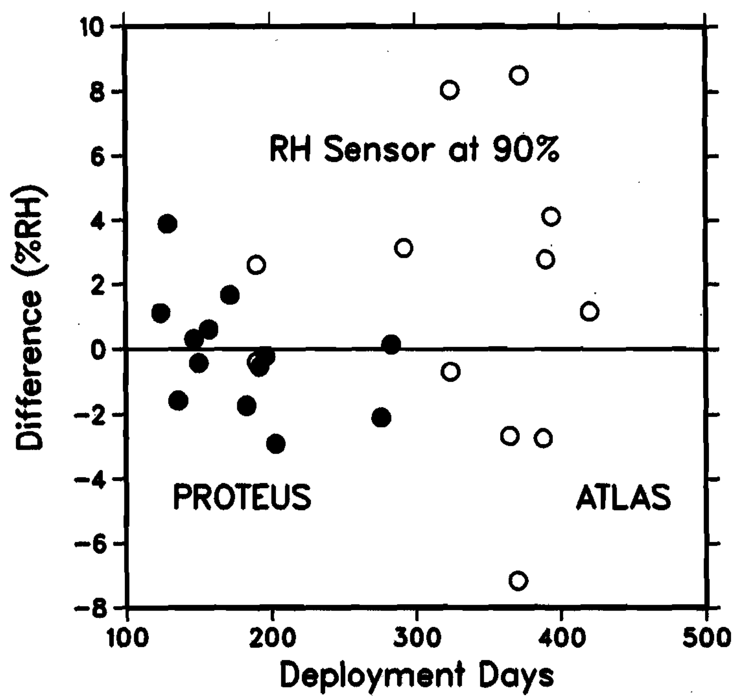

Fig. 5. PROTEUS (●) and ATLAS (○) relative humidity sensor calibration differences at 90% RH vs. the number of days the sensors were deployed at sea.

twice as large as those for PROTEUS sensors (1.77% RH). Mean differences were positive (0.94% RH) for ATLAS sensors, but negative (–0.32% RH) for PROTEUS sensors. The cause of these differences is not readily obvious. Positive differences would result if post-deployment calibrations were not allowed to equilibrate before readings were taken. PROTEUS RH sensors were calibrated with the filters removed, while ATLAS RH sensors were calibrated in the filters installed. As noted above, clogged filters could significantly increase the sensor response time. Since ATLAS RH sensors were on average deployed for relatively long periods (335 days as opposed to 181 days for PROTEUS sensors) it could be that they became more fouled (e.g., from sea spray induced salt incrustation) due to longer deployments. While large calibration differences did occur on ATLAS sensors which had been deployed longer than 300 days, these large differences were both negative and positive (Fig. 5).

3.6 Relative Humidity I/O Board

RMS RH I/O board calibration difference of 0.07% RH for PROTEUS boards was less than half that of the RMS maximum residual for individual board calibrations, which indicates that no measurable drift in RH board calibration occurred between calibrations. On the other hand, ATLAS RH board RMS difference between calibration pairs was much larger (0.48% RH) and nearly double its RMS maximum residual for individual board calibrations. The reason for the difference between PROTEUS and ATLAS boards is unclear, but may be related to the fact that calibration coefficients for ATLAS boards include the voltage = 0 calibration point, while PROTEUS boards do not. Nevertheless, RH I/O board drift for both PROTEUS and ATLAS boards were an order of magnitude smaller than the drift of the RH sensors.

3.7 Shortwave Radiation Sensors

As noted above, shortwave radiation sensor calibrations were performed by the manufacturer. Eight sensors have been calibrated more than once. RMS SWR sensor calibration difference was 13.7 W m^{-2} (Table 4) at 700 W m^{-2}, implying a relative accuracy of about 2%. With the exception of one sensor all drifts were in the same direction, resulting in a mean difference (11.8 W m^{-2}) comparable to the RMS. The sense of the drift is that pre-deployment calibration coefficients would underestimate radiation towards the end of the record. Eppley does not specify drift characteristics for this sensor, but informally the manufacturer suggests that in a tropical marine environment the drift could be as much as 2.5% per year (George Kirk, personal communication). Drift is the result of the black lacquer coating on the sensor fading. Our mean drift of 1.7% (11.8 W m^{-2} at 700 W m^{-2}) normalized over 157 mean deployment days would exceed 2.5% per year, but this could be due to the fact that the drift rate is maximum when the sensor is new and should decrease as the sensor ages (ibid.).

3.8 Shortwave Radiation I/O Board

RMS SWR I/O board calibration difference was 7.7 W m^{-2}, four times the individual calibration RMS maximum residual, indicating that measurable differences occurred between calibrations. It should be noted though that the SWR board measures relatively small voltages (order 10 μv resolution, 10 mv full scale). The RMS calibration difference of 7.7 W m^{-2} is roughly 6 bits or 60 μv which may be beyond the accuracy of the PMEL test equipment as presently used. At this level of accuracy it would be necessary to calibrate the PMEL voltage sources against a more accurate standard on a periodic basis and to monitor their output during each board calibration.

3.9 Subsurface Temperature Sensors

Subsurface temperature sensor calibration differences (Table 4) are significantly larger than individual calibration uncertainties, indicating that measurable drift has occurred between calibrations. RMS difference of 0.094°C was 3 times that for the ATLAS SST sensor and the manufacturer's specification for annual drift. Some of the difference could be due to outliers (Appendix B) in the calibration database. Additionally, since the SBT sensors and I/O boards are calibrated as one, some of the increased drift could be due to the I/O boards. While the SBT V/F converters are the same ones used in the SST I/O boards (which exhibited RMS differences of 0.005°C) they are used in a different fashion. These include being physically mounted in a different manner, being exposed to pressures of up to 500 dbar and using different logic to convert their output. The SBT circuitry included a precision Vishay resistor which is used periodically to check circuit stability. Preliminary evaluation of the Vishay records indicate that measured resistances begin to drift a few weeks after deployment, rising typically to (a temperature equivalent of) 0.1°C, but on occasion to as large as 0.3°C. These drifts decrease on recovery, but can be as large as 0.1°C at the time of post-deployment calibration. This apparent drift in the SBT V/F boards has little affect on first-deployment data quality as the drift in Vishay resistance is used to correct the output SBT values in the TAO database. Vishay resistances were not used during calibration and therefore would affect calibration differences. Thus the apparent SBT drift of 0.094°C in Table 4 is probably too large. Second-deployment (and later) data would be adversely affected by the overestimation of drift as their calibration coefficients would include this drift.

