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The Influences of Thermal Diffusivity and Weather on Shallow (2-Meter) Temperature Measurements

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Keywords

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ABSTRACT

Multiple measurements of shallow temperatures over time and at multiple depths have been used in combination with surface weather data to better characterize and quantify the effects of thermal diffusivity and weather variations on 2-meter temperature surveys. Shallow soil and rock thermal diffusivities were calculated by measuring the attenuation of the annual temperature wave between depths of 1.5 and 2 meters. The results indicate that thermal diffusivity-induced temperature variations are relatively minor at Desert Peak, typically on the order to 0-1°C at a depth of 2 meters, compared to the strength of the geothermal heat flux signature. The results also confirm that thermal diffusivity effects are minimized in surveys run shortly after the autumn and spring equinoxes, compared with other times of year. The influences of weather patterns are easily seen at a depth of 1 meter but are more negligible at 2 meters, which provides an incentive to conduct surveys at the greater 2-meter depth, as opposed to 1 meter.

Introduction

The Great Basin Center for Geothermal Energy (GBCGE) is continuing research on improving methods for conducting shallow temperature surveys. The basic techniques for conducting shallow temperature surveys was improved by developing a 2m temperature probe system that was relatively low cost in terms of geophysical techniques and was significantly more efficient than previous shallow temperature measurement methods in terms of deployment and temperature equilibration times (Coolbaugh et al. 2007; Sladek et al., 2007). Improvements are continually being made in basic measurements and data analysis. The use of remote sensing has been used to correct for albedo to improve the distinction of geothermal anomalies from solar radiation-related anomalies (Kratt et al. 2009). Digital elevation models allow for correction for the influence of elevation on 2m temperatures (LeSchack and Lewis, 1983; Coolbaugh et al., 2011) and the use of three zone temperature measurements and plotting of shallow temperature gradients helps to verify the character of various anomalies (Sladek et al., 2009).

Recently completed year-long studies at Desert Peak, Churchill County, Nevada are adding to the understanding of these various factors and what corrections or adjustments in survey methods can be made to improve signal to noise ratios. In addition to providing data for testing the above methods, the collection of data over a year-long period has allowed for calculation of thermal diffusivity for a large number of points to help assess the influence of soil properties on geothermal heat flux and shallow temperature measurements, and to help assess the impact of weather changes on 2m temperatures.

Long Term Temperature Methods

A temperature survey consisting of 107 points encompassing a 20 km^2 area was conducted at Desert Peak, NV over a one year period. The survey area was selected to include a range of elevations, slope aspects, and surface albedos, and include the known thermal anomaly of Desert Peak, to facilitate the development of correction techniques for surface radiation and other affects on shallow temperature measurements (Coolbaugh et al., 2011). The collection of data for a period of over one year made it possible to calculate of thermal diffusivity and evaluate its influence on shallow temperature measurements. Weather data was also collected to study the influences of weather on shallow temperatures. Soil properties, primarily soil moisture, were also assessed as a potential significant factor.

Calculation of Thermal Diffusivity

Temperatures measured at shallow depths greater than 1 meter (the approximate maximum depth of penetration of the diel (24-hour) temperature cycle) can be approximated by a sinusoidal annual curve that dampens exponentially with depth (Lange et al., 1982). The collection of temperatures at multiple times over a period of a year thus allows for approximating the subsurface temperature cycle by fitting the data to a sine function (Fig. 1).

