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Evaluation of a low-cost temperature measurement system for environmental applications

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Abstract

Thermochron iButtons incorporate the latest in digital technology, making them smaller, less expensive, durable and potentially more reliable than many other temperature logging devices. The objective of this study was to test the accuracy of an inexpensive air temperature measurement system, composed of a Thermochron iButton and radiation shield. Sixty-one iButtons were subjected to a sequence of two water baths (0 °C and 24·9 °C) to assess the absolute accuracy of the sensors. Five solar radiation shields were tested in a greenhouse setting to evaluate the reduction in radiative heating. Significant differences ($p < 0{\cdot}05$) were detected between instruments subsequent to both water-bath treatment analyses. The accuracy of the sensors was well within the manufacturer's stated specification of ±1·0 °C with a collective temperature variance of ±0·21 °C. Temperature responses generated by the Thermochron iButtons in different radiation shields were consistent, but varied significantly ($p < 0{\cdot}05$) from 28 to 44 °C based on diurnal temperature ranges. Results indicate that the Thermochron iButton is an accurate, inexpensive alternative to more expensive temperature data-logging systems, and is well suited for obtaining quality spatially distributed data for hydrologic and water quality investigations. Copyright © 2005 John Wiley & Sons, Ltd.

Introduction

Temperature is one of the most frequently measured environmental variables for hydroclimatic investigations. Given the variability of air temperature in natural systems, especially in complex mountainous terrain, it is often most desirable to obtain spatially distributed continuous measurements. For example, air temperature data are frequently needed to assess micrometeorological variability for investigations dealing with snow-cover processes, evapotranspiration rates, atmospheric boundary-layer processes such as cold air drainage, water temperature dynamics, and ecological processes. A number of small, relatively inexpensive sensors for environmental applications have recently entered the market (e.g. Hobo, Stowaway Tidbit, Optic Stowaway, Thermochron iButton). When these sensors are used to measure air temperature, radiation shields are also required to reduce sensor heating. The cost and size of these sensors make them ideal for spatially distributed applications; however, the performance of both the sensors and radiation shields must be evaluated to assure data quality.

The Thermochron iButton (Maxim/Dallas, Dallas, TX) is a self-contained temperature sensor and data logger enclosed in a watertight

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two-terminal stainless steel can (Figure 1). This study focuses on the DS1921L-F52 temperature data logger, which is the most applicable for hydrologic applications given the specified temperature range of −20 to +85 °C at 0·5 °C resolution and with a manufacturer's stated accuracy of ±1 °C. Each iButton has a unique digital identification code and can store up to 2048 data points configurable from 1 to 255 min time intervals. The unit contains 512 bytes of non-volatile memory to store time, temperature, and a code for the sampling location. It can also be programmed to fill-and-stop, or overwrite (ring-mode) final data storage. The iButton can log data for up to one million total temperature measurements over the expected lifetime of the unit (Marsh, 2003). The internal clock measures seconds to years accurately to within ±1 min per month (Maxim/Dallas, Dallas, TX). Data are stored as both raw values and in histogram format. The data logger can be configured to record events outside of a specified temperature range, as well as the start time, duration, and whether the temperature was above or below a given value (Marsh, 2003). Internal power comes from a 3 V lithium power source that switches to 'parasite mode' to obtain power from a peripheral device during data transfer. The power unit can last up to 10 years, depending on mode of application.

Within its protective stainless-steel enclosure, a single silicon chip integrates a digital thermometer, clock/calendar and protected memory. The iButton uses a DS18S20 temperature sensing integrated circuit (IC) to measure temperature. IC temperature sensors differ from many other types of sensor in two important ways. The first is operating temperature range. Normally, the full range possible for temperature sensing ICs is −55 to +150 °C. However, some devices are designed to go beyond this range, whereas others, because of package or cost constraints, operate over a narrower range. The second major difference is functionality. A silicon temperature sensor is an IC and can, therefore, include signal-processing circuitry within the same small package as the sensor (Maxim/Dallas, Dallas, TX). The sensing element of the Thermochron iButton is a band-gap circuit, which outputs a differential voltage proportional to temperature. The digital thermometer measures temperature with 8-bit (±0·5 °C) resolution by employing a differential measurement between two diodes operating at different bias currents to derive temperature values. Differential voltage is less prone to process variations relative to a single diode (Marsh, 2003). Further discussion regarding the functionality of this device is beyond the scope of this study but can be accessed through the Dallas/Maxim iButton Website (www.ibutton.com). At the time of writing, Thermochron iButtons sell for less than 16·00 USD each and require a 15·00 USD interface kit and a PC with a serial port (Maxim/Dallas, 2004).

