Borehole temperatures and climate change: Ground temperature change in south India over the past two centuries

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[1] Seventy-five borehole temperature-depth profiles in south India, located between 8° and 15°N, are analyzed to infer past changes in surface ground temperature. Solutions for a linear surface temperature change indicate average warming of about 0.9 ± 0.3°C over the past 127 ± 25 years at the 95% level of confidence for the entire data set, albeit with considerable geographic variability. Some sites in a restricted region exhibit surface ground temperature cooling during the last 50 to 100 years while a number of other borehole sites show large surface warming amplitudes in the range 1–3°C with onset times during the last few decades to less than a Century. Such rapid changes may represent effects of local land use changes superimposed on the long-term climate change. Results of borehole analysis do not support a latitude effect in climate change. A set of 28 meteorological surface air temperature (SAT) records, distributed in the three major climatic provinces (Interior Peninsula, West Coast and East Coast) in south India yield an average warming trend of 0.6 ± 0.2°C/100 years over the period 1901–2006 for which records exist. Combined analysis of borehole temperatures and SAT data yields a long-term, pre-observational mean temperature (baseline) 0.6 ± 0.1°C lower than the 1961–1990 mean SAT. With an additional 0.35°C of warming beyond the 1961–1990 mean, the total warming from the ~1800 baseline is 0.95°C. Given multiple uncertainties, we consider the 0.9°C of warming from borehole temperature inversion and 0.95°C of warming from the hybrid borehole temperature-SAT analysis to be consistent if significant warming occurred in the 19th Century, prior to the onset of SAT records. The present data set together with the set of 70 temperature profiles in India analyzed earlier constitute an extensive documentation of climatic warming for the low latitude region 0°–20° N that was previously under-sampled in global geothermal climate change studies.

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1. Introduction

[2] Variations in surface ground temperature (SGT) at the Earth's surface diffuse downward in a predictable way causing systematic perturbations to the subsurface temperature field. The pioneering study of *Lachenbruch and Marshall* [1986] in Alaska demonstrated that present-day borehole temperature-depth profiles have the potential to reveal a surface ground temperature history over past several decades to a few centuries. Through the process of heat diffusion the Earth acts as a low-pass filter and a recorder of past surface temperature variations. Borehole temperature-depth profiles thus serve not only to complement the meteorologic record of climate change, but also provide important constraints on temperature trends prior to the occurrence of a global instrumental meteorological record (i.e., ~1860 A.D.) and in areas where there is a paucity of instrumentally recorded data.

[3] The technique for analysis of borehole temperature and meteorological records in deciphering past climate change is now established, and studies have been carried out in several regions of the globe, wherever suitable data are available [see, e.g., *Harris and Chapman*, 2001; *Huang et al.*, 2000; *Beltrami et al.*, 2003]. *Harris and Chapman* [1997] further demonstrated that a combined analysis of borehole temperature records and meteorological surface air temperature records is able to establish long-term pre-observational mean temperatures (i.e., prior to the occurrence of instrumental station records). Using borehole and meteorological data for the northern hemispheric midlatitude region, they estimated a pre-observational mean temperature (POM) of −0.7°C relative to the 1961–1990 mean surface air temperature. Their data, however, were concentrated in the latitude band 30 to 60°N.

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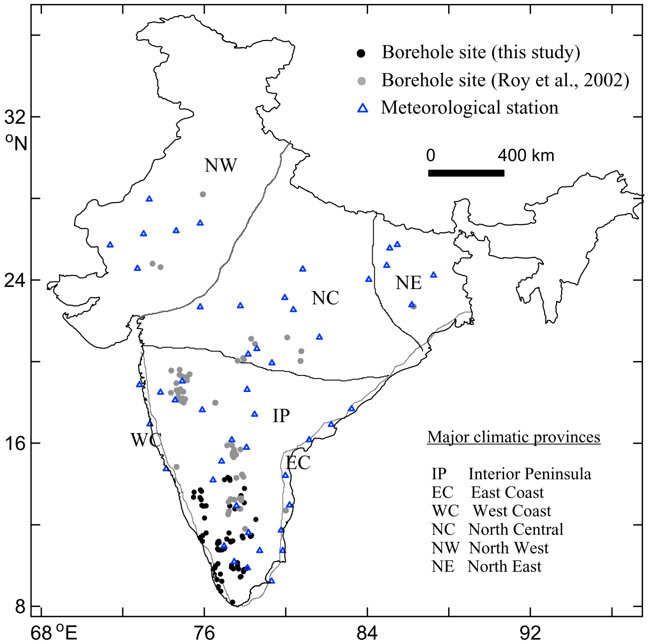

Figure 1. Outline map of India showing the distribution of borehole sites (filled black circles) and meteorological stations (open triangles) used in the present study. The borehole locations of the previous study [*Roy et al.*, 2002] are shown by filled gray circles. Major climatic provinces after *Hingane et al.* [1985] are indicated.

