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A physically based method for correcting temperature profile measurements made using thermocouples

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Abstract

High frequency (diurnal) temperature variations occur simultaneously at multiple depths separated by metres of snow in at least several and probably many Arctic and Antarctic thermocouple data sets. These temperature variations cannot be caused by heat conduction from the surface because their amplitudes are too large and there is no phase lag with depth, and they cannot be caused by heat advection because the air flux required is greater than is available. Rather, the simultaneous temperature variations (STVs) appear to originate within the box that houses the data logger as thermocouple-like offset voltages, wire heating, or thermistor error. The STVs can be corrected by requiring that the temperatures vary smoothly with time at the greatest depth at which temperature is measured. The correction voltage determined in this fashion, when applied to the thermocouples at other depths, corrects the entire data set. The method successfully removes STVs with 24 hour period that are up to 3.8°C in amplitude and is superior to the averaging techniques that are commonly used to correct thermocouple data because it introduce no spurious (non-physical) temperature variations. The correction method described can be applied to all thermocouple data where temperature measurements have been made at depths >~0.5 m into the snowpack. The corrections should allow more physical process and parameter information to be extracted more confidently from existing firn temperature data. Identification of the STVs and their probable cause also suggests how better data could be collected in the future.

Introduction

Thermocouples are commonly used to record changes in temperature with time. This is especially true when measurements are made at remote sites with power limitations or when large arrays of temperature sensors are deployed. Temperature measurements in snow-packs are commonly made in conjunction with snow process studies (e.g. Andreas and others, 2004), or to determine heat flux (e.g. Sturm and others, 2002), or to infer the physical properties such as thermal conductivity and diffusivity of the snow-pack (e.g. Schwerdtfeger 1965 and Jun & Zwally, 2002). Such studies require accurate and precise temperature measurements (Zhang &Osterkamp, 1995). An absolute accuracy of greater than ~0.1C is desired.

While investigating temperature profiles in polar firn we noticed simultaneous temperature variations (STVs) of ~0.8C at depths greater than 0.25 m that were correlated or anti-correlated with the thermistor reference temperature measured in the box housing the data logger. The temperature profile is show in Figure 1, with the simultaneous temperature variations explicitly shown in 1b, 1c and 1d. The simultaneous temperature variations did not decrease with depth into the snow-pack as expected, nor was there the phase shift that would be expected for a temperature wave propagating into the firn. Subsequently we have found that similar, but usually smaller, STVs exist in other data sets. Because the STVs occure at multiple depths, we argue here that these STVs are caused by an uncorrected voltage introduced within the data logger enclosure.

A thermocouple is a thermoelectric circuit made up of two dissimilar wires joined at one end. The temperature-dependent voltage, called the Seebeck effect, exists across the thermocouple wire junction where two compositionally dissimilar wires are joined. In practice, there are two locations where two dissimilar metals are joined. As shown in Figure 2, one is where the two dissimilar metals are soldered together to make the thermocouple (J1 in Figure 2), and the other is where the constantan wire is connected to a copper junction on data logger (J2 in Figure 2). For the thermocouple to be useful in measuring temperature, it must depend only on the temperature at J1. The voltage shift at J2 must be known, and subtracted. This is done by measuring the temperature at J2 with a thermistor, and predicting the thermocouple effect at junction J2 using polynomial equations published by NIST (Burns and others, 1993). We refer to temperatures measured by the thermistor in the data logger box as the reference temperature.

This purpose of this paper is to investigate the origin of the observed simultaneous temperature variations (or STVs) in thermocouple measurements. We show that it is very unlikely they are related to physical processes in the firn, and we show how they can be eliminated using temperature measurements deeper in the firn. At any time a single voltage correction eliminates the STVs in all the thermocouples in the array. In some cases this correction correlates with the reference temperature, but in other cases the correction for the same reference temperature is different depending on when the temperature was recorded. Regardless of the source of the error or it's dependence on the reference temperature, it is possible to correct the data, and confidence in the correction is provided by the fact that it can be shown to be appropriate for all thermocouples in the array.

The Temperature Data

Four data sets are analyzed in this paper. We discuss in detail our analysis of a temperature data set we collected from a near surface thermocouple array deployed between March 20th through April 30th, 2004 at Summit, Greenland (elevation 3200 metres). We present more briefly an analysis of a data set collected by others at Siple Dome (elevation 615 metres), Antarctica, in 1998 (Albert, 2001), and laboratory experiments we conducted in a University of Chicago cold room to investigate STVs under laboratory conditions. Examination of raw data from the Greenland Climate

Network automated weather station at Summit Greenland (Steffen and others, 1996) shows STVs, but their magnitude is much smaller than those found in the data we collected. The magnitude of the STVs appears to depend on data logger installation methods. We refer to the weather station data as the Summit AWS data set to distinguish it from the data we collected at Summit, Greenland.