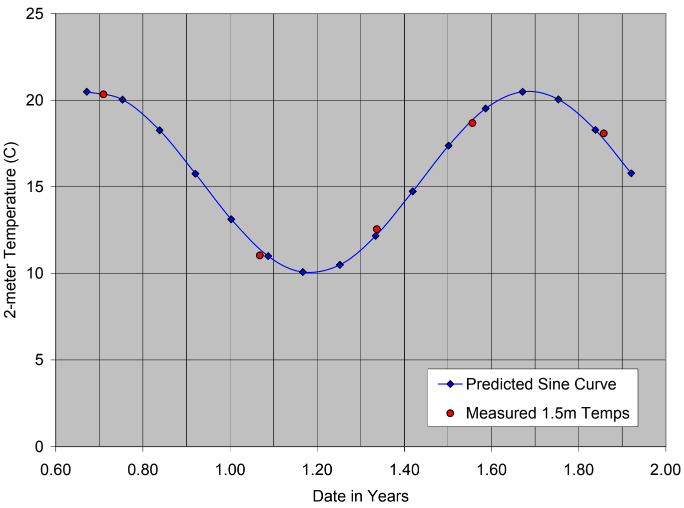

Figure 1. Fitting of five temperature measurements to sine curve for calculation of annual temperature amplitude (maximum minus minimum temperatures) for use in calculating thermal diffusivity. The curve was fit to the data using an iterative least-squares calculation in Excel.

From this curve, the amplitude (maximum minus minimum temperatures) of the annual temperature wave can be calculated.

For this study, annual amplitudes were calculated at depths of 1, 1.5 and 2 meters, which correspond to the depths at which temperatures were measured. Because the shallowest portion, through a depth of about 1.0 m, of the soil profile is more influenced by surface factors including weather (see below), the temperatures at 1.5 and 2m depth were used for thermal diffusivity calculations using the equation below, taken from Jury et al. (1991):

$$K_T = \pi\left[\frac{z_1 - z_2}{\ln[\Delta T(z_1)/\Delta T(z_2)]}\right]^2 / \tau$$

where K_T = thermal diffusivity, z = depth, τ = period of temperature cycle (1 year), and $\Delta T(z_1)$ and $\Delta T(z_2)$ = temperature amplitudes over 1 year at depths z_1 and z_2 respectively.

The calculated thermal diffusivities for 57 locations show a significant range of values (Fig. 2). Comparison of thermal diffusivity with soil properties inferred by geographic distribution indicates, except for the extreme ends of the spectrum, such as saturated soil and bedrock, there exists only a weak correlation. For simplicity, soil at Desert Peak will refer to substrates in which bedrock was not encountered in the top few centimeters. Thermal diffusivity is influenced by the soil or rock composition and water content. Our results support data from Sabin (1978) indicating that bedrock tends to have higher thermal diffusivities than soils (Fig. 2). Soils are dominantly aeolian sand at the surface with locally rocky areas with interstitial sand, and local areas of desert pavement. Several locations were dominated by silty soil and at least one location was in a playa containing silty clay.

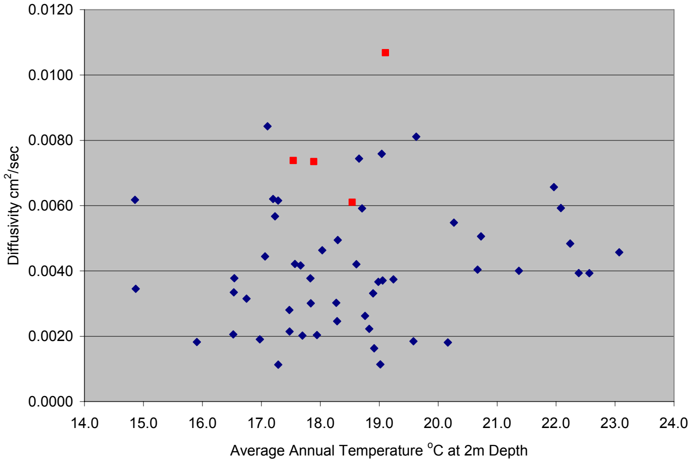

Figure 2. Thermal diffusivity calculated for 1.5 to 2m depth verses average annual temperature for select locations at Desert Peak. Blue diamonds correspond to soils, red squares correspond to bedrock.

Figure 3 shows thermal diffusivities of two hypothetical soils, calculated using the model of Campbell (1985), of a composition that might be expected to be encountered at desert peak. Thermal diffusivity, while dependent on the mineral phase, is highly influenced by soil moisture (Fig. 3). Thermal diffusivity initially rises rapidly with increasing water content and then tapers off to a value specific to the soil composition and water saturation. This is because of the high thermal conductivity of water, which initially increases the thermal conductivity of the soil by increasing the thermal contact between soil particles. As water fills up more of the pore space in the soil, the high specific heat of the water becomes more of a factor, and heat transfer rates are reduced.