[4] The first extensive study in low latitudes was carried out using 70 temperature-depth profiles from India, distributed in five major climatic provinces and covering the latitude range 12°–28°N [*Roy et al.*, 2002] (Figure 1). The study provided evidence for a mean warming of 0.9° ± 0.1°C in surface ground temperatures over the past ~150 years. Furthermore, combined analysis of borehole temperature data and meteorological surface air temperature (SAT) data indicated a long-term, pre-observational mean (POM) temperature 0.8° ± 0.1°C lower than the 1961–1990 mean SAT. The significantly low POM relative to the 1961–1990 mean SAT suggest that the warming trends observed in the SAT records represent significant increases from the pre-instrumental (19th century) conditions.

[5] In the present study, we analyze a set of 75 additional borehole temperature-depth (T-z) profiles distributed in the latitude band 8°–15°N in south India for evidence of past surface ground temperature variations. The present data set, together with the set of 70 T-z profiles from India analyzed in the previous study [*Roy et al.*, 2002] constitute an extensive compilation for the low latitude band 0°–30°N (Figure 1). We also summarize the climate change results based on SAT records from 28 meteorological stations and carry out a combined analysis of borehole and SAT records to investigate trends in south India prior to the widespread recording of SAT data.

2. Borehole Temperature-Depth Data and Analysis

[6] Borehole temperature-depth data from over 100 sites distributed in the Precambrian hard rock terrain of south India have been acquired during the period 1997–2008 as part of systematic heat flow investigations. These include measurements in 14 "dedicated" heat flow boreholes that were carefully sited in areas of low groundwater yield and relatively homogeneous rock type. The great majority of the measurements were made in boreholes drilled for groundwater exploration, many of which were either dry or poor-yielding, and were abandoned or unused for at least 3 months and up to few years prior to logging. Thus, while all temperature measurements are free from drilling-induced perturbations and represent equilibrium conditions, measurements in a few boreholes may contain artifacts caused by fracture-controlled groundwater flow in them.

[7] Temperature data were acquired at intervals of 3 m in each borehole by manually lowering a calibrated, 1 KΩ thermistor probe and measuring the transducer resistance to a precision of 0.1 Ω using a Wheatstone bridge. Our recent measurements (since year 2008) employ a Hart Scientific CHUB E4 data logger. The temperature precision is typically ±3 mK, but comparisons of multiple and repeated temperature-depth logs in boreholes show that temperatures are generally reproducible to better than 20 mK [*Roy and Rao*, 2000; *Roy et al.*, 2002].

[8] We screened the borehole data using the same criteria as those adopted in the previous study by *Roy et al.* [2002]. These are: (1) boreholes should intersect rocks with relatively uniform thermal conductivity to avoid misinterpreting thermal gradient variations; (2) boreholes should be located in low-relief crystalline terrains to minimize topographic and fluid flow effects; and (3) temperature-depth profiles should have no visible features that are related to groundwater movement. An additional requirement for geothermal climate change studies is the need to separate the background thermal regime from the climatically perturbed regime. Thus we also require T-z logs to extend to at least 150 m. Of the available T-z profiles, 75 profiles which met our criteria were selected for analysis.

[9] Locations of the boreholes used in the present study are shown by dark solid circles in Figure 1. For completeness, the borehole locations of the previous study [*Roy et al.*, 2002] are shown by gray solid circles; major climatic provinces [*Hingane et al.*, 1985] are also indicated. Sites addressed in this study are limited to the southern part of India between 8°N and 15°N latitudes and covering the three states of Karnataka, Tamil Nadu and Kerala. The majority of the boreholes are distributed in the Interior Peninsula climatic province; a few lie in the proximity of the West Coast province whereas the East Coast province is unrepresented.

[10] Figure 2 is a complete set of T-z profiles from the 75 sites. Because annual temperature variations extend to a depth of about 20 m, temperatures in the top 20 m are not useful for extracting decade to century scale ground temperature perturbations. Therefore, these temperatures have not been plotted. The deeper portions of the profiles show systematic increase of temperature with depth reflecting the upward flow of heat from the Earth's interior toward the surface by conduction under steady state conditions. A constant temperature gradient g is identified below a depth z_{top} at each site as a background thermal gradient, which when extrapolated to the surface yields a temperature intercept T_0 (Table 1). Temperatures in the uppermost 100 to 300 m, depending on the site, depart from the linear

