Evaluation and Recommendations for Improving the Accuracy of an Inexpensive Water Temperature Logger

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(Manuscript received 27 September 2012, in final form 30 November 2012)

ABSTRACT

Onset's HOBO U22 Water Temp Pros are small, reliable, relatively inexpensive, self-contained temperature loggers that are widely used in studies of oceans, lakes, and streams. An in-house temperature bath calibration of 158 Temp Pros indicated root-mean-square (RMS) errors ranging from 0.01° to 0.14°C, with one value of 0.23°C, consistent with the factory specifications. Application of a quadratic calibration correction substantially reduced the RMS error to less than 0.009°C in all cases. The primary correction was a bias error typically between −0.1° and 0.15°C. Comparison of water temperature measurements from Temp Pros and more accurate temperature loggers during two oceanographic studies indicates that calibrated Temp Pros have an RMS error of ~0.02°C throughout the water column at night and beneath the surface layer influenced by penetrating solar radiation during the day. Larger RMS errors (up to 0.08°C) are observed near the surface during the day due to solar heating of the black Temp Pro housing. Errors due to solar heating are significantly reduced by wrapping the housing with white electrical tape.

1. Introduction

Onset's HOBO U22 Water Temp Pros are small, reliable, relatively inexpensive, self-contained temperature loggers. Consequently, Temp Pros have been widely used to characterize the temporal and spatial structure of ocean, lake, and stream water temperatures (e.g., Blicher et al. 2010; Davis et al. 2011; Huang et al. 2011; Lentz et al. 2008; Oda and Kanda 2009; Oliver and Palumbi 2011; Ruiz-Ochoa et al. 2012; Shcherbina and Gawarkiewicz 2008; Troy et al. 2012; and many others).

Factory specifications suggest Temp Pros are less accurate than more expensive temperature loggers. However, comparisons of water temperature measurements from Temp Pros with more accurate temperature measurements during several ocean deployments suggested the Temp Pro accuracy could be substantially improved by removing a bias. This observation motivated a more thorough evaluation of the accuracy of the Temp Pro water temperature measurements using both a calibration bath facility at Woods Hole Oceanographic Institution (WHOI) and in situ comparisons to more accurate Sea-Bird Electronics MicroCAT temperature measurements during ocean deployments over the continental shelves south of Martha's Vineyard, Massachusetts (Lentz et al. 2008), and the Red Sea near Jeddah, Saudi Arabia (Davis et al. 2011).

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DOI: 10.1175/JTECH-D-12-00204.1

2. Instrument description

The HOBO U22 Water Temp Pro v2 is a small (3-cm diameter, 11.4-cm length) temperature logger in a black polypropylene housing that is waterproof to 120-m depth and can store 42 000 12-bit temperatures (http://www.onsetcomp.com/products/data-loggers/u22-001). The manufacturer's specifications are an accuracy of 0.2°C, a resolution of 0.02°C, a drift of 0.1°C yr^{-1}, and an internal clock accuracy of ±1 min $month^{-1}$ over the temperature range 0°–50°C. The thermistor is located inside the polypropylene housing. Consequently, the response time is relatively slow, 5 min in water to reach 90% of ambient temperature, according to the manufacturer. The instrument sampling scheme can be set up and the data downloaded without opening the pressure case using an optical reader that connects to a computer.

