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Evaluation of the ACR SmartButton thermometer and a low-cost protective case for continuous stream temperature measurement

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ABSTRACT

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Water temperature is a common variable of interest in stream ecology studies. In this paper, the performance of the ACR SmartButton thermometer and a low-cost protective case were evaluated for stream temperature measurement. The accuracy of the SmartButtons at 0, 10 and 15 °C was well within the ± 1 °C range specified by the manufacturer. For 50-60 % of the readings performed, the error was greater than the ± 0.2 °C correction factor accepted for meteorological temperature measurements. However, the observed level of accuracy is most likely sufficient for most biological applications if the loggers are calibrated against a reference standard. The metallic case that we used had a negligible effect on temperature measurements and offers a reliable way to protect the SmartButton during use in small streams.

Key words: Water temperature, river, stream, digital thermometer, methodology, calibration.

RESUMEN

Evaluación de los termómetros ACR SmartButton y de una carcasa protectora de bajo coste para la medición en contínuo de la temperatura del agua en ríos

La temperatura del agua es una variable de interés en los estudios de ecología fluvial. En este trabajo, se evalúa el rendimiento de los termómetros ACR SmartButton y de una carcasa protectora de bajo coste para la medida de la temperatura en ríos. La precisión de los SmartButton a 0, 10 y 15 °C se encuentra dentro del rango de ± 1 °C que especifica el fabricante. El error observado en las lecturas sobrepasa el factor máximo de corrección de ± 0.2 °C que se acepta para la medida meteorológica de la temperatura en el 50-60 % de los datos recogidos. Sin embargo, la precisión observada es probablemente suficiente para otras aplicaciones biológicas, si los termómetros se calibran frente a una referencia estándar. Las carcasas protectoras que hemos utilizado tienen un efecto despreciable en las medidas de temperatura y representan un método seguro para instalar los SmartButtons en arroyos.

Palabras clave: *Temperatura del agua, río, arroyo, termómetro digital, metodología, calibración.*

INTRODUCTION

Temperature is a common variable of interest in stream studies because it influences in-stream processes (*e. g.*, organic matter decomposition, Stout, 1989) and the distribution, physiology and behaviour of stream biota (Wehrly *et al.*, 1998; Lewis *et al.*, 2000; Dunham & Chandler, 2001). Various methods are currently used for measuring temperature in aquatic systems, including Raman backscatter distributed temperature sensing (Selker *et al.*, 2006; Tyler *et*

al., 2009), infrared remote sensing (Wawrzyniak *et al.*, 2012) and ground-based thermography (Cardenas *et al.*, 2008; Tonolla *et al.*, 2010). However, the use of digital thermometers with datalogging capability is still the most affordable and common method for monitoring water temperature (*e. g*., Malard *et al.*, 2001; Johnson *et al.*, 2005; Herb & Stefan, 2011). Attempts to assess stream temperature across large regions have been limited by the high equipment and travel costs associated with maintaining a large number of thermometers spread out over many sites (Wehrly *et al.*, 1998), but the recent development of small, more affordable sensors has resulted in an increased number of individual datasets collected by private and public organisations (*e. g*., Lewis *et al.*, 2000). The utility of such collective efforts may be limited, however, if variation in measurement quality prevents the comparison of multiple datasets from different sources. A situation may develop in which large datasets exist but the information that can be extracted from them is not reliable (the data-rich-but-information-poor syndrome; Ward *et al.*, 1986; Timmerman *et al.*, 2010). The information in multi-source water temperature datasets will be useful if, among other things, it is credible and the users perceive it to be accurate, valid and of high quality (Cash *et al.*, 2003). In addition to data acquisition, efforts should be directed towards documenting and assuring the quality of stream temperature measurements.

Standards for the quality of environmental temperature measurements have been established by the World Meteorological Organization (WMO, 2008). However, it is not economical to use thermometers that meet these requirements directly. Typically, less expensive thermometers are used by calibrating the thermometer in the laboratory and applying correction factors to the collected data as needed. Calibration involves comparison of the thermometer readings with a standard to determine how closely the instrument matches the standard. Calibration standards for many environmental variables (*e. g*., concentrations of chemicals in water) can be easily produced in the laboratory for measurement (*e. g*., a calibration curve for a

spectrophotometer). In contrast, the standard scale for temperature measurement is based on the thermodynamic state of various substances at triple point or freezing point equilibrium as measured with a platinum resistance thermometer (Preston-Thomas, 1990). Because the reproduction of this scale for routine calibration is not feasible, a need arises to calibrate against another thermometer that is traceable back to the international temperature standard. Performing periodic calibrations of the thermometers against a reference standard is also useful for detecting those that become defective due to malfunction or age (Dunham *et al.*, 2005).

In addition to the issue of calibration, the use of temperature dataloggers in streams requires making decisions about the installation of the sensor in the field. Installation of a thermometer in a stream commonly requires the use of a protective case to avoid physical damage to the instrument. The case can be either a part of the instrument itself or a commercially manufactured or individually constructed enclosure. Water-resistant sensors and cases that allow the flow of water through the case are preferred for making measurements in aquatic systems because the temperature of air trapped inside a watertight case equilibrates with the surrounding water too slowly and causes a time lag in measurements (Dunham *et al.*, 2005). The material and colour of the case are also important (Dunham *et al*., 2005). Some materials, such as wood and plastic, are poor conductors of heat, which can lead to differences between the temperature measurements and actual temperatures. In the case of colour, metallic and white surfaces are preferred because dark surfaces result in increased heating of the thermometer when exposed to sunlight. In any case, testing of the protective case is required to ensure that the case does not interference with the temperature measurements (Hubbart *et al.*, 2005).

