LIMNOLOGY
and
OCEANOGRAPHY: METHODS

Limnol. Oceanogr.: Methods 14, 2016, 338–342

doi: 10.1002/lom3.10093

Influence of solar irradiance on underwater temperature recorded by temperature loggers on coral reefs

Keisha D. Bahr,* Paul L. Jokiel, Ku'ulei S. Rodgers
University of Hawai'i Hawai'i Institute of Marine Biology, Kāne'ohe, Hawaii

Abstract

The use of miniaturized digital temperature logging devices on coral reefs is increasing dramatically due to the threat of global warming. Shallow coral reef environments are characterized by extremely high solar radiation and highly transparent seawater, raising the possibility of solar heating of devices deployed in these settings. In this study, we compared temperature measurements under a variety of shading treatments to investigate the potential error associated with high irradiance levels in shallow, clear waters. Results of this experiment showed that mid-day water temperature readings by unshaded loggers were significantly higher by 2.2°C on average compared with shaded loggers. Loggers shielded with reflective tape showed less error but still reported significant heating, with water temperatures that were on average 0.15°C higher than shaded loggers. There were no significant differences among shade treatments during nighttime hours, indicating that irradiance is the source of the errors documented here. Care must be taken to shield temperature loggers from irradiance while providing good circulation of water around the sensors. One option is to place the loggers in a naturally occurring, cryptic or shaded habitat on the reef. When deployed in open reef areas, in mesocosms, or in experimental aquaria, loggers can be shielded in protective, opaque plastic tubes that are open at both ends.

Global warming has resulted in severe coral bleaching events throughout the world and are causing high coral mortality (Donner et al. 2005). The increasing frequency and severity of these events has led to the rapid expansion of monitoring and research on effects of high temperatures on corals. This work has been greatly facilitated by the availability of inexpensive miniaturized digital water-proof devices that can continually log time and temperature in remote field applications, experimental aquariums and mesocosms for long periods of time. Electronic thermistor sensors came into use on coral reefs over 40 yr ago (Jokiel and Coles 1977), but were not self-contained and required an underwater wire connection from the thermistor to the data recording device. The early workers quickly noticed that solar radiation heats the submerged thermistor beads directly and can give an erroneously high reading of water temperature related to intensity of irradiance striking the thermistor. The problem was solved by inserting the thermistor into an open ended section of plastic pipe that shielded the bead from solar irradiance without reducing the free movement of water to the sensor. The more recently developed waterproof digital thermographs are self-contained, but potentially vulnerable to error caused by solar heating, especially in tropical areas with high irradiance in the clear shallow waters characteristic of coral reefs.

Several published reports illustrate the application of these devices on coral reefs. Onset® HOBO® Tidbit® and Onset® HOBO® Pro v2 units have been used to measure temperature continuously since 1999 in shallow backreef pools off Ofu Island in Samoa (Craig et al. 2001; Smith and Birkeland 2007; Oliver and Palumbi 2011). These authors apparently were aware that irradiance striking the loggers could result in errors and placed them in shaded habitats on the reef. Gorospe and Karl (2011) published a study that involved placing 85 unshielded Thermochron® iButton® temperature loggers over a small coral reef to monitor fine-scale distribution of coral reef temperatures.

Most of the scientists conducting coral bleaching work in Hawai'i are members of the Hawai'i Coral Bleaching Group. A questionnaire was sent to these members with the following response from 14 of the principle investigators (PIs): The majority (12 PIs) report using Onset® HOBO® brand loggers with two groups using SeaBird® electronics (model 39 and model 56). Eight of the PIs are using unshielded devices. The remaining investigators are shielding their loggers in various ways including: reflective tape, placement inside a structure (e.g., cement, plastic), and shading by placement within a cryptic habitat. Therefore, there is no standardized

