Evaluating methods for measuring the mean soil temperature

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Abstract

Measurements of temperatures that are averaged or integrated over long time spans are needed for a variety of purposes such as soil resource inventory and climate studies. Mean temperatures usually are obtained in a two-step process of observation and numerical integration of periodic values. Pallmann introduced a technique using a temperature driven chemical reaction to integrate temperature over a period time. In this research, we illustrated the field application of the Pallmann method to measure mean soil temperature in a long-term climate change investigation project. The accuracy and consistency of the Pallmann method were evaluated by comparing two other temperature measurement methods: thermistor sensor and diffusion-cell method. The consistency of the Pallmann method is quite good. On average, the mean annual soil temperatures measured by the Pallmann method were 0.27 °C lower than those measured by the diffusion-cell method and were 0.64 °C higher than those measured by the thermistor sensor method. While statistical analysis showed that there was significant difference between the means of these three methods, the Pallmann method may better reflect the real ecological processes in soil in comparison with the arithmetic-mean temperature measured by the thermal sensors. It is an ideal method for studying the spatial variation in soil temperature and long-term climate changes.

Keywords:
Soil temperature
Pallmann method
Thermistor sensor
Diffusion-cell method

1. Introduction

Soil temperature is an important environmental factor that regulates the exchange of heat energy between the land surface and atmosphere (Jackson et al., 2008). It determines the rates of physical, chemical, and biological reactions in soils and has strong influences on plant growth and over the long run on soil formation (Trumbore et al., 1996; Tenge et al., 1998; Seyfried et al., 2001; Qi and Song, 2003; Brooks et al., 2004). Soil temperature is a key parameter in soil taxonomy (Soil Survey Staff, 1999). It is incorporated into the soil classification system through the soil temperature regimes, namely the mean annual soil temperature (MAST) and the difference between mean summer temperature and mean winter soil temperature.

Mean annual soil temperature, a standard index for the thermal climates of soil, is necessary for accurate soil resource inventory and for climate studies. It has been universally used as an independent variable relating the average reaction rates of physical and biological processes occurring in soil environment (Lee, 1969). Measurements of mean temperature usually require integration and sampling over a temporal scale. However, it introduces two potential sources of bias, sampling method and data interpolation, into estimates of temperature. The common way to measure the soil temperature is to bury soil temperature sensors at a given depth in the soil connecting with various types of automated data acquisition system such as data loggers. Thermistors and thermocouples are standard soil temperature sensors that are available. This kind of approach is costly, especially when a large numbers of sensors are needed to cover the spatial variation in soil temperature in a large region (Costello and Horst, 1991; Plauborg, 2002). Annual or seasonal estimates of mean soil temperature must balance the accuracy of frequent sampling against the logistical costs of maintaining functional sensors for long periods of time, and the storing and transferring data for analyses.

With technology development, temperature can be measured rapidly, continuously and precisely. However, the arithmetic-mean soil temperature measured by thermal sensors may not reflect the real ecological processes in soil as the biochemical reactions respond in a nonlinear manner to temperature (Friedman and Norton, 1981). According to Vant Hoff’s law, the rate of chemical reaction doubles for each 10 °C rise in temperature (Van Wambeke, 1992).

The Pallmann technique, developed in the 1940s, offers an alternative to data collection by temperature sensors. The Pallmann technique was based on rate of a temperature driven chemical reaction (Pallmann et al., 1940). A sampling unit may be planted in the ground and recovered after a set time interval, and the chemical reaction rate would reflect the mean temperature for that period of time. The technique is ideally suited for areal-wide studies that require simultaneous measurements of the temperature at multiple locations, especially measurement sites that are unattended, infrequently visited, or difficult to maintain. The Pallmann method had been employed in many soil temperature studies (Murdock, 1956; Schmitz and Volkert, 1992).
velocity coefficient of x

log reciprocal of absolute temperature

the logarithm of the velocity coefficient

concentration $[H+]$ (i.e. proportion to $pH$). Change of sucrose concentration can be expressed in terms of rotation angle. Under specific $pH$, Eq. (2) becomes:

\[ \Xi = \left(1 / [H^+]t\right) \log \left([R_0 - R_n] / (R_t - R_n)\right) \]  

or

\[ \log \Xi = pH - \log t + \log [R_0 - R_n] - \log (R_t - R_n) \]  

where $R_0$, $R_n$, and $R_t$ refer to the rotation angles of sucrose solution in degree at time of 0, $t$, and infinity (when all the sucrose has inverted to invert sugar), respectively.