In this study, we evaluated the use of the ACR SmartButton thermometer (ACR Systems Inc., 2010) for continuous water temperature measurement and tested the effects of a new protective case on temperature measurements. We also proposed a protocol for the calibration of the thermometer and the correction of sensor temperature data.

MATERIALS AND METHODS

Reference standard measurement for temperature

The current accepted international standard for temperature measurements is the International Temperature Scale of 1990 (Preston-Thomas, 1990; ITS-90, 1999), which establishes the temperature values for various substances at triple point or freezing equilibrium. As an example, standards within the range −40 to 30 °C, which are significant for measuring environmental temperatures, include the triple point of mercury (−38.8344 °C), the triple point of water (+0.01 °C) and the freezing point of gallium (+29.7646 °C).

A calibration must be performed against a thermometer that is traceable back to this standard scale. As a reference thermometer, we used an ASTM 63C mercury thermometer (measuring range −8.0-32.0 °C, resolution 0.1 °C). For this thermometer, the supplier provides a certificate from a calibration laboratory that gives correction factors at 0, 10.0, 20.0 and 30.0 °C.

ACR button thermometer

The ACR SmartButton datalogger (17.35 mm diameter × 5.89 mm height) has a stainless steel case and a weight of 4 g (ACR Systems Inc., 2010). The measuring element is a silicon thermistor that has an operational range of −40 °C to 85 °C with a stated accuracy of ± 1.0 °C from −30 °C to 45 °C and a resolution of 0.5 °C. The SmartButton stores up to 2048 temperature measurements and the sampling interval can be programmed from 1 to 255 minutes. If measurements are recorded at 1-hour intervals, which would detect stream maximum daily temperature within ± 1 °C with a probability of 98 % (Dunham *et al.*, 2005), the SmartButton has the storage capacity to continuously record measurements of stream water temperature for 85 days.

Accuracy tests

All accuracy tests were performed using water in a plastic tray that was placed over a 2-cm
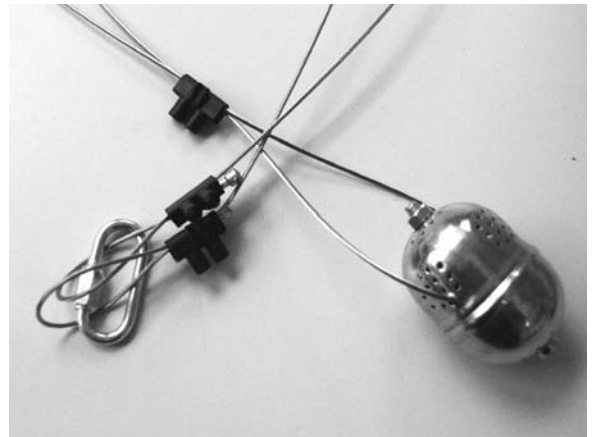
Figure 1. Completed protective case with stainless steel wire attached. *Carcasa protectora terminada con el cable de acero inoxidable.*

polystyrene plate for isolation. In the first accuracy test, the ice bucket method (Dunham *et al.*, 2005; Hubbart *et al.*, 2005) was used by adding ice to the plastic tray. The second and third accuracy tests were performed in an INFOR Multitron incubator with target temperatures of 15 and 10 °C, respectively. In the accuracy tests, the temperature of the water in the tray was measured at 15-minute intervals with the reference mercury thermometer. Based on the observations from the accuracy tests, we developed a method for routine calibration of the SmartButton and calculated discrete values (−1.0, −0.5, 0.0, +0.5 and +1.0 °C) to correct sensor readings (see Appendix).

Construction and testing of the protective case

The protective case was constructed from a stainless steel tea filter (Fig. 1). The two halves of the tea filter were separated, and a hole was drilled into the top of each piece with a 6-mm metal drill bit. The two halves were held together with a stainless steel screw (6-mm diameter, 40-mm length) and two bolts. The screw was fixed to one half of the filter case with one of the bolts such that the other half could slide on and off the screw for opening and closing the case. The sliding half was secured in position with the second bolt.

The anchorage cable was made with stainless steel wire. We used bicycle brake wires because they are conveniently riveted in one ending. The

wire was passed through two of the small holes in the filter and an electrical connector was use to secure the case in the center of the wire. Two other electrical connectors make the ending wire loops that fix the case in the field. Each set of case and attachment wire was supplied with a galvanized iron karabiner (5 or 6 mm thickness) that allows fixing easily the thermometer to the roots and branches that are found in the stream.

To test for a possible effect of the protective case on temperature measurements, two incubations were performed in a 5-L bucket filled with water. The first incubation test was performed in the field, and the second one was performed in an incubation chamber held at a constant temperature (11 °C). Four ACR SmartButtons were labelled (T1, T2, T3 and T4) and programmed for data acquisition at 5-minute intervals. Each incubation lasted for two weeks. During the first week, all four thermometers were incubated without a protective case. During the second week, T1 and T2 were incubated without a protective case and T3 and T4 were each wrapped in small plastic Ziploc bag (13 × 7 cm) and incubated inside a protective case. The data from thermometers T1 and T2 from the second week were used to estimate the response of thermometers T3 and T4 without the case. The estimates were calculated with linear regressions that used the temperature measurements from thermometers T3 and T4 as the dependent variables and the mean values of the temperature measurements from thermometers T1 and T2 as the predictor variable. The data collected on the first and last day of the incubations were discarded so that only the data from the days in which the whole daily temperature cycle was measured were used in the analysis.

