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Geothermal climate change observatory in south India 1: Borehole temperatures and inferred surface temperature histories

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ABSTRACT

Temperature–depth profiles measured in boreholes contain records of changes in surface ground temperature over the past few centuries. We have recently set up a geothermal climate change observatory at the Choutuppal campus of National Geophysical Research Institute (17.29 °N, 78.92 °E) to measure subsurface temperature changes on annual to decadal timescales and quantify how well they track surface temperature changes. The site is located about 60 km to the east of Hyderabad in south India, in a designated reserved forest land and far from potential urban heat islands. In April 2009, two boreholes were drilled to depths of 210 m and 21 m respectively after careful site selection to minimize perturbations to the subsurface temperatures on account of groundwater flow in the borehole, large thermal conductivity contrasts and rugged topography. Temperature measurements in the two holes are being carried out periodically. Analysis of equilibrium temperature–depth profile in the 210 m deep borehole reveals at least two ongoing events that started during the past Century: (i) surface ground warming of 0.5 ± 0.1 °C over the past 92 ± 7 years, and (ii) a more recent cooling of ~1 °C over the past ~39 years, probably representing local changes to surface vegetation caused by the presence of a thicker grass cover throughout the year inside the campus since 1967 AD compared to the short cropping of grass outside it. The inferred surface ground warming is consistent with estimates from temperature measurements in three other boreholes (170–300 m deep) distributed in a 10×5 km^2 area in the vicinity of the observatory (mean: 0.5 ± 0.1 °C over the past 93 ± 21 years), and is characteristic of the Interior Peninsula region of south India.

1. Introduction

Under ideal conditions, a temperature–depth (T–z) curve representing the subsurface temperature regime below a depth of ~20 m, at which the effect of diurnal and annual changes in ground temperature are absent, should show a simple linear increase in temperature. The rate of increase (i.e., the geothermal gradient) would be governed by the outward heat flow to the surface from geological causes and the thermal conductivity of the rock layer in which the linear increase is seen. The intercept of the linear section of such a temperature–depth graph would correspond to the present-day mean annual ground temperature at the surface. The mean annual ground temperature at the surface is generally considered to be ~1 °C higher than the mean annual surface air temperature. However with the long-term changes in the mean surface air temperature that have taken place in the past, concomitant changes in ground temperature at the surface have taken place. The diffusion of such ground temperature changes into the subsurface is a natural physical consequence. The result is, not a simple linear increase in temperature with depth, but a systematic departure from linearity, generally to depths of 150–300 m. A typical T–z profile from south India is shown in Fig. 1.

The subsurface transient temperature perturbations $\Delta T(z,t)$ (observed in the upper part ~20–160 m of the T–z profile) satisfy the one-dimensional heat diffusion equation (Carslaw and Jaeger, 1959),

$$\frac{\partial^2 \Delta T(z,t)}{\partial z^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad (1)$$

where z is depth (positive downward) and α is the thermal diffusivity of the Earth medium. With appropriate initial and boundary conditions, solutions to Eq. (3) provide a basis for interpreting the curvature in the subsurface temperature field in terms of SGT variations. The deeper part of the profile then satisfies Laplace's Law (i.e. steady-state) given by:

$$\frac{\partial^2 T}{\partial z^2} = 0 \qquad (2)$$

The thermal gradient dT/dz in the deeper part of the T–z profile (160–300 m) is unaffected by transient perturbations and reflects

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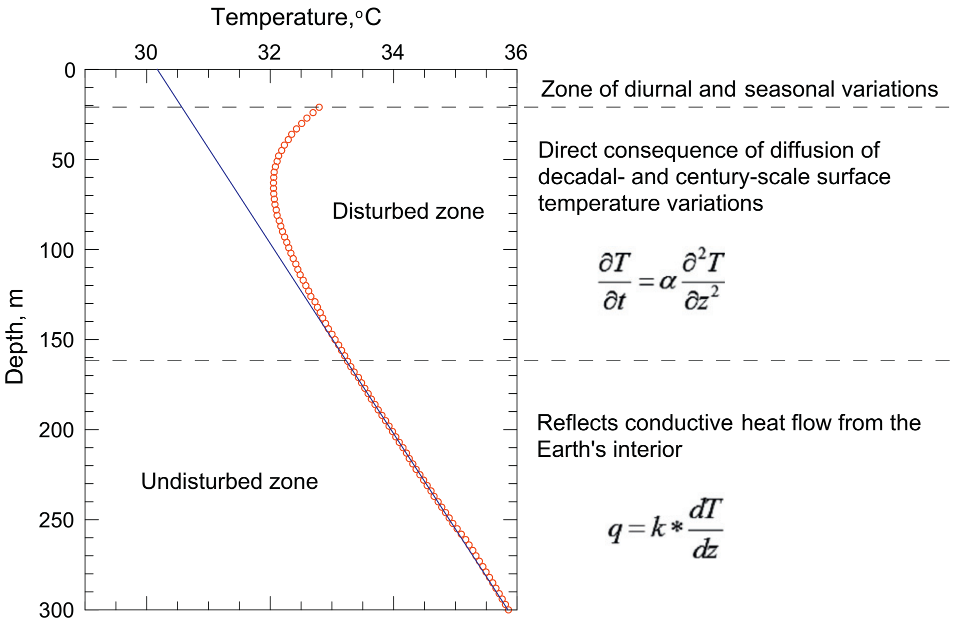

