LIMNOLOGY
and
OCEANOGRAPHY: METHODS

Limnol. Oceanogr.: Methods 7, 2009, 648–656

Pinnipeds as ocean-temperature samplers: calibrations, validations, and data quality

Samantha E. Simmons, Yann Tremblay, and Daniel P. Costa*
Department of Ecology and Evolutionary Biology, University of California Santa Cruz, Center for Ocean Health, 100 Shaffer Road, Santa Cruz, California 95060-5730, USA

Abstract

Recently marine organisms have emerged as ocean-sensing platforms, generating data useful to biologists and oceanographers. However, sensor calibrations, performance over time, and effects of behavior and sampling frequency on data quality have not been adequately examined. We performed temperature calibration trials on 36 Wildlife Computers Mk9 time-depth recorders (stated accuracy 0.1°C ± 0.05°C) versus Rosemount Model 162CE standard platinum resistance thermometer (0.001°C, ± 0.0001°C). Sixty-four percent of trials were within ± 0.1°C. Subtracting 0.05°C from all calibrations brought this to 83%. Six instruments calibrated before and after deployment on free-ranging pinnipeds, showed no significant drift in temperature measurements. Mk9 performance was tested against a Seabird© CTD (SBE-19). Root mean square (rms) difference between CTD and Mk9 temperature was 0.15°C (max. 0.45°C, min. 0.10°C). Applying a 1-s time-lag improved the data fit. To assess animal effects on thermal data, Mk9s were deployed on juvenile elephant seals released between CTD casts. Overall rms were within ± 0.1°C. Subsampling of Mk9 data revealed a sampling frequency of 10 s was sufficient to accurately resolve thermal features, e.g., thermocline depth, for these CTD experiments. We present four equations to assess temperature data quality from diving marine animals around the globe carrying different thermistors.

Introduction

In the last 15 years, marine organisms have emerged as platforms for ocean sensing (Costa 1993; Boehlert et al. 2001; Charrassin et al. 2002; Lydersen et al. 2002; Fedak 2004). This has been facilitated by technological advances and a need to understand climate change relative to both physical processes and their effects on flora and fauna. By using organisms to survey their environment, data can be obtained that are useful to a diverse array of disciplines including marine biologists, biological and physical oceanographers, and climatologists. However, as these instruments were not originally designed to collect oceanographic data, the design of the tag as well as the animal's behavior may impact the quality of the environmental data collected. We examine sensor accuracy and performance over time under controlled conditions and in the field in relation to standard CTD data, as well as examining the effects of animal behavior and different sampling regimes on the quality of animal-derived temperature data.

Instrument calibration—Whereas instruments are calibrated by the manufacturers prior to distribution, independent validation is necessary to assure that the sensors function as needed before, during, and after field deployment. Some instruments relay their data via satellite and may never be recovered; hence a postdeployment calibration is not possible. However, it is still possible to verify the quality and validity of data collected by comparisons with concurrent sampling from standard oceanographic instrumentation. In this study, we report on pre- and postdeployment calibrations of a recently developed rapid-response external temperature sensor of a widely used time-depth recorder (TDR), the Wildlife Computers Mk9.

Sampling regimes—Interpretation of simple diving behaviors using time-depth recorders (TDRs) is affected by the sampling

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*Corresponding author: E-mail: simmons@biology.ucsc.edu

Acknowledgments

Funding: Research and logistic support was funded by grants to SE Simmons from the Earl and Ethel Myers Oceanographic Trust and Friends of LML and to DP Costa from the Office of Naval Research, National Oceanographic Partnership Program and Tagging of Pacific Predators (TOPP). All research was conducted under NMFS permit 836 and animal handling procedures were approved by the Chancellor's Animal Research Committee (IACUC) UC Santa Cruz. The authors would like to thank Jim Stockel and Tarry Rago at the Naval Postgraduate School for the use of the water bath and Platinum resistance thermometer, Patrick Robinson for running calibrations, Dr. Raphael Kudela at UCSC for the use of the Seabird© CTD, Pete DalFerro & Rich Walsh for boat support, acknowledge field assistance from Birgitte McDonald, Carey Kuhn, Daniel Crocker, Ben Lester, Ann Allen, Martin Biuw, and Scott Seganti, and thank Roger Hill for derivation of equation 5.

frequency used (Boyd 1993; Wilson et al. 1995; Ropert-Coudert and Wilson 2004). Too low a sampling frequency results in a loss of detail. However, there is a trade-off between sampling frequency and total duration of data collection, due to the memory capacity of the instrument. Thus, too high a sampling frequency limits the time period over which the animal and environment can be studied. Although these issues are recognized in relation to behavioral data, as far as we are aware, they have not been addressed in relation to the quality of animal-collected thermal data. We use subsampling to examine effects of lower sampling frequencies on the detail and resolution of thermal features, such as thermocline depth.

Sampling frequency must also be appropriate relative to the response of the sensor. Previous studies using slower responding internal thermistors used a simple time lag to account for the response of the thermistor (Boehlert et al. 2001). Although this simple correction worked reasonably well, it was fortuitous that the sampling frequency corresponded well with the response of the thermistor. Several factors affect sensor performance, including temperature change in the water column, time taken to transit that temperature change, i.e., the descent or ascent rate of the animal, as well as sampling frequency. In this article, we provide a simple approach for researchers to assess errors associated with different sampling frequencies when the thermal time constant of the sensor and a few key environmental and behavioral details are known.