In addition, to test for the effect of the correction factors on measurements obtained under field conditions, six thermometers were placed in a small stream for 36 hours, and the mean, minimum and maximum temperatures of each thermometer were calculated before and after applying the correction factors obtained from the calibration test. The thermometers used in this test were selected to represent the range of error observed in the accuracy tests. Thus, two

thermometers had error values < -0.5 °C, two thermometers had error values between -0.5 and 0.5 °C and the remaining two thermometers had error values > 0.5 °C.

Statistical analysis

The SmartButton mean temperatures and the reference temperatures from the accuracy tests were compared using one sample t-tests, and the raw and corrected temperature measurements were compared using paired t-tests. The variance of the raw measurements and the variance of the corrected measurements were compared with an F test. The comparison analyses followed Zar (2010). Least square linear regressions were performed following Montgomery *et al.* (2001) to determine the effects of the protective case on temperature measurements. All statistical analyses were performed with R (R Development Core Team, 2011).
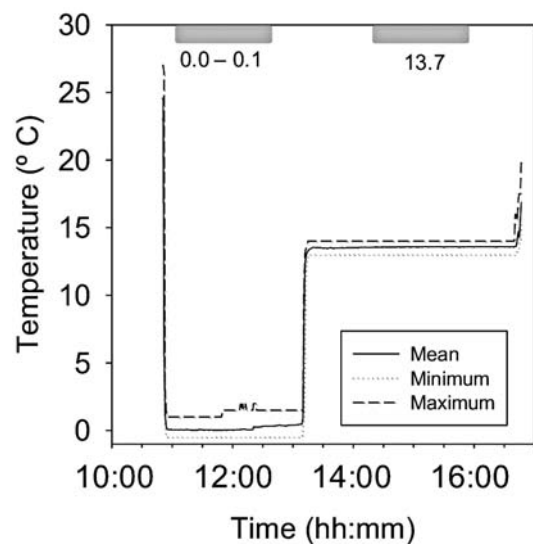
Figure 2. Temperatures measured with SmartButtons (*n* = 35) during the first and second calibration tests (mean, minimum and maximum temperatures are shown). Gray bands indicate the data that were used for the analysis of the accuracy of the SmartButtons and the reference thermometer measurements. *Temperaturas medidas con los Smartbuttons (*n = 35*) durante la primera y la segunda prueba de calibración (se muestran la temperatura media, mínima y máxima). Las bandas grises indican los periodos que se utilizaron para analizar la precisión de los SmartButtons y la temperatura medida con el termómetro de referencia.*

Table 1. Error values for temperature measurements taken with SmartButton thermometers in the three accuracy tests before and after corrections were applied (target temperature: temperature at which the thermometer is to be calibrated; incubator setting: temperature that is set manually using the incubator thermostat; reference temperature: temperature measured with the reference mercury thermometer placed inside the incubator). *Error de las medidas de temperatura recogidas con SmartButtons en las tres pruebas de precisión antes y después de aplicar correcciones (temperatura objetivo: temperatura a la que queremos calibrar los termómetros; ajuste de la incubadora: temperatura que introducimos manualmente en el termostato de la incubadora; temperatura de referencia: temperatura medida con el termómetro de mercurio de referencia dentro de la incubadora).*

	Test 1 $n = 3185$		Test 2 $n = 3185$		Test 3 $n = 1325$	
Target temperature (°C)	0.00		15.00		10.00	
Incubator/bath setting (°C)	0.00[a]		15.00		11.20	
Reference temperature (°C)						
Mean ± SD	0.06 ± 0.05		13.70 ± 0.00		9.60 ± 0.00	
Uncorrected sensor readings						
$x < -1.0$ °C	0	0.0 %	0	0.0 %	0	0.0 %
$-1.0 \leq x < -0.5$ °C	592	18.6 %	224	7.0 %	58	4.4 %
$-0.5 \leq x \leq 0.5$ °C	2456	77.1 %	2961	93.0 %	1267	95.6 %
$0.5 < x \leq 1.0$ °C	86	2.7 %	0	0.0 %	0	0.0 %
$x > 1.0$ °C	51	1.6 %	0	0.0 %	0	0.0 %
Corrected sensor readings						
$x < -1.0$ °C	0	0.0 %	0	0.0 %	0	0.0 %
$-1.0 \leq x < -0.5$ °C	76	2.4 %	1	0.0 %	15	1.1 %
$0.5 < x \leq 1.0$ °C	3060	96.0 %	3184	100.0 %	1310	98.9 %
$-0.5 \leq x \leq 0.5$ °C	49	1.5 %	0	0.0 %	0	0.0 %
$x > 1.0$ °C	0	0.0 %	0	0.0 %	0	0.0 %

[a] A bath filled with ice and water was used (0.00 °C is the melting point of water).