The thermocouples used in all the data sets discussed here were type T copper-constantine thermocouples. Prior to installation of our thermocouple array in Summit Greenland, the thermocouple–data logger system was calibrated by inserting the thermocouples into a well-mixed ice bath and reading the temperatures recorded by the data logger. All readings were between 0.1^{o} of 0^{o}C. Similar procedures were reported to have been done for the other data sets. The Data logger enclosures varied between data sets, and details were not given in literature. For data collected in 2004 at Summit Greenland, the data logger was located inside a standard weather-resistant fiberglass case that rested on a metal support structure approximately 1m above the snow surface.

Figure 1 plots the temperatures recorded at Summit, Greenland, at four depths, surface, 0.5, 1 and 1.5 metres, and the reference temperature. Temperature was measured at ten different depths. To simplify the graph, only four are shown in Figure 1. Surface temperatures (light gray) show a large (20°C) daily variation, but on average decline slightly until ~ April 11^{th} when they rise ~10°C over 3-4 days, fall until ~April 19^{th}, and then begin a steady rise. If we examine the data series more closely (selections b, c and d in Figure 1), we find that at some times (e.g., Figure 1b) the temperature at depth is anti-correlated with reference temperature, while at other times (Figure 1d) it is correlated. The amplitude of the temperature variation at 1.5 m depth is typically ~0.8°C (Figure 1a), but can reach 3.8°C (Figure 1c). The diurnal temperature variation is simultaneous at 0.5, 1, and 1.5 metres and so can not be explained by temperature wave propagation. Figure 3 shows a portion of the 2000 Summit AWS record for thermocouples at approximately 5, 8 and 10 metres depth. These data also show simultaneous temperature variations, although the variations are much smaller then those observed in the data presented in Figure 1 (0.1 rather than 0.8°C).

No Obvious Natural Origin for the STVs

The STVs do not have an obvious physical origin. Possible physical processes that can change the temperature within the snowpack include thermal conduction and air advection, but neither is capable of producing the STV signal observed.

Carslaw and Jaeger derive an analytical equation for temperature variations within a conductive half-space whose surface is subject to sinusoidal temperature variations:

$$T = Ae^{-z\sqrt{\frac{\varpi}{2\kappa}}}\cos\left(\varpi t - z\sqrt{\frac{\varpi}{2\kappa}} + \varepsilon\right). \qquad \text{Eq. 1}$$

Here T is temperature, A is the amplitude of the temperature change at the surface, z is the depth (positive z) into the material, κ is the thermal diffusivity of the material, and ω is the angular frequency (=2π/period of the surface temperature variation). From this equation it is clear that the changes in surface temperature exponentially decrease as they propagate into the media, and that the phase velocity, v, with which they propagate is:

$$v = \varpi \Big/ \sqrt{\frac{\varpi}{2\kappa}} \ . \qquad \text{Eq. 2}$$

The time lag between a temperature at the surface and its induced value at depth is $\Delta t = z/v$. For a typical snowpack with diffusivity of κ=1.14*10^{-3} m^2 $hour^{-1}$ a daily temperature variation has a phase velocity, v, of 0.24 m hr^{-1}. If the amplitude of the daily temperature change is 10°C, the amplitude of the temperature change produced at 0.5 m depth is 0.05°C and the phase shift is 21 hours. At 1.5 m depth the amplitude of the temperature change is 1*10^{-6}°C and the phase shift 63 hours. On the same basis we would predict that an annual temperature cycle of 25°C amplitude would produce a temperature change at 10 meters of 0.1°C. This agrees with the well-known observation that the annual temperature variation propagates to an average depth of ~12 meters (Shuman and others, 2001). It is clear from this analysis, that daily temperature variations of the magnitude recorded at 1.5 m depth are not expected, nor is the lack of amplitude change and phase shift with depth. Thermal conduction cannot be the cause of the daily temperature changes we observe at depths >0.25 m.

Advection of heat by air flow also cannot be the cause of the STVs we observe either. In March and April deep subsurface temperatures are warmer than the snowpack at 1.5 m depth, and upward movement of air from depth could, in principal, warm the snow. However, the specific heat of ice is 2 kJ kg^{-1} K^{-1}. The specific heat of air is 1 kJ kg^{-1} K^{-1}. Assuming a porosity of 0.65, and an air density of 1.14 kg m^{-3}, the specific heat of snow is 640 kJ m^{-3} K^{-1}. A temperature increase of 0.8°C would thus require 512 kJ per cubic meter of snow. If air entered such a volume 4°C warmer than it left, 128 cubic meters of air would be required to introduce this much heat. However the snowpack compacts roughly linearly between the surface and 70 m depth and thus contains only ~22m^3 of air per m^2 of snow surface. There is thus not enough air in the snowpack to achieve the required warming. Airflow from the colder surface would cool the snow. Daily airflow of the magnitude and temperature required to explain the typical STVs is not possible. The largest STVs (3.8°C) would require 4.75 times more air flow.

Correcting The Thermocouple Data

We have shown above that the temperature at 1.5 m depth should not change significantly over a daily time period. Using this, we can easily correct the data. The correction method is basically to fit a smooth curve through the temperature time series at 1.5 m depth and use the deviation from this smooth curve to correct all the time series from the other thermocouples.

