# Ground surface warming in peninsular India: evidence from geothermal records

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**Analyses of borehole temperature profiles provide useful information about regional climate change over a few centuries. Data from 146 borehole sites in the crystalline terrain of peninsular India were used to reconstruct surface ground temperature history. Depths of the boreholes ranged from 150 to 1522 m. The temperature profiles were characteristic of heat flow by conduction, being largely unaffected by perturbations due to groundwater flow. The profiles show temperature anomalies in the top few hundred metres that is consistent with changing surface temperature over the past two–three centuries. Analysis of individual profiles for a ramp change in temperature reveals predominant surface ground warming in peninsular India with a mean magnitude of 1.0 ± 0.2°C for 129 ± 18 years at 95% confidence level corresponding to onset *ca* 1860 AD for the change.**

**Keywords:** Borehole temperatures, ground temperature history, peninsular India, surface air temperature.

METEOROLOGICAL surface air temperature (SAT) records obtained from a worldwide network of stations provide unambiguous evidence of warming over the past 150 years[1,2]. However, to constrain surface temperature change and climate variability over the past millennium for which direct observations are unavailable, proxy indicators of temperature change, such as tree rings, sediment cores, ice cores and corals[3–11] are considered. Reconstruction of surface temperature from conventional proxy indicators provides high temporal resolution, but it cannot resolve low frequency components or provide a long-term mean temperature. Moreover, the proxy records only provide an indirect measure of temperature and therefore require additional calibration. On the other hand, borehole temperature–depth profiles, down to a few hundred metres, provide a direct measure of changing surface ground temperature averaged over a much longer period[12–15]. The geothermal signature is a result of thermal diffusion process; the earth efficiently and continuously filters the short-period surface temperature changes on diurnal and annual timescales while retaining a record of the long-term mean and the departures from it[12]. Recent observational studies demonstrate the strong coupling between surface temperature changes and transient anomalies gleaned from borehole temperature profiles[16]. In this way, borehole temperature–depth data complement surface air temperature and multi-proxy reconstructions of climate change.

Analyses of several hundred borehole temperature profiles distributed mainly in the Northern Hemisphere have revealed important information regarding past climate change[11,14,15]. The salient features are[11]: (i) Majority of geothermal climate change studies are based on data from the mid-latitude band in the Northern Hemisphere. (ii) The last century experienced widespread warming compared to cooler conditions in the four prior centuries. (iii) The magnitude of warming from 1850 to 1990 is estimated to be approximately 0.7 ± 0.2°C, consistent with the meteorological surface air temperature records. (iv) Reconstructions of surface ground temperature (SGT) from geothermal records have decadal- to century-scale resolution and thus constrain the long-term temperature trends, but not the annual or sub-annual scale variations.

In the recent past, borehole temperature profiles from different climatic provinces in India were studied to infer past climate change. Roy *et al.*[17] studied the database of borehole temperature profiles in India and analysed 70 temperature profiles on the basis of well-established criteria. The data covered six major climatic provinces[18]: interior peninsula (IP), east coast (EC), west coast (WC), north-central (NC), north-east (NE) and north-west (NW). Analyses of data revealed mean warming of 0.9 ± 0.1°C with onset ~1850 AD. Akkiraju and Roy[19] made a detailed study of temperature–depth data obtained from a specially drilled borehole located near Hyderabad in the Interior Peninsula and found the regional warming consistent with other parts of the IP province. They also found signature of recent cooling attributable to land-use change in the vicinity of the borehole during the past few decades. Another study[20] compiled new data from south India and analysed it together with the previous dataset from south India. Combined data analysis from 74 sites yielded a mean warming of 0.9 ± 0.3°C with onset centred around 1850 AD.

In the present study, data from 146 sites selected according to criteria adopted previously[20], were analysed to infer the past climate change in peninsular India. The dataset includes those from previous studies[17,20] and new data from Koyna in WC province and Choutuppal area near Hyderabad in IP province. Clearly, the IP and WC provinces have better coverage when compared to the other provinces. Nevertheless, the 146 temperature profiles together provide a compelling dataset to cover the low latitude range 8°–29°N, which is under-represented in geothermal climate change studies. Importantly, the

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present data set is unaffected by complications due to both snow cover and variable insolation when compared to higher latitudes in the Northern Hemisphere where north-facing slopes receive less insolation than south-facing slopes. All borehole sites of the present study are shown in Figure 1.