RESULTS

Accuracy tests

The reference temperature varied between 0.0 and 0.3 °C during the ice bucket incubation, but only the measurements from the period in which the temperature oscillated between 0.0 and 0.1 °C were used for the accuracy test (Fig. 2, Table 1). In the second and third accuracy tests, the reference temperature held constant at 13.7 °C (Fig. 2, Table 1) and 9.7 °C (not shown, Table 1). In both cases, the reference temperature was lower than the target temperature and also differed from the thermostat setting of the incubator (Table 1).

The error values for the sensor readings in the accuracy tests are presented in Table 1. During the ice bucket incubation, 3185 temperature measurements were taken, of which 51 (1.6 %) differed from the reference temperature by more than 1 °C, 678 (21.3 %) differed from the reference temperature by between 0.5 and 1.0 °C and 2456 (77.1 %) differed from the reference temperature by less than 0.5 °C. During the accuracy test at 13.7 °C, 3185 measurements were taken. Of these measurements, none differed from the reference temperature by more than 1.0 °C, but 224 (7.0 %) differed from the reference temperature by between 0.5 and 1.0 °C and 2961 (93.0 %) differed from the reference temperature by less than 0.5 °C. During the accuracy test at 9.7 °C, 1325 measurements were taken, of which none differed from the reference temperature by more than 1 °C, but 58 (4.3 %) differed from the reference temperature by between 0.5 and 1.0 °C and 1267 (95.6 %) differed from the reference temperature by less than 0.5 °C.

The mean values of the temperature measurements taken with the SmartButtons in the accuracy tests differed slightly from the reference temperatures (Table 2); however, a significant difference between the reference and mean measured temperature (Student's t, $p < 0.05$) was only observed in the second accuracy test. The

error values for the SmartButton measurements ranged from −0.13 to 0.07 °C and the repeatability of the measurements (calculated as the standard deviation of the error) ranged from 0.25 to 0.37 °C, which indicated that 95 % of the SmartButton mean temperatures were within ± 0.73, ± 0.49 and ± 0.53 of the reference temperature for the first, second and third accuracy test, respectively.

Based on the accuracy tests, we calculated correction factors for each sensor that ranged from −1 to 1 °C (Appendix). After the corrections were applied, the percentage of measurements that were within 0.5 °C of the reference temperature increased from 77.1 to 96.0 % for the first accuracy test, from 93.0 to 100.0 % for the second accuracy test and from 95.6 to 98.9 % for the third accuracy test, indicating that the error in the sensor readings decreased (Table 1). The corrected mean temperatures from the SmartButtons (Table 2) were significantly different (paired Student's t-test, $p < 0.001$) from the reference temperatures for the three accuracy tests. The standard deviations of the measurements decreased significantly (F test, $p < 0.01$) after the corrections were applied. The standard deviations ranged from ± 0.04 to ± 0.07 °C, indicating that 95 % of the mean temperatures values from the SmartButtons were within ± 0.15 °C of the mean temperature for the first and second accuracy tests and within ± 0.09 °C for the third accuracy test. The calibration process increased the repeatability of the measurements and the error values were

maintained within ± 0.25 °C of the reference temperatures. The significant differences between the SmartButton measurements and the reference temperatures after the correction were a result of the higher repeatability and lower variance of the SmartButton measurements.

Incubation tests

During the first week of the field incubation, temperature varied between 4 and 14 °C (Fig. 3A, Table 3), and the mean temperature according to the measurements of SmartButtons T1 and T2 was 9.78 °C. Differences between the Smart-Buttons that displayed the lowest and highest temperature were equal to or less than 0.5 °C for 96.7 % of the measurements ($n = 7752$) and equal to or less than 1.0 °C for 99.8 % of the measurements ($n = 7752$). The data collected during the field incubation were used to build linear models showing the relationships between the data from T3 and T4 (y) and the mean values of the data from T1 and T2 (x):

$$T3, y = 0.99x + 0.01, \ r^2 = 0.99, \ p < 0.001 \quad (1)$$

$$T4, y = 1.01x + 0.20, \ r^2 = 0.99, \ p < 0.001 \quad (2)$$

In the second week of the field incubation (Fig. 3B, Table 3), the temperature measurements varied between 3 and 14 °C, and the mean temperature was 8.34 °C, approximately 1.5 °C lower than in the first week. Differences

Table 2. Temperature (mean ± standard deviation, °C) measured with the SmartButtons in the three accuracy tests before and after corrections were applied. *Temperatura (media ± desviación estándar, °C) medida con los SmartButtons en las tres pruebas de precisión antes y después de aplicar correcciones.*

	Test 1 $n = 35$	Test 2 $n = 35$	Test 3 $n = 25$
Reference temperature (°C)			
Mean ± SD	0.06 ± 0.05	13.70 ± 0.00	9.60 ± 0.00
Measured temperature (°C)			
Mean ± SD	0.07 ± 0.37	13.57 ± 0.25	9.67 ± 0.27
Error ± SD	0.01 ± 0.37	−0.13 ± 0.25	0.07 ± 0.27
Corrected temperature (°C)			
Mean ± SD	0.03 ± 0.07	13.52 ± 0.07	9.51 ± 0.04
Error ± SD	−0.03 ± 0.07	−0.18 ± 0.07	−0.09 ± 0.04