Animal effects—These include potential effects from physical attachment of the instrument to an animal, such as those found by McCafferty et al. (1999), as well as behavioral effects on recorded data, such as those found with conductivity instruments using an inductive field. This is possible because the animal generates a near-field effect that results in an offset in conductivity data (Hooker and Boyd 2003). In the latter case, the data are corrected with post hoc calibrations, but the instruments must be physically recovered or calibrated against another in situ data set (McMahon et al. 2005).

Exhalation on ascent affected conductivity and acoustic recorders (Hooker et al. 2005), and measures of ocean temperature from female Antarctic fur seals (*Arctocephalus gazella*) showed errors associated with thermal radiation when seals spent long periods at the surface (McCafferty et al. 1999). Both are examples of behavioral effects. In this article, we address the question of animal effects on thermal data by comparing temperature data collected by juvenile northern elephant seals (*Mirounga angustirostris*) released in the same region with temperature data collected from CTD casts at the same time.

Previously obtained temperature data from northern elephant seals have been quality controlled and included in the World Ocean Database (Boehlert et al. 2001). These data were collected with slow responding thermistors with an accuracy of 0.5°C ± 0.1°C. Improvements to the response time of thermistors will improve the quality of data from animal-borne sensors (Daunt et al. 2003). Here, we assess performance of Mk9s with a rapid response external thermistor, which improves accuracy to 0.1°C ± 0.05°C. We address the lack of calibrations for temperature data from Wildlife Computers Mk9 TDRs. Although the experiments we describe are limited to Mk9s, many of the components and configurations used in this model are the same as in both older and newer instruments, and instrument performance may therefore be directly comparable. This instrument was selected for large-scale deployments on elephant seals as part of the Tagging of Pacific Predators (TOPP) project (www.topp.org). From over 80 deployments on adult females between 2004 and 2006, the data set already contains over 750,000 dives or 1.5 million temperature profiles taken across the north Pacific throughout the year, and these numbers continue to grow as deployments continue. For these data to be useful to biologists, oceanographers, or climatologists, their quality and limitations must be known.

Materials and procedures

Temperature calibrations in the laboratory—Temperature calibrations were conducted using 36 Wildlife Computers Mk9 time-depth recorders (TDRs) with an external, rapid-response thermistor. The manufacturer specifies an accuracy of 0.1°C and a precision of ± 0.05°C. A total of 46 calibrations were spread over three calibration days in November 2004, January 2005, and October 2005 at the Naval Postgraduate School (Monterey, CA). Eight TDRs were calibrated twice, and one TDR was calibrated on all three dates. These repeat calibrations were done to examine the possibility of sensor drift over time or following deployment on an animal. Of the eight TDRs calibrated twice, six were deployed on animals between calibrations and two were not. The instrument calibrated three times was not deployed between calibrations.

The TDRs were set to sample temperature every 1 s in the November and January calibrations, and every 4 s in the October calibration. Tags were placed in a constant temperature water bath at an initial temperature close to 0°C; the bath was allowed to stabilize for 10 min (i.e., variation in temperature <0.0001°C). Following this 10-min period, warm water was added to the temperature bath until there was an increase of approximately 5°C and then temperature was held constant for 10 min. This stepwise increase in temperature was repeated five to seven times for a range of temperatures between 0 and 25°C. The water bath temperature was recorded in relation to time using a Rosemount Model 162CE standard platinum resistance thermometer measured with a Neil Brown ATB1250 automatic temperature bridge (accuracy 0.001°C, precision ± 0.0001°C).

The temperatures recorded by the rapid response thermistor were compared with the records from the Rosemount thermometer. When temperatures were stable, the median from the Rosemount thermometer was calculated and compared with the median value from the Mk9s during the equivalent time window. All differences were calculated by subtracting the Mk9 measured temperature from the Rosemount thermometer measured temperature.

Comparisons with in situ CTD temperature data—We conducted a series of field tests with the rapid-response Mk9 TDR. Over the course of 3 weeks during April–May 2004, 6 CTD casts to 250 m were performed over the Monterey Canyon using a Seabird CTD (SBE-19) also carrying an Mk9. The Mk9 was programmed to sample depth and temperature every second, and the CTD used a scan rate of 0.5 s. Differences in temperature between CTD and Mk9 were compared over the whole cast using root mean square (rms) differences. We also considered differences in more detail by calculating meter by meter differences for each cast. The SBE-19 is calibrated annually by SeaBird, with the most recent calibration at the time of collection being January 2004.

Animal effects—To examine the effect of the animal or its behavior on the quality of the Mk9 data, we released a total of six juvenile elephant seals from the boat between CTD casts. For each week of the study, we captured two juvenile northern elephant seals from the rookery at Año Nuevo State Reserve (San Mateo County, CA, USA). Capture and handling methods were the same as those described in Oliver et al. (1998) and Le Boeuf et al. (2000). Briefly, the animals were captured at Año Nuevo and transported in specially designed aluminum cages back to Long Marine Laboratory (UC Santa Cruz, CA, USA). At the lab, they were sedated and an Mk9 was attached to the dorsal pelage on the midline at about midbody using quick set 5-min epoxy (Loctite). The Mk9 was programmed to sample depth and temperature every second. A satellite platform transmitter terminal (PTT, Telonics) and a VHF radio tag (ATS) were also attached at this time. The PTT was used to track the seals on their return to the rookery, and the VHF used to relocate the animals once there.