Fig. 1. A typical borehole temperature–depth profile (open circles) showing (i) the zone affected by diurnal and seasonal variations of surface temperature, (ii) the zone affected by decadal- and century-scale surface temperature variations, and (iii) the zone unaffected by transient perturbations, reflecting the steady-state heat flow from the interior of the Earth by conduction. The solid line represents the background temperature gradient based on a linear fit to the deeper portion of the data. The intercept of the background temperature gradient on the temperature axis is a measure of the mean annual surface ground temperature at the site. [T: temperature; t: time; z: depth; α: thermal diffusivity; q: heat flow; k: thermal conductivity].

the steady-state heat flow from the interior of the Earth by conduction according to Fourier's Law:

$$\frac{dT}{dz} = \frac{q}{k} \tag{3}$$

where q is heat flow and k is thermal conductivity.

The depth to which equilibrium temperatures are perturbed in a given time is governed by the thermal diffusivity of the Earth medium. For typical rocks, a thermal front (e.g., a 5% change) propagates to about 15 m in 1 year, 160 m in 100 years, and 500 m in 1000 years. Therefore, the surface ground temperature (SGT) history of the Earth over the last millennium is captured in the uppermost 500 m of the crust. The Earth thus acts as a recorder of past surface temperature variations and these records can be effectively used for constraining temperature trends prior to the occurrence of instrumental meteorological records and in areas where there is a paucity of instrumentally recorded data. The shape of the perturbation reveals details of the surface ground temperature history. Positive temperature perturbations signify past warming; negative anomalies indicate cooling.

The SGT histories provided by the geothermal method are now widely recognized as a valuable supplement to established climate proxies (National Research Council, 2006). Analyses of temperature–depth data from several hundred boreholes distributed in continental areas worldwide have brought forth the following salient results (Lachenbruch and Marshall, 1986; Chapman et al., 1992; Huang et al., 2000; Harris and Chapman, 1997, 2001; Roy et al., 2002; Beltrami et al., 2003; National Research Council, 2006; Harris, 2007): (i) Widespread warming has taken place during the most recent Century and cooler conditions prevailed for the four prior centuries. (ii) The magnitude of warming from 1850 to 1990 is estimated to have been approximately 0.7 °C ± 0.2 °C, consistent with the instrumental record. (iii) Surface ground temperature reconstructions from geothermal records have decadal- to century-scale resolution and thus provide information about long-term temperature trends, but not about annual variations. (iv) Combined analysis of borehole temperature–depth (T–z) profiles and SAT records from meteorological stations in the Northern Hemisphere yields a long-term pre-observational mean temperature, 0.6–0.7 °C lower than the 1961–1990 mean SAT.

The underlying assumption in these studies is that the subsurface temperature changes track the surface air temperature (SAT) changes with time and that heat transport within the subsurface is conductive. Climatic interpretations of surface ground temperature (SGT) reconstructions also assume that SGT is strongly coupled to surface air temperature (SAT) on timescales of decades and longer. Although a few observational studies on a limited scale have attempted to address similar questions (e.g., Baker and Ruschy, 1993; Vernekar et al., 2002), the first systematic study was started only in 1993 at a site in northwest Utah (Putnam and Chapman, 1996; Bartlett et al., 2006). A few other studies were initiated in the early years of this Century (Cermak et al., 2000, 2010; Beltrami, 2001; Smerdon et al., 2004). All of those studies are being carried out at sites located in the high latitude (north of 40 °N) regions. Some sites have additional complications due to presence of snow over several months each year.

We set up a geothermal climate change observatory at Choutuppal (17.29 °N, 78.92 °E), near Hyderabad in south India, where both subsurface temperatures as well as surface (meteorological) variables are being measured since July 2009. The observatory is the first of its kind in the low latitude region. In this paper, we report on (a) the selection of the site and set-up of the borehole observatory, (b) temperature measurements in a specially drilled borehole to depth of 210 m within the observatory and other boreholes of opportunity in its vicinity, and (c) data analyses for reconstruction of surface ground temperature history at the site. In a companion paper (Akkiraju and Roy, 2011), we report on the set-up of the weather station at the same site and the datasets obtained during the first few months of operation.

2. Observatory set-up

2.1. Site selection

The selection of our observatory site was guided by two primary requirements: (i) a remote and rural location to minimize