between the thermometers that displayed the lowest and highest temperature were equal to or less than 0.5 °C for 96.3 % of the measurements ($n = 7752$) and equal to or less than 1.0 °C for 100 % of the measurements ($n = 7752$). We estimated that the use of the protective case increased the temperature measurements of the SmartButtons by 0.05-0.10 °C (Table 3). The chamber incubations (Fig. 3C and 3D) confirmed the field observations, showing that the effect of the case on the temperature measurements was negligible (Table 3). In summary, the differences in measurements among the thermometers in the incubation tests were within 0.5 °C, which
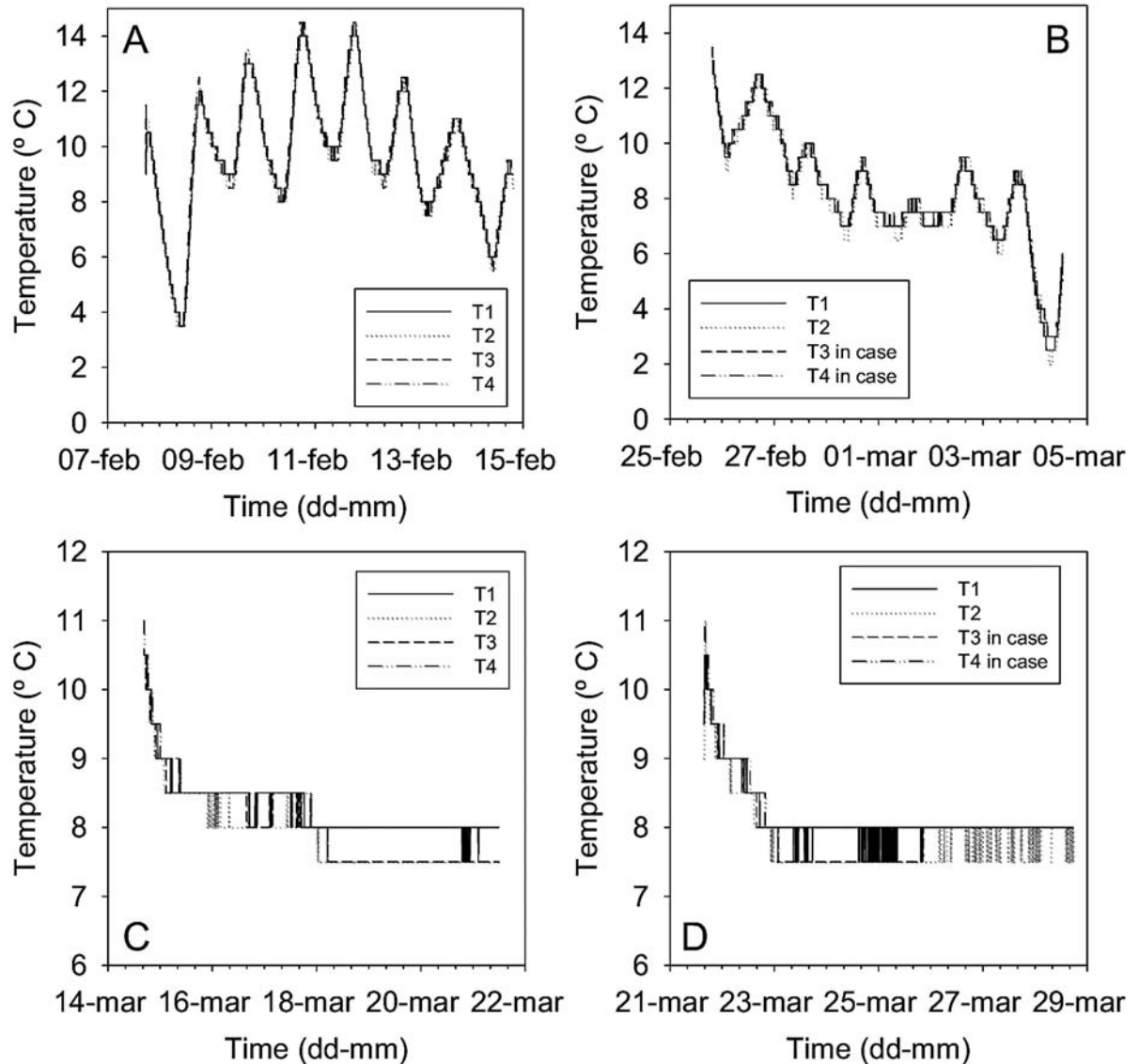
Figure 3. Temperatures measured with SmartButtons ($n = 4$) during the incubation tests (A, first week of field incubation; B, second week of field incubation; C, first week of chamber incubation; D, second week of chamber incubation). *Temperaturas medidas con los SmartButtons (*n = 4*) durante los experimentos de incubación (A, primera semana de incubación en el campo; B, segunda semana de incubación en el campo; C, primera semana de incubación en cámara fría; D, segunda semana de incubación en cámara fría).*

Table 3. Temperature (mean ± standard deviation, °C) measured during the incubation experiments and estimation of the effect of the protective cases (T1 and T2 are control thermometers incubated without protective cases, T3 and T4 are test thermometers incubated without a protective case during the first week and inside a protective case during the second week). *Temperatura (media ± desviación estándar, °C) medida durante los experimentos de incubación y estimación del efecto de las carcasas protectoras (T1 y T2 son los termómetros de control incubados sin carcasas protectoras, T3 y T4 son los termómetros de prueba incubados sin carcasas protectoras durante la primera semana y dentro de las carcasas protectoras durante la segunda semana).*