In the Pallmann method, it was assumed that the reaction depends on temperature according to the Van Hoff–Arrhenius law, namely, the logarithm of the velocity coefficient $\kappa$ varies linearly with the reciprocal of absolute temperature $T$.

\[ \log \kappa = b - \frac{a}{T} \]  

where $a$ and $b$ are empirical constants. Combining Eqs. (3b) and (4), the mean temperature, $T$ in degrees Kelvin (K) over a period of time $t$ (days) may be calculated by the following equation:

\[ T(K) = \left(\frac{-a}{pH - b - \log t + \log [log (R_0 - R_n)] - \log (R_t - R_n)}\right) \]  

Eq. (5) allows the calculation of the mean reaction temperature of sucrose hydrolysis if the $pH$, reaction time, and the three specific rotation angles are known.

In general, a difference in ambient temperature of 0.1 °C corresponds to an optical rotation difference of about 0.4°. If $R_0 = 60°$, $R_t = 20°$, and $R_n = -20°$, $\Delta T/\Delta R_t = 0.25 \, °C^{-1}$. Based on polarimeter accuracy of ±0.01°, therefore, read-out sensitivity is equivalent to ±0.0025 °C. Norton and Friedman (1981) demonstrated that the precision of the Pallmann method is less than 0.1 °C.

The absolute accuracy of the Pallmann method is influenced by laboratory and field measurement issues. Several approaches may be adapted to improve the accuracy of the Pallmann method: 1) preventing the hydrolysis during the period of preparation and transportation to the field by freezing the sensors; 2) adjusting the pH of the sensing solution to insure that inversion occurs rapidly enough to be measured accurately; 3) preventing the deterioration of the solution by bacterial growth by adding a small amount of formaldehyde to the solution; 4) avoiding direct exposure to solar radiation; 5) adding reagent grade sodium chloride to prevent freezing of the Pallmann solution at low temperatures.

2.2. Data collection

Data collected for this study were from a project initiated in the early 1980s by Dr. Lanny Lund at the University of California, Riverside to study the climate changes and their impacts on vegetation distribution in the Mojave Desert region. In this project, soil temperature data were continuously collected at 75 sites from 1982 to 2000 based on the Pallmann method. Fig. 1 illustrates the spatial distribution of the monitoring sites. The elevation of these sites varies from below sea level (−59 m) to 2363 m.

The procedures for the soil temperature collection were summarized as follows: 1) making the Pallmann solution according to those given by O'Brien (1971); adjusting the $pH$ of the solution by varying the concentration of HCl to make sure that about 30–40% of the hydrolysis was completed at the field sites during one year period; and then adding a small amount of formaldehyde to the solution to prevent deterioration of the solution by bacterial growth; 2) making the Pallmann temperature sensors by filling 4 ml glass ampoules with the Pallmann solution, sealed, and kept frozen; 3) burying the self-made Pallmann temperature sensors 50 cm below the surface at the temperature collection sites; and then removing the temperature sensors from the ground one year later and placing the sensors immediately in a container with dry ice for transporting to the laboratory; and 4) measuring the optical rotation angles of the samples with a Rudolph Model 52A2 Polarimeter with a mercury lamp at 546.07 nm and then obtaining the MAST at each collection site based on the standard curve derived in the laboratory (see Eq. (7)).

Batch of laboratory experiments was conducted to obtain the standard curve for calculating MAST at field sites and to check the linearity of the Pallmann method, namely, whether the hydrolysis reaction of sugars was dependent on the temperature according to the Van Hoff–Arrhenius law (Eq. (4)). In the batch experiments, 9 different $pH$s of the Pallmann solutions from 1.9 to 4.1 were chosen and the temperature varied from 0 to 35 °C. The length of time used for the laboratory experiments ($t$ in Eq. (5)) varied from 30 to 90 days depending on the $pH$ of the solution.