Seals were released from the boat between CTD casts on all 3 d; the seals returned to the rookery within a few days, at which time instruments were recovered and the seals were left to complete their annual molt. Temperature data from the Mk9 on the CTD and from the first two dives of the seal were compared to ascertain if animal/behavior effects were present.

Data handling—Mk9 data from the TDR on the CTD and those on the seals were treated the same way. Each record was zero-offset corrected (ZOC) using purpose-written software in Matlab R2007a. (IKNOS toolbox, Tremblay unpubl. data). The data were then divided based on the direction of travel of the instrument through the water, i.e., one up- or downcast for each dive. Mk9 data were interpolated using a hermite spline to produce one temperature value for every meter in a cast. This was done so that the data were directly comparable with CTD output temperature data. A hermite spline interpolation was chosen because it has no overshoot and has a very tight fit to the data. As we were sampling at 1 s, we had an actual measure of temperature at most depth intervals and averaging these was actually more significant than interpolating to fill gaps between depths. Differences between these casts and the CTD temperature data were calculated.

Assessment

Temperature calibrations in the laboratory—A total of 46 calibration trials were run on 36 Mk9s. There were 258 comparisons between Mk9s and the Rosemount thermometer at various temperatures. Of these 165 (or 64%) were within the manufacturer specified accuracy of ± 0.1°C. For 12 instruments, for at least one calibration temperature, there was more than 0.1°C difference from the Rosemount thermometer. In all cases, these Mk9s were registering a higher temperature than the Rosemount thermometer. There were no Mk9s that differed by more than 0.2°C from the Rosemount thermometer–measured water bath temperature. The maximum difference recorded was –0.2°C, the minimum was 0°C, and the average was –0.079°C (Table 1) or –0.1°C to the precision of the tag (± 0.05°C, Hill pers. comm.).

Across a range of temperatures from 0 to 25°C, only 0.4% of the calibrations showed a significant (larger than the precision of the tag) drift. Further, none of the Mk9s that were calibrated more than once showed significant (larger than the precision of the tag) or systematic drift in their temperature measures, regardless of whether or not they had been deployed on animals between calibrations. Animal deployments included adult female elephant seals and adult female California sea lions (*Zalophus californianus*). This indicates that temperatures recorded throughout the deployments are reliable and stable. There was no significant decay in the sensor over the 1-y period tested in this study.

When instrument calibrations are not possible, we recommend correcting all temperature data with a subtraction of 0.05°C. We selected this value because the Mk9s were measuring 0.079°C greater than the thermistor on average (Table 1),

Table 1. The differences between the median temperatures collected by Rosemount thermometer and Mk9s. Numbers are given to the accuracy of the Rosemount thermometer for detail.

Temperature difference	Nov (*n* = 3)	Jan (*n* = 29)	Oct (*n* = 14)	Overall
Maximum	0.199	0.200	0.202	0.202
Rms	0.118	0.116	0.112	0.115
Mean (absolute)	0.100	0.085	0.081	0.084
Mean	–0.100	–0.081	–0.074	–0.079
SD	0.065	0.080	0.078	0.078

n = number of tags calibrated on each date thus by subtracting 0.05°C (which equals the precision of the Mk9s, so is the smallest correction feasible) from all the instrument recorded temperatures, the mean difference was reduced to 0°C (to the precision of the instruments). Additionally, only a few Mk9s recorded temperatures below that of the Rosemount thermometer, so by subtracting 0.05°C from all data points the total percentage of measures within the precision and accuracy of the Mk9s was increased. From our calibrations, this simple correction brought an additional 19% of the tags (to a total of 83% or 30 out of 36 Mk9s) within the manufacturer specified accuracy (± 0.1°C).

Comparisons with in situ CTD temperature data—CTD casts were conducted approximately 15 min apart with seal releases between. We assessed the differences between CTD casts on each day and selected the translocation day (30 April) with the smallest difference between CTD casts for all temperature comparisons. Presumably, this represented the most stable water column conditions, and therefore, the best situation for comparisons. Rates of descent and ascent were comparable for the CTD and the Mk9s carried by the seals, at around 1 ms^{-1}. The overall root mean square (rms) difference between CTD and raw Mk9 temperature was 0.15°C (maximum difference 0.45°C, minimum difference 0.10°C). Our suggested 0.05°C correction for the Mk9 data brought all rms comparisons within ± 0.1°C, i.e., within the specified accuracy of the instrument.

The greatest differences between Mk9 and CTD measures were seen at the same depth as thermoclines (Figs. 1a and 1b), and similar differences are seen between XBT and CTD data (Reseghetti et al. 2007). These regions contain the greatest changes in temperature with depth and are therefore most likely to result in errors due to the thermal response of the thermistor. Another indicator that the response of the thermistor should be considered was the 'mirror image' of errors for up- and downcasts (Fig. 1b). As we always subtracted Mk9 temperature from CTD temperature, the mirror image implies that on downcasts the Mk9 measures tended to be greater than the CTD, as would be expected if there was a delay in sensor response transiting from warm water to colder water (i.e., on a downcast). Whereas on upcasts these differences were smaller or reversed, Mk9 measures were less than CTD measures, as would be expected with a sensor delay when transiting from cold to warmer water (upcasts). Thus, applying a time lag to the data may improve the fit.