Fitting a slowly varying temperature function through the data requires a criterion for sub-sampling the temperature time series at times where the measured temperature is “correct”. This process is different for each data set, and there is no way to be sure that the sampled data are in fact correct temperatures other than to check after the data is processed and see if the correction is reasonable. In the Greenland Data set the “correct” subset was selected with the criteria that the reference temperature lie between –30 and -33°C. This temperature interval was chosen because the STVs switch from being anti-correlated to correlated with the reference temperature over this range. This was also a range of reference temperature that the reference temperature crossed throughout the entire collection period. Whenever the reference temperature was between –30 and -33°C the temperature recorded by the thermocouple at 1.5 m depth was assumed to be the correct temperature. Times when the reference temperature, T_{ref}, is between –30 and -33°C are shown as black diamonds on the $T_{1.5}$ data in Figure 4. We fit a 9^{th} order polynomial through these points as shown in Figure 4, and assume that this curve represents the "actual" temperature at 1.5m depth, ${}_{A}T_{1.5}(t)$.

The selection criteria for the Siple Dome data was not as simple. The reference temperature did not pass through any narrow temperature interval over the collection period. Figure 5 show the reference temperature and the temperatures measured at 4 m and 6.15 m. When the reference temperature is warm and relatively constant, the thermocouple data is very smooth. As the Austral winter sets in the reference temperature decreases and begins to vary over a range of 5 to even 10°C, and the temperature at 4 m 6.15 m thermocouples begin to display STVs. The selection criteria chosen was that the reference temperature did not vary over 3 hours and was either greater then -20°C, or between –30 and -33°C. The data selected by these criteria are shown as black dimonds in Figure 5.

Once a reasonably sparce subset of temperature measurements has been selected, a polynomial can be fit to the subset which defines a smooth temperature variation with time. Converting both the thermocouple temperatures measured at 1.5 m depth, ${}_{M}T_{1.5}$, and the smooth "actual" temperatures at 1.5 m depth from the polynomial, ${}_{A}T_{1.5}(t)$, to voltages using the NIST equations:

$$
\begin{aligned}
{}_{A}T_{1.5} &\rightarrow {}_{A}V_{1.5} \\
{}_{M}T_{1.5} &\rightarrow {}_{M}V_{1.5},
\end{aligned}
$$

we obtain the voltage offset needed to correct the 1.5m data:

$$\Delta V = {}_{M}V_{1.5} - {}_{A}V_{1.5}.$$

This voltage correction can be applied to correct all the thermocouple measurements. We apply it by converting the thermocouple measurements to voltages using the NIST thermocouple equation, adding the correction, and reconverting to temperature:

$$
\begin{aligned}
{}_{M}T &\rightarrow {}_{M}V \\
{}_{C}V &= {}_{M}V - \Delta V \\
{}_{C}V &\rightarrow {}_{C}T,
\end{aligned}
$$

where ${}_{C}V$ and ${}_{C}T$ are corrected voltages and temperatures.

Figure 6 shows the corrected data in the same format as Figure 1. The change in temperature with depth follow expected trends. Temperatures at depths >0.25 m show very little temperature variations on a daily period. The data correction is equally valid at all depths, and both the correlated (inserts d) and anti-correlated (inserts b) variations are removed. The 3.8°C STV shown in 1c is almost completely removed in 6c. All the data sets can be corrected by requiring the temperature variations of the deep thermocouple be smooth on a weekly basis. Figure 7 compares corrected and uncorrected data for the Siple Dome Data set. The corrections are also very good in this case.

The Origin of the STVs

Our analysis of the data suggests that the source of the STVs is within the data logger box. Beyond that we can only speculate. It could be errors in the thermistor, wire heating or a temperature dependent voltage offset produced within the electronics of the data logger (location J_3 in Figure 2) which, perhaps in conjunction with other effects, sum to creates an additional signal. Schraff (1996) discussed the voltage offset introduced in Daqbook's internal electronics and showed that correcting for the offset changes the measured temperature by 4.7°C. Daqbooks are manufactured by IOtech and are similar to the Campbell scientific CR10 data logger used in our experiment. Schraff does not mention any temperature dependence for the voltage offset. However, it seems possible that it could exist. The thermistor used in the data logger in our experiment was a Campbell Scientific CR10TCRF. This thermistor is a semiconductor created to have a resistance that varies significantly as a function of temperature between -53°C to 48°C. The CR10TCRF is capable of measuring temperature to better then ±0.2°C (Campbell Scientific CR10TCRF manual and *Gyorki, 2004*). It could be that the signal we see in the thermocouple data is systematic variation within the thermistor data.

Independent of the exact origin of the voltage offset, we can further explore the nature of the voltage correction by plotting it as a function of the reference temperature. This is done in Figure 8. For the Greenland data, the voltage correction varies as a simple non-linear function of the reference temperature. An 8th order polynomial can be regressed to the data with an R^2 of 0.98, and this polynomial can be used to correct the thermocouple data using only the reference temperature. Resulting corrected data in not as smooth as data corrected with the method described in the previous section. Notice that ΔV increases as reference temperature either increases or decreases from ~-32°C. This explains why the correlation of subsurface temperature shifts from correlation to anti-correlation at ~ -32°C.