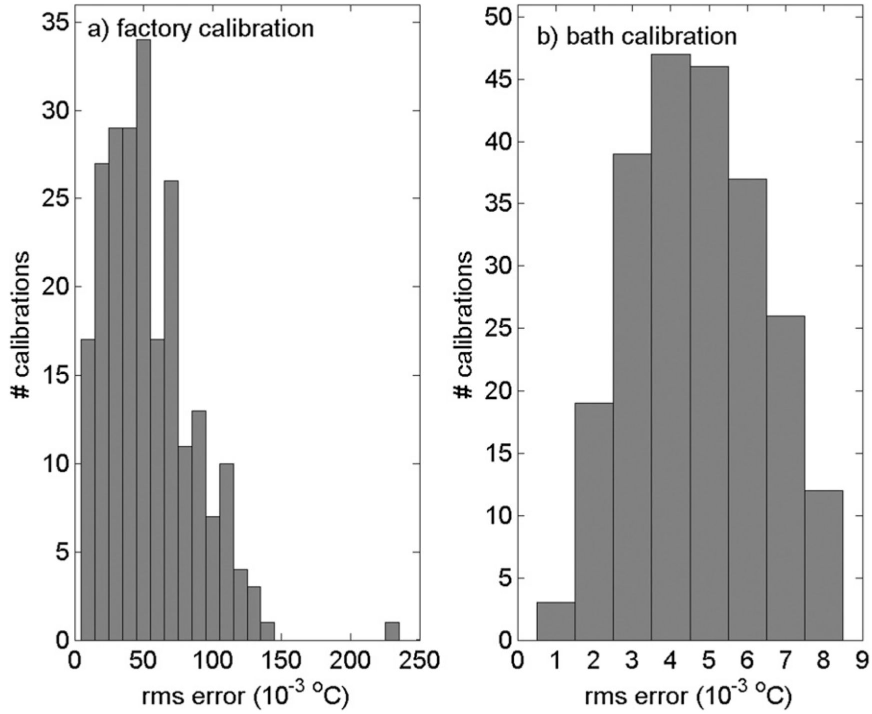

FIG. 1. Distribution of the RMS error for 158 Temp Pros relative to a calibration bath (a) using factory calibration and (b) after applying a calibration correction based on a quadratic fit to the bath temperatures. Note change in RMS error range between (a) and (b).

3. Bath calibration

a. Procedure

Temp Pros were calibrated in a Hart Scientific (model 7041) water temperature bath at WHOI. Bath temperatures were monitored by a Hart Scientific model 1590 thermometry bridge and two Thermometrics AS125 probes. This system is routinely checked with both triple point of water (TPW) and gallium melt cells and has proven to be stable and accurate to about 0.001°C. Short-term stability of the bath is 0.001°–0.002°C, depending on the target temperature. The bath is well stirred and provides excellent temperature uniformity in the interior, 2.5 cm or more from the walls. The probes of the temperature standard and the Temp Pros are located as close to the center of the bath as possible. Care is also taken to ensure that there is good water flow between the units under test.

A total of 187 Temp Pros were calibrated in six batches, done in July 2008, January 2009, February 2009, August 2009, March 2010, and November 2011. The bath temperature was increased at 5°C increments, from 10° to 35° or 40°C for Temp Pros used in the Red Sea study, and from 0° to 25° or 30°C for Temp Pros used in the Martha's Vineyard study. At each 5°C increment, the temperature of the bath was held steady for 40–90 min to ensure that the bath and Temp Pros reached an equilibrium temperature. The standard deviations of the bath temperatures over the last 5 min of each 5°C temperature increment ranged from 0.0002° to 0.0006°C. As shown below, the Temp Pros have an exponential thermal response time constant of about 3 min, indicating that after 40 min they should have equilibrated to within 10^{-5}°C of their final temperature. Calibrations were based on the average bath and Temp Pro temperatures over the last 5 min at each temperature increment.

b. Bath calibration results

The root-mean-square (RMS) difference between the average Temp Pro and bath temperatures ranged from 0.01° to 0.14°C, with one value of 0.23°C (Fig. 1a). To calibrate the Temp Pros, the 5-min average temperatures from the Temp Pros were fit to the corresponding average bath temperatures using a least squares fit to a quadratic function $T_c = a + bT_p + cT_p^2$, where T_c is the calibrated temperature, T_p is the Temp Pro temperature, a is the bias, b is the slope, and c is the curvature. Biases were typically between −0.1° and 0.15°C, with two biases exceeding 0.18°C (Fig. 2a). Slopes ranged from 0.99 to 1.0, with an average value of 0.996 (Fig. 2b). Curvatures were typically positive between $0.4 \times 10^{-4\circ}$ and $1.5 \times 10^{-4\circ}\mathrm{C}^{-1}$, with an average value of $0.6 \times 10^{-4\circ}\mathrm{C}^{-1}$ (Fig. 2c).

