Evaluation of Sea Surface Temperature Measurements from Drifting Buoys

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ABSTRACT

Three drift-buoy designs have been deployed since 1988 in substantial numbers in the tropical Pacific Ocean by United States participants as part of the Tropical Ocean Global Atmosphere (TOGA) Pan Pacific Surface Current Study. These include the Low Cost Tropical Drifter designed and built at the Atlantic Oceanographic and Meteorological Laboratory, the Low Cost Drifter (LCD) designed and built by the Massachusetts Institute of Technology Draper Laboratories, and the Ministar Drifter designed and built at the Scripps Institution of Oceanography and built by Tecnocean Inc., San Diego, California, which has subsequently become known as the World Ocean Climate Experiment standard drifter. This report contains an evaluation of the performance of the sea surface temperature measurement system carried by these buoy designs. Based on comparisons of the monthly mean SST derived from the available XBT and CTD casts and on intercomparisons among each of the buoy types, all three designs appear to include a warm bias in the surface temperatures they report. The LCD showed a larger mean bias and diurnal variation from solar heating than the other two buoy types. This difference is probably due to the location chosen for its sensor, resulting in poor thermal contact with the surrounding water.

1. Introduction

Accurate knowledge of sea surface temperature (SST) is vital for diagnosis and predictions of many weather and climate phenomena. The international Tropical Ocean Global Atmosphere (TOGA) program presently under way, for instance, requires SST mapping with a resolution of 200 km and 15 days and an accuracy of at least 0.3°C in the high-temperature tropical oceans (ITPO 1990). Satellite infrared measurements can provide the space–time coverage for SST, but variable atmospheric attenuation of the surface radiation resulting from aerosols of volcanic origin lead to large-scale SST errors in excess of 0.5°C (R. W. Reynolds, personal communication). The SST observations from volunteer observing ships are somewhat helpful in reducing these errors, but ship observations tend to be limited to a few well-traveled routes and generally are of low quality. Inexpensive drifting buoys, with position and sensor information relayed by satellite telemetry, have emerged as the apparent premier technology for obtaining SST ground-truth measurements over broad areas of the ocean. It is important, therefore, to attempt an evaluation of how the measurements of various, recently used drifting-buoy designs compare under field conditions.

As part of the Equatorial Pacific Ocean Climate Study (EPOCS), the TOGA program, and other related studies, drift buoys have been deployed throughout the tropical Pacific Ocean for a number of years. During the past few years, several types of drifters have been designed, primarily to lower individual buoy cost and allow more to be deployed within the program budget constraints. To keep the cost low, drifters are designed to carry only limited on-board instrumentation, namely, an SST sensor and some internal diagnostic measurements. The drifters have also been optimized as Lagrangian tracers to follow the movement of the water as well as possible over a useful range of wind and sea surface conditions.

The TOGA specification for drifting buoys (World Climate Programme 1985) was developed to define the performance standards of drift buoys in a number of areas, including slippage limits when used as Lagrangian tracers and the acceptable error limits for a number of on-board sensors commonly carried by drift buoys. For SST measurements, the standard specifies an absolute accuracy of ±0.1°C. Using the TOGA specification as a guideline, three designs have been used by United States participants in the TOGA Pan Pacific Surface Current Study; the Low Cost Tropical Drifter (LCTD) (Bitterman 1986), designed and built at the National Oceanographic and Atmospheric Administration (NOAA) Atlantic Oceanographic and Meteorological Laboratory (AOML); the Low Cost Drifter (LCD) (Dahlen 1986), designed and built by the Massachusetts Institute of Technology Draper Laboratories; and the Ministar Drifter (Niiler 1987), designed at the Scripps Institution of Oceanography and built by Tecnocean Incorporated, San Diego, California. This re-

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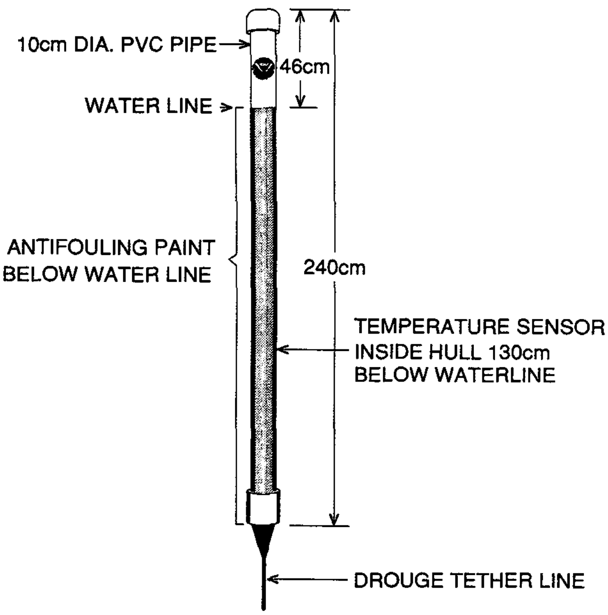

FIG. 1. The LCTD hull diagram showing the location of the SST sensor.

port contains the results of a study of the performance of the SST measurement of these three drifter designs based on data from deployments in the tropical Pacific.