4. SUMMARY

The following generalizations and conclusions may be drawn from the above discussion.

- Calibration residuals for sensors were generally equal to or larger than calibration residuals for I/O boards.
- Pre/post-deployment calibration differences (drifts) were generally equal to or larger than calibration residuals.

- Sensor calibration differences (drifts) were generally larger than I/O board drift.
- AT and SST sensors performed as well as or better than specified by the manufacturer.
- SBT sensor-board systems did not meet the specifications of the sensor manufacture. An apparent drift in the SBT board which caused this large calibration drift probably has less affect on the data itself. A modification of the calibration procedure may improve the error estimate.
- While no drift specifications are published for the SWR sensor, our experience was similar to what the manufacturer has informally suggested under conditions on TAO moorings.
- The RH sensor drift was 4 times larger than the manufacturer's specifications. We believe the larger than expected error was due to a combination of calibration method and environmental fouling of the sensors.

The combined effect of board and sensor drifts shown in Table 6 is computed as (board drift^2 + sensor drift^2)$^{1/2}$, where it is assumed that board and sensor drifts are independent of one another. PROTEUS AT combined error was 80% of the ATLAS value. We speculate that the ATLAS value would approach the PROTEUS value if the ATLAS I/O board calibration coefficients were computed in a fashion similar to the PROTEUS. PROTEUS SST and RH combined errors were half those for ATLAS. Possible reasons for the larger ATLAS values include longer ATLAS deployments (both SST and RH), errors in the calibration data base (SST only), and calibration procedures (RH only).

Table 6. Combined instrumental error for each measured parameter.

Measured Parameter	PROTEUS Instrumental Error	ATLAS Instrumental Error
AT	0.161°C	0.202°C
SST	0.014°C	0.030°C
RH	1.77 % RH	4.07% RH
SWR	15.7 W m^{-2}	—
SBT	—	0.094°C

5. CONCLUSIONS

This study quantified calibration accuracy and sensor performance on ATLAS and PROTEUS moorings of the TAO Array and in most cases found that measurement errors met the specifications of the sensor's manufacturers. In addition, this study highlighted the need for modification in calibration procedures. ATLAS air temperature I/O board calibrations, for example, no longer include a 0°C calibration point. Also, the RH sensor calibration method described above is fairly time consuming and labor intensive. PMEL technicians have found that at higher humidity values the sensor response time is much longer than that quoted by the manufacturer. A calibration over the range 20% RH to 95% RH can take an elapsed time of 1 day and only one sensor can be used per calibration chamber. In order to decrease the time required for sensor calibration and to hopefully decrease errors in the calibration procedure, we have modified humidity calibrations in two ways. First, calibrations will only be performed over the range 50% RH to 95% RH since tropical humidity rarely (if ever) is below 50% RH. Secondly, a series 2500 Humidity Generator has been purchased from Thunder Scientific Corp. of Albuquerque, New Mexico. This chamber can accommodate up to 20 sensors at once and can be monitored and controlled by an unattended computer program. A series of experiments will be conducted to more accurately determine sensor response time and the effect of the filter presence and condition.

As a result of our study, ATLAS RH data based on the previous calibration techniques have been recomputed using the manufacturer's specified coefficients as we sense that these will give better values than the 4% error indicated in Table 4. Nevertheless, we adhere to 4% as a conservative error for ATLAS RH measurements for the present, but expect that future calibrations will lower this error estimate.

6. ACKNOWLEDGMENTS

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7. REFERENCES

Hayes, S.P., L.J. Mangum, J. Picaut, A. Sumi, and K. Takeuchi (1991): TOGA-TAO: A moored array for real-time measurements in the tropical Pacific Ocean. *Bull. Am. Meteorol. Soc., 72*, 339–347.

McPhaden, M.J. (1993): TOGA-TAO and the 1991–93 El Niño-Southern Oscillation Event. *Oceanography, 6*, 36–44.

McPhaden, M.J., H.B. Milburn, A.I. Nakamura, and A.J. Shepherd (1990): PROTEUS—Profile Telemetry of Upper Ocean Currents. In: *Proceedings of the Marine Tech. Soc. Conference*, September 25–28, 1990, The Marine Technology Society, Washington, D.C., 353–357.

APPENDIX A: Sample calibrations

Sample air temperature sensor calibration

AT208, 28 FEB 94

Calib. Coefficients
a = 0.7129376E-01
b = 0.1003214E+03

---volts---	--------temperature °C---------		
	bath	sensor	residual
0.138300002	13.9662	13.9457	0.0205
0.168599993	16.9667	16.9855	-0.0188
0.198200002	19.9655	19.9550	0.0105
0.228400007	22.9657	22.9847	-0.0190
0.258199990	25.9665	25.9743	-0.0078
0.287999988	28.9651	28.9639	0.0012
0.317799985	31.9668	31.9534	0.0134

MAXIMUM RESIDUAL = 0.0205
STANDARD ERROR = 0.0172

Sample air temperature i/o board calibration

AP09 I/O, BOARD 4 AIR TEMP.

Calib. Date: 250692

Calib. Coefficients
a = 0.5541608E-03
b = 0.3976892E-03

----counts----		------------volts-------------		
hex	decimal	input	output	residual
7c	124.	0.0500	0.0499	0.0001
fa	250.	0.1000	0.1000	0.0000
178	376.	0.1500	0.1501	-0.0001
1f6	502.	0.2000	0.2002	-0.0002
273	627.	0.2500	0.2499	0.0001
2f1	753.	0.3000	0.3000	0.0000
36f	879.	0.3500	0.3501	-0.0001
3ec	1004.	0.4000	0.3998	0.0002

MAXIMUM RESIDUAL = -0.00019
STANDARD ERROR = 0.00014

Sample humidity sensor calibration

RH208, 16 FEB 94

Calib. Coefficients
a = -0.1165664E+02
b = 0.1094899E+03

---volts---	--------humidity %RH--------		
	chamber	sensor	residual
0.561999977	50.00	49.88	0.12
0.702199996	65.00	65.23	-0.23
0.836399972	80.00	79.92	0.08
0.973900020	95.00	94.98	0.02