The standard representation of temperature response is: $\Delta T_t = \Delta T_0 e^{-bt}$. Where ΔT_t is the difference between the measured temperature and the final temperature at some time t, ΔT_0 is the temperature difference from initial temperature to final temperature (i.e., when $t = 0$) and t is time (in seconds), then b is the rate at which the tag responds to temperature, and $1/b$ is called the time constant. The established thermal time

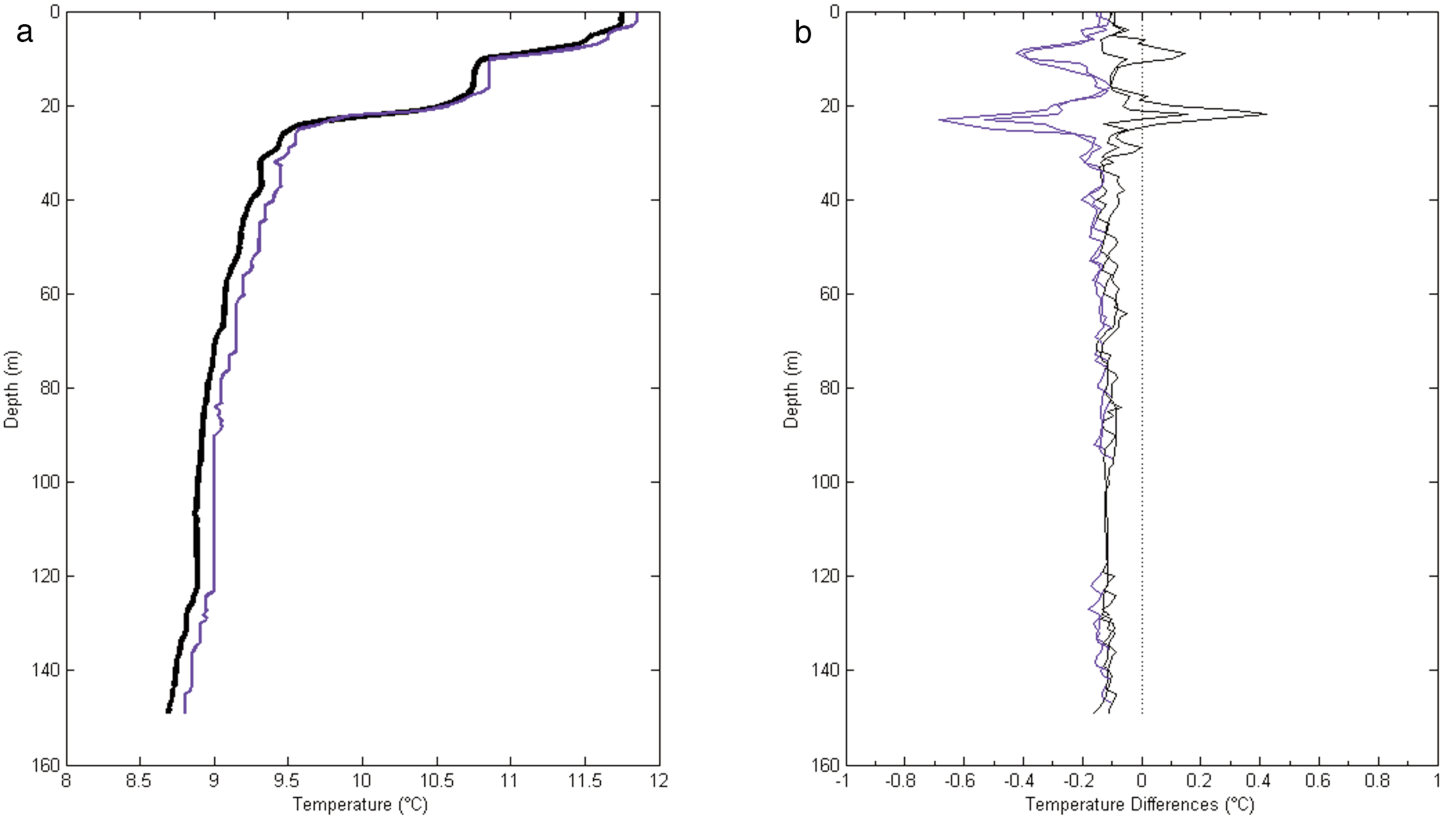

Fig. 1. (a) CTD temperature profile (black) and Mk9 on the CTD (blue) for the first cast on 30 April 2005. (b) Temperature differences between the Mk9 and CTD for two downcasts (blue) and upcasts (black) from 30 April 2005. Small dotted line represents the line of equality.

constant for the Mk9 rapid response thermistor is 0.52 s (Hill pers. comm.). Applying a 1-s time lag minimized the differences in temperature between the CTD and Mk9 (Fig. 2b). An increase to a 2-s time lag did not further improve the fit of the data with the CTD (Fig. 2c). It is interesting to note how the error for the up- and downcasts reverses sign with increasing time lag (Fig. 2a–c). We conclude that a 1-s sampling frequency with a 1-s time lag provides temperature data with the greatest accuracy. If sampling at lower rates than 1 s, implementation of a time lag should be assessed relative to thermistor response, descent rate, and thermal characteristics of the water column (see Eqs. 1–5) as the time lag may actually overcorrect the data (Fig. 2c).