2. Drifter description

Figures 1, 2, and 3 show the configurations of the LCTD, LCD, and Ministar hulls, respectively. The surface float contains the Argos transmitter electronics, batteries, and sensors, and is tethered to a relatively large subsurface float to couple the drifter to the water layer between 10 and 20 m below the surface. Each drifter design uses an inexpensive thermistor as the temperature-sensing element. The electrical resistance versus temperature calibrations varies depending on the manufacturer of the thermistor used, but for all three designs, the error of each thermistor relative to nominal calibration curves published by the manufacturers is ±0.1°C. None of the drifters included in this intercomparison had individually calibrated thermistors. The temperatures were derived using only the nominal curves combined with the transfer functions of the electronic circuitry that relates the electrical resistance of the thermistor to a binary count that is transmitted to the satellite.

The LCTD consists of a 10-cm-diameter × 2.4-m-long polyvinylchloride (PVC) hull with the Argos transmitter and antenna mounted internally in the top end of the tube and the batteries in the bottom end. A Yellow Springs Instrument Company model 44018 thermolinear element is pressed against the inside wall of the tube by a urethane foam block approximately

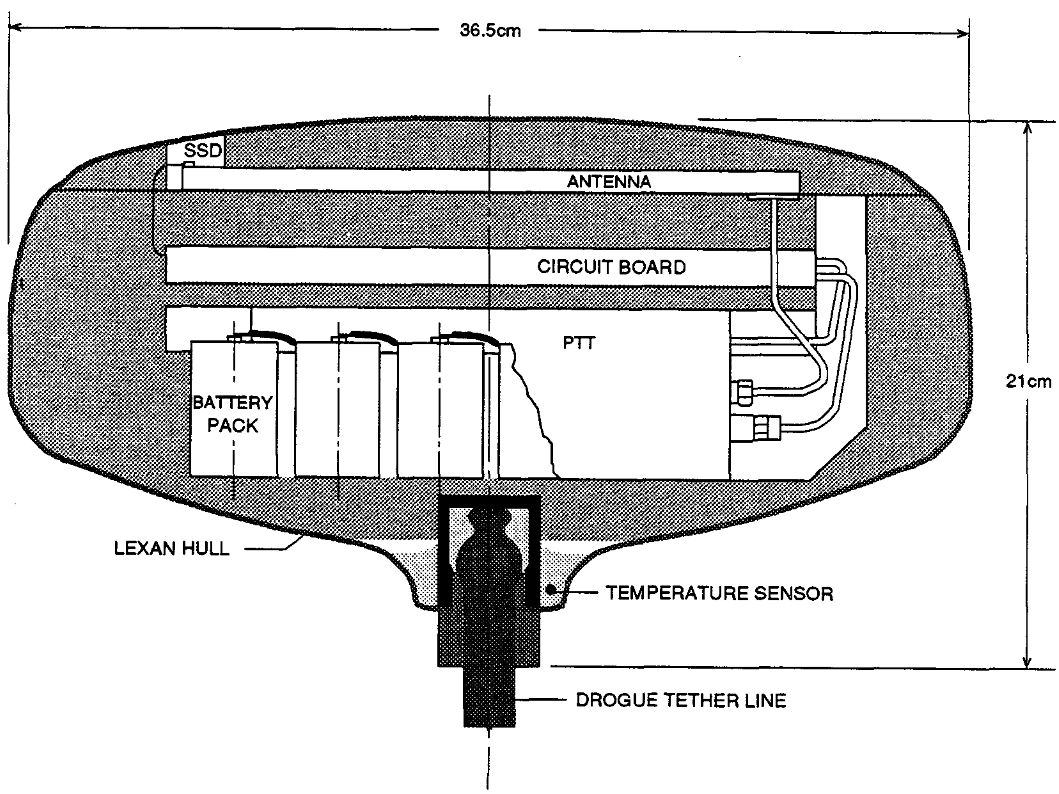

FIG. 2. The LCD hull showing the location of the internal components and SST sensor.