MAXIMUM RESIDUAL = -0.0023
STANDARD ERROR = 0.0019

Sample humidity i/o board calibration

AP09 I/O, BOARD 4 HUMIDITY

Calib. Date: 250692

Calib. Coefficients
a = 0.1743969E-02
b = 0.3906189E-02

----counts----		------------volts------------		
hex	decimal	input	output	residual
19	25.	0.1000	0.0994	0.0006
33	51.	0.2000	0.2010	-0.0010
4c	76.	0.3000	0.2986	0.0014
66	102.	0.4000	0.4002	-0.0002
80	128.	0.5000	0.5017	-0.0017
99	153.	0.6000	0.5994	0.0006
b3	179.	0.7000	0.7010	-0.0010
cc	204.	0.8000	0.7986	0.0014
e6	230.	0.9000	0.9002	-0.0002

MAXIMUM RESIDUAL = -0.00174
STANDARD ERROR = 0.00116

Sample sea-surface temperature sensor calibration

CALIBRATION OF - ST203

Calib. Coefficients
a = 0.1027520E-02
b = 0.5515591E-03
c = 0.1874862E-05

resistance Ω	-------temperature °C-------		
	bath	sensor	residual
15857.00000	13.9480	13.9492	-0.0012
13958.00000	16.9470	16.9459	0.0011
12311.00000	19.9470	19.9453	0.0017
10880.00000	22.9460	22.9466	-0.0006
9635.00000	25.9460	25.9474	-0.0014
8550.00000	28.9450	28.9462	-0.0012
7602.00000	31.9460	31.9446	0.0014

MAXIMUM RESIDUAL = 0.0017
STANDARD ERROR = 0.0017

Sample sea-surface temperature i/o board calibration

AP09 I/O, BOARD 4 SST

Calib. Date: 250692

Calib. Coefficients
a = -0.1271209E+02
b = 0.3829800E+09

		-------------ohms-----------------		
counts	counts^{-1}	input	output	residual
5eac	0.412609E-04	15790.0000	15789.4004	0.5996
6b87	0.363280E-04	13900.0000	13900.1738	-0.1738
79e5	0.320461E-04	12260.0000	12260.3213	-0.3213
89d7	0.283390E-04	10840.0000	10840.5771	-0.5771
9b8b	0.251136E-04	9605.0000	9605.3096	-0.3096
af45	0.222871E-04	8523.0000	8522.8027	0.1973
c513	0.198212E-04	7579.0000	7578.4160	0.5840

MAXIMUM RESIDUAL = 0.59961
STANDARD ERROR = 0.51027

Sample shortwave radiation i/o board calibration

AP09 I/O, BOARD 4 EPPLY

Calib. Date: 250692

a = -0.3015973E-04
b = 0.1131375E-04

----counts----		------------volts------------		
hex	decimal	input	output	residual
5b	91.	0.001000	0.000999	0.000001
b4	180.	0.002000	0.002006	-0.000006
10c	268.	0.003000	0.003002	-0.000002
164	356.	0.004000	0.003998	0.000002
1bc	444.	0.005000	0.004993	0.000007
215	533.	0.006000	0.006000	0.000000
26d	621.	0.007000	0.006996	0.000004
2c6	710.	0.008000	0.008003	-0.000003
31e	798.	0.009000	0.008998	0.000002
377	887.	0.010000	0.010005	-0.000005

MAXIMUM RESIDUAL = 0.00001
STANDARD ERROR = 0.00000

Sample subsurface temperature sensor calibration

Thermistor Cable Calibration - 5023

R = 3.072E+08/Counts

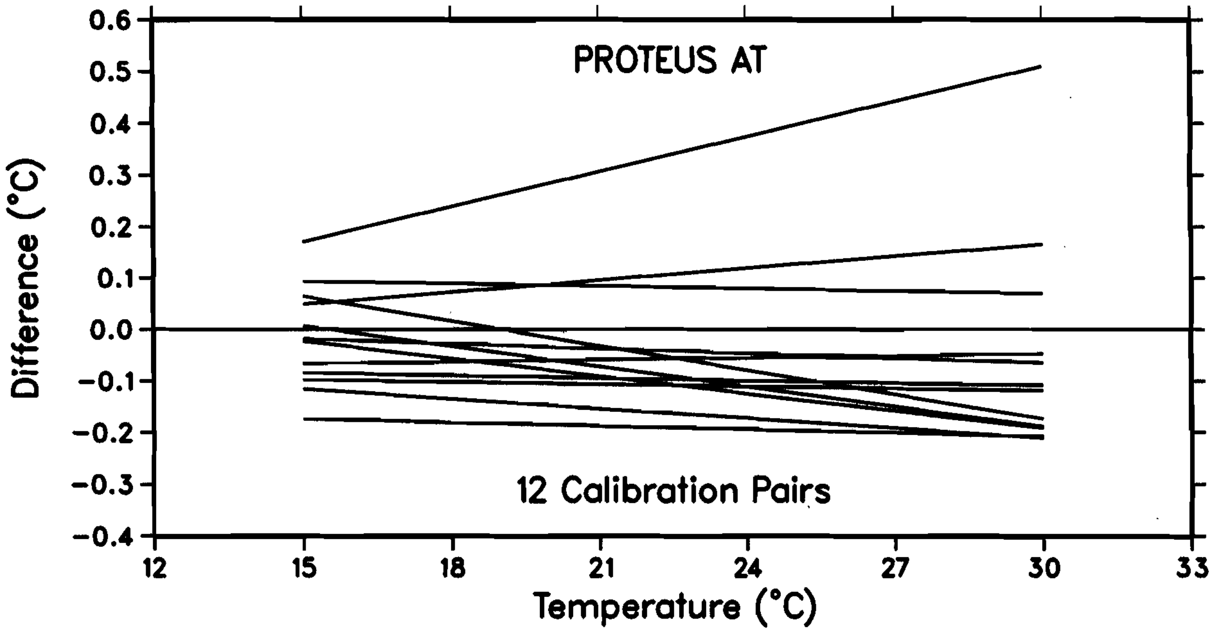
Calib. Coefficients
a = 0.1006436E-02
b = 0.5613413E-03
c = 0.1673951E-05