Animal effects—McCafferty et al. (1999) found a thermal offset when attaching instruments directly to the animal versus attaching them to a strap. However, those instruments used an internal thermistor that may have been affected by radiation from the animal. The rapid response thermistors in our instruments that protrude from the Mk9 were not susceptible to the same effects of direct attachment to the animal (Fig. 3).

To identify any behavioral effects, we used data from the first two dives of each seal released between CTD casts on 30 April as this was the day with the smallest difference between the CTD casts, rms = 0.055°C (Fig. 3a). We considered differences in temperature among Mk9s on the CTD (rms = 0.05°C) and Mk9s on the seals (rms = 0.10°C) for the upcast of two dives (Fig. 3b), as well as differences between these two instrument deployments (rms = 0.10°C, Fig. 3d).

A large temperature difference at the start of the first seal dive (Fig. 3d) was likely due to the instrument heating up during transit in the aluminum cages. Even with this initial error, the overall rms was within ± 0.1°C, the specified accuracy of the instrument, and we did not detect any significant effects of the instruments being carried by a seal versus being placed on a CTD unit.

Discussion

Temperature calibrations in the laboratory—In general, calibrations should be performed before and after deployment wherever possible to ensure the highest data quality. However, if calibrations are not possible, we suggest a subtraction of 0.05°C from Mk9 rapid response thermistor data because 79% of measures were above those derived from the Rosemount thermometer, with 49% being over by more than 0.05°C. This small correction brought a total of 83% of our calibrated tags within ± 0.1°C. Without the correction 64% of the instruments across all temperatures were within ± 0.1°C, the accuracy as specified by the manufacturer. No instruments exhibited significant drift over time, whether or not deployed on free-ranging

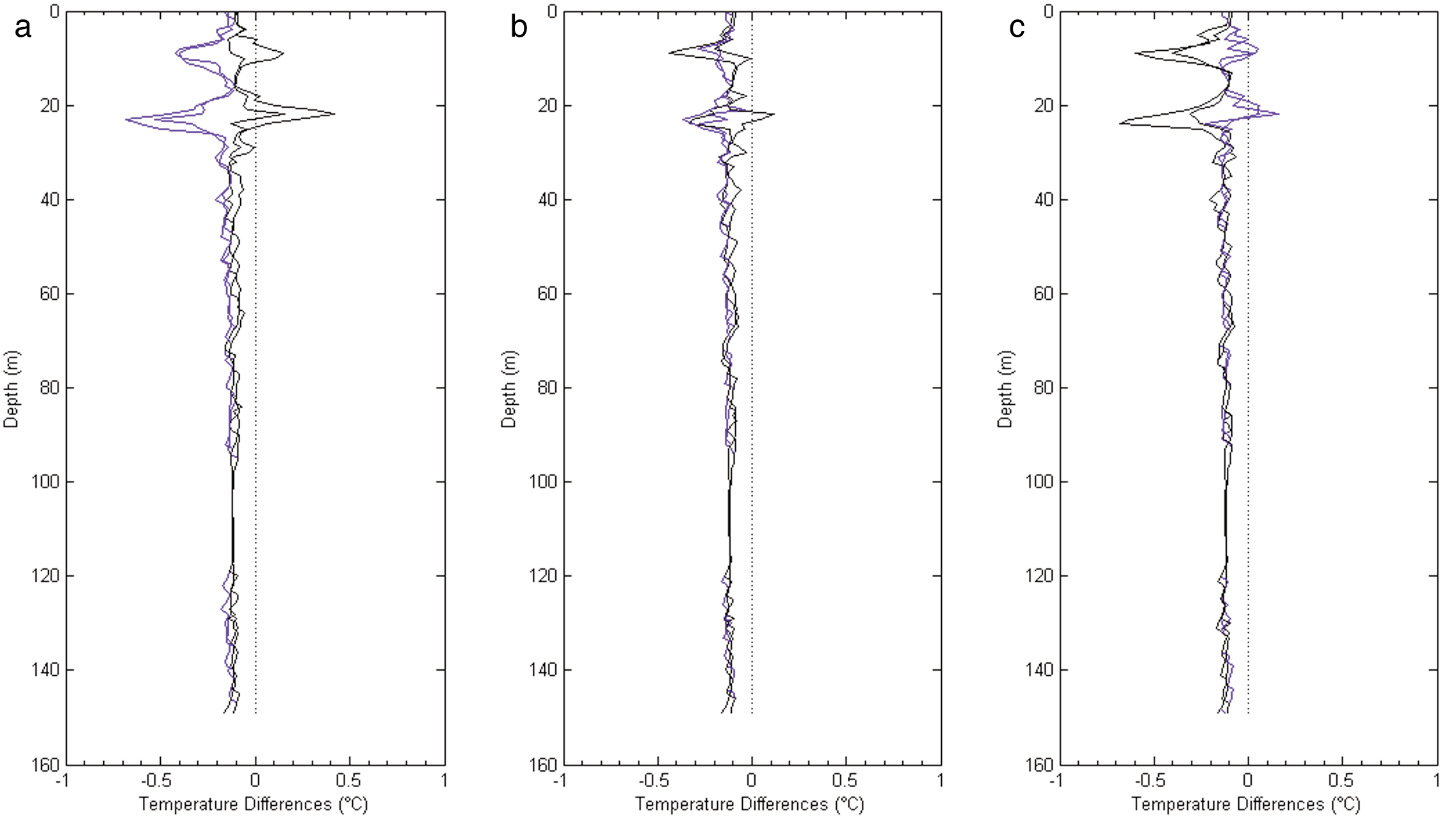

Fig. 2. Temperature differences between Mk9 and CTD for two downcasts (blue) and upcasts (black) from 30 April 2005 with (a) no time lag, (b) a 1-s time lag, and (c) a 2-s time lag. Small dotted line = the line of equality in each subplot.