---

*Correspondence: kbahr@hawaii.edu

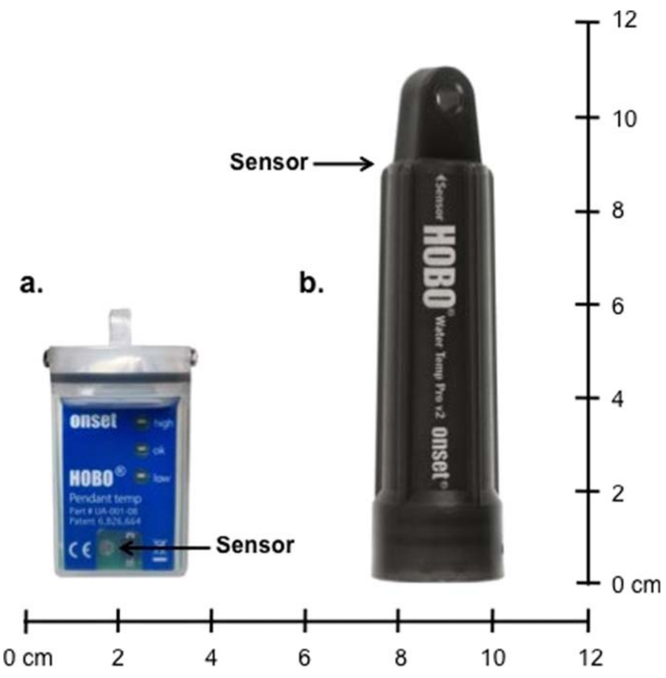

Fig. 1. Photograph of the HOBO® Pendant® (**a**) and the HOBO® Pro v2 (**b**) evaluated in this study. ©Onset Computer Corporation.

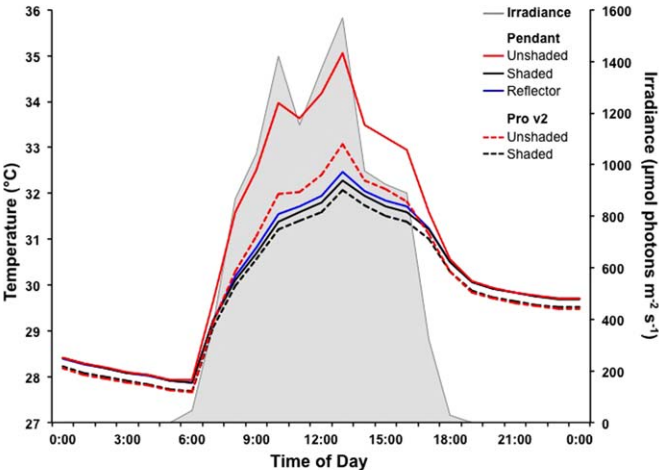

Fig. 2. Mean hourly water temperatures (°C) measured by unshaded (red solid line), shaded (black solid line) and reflector (blue solid line) Onset® HOBO® Pendant® loggers and Onset® HOBO® Pro v2 loggers unshaded (red dashed line) and shaded (black dashed line) over a 24-h experimental period. Mean hourly irradiance levels (μmol photons m^{-2} s^{-1}) are indicated by solid gray shading.

methodology on deployment nor has there been rigorous testing of accuracy from these different deployments. Quantitative data are lacking on the possible impact of solar heating on temperature measurements made with these devices. Thus, we undertook measurements comparing unshielded units vs. shaded units and units wrapped in reflective tape to evaluate the possible errors associated with high irradiance levels.

Methods and materials

This research was conducted at University of Hawai'i's Hawai'i Institute of Marine Biology (HIMB) at Moku o Lo'e, Kāne'ohe Bay, Hawai'i (21.4°N, 157.8°W) in a continuous-flow mesocosm facility that mimics the physical, chemical, and biological conditions and natural diurnal fluctuations in seawater chemistry that occur on the inshore reef of Moku o Lo'e (Jokiel et al. 2014). Two of the most commonly used waterproof devices were evaluated (Fig. 1). The Onset® HOBO® Pro v2 logger (U22-001) measures temperatures between −40°C and 70°C in the air and up to 50°C in the water with a reported ± 0.2°C accuracy. Onset® HOBO® Pendant temperature data loggers (UA-001-08) are reported by the manufacturer to measure temperatures between −20°C and 70°C with a ± 0.53°C accuracy. Solar radiation shields are available from the manufacturer for air temperature measurements in direct sunlight; however, shields are not presently available for underwater applications.