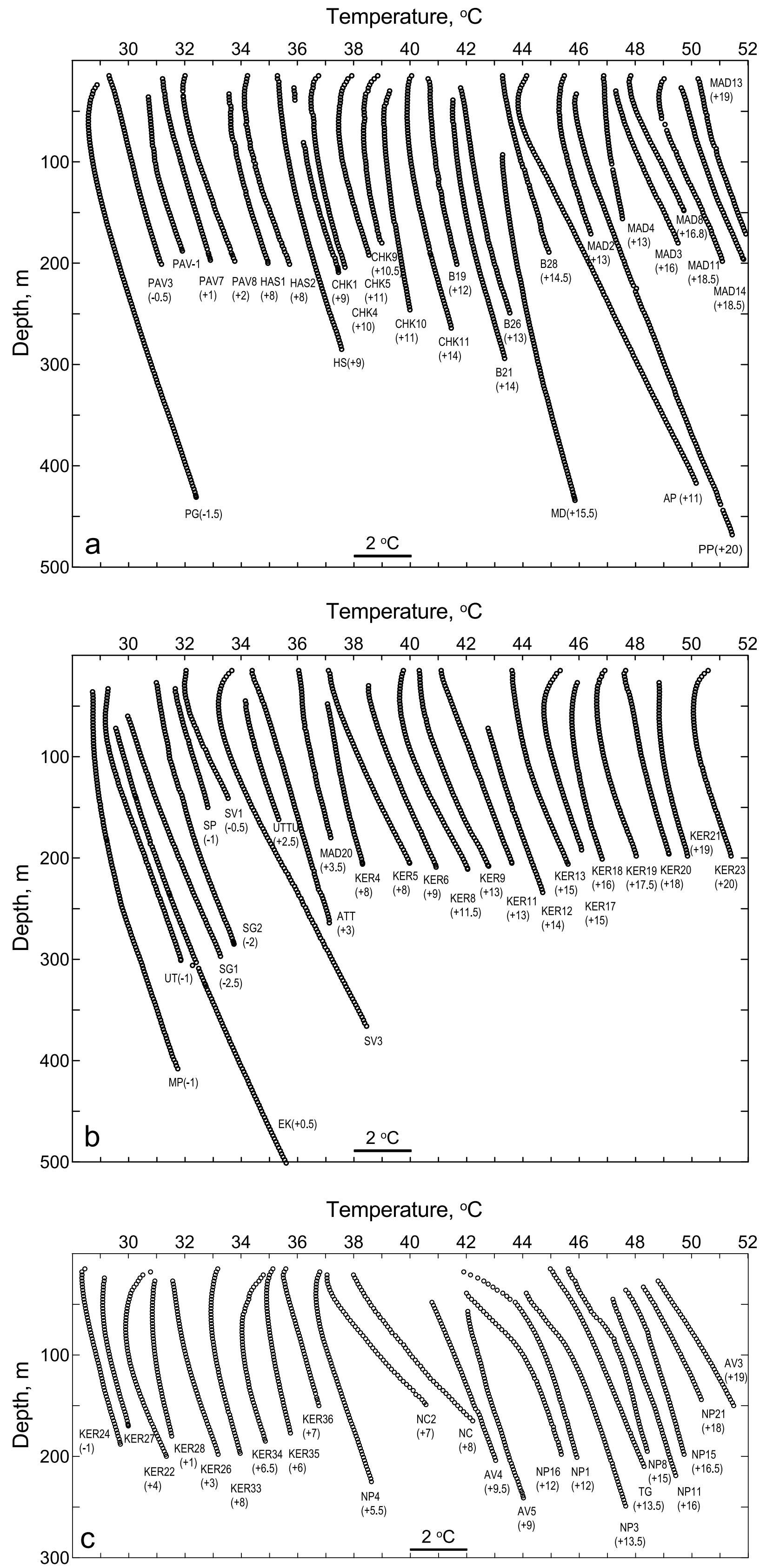

Figure 2. (a, b, c) Plots of temperature-depth profiles from 75 sites in south India analyzed in the present study. Borehole identification numbers are indicated at the bottom of each profile, together with horizontal temperature offsets (in °C) to avoid overlap.

Table 1. Borehole Site, Temperature-Depth Profile and Inversion Details[a]