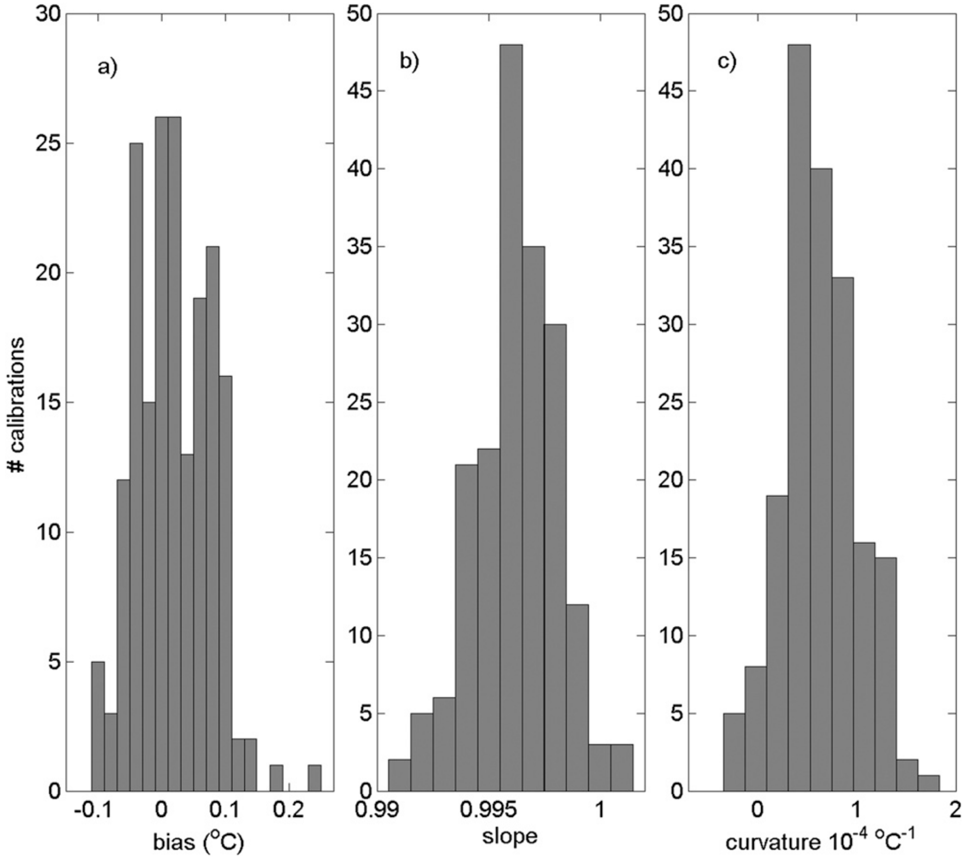

FIG. 2. Distributions of the (a) bias, (b) slope, and (c) curvature of a quadratic fit of each Temp Pro to the calibration bath temperatures.

Use of the quadratic fit reduced the RMS difference between the calibrated Temp Pro temperature and the bath temperature to less than 0.009°C in all cases (Fig. 1b). Use of a cubic or higher-order polynomial did not significantly improve the fits. Removing just a bias from each Temp Pro reduced the RMS error to less than 0.05°C in all cases and to less than 0.03°C for 93% of the Temp Pros.

To determine the longer-term stability of the calibration coefficients, 12 of the Temp Pros were recalibrated once and 15 were recalibrated twice. Recalibrations were more than a year apart.

For the Temp Pros that were recalibrated, the bias corrections were relatively stable, that is, the variations in the bias were smaller than the average bias (Fig. 3a). The standard deviation of the difference in bias corrections was 0.012°C, and the maximum difference was 0.037°C. There was a slight tendency for the bias correction to increase with time, resulting in a mean difference in the bias corrections between the first and subsequent calibrations of 0.007°C over a year or more. Relative variations in the slope correction were larger than for the bias correction, with a standard deviation of 0.0015 and no significant mean (Fig. 3b). The curvature corrections were uncorrelated from one calibration to the next, indicating the curvature correction is not stable enough to be useful on longer time scales.