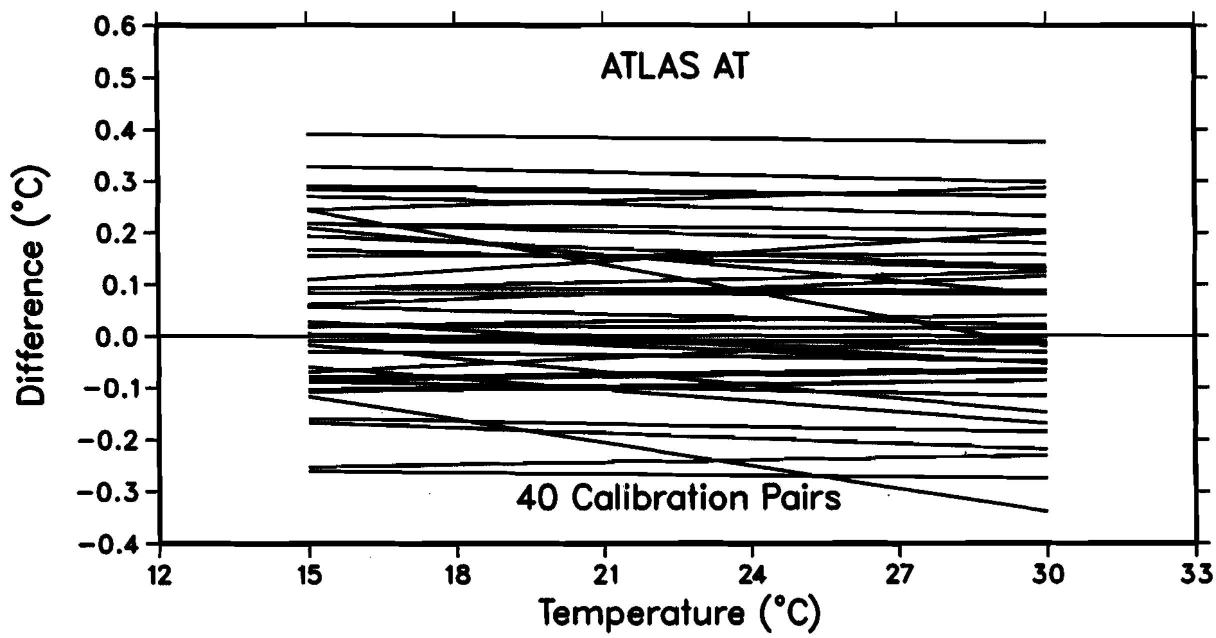
	---Resistance Ω-----		-----Temperature °C---------		
Counts	R	output	bath	sensor	residual
362F	13871	22146.92578	5.9470	5.9471	-0.0001
3B43	15171	20249.16016	7.9470	7.9473	-0.0003
43A7	17319	17737.74414	10.9480	10.9474	0.0006
4D0E	19726	15573.35449	13.9470	13.9473	-0.0003
5792	22418	13703.27441	16.9480	16.9478	0.0002
634D	25421	12084.49707	19.9480	19.9473	0.0007
705F	28767	10678.90332	22.9480	22.9484	-0.0004
7EE6	32486	9456.38086	25.9490	25.9495	-0.0005
8F02	36610	8391.15039	28.9490	28.9496	-0.0006
A0D9	41177	7460.47559	31.9510	31.9503	0.0007