Field incubation	T1 (°C)	T2 (°C)	T3 (°C)	T4 (°C)
First week	10.05 ± 2.29	9.51 ± 2.29	9.62 ± 2.28	9.91 ± 2.30
Second week	8.50 ± 1.55	8.28 ±1.26	8.47 ± 1.51	8.70 ± 1.53
Estimated values[1]	—	—	8.37 ± 1.54	8.65 ± 1.56
Case effect	—	—	+0.10	+0.05
Chamber incubation	**T1 (°C)**	**T2 (°C)**	**T3 (°C)**	**T4 (°C)**
First week	8.28 ± 0.45	7.89 ± 0.53	8.00 ± 0.59	8.33 ± 0.57
Second week	8.13 ± 0.47	7.84 ± 0.52	7.96 ± 0.48	8.19 ± 0.49
Estimated values[1]	—	—	7.87 ± 0.56	8.23 ± 0.46
Case effect	—	—	+0.11	+0.04

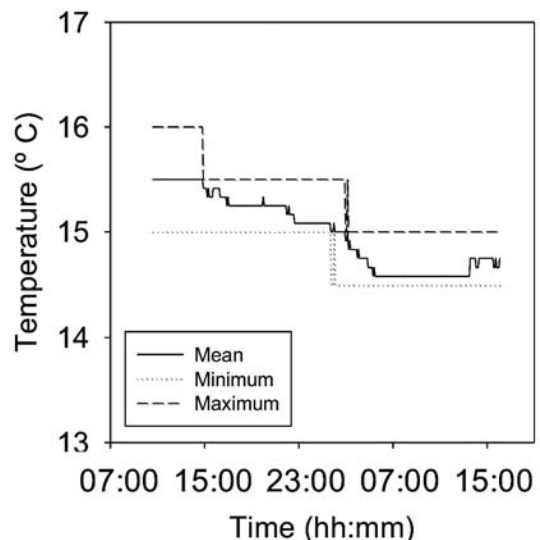[1]Estimated with linear models (1) and (2).

Table 4. Temperature (mean ± standard deviation, °C) measured with calibrated and uncalibrated SmartButtons in a small stream over a 36-hour period (*n* = 6). *Temperatura (media ± desviación estándar, °C) medida con SmartButtons calibrados y sin calibrar en un arroyo durante 36 horas (*n = 6*).*

	Mean temperature (°C)	Minimum temperature (°C)	Maximum temperature (°C)
Uncorrected	15.16 ± 0.22	14.67 ± 0.26	15.58 ± 0.20
Corrected	15.00 ± 0.12	14.50 ± 0.00	15.42 ± 0.22

Figure 4. Temperatures measured with Smart Buttons (*n* = 6) during incubation in a stream (mean, minimum and maximum temperatures are shown). Correction factors have been applied to the sensor readings. *Temperaturas medidas con los Smart-Buttons (*n = 6*) durante su incubación en un arroyo (se muestran la temperatura, media, mínima y máxima). Se han aplicado los factores de corrección a las lecturas de los sensores.*

was similar to the resolution of the SmartButtons. Furthermore, the protective cases did not interfere with the temperature measurements.

During the stream test, temperature in the stream was fairly constant and varied between 14.5 and 15.5 °C (Fig. 4). The difference between the thermometers that displayed the lowest and the highest temperature was 0.5 °C for 90 % of the measurements (*n* = 355) and 1.0 °C for 10 % of the measurements (*n* = 355). After the correction factors were applied, these differences decreased to 0.0 °C for 38 % of the measurements and 0.5 °C for 62 % of the measurements. However, there were no significant differences (paired Student's t-test, *p* > 0.05) in the mean, minimum and maximum temperatures from the SmartButtons before and after applying the correction factors (Table 4). After the corrections were applied, the standard deviations of the

mean and minimum temperatures decreased, an indication of improved repeatability; however, the difference was only significant (F test, *p* < 0.001) for the minimum temperature values. In contrast, the standard deviation of the maximum temperature values increased after the

calibration factors were applied, although the difference was not significant (F test, $p > 0.05$).

DISCUSSION

The results of our analyses indicate that the accuracy of the SmartButtons is well within the ± 1.0 °C accuracy quoted by the manufacturer (ACR Systems Inc., 2010). Given a similar range of temperatures to that which we found in small streams in our geographical area, the sensor readings are within ± 0.5 °C of the actual water temperature 90 % of the time. Based on this study, the mean error of the SmartButtons falls within the ± 0.1 °C of variation from the correction factor for each 10°C range that is considered acceptable by the World Meteorological Organization (WMO, 2008). However, the standard deviation of the error values indicated that 50 to 60 % of the thermometers require a correction factor that is outside the ± 0.2 °C range accepted by the World Meteorological Organization (WMO, 2008) for meteorological measurements. Therefore, the SmartButtons are not suitable for regular meteorological use. However, their low cost and small size, combined with the ease of programming data collection and retrieving data, makes them highly attractive for other environmental uses. The repeatability of the measurements taken with the SmartButtons and the accuracy of the sensor readings are significantly improved by calibrating the sensors against a traceable reference standard. Our observations suggest that the degree of accuracy obtained through calibration will likely suffice for most biological applications. In the case that greater accuracy is required, Hubbart et al. (2005) proposed a screening method for discarding thermometers with relatively low accuracy. For SmartButtons, this would most likely mean discarding approximately 40 % of a batch of new SmartButtons to use only thermometers that do not require corrections. This information should be taken into account when calculating the costs of acquiring the equipment.