Location, Borehole	Longitude (°E)	Latitude (°N)	Log Year	Ramp Inversion							Data Reference[c]
				z_{top}[b] (m)	g (mK m^{-1})	T_0 (°C)	ΔT (°C)	t^* (years)	RMS (mK)	Onset Year	
Pavagada, PAV8	77°09′02″	14°18′58″	2002	165	13.4	29.1	0.9	72	0.007	1930	5
Pavagada, PAV1	77°14′39″	14°16′09″	2002	165	12.7	29.5	1.7	113	0.029	1889	5
Pavagada, PG	77°09′37.3″	14°12′20.5″	2005	255	12.3	28.6	1.9	207	0.022	1798	5
Pavagada, PAV7	77°15′30″	14°10′45″	2002	117	11.0	29.8	0.5	47	0.004	1955	5
Bangalore, B28	77°58′18″	13°46′58″	2000	57	10.6	28.4	0.4	28	0.015	1972	1
Chikmagalur, CHK9	75°48′25″	13°42′51″	2002	132	8.3	27.0	1.5	98	0.022	1904	1
Chikmagalur, CHK10	75°51′30″	13°38′33″	2002	156	6.3	27.5	1.2	78	0.015	1924	1
Chikmagalur, CHK1	75°29′50″	13°36′10″	2002	162	12.2	25.9	1.0	177	0.029	1825	1
Bangalore, B26	77°48′15″	13°25′30″	2000	213	11.7	27.6	1.3	334	0.045	1666	1
Chikmagalur, CHK4	75°27′57″	13°21′02″	2002	171	11.2	25.4	1.3	166	0.023	1836	1
Chikmagalur, CHK5	75°47′20″	13°20′02″	2002	150	11.3	25.4	1.8	84	0.012	1918	1
Chikmagalur, CHK11	75°51′13″	13°14′03″	2002	216	10.4	24.7	1.4	197	0.010	1805	1
Bangalore, B21	77°57′51″	13°04′37″	2000	201	10.5	26.3	1.5	227	0.023	1773	1
Hassan, HAS1	75°53′02″	12°57′02″	2002	153	11.8	24.6	1.2	104	0.017	1898	1
Hassan, HS	76°05′32.1″	12°55′59.7″	2005	225	11.9	25.2	1.2	270	0.015	1735	1
Magadi, MD	77°14′53.8″	12°55′5.1″	2005	318	9.9	26.1	2.0	497	0.018	1508	5
Hassan, HAS2	75°56′52″	12°54′44″	2002	129	13.4	25.0	1.4	95	0.019	1907	1
Bangalore, B19	77°30′02″	12°46′51″	2000	150	8.6	27.9	0.9	140	0.019	1860	1
Piriyapatna, PP	76°00′51.5″	12°19′47.3″	2008	324	14.7	24.6	1.0	337	0.031	1671	1
Uttangarai, UT	78°32′04″	12°15′52″	1997	108	12.8	29.0	1.7	89	0.032	1908	3
Kalpetta, KER33	76°05′10″	11°36′00″	2002	138	10.1	24.0	1.5	85	0.012	1917	1
Attayampatti, ATT	78°01′56″	11°32′25″	1998	36	10.8	31.3	−0.4	14	0.015	1984	2
Namagiripettai, NP11	78°19′30″	11°29′	1998	144	11.1	31.0	−0.8	153	0.020	1845	4
Namagiripettai, NP16	78°16′20″	11°28′05″	1998	171	11.2	31.2	−4.3	93	0.051	1905	4
Vettizhinjathottam, KER34	75°55′07″	11°27′55″	2002	153	11.4	26.3	2.9	85	0.016	1917	1
Namagiripettai, NP4	78°17′	11°27′50″	1998	117	12.5	30.3	1.3	42	0.006	1956	4
Namagiripettai, NP3	78°15′	11°27′36″	1998	204	11.6	31.3	−2.9	104	0.032	1894	4
Namagiripettai, NP1	78°15′	11°27′36″	1998	162	10.0	31.9	−3.6	51	0.028	1947	4
Namagiripettai, NP8	78°18′50″	11°27′30″	1998	108	9.6	31.5	−1.9	89	0.076	1909	4
Namagiripettai, NP15	78°16′	11°27′30″	1998	162	9.9	31.3	−1.0	82	0.016	1916	4
Namagiripettai, NP21	78°15′00″	11°27′20″	1998	123	15.6	30.1	−0.7	89	0.012	1909	4
Tiruchengodu, TG	77°51′38″	11°26′22″	1997	93	14.7	31.7	−0.9	42	0.008	1955	2
Sankari, SG1	77°51′36″	11°25′48″	1998	225	15.6	31.1	1.0	257	0.012	1741	3
Sankari, SG2	77°52′48″	11°24′56″	1998	210	14.2	31.7	1.3	271	0.026	1727	3
Kakkur, KER35	75°49′18″	11°23′08″	2002	150	8.8	28.2	1.0	81	0.009	1921	1
Chelapuram, KER36	75°47′51″	11°20′12″	2002	30	10.2	28.2	0.0	210	0.010	1792	1
Sevagoundapalayem, SP	78°09′05″	11°20′23″	1998	57	10.8	32.2	0.8	13	0.007	1985	2
Nallagoundampalayam (Uthukuli), UTTU2	77°25′58″	11°11′40″	1998	126	12.5	30.8	1.1	58	0.006	1940	2
Malappuram, MP	75°54′32.2″	11°11′17.8″	2008	273	12.2	27.7	2.4	396	0.043	1612	1
Melechundapatti, KER28	76°42′34″	11°11′21″	2002	138	8.6	29.0	1.3	94	0.016	1908	1
Avinashi, AV5	77°16′39″	11°11′21″	1998	195	12.9	31.9	0.9	214	0.015	1784	3
Avinashi, AV4	77°15′25″	11°10′24″	1998	156	13.2	30.9	−0.4	226	0.015	1772	2
Chavadiyur, KER27	76°40′04″	11°09′39″	2002	120	10.1	28.3	1.3	60	0.011	1942	1
Avinashi, AV3	77°17′	11°09′36″	1998	132	18.8	29.7	−0.7	95	0.017	1903	2
Kottathara, KER24	76°42′02″	11°08′17″	2002	144	10.7	28.7	0.6	119	0.011	1883	1
Kottathara, KER23	76°40′56″	11°07′56″	2002	129	12.3	28.0	1.9	65	0.013	1937	1
Vattulukki, KER26	76°43′38″	11°07′54″	2002	141	12.8	27.7	1.1	112	0.020	1890	1
Chittur, KER22	76°39′17″	11°03′55″	2002	159	16.0	24.1	3.2	99	0.022	1903	1
Vattapara, KER19	76°58′69″	10°49′36″	2001	144	13.3	27.9	1.7	100	0.017	1901	1
Akkathethara (Palghat), KER21	76°38′55″	10°49′26″	2002	153	10.5	28.8	1.4	117	0.022	1885	1
Kerampara, KER18	76°52′49″	10°46′17″	2001	165	11.8	28.4	1.9	133	0.017	1868	1
Palghat, KER20	76°41′35″	10°45′54″	2002	159	11.2	29.0	0.6	190	0.030	1812	1
Para, KER17	76°46′17″	10°45′28″	2001	153	12.3	28.7	2.1	53	0.011	1948	1
Devadanapatti, MAD20	77°37′38.4″	10°08′12″	1997	138	9.1	32.0	0.6	78	0.011	1919	4
Nadukani, KER13	76°40′15″	10°05′25″	2001	162	15.5	27.4	1.4	132	0.031	1869	1
Bodi, MAD14	77°20′49″	10°01′	1997	135	15.7	30.3	0.8	130	0.021	1867	4
Aundipatty, AP	77°37′32″	09°59′39″	1999	66	17.6	31.8	2.4	21	0.015	1978	3
Vadakkanmaradi, KER12	76°33′30″	09°59′10″	2001	153	13.1	27.7	1.0	111	0.009	1890	1
Muvattupuzha, EK	76°32′10.1″	09°57′33.3″	2005	315	16.2	26.9	1.9	634	0.031	1371	1
Palkalainagar, MAD4	78°03′	9°55′36″	1997	93	7.2	32.4	0.6	60	0.012	1937	4
Sankarapuram, MAD13	77°19′54″	9°54′48″	1997	102	13.2	30.7	0.7	61	0.016	1936	4
Onakkur, KER11	76°31′00″	09°53′30″	2001	39	13.5	27.8	0.0	20	0.006	1981	1
Nilayur, MAD3	78°03′42″	9°51′18″	1997	102	17.0	30.5	0.8	49	0.009	1948	4
Odaipatty, MAD11	77°25′48″	9°50′42″	1997	51	15.6	29.5	1.9	17	0.020	1980	4
Mallapuram, MAD8	77°40′54″	9°49′48″	1997	45	17.5	30.4	1.1	12	0.011	1985	4
Thirali, MAD2	77°56′42″	9°48′12″	1997	153	12.8	31.2	1.4	85	0.007	1912	4
Anaikal, KER9	76°47′15″	09°34′30″	2001	150	18.6	25.9	1.5	139	0.021	1862	1
Sivakasi, SV3	77°47′42″	09°27′43″	1998	126	18.8	31.6	2.4	83	0.017	1915	3