The bath calibrations were also used to check the response time of the Temp Pros (Fig. 4). The Temp Pros have a roughly exponential thermal response with a time constant of about 3 min. They reach 80% of the equilibrium temperature in 5 min and 99% in 15 min, roughly consistent with the factory specifications. The time response was similar for all the Temp Pros tested (as seen for the 70 Temp Pros shown in Fig. 4).

4. Evaluation in ocean deployments

a. Procedure

To determine the in situ accuracy in ocean deployments, calibrated Temp Pro temperature measurements from moorings deployed on the Red Sea continental shelf near Jeddah and to the south of

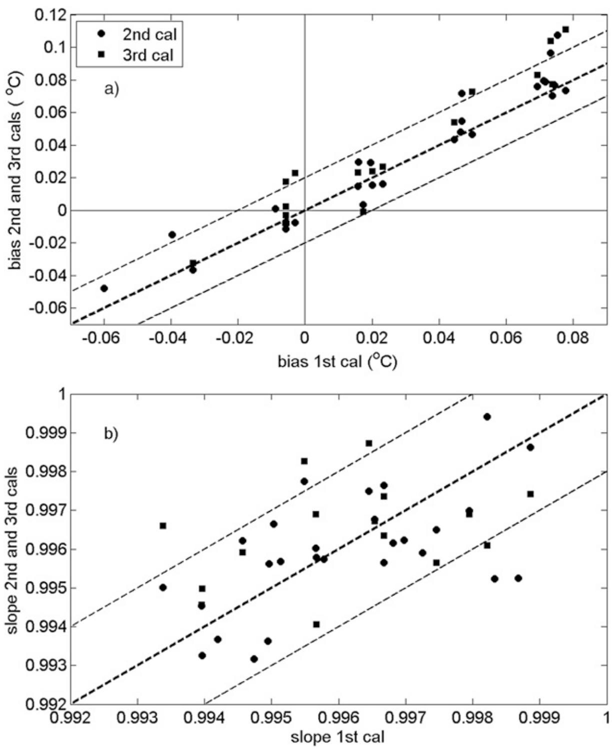

FIG. 3. Variations in bias and slope over two or three calibrations separated by more than a year. The thick dashed lines indicate no change in the bias or slope between the first and subsequent calibrations. The thin dashed lines indicate a change of (a) ±0.02°C in the bias and (b) ±0.002 in the slope.

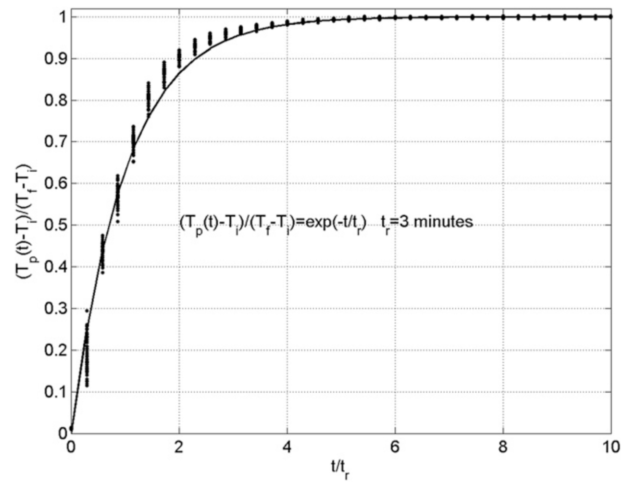

FIG. 4. Time response of the temperature $T_p(t)$ measured by 70 Temp Pros (dots) when the calibration bath temperature was abruptly increased from $T_i = 25°C$ to $T_f = 30°C$. The exponential response assuming a response time of $t_r = 3$ min (line) is shown for comparison.

Martha's Vineyard on the New England continental shelf are compared to more accurate temperature measurements from Sea-Bird SBE-37 MicroCATs deployed on the same moorings.