We found a more complicated relationship between the reference temperature and the voltage correction in the other data sets. The Siple Dome data exhibits significant hysteresis, and is shown in Figure 8b. At any reference temperature the voltage correction has a single value at any given time that relates smoothly to values at adjacent times, but at significantly later times the voltage correction may be quite different for this same reference temperature. The curve loops around with time as shown by the arrows, in a typically hysteretic fashion

The measured voltage offset and reference temperature also shows strong hysteresis in our laboratory measurements. We shorted one of the channels in the Data logger with a copper wire, placed the data logger in a cold room and varied the temperature of the room. Measuring the voltage across the shorted channel should give just the voltage offsets within the data logger. If there were no temperature-dependent junction voltages in the data logger, the measure voltage should be constant. In fact it was found to vary with the temperature of the data logger in the fashion as shown in Figure 8c. Neither the voltage correction in the Siple Dome data, nor the voltage offset measure in the lab are as large as the voltage correction in the Greenland data. But the STVs observed in the Greenland data set were also much greater then in the Siple Dome data set, and the frequency of time variation of the Greenland reference temperature was much greater than in the Siple Dome data. The Greenland reference temperature reached much colder values than was reached in the laboratory. These could be possible reasons for the larger STVs in the Greenland data.

Discussion

Two matters warrant discussion. The first is how our new correction compares to other methods of correction. The second regards implications for improving data collection methods and instrumentation.

Figure 9 plots our corrected temperature at 1.5m depth (${}_{C}T_{1.5}$), and the uncorrected temperature at 1.5m depth (${}_{M}T_{1.5}$) against time. Two common methods of data correction are to report average daily temperatures, or to apply a 5 day running mean. When this is done the triangular data points connected by straight line segments are obtained for the daily measurements, and the circles connected by a line are the 5 day running mean. A curve through the 24 hour average data shows an ~9 day, 0.5°C amplitude variation in the temperature at 1.5m depth that is, by our correction, entirely fictitious. The five day running mean has similar variation, but with an amplitude of 0.2°C. This false temperature variation would be detrimental to attempts to use the temperature profiles to infer heat flux or snow properties, and in fact suggest the operation of entirely fictitious processes. Averaging thermocouple data is clearly a much less satisfactory method of correcting the data than requiring the data be smooth at temporal frequencies at which we have good physical reasons to believe it must be smooth.

Because the correction applies to all thermocouples equally, and because in one case a simple relation could be found between the temperature of the data logger and the voltage offset needed to correct the thermocouple data, it seems clear to us that the origin of the STVs is in the data logger box. The immediate implication is that higher quality temperature data could be collected if the data logger box were kept at more constant temperature. This could be done with a heating mechanism, or by burying it a meter or so below the snow surface (which my have been done for some of the data shown). A second implication is that it might be possible to correct for the voltage offsets within the data logger by electronic design or by using more accurate reference thermistors.

The most important aspect of this paper, however, is it's demonstration that simultaneous temperature variations exist in Arctic and Antarctic thermocouple data that are related to temperature variations that commonly occur in the box that houses the data logger. We discovered these STVs because the data logger box in the data we collected and analyzed showed unusually large STVs that were coherently related to the reference temperature in the data logger box.   The ambient temperature changes in our data were particularly large, being collected over the termination of the arctic winter, and our enclosure was deployed in an exposed setting.   Because the STVs were large and clear we able to recognize their non-physical nature, devise a way to eliminate them, and also infer that they must originate from within the data logger enclosure. Examining other data sets, we seem always to find similar, but usually smaller STVs. Because subsurface temperature is such an important parameter in Arctic and Antarctic research, recognition of these non-physical STVs is important, particularly since, once recognized, they can be removed in a much better fashion than by simple averaging techniques.

Summary

Simultaneous non-physical temperature variations with a daily frequency exist in a number of Arctic and Antarctic thermocouple data sets. They appear to arise within the electronics housed in the data logger enclosure. The simultaneous temperature variations (STVs) can be removed if the thermocouple temperature measurements were made over a range of depths below the snow surface by requiring that temperatures at depth be slowly varying. The deepest thermocouple is used to calculate a correction, which, when applied to the entire array corrects the temperature time series at all depths. Due to the slight nonlinear nature of the thermo-electric thermocouple relation, all corrections are made in voltage space, and then converted back to temperatures. After the STVs are removed, there may remain a temperature offset (relative to the actual temperature) of all thermocouple data. Our method does not guarantee the correct absolute temperatures have been measured, but merely removes non-physical time variations in the data in a fashion that does not appear to introduce new non-physical variations. The method of correcting thermocouple data we describe can be applied to any thermocouple data for which temperatures are measured at depths more then 0.5 m into the snowpack.