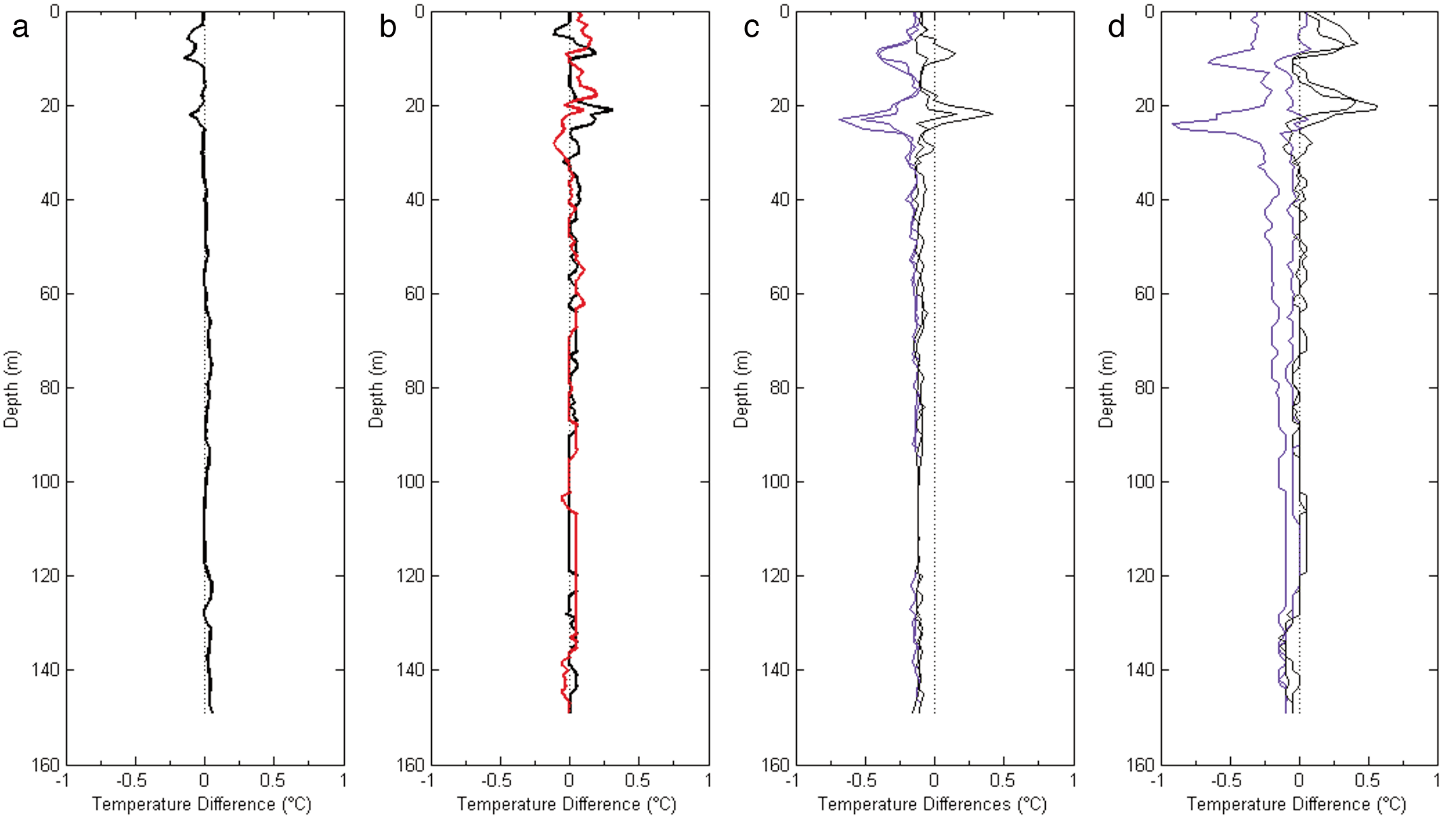

Fig. 3. (a) Temperature differences between the two CTD casts on 30 April 2005. (b) Temperature differences between two consecutive upcasts from the Mk9 on the CTD (black) and two consecutive upcasts from an Mk9 on a seal (red). Differences are comparable with those between consecutive CTD casts. (c) Temperature differences between the Mk9 on the CTD and the CTD for two downcasts (blue) and upcasts (black) on 30 April 2005. (d) Temperature differences between the Mk9 on CTD and Mk9 on one seal for two downcasts (blue) and upcasts (black) from 30 April 2005. Small dotted line = line of equality.

pinnipeds. Mk9s with a rapid response thermistor offer a high-performance temperature sensor for animal-derived thermal data.