The manufacturer's specifications for the MicroCATS are an accuracy of 0.002°C over a range of 5°–35°C, a resolution of 0.0001°C, and a stability of 0.0002°C month^{-1} (http://www.seabird.com/products/spec_sheets/37smdata.htm). The MicroCAT thermistor is isolated from the housing and exposed to the ocean water, so the response time is order 1 s, relatively fast compared to the Temp Pro. The MicroCATs used in this study were calibrated by the manufacturer before and after each deployment.

Comparisons were made using temperature observations from five mooring deployments in the Red Sea, in water depths ranging from 13 to 50.5 m. Deployments were typically 13 months, with one 7-month deployment. The moorings supported 3–6 MicroCATs spanning most of the water column, with 5–10 Temp Pros situated between the top and bottom MicroCATs. Data from Temp Pros above the top MicroCAT or below the bottom MicroCAT were not considered in this analysis. Water temperatures ranged from a winter minimum of ~24°C to a summer maximum of ~33°C. Water visibility easily exceeded 10 m during mooring deployment and recovery operations.

Temperature observations from three mooring sites south of Martha's Vineyard, at water depths of 12, 17.5, and 27.5 m, were also analyzed. There were three deployments at each site, each lasting 5–8 months, giving total durations of 22 months (12-m site) and 16 months (17.5- and 27.5-m sites). The moorings supported five to eight MicroCATs spanning most of the water column, with four to five Temp Pros between the top and bottom MicroCATs. Water temperatures ranged from a winter minimum of 0.5°C to a summer maximum of 23°C. Water visibility varied but was often less than 2 m.

Similar processing was applied to the Temp Pro and MicroCAT data from both field programs. The quadratic calibration corrections, described in section 3, were applied to each Temp Pro temperature time series. The Temp Pros sampled at 10- (Martha's Vineyard) or 15-min (Red Sea) intervals. The MicroCATs sampled at 1.5- (Martha's Vineyard) or 2.5-min (Red Sea) intervals. Temperatures were low-pass filtered and interpolated onto a common time base—20 min for Martha's Vineyard and hourly for the Red Sea.

The Temp Pro and MicroCAT temperature measurements were compared during periods when the water temperature at a mooring site was vertically uniform, specified as the times when all MicroCAT temperatures on a mooring were within 0.02°C of their vertical average. The temperature difference ($\Delta T = T_c - T_{\mathrm{mc}}$) between each calibrated Temp Pro temperature (T_c) and

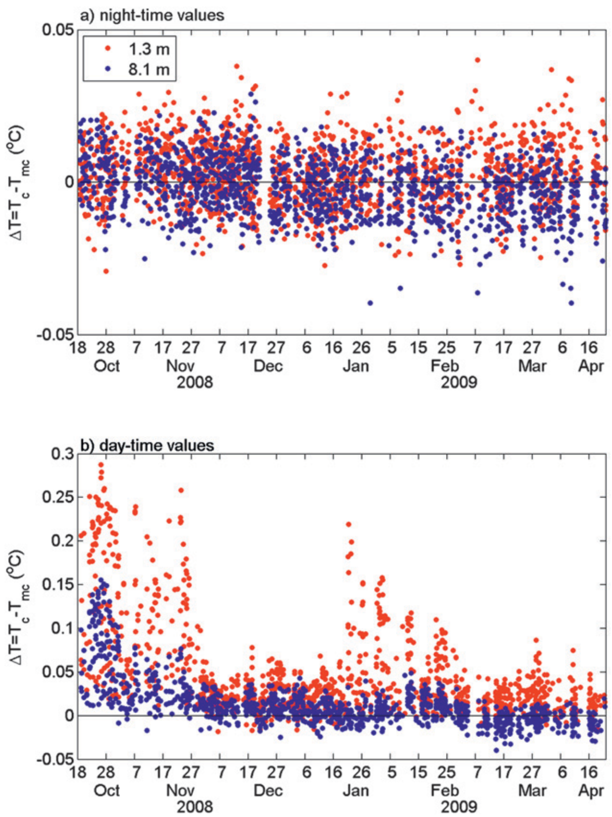

FIG. 5. Time series of the temperature difference between calibrated Temp Pros at 1.3- and 8.1-m depth (T_c) and the depth-averaged MicroCAT temperatures (T_{mc}) when the temperature in the upper 10 m is vertically uniform, during the (a) night and (b) day from a mooring in the Red Sea. Note the much larger temperature difference range in (b) relative to (a).