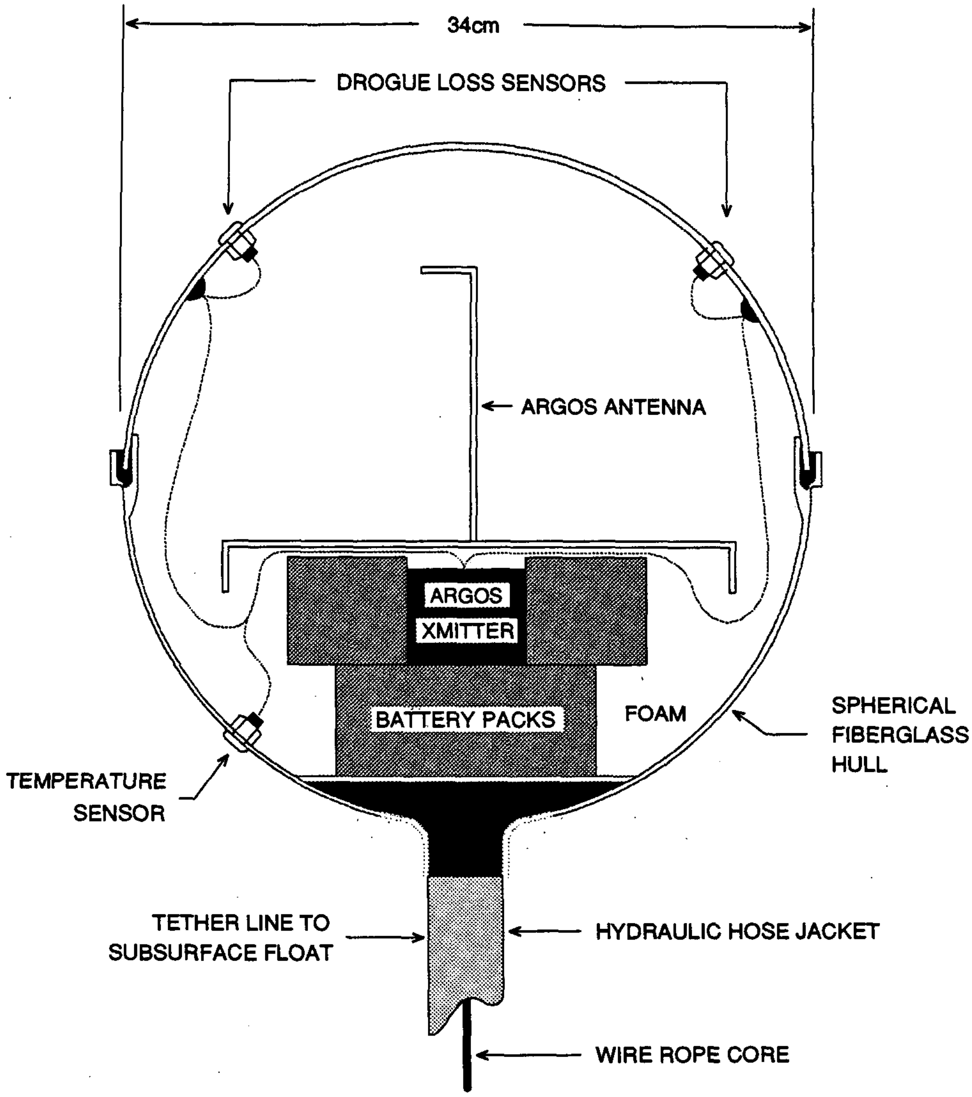

FIG. 3. The Ministar hull showing the location of the internal components and SST sensor.

1.3 m below the waterline. The wall thickness of the tube is 0.64 cm. The electrical resistance of the thermistor is converted to a voltage and digitized by a 10-bit analog-to-digital converter to encode the signal for transmission to the satellite. The resulting measurement covers the range −5.00° to 46.15°C, with a resolution of 0.05°C.

The LCD is constructed of lexan with a pill-shaped hull, 36.5 cm in diameter by 15.2 cm thick, containing the Argos transmitter, batteries and a planar antenna. A type DC95F502V thermistor manufactured by Thermometrics Incorporated is used as the temperature-sensing element. A neck protruding from the center of the lower face of the hull is filled with a polyurethane adhesive to bond the drogue tether line to the hull. The thermistor is inserted in this neck when the adhesive is poured and is electrically connected to a digitizer to give a 12-bit binary number proportional to the temperature. The resulting measurement covers the range −2.0° to +34.2°C and is nonlinear with a resolution of approximately 0.02°C at the high end of the range and 0.006°C at the low end.

The Ministar drifter uses a 34-cm diameter, fiberglass, spherical hull for the surface float with a Yellow Springs Instrument Company Model 46007 thermolinear element for the temperature-sensing element. The sensor is bonded to a 316-alloy stainless steel screw that protrudes through the wall of the surface sphere to make good thermal contact with the seawater. The screw is positioned approximately 7.5 cm above the bottom of the sphere and roughly 4 cm below the waterline. A 10-bit analog-to-digital converter in the electronics digitizes the signal over a range of −5.86° to 35.2°C to produce a slightly nonlinear calibration, with a resolution of about 0.04°C within the range of temperatures encountered.