The temperature distribution in the earth is controlled by the outward flow of heat through conduction following Fourier's law and the temperature condition at the surface $z = 0$. Temporal changes in surface temperature diffuse downward into the subsurface, causing transient temperature perturbations $\Delta T(z, t)$ that can be represented by the one-dimensional heat diffusion equation[21]

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

where $z$ is the depth (positive downward) and $\alpha$ is the thermal diffusivity of the earth. The transient temperature perturbations manifest as a curvature in the upper part of a temperature profile. With suitable initial and boundary conditions, solutions to eq. (1) allow an interpretation of the transient perturbations in terms of temperature changes at the surface with time.

In practice, the background thermal field is isolated from the climatically perturbed regime in individual temperature–depth profiles. The residual transient temperatures or reduced temperatures thus obtained at each depth, $\Delta T_R(z)$ is given by

$$\Delta T_R(z) = T(z) - [T_0 + gz], \tag{2}$$

where $T_0$ and $g$ are surface temperature intercept and temperature gradient respectively. $g$ and $T_o$ are estimated through a least square regression of the temperature–depth observations. The method is illustrated using a typical temperature–depth profile obtained from precise measurements[22] in a borehole located in Pavagada area in Karnataka (Figure 2 *a*). The corresponding reduced temperature profile is shown in Figure 2 *b*. Inversion of the reduced temperature profile yields estimates of surface ground temperature history. While different models for surface temperature change are possible, a ramp model is adopted to maintain consistency with previous studies from India[17,19,20]. This method emphasizes first-order variations in the reduced temperature profiles and provides a robust estimate of recent change in surface ground temperature.

The model is parametrized in terms of a temperature change of magnitude $\Delta T$ and a duration time $t^*$ expressed as[12]

$$\Delta T(z) = 4\Delta T i^2\text{erfc}\left(\frac{z}{\sqrt{4\alpha t^*}}\right), \tag{3}$$

where $i^2$erfc is the second integral of the complimentary error function. A uniform thermal diffusivity ($\alpha$) of $10^{-6}$ m$^2$ s$^{-1}$ is assumed throughout this analysis for consistency.

Reduced temperature profiles for all 146 borehole sites are plotted in Figure 3. The great majority of borehole sites reveal positive reduced temperatures that extend down to 200 m depth whereas a few profiles extend deeper to about 300 m. Following a simple rule of thumb, typical thermal diffusion time associated with 200 m depth is ~300 years. Overall, 88% of boreholes show positive reduced temperatures, indicating predominant ground surface warming in peninsular India during the past three centuries. Reduced temperature profiles from 18 borehole sites, mostly restricted to a few localities, reveal negative reduced temperatures indicating local surface cooling.

The ramp amplitudes and time durations obtained from inversion of individual reduced temperature profiles are shown as histogram plots in Figure 4. The mean amplitude for the sites that show warming is $1.3 \pm 0.1$°C at 95% level of confidence. Duration times for warming at individual sites show much greater variation compared to amplitudes, from a decade or two at the short time scale to centuries at the long time scale. The remaining 18 profiles show local cooling, with a mean of $-1.2 \pm 0.6$°C for a duration of $84 \pm 33$ years at 95% level of confidence. Many of these sites show significant cooling during the recent past, likely due to local site conditions such as irrigation and land-use changes[19,20]. Overall, the inter-site variability is large (3.6°C to –4.3°C), possibly attributable to the widely varying physiographic conditions as