Nine Onset® HOBO® Pendant loggers and six Onset® HOBO® Pro v2 loggers were used in this evaluation and were first calibrated in 0°C and 35°C water baths. Onset HOBO® Pendant loggers were evaluated under three shielding treatments ($n = 3$ loggers per treatment). The first treatment consisted of loggers shaded with reflective metallic aluminum foil tape (reflector treatment) (Nashua Tape Products, Waterproofing Repair Tape). The second treatment consisted of loggers shaded by an opaque plastic pipe that was open at both ends to allow water circulation (shaded treatment), and the third treatment consisted of loggers placed in direct sunlight (unshaded treatment). Treatments for the Onset® HOBO® Pro v2 ($n = 3$ loggers per treatment) included shielded with an open pipe (shaded treatment) and in direct sunlight (unshaded treatment). The Onset® temperature loggers were programed to record time and temperature every minute. Irradiance above the mesocosm facility was continuously measured using a cosine corrected quantum sensor (Li-Cor, Lincoln, Nebraska, U.S.A.) (Fig. 2). Temperature loggers were randomly placed in a well-flushed 500 L flow-through experimental mesocosm located in full natural sunlight to avoid variation in temperature and irradiance due to tidal changes. Loggers were deployed for 72-h at a depth of 35 cm in a well mixed mesocosm. Flow rate through the mesocosm was maintained at a rate of 8 L min^{-1} resulting in a seawater turnover rate of 45 min.

Mean temperature for each logger within each treatment was calculated for mid-day (11:00–14:00) and night (23:00–02:00) within a 24 hr period. An one-way analysis of variance (ANOVA) was used to detect significance of differences in mean temperature values between the treatment variables. Where significant differences did occur ($p < 0.05$), *post hoc* multiple comparison tests of means were followed using Tukey's honestly significant difference (HSD) test for the Onset® HOBO® Pendant loggers and a Student's *t*-test was used for Onset® HOBO® Pro v2 loggers (Sokal and Rohlf 1981; Zar 1996). A linear regression analysis was used to test the relationship between hourly irradiance and hourly temperature differences between treatments and the shaded loggers.

Results

HOBO® Pendant® (UA-001-08)

Reported average mid-day (11:00–14:00) temperatures varied among logger treatments (one-way ANOVA $F_{(2,8)} = 1324.1$, $p < 0.0001$). The highest mid-day average temperature readings were recorded in the unshaded loggers (34.09 ± 0.03°C) (mean ± SE). Tukey *post hoc* comparisons revealed significant differences in mean mid-day temperature among all logger treatments. Unshaded loggers were 2.2°C higher than shaded loggers (31.90 ± 0.01) ($p < 0.0001$) and 2°C higher than reflector-protected loggers (32.05 ± 0.01°C) ($p < 0.0001$) (Fig. 2). Reflector treatment loggers recorded mean mid-day temperatures that were 0.15°C higher than shaded treatment loggers ($p = 0.041$) (Table 1). The maximum temperature of 35.65°C for the unshaded device was 3.2°C higher than the actual water temperature (32.50°C) measured by the shaded device (Table 1). No statistical difference was found among treatment levels during night temperatures (23:00–02:00) (one-way ANOVA $F_{(2,8)} = 0.264$, $p = 0.776$). Differences in mean hourly temperature readings between treatment loggers and the reference shaded loggers significantly increased with increasing irradiance (unshaded: $R^2 = 0.82$, $p < 0.0001$; reflector: $R^2 = 0.72$, $p < 0.0001$). These differences were as high as 3°C for unshaded loggers and as high as 0.4° in reflector loggers (Fig. 3).