Acknowledgments

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Figure Captions

Figure 1. (a) Thermocouple data collected from the surface and various depths within the unperturbed snowpack in Summit Greenland between March 20 and April 30, 2004 shows strong daily variations superimposed on a seasonal change. The daily variations decrease with depth to ~0.25m depth and show little change at depths greater than 0.25m. The deep temperature variations are both anti-correlated (b) and correlated (d) with the surface temperature. Daily changes at 1.5m can reach 3.8°C (c). Figures (b) and (c) have the same temperature scales on the vertical axis.

Figure 2. Schematic of data logger and thermocouples. J1-J3 indicate wire junctions where Seebeck effect voltage offsets occur.

Figure 3. Simultaneous temperature variations in Greenland Climate Network's raw data from the Summit AWS. The magnitude of the STVs is 10 times less then in Figure 1

Figure 4. Measured thermocouple temperatures (10 minute average) at 1.5m depth (gray triangles). Measurements when the data logger thermistor reference temperature was between -30 and –33°C are indicated by black diamonds. The solid line is a 9th order regression through the black diamonds.

Figure 5. STVs in Siple Dome Data are only present in the later half of the time series, when the reference temperature begins to decrease and show larger temporal variations. The subset of data that were fit to the 9th order polynomial that defines the smooth, physical reasonable variation in temperature at 6.15 m depth are shown by large black diamonds.

Figure 6. Corrected version of thermocouple data shown in Figure 1.

Figure 7. Siple Dome Data, raw (grey) and corrected (black) data at 4 and 6.15 meters depth.

Figure 8. (a) Voltage correction as a function of reference temperature for the Greenland Data we collected. (b) Voltage correction as a function of reference temperature for Siple Dome Data. (c) Measured voltage offset as a function of reference temperature for laboratory measurements. Note the hysteresis in (b) and (c). In each successive plot, the voltage correction/offset is about an order of magnitude less than the previous plot. This is partly because the data loggers at Simple Dome and in the laboratory did not reach temperatures as low as the data logger at Summit Greenland.

Figure 9. Corrected (black diamonds) and uncorrected (gray dots) thermocouple data at 1.5m depth for our Greenland data set. Averaging the measured data over 24 hours (gray triangles) or applying a 5 day running mean (black circles) will produce fictitious temperature variations with 0.2 – 0.5°C amplitude and ~9 day period.

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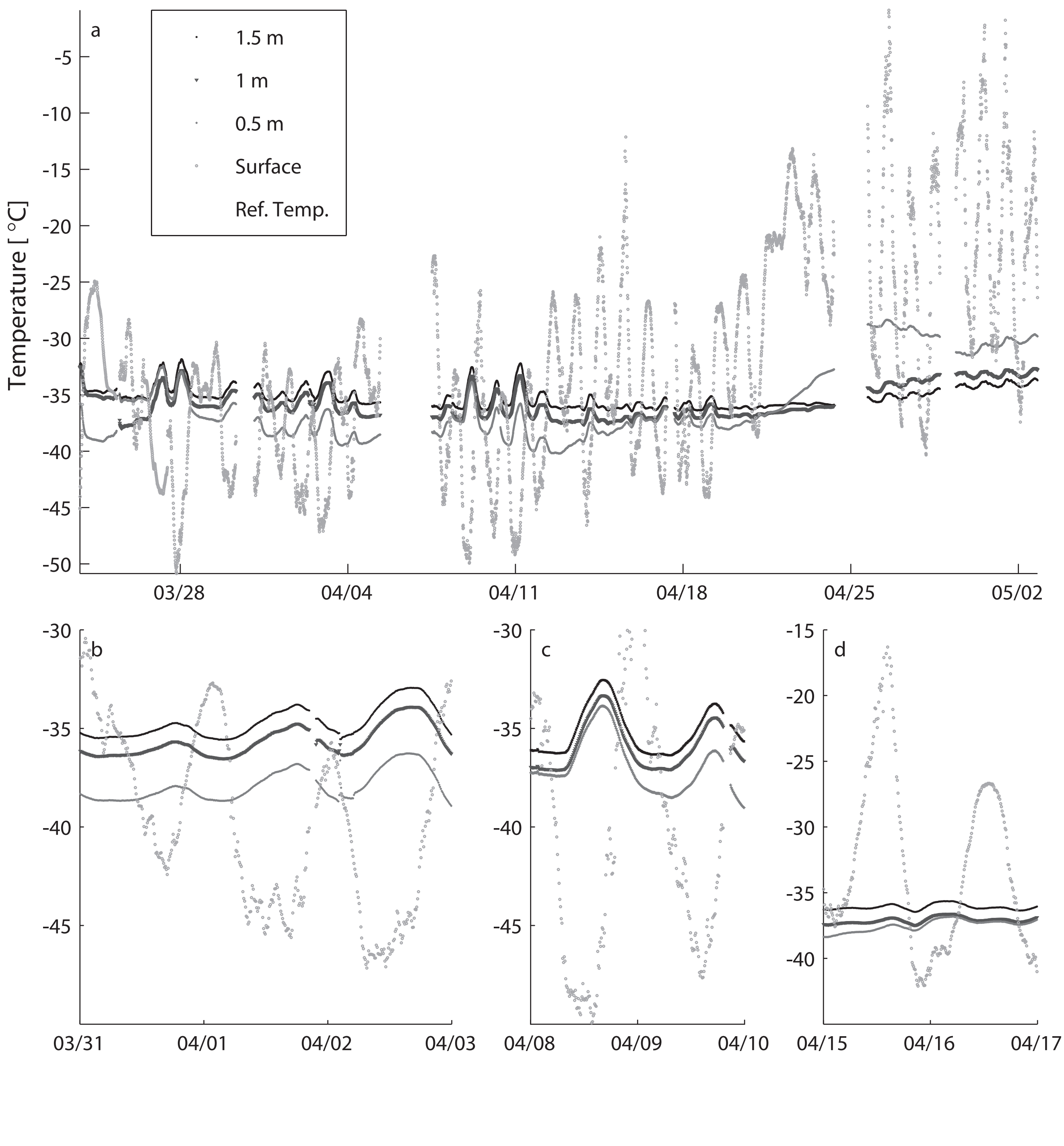
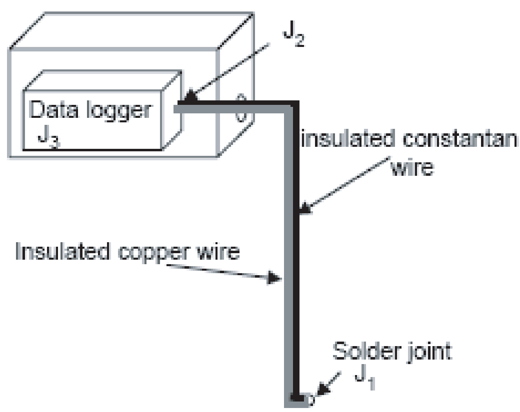