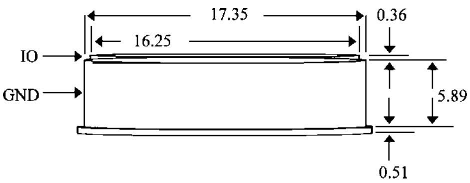

Figure 1. The dimensions (mm) of the Thermochron iButton are identical for the entire DS1921 family and others. IO: input/output. GRD: ground. A single data lead and ground is all that is needed for data transfer

To date, there has been no independent assessment of the accuracy and precision of Thermochron iButtons that we are aware of. The objectives of this study were to test the performance of iButton units and assess their efficacy within a solar radiation shield for distributed air temperature measurement. The first specific objective was to test the accuracy of the DS1921L-F52 iButton, the stability of measurement over time, and the variability between individual devices. This work was also undertaken to assess whether Thermochron iButtons are accurate to within Dallas/Maxim specifications (i.e. ±1 °C). The second specific objective was to test the efficacy of different solar radiation shields and quantify the maximum expected error due to solar heating.

Methods

Sensor variability assessment

Sixty-one Thermochron iButtons were evaluated in 0 °C and 24·9 °C water baths to span the range of relevant temperatures for most warm-season environmental investigations. The 0 °C ice bath consisted of deionized water and deionized crushed ice that were mixed to create an ice slurry in an insulated container. A calibrated and certified mercury thermometer (Kessler Instruments Inc., Amityville, NY) with a range of −8 to +32 °C and resolution of 0·1 °C was used to record the temperature of the ice bath. The ice bath was agitated continuously throughout the 20 min test period to maintain a homogeneous temperature of 0 °C throughout. Since they are watertight, the iButtons were placed directly in the ice bath and, therefore, were free to move around during the agitation process. The iButtons were programmed to log time and temperature data every minute during the experiment. The warm water bath consisted of the same regimen as the ice bath. The warm water bath portion of the experiment took place in a *Magni Whirl* temperature bath (Lindburg/Blue M Co., Asheville, NC), at a constant temperature of 24·9 °C for 20 min. The *Magni Whirl* contained two trays that were submerged in deionized water and mechanically agitated. The same calibrated mercury thermometer was used to establish the reference temperature. The procedures for both the ice and the warm water baths were consistent with those outlined for mercury thermometer calibration in the American Society for Testing and Materials (ASTM, 1981) and the National Committee for Clinical Laboratory Standards (NCCLS, 1990).

Radiation shield assessment

Five iButtons were installed in a greenhouse to assess and compare the efficacy of different solar radiation shields relative to an unshielded sensor. The radiation shield experiment was designed to subject the sensors to a worst-case scenario (e.g. solar heating with negligible ventilation), to gain a better appreciation for temperature response of the sensors in varying shield types. Three Gill model 41 002, six-plate radiation shields (R. M. Young Co., Traverse City, MI) and one Spectrum six-plate (Spectrum Technologies, Plainfield, IL) radiation shield were used for the radiation shield experiment. One of the Gill shields was aspirated with a 12 V (1·6 W) 5 cm^2 computer processor cooling fan as a reference shield. It is generally accepted that mechanically aspirated temperature measurements are the most accurate (WMO, 1996). For the aspirated shield used here, the fan was sandwiched between the third and fifth plates (fourth plate removed) of the radiation shield, thereby pulling air up past the iButton data logger and out beneath the top plate of the shield. The cost of each of these shields is approximately 160·00 USD and 45·00 USD for the Gill and Spectrum shields respectively.

All five iButtons and their respective shields (one without a radiation shield) were installed in a greenhouse for a 24 h period under cloudless conditions to assess thermal response variation between differing types of shield. All windows and doors were closed and no fans operated in the greenhouse during the experiment. The radiation shields were oriented approximately 2 m above the ground on PVC scaffolding created for this experiment. The shields were held in a nearly concentric ring around the centre of the scaffold with a distance of at least 40 cm from each other. In this manner, all shields were occupying similar space, without altering the microclimate of a neighbouring shield. Data acquired using the two non-aspirated Gill shields were averaged for subsequent analysis.