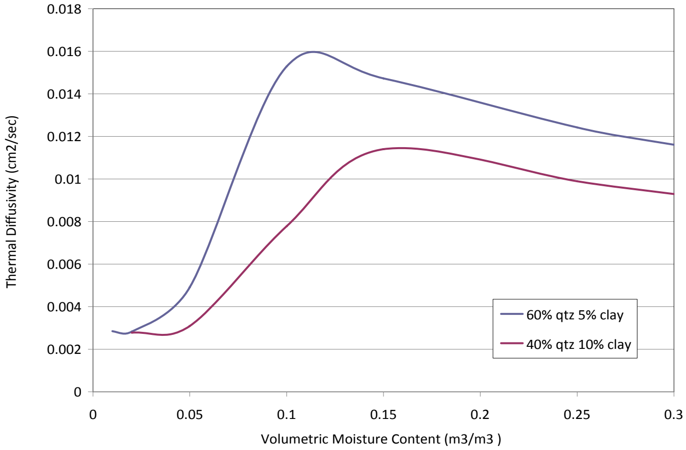

Figure 3. Calculated thermal diffusivities using the method of Campbell (1985) for hypothetical soils showing the influence of composition and water content. Values were calculated for soils containing 60% quartz and 5% clay fraction, and 40% quartz and 10% clay fraction. A bulk density of 1.86 and a porosity of 30% was used for both soils.

The behavior of thermal diffusivity at lower volumetric water mimics the range of values of thermal diffusivity observed at desert peak. We propose therefore, that given the unclear correlation of thermal diffusivities at Desert Peak with geologic or geomorphic features (with the exception of bedrock as noted above), that much of the variation in thermal diffusivities observed may be due to small variations in soil moisture content.

Impact of Thermal Diffusivities on 2-Meter Temperature Surveys

Variations of thermal diffusivity in the field have the potential to create "false" 2-meter temperature anomalies unrelated to

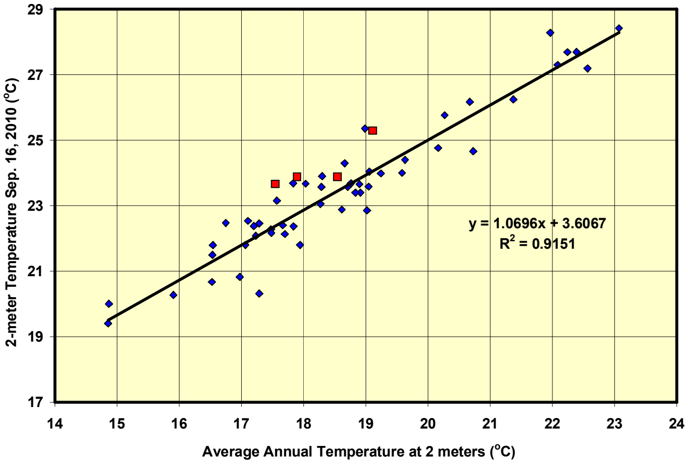

Figure 4. Two-meter temperatures measured in September, 2010 compared to calculated average annual temperatures at the same locations and depth. Blue diamonds correspond to soils while red squares correspond to bedrock. The average absolute temperature difference between Sept. soil temperatures and the linear best-fit line is 0.52°C, while the average difference between bedrock temperatures and the same line is +1.0°C.