Table 1. (continued)

Location, Borehole	Longitude (°E)	Latitude (°N)	Log Year	Ramp Inversion z_{top}[b] (m)	g (mK m^{-1})	T_0 (°C)	ΔT (°C)	t^* (years)	RMS (mK)	Onset Year	Data Reference[c]
Sivakasi, SV1	77°47′22″	09°26′04″	1998	87	17.3	31.6	1.3	29	0.008	1969	3
Chenganur, KER4	76°37′15″	09°18′20″	2001	159	10.0	28.3	0.9	160	0.020	1841	1
Koni, KER8	76°51′25″	09°13′55″	2001	135	18.9	26.6	2.0	88	0.017	1913	1
Kundara, KER6	76°41′20″	08°58′	2001	171	16.0	28.6	1.0	67	0.009	1934	1
Tottakadu, KER5	76°48′25″	08°44′15″	2001	144	18.2	28.3	0.8	116	0.010	1885	1
Nagercoil, NC2	77°23′39″	08°11′41.9″	2005	108	35.4	28.3	1.7	58	0.023	1947	1
Nagercoil, NC	77°23′39″	08°11′41.9″	2008	120	35.6	28.4	1.4	102	0.029	1906	1

[a]Abbreviations: g, gradient; T_0, zero-depth (surface) intercept of linear fit; ΔT, magnitude of ramp change of surface temperature over a duration time t*; RMS, root mean square misfit between reduced temperature profile and ramp fit.

[b]Start depth of T-z profile used for computation of background temperature gradient.

[c]References: 1, S. Roy et al. (manuscript in preparation, 2012); 2, *Roy et al.* [2003]; 3, *Ray et al.* [2003]; 4, S. Roy et al., unpublished data, 1995; 5, *Roy et al.* [2008].

profile, identifying a temperature anomaly that is likely caused by changing surface temperature over the last two centuries, and is often termed as the transient component of the profile.

[11] The subsurface transient temperature perturbations $\Delta T(z,t)$ satisfy the one-dimensional heat diffusion equation [*Carslaw and Jaeger*, 1959],

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

where z is depth (positive downward) and α is the thermal diffusivity of the Earth medium. With appropriate initial and boundary conditions, solutions to equation (1) provide a basis for interpreting the curvature in the subsurface temperature field in terms of surface ground temperature variations.