Although the ice bucket method is an accepted method for the calibration and screening of thermometers (Dunham et al., 2005; Hubbart et al., 2005), our experience suggests that it is difficult to maintain a constant ice bath temperature, and therefore, we have discarded this method as an option for the routine calibration of SmartButtons. In our case, shifts in the temperature of the ice bath seem to have occurred as a function of the overall temperature of the laboratory. Using an incubator that has been demonstrated to maintain a constant temperature is preferred over the ice bucket method. Based on the results of our accuracy tests, we propose a calibration method for the SmartButtons. We used an INFOR Multitron incubator, which has a transparent lid that is very convenient for checking the temperature of the reference thermometer during calibration without opening the equipment. Additionally, calibration against a certified thermometer must be performed independently of the calibration method (WMO, 2008). Performing a calibration of the incubator helped to reduce uncertainty during the calibration of the SmartButtons (e. g., by making it easier to find the thermostat setting for a given target temperature). However, the thermostat setting, the incubator thermometer readings and the temperature inside the incubator differed slightly even after calibration of the incubator. A record of the reference temperature during calibration and the correction factors for each thermometer should be kept for documenting the conversion from field measurements to the final corrected dataset.

Our short field incubation in a stream showed that the calibration of the SmartButtons improved the repeatability of the measurements but did not improve detection of maximum temperatures. These results suggest that the SmartButton might function differently when cooling down or heating up. Similarly, Hubbart et al. (2005) observed differences in the performance of small button thermometers at low and high temperatures. Temperature measurements by semiconductor thermometers (or thermistors) are based on the change of electrical resistance of a measuring element (a silicon sensor in the case of the SmartButton). The passage of electricity through the measuring element produces heat and self-heating of the thermometer causes the

temperature of the instrument to become higher than the temperature of its surroundings. This self-heating effect is greater in small thermistors than in large ones (WMO, 2008). The impact of self-heating on the quality of temperature measurements is probably negligible for most environmental applications, but special care should be taken if obtaining maximum stream temperature data is important for fulfilling the objectives of a project (*e. g.*, determining habitat suitability for salmonids).

Water leakage was not a problem in our laboratory tests, although leakage appears to have caused malfunctioning of loggers and data loss with other thermistor models (Wolaver & Sharp, 2007). Coating the thermometer with plastic is an alternative if waterproofing the thermometer is necessary, although the coating interferes with temperature measurements if the thermometers are directly exposed to the sun (Roznik & Alford, 2012). Before introducing the SmartButtons into the metallic protective cases, we wrapped each of them in a small Ziploc bag for additional protection from dirt and for convenient handling (*e. g.*, the bag is easily labelled with a permanent marker). This method can also be used with thermistors that are not waterproof because the size of the resulting package is not much bigger than the instrument itself.

The protective case that we used provides a reliable way to protect the SmartButtons during instream use at a cost of approximately 6 Euros per case, which is lower than commercial metallic cases. The effect of the case on temperature measurement was negligible and was similar in magnitude to the effects that have been observed for other cases (*e. g.*, Malard et al., 2001). However, we observed that silt tends to accumulate inside the case, so these cases are not suitable for temperature measurements in streams that transport large loads of fine sediment. The design of the case and the anchoring system has been improved through several field trials. In a recent study we used 50 cases, of which 3 were lost due to human vandalism and one was lost due to breakage at the anchoring point. To date, we have not lost any sensors due to failure of the anchoring cable or damage to the case itself.

ACKNOWLEDGEMENTS

REFERENCES

ACR SYSTEMS INC. 2010. ACR SmartButton temperature datalogger. Product specifications. http://www.acrsystems.com/products/smartbutton/. Accessed on July 2011.

CARDENAS, M. B., J. W. HARVEY, A. I. PACKMAN & D. T. SCOTT. 2008. Ground-based thermography of fluvial systems at low and high discharge reveals potential complex thermal heterogeneity driven by flow variation and bioroughness. *Hydrological Processes,* 22: 980–986.

CASH, D. W., W. C. CLARK, F. ALCOCK, N. M. DICKSON, N. ECKLEY, D. H. GUSTON, J. JÄGER & R. B. MITCHELL. 2003. Knowledge systems for sustainable development. *Proceedings of the National Academy of Science*, 100: 8086–8091.

DUNHAM, J. B. & G. L. CHANDLER. 2001. *Models to predict suitable habitat for juvenile bull trout in Washington State.* Washington Bull Trout Habitat Study. Rocky Mountain Research Station, Boise, Idaho, US. 75 pp.

DUNHAM, J., G. CHANDLER, B. RIEMAN & D. MARTIN. 2005. *Measuring stream temperature with digital data loggers: a user's guide*. USDA Forest Service, Gen. Tech. Rep. RMRS-GTR-150WWW. Rocky Mountain Research Station, Boise, Idaho, US. 15 pp.

HERB, W. R. & H. G. STEFAN. 2011. Modified equilibrium temperature models for cold-water streams. *Water Resources Research*, 47: W06519.

HUBBART, J., T. LINK, C. CAMPBELL & D. COBOS. 2005. Evaluation of a low-cost temperature measurement system for environmental applications. *Hydrological Processes*, 19: 1517–1523.

ITS-90. 1999. International Temperature Scale of 1990. http://www.its-90.com/. Accessed on July 2011.