Statistical analyses

Descriptive statistics were followed with one-way analysis of variance (ANOVA) to detect significant differences (95% confidence interval) in mean values between control and treatment variables. Where significant differences did occur ($p < 0·05$), one-way ANOVA was followed by *post hoc* multiple comparison tests of specific means using the Dunnett test or Tukey's honestly significant difference (HSD) test (Sokal and Rohlf, 1981; Zar, 1996). The Dunnett test treats one group (data set) as a control and compares all other groups against it and was thus used for the ice and warm water bath experiments where the control was the calibrated mercury thermometer. Tukey's HSD test compares all groups against each other and, therefore, was used for the solar radiation shield assessment (Sokal and Rohlf, 1981; Zar, 1996).

Results

During the ice bath experiment, all of the Thermochron iButtons recorded temperatures within the Maxim/Dallas stated accuracy of ±1 °C. The minimum temperature recorded was −0·5 °C. The collective mean of temperature data collected by the iButton sensors during the ice bath experiment was 0·19 °C, which is well within the stated accuracy range of ±1 °C. Of the total 1220 data points (time and temperature) collected during the ice bath portion of this experiment 34, 712, 454, and 20 (3%, 58%, 37%, and 2% respectively) of those data points corresponded to −0·5 °C, 0·0 °C, 0·5 °C, and 1·0 °C respectively

(Figure 2). One-way ANOVA generated for the ice water bath revealed that despite close proximity to the reference temperature (0·0 °C), with a collective mean temperature of 0·19 °C, there was a significant difference ($p < 0{\cdot}05$) detected between the reference temperature and the group mean of the Thermochron iButtons (0·19 °C).

For treatment and control multiple comparisons, one-way ANOVA was followed by the Dunnett test. Results indicated that at the $p < 0{\cdot}05$ confidence interval, 28 of the 61 Thermochron iButtons used in this portion of the experiment recorded mean temperatures significantly different from the mean temperature of the calibrated thermometer (0·0 °C) for a total of 45·9% of the devices. This indicates that these 28 devices, at some point in the experiment, recorded temperatures that were between 0·5 and 1·0 °C different than the reference temperature. This is still within the Maxim/Dallas stated accuracy of ±1 °C.

Descriptive statistics of the warm water bath experiment showed that the Thermochron iButtons again recorded temperatures within the Maxim/Dallas stated accuracy of ±1 °C. In this portion of the experiment all iButtons recorded temperatures that were within 1 °C of the calibration temperature of 24·9 °C. The overall minimum temperature recorded by a Thermochron iButton was 24·0 °C, and the maximum was 25·5 °C. The overall mean for this portion of the experiment was 24·67 °C, placing the iButtons well within the stated accuracy range with a collective average only 0·23 °C below the reference temperature of 24·9 °C.

Of the total 1220 data points collected during the warm water bath portion of this experiment, 20, 776, 404, and 20 (2%, 63%, 33%, and 2% respectively) of the data points corresponded to 24·0 °C, 24·5 °C, 25·0 °C, and 25·5 °C respectively (Figure 3). One-way ANOVA indicated that, again, despite the relative proximity to the calibrated thermometer temperature (24·9 °C), there was a significant difference at the $p < 0{\cdot}05$ level detected between the calibrated mercury thermometer mean and the group mean of the Thermochron iButtons (24·67 °C). For treatment versus control multiple comparisons of the warm water bath, the Dunnett multiple comparison test followed one-way ANOVA. Results indicated that, at the $p < 0{\cdot}05$ level, 55 out of the total 61 Thermochron iButtons used in this portion of the experiment resulted in mean temperatures that were significantly different from the mean temperature of the reference thermometer (24·9 °C) for a total of 90·2% of the devices. During at least some of the recording time, these 55 devices recorded temperatures that were between 0·5 and 0·9 °C different than the reference temperature (still within the Maxim/Dallas stated accuracy of ±1 °C).

Solar radiation experiment

Descriptive statistics for the solar radiation data (Table I) revealed that mean temperatures recorded by the Thermochron iButton shielded by the aspirated Gill radiation shield were lower and less variable than all other radiation shields, with a mean temperature of 18·26 °C collected at 1 min resolution. The

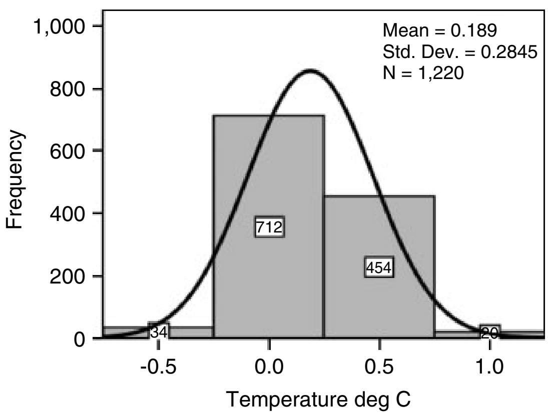

Figure 2. Temperature data frequencies (data points) as recorded by 61 Thermochron iButtons in a 0·0 °C water bath