Maximum Residual = 0.0007
Standard Error = 0.0006

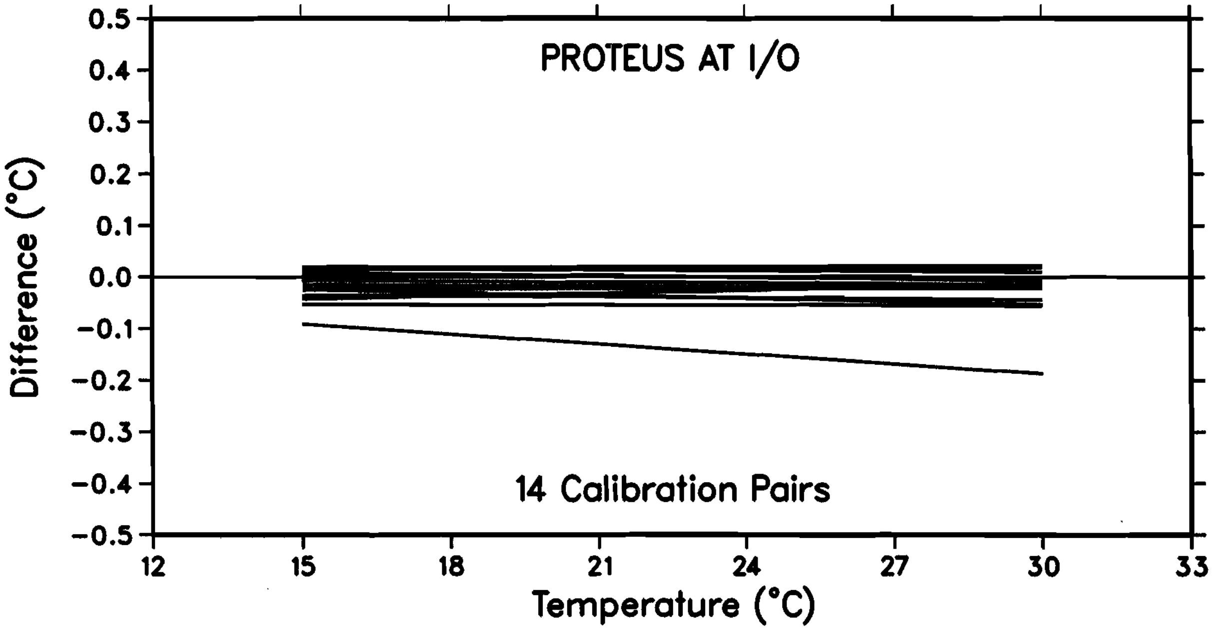
APPENDIX B: Calibration Differences

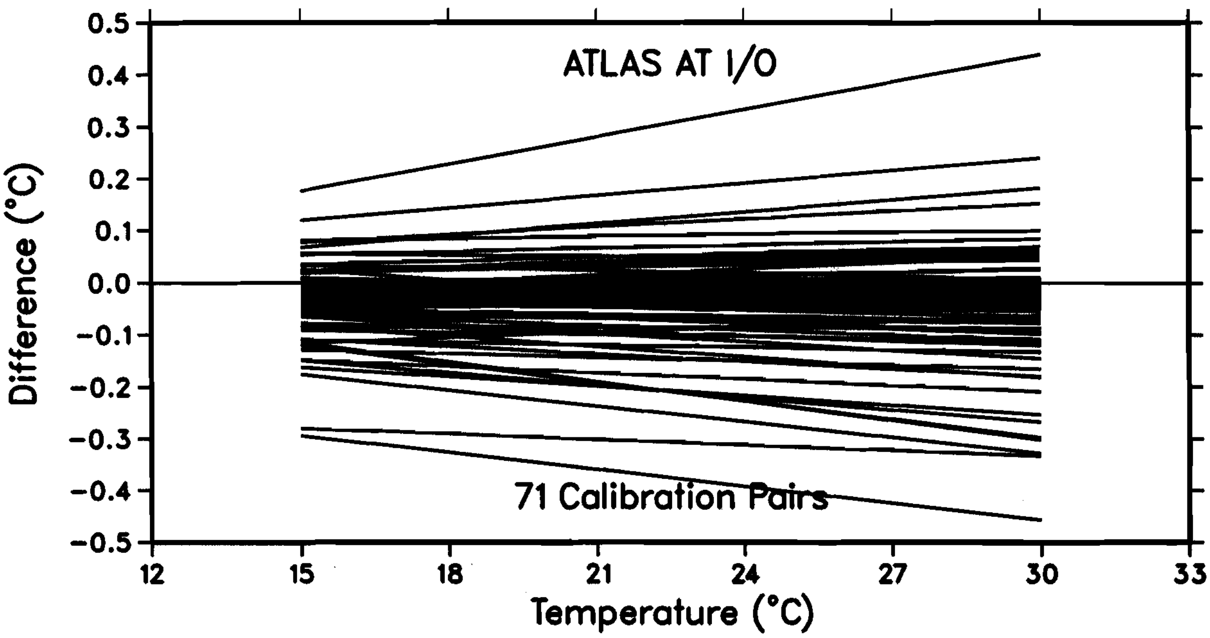
Plots of individual sensor and I/O board calibration differences across the entire measurement range.



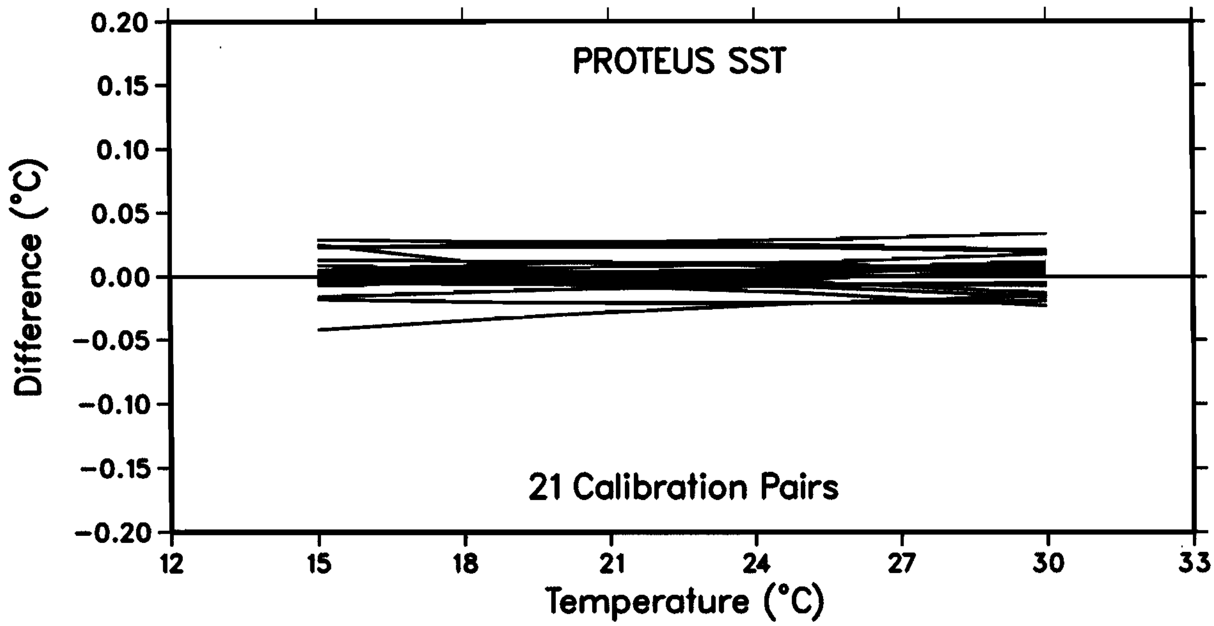


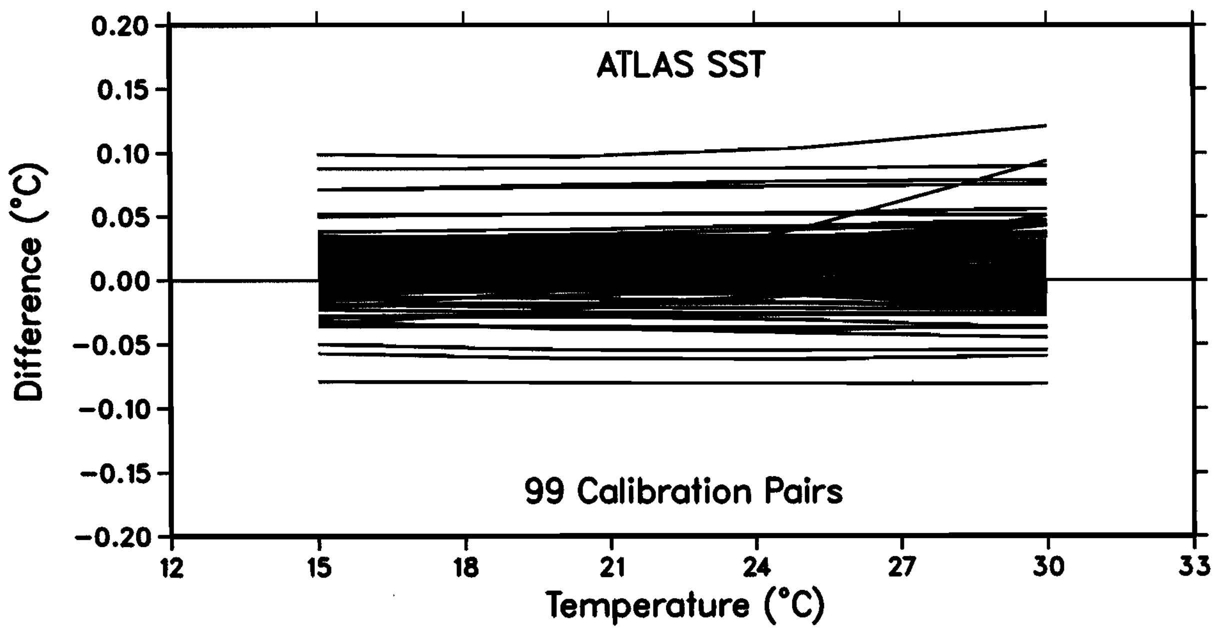
Air temperature sensor calibration differences.