JOHNSON, A. N., B. R. BOER, W. W. WOESSNER, J. A. STANFORD, G. C. POOLE, S. A. THOMAS & S. J. O'DANIEL. 2005. Evaluation of an inexpensive small-diameter temperature logger for documenting ground water-river interactions. *Ground Water Monitoring and Remediation*, 25: 68–74.

LEWIS, T. E., D. W. LAMPHEAR, D. R. MCCANNE, A. S. WEBB, J. P. KRIETER & W. D. CONROY. 2000. *Regional assessment of stream temperatures across Northern California and their relationship to various landscape-level and site-specific attributes*. Forest Science Project. Humboldt State University Foundation, Arcata, California, US. 15 pp.

MALARD, F., A. MANGIN, U. UEHLINGER & J. WARD. 2001. Thermal heterogeneity in the hyporheic zone of a glacial floodplain. *Canadian Journal of Fisheries and Aquatic Sciences*, 58: 1319–1335.

MONTGOMERY, D. C., E. A. PECK & G. C. VINING. 2001. *Introduction to linear regression analysis*. Wiley & Sons, New York. 641 pp.

PRESTON-THOMAS, H. 1990. The International Temperature Scale of 1990 (ITS-90). *Metrologia*, 27: 3–10.

R DEVELOPMENT CORE TEAM. 2011. R: *A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0. http://www.R-project.org/. Accessed on November 2011.

ROZNIK, E. A. & R. A. ALFORD. 2012. Does waterproofing Thermochron iButton dataloggers influence temperature readings? *Journal of Thermal Biology*, 37: 260–264.

SELKER, J., N. VAN DE GIESEN, M. WESTHOFF, W. LUXEMBURG & M. B. PARLANGE. 2006. Fiber optics opens window on stream dynamics. *Geophysical Research Letters*, 33: L24401.

STOUT, R. J. 1989. Effects of condensed tannins on leaf processing in mid-latitude and tropical streams: a theoretical approach. *Canadian Journal of Fisheries and Aquatic Sciences*, 46: 1097–1106.

TIMMERMAN, J. G., E. BEINAT, K. TERMEER & W. COFINO. 2010. Analyzing the data-rich-but-information-poor syndrome in Dutch water management in historical perspective. *Environmental Management*, 45: 1231–1242.

TONOLLA, D., V. ACUÑA, U. UEHLINGER, T. FRANK & K. TOCKNER. 2010. Thermal heterogeneity in river floodplains. *Ecosystems*, 13: 727–740.

TYLER, S. W., J. S. SELKER, M. B. HAUSNER, C. E. HATCH, T. TORGERSEN, C. E. THODAL & S. G. SCHLADOW. 2009. Environmental temperature sensing using Raman spectra DTS fiber-optic methods. *Water Resources Research*, 45: W00D23.

WARD, R. C., J. C. LOFTIS & G. B. MCBRIDGE. 1986. The "Data-rich but Information-poor" syndrome in water quality monitoring. *Environmental Management*, 10: 291–297.

WAWRZYNIAK, V., H. PIÉGAY & A. POIREL. 2012. Longitudinal and temporal thermal patterns of the French Rhône River using Landsat ETM+ thermal infrared images. *Aquatic Sciences*, 74: 405–414.

WEHRLY, K. E., M. J. WILEY & P. W. SEELBACH. 1998. Landscape-based models that predict July thermal characteristics of lower Michigan rivers. Michigan Department of Natural Resources, Fisheries Research Report No. 2037, Ann Arbor, Michigan, US.

WMO. 2008. *Guide to meteorological instruments and methods of observations. World Meteorological Organization No*. 8, 7th edition. Geneva. 681 pp.

WOLAVER, B. D. & J. M. SHARP Jr. 2007. Thermochron iButton: Limitation of this inexpensive and small-diameter temperature logger. *Ground Water Monitoring and Remediation*, 27: 127–128.

ZAR, J. H. 2010. *Biostatistical analysis*. 5th. Ed. Prentice Hall, Upper Saddle River, New Jersey. 944 pp.

APPENDIX: Calibration method for the ACR SmartButtons

MATERIALS

Plastic tray filled with water

2 cm polystyrene plate

ASTM 63C thermomether with calibration bulletin (certified reference thermometer)

Incubator INFOR Multitron

PROCEDURE

1. Program the SmartButtons for data collection at 2 minute intervals.

2. Set-up the incubator for a reference temperature of interest.

3. Place the SmartButtons and the reference thermometer in the plastic tray and introduce the plastic tray in the incubator over a 2 cm polystyrene plate. Make sure that the scale of the reference thermometer can be read through the glass door of the incubator. Wait 2 hours for temperature equilibration.

4. Check the temperature of the reference thermometer at 15 minute intervals (Tr). Collect data for 2 hours. The reference temperature should not change during this period.

5. Download data and calculate the mean temperature for each SmartButton for the two hours period (Ts).

6. Calculate the difference between each SmartButton and the reference thermomether, $D = Ts - Tr$.

CORRECTION FACTORS

Correction factors are calculated as a function of D:

$D > 1.0$	Probable malfunction (discard thermometer)
$0.75 < D < 1.0$	-1
$0.25 < D < 0.75$	-0.5
$-0.25 \leq D \leq 0.25$	0 (no correction required)
$-0.75 \leq D < -0.25$	0.5
$-1.0 \leq D < -0.75$	1
$D < -1.0$	Probable malfunction (discard thermometer)