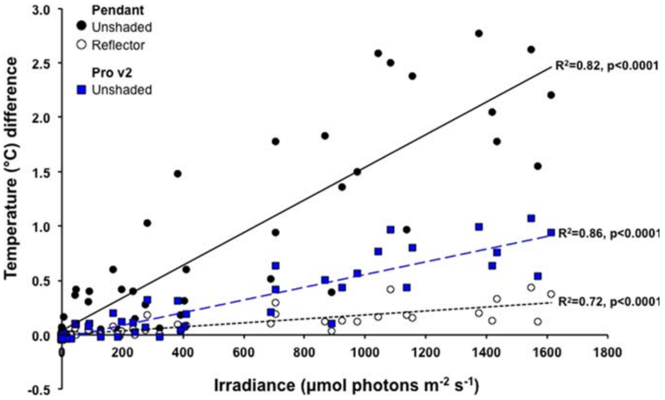

Fig. 3. Mean hourly temperature differences between treatment and reference shaded loggers as a function of mean hourly irradiance over the 3-d period. Onset® HOBO® Pendant® treatments included unshaded (solid circle) and reflector (open circle). Onset® HOBO® Pro v2 treatment was unshaded (blue squares).

HOBO® Pro v2 (U22-001)

Mean mid-day temperature (11:00–14:00) values for the Onset® Pro v2 unshaded temperature loggers were statistically higher (32.45 ± 0.02°C) than shaded temperature loggers (31.70 ± 0.01°C) (one-way ANOVA $F_{(1,5)} = 29.898$, $p = 0.0054$) (Fig. 2). Mean night temperatures (23:00–02:00) did not statistically differ among logger treatments (one-way ANOVA $F_{(1,5)} = 0.5205$, $p = 0.5106$). The maximum temperature of 33.84°C recorded for the unshaded logger was 1.5°C higher than the shaded logger (Table 1). Differences in mean hourly temperatures between unshaded and shaded Pro v2 loggers significantly increased with increasing irradiance ($R^2 = 0.86$, $p < 0.0001$) (Fig. 3). The highest differences (1°C) were observed at the highest irradiance regimes.

Discussion

The data provided here demonstrate that irradiance in shallow, tropical waters can result in erroneously high underwater temperature measurements when using unshaded temperature loggers. The assumption that water provides an adequate irradiance heat shield for digital temperature-logging devices is flawed. Tropical environments are characterized by extremely high solar radiation and highly transparent seawater. Temperature data loggers can absorb solar radiation and can be subject to extreme solar heating. In these situations, the loggers will give anomalously high temperature readings. Results of this experiment show that mid-day water temperature readings under high irradiance for an unshielded device in shallow water can be

Table 1. Water temperature characteristics recorded by Onset® HOBO® temperature Pendant and Pro v2 loggers by shading treatments ($n = 3$) at mid-day (11:00–14:00) and night (23:00–02:00) over a 24-h period.

Onset HOBO temperature logger	Treatment ($n = 3$)	Mid-day (11:00–14:00)			Night (23:00–02:00)		
		Min	Max	Mean ± SE	Min	Max	Mean ± SE
Pendant UA-001-08	Unshaded	32.29	35.65	34.09 ± 0.03	28.06	29.75	28.65 ± 0.02
	Shaded	31.47	32.50	31.90 ± 0.01	28.16	29.75	28.64 ± 0.02
	Reflector	31.47	32.70	32.05 ± 0.01	28.06	29.75	28.64 ± 0.02
Pro v2 U22-001	Unshaded	31.51	33.84	32.45 ± 0.02	27.88	29.60	28.42 ± 0.02
	Shaded	31.18	32.30	31.70 ± 0.01	27.85	29.60	28.45 ± 0.01

more than 3°C higher than for a shaded device. This is an extremely large error given coral sensitivity to small temperature differences. For example, the prolonged maximum upper lethal temperature of reef corals is only 1–2°C above summer maximum (Coles et al. 1976). The error due to solar heating is much greater than the accuracies reported by the manufacturer. This error is easily avoidable by simply adopting a deployment strategy that provides shading of the sensor.