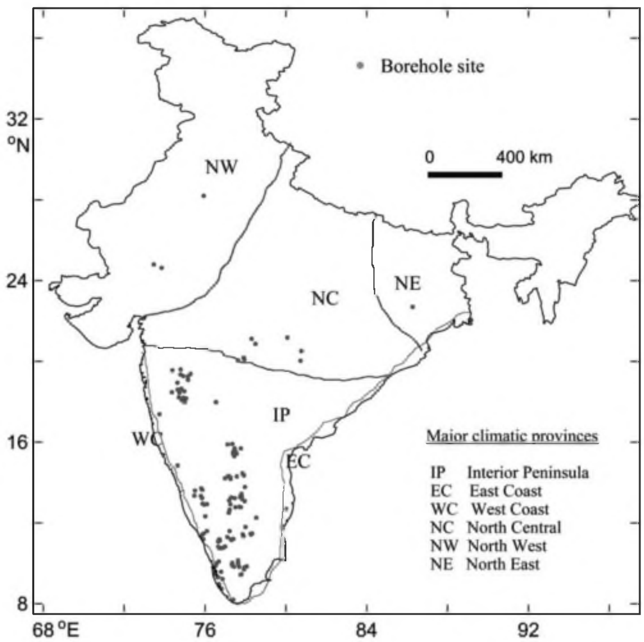


**Figure 1.** Outline map of India showing the distribution of 146 borehole sites (filled black circles) studied. Major climatic provinces[18] are also shown.

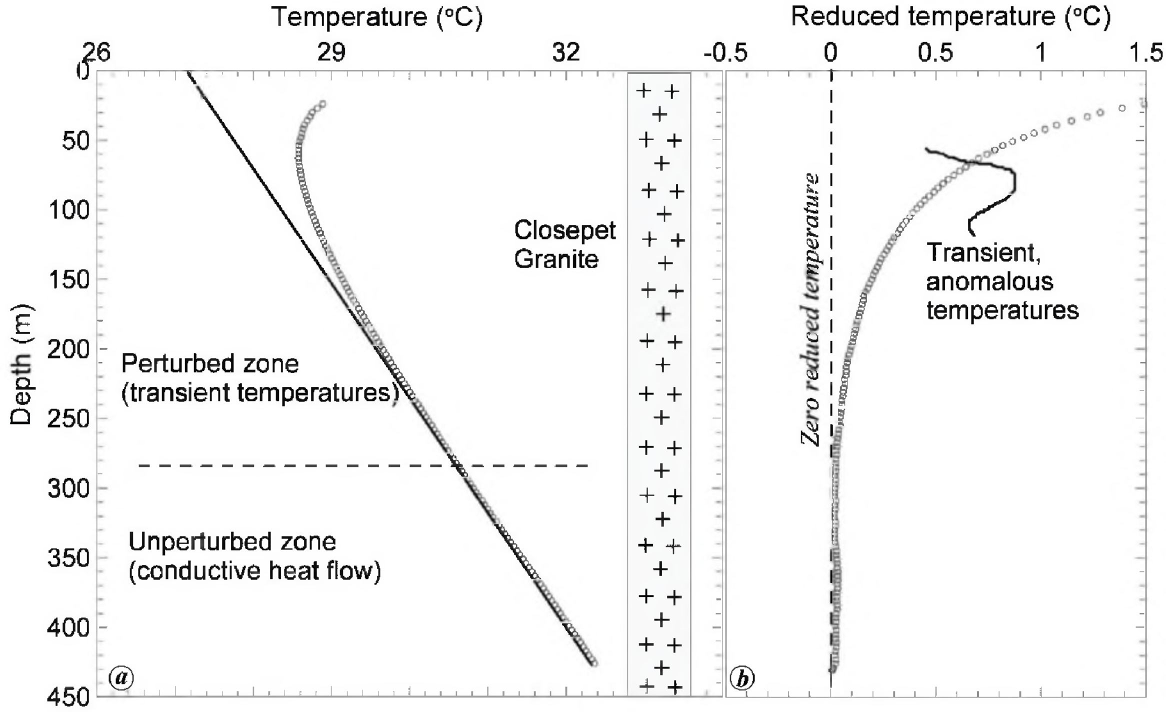


**Figure 2.** ***a***, Temperature–depth profile (open circles) measured in a borehole passing through Closepet Granite formation in Pavagada, Karnataka. Background thermal regime is shown by black solid line. ***b***, Reduced temperature profile (open circles) calculated by subtracting the background thermal regime from the measured temperatures. The dashed line corresponds to zero reduced temperature.