3. Data distribution and quality control

The design of the LCTD has been evolving since deployments in the tropical Pacific began in 1983, while the LCD and Ministar are newer designs and were first deployed in substantial numbers during 1988. For the purposes of this report, the data from the LCTD and LCD were restricted to buoys operating during the period June 1988–May 1990, while the Ministar data were limited to buoys deployed and operating between January 1989 and May 1990. Geographical coverage was also restricted to buoys operating within the range bounded by 25°S–25°N and 120°E–80°W. Buoys deployed after 1 June 1988 generally had no configuration changes that would complicate the data analysis.

Thirty-four LCDs were deployed in the western Pacific during June and July 1988, and three LCDs were deployed near the equator in the central Pacific from the NOAA ship *Oceanographer* in July 1988. Significant deployments of the Ministars began in late 1988 from volunteer ships of opportunity and research ships operating in the central and eastern Pacific. Because, however, of technical problems with the temperature sensor on many of these early deployments, only Ministars deployed during or after January 1989 were used in this study. Deployments of LCTDs from research ships and ships of opportunity continued during the whole period of this study and were spaced relatively uniformly throughout all regions of the tropical Pacific Ocean. Figure 4 illustrates the geographical distribution of each of the drifters. Each dot represents a 1° × 1° geographical square from which at least one temperature transmission was received during the time period of the study. Disregarding the buoys that failed prematurely or had defective sensors, data from 163 LCTDs, 35 LCDs, and 77 Ministars were used. This summary does not address the longevity of the measurement from each of the buoys; it addresses only the fact that the buoys provided useful data at some time during these periods.

Buoy temperature data were derived from the monthly DISPOSE files (Service Argos 1988) that Service Argos disseminates to the principal investigator for each experiment. Typically, during each satellite pass over a buoy, Service Argos generates one position determination and numerous temperature values that are recorded in these files. Before doing any processing on these raw data, they were first passed through a few basic data filters. The data from each of the buoys were first ordered chronologically, and all data points outside the aforementioned time limits were removed. Under certain conditions, such as transmitter-frequency drift, unfavorable orbit geometry between the satellite and the buoy (or marginal communication to the satellite) data are received from the buoy, but no position can be computed for the satellite pass. These temperature measurements that were received without position information were assigned a geographical location equal to the nearest known position in time. All temperatures outside the range 17.0°–35.0°C were deleted, which eliminated approximately 3.1% of the LCTD data, 4.5% of the Ministar data, and 6.0% of the LCD data. The resulting data total approximately 151 000 LCTD measurements, 39 000 Ministar measurements, and 24 000 LCD measurements.

Unfortunately, there are very few direct measurements of SST available from other sources in the open Pacific with which to make quantitative comparisons. Conductivity, temperature, and depth (CTD) data from research ships operating in the region are available but are very limited both in geographical coverage and in the number of casts. Expendable bathythermograph (XBT) casts from both research ships and ships of opportunity are more numerous but of somewhat lower quality, especially for SST. Delacroix (1989), for example, has noted mean differences of 0.1°–0.2°C between XBTs and bucket surface temperatures. Although neither is particularly well suited for determining SST, the data, however, are easily obtainable and are nearly the only data available for field-condition comparisons.

The XBT data, consisting of 2760 individual casts, were obtained from the National Ocean Data Center: CTD data, totaling 672 casts, were obtained from AOML, NOAA Pacific Marine Environmental Laboratory, and Woods Hole Oceanographic Institution scientific cruises. The data consisted of depth-averaged temperature values spaced at 2-m intervals, and the surface temperatures used in these comparisons were derived from the temperature values for the depth bin nearest the surface. The available CTDs for this test, Fig. 5 (top), were mainly concentrated in the eastern Pacific north of the equator, with one section at 10°N spanning the whole Pacific basin. The XBTs, Fig. 5 (bottom), were also most densely distributed to the east of 160°W and north of the equator, although there were substantial numbers in other areas also. Unfortunately, the eastern Pacific north of the equator, where eddy activity generated near the Central American coast and tropical instability waves (Hansen 1984; Pullen 1987) are common, is one of the most energetic regions of the entire Pacific, and there can be large spatial and temporal variability to the SST.