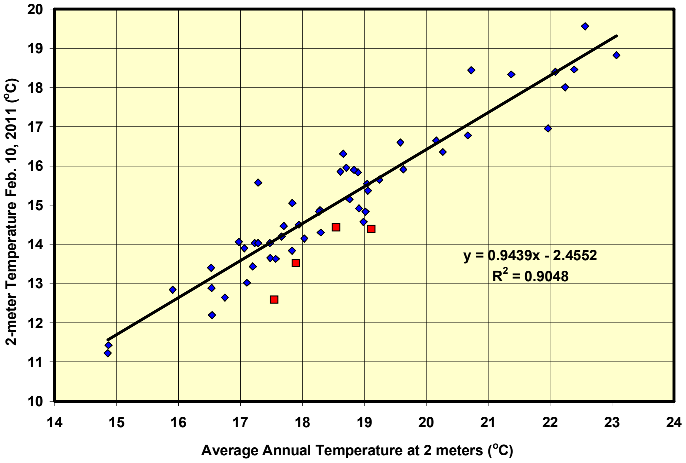

Figure 5. Two-meter temperatures measured in February, 2011 compared to calculated average annual temperatures at the same locations and depth. Blue diamonds correspond to soil while red squares correspond to bedrock. The average absolute temperature difference between February soil temperatures and the linear best-fit line is 0.49°C, while the average difference between bedrock temperatures and the same line is -1.1°C.

geothermal heat flux. For example, in the late summer or early fall, soils or rocks at a depth of 2 meters that have relatively high thermal diffusivities will heat up more quickly than surrounding ground with lower thermal diffusivities, producing higher temperatures when measured in a 2-meter survey at that time of year. In the late winter or early spring, the same area will generate a negative temperature anomaly, because the higher thermal diffusivities allow the soil and/or rock to cool off more quickly than surrounding areas.

One method of evaluating the effect of thermal diffusivity is to compare 2-meter temperatures measured at a given point in time to the average annual temperature at the same sites (Fig. 4, 5, and 6). The average annual temperature, calculated as described above, is independent of thermal diffusivity (assuming that thermal diffusivity remains constant over the course of the year, which is not strictly true). If thermal diffusivities and other factors, such as evapotranspiration, affecting soil heat flux are constant, the data on Figs. 4-6 should plot on a straight line. Departures from the linear correlation are caused by, among other factors, differences in thermal diffusivity, because at different times of year, some areas will heat up or cool down more quickly, than other areas. A maximum temperature "error" associated with thermal diffusivity, assuming all of the error is caused by thermal diffusivity, and not by weather or other factors, can be represented by the difference in the measured temperature and the linear best-fit between the average annual temperature and the temperatures at the time of the survey (Figs. 4-6).

The results from Desert Peak indicate that the impacts of thermal diffusivity variations on 2-meter temperatures are relatively minor. The magnitude of temperature "error" is almost always less than 1°C, and averages about 0.5°C. These differences are relatively small compared to the magnitude of the geothermal temperature anomalies detected at both Desert Peak (up to 10°C, Coolbaugh et al., 2011) and the nearby Desert Queen area (up to 19°C, Coolbaugh et al., 2007; Sladek et al., 2007). A similar conclusion regarding the relatively minor impact of thermal diffusivities was reached for a temperature survey completed at Desert Queen area located northeast of Desert Peak (Coolbaugh et al., 2010).

It is interesting to note that the linear correlation between 2-meter temperatures and average annual temperatures is better for the November survey (Fig. 6) than it is for the September and February surveys (Figs. 4, 5). This could be predicted on the basis that the November temperatures were measured approximately 1-2 months after the autumn equinox (Coolbaugh et al., 2010), at which time the temperature effect produced by thermal diffusivity passes through a minimum as 2-meter temperatures change from hotter to cooler than average. The average absolute temperature "error" measured for soil in November was 0.34°C, compared to 0.52 and 0.49°C, respectively for September and February.