a
1.5 m
1 m
0.5 m
Surface
Ref. Temp.
Temperature [°C]
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
03/28
04/04
04/11
04/18
04/25
05/02
b
03/31
04/01
04/02
04/03
c
04/08
04/09
04/10
d
-15
-20
-25
04/15
04/16
04/17

Figure 1

Figure 2

Data logger enclosure



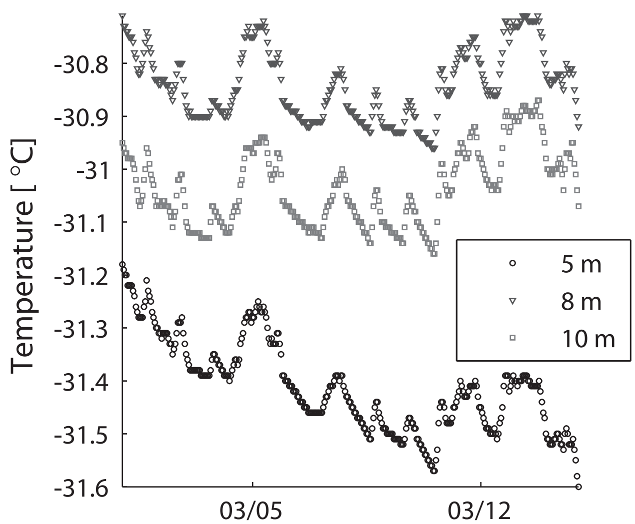

Temperature [°C]
-30.8
-30.9
-31
-31.1
-31.2
-31.3
-31.4
-31.5
-31.6
03/05
03/12
5 m
8 m
10 m