4. Intercomparison of drifter temperature sensors

Several intercomparisons of the buoy temperature data were carried out to determine the consistency of, and if possible to quantify, the accuracy of the measurements. Ideally, one would like to base the evaluation on coincident measurements. Because there were very few truly coincident measurements, we were forced to treat the data in a manner similar to the way

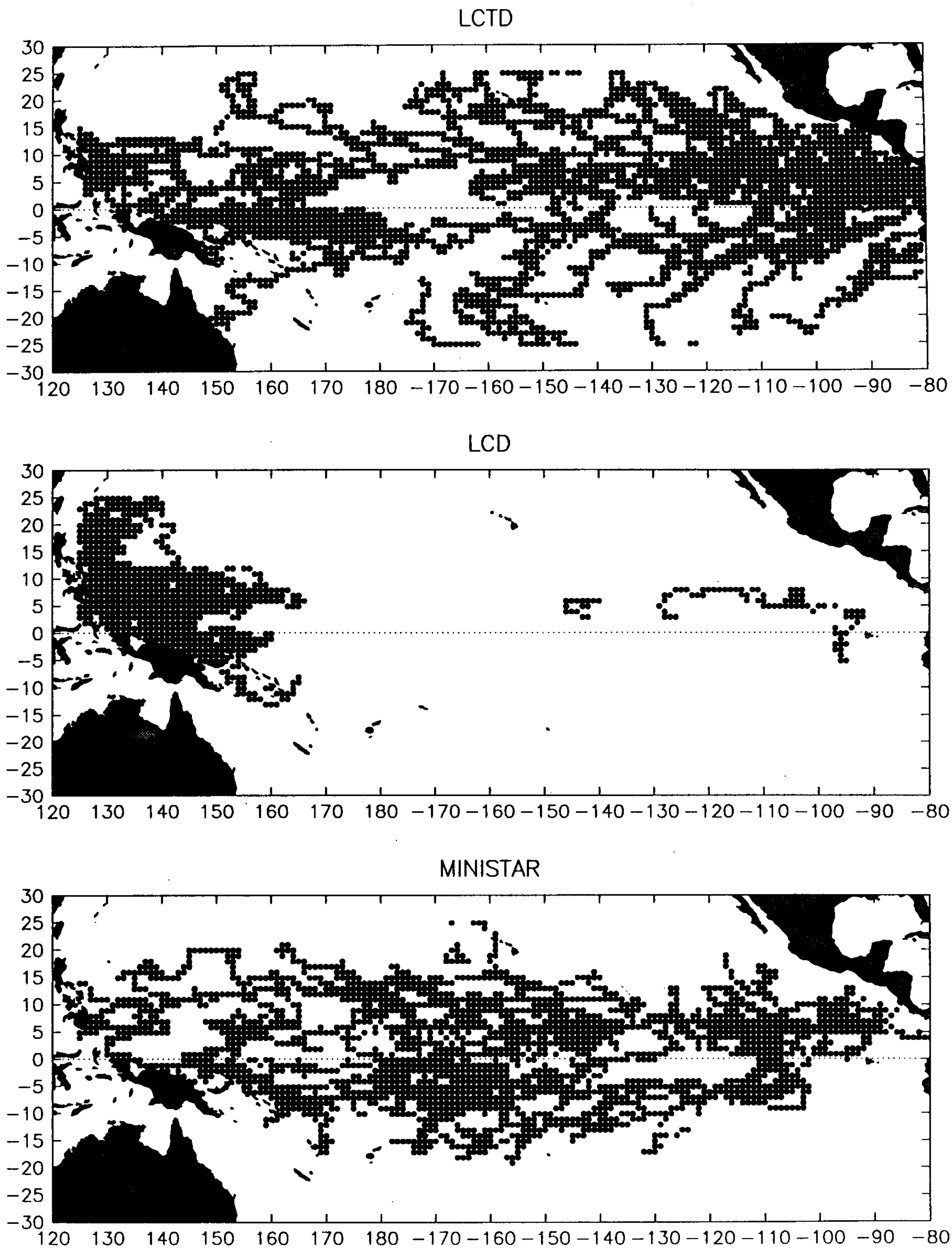

FIG. 4. Geographical distribution of each buoy type. Each dot represents a 1° × 1° geographical square from which at least one SST transmission was obtained during the time period of this study.