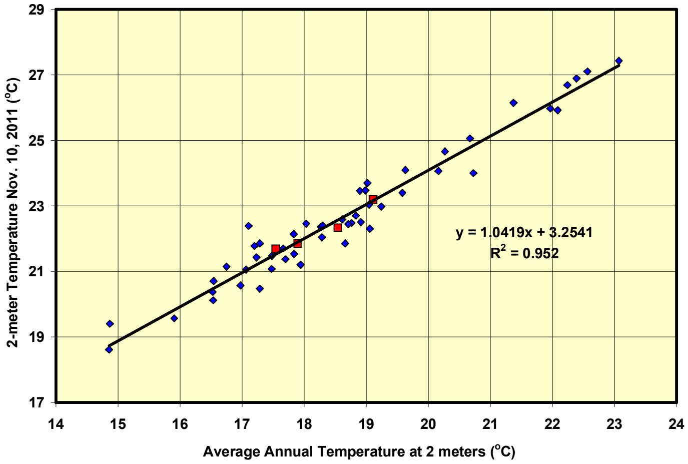

Figure 6. Two-meter temperatures measured in November, 2011 compared to calculated average annual temperatures at the same locations and depth. Blue diamonds correspond to soil while red squares correspond to bedrock. The average absolute temperature difference between November soil temperatures and the linear best-fit line is 0.34°C, while the average difference between bedrock temperatures and the same line is -0.02°C.

Two-meter temperatures measured in bedrock show a similar temperature swing. As predicted on the basis of their higher thermal diffusivities, bedrock temperatures are anomalously high in September, but are anomalously low in February, and are very similar to temperatures of soil in November. Thus, the data corroborate the fact that thermal diffusivity effects are minimized when surveys are run after the spring or fall equinoxes, though in any case, at least for the Desert Peak and Desert Queen areas, the effects of thermal diffusivities on 2-meter temperatures appear to be relatively minimal.

Weather Influences

Daily temperature variations rapidly attenuate with depth and generally have little influence at depths greater than 0.5m. The seasonal drift typically forms a predictable sign wave and is easily corrected for (Fig. 1). But the influences of weather variations are less predictable. As can be seen in Fig. 7, significant variations in air temperature and solar radiation over a period of several days can clearly be seen influencing temperatures at a depth of 1m, but this affect is significantly attenuated by 2m and is difficult to detect at the scale in Fig. 7. But, large changes in surface temperature of several days or longer related to major changes in weather have the potential of influencing 2m temperatures by several tenths of a degree or more, which is well within the resolution at which 2m temperatures are measured. Figure 8 shows the influence of a significant change in air temperatures and solar radiation and its propagation through the soil column. Because of the variations in thermal diffusivity, not all areas may be impacted to the same degree or at the same rate. Differences in seasonal corrections calculated from multiple base stations noted for extensive 2m temperature surveys by researchers at the GBCGE may related to this type of weather behavior.

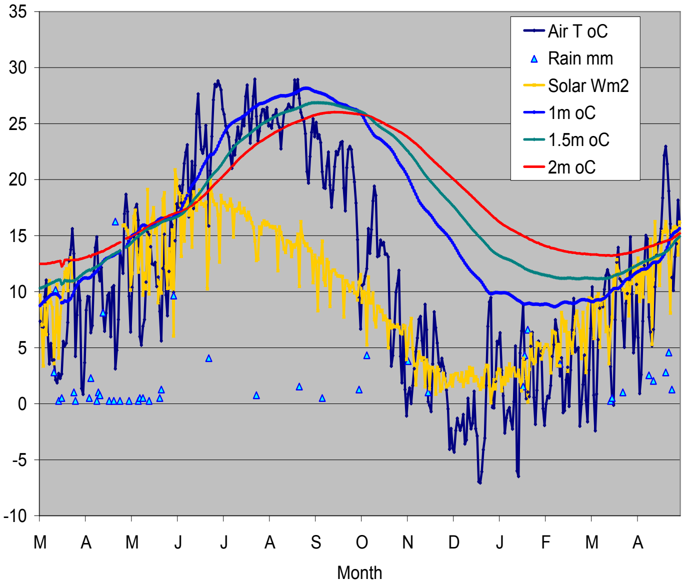

Figure 7. Weather and soil temperature data from March 2011 to May 2012 showing air temperature, precipitation, net radiation, and soil temperatures at 1,1.5 and 2m depth. Significant variations in air temperature and solar radiation are seen resulting in significant noise in the 1m temperature annual curve, but is virtually attenuated out at 2m