[12] For constant thermal conductivity, the transient perturbations can be isolated from the background thermal gradient based on a linear fit to the deeper portion of the data. We chose the depth of minimum absolute curvature in the T-z profile as the depth to the start of the linear fit. Because we are only removing a constant gradient from the T-z profile and it is the subsurface curvature that is mapped into the surface ground temperature variations according to equation (1), this step does not remove any climatic signal below the start depth to the linear fit.

[13] Reduced temperatures at each depth, $T_R(z)$ are defined as,

$$T_R(z) = T(z) - [T_0 + gz] \quad (2)$$

where T_0 and g are a surface temperature intercept and thermal gradient, respectively, fit to data from the deeper part of each borehole. A composite of reduced temperature profiles for all 75 boreholes is given in Figure 3. This composite plot is useful to show both predominant behavior of the transient temperatures and also the outliers. The majority of boreholes exhibit positive reduced temperatures that extend to a depth of about 150 m; the thermal diffusion time associated with this depth is roughly 175 years. Four boreholes also show positive reduced temperatures but with both greater magnitude and greater depth extent; the depth extent of the reduced temperature anomaly suggests an origin other than current climate change. Eleven sites show negative reduced temperatures indicating cooling at the surface. Most of those sites are located in Namagiripettai area of Tamil Nadu state. Their profiles depart from background starting between depths of 50 m and 100 m that indicate surface temperature changes within the last 50–80 years. This variability in reduced temperatures is a common feature in studies elsewhere [*Harris and Chapman*, 1998, 2001; *Roy et al.*, 2002]; it may be caused by local and regional variations in climate change, or by local ground surface effects such as land use changes.

[14] To quantify estimates of recent ground temperature change, we invert the reduced temperature profiles for a surface ground temperature history. There are many possible inversion techniques that have been applied to this problem [*Shen and Beck*, 1991; *Clow*, 1992; *Wang*, 1992; *Mareschal and Beltrami*, 1992; *Harris and Chapman*, 1995; *Huang et al.*, 2000]. We choose to model the reduced temperature profiles in terms of a linear or ramp change in surface temperature as did *Lachenbruch and Marshall* [1986] in their seminal study of borehole temperatures in Alaska. This approach is identical to that of *Roy et al.* [2002] and provides consistency in comparing results for India.

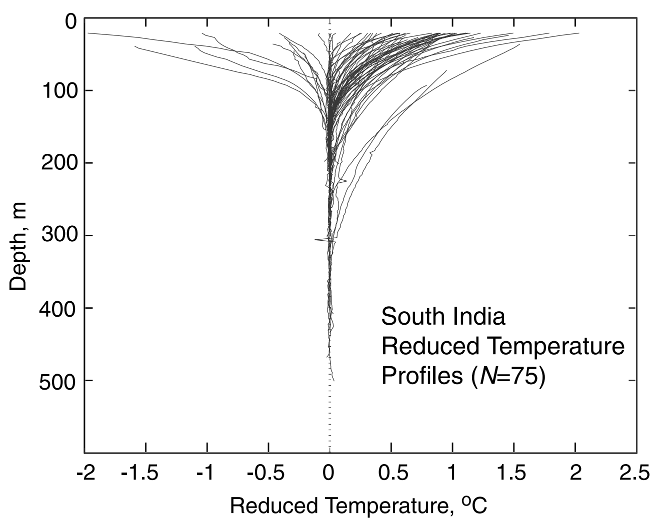

Figure 3. Reduced temperature-depth profiles for all 75 boreholes of the present study.

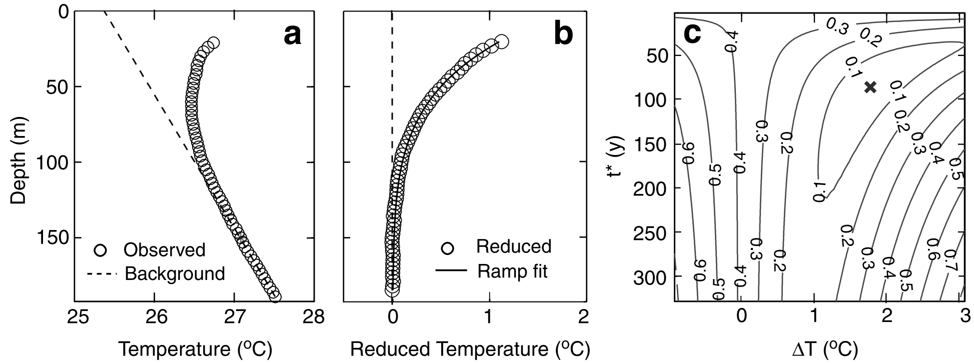

Figure 4. Illustration of the method of analysis for the borehole temperature profile CHK5. (a) Temperature-depth measurements (open circles) and background thermal regime (dashed line). (b) Reduced temperatures are calculated by subtracting the background thermal regime from the measured temperatures. The dashed line corresponds to zero reduced temperature. The solid line represents the fit to the reduced temperature profile with a ramp function (see text). (c) Solution-resolution diagram contouring the RMS misfits for specific parameter values ΔT and $t*$ in equation 3. The optimum solution is shown by the bold cross.