the vertically averaged MicroCat temperature (T_{mc}) was then computed for all Temp Pros between the near-surface and near-bottom MicroCATs. The temperature differences are assumed to represent the error in the Temp Pro measurements. For reasons discussed below, the temperature differences were separated into night and day periods. Night was defined as a period when downward solar radiation was less than 5 W m^{-2} and day as a period when downward solar radiation was greater than 100 W m^{-2}. In the Red Sea, downward solar radiation was measured on a meteorological buoy ~30 km offshore (west) of the mooring sites. In the Martha's Vineyard study, downward solar radiation was measured at an Air–Sea Interaction Tower less than 7 km from the mooring sites.

b. *Results of in situ evaluation*

The Temp Pro temperature errors were much larger during the day than at night. At night, ΔT for Temp Pros deployed at 1.3- and 8.1-m depth on one of the Red Sea moorings was typically within ±0.02°C, and never exceeded ±0.05°C (Fig. 5a). However, during the day, ΔT at 1.3 m often exceeded 0.1°C and on one occasion reached nearly 0.3°C (Fig. 5b). The ΔTs were smaller, though still substantial at 8.1 m. In general, ΔT tended to be positive during the day until late in the deployment, indicating the Temp Pros were measuring warmer temperatures than indicated by the three MicroCATs on the mooring. Daytime ΔT varied substantially on time scales of days to weeks. There were longer-term trends of decreasing ΔT at all the mooring sites in both locations. For all mooring sites and depths below the surface, nighttime RMS temperature errors were generally ~0.01°C and always less than 0.03°C (blue circles, Fig. 6). Daytime RMS errors were largest near the surface and approached nighttime values at deeper depths: below 5 m near Martha's Vineyard (red circles, Fig. 6a) and below 30 m in the Red Sea (red circles, Fig. 6b).

We hypothesized that the large, near-surface, daytime temperature differences were due to direct solar heating of the black Temp Pro housings. A number of factors are likely to influence the magnitude of the solar heating of the Temp Pros, including the water clarity (which determines how much solar radiation reaches the instrument), biological growth on the instruments (which changes the absorption characteristics of the casing), and the flow (which influences the amount of heat transfer between the logger housing and the surrounding water). Water clarity differences would explain why the large daytime temperature differences extend farther below the surface in the clearer water of the Red Sea than near Martha's Vineyard (cf. Figs. 6a and 6b). Biological growth would explain the general tendency for the temperature differences to decrease with time. There was also a clear correlation between downward solar radiation and ΔT during the first month of deployments, when biological growth on the instruments was less of an issue (Fig. 7). The response of ΔT at 1 m to downward solar radiation (at the surface) was similar for the Red Sea and Martha's Vineyard sites.

To reduce direct solar heating of the Temp Pros in a subsequent Red Sea deployment, we wrapped each Temp Pro in white electrical tape (wrapping the Temp Pros in electrical tape has the added benefit of making it easier to clean the instruments after recovery by simply removing the tape). This reduced the near-surface RMS errors of the daytime values (Fig. 6c compared to Fig. 6b), though examination of the time series (not shown) indicates little difference after 1 or 2 months, presumably because of biological growth over the temperature loggers. An alternate approach for reducing the solar heating of the Temp Pros would be to use solar shields like those used on air temperature sensors. While not