In the project, the MASTs were also measured with two other sensing techniques, thermistor sensor and the diffusion-cell method, at 21 of the 75 monitoring sites which were sites 1, 4, 9, 10, 13, 16, 18, 21, 26, 27, 28, 29, 30, 40, 42, 45, 46, 71, 72, 73, and 74. The data collected by thermistor sensor were from 1984 to 1999, while the data collected by the diffusion-cell method were from 1992 to 1999.

A Fenwal Electronic UUT51J1 thermistor in water resistant coating (Campbell Scientific, Inc. (CSI), model 107) was used for the MAST measurement at those selected sites by the thermistor sensor method. The
accuracy of the probe, in the worst case scenario, is ±0.4 °C as specified by the manufacturer. The sensor was placed at 50 cm depth below the soil surface and the temperature was recorded every 10 min with CSI CR10 data logger. The recorded data were then averaged to derive the MAST. Under the field temperature range, the precision of the thermistor sensor method is less than 0.1 °C.

The diffusion-cell method described by Trembour et al. (1988) was followed for the measurement of MAST at those selected sites. The temperature sensor was made by separating the water and sodium chloride solution by a hollow sphere of water-permeable plastic putting inside a polycarbonate test tube. After removing the sensor from the ground (50 cm depth), the weight of the water cell was recorded. The MASTs were calculated as:

\[
\text{MAST}(^\circ\text{C}) = \log R + 0.76 / 0.027
\]

where \( R \) is the weight change of the cell (mg day\(^{-1}\)). The diffusion-cell method yields a precision of ±0.2 °C when exposed for one year at temperatures that range from 0 to 40 °C.

2.3. Data analysis

Paired data of MAST, namely measured from the same site and the same year, were used to compare the differences among the three methods. There were data missing. Totally, 157, 301 and 129 paired data were collected for comparison of the Pallmann method with the diffusion-cell method, comparison of the Pallmann method with the thermistor probe method, and comparison of the diffusion-cell method with the thermistor probe method, respectively. The comparisons of these three methods were achieved through SAS for Windows (version 9.0).

3. Results and discussion

3.1. Linearity of the Pallmann method

The correlations between \( \log k \) and the temperature under different solution pH are illustrated in Fig. 2. The data were fitted to the Arrhenius equation (Eq. (4)). The obtained \( \log k \) decreased linearly when the temperature decreased from 35 °C to 0 °C. Theoretically, constants \( a \) and \( b \) should not change with the solution pH. The fitted constant \( a \) varied from 5738 to 6047 with mean = 5916 and standard deviation = 111. The coefficient of variation (CV) of constant \( a \), for pH varied from 1.9 to 4.1, was less than 2% indicating a narrow dispersion of the data (Table 1).

The outcomes were comparable to those reported by Pallmann et al. (1940) and Norton and Friedman (1981) that constant \( a \) varied from 5914 to 5867 with mean = 5846 and standard deviation = 66. The fitted
constant $b$ varied from 16.88 to 19.48 with mean = 17.78 and standard deviation = 0.88. The CV of constant $b$ was less than 5% indicating a narrow dispersion of the data. The outcomes were a little lower than those reported by Pallmann et al. (1940) and Norton and Friedman (1981) that mean = 20.17 and standard deviation = 0.25. The constant $a$ is the intercept of the linear regression. The results suggested that there was a systemic difference between this study and those conducted by Pallmann et al. (1940) and Norton and Friedman (1981). However, in all experiments, the hydrolysis reaction responded to temperature in the same pattern (no significant difference between the slopes of the regression). In all, the linearity of the hydrolysis reaction with respect to temperature was verified.