[15] Our model is parameterized in terms of a total warming (or cooling) magnitude ΔT and a duration time $t*$ expressed as [*Carslaw and Jaeger*, 1959; *Lachenbruch and Marshall*, 1986],

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

where i^2 erfc is the second integral of the complimentary error function. A uniform thermal diffusivity (α) of 10^{-6} m^2 s^{-1} is assumed throughout this analysis for consistency. For other values of diffusivity the ramp duration $t*$ is easily adjusted by keeping the product ($\alpha t*$) constant. Application of this inversion is illustrated in Figure 4 for site CHK5. The raw temperature-depth profile (Figure 4a) is converted to a reduced temperature-depth profile (Figure 4b) so that regional heat flow and hence different background thermal gradients do not play a role in the analysis. The inversion then yields a preferred ΔT (amplitude) and $t*$ (duration) of a ramp change that explains the transient reduced temperature and a solution-resolution diagram that indicates how well the parameters are resolved (Figure 4c).

[16] Prior to examining results at individual sites, one should note the potential hazards of the ramp inversion caused by the inversion algorithm itself, by the nature of temperature measurements in boreholes, and by the sources of noise in subsurface temperatures. First, the ramp amplitude is much better resolved than the onset time, as is shown in the resolving diagram (Figure 4c). The onset time resolution becomes particularly problematic for very small ramp amplitudes: zero change can happen anytime. The ramp amplitudes would be better constrained if one were able to use temperatures up to the surface, but one cannot use the uppermost 20 m of the borehole because the annual temperature cycle extends to this depth. Furthermore, it is time consuming and often inaccurate to measure temperatures in air, thus many practitioners only start logging temperature when the probe has reached the water table that may be at a depth of a few tens of meters. Finally, some curvature in temperature profiles may be caused by effects other than transient surface temperature changes [*Chisholm and Chapman*, 1992, Appendix 1].

[17] Results for the 75 new borehole sites represented in this study are given in Table 1. Information for each site includes the site name and location, the year in which the temperature log was obtained, the top depth that defines the undisturbed part of the borehole, the background temperature gradient determined from the deepest section of the borehole below the section that is affected by recent climate change, and the surface temperature extrapolated from this deep section. For the ramp fit of temperature change, Table 1 includes the ramp amplitude, the time interval between the onset of warming or cooling and logging of the borehole, and the RMS misfit between observed temperatures and those predicted from the ramp fits.

[18] Amplitudes of ground temperature change at individual sites vary considerably from 3.2°C to –4.3°C. The mean amplitude of the sites that indicate warming is 1.3 ± 0.6 (SD) °C, not significantly different from the earlier result of *Roy et al.* [2002]. Onset times for individual sites show even greater variation than amplitudes, from a decade or two at the short time scale to centuries at the long time scale. The ramp amplitudes and time durations for individual boreholes are shown as histogram plots in Figure 5. The mean amplitude for the 75 sites is 0.9 ± 0.3°C at 95% level of confidence and the median amplitude is 1.2°C. The mean onset time prior to the logging year is 127 ± 25 years at the 95% level of confidence corresponding to onset in the 1880 s, and the median onset time is 95 years.

[19] Eleven of the sites show cooling and 7 of these are concentrated in a small area ($\sim$10 km $\times$ 5 km) in Namagiripettai near Salem, Tamil Nadu state. The magnitude of cooling inferred in the area ranges from 0.7 to 3.6 °C with variable onset times during the past $\sim$100 years. We speculate that the cooling may be caused by extensive sago cultivation in the past several decades resulting in the presence of vegetation almost throughout the year, but that process does not appear to be widespread in the other studied areas of south India. The other 4 sites are distributed over a larger ($\sim$60 km $\times$ 30 km) region, in the adjacent

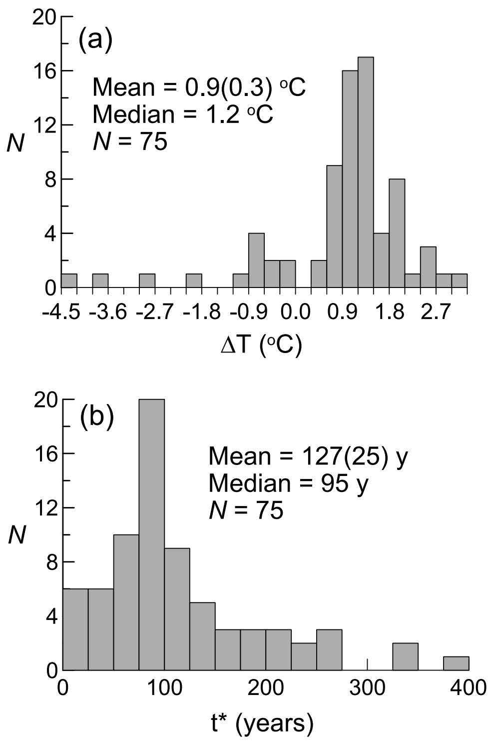

Figure 5. Histograms showing the distribution of (a) ramp amplitudes (ΔT) and (b) duration times (t^*) obtained from analysis of 75 borehole temperature-depth profiles in south India. Mean values, along with 95% confidence limits (in parentheses) are shown for each distribution. The width of the bins is approximately equal to the uncertainty (95% confidence limit) in each case. Ramp durations for two borehole temperature profiles, MD (497 years) and EK (634 years) are not shown in Figure 5b.