Figure 3

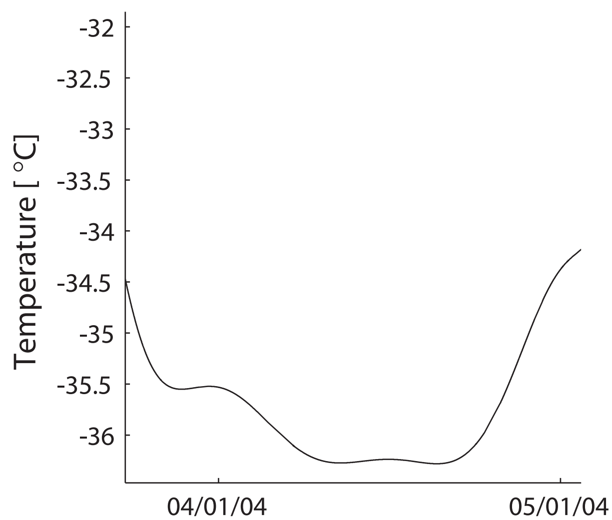


Figure 4

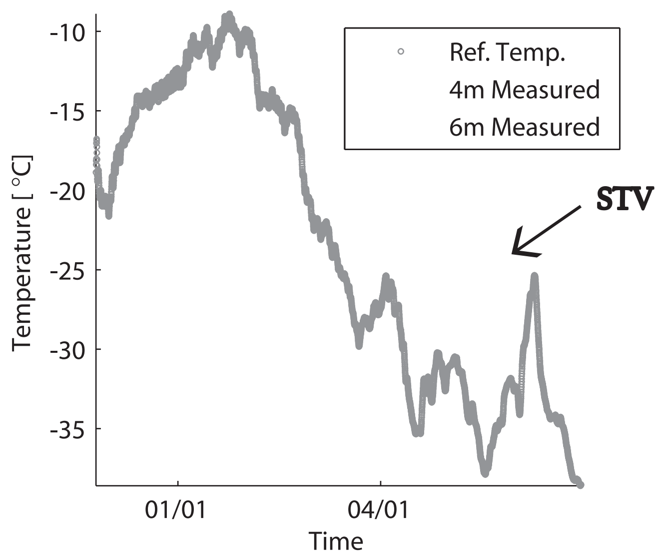
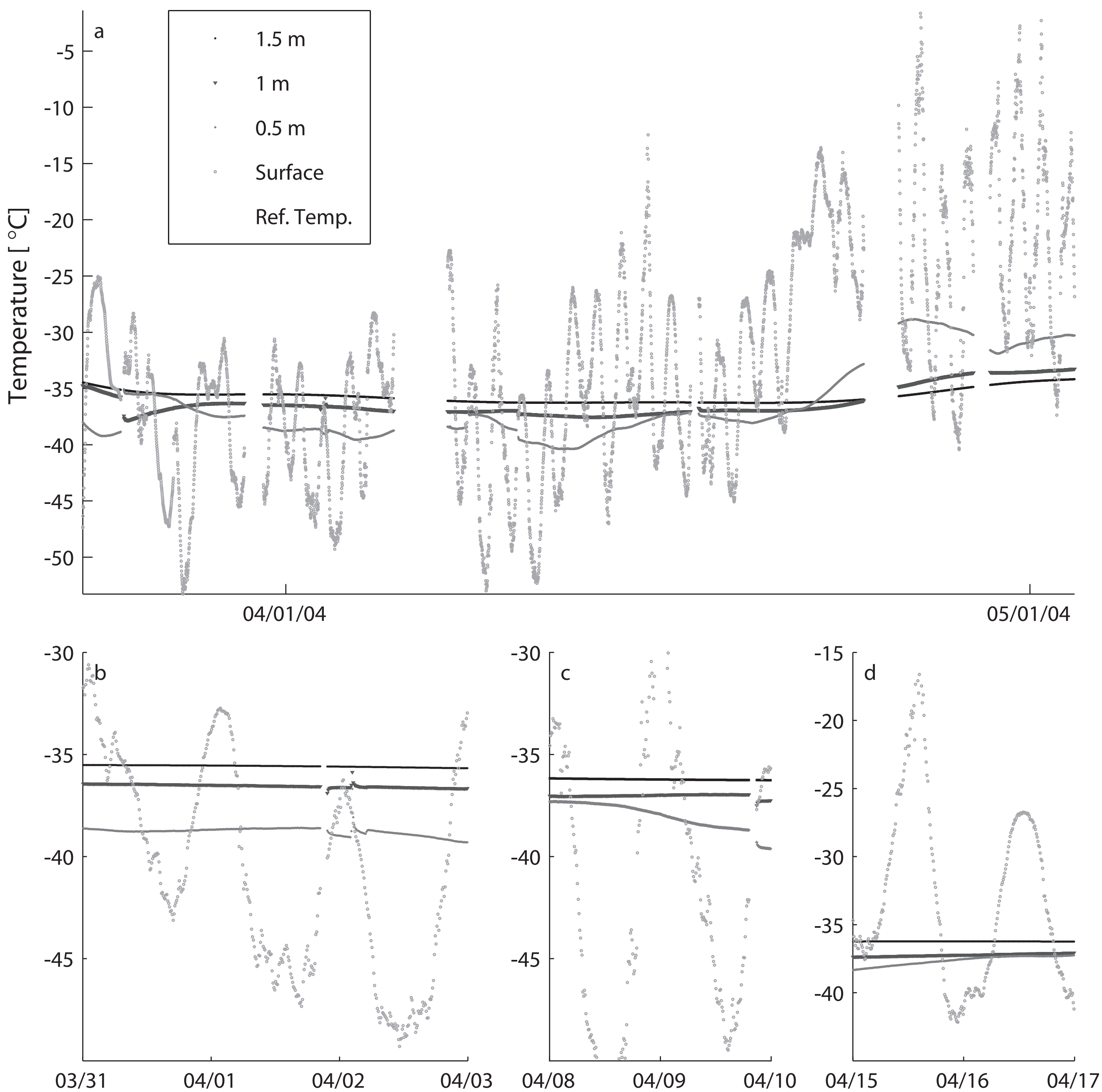

-10
-15
-20
-25
-30
-35
Temperature [°C]
01/01
04/01
Time
Ref. Temp.
4m Measured
6m Measured
STV

Figure 5


a
1.5 m
1 m
0.5 m
Surface
Ref. Temp.
Temperature [°C]
04/01/04
05/01/04
b
03/31
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d
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04/16
04/17