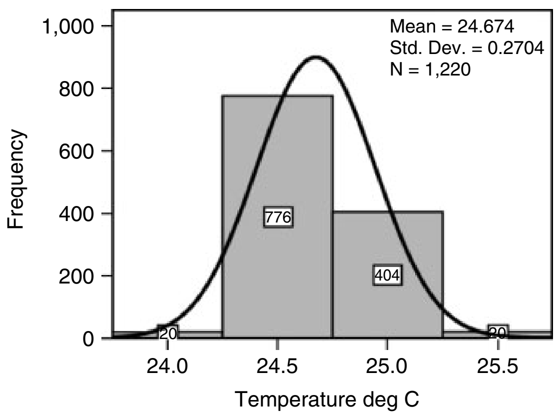

Figure 3. Temperature data frequencies as recorded by 61 Thermochron iButtons in a 24·9 °C water bath

unshielded iButton recorded the highest mean daily temperature of 23·42 °C during the same time period. The non-aspirated Gill and Spectrum radiation shields exhibited mean daily temperatures of 20·46 °C and 20·59 °C respectively during the same time period.

One-way ANOVA indicated that, despite their relative proximity to the control instrument (aspirated Gill), there was a significant difference ($p < 0{\cdot}05$) between the daily temperature means of one or more data sets (shield types). Results of Tukey's HSD indicated that the control (aspirated Gill) mean and the unshielded iButton mean differed significantly from each other and all other shield types at the $p < 0{\cdot}05$ level, whereas the naturally ventilated Gill and Spectrum shields did not exhibit daily means that differed significantly from each other (Figure 4).

Table I. Summary table of descriptive statistics for solar radiation data collected by Thermochron iButtons in differing radiation shields (one iButton unshielded), where the control is the aspirated Gill shield

Shield type	*N*	Mean Temp. (°C)	Min. Temp. (°C)	Max. Temp. (°C)
Gill Aspirated	1440	18·26	7	35
Gill non-aspirated*	1440	20·46	8	40·25
Spectrum	1440	20·59	8	40·5
No shield	1440	23·42	7·5	51·5

The diurnal temperature ranges recorded were 28·0 °C, 32·25 °C, 32·5 °C, and 44·0 °C, for the aspirated Gill, non-aspirated Gill, Spectrum and unshielded loggers respectively. The maximum temperature difference observed was 16·5 °C between the aspirated Gill shield and the unshielded temperature logger. Other temperature differences between shields at the time of maximum temperature ranged from 5·25 to 6·5 °C, relative to the 35 °C maximum temperature recorded by the sensor in the aspirated Gill shield.

Discussion

Controlled-temperature environment

Collectively (ice and warm water bath total data points: 2440), the majority of data points (1488) logged during this experiment corresponded exactly to the reference temperatures of 0·0 and 24·9 °C. Although 40 data points were between 0·5 and 1·0 °C beyond the reference temperature, it is notable that they were still within the Maxim/Dallas

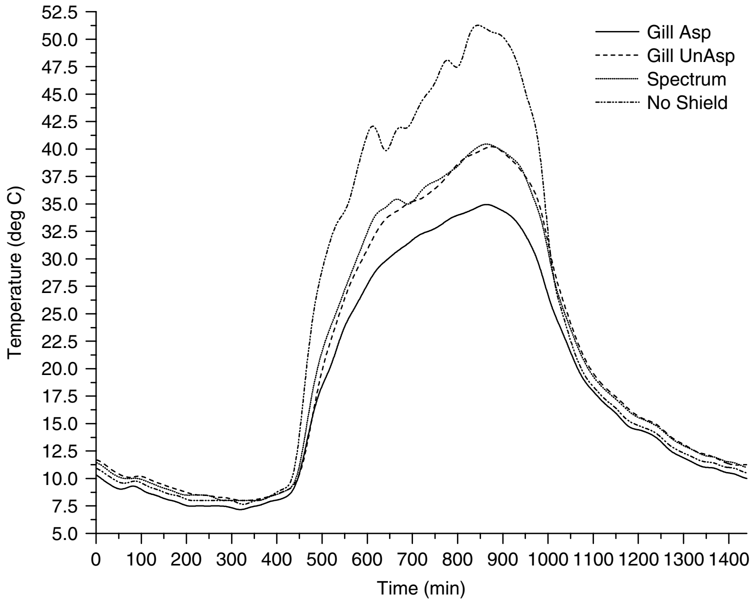

Figure 4. Temperature responses of Thermochron iButtons placed in a greenhouse setting employing different solar radiation shields (one without shielding). Although all iButtons responded to solar diurnal cycling, temperature response means between shields varied significantly ($p < 0{\cdot}05$). Graphs presented with 25-point smoothing

stated accuracy. Within the group of iButtons, only two devices logged temperatures that were exactly 1·0 °C over the calibration temperatures, and no instruments registered temperatures greater than ±1 °C beyond the respective reference temperatures. Since all the Thermochron iButtons received the same treatment in these experiments, it is assumed that the temperature departure is attributable to variations in instrument manufacture.