Irradiance distribution on coral reefs is very heterogeneous at the microhabitat level. Brakel (1979) showed that substrate type, slope, and exposure had a marked influence on irradiance patterns at any particular reef locality, with small horizontal spatial differences between microhabitats sometimes equivalent to large differences in depth. Radiation that penetrates seawater has previously been shown to increase the temperature of the surfaces that it strikes. Jimenez et al. (2011) employed temperature microsensor measurements at the surface of illuminated stony corals which revealed millimeter-scale increases in tissue surface heating. The temperature increase was generally on the order of several tenths to one °C depending on factors such as water flow, irradiance intensity and surface roughness of the coral. Unshielded temperature loggers will consistently give higher temperature readings in microhabitats experiencing higher irradiance. Thus unshielded temperature loggers might show spatial variation in temperature that is due to spatial variation in irradiance. Gorospe and Karl (2011) used unshielded Thermochron® iButton® temperature and time data loggers situated 4 m apart in a grid pattern to monitor temperature among corals at 85 sites on a single patch reef and found consistent spatial differences over small horizontal distances.

In hindsight, data provided on the importance of shielding these instruments when measuring air temperature should have prompted more concern about shielding them in marine and aquatic environments. Solar radiation shields have been developed for outdoor air temperature sensors that are mounted in direct sunlight. Onset®, the company that manufactures the devices used in this study, offers the RS3 solar radiation shield for measurements of air temperature that works with most of their external air temperature measuring instruments including the HOBO® Pendant data loggers. Air temperature recording by Thermochron® iButtons® used in the study by Gorospe and Karl (2011) can be influenced by irradiance. Hubbart et al. (2005) previously evaluated the Thermochron® iButton for air temperature measurement and showed that shielding the device from solar radiation is extremely important. In greenhouse experiments of air temperature, the unshielded iButton® showed a mean temperature of 23.4°C compared with 18.3°C for the shielded and ventilated device. At mid-day the unshielded device reported a 51.5°C while the shielded ventilated device measured 35.0°C. Likewise, field investigations of air temperature using the Onset® Computer Corporation HOBO® H8 Pro demonstrated the importance of shielding temperature loggers from solar radiation (Whiteman et al. 2000). Unshielded loggers can produce air temperature readings that are several °C higher than actual air temperature when wind speeds are low. These errors will be of lower magnitude in seawater due to its high specific heat, but our results demonstrate that it is still important to shade loggers deployed in shallow tropical waters.

Comments and recommendations

Properly calibrated loggers (both shielded and unshielded) at the same location will give an accurate temperature reading at night when solar irradiance is absent (Fig. 2). However, during daylight the unshielded logger will give an erroneous higher reading that is proportional to the level of irradiance throughout the daylight hours (Fig. 3). We recommend that care be taken to shield temperature loggers from irradiance while providing good circulation of water around the sensor. One option is to place the loggers in a naturally occurring cryptic shaded habitat on the reef (Craig et al. 2001; Smith and Birkeland 2007; Oliver and Palumbi 2011). In open reef areas, mesocosms and aquaria the logger can be inserted in a protective opaque plastic tube that is open at both ends.

In this study, the reflective tape used as shielding was new and clean during the duration of the measurements. However, in field applications the surface will quickly become fouled with fleshy algae, crustose calcareous algae and various invertebrates that will vary with the environment. These organisms will reduce reflectance of the tape and will further insulate the device from the seawater with an unknown impact on the accuracy of the temperature measurements. Thus, we recommend shading with an open-ended section of pipe that allows water ventilation or by placing the device in small shaded caverns or under overhangs on the reef. Placing loggers in plastic tube shields will reduce solar heating errors and allow circulation of water around the sensors to be comparable among sites.