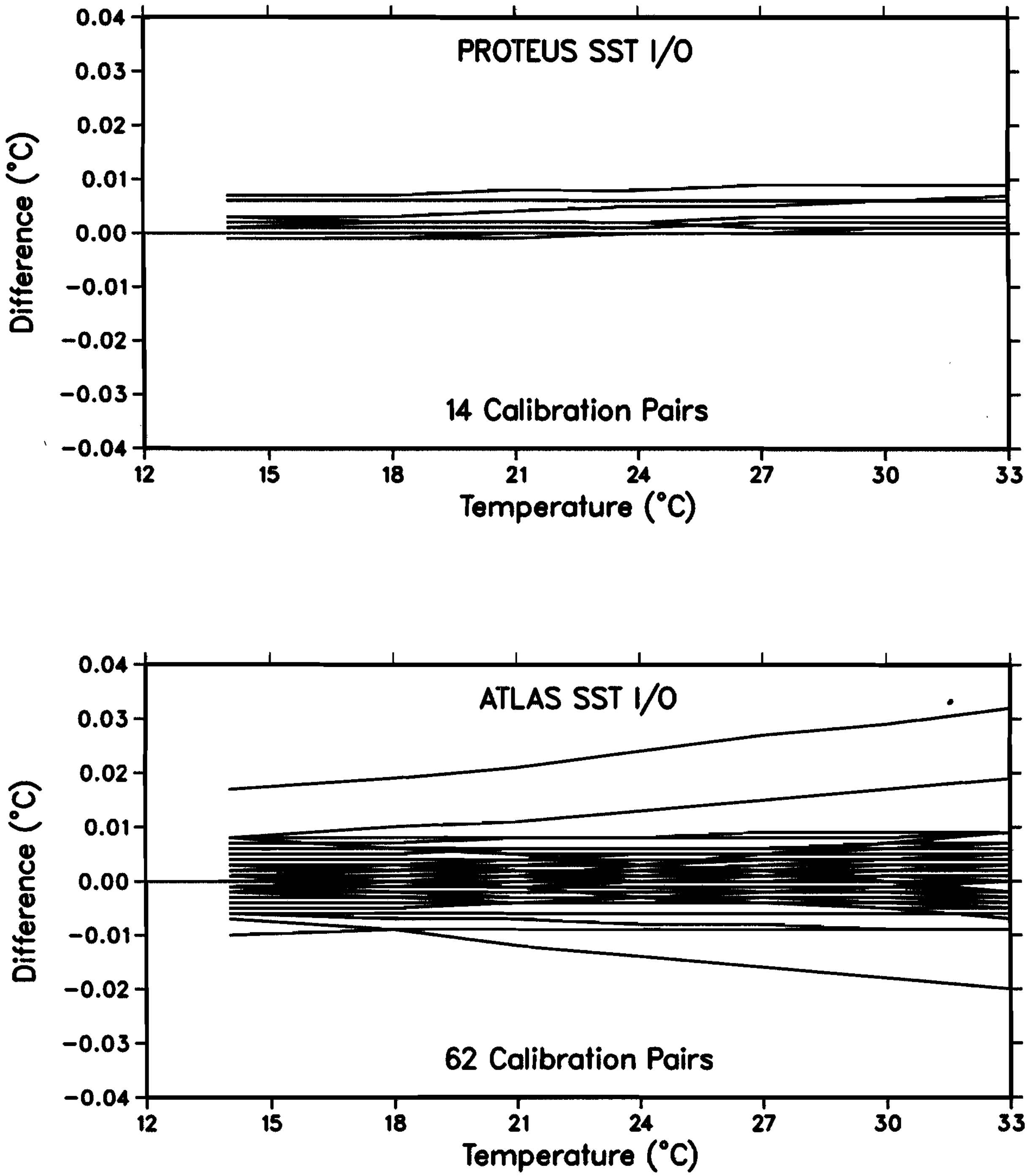


Air temperature I/O board calibration differences.