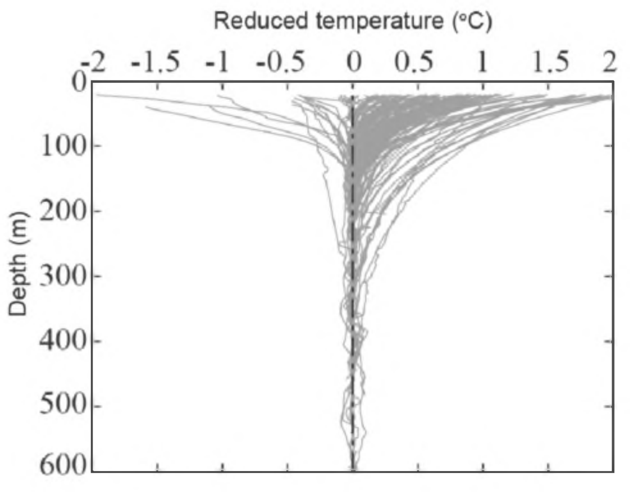


**Figure 3.** Reduced temperature–depth profiles for all 146 boreholes studied.

well as site-to-site changes in microclimatic conditions. When all 146 sites in peninsular India are considered, the mean amplitude is 1.0 ± 0.2°C and the mean duration is 129 ± 18 years at 95% level of confidence corresponding to onset in the 1860s. Thus, the present study provides unambiguous evidence for ground surface warming generally during the past two centuries over a large region in peninsular India.

It is instructive to compare the surface temperature change obtained from analyses of geothermal data with the SAT data from meteorological stations in the region that are available extensively since 1901 AD. Mean annual SAT data for 49 meteorological stations in peninsular India for the period 1901–2006 was obtained from India Meteorological Department. The SAT dataset shows large inter-site variability, comparable to the borehole temperature dataset. Therefore, the average of SAT time series from all 49 stations in peninsular India was considered (Figure 5 *a*). The mean annual SAT anomalies computed with respect to the 1961–1990 mean and averaged over 49 meteorological stations yield a linear trend of 0.5 ± 0.2°C/100 years (95% confidence limit for the mean). For consistency in comparison, all 146 reduced *T–z* profiles in peninsular India shown in Figure 3 are also averaged. The mean reduced temperature profile is inverted for a SGT history in terms of a ramp change in surface temperature, which yields 0.9 ± 0.02°C during the past 151 ± 8 years (Figure 5 *b*). Thus, the average long-term trends in surface temperature obtained from analyses of geothermal and meteorological SAT records are generally comparable. The geothermal record, however, extends farther back in time than the SAT record. The slightly larger magnitude of recent warming inferred from borehole temperatures could be attributed to the fact that the earth records the sum total of surface temperature

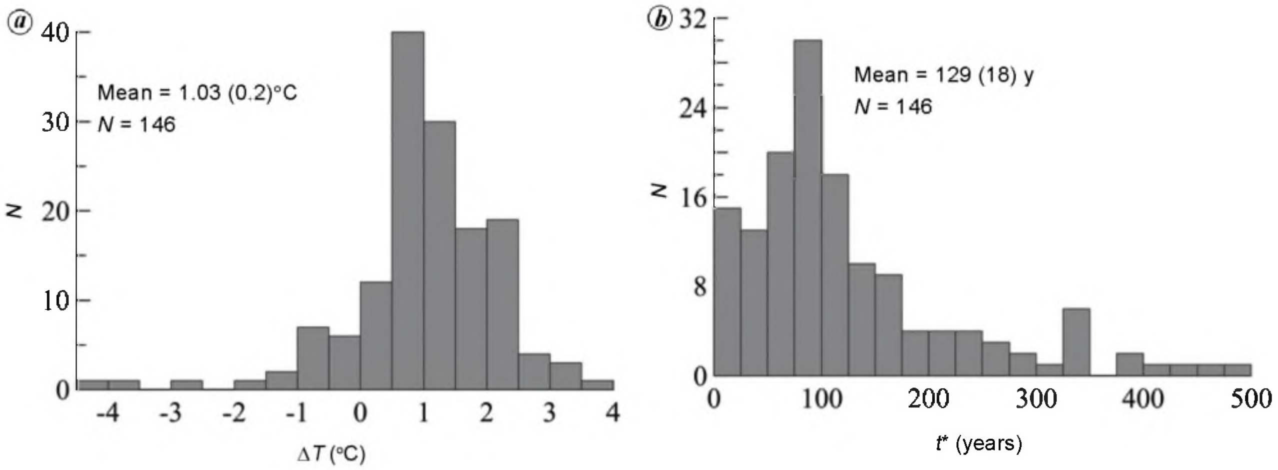


**Figure 4.** Histograms showing the distribution of (***a***) ramp amplitudes ($\Delta T$) and (***b***) duration times ($t^*$) obtained from analysis of 146 borehole temperature–depth profiles in peninsular India. Mean values, along with 95% confidence limits (in parentheses) are shown for each distribution.