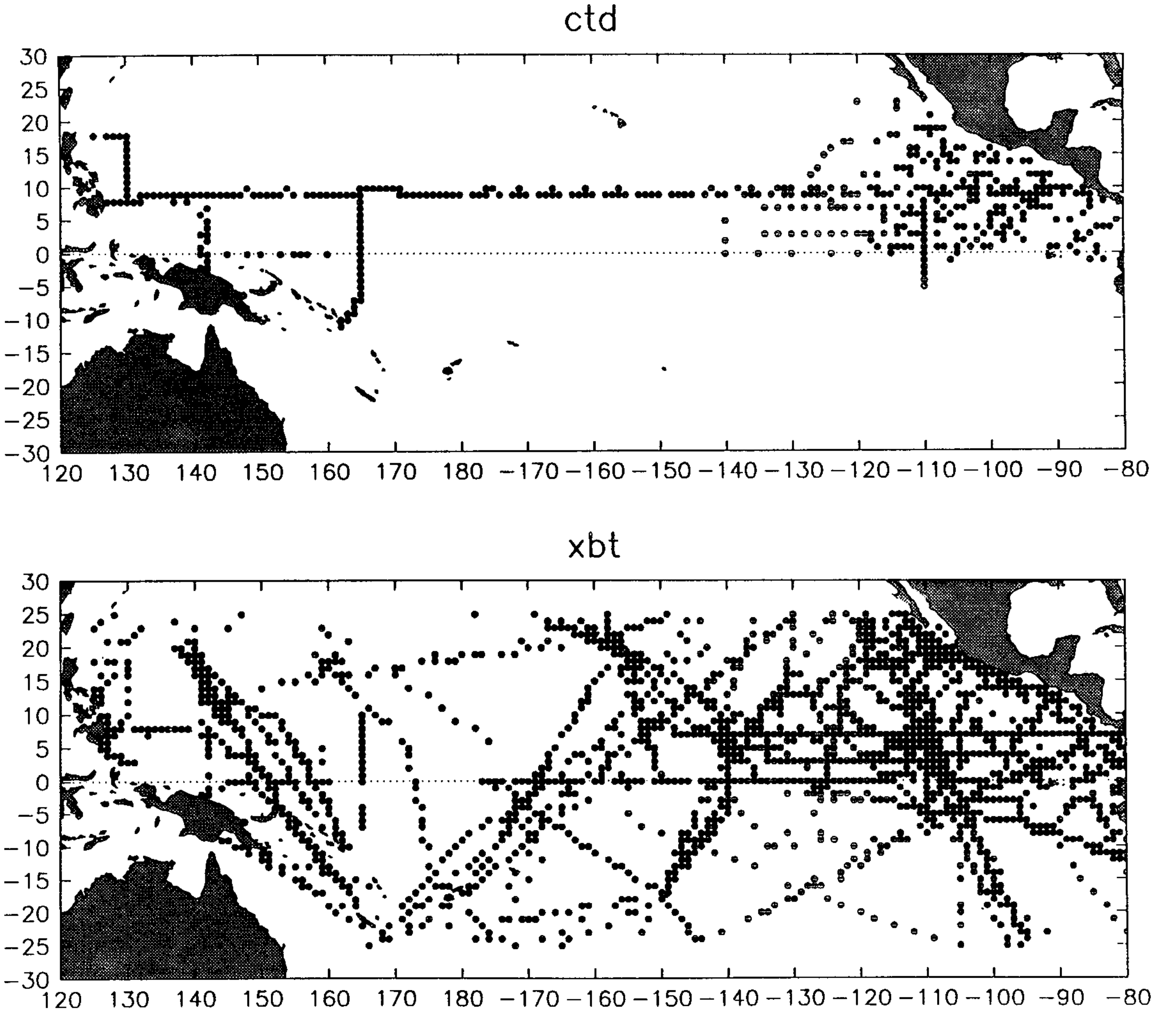

FIG. 5. Geographical distribution of XBT and CTD casts. Each dot represents a $1° \times 1°$ geographical square that contained at least one XBT or CTD cast.

in which they are used in operational SST analyses. The data of each type were "binned" by month of year and $1° \times 1°$ geographical squares. The monthly mean temperature in each square was then computed separately from the XBT, CTD, and three types of buoy data. Using these values, the mean temperature difference, $\Sigma(T_1 - T_2)/N$, and standard error of the mean, given by $\sigma_{T_2-T_1}/N^{1/2}$ (Meyer 1975), were then computed for the differences between each type of buoy and the XBT and CTD surface temperatures for those buoy temperatures and XBT or CTD casts that occupied the same square during the same month. In these expressions, N is the total number of common squares and $\sigma_{T_1-T_2}$ is the standard deviation computed for the N individual differences. The results are shown in Table 1.

In this table, the CTD or XBT temperatures were subtracted from the buoy temperatures. The number of individual XBT casts totaled 267, 52, and 84 for the LCTD, LCD, and Ministar comparisons, respectively. Similarly, the number of individual CTD casts totaled 93, 18, and 16.

The temperatures reported by both the LCTD and Ministar exhibit a mean negative bias relative to the XBT temperatures, while the LCD shows a small mean positive bias. All the buoys show a definite positive bias relative to the CTD temperatures. As a check on the data quality of the XBT and CTD measurements,

TABLE 1. Buoy minus XBT and CTD mean temperature differences (°C).

	Buoy type		
	LCTD	LCD	Ministar
Buoy − XBT	−0.04 ± 0.06	+0.05 ± 0.09	−0.15 ± 0.08
Buoy − CTD	+0.08 ± 0.14	+0.27 ± 0.28	+0.15 ± 0.28

TABLE 2. XBT − CTD Mean temperature difference (°C).