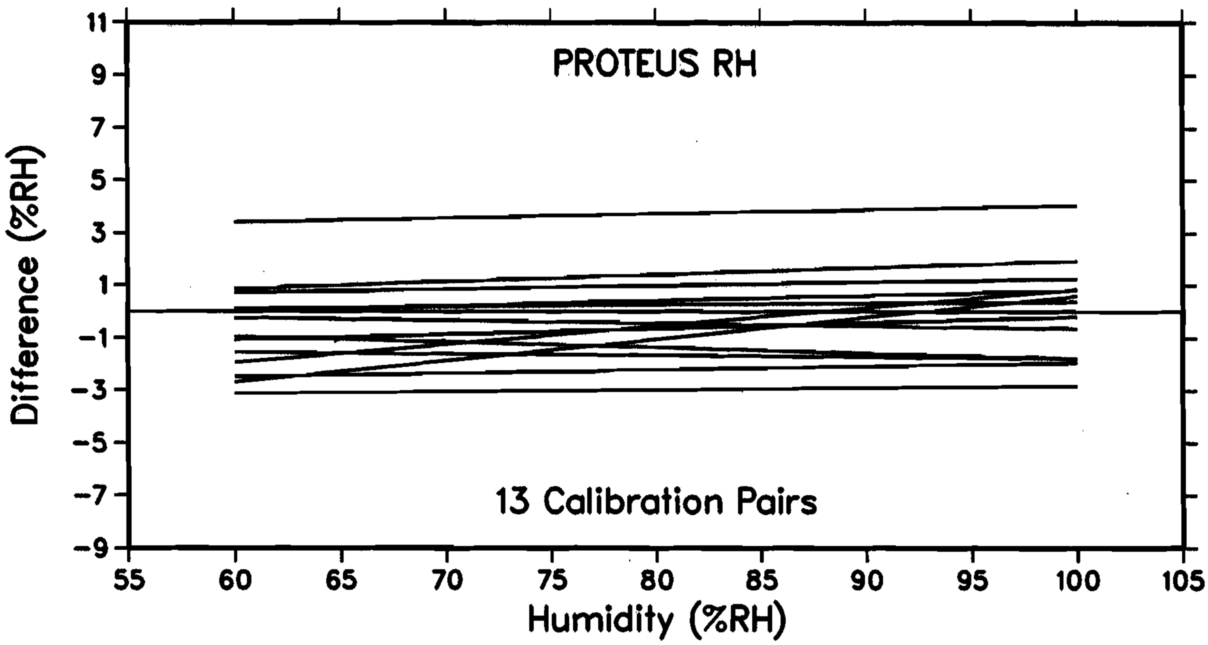


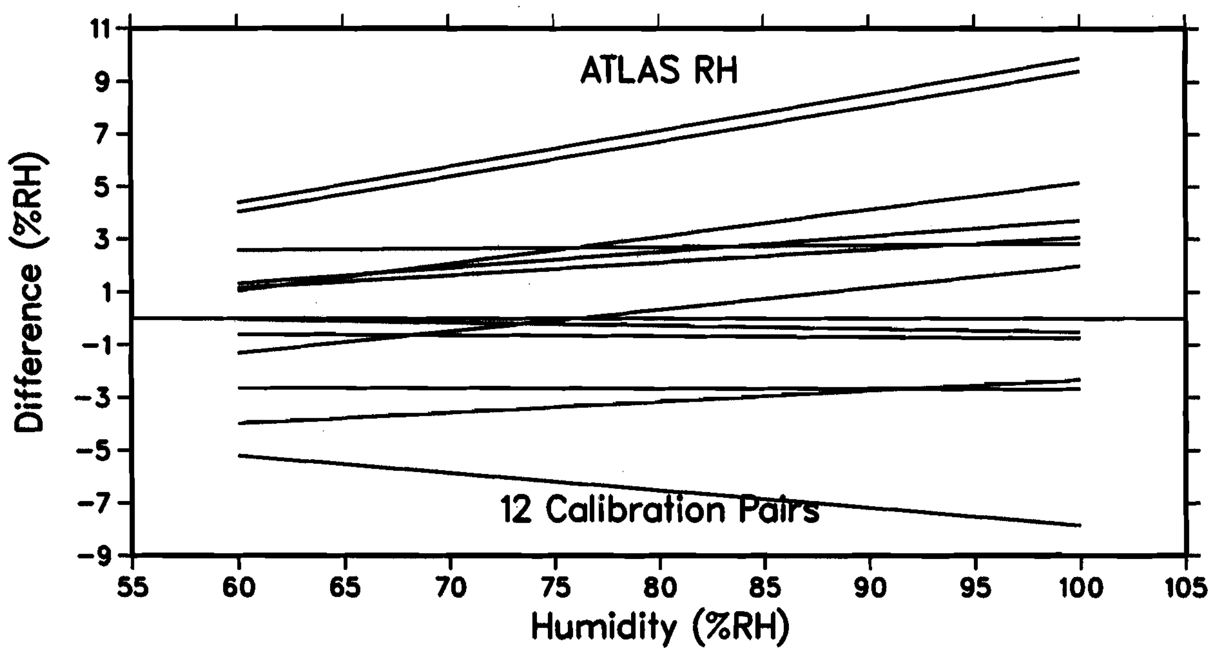


Sea surface sensor calibration differences.