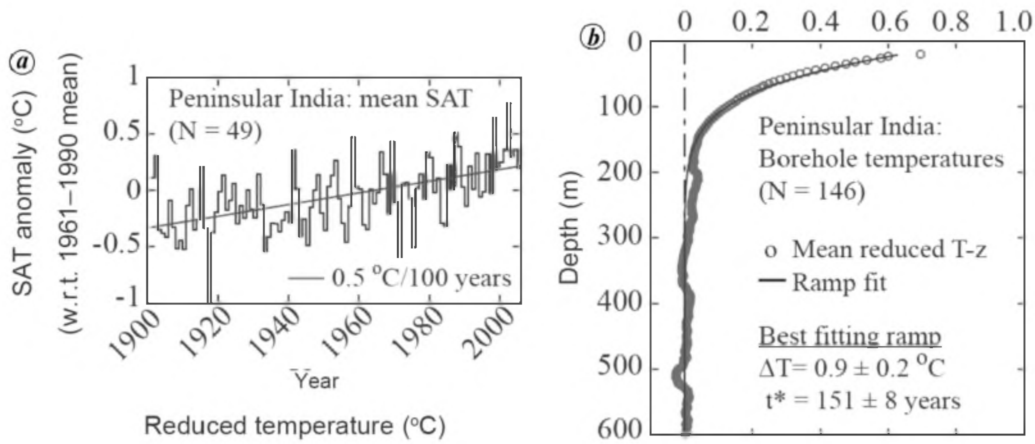


**Figure 5.** ***a***, Plot showing surface air temperature anomalies computed with respect to the 1961–1990 mean and averaged over 49 meteorological stations in peninsular India for the period 1901–2006. ***b***, Mean reduced temperature profile for peninsular India computed by averaging borehole data from 146 sites (open circles) and the best fitting ramp model (solid line).

variations that took place since a much longer time than the instrumental records. Also, the resolution of individual events from geothermal records is poorly constrained. Nevertheless, the study reinforces the benefits of geothermal records in providing independent evidence for ground surface warming in the past, extending prior to the availability of SAT records.


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# Bank material characteristics and its impact on river bank erosion, West Tripura district, Tripura, North-East India

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**In West Tripura district, river bank erosion becomes very common during monsoons along the Haora River and the Sonai Gang. Erosion occurs across 45.39 km (96% of the total length) of the Haora River and 20.12 km (90% of the total length) along the Sonai Gang. The main cause of river bank erosion in the district is the nature of bank material with respect to its erodibility factor (resisting force). The objectives of this study were to identify the nature of bank material of the rivers in West Tripura district and to analyse the shear strength of these materials. Samples were collected from twelve sites at various depths from top of the river bank up to the water level. Hydrometer test and grain size were also analysed. Uniformity coefficient ($C_u$) and coefficient of curvature ($C_c$) were calculated to identify the shear strength of bank soil. Tests revealed that the bank soils contain more than 90% sand and less percentage of silt and clay. This makes the soil non-cohesive and leads to maximum erosion.**

**Keywords:** Bank erosion, bank material, grain size, shear strength, West Tripura district.

RIVER bank erosion is a dynamic process which affects the concave side of the bank, while the eroded materials are dropped on its opposite side[1]. It is usual for a river to meander in its middle course, however, in many places the rate of erosion is amplified owing to hydraulic processes[2]. This is common in the mature stage when the river becomes sluggish and wanders[3]. Lateral shifting is evident from asymmetric shape of the river valley which also represents its spatio-temporal change[4].

In the West Tripura district, river bank erosion becomes very common during monsoons along the Haora River and the Sonai Gang (a stream). Here erosion occurs along 45.39 km (96% of the total length) of the Haora River and 20.12 km (90% of the total length) along the Sonai Gang. The main causes of river bank erosion are erodibility and erosivity that are considered the resisting and driving forces respectively. The variables of

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