Figure 6

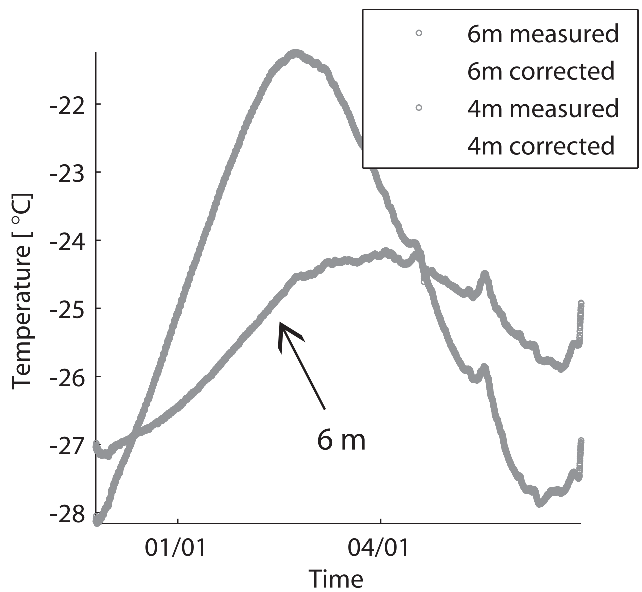
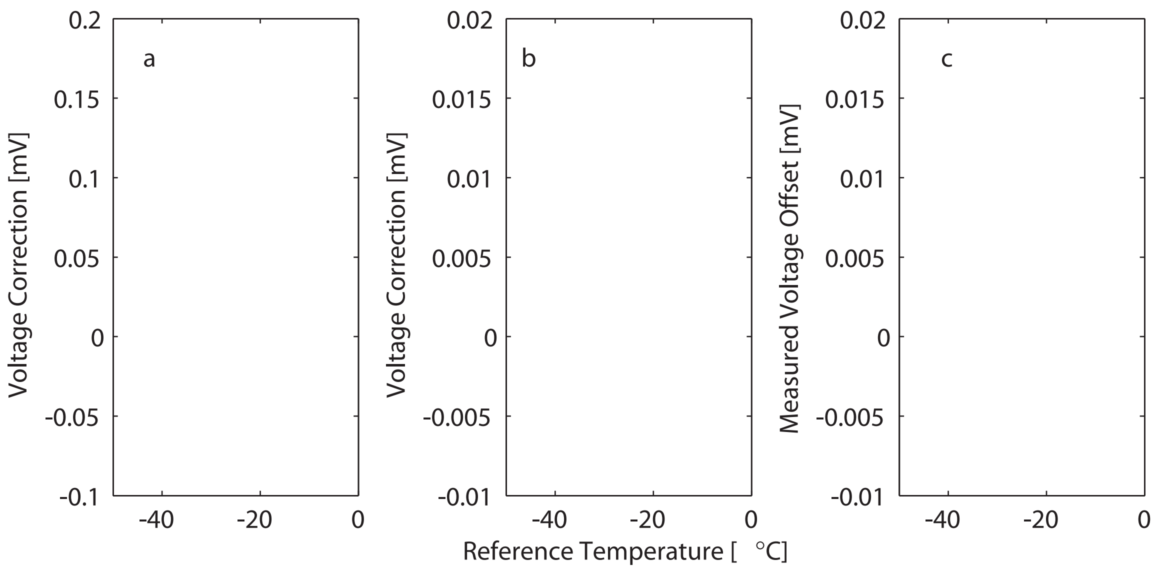

6m measured
6m corrected
4m measured
4m corrected
-22
-23
-24
-25
-26
-27
-28
Temperature [°C]
6 m
01/01
04/01
Time

Figure 7



a
b
c
Voltage Correction [mV]
Voltage Correction [mV]
Measured Voltage Offset [mV]
0.2
0.15
0.1
0.05
0
-0.05
-0.1
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-40
-20
0
Reference Temperature [°C]

Figure 8

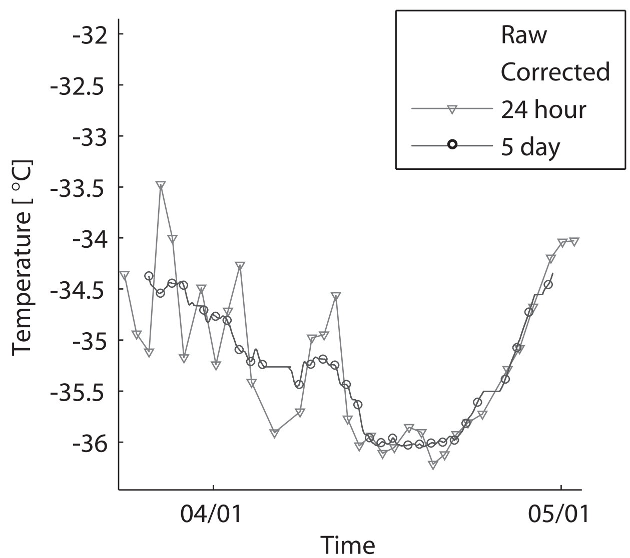

Raw
Corrected
24 hour
5 day
-32
-32.5
-33
-33.5
-34
-34.5
-35
-35.5
-36
Temperature [°C]
04/01
05/01
Time

Figure 9