Tiruchengodu-Avinashi areas to the west of Salem, but the sites are separated from one another by several kilometers to a few tens of kilometers. The cooling at these sites are likely attributable to local site conditions.

[20] Four boreholes (MD, PP, MP and EK) exhibit positive reduced temperatures down to depths of ~300 m which taken at face value could be interpreted as warming that started as early as 700 years before present. Analysis of these profiles yield onset times that range from 400 to 650 years before present. These four sites are clearly anomalous relative to the remaining 71 sites in south India, which yield surface temperature histories that date back to ~300 years at the most.

3. Meteorological Data Update and Infilling

[21] Surface air temperature (SAT) data recorded at meteorological stations are a critical part of our climate change analysis. Meteorological data were obtained from the India Meteorological Department (IMD) for 28 localities distributed across the three climatic provinces of south India given by *Hingane et al.* [1985] (Figure 1). Geographic coverage is good in the Interior Peninsula and East Coast climatic provinces; the West Coast climatic province has data from only three meteorologic stations, all concentrated in the northern half of the region.

[22] The SAT data consist of annual mean temperatures from the initiation of recording at a particular station to about 1996 and monthly mean temperatures from 1997 to 2006. The monthly values update the data used by *Roy et al.* [2002]. Figure 6 shows the temporal completeness of the updated data set: data are 94% complete in general but with some geographic variability. For example, station Bombay (BOM) is 100% complete for the entire period 1901 through 2006, as is Pune (PUN). Other stations such as Karwar (KAR) or Madurai (MAD) have decade or greater gaps in the middle of the century or, as with Bellary (BEL) are missing only a few years in recent times. More problematic are the four stations Baramati (BAR), Satara (SAT), Hyderabad (HYD), and Tiruchirapalli (TIR) which are missing the first half of the century. Fortunately, in most cases where we are missing data there are other relatively nearby stations that can be used to infill for the missing data.

[23] Because we require complete time series for our climate change analysis we follow an infilling protocol to treat temporal data gaps. For any station with missing data we examine nearby stations from the same climatic province to see which stations exhibit similar temperature responses on an annual or monthly basis. That is, does a cold/warm month or year at one station correspond to a comparatively cold/warm month or year respectively at the other station? On the basis of a positive spatial correlation between temperature residuals, we identify pairs of stations for infilling. When dealing with annual temperatures, a temperature residual for

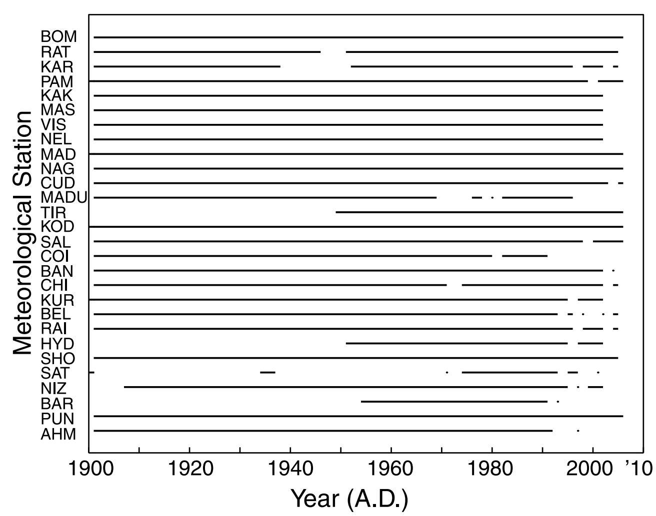

Figure 6. Temporal completeness (thick line) of SAT data from 28 meteorological stations in south India during the period 1900–2006. The stations are identified as follows. AHM: Ahmadnagar; PUN: Pune; BAR: Baramati; NIZ: Nizamabad; SAT: Satara; SHO: Sholapur; HYD: Hyderabad; RAI: Raichur; BEL: Bellary; KUR: Kurnool; CHI: Chitradurga; BAN: Bangalore; COI: Coimbatore; SAL: Salem; KOD: Kodaikanal; TIR: Tiruchirapalli; MADU: Madurai (all in Interior Peninsula province); CUD: Cuddalore; NAG: Nagapattinam; MAD: Madras; NEL: Nellore; VIS: Visakhapatnam; MAS: Masulipatnam; KAK: Kakinada; PAM: Pamban (all in East Coast province); KAR: Karwar; RAT: Ratnagiri; BOM: Bombay (all in West Coast province).