Animal effects—We detected no effects of instrument attachment to the seals. However, the behavior of the animal in relation to the response of the tag and sampling frequency may still affect the ability to resolve thermal features in the water column. It may be possible to re-create thermal features such as the thermocline from a slow swimming animal, even with a slower responding thermistor, given an appropriate sampling frequency.

Wilson et al. (1995) suggested that depth should be collected at a minimum rate corresponding to 10% of the total dive duration to provide sufficient data to resolve diving behavior. Mk9s on both the CTD and seals sampling every second provided a baseline data set to assess the effects of sampling frequency on the quality of the temperature data. We subsampled the data sets from the Mk9 on the CTD at 4, 8, and 30 s. These time intervals were chosen as 4 and 8 s are the sampling frequencies currently used on the free-ranging adult female northern elephant seals, and there is a wealth of historic data sampled at 30 s from this and other species.

Subsampling of data from the Mk9 on the CTD and comparisons with the CTD data revealed that although there were slight differences in depths at which thermocline and mixed layer were defined when sampling at 4 and 8 s, these differences were only 2 to 4 times the depth resolution of the Mk9 pressure sensor (± 0.5m). However, there were significant differences in thermal structure (thermocline depth, mixed layer depth, surface temperature, etc.) when using a 30 s data set. In several profiles subsampled at 30 s, so much detail was lost that a thermocline was not detected, even though it was present at higher sampling frequencies (Fig. 4).

We conclude that the use of sampling rates of 4 or 8 s in combination with a rapid response thermistor deployed on elephant seals provide data of sufficient quality to re-create the thermal structure of the water column with similar detail to XBT data (Reseghetti et al. 2007). These data further support the use of elephant seals to collect high quality thermal data on an unprecedented scale across the north Pacific.

We expect the use of animals as ocean sensors will continue to grow in the future and present a simple method to assess potential error in an animal-derived temperature data set, given differing behaviors (dive depths and descent/ascent

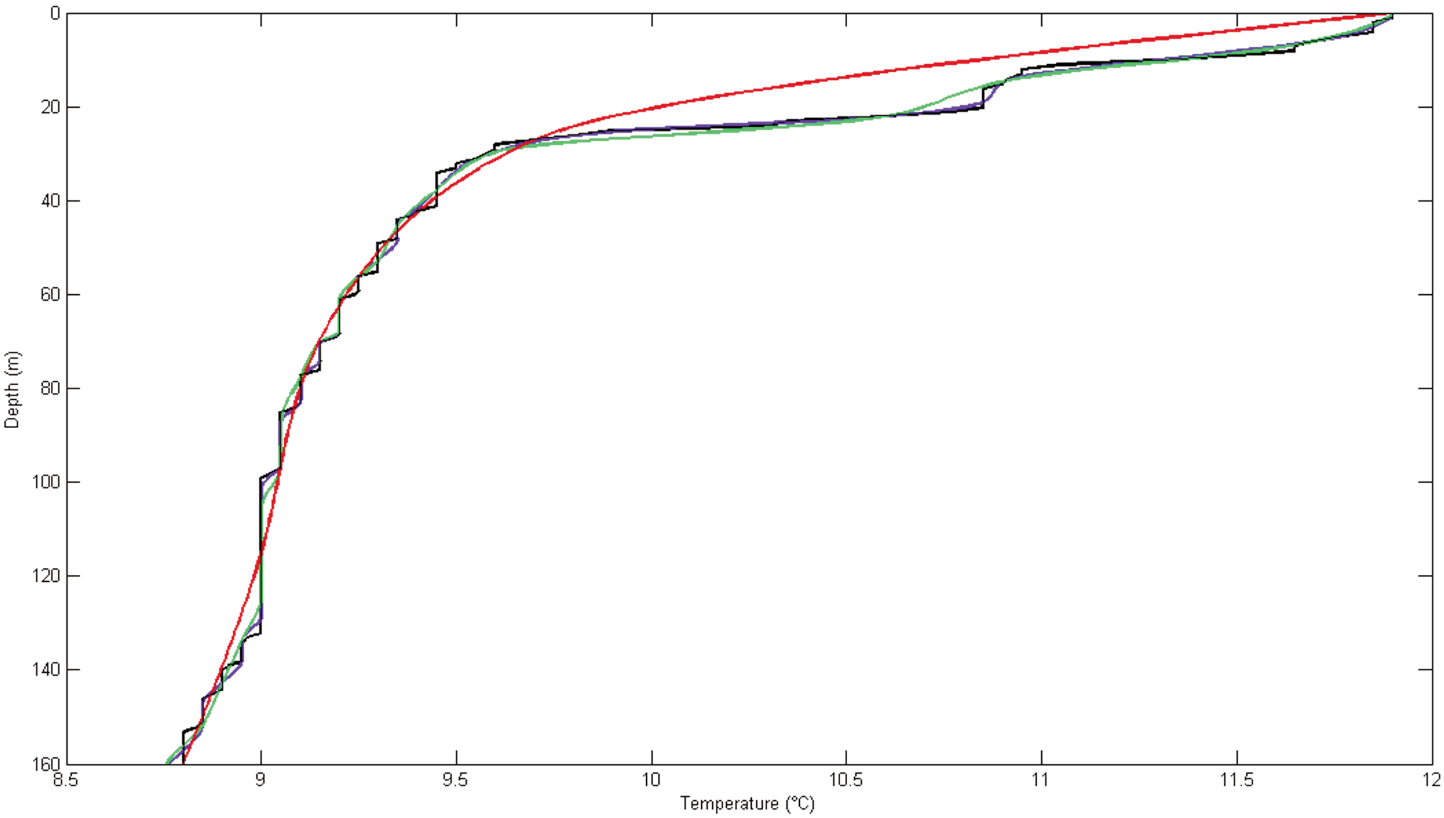

Fig. 4. Temperature profiles as sampled or subsampled at 1 s (black), 4 s (blue), 8 s (green), and 30 s (red) from the MK9 on the CTD. Basic thermal structure is conserved at 4 and 8 s but begins to be lost at 30 s.