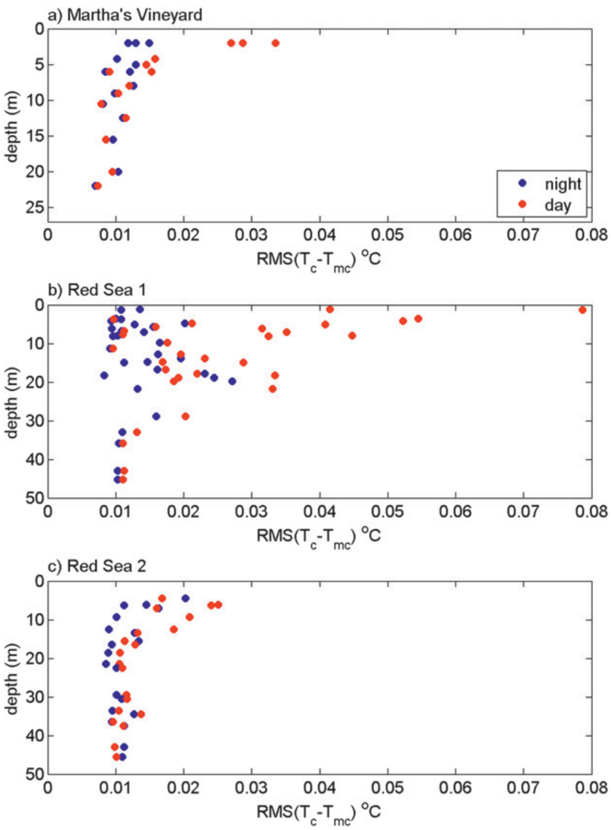

FIG. 6. RMS differences between T_c at different depths and the depth-average T_{mc} during the day (red) and night (blue) when the water column is well mixed. RMS differences are from (a) three mooring sites south of Martha's Vineyard, (b) three Red Sea mooring sites, and (c) three Red Sea mooring sites with the Temp Pros wrapped in white electrical tape to reduce solar heating of loggers. Water column is defined as well mixed when all MicroCAT temperatures are within 0.02°C of the depth-average T_{mc}. Night is defined as times when downward solar radiation is less than 5 W m^{-2} and day when downward solar radiation is greater than 100 W m^{-2}.

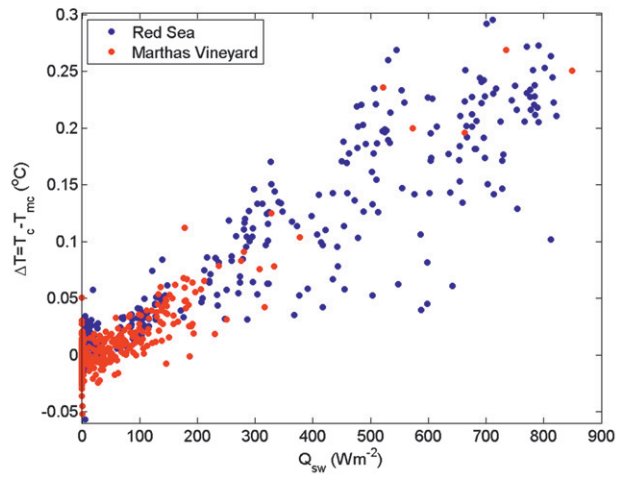

FIG. 7. Temperature difference between T_c at 1.3 or 1.0 m and T_{mc} at 0.6 m when the upper 10 m is well mixed, as a function of solar radiation (Q_{sw}). The values shown are for the initial month of a deployment in the Red Sea and two deployments south of Martha's Vineyard.

considered in this study, this approach has been used to improve the accuracy of near-surface ocean temperature measurements (Weller et al. 1998).

5. Summary

Onset Temp Pros are more accurate than indicated by the factory specification (0.2°C), provided they are calibrated. After calibration, the Temp Pros affixed to oceanic moorings have an in situ RMS error, based on a comparison with more accurate temperature loggers, of less than 0.02°C throughout the water column at night and beneath the surface layer influenced by penetrating solar radiation during the day. However, during the day, Temp Pros near the surface have a much larger error (up to 0.3°C seen here) due to solar heating of the black Temp Pro housing. Wrapping the Temp Pros in white electrical tape reduces this error, at least temporarily until biological growth covers the instrument, altering the absorption characteristics.

Acknowledgments. This work is based on research supported by Awards USA 00002 and KSA 00011 made by King Abdullah University of Science and Technology (KAUST) and by the Ocean Sciences Division of the National Science Foundation under Grant OCE-0548961. The authors appreciate helpful comments and suggestions from Anthony Kirincich and three anonymous reviewers.

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