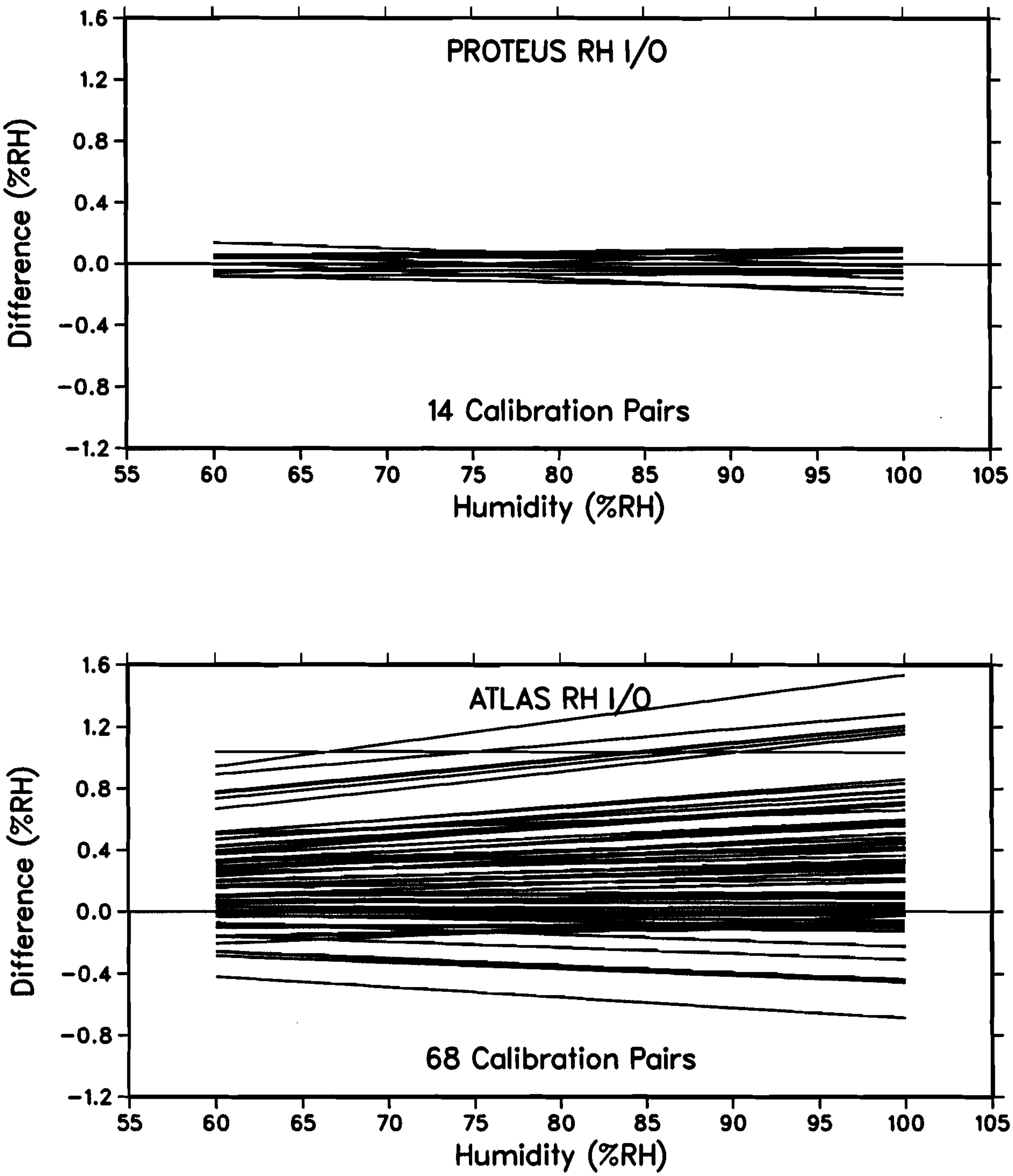


Sea surface I/O board calibration differences.

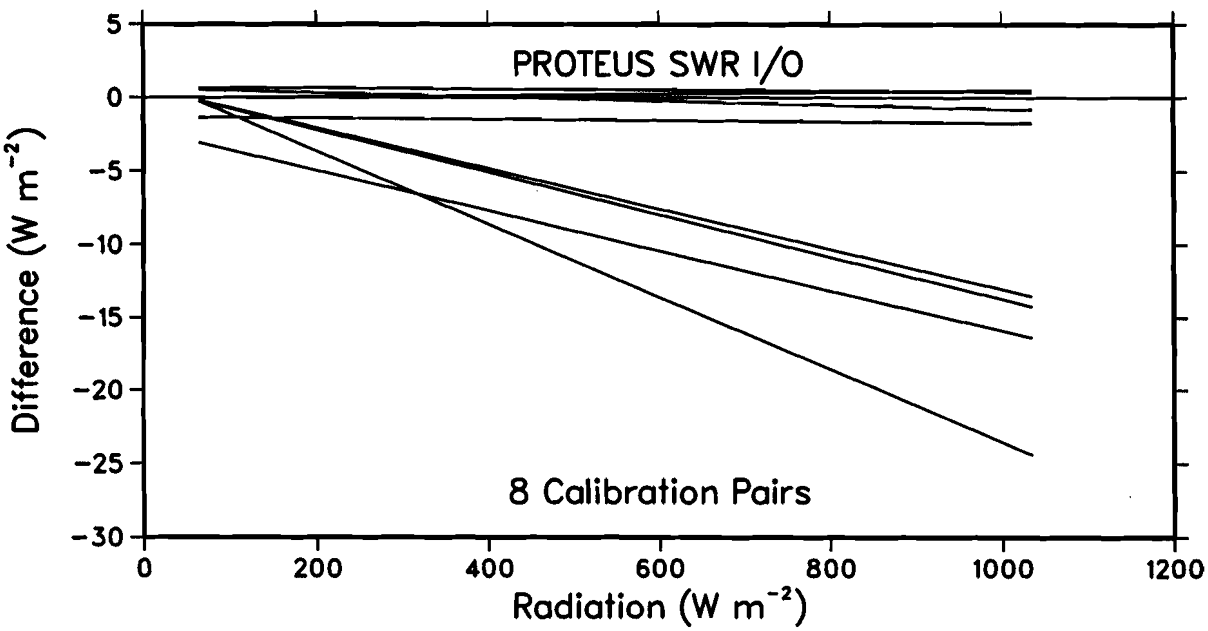




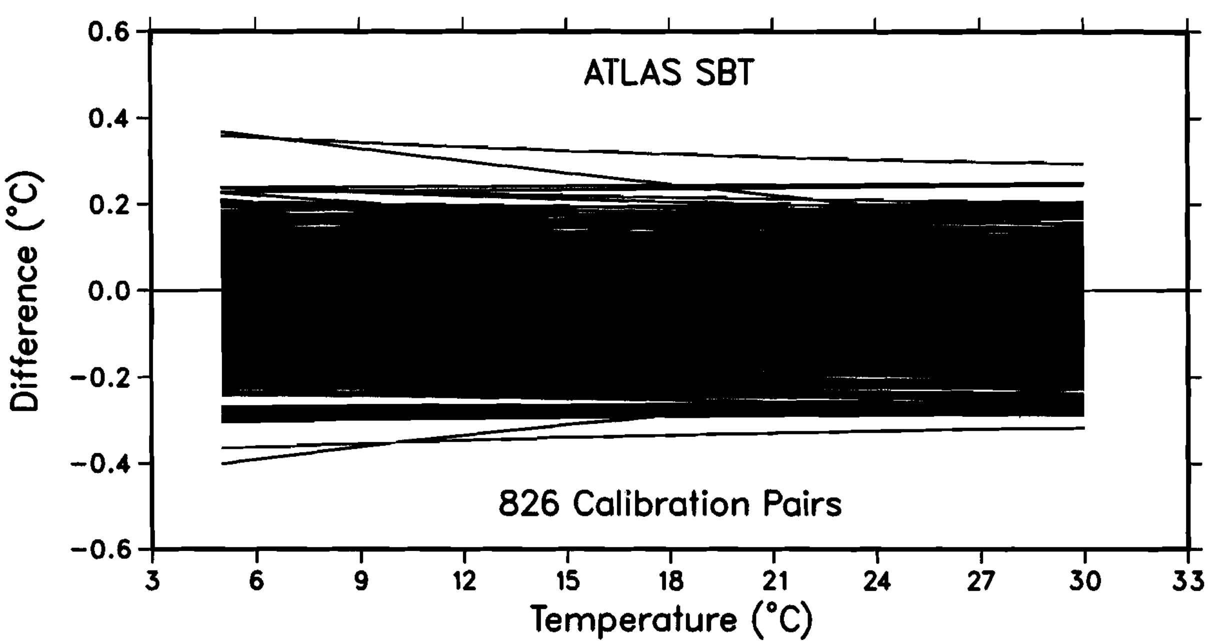
Relative humidity sensor calibration differences.



Relative humidity I/O board calibration differences.



Shortwave radiation I/O board calibration differences.



Subsurface temperature (sensor and I/O board) calibration differences.

*U.S. GOVERNMENT PRINTING OFFICE:1995-673-018/00066