XBT − CTD	+0.29 ± 0.01

the same comparison was done for these as was done with the buoys, and the results are shown in Table 2. Again, the mean and standard error of the mean were computed for the difference between the XBT bin temperatures and the CTD bin temperatures (XBT − CTD) for those casts within the same square in the same month. These calculations are based on a total of 204 individual XBT casts and 141 CTD casts in 118 common bins. The XBT casts used here can be seen to have a substantial mean positive bias relative to the CTD casts, which is generally consistent with, although somewhat larger than, the biases obtained from the buoy–CTD intercomparisons. The mean difference shown in Table 2 is almost exactly the difference implied for the same quantity by the Ministar averages shown in Table 1.

To intercompare the buoys directly, the same analysis was done for buoy pairs as was done with the CTD and XBT data. The results are shown in Table 3 and are based on 153 LCTD–LCD common bins, 241 LCTD–Ministar bins, and 112 LCD–Ministar bins.

The LCDs were deployed primarily in the western Pacific during June and July 1988, whereas the Ministars used in this study were deployed in the central and eastern Pacific, so the overlap between these two was very limited. The LCTD deployments were more uniformly distributed throughout the region, so a larger number of buoy pairs were included in the LCTD comparisons. The mean differences obtained are small, and no consistent pattern of bias appears in this evaluation.

5. Temporal structure of measurements

The structure function, defined for our drifting-buoy temperature data as

$$S(\Delta t) = \frac{1}{2}\langle [T(t) - T(t + \Delta t)]^2 \rangle , \qquad (1)$$

in which angle brackets denote an average over an ensemble of temperature data T from individual buoys of each design, is a familiar tool for analysis of variance (Kolmogorov 1941). We computed structure-function values from each buoy design from $0 < \Delta t \leq 3$ days at binned intervals of $1/6$ day from measurements made between 120°E and 180°, where the LCDs were deployed. The number of samples totaled about 220 000, 272 000, and 643 000 data pairs for the Ministar, LCD, and LCTD, respectively. The results are displayed in Fig. 6. The distributions of each of the sets of structure-function values suggests their interpretation in terms of a periodic diurnal component, a nonzero intercept, and a secular growth of variance. We interpret these components as follows: diurnal solar warming of the upper ocean and, possibly, the buoy hull; temperature variance at less than 2 h, which can be induced by noise in the measurement system, buoys crossing thermal fronts, or cloud shadowing; and secular growth of variance associated with the primary objective of the measurement. The magnitude of each of these components was estimated by a linear least-squares fit of the data to the functional form

$$S = A_1 + A_2\Delta t + A_3[1 - \cos(2\pi\Delta t)] . \qquad (2)$$

The coefficients resulting from the least-squares fitting are summarized in Table 4, and the implied function is also plotted in Fig. 6. It is apparent from Table 4 and Fig. 6 that the buoys yield substantially the same result for the secular increase of variance, a property of the ocean, and that the LCTD and the Ministar are essentially equivalent in other components as well but that the LCD exhibits substantially larger high-frequency noise and diurnal variation. We conjecture that the LCD is more affected by direct solar heating of the buoy hull, the diurnal variance corresponding to the diurnal cycle and the high-frequency noise being associated with short periods of cloud shadowing. Nighttime data from these buoys probably are of higher quality than daytime values.

TABLE 3. Buoy temperature differences (°C).

	Buoy pair		
	LCTD–LCD	LCTD–Ministar	LCD–Ministar
Mean difference	−0.03 ± 0.04	+0.11 ± 0.06	−0.07 ± 0.04

6. Discussion of results

Comparisons of the monthly mean surface temperatures derived from XBT and CTD casts (Table 2) indicate that the XBT temperatures exhibit substantial warm bias, +0.29°, relative to the CTD temperatures. This agrees closely with the results reported by Heinmiller (1983), who found XBT temperatures to be +0.10° to +0.30° warmer than those dervied from simultaneous CTD casts. Other investigators (Yoshida 1988) have also noted systematic differences between XBT and CTD temperatures, and while their comparisons were generally restricted to depths of 50 m

TABLE 4. Structure-function model constants

	Constant ($\times 10^3$)		
Buoy	A_1	A_2	A_3
LCTD	9.6	0.34	9.4
LCD	17.9	0.24	17.3
Ministar	10.7	0.26	9.0

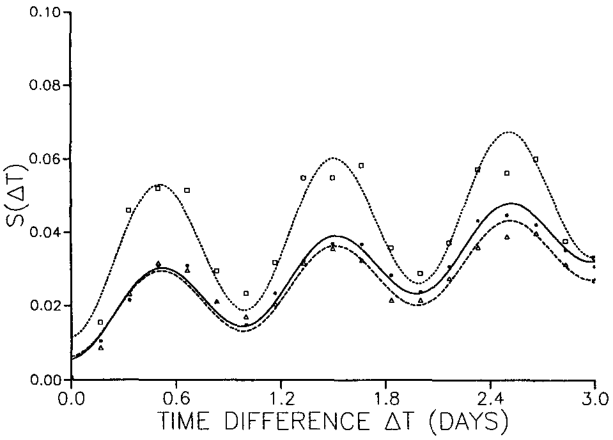

FIG. 6. Temperature structure-function models for the LCTD (solid line, solid dots), LCD (dotted line, squares), and Ministar (dashed line, triangles).

and more, our results indicate that these differences also apply to surface temperatures. Heinmiller also noted close agreement between the CTD and reversing thermometers, indicating that the CTD temperatures represent the better estimate of the true temperature of the water.

