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Influences on shallow ground temperatures in high flux thermal systems

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ABSTRACT

Ground temperature measurements are a useful indication of subsurface processes and heat flux, particularly in volcanic and hydrothermal systems, but obtaining reliable data at sufficient resolution can be difficult. Investigators commonly use temperature measurements at 1 m depths to minimize land surface boundary impacts; however, these measurements are time-consuming and invasive, limiting the number of points that can be surveyed. Alternatively, shallow ground temperature measurements (≤25 cm depth) offer a rapid and minimally-invasive way to collect a large number of observations in a target area. Although this method has obvious appeal, changing atmospheric conditions can impact the observed temperatures, and thus may reasonably be expected to influence interpretations arising from the data. Here we examine the impact of precipitation and changing air temperature on shallow ground temperatures in the vicinity of a group of hot springs located in Yellowstone National Park, Wyoming. We find that the mean, the range, and the skewness of the observed temperatures were decreased by changing atmospheric conditions; however, the model variogram representing data taken after several days of moderate precipitation adequately described the spatial correlation of data taken before precipitation. We therefore conclude that the ability to differentiate between high- and low-flux areas may be somewhat reduced by moderate precipitation and changing atmospheric conditions, but that interpretations made on the basis of characteristics of the inferred variograms are likely to be robust to such perturbations in high heat flux environments.

1. Introduction

Ground temperatures are an inexpensive, versatile, and widely used approach to the investigation of shallow subsurface processes. In the earth and environmental sciences they are often applied to the study of volcanic and/or geothermal systems; for example, they have been used to estimate geothermal heat fluxes (Dawson, 1964; Sorey and Colvard, 1994; Ingebritsen et al., 2001; Hurwitz et al., 2012), to track the development of a geothermal field after a volcanic eruption (Saba et al., 2007), to determine patterns of hydrothermal manifestations on an active volcano (Miller and Mazot, 2013), and to examine structural controls on hydrothermal systems (Anderson and Fairley, 2008; Rissmann et al., 2011). Outside of geothermal and volcanic systems ground temperature measurements have been used to analyze heat transfer in forested valley regions (Kawanishi, 1983), assess slope failure from shallow groundwater (Furuya et al., 2006), and in studies of the relationship between seismic noise and ground temperature (Gordeev et al., 1992). Near surface temperature fields have even been applied to archeological studies; for example, Mori et al. (1999) showed that diurnal ground temperature changes at the Kirui–Otsuka mounded tomb were quantitatively different over the central burial mound in comparison to sites remote from the tomb. Ground temperature measurements have also featured prominently in studies of fault permeability (Fairley and Hinds, 2004b; Fairley, 2009) and fault-controlled hydrothermal circulation (Fairley and Hinds, 2004a).

The majority of ground temperature studies rely on measurements at depths of about 1 m. This depth is chosen to minimize the influence of changing atmospheric conditions—particularly diurnal temperature variations—and arises from the well-known result that the amplitude of periodic temperature variation decreases with depth according to (Carslaw and Jaeger, 1959):

$$A(z) \propto A(z=0)\exp\left(-z\sqrt{\frac{\omega}{2D}}\right), \quad (1)$$

where z is the depth below landsurface [L], A is the amplitude of temperature variation at depth z, D is the soil thermal diffusivity [L^2/T], and ω is the angular frequency [$2\pi/T$]. For a soil with thermal diffusivity of 10^{-6} m^2/s, the amplitude of diurnal temperature changes should therefore have decayed to less than 1% at a depth of 1 m.

The idea of limiting atmospheric influence on measured temperatures is attractive; however, other considerations weigh against such methods. Perhaps most important is that digging or augering a 1 m deep hole requires a considerable investment of time and effort, and the resulting thermal perturbation must dissipate prior to obtaining a representative temperature measurement. Furthermore,

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these observations are relatively intrusive, and may be frowned upon or even prohibited in sensitive areas (e.g., national parks, wilderness areas). Because of the time- and labor-intensive nature of 1 m depth measurements, there is a limit to the number of points that can be obtained, and data collection may be restricted in some areas.

In an effort to circumvent some of the more restrictive aspects of 1 m deep temperature measurements, some researchers have used ground temperature observations from shallower depths, typically in the range of 15–25 cm. The use of shallow temperature surveys was pioneered by Dawson (1964), who developed an empirical relationship between shallow (15 cm) ground temperature measurements and heat flow through soils in the Wairakei hydrothermal system in New Zealand. The investigator recommended the use of 1 m depth temperature measurements for relatively low heat flow areas in which heat transfer is dominated by conduction, citing the work of Thompson (1960). In higher heat flow areas dominated by convective heat transfer, the investigator proposed the use of temperature measurements at a depth of 15 cm, and gave an empirical formula relating heat flow, H (in units of cal/m^{2}s), to the temperature in degrees Celsius at 15 cm depth (T_{15}) (Dawson, 1964):

$$H = 1.24T_{15}^4 \times 10^6. \quad (2)$$

The Dawson (1964) formula (i.e., Eq. (2)) was later modified to account for the effects of elevation by Sorey and Colvard (1994) for use in Lassen Volcanic National Park (Ingebritsen et al., 2001), where those investigators developed a comprehensive heat flow budget for the Lassen volcanic system.