Results of this study demonstrate the importance of appropriate deployment methods for monitoring and recording water temperatures in shallow reef environments. Detailed description of shielding, placement and treatment of temperature loggers should be included in the methods section of research reports. The possibility of errors associated with solar heating should be considered when planning new studies as well as in the use of data from past studies.

References

Brakel, W. H. 1979. Small-scale spatial variation in light available to coral reef benthos: Quantum irradiance measurements from a Jamaican reef. Bull. Mar. Sci. **29**: 406–413.

Coles, S. L., P. L. Jokiel, and C. R. Lewis. 1976. Thermal tolerance in tropical versus subtropical Pacific reef corals. Pac. Sci. **30**: 156–166.

Craig, P., C. Birkeland, and S. Belliveau. 2001. High temperatures tolerated by a diverse assemblage of shallow-water corals in American Samoa. Coral Reefs **20**: 185–189. doi: 10.1007/s003380100159

Donner, S. D., W. J. Skirving, C. M. Little, M. Oppenheimer, and O. Hoegh-Guldberg. 2005. Global assessment of coral bleaching and required rates of adaptation under climate change. Glob. Chang. Biol. **11**: 2251–2265. doi:10.1111/j.1365-2486.2005.01073.x

Gorospe, K. D., and S. A. Karl. 2011. Small-scale spatial analysis of *in situ* sea temperature throughout a single coral patch reef. J. Mar. Biol. **2011**: 719580. doi:10.1155/2011/719580

Hubbart, J., T. Link, C. Campbell, and D. Cobos. 2005. Evaluation of a low-cost temperature measurement system for environmental applications. Hydrol. Process. **19**: 1517–1523. doi:10.1002/hyp.5861

Jimenez, I. M., M. Kühl, A. W. D. Larkum, and P. J. Ralph. 2011. Effects of flow and colony morphology on the thermal boundary layer of corals. R. Soc. Interface **8**: 1785–1795. doi:10.1098/rsif.2011.0144

Jokiel, P. L., and S. L. Coles. 1977. Effects of temperature on the mortality and growth of Hawaiian reef corals. Mar. Biol. **43**: 201–208. doi:10.1007/BF00402312

Jokiel, P. L., K. D. Bahr, and K. S. Rodgers. 2014. Low-cost, high-flow mesocosm system for simulating ocean acidification with CO2 gas. Limnol. Oceanogr.: Methods **12**: 313–322. doi:10.4319/lom.2014.12.313

Oliver, T. A., and S. R. Palumbi. 2011. Do fluctuating temperature environments elevate coral thermal tolerance? Coral Reefs **30**: 429–440. doi:10.1007/s00338-011-0721-y

Smith, L. W., and C. Birkeland. 2007. Effects of intermittent flow and irradiance level on back reef *Porites* corals at elevated seawater temperatures. J. Exp. Mar. Biol. Ecol. **341**: 282–294. doi:10.1016/j.jembe.2006.10.053

Sokal, R. R., and F. J. Rohlf. 1981. Biometry: The principles and practice of statistics in biological research, 2nd ed. Freeman.

Whiteman, C. D., J. M. Hubbe, and W. J. Shaw. 2000. Evaluation of an inexpensive temperature datalogger for meteorological applications. J. Atmos. Ocean. Technol. **17**: 77–81. doi:10.1175/1520-0426(2000)0172.0.CO

Zar, J. H. 1996. Biostatistical analysis, 3rd ed. Prentice-Hall.

Acknowledgments

We would like to thank two anonymous reviewers for their time, advice and comments which have helped improve the manuscript significantly. We would like to also thank those members of the Coral Bleaching Group who participated in our voluntary questionnaire. This research was partially supported by United States Geological Survey Pacific Coastal Marine Science Center award G13AC00130. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government. This is the Hawai'i Institute of Marine Biology (HIMB) contribution #XXX.

Submitted 21 September 2015
Revised 20 November 2015; 19 January 2016
Accepted 27 January 2016

Associate editor: Clare Reimers