Based on the experimental data (Fig. 2) and approximation of Eq. (4), the temperature in degrees Celsius (°C) can be empirically obtained from the linear regression equation as:

$$T(°C) = a' + b' \log k$$

where $a'$ and $b'$ are the empirical linear regression constants. By definition of $k'$ as:

$$k' = (1/t) \log [(R_0 - R_w)/(R_t - R_w)]$$

Eq. (7) can be reformatted as:

$$T(°C) = a' + b' (\log k' + pH).$$

In this manner, the data under different pH can be pooled together. Fig. 3 shows the pooled data of the temperature (in degree, °C) in response to the sum of $\log k'$ and pH. The linear correlation was good and the mean temperature (in degree, °C) under known pH can be obtained as:

$$T(°C) = 10.88 - 14.975(\log k' + pH).$$

### 3.2. Consistency and accuracy of the soil temperature measurement methods

The MAST of the monitoring sites varied from approximately 10 °C to over 25 °C (Fig. 4). The MASTs measured by the Pallmann method and diffusion-cell method were comparable (Fig. 4). While the differences between the corresponding measurements varied from −1.01 °C to 1.06 °C, 70% of the MASTs measured by these two methods were apart by ±0.5 °C or less. On average, the MAST obtained by the Pallmann method was lower than that measured with the diffusion-cell method by 0.27 °C.

While both the Pallmann method and the diffusion-cell method measure the mean temperature directly, they are based on quite different principle. The former is based on chemical reaction rate, while the later is based on the diffusion rates of water. It is not unexpected that there is a systemic difference for the measurement of the mean soil temperature.

The MASTs measured by the Pallmann method were generally higher than those measured by the thermistor probe method (Fig. 5). Over 80% of the MASTs measured by the Pallmann method were higher than those measured by the thermistor sensor. While differences of the MASTs measured by the Pallmann method and the corresponding MASTs measured by thermistor sensor varied from −1.72 °C to 2.70 °C, 70% of them differed by ±1.0 °C or less. The MASTs obtained by the Pallmann method were on average higher than those measured with the thermistor sensor by 0.64 °C.

In Pallmann method, the reaction of converting sucrose to glucose and fructose is nonlinear with respect to the soil temperature. An increase in temperature accelerates the cumulative reaction faster than a decrease in temperature of equal magnitude that will decelerate it. Therefore, if the sucrose solution experiences a fluctuating temperature, the reaction will be the same as if the sucrose was exposed to a constant temperature that is higher than the arithmetic-mean temperature. Therefore, it is reasonable that the temperatures measured by the Pallmann method are slightly higher than the arithmetic mean of the probe data (Norton and Friedman, 1981). The MAST estimated by the Pallmann method is consistent and reliable and the outcomes may better reflect the real ecological processes in soil.
The paired MASTs measured by the diffusion-cell method and the thermistor sensor are illustrated in Fig. 6. Most of the MASTs measured by the diffusion-cell method were higher than those measured by the thermistor sensor. The differences of the MASTs measured by the diffusion-cell method and the corresponding MASTs measured by thermistor sensor varied from $-1.14 \, ^\circ C$ to $3.47 \, ^\circ C$. The MASTs obtained by the diffusion-cell method were on average higher than those measured with the thermistor sensor by $1.09 \, ^\circ C$.

Statistical analysis showed that the three paired samples were highly correlated (Table 2). The standard deviations of the three paired group data were almost identical. The slopes of the linear regression were very close to 1, which were $1.033$, $0.993$, and $0.953$ for diffusion-cell vs. Pallmann, thermistor probe vs. Pallmann, and diffusion cell vs. thermistor probe, respectively. The standard errors of the slope coefficient were quite small. The $95\%$ confidence intervals of the difference for these three paired data were quite narrow (Table 3). The results indicated that these three methods were interchangeable and comparable.

4. Conclusions

There are wide selections of devices that may measure the temperature with high resolution, fast response, and remote access. The accuracy and consistency of the mean annual soil temperature measured over a wide spatial scale and over a long temporal period by three methods namely the thermistor sensor, Pallmann sucrose hydrolysis, and sodium chloride diffusion cell were comparable and the methods could be used interchangeably without introducing significant measurement error.

For measuring the mean temperature, a direct method of observation and integration has become feasible and incorporates several distinct advantages. In climate change and ecological investigations, the spatial and temporal coverage are more significant than the speed of the measurement, the Pallmann sucrose hydrolysis and sodium chloride diffusion-cell methods offer economical, reliable, and convenient approaches of collecting mean annual soil temperatures instead of building an electronic sensing network.
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References