More recently, some investigators have favored shallow (≤25 cm) ground temperature measurements for investigations in geothermal areas because the shallow depth of penetration and short equilibration times allow the collection of hundreds or thousands of data points in a day (e.g., (Fairley and Hinds, 2004a, 2004b; Heffner and Fairley, 2006; Anderson and Fairley, 2008). The cited studies reported measurements at high resolutions (generally between 1 × 1 to 5 × 5 m spacing) over domains ranging up to 100 × 800 m. These relatively large, spatially-referenced and high-resolution data sets may be useful for developing spatial-statistical representations of the underlying generating process(es) (Anderson and Fairley, 2008), or inferring aspects of the near-subsurface fluid flow paths (Fairley and Hinds, 2004a; Fairley and Nicholson, 2006). In addition, the method is minimally invasive, and may often be allowed in areas where the augering of even a few 1 m deep holes would be prohibited.

In spite of the obvious attractions of shallow temperature surveys, the fact that changing atmospheric conditions perturb subsurface temperatures raises questions about the robustness of inferences made on the basis of shallow temperature measurements. In the present study, our goal is to examine the extent to which patterns of shallow ground temperatures are impacted by precipitation and changing atmospheric conditions in an area of relatively high heat flux, located in the Morning Mist Springs area of the Yellowstone caldera. We find that changing environmental conditions in our study area reduced the mean and the range of measured temperatures, as well as decreasing the skewness of the measured data. However, an analysis of kriging residuals before and after a series of precipiation events demonstrated that the model variogram representing the shallow temperature distribution was not particularly sensitive to variations in the surface boundary condition.

2. Site description

The study area is located in Yellowstone National Park, northwestern Wyoming (Fig. 1). The Park is located in the Yellowstone Plateau Volcanic Field (YPVF), which is part of the most recent string of large calderas formed along the Snake River Plain over the past 17 million years (Pierce and Morgan, 1992; Hurwitz and Lowenstern, 2014) from the migration of the North American Plate over the Yellowstone hot spot (Pierce and Morgan, 1992; Love et al., 2007). The YPVF is home to a large hydrothermal system, the surface expression of which comprises over 10,000 hydrothermal features, including fumaroles, geysers, mud pots, thermal springs, and hydrothermal explosion craters (Hurwitz and Lowenstern, 2014). Almost all of the heat, and a considerable fraction of the noncondensible gases, discharged on the YPVF are derived from the underlying magmatic source and transported through the shallow hydrothermal system (Hurwitz and Lowenstern, 2014; Lowenstern et al., 2015).

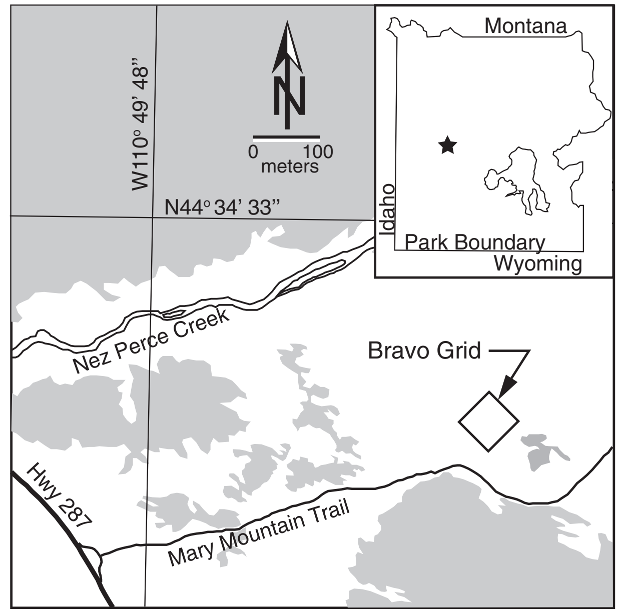

Fig. 1. Location map of the study area. The study area is one kilometer along the Mary Mountain Trail from the trailhead on Route 287 in Yellowstone National Park. The approximate location of the study area within the Park is marked by a star on the inset.

The present study took place in the Lower Geyser Basin, near the western entrance to the Park. We measured spring and shallow ground temperatures in the vicinity of spring LCBNN159 (Rodman and Guiles, 2008), which is actually a group of six small thermal springs (one main spring and five smaller, subsidiary springs) located about 60 m off the Mary Mountain/Nez Perce Creek Trail, about 1 km east of the trailhead on Highway 287 (Fig. 1). The springs are positioned in a large, open meadow, just to the north of a line of small hills, in an area of sparse vegetation that is consistent with a high conductive heat flux. Surficial deposits in the area consist of white to light brownish-gray diatomaceous silt deposited in flat, marshy areas (Muffler et al., 1982); away from the thermal springs, surficial deposits consist of gray to light brown, moderately- to well-sorted unconsolidated sands and gravels interpreted to be outwash from the Pinedale glaciation (Muffler et al., 1982). Details of the regional geology are given in Pierce and Morgan (1992) and Love et al. (2007). The Yellowstone hydrothermal system is described in Hurwitz and Lowenstern (2014), and the geology specific to the study site is summarized in Lubenow (2015).

3. Methods and analysis

3.1. Data collection

We measured ground temperatures in a 72 × 72 m area, with the main spring LCBNN159 approximately centered in the grid. For identification purposes we called the grid "Bravo" to differentiate it from other temperature grids in the same area (Lubenow, 2015). The study area's small spatial extent allowed a high density of