Although the observed temperature differences between those iButtons that did not measure temperatures exactly the same as the mercury thermometer (total data points: 952) do not surpass the guaranteed accuracy of ±1 °C (most less than ±0·5 °C of calibration temperatures), quantitatively the temperature differences are significant at the 95% confidence level, as demonstrated by statistical analysis.

With 61 instruments and 1220 data points (time and temperature), the ice bath experiment yielded an average iButton temperature of 0·19 °C above the reference temperature of 0·0 °C whereas iButtons in the warm water experiment averaged 0·23 °C below the reference temperature of 24·9 °C recorded by the reference thermometer. It may be worth noting that the average difference was greater for the warm water bath than the ice bath. Although this may be negligible, it may indicate that Thermochron iButtons respond to higher temperatures differently than lower temperatures. This can only be ascertained through further investigation. Of the data collected by the Thermochron iButtons in the ice bath, 95% were within ±0·5 °C of the reference temperature of 0·0 °C, and 98% were within ±0·5 °C of the reference in the warm water.

Although an accuracy of ±1 °C may be acceptable for many hydrological investigations, this research suggests that pre-screening sensors in controlled-temperature environments may improve upon the manufacturer-specified accuracy. For example, sensors that measure absolute temperature differences in excess of 0·5 °C could be discarded, such that the remaining sensors all exhibit accuracy within 0·5 °C of reference temperatures. Results from this investigation indicate that less than 3% of sensors would be rejected given these constraints. Given the low cost of these devices, rejection of a small percentage of sensors may be an acceptable option.

Radiation shield experiment

The results of the work conducted with differing radiation shield types will be of value to researchers requiring spatially distributed air temperature measurements. The resulting data analysis showed comparable trends yet contrasting maximum responses due to solar diurnal cycling on the part of all the iButtons.

In light of the large difference in cost of the devices used in this work (~45·00 USD and ~160·00 USD for the Spectrum and Gill shields respectively), the relatively small difference in accuracy between devices may not be worth the extra expense. It is worth noting that these results represent a worst-case scenario for air temperature measurement because of the low natural ventilation in the greenhouse setting. In a natural setting, the differences between the naturally ventilated and mechanically aspirated shields are expected to be lower. However, large differences may result under clear conditions when installed over a high-albedo surface, causing sensors to receive upwelling solar radiation (Georges and Kaser, 2002).

Conclusions

The Thermochron iButton temperature data logger is factory guaranteed to measure temperature to within ±1 °C. The results showed that, collectively, the Thermochron iButtons were accurate well within ±1·0 °C greater than 99% of the time. Statistical analyses showed that there was a significant difference between temperatures recorded by some Thermochron iButtons, although these differences may be negligible depending on the application. Pre-screening of sensors using similar methods may increase the accuracy of a group of sensors to within ±0·5 °C, which is suitable for most hydrological or other environmental applications. The solar radiation shield experiment showed a relatively close relationship between the control (aspirated Gill shield) and the other shield employed, indicating that the type of radiation shield may not be as important as whether or not it is aspirated. Future validation studies for the Thermochron iButton should involve field-testing procedures similar to those conducted here, testing a wider range of environmental conditions and the significance of ventilation relative to shielding, as well as considering whether the calibration of Thermochron iButtons changes with use and sensor aging.

Thermochron iButtons exhibit many advantages over other temperature data-logging systems, the primary one being their cost. Other benefits include their small size and applicability to a vast range of environmental research questions. Disadvantages of Thermochron iButtons include a lack of final storage space. Storage space equipped to handle 2048 data points often does not allow for long term, high-resolution recordings. This number has recently been doubled in the DS1922L/T sensor to 4096 data points. However, this can still be somewhat limiting for environmental applications. Results from this study showed that the Thermochron iButton is a practical, inexpensive replacement for more expensive temperature data-logging systems, and is thus well suited for obtaining quality spatially distributed data for hydrologic and water quality investigations.

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