The buoy–XBT and buoy–CTD comparisons (Table 1) are consistent with the XBT–CTD results. The mean temperatures reported by the LCTD and Ministar are warmer than the CTD mean temperatures and cooler than the XBT temperatures. Similarly, the mean LCD temperatures are slightly warmer relative to the XBTs, +0.05°C, and significantly warmer, +0.27°C, than the CTD temperatures.

Assuming the temperatures reported by the CTD represent the best estimate of the true ocean mixed-layer temperature, all three buoy designs appear to include a warm bias in their SST measurements. Unfortunately, the CTD populations available in the LCD–CTD and Ministar–CTD comparisons were very small, which resulted in large uncertainties in the computations. The LCD was the only buoy of the three to report mean SSTs warmer than both CTDs and XBTs. In the comparison with the CTD, the mean bias, +0.27°C, very nearly equaled the uncertainty, ±0.28°C, associated with the calculation. The Ministar mean temperature was significantly cooler than that derived from XBTs, and while it was also significantly warmer than the mean CTD temperature, +0.15°C, the difference is comfortably within the uncertainty, ±0.28°C, of the computation. The LCTD, benefiting from somewhat larger available XBT and CTD populations, which reduced the uncertainty to about half that of the other buoys, showed results similar to those of the Ministar. The LCTD–CTD mean temperature difference, +0.08°C, was well within the uncertainty, ±0.14°C, of the computed mean.

The buoy–buoy intercomparisons showed no discernible systematic bias, and differences among the three designs appear to reflect the random variability of the SST throughout the ocean. The LCTD–LCD and LCD–Ministar mean differences were well below 0.1°C. Although the LCTD–Ministar difference was considerably larger, the uncertainty, ±0.06°, was also much larger, reflecting much higher variability in the individual bin temperatures.

Significant vertical temperature gradients can exist near the surface, and much work has been done in this area documenting the near-surface temperature distribution (Stramma 1989; Heppelwhite 1989; Schluessel 1987). Differences of several tenths of a degree and more have been noted under varying wind and cloud-cover conditions, thermocline depth, and diurnal cycles. This leads logically to considerations of the differences in location of the temperature measurement on each of the buoy designs. We expect that SST measurements from all of three buoy designs are sufficiently macroscopic to be free of uncertainties arising from skin temperature and similar microscopic effects.

The mean and diurnal signal in the LCD SSTs were significantly larger than those of the LCTD or Ministar, and are presumably a combination of the warming of the surface water and solar heating of the buoy hull. The Ministar diurnal signal was essentially the same as that of the LCTD. Whereas the LCTD temperature sensor is located approximately 1.3 m below the surface, the LCD and Ministar measurements are made within a few centimeters of the surface. Because of the depth of its sensor and the small cross section of the hull when viewed from above, one would expect that the LCTD temperatures should be affected minimally by solar heating of the hull and sensor and that the diurnal signal closely approximates the actual warming of the water. Since the Ministar diurnal signal is the same as that of the LCTD and is located at roughly the same depth as that of the LCD, it seems likely that the LCD is significantly affected by the incident solar radiation. Whereas the LCD thermistor is embedded in potting material in the hull, the design of the Ministar provides better thermal contact with the water through the stainless steel fitting on which it is mounted. It is reassuring that the SST measurement, with negligible contamination, can be made from a very shallow draft-surface float.

7. Conclusions

The evaluation of the performance of SST measurements made from drifting buoys by comparing them to in situ measurements is severely hampered by the limited number of alternative, coincident, high-quality SST samples. Using the available CTD data as the best estimate of the true SST indicates, however, that monthly mean temperatures reported by all the buoys contain a warm bias. The mean SST derived from the LCTD samples falls within the 0.1°C limits of the TOGA standard, while the mean SST measured by the LCD shows a substantial warm bias. The mean SST from the Ministar had a bias somewhat warmer than that of the LCTD but is based on a CTD population that is too small to confidently characterize its performance.

On shorter time scales, the LCTD and Ministar perform nearly identically, whereas the diurnal variability of the LCD was substantially larger than that of the other two designs. We conjecture that this is due to solar heating of the buoy hull and insufficient thermal coupling of the sensor to the surrounding water. The shallow draft of the Ministar does not appear to have compromised its ability to provide uncontaminated SST information.

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