Soil Moisture

Significant drops in 2m temperatures, on the order of 4°C or more, are commonly encountered in low-lying areas with high and/or saturated moisture conditions, especially in and near playas in Nevada and California (e.g., Pyramid Lake Paiute Reservation, Coolbaugh et al., 2006; Desert Queen, Coolbaugh et al., 2007; Rhodes Marsh, Kratt et al., 2008), as well as in low-lying areas at Desert Peak. The low temperatures do not appear to be a direct result of moisture-related thermal diffusivity changes, because these low temperatures have been observed at all times of the year. The consistently low temperatures are believed caused either by convective linkage with underlying groundwater or by evapotranspiration effects where significant amounts of vegetation are present. The influence of these low temperatures is usually accounted for in data analysis by considering the geographic context of the survey, such as noting where survey points approach a playa, a low lying area, or an area where vegetation changes suggest higher soil moisture or shallow ground water. Areas such as this, or changes in the surface soil cover such as a transition form sandy to rocky surface or changes in vegetation can typically be accounted for by good field observations and viewing these areas differently during data analysis.

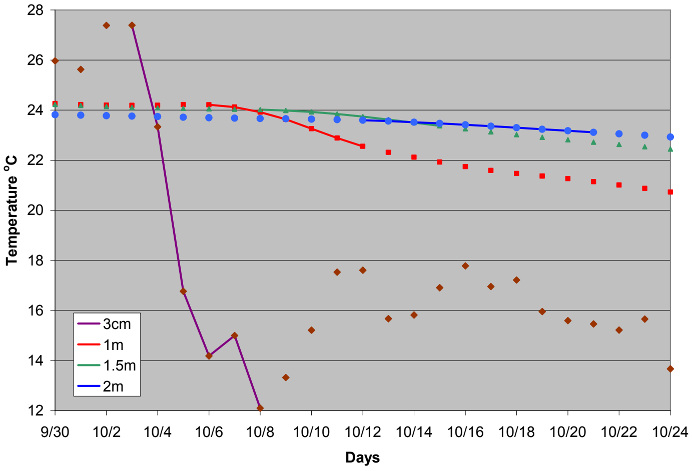

Figure 8. Soil temperatures at 3cm, 1m,1.5, and 2m showing a 15.3 °C weather induced temperature drop over a period of 5 days in soil temperature at 3cm (violet line) propagating through the soil column, at 1m red, 1.5m green and 2m blue lines. This 15.3 °C drop in surface temperature appears to translate to a 0.5 °C temperature change over 9 days at 2m that starts approximately 9 days later. Dots represent data logger temperature points and line segments represent the inferred weather induced temperature change at the specific depth.

Conclusions

Comparison of calculated thermal diffusivity and 2m temperatures at Desert Peak indicate that except for end members such as extremely dry or saturated soils and bedrock locations, thermal diffusivity does not appear to exercise a significant influence on 2m temperatures. This is likely due to the attenuation of short cycle surface temperature excursions at a depth of 2m. Other factors such as proximity to a playa or other significant changes in soil or cover that would suggest significant changes in moisture content or water-saturated conditions, may be addressed in data analysis by extrapolation/interpolation into areas with similar groundwater/vegetation characteristics. The influence of weather can have measurable impacts in the temperatures at 2m, but the effects are typically smaller than most thermal anomalies, and in many cases may be within analytical error of temperature measurements and can normally be considered insignificant. At the Desert Peak area, minor influences were seen approximately 9 days after a significant weather event, and have caused as much as a 0.5 °C change over a period of approximately one week at a depth of 2 meters. The period of delay between a significant weather event and its influence in temperatures at 2m will vary depending on local soil properties such as thermal diffusivity. Large precipitation events will likely influence temperatures at depth to a greater degree and more rapidly than air temperature or solar radiation changes alone because of the transport of heat energy by percolating soil moisture. Because weather influences and differences in thermal diffusivity are sources of at least some noise in 2m temperatures, it is preferable when possible to conduct surveys at times when weather is relatively constant and after the equinoxes. However, it is clear that in many cases these effects are dwarfed by the temperature anomalies produced by geothermal heat flux.

Additional testing using a down-probe thermal conductivity instrument (Coolbaugh et al, 2010) are planned at the Desert Peak area to refine the data collected in this study and learn more about the time-varying nature of soil moisture and its impact on thermal diffusivities.

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