rates) of animals in varying thermal environments. It is important to understand these potential errors when using the temperature data in heat flux calculations, for example. We also address how these errors may be offset by adjusting sampling frequency.

The method is based on the equation for standard representation of thermal response. First we use behavioral data to calculate an absolute minimum sampling frequency, which would provide only one data point per dive:

$$t = dd/dr \tag{1}$$

where t = time (s), dd = mean or maximum dive depth (m) for an animal of interest (or specific dive), and dr = rate of descent (or ascent) of the animal through the water column (ms^{-1}).

Then we calculate the error (difference between measured and final temperature) at the bottom of the dive, i.e., at time (t):

$$E = \Delta T\, e^{-bt} \tag{2}$$

when E = error, ΔT = temperature change in the water column (i.e., surface temperature – bottom temperature), b = thermal time constant of the thermistor in the instrument, and t = time as calculated in Eq. 1.

We account for changes in sampling frequency assuming that temperature change through the water column is constant. Thus, by increasing sampling frequency, there is a proportional decrease in ΔT as well as our value for time (t):

$$\mathrm{new}\,\Delta T = \Delta T\,[(dr \times sf)/dd] \tag{3}$$

where ΔT = temperature change from surface to bottom, dd = dive depth, dr = rate of descent (or ascent), and sf = sampling frequency.

We can then calculate a value for the error at each point sampled using

$$E_{sf} = \mathrm{new}\,\Delta T\, e^{-b(sf)} \tag{4}$$

These four equations offer a simple way to assess thermistor performance and hence potential errors in derived temperature data, given a little general knowledge about the behavior of the animal (dive depth and swim speed), the thermal environments the animal is likely to encounter, and the response of the thermistor.

We do not account for rapid changes in temperature with depth, as seen within the thermocline. However, the variables used could easily be adapted to reflect temperature and depth changes within the smaller thermocline feature and assess the quality of data collected in this zone in relation to sampling frequency and swim speed. For example, a thermocline 35 m in breadth with temperature change of 5°C would be traversed by an animal swimming at 4 ms^{-1} in 8.75 s. Thus, to obtain data from within the feature, a sampling frequency of at least

8 s is required. However, the same feature encountered by an animal descending at 1 ms^{-1} would take 35 s to cross. In this case detection and characterization of this feature would be possible with a much lower sampling frequency and a rapid response thermistor, or even a slower responding thermistor with a higher sampling frequency.

At some point increasing the sampling frequency adds no further value (error reduction) to the collected temperature data. This point can be identified using:

$$\text{Max sampling frequency (Hz)} = \text{(Resolution of temperature sensor)}/(b * \Delta T) \qquad (5)$$

where b = thermal time constant of the thermistor and ΔT = temperature differential between the tag and its surroundings.

For deep diving and relatively slow moving animals such as elephant seals, lower sampling frequencies and slower responding thermistors may still provide accurate and valuable data on the thermal structure of the water column from a single dive, as well as from the averaging or interpolation of thermal data over several consecutive dives. The ability to assess the quality of such data sets allows exploration of the behavior of animals in relation to their environment at fine temporal and spatial scales.

Environmental data sets generated from animal-borne instruments may provide the scope, both geographic and temporal, and detail necessary to fully understand the current and ongoing changes in climate as well as their effects on the animals. However, the validity of these data must be carefully assessed in relation to instrument calibration, sampling regimes, and possible effects of animal behavior on the data.

Comments and recommendations

Calibration of the instruments before (and where possible following) deployment will verify performance. However, when individual calibrations cannot be carried out a 0.05°C subtraction from Mk9 rapid response thermistor data and implementation of a 1-s time lag will maximize the data accuracy.

To ensure data quality, careful thought about an appropriate sampling frequency is required, given the average transit rate of the animal through the water column and the response time of the sensor in question. For the elephant seal data examined in this study, a sampling frequency of less than 10 s was sufficient to generate temperature profiles from each ascent or descent that were comparable with CTD data. Historically, there has also been a trade-off between sampling frequency and duration of the record given memory capacity of the instrument. With memory capacity increasing exponentially, it is likely that this trade-off will soon become obsolete. We recommend a 1-s sampling rate with implementation of a 1-s time lag at analysis when using a rapid response thermistor to produce the highest quality data sets. The performance of Mk9s in relation to CTD data is comparable with that of XBTs (Reseghetti et al. 2007). When deployed on elephant seals, Mk9s offer a reliable, high quality thermal data set and outperform XBTs with regard to the number of profiles collected and the range of environments sampled by a single instrument.

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Submitted 27 May 2008
Revised 15 May 2009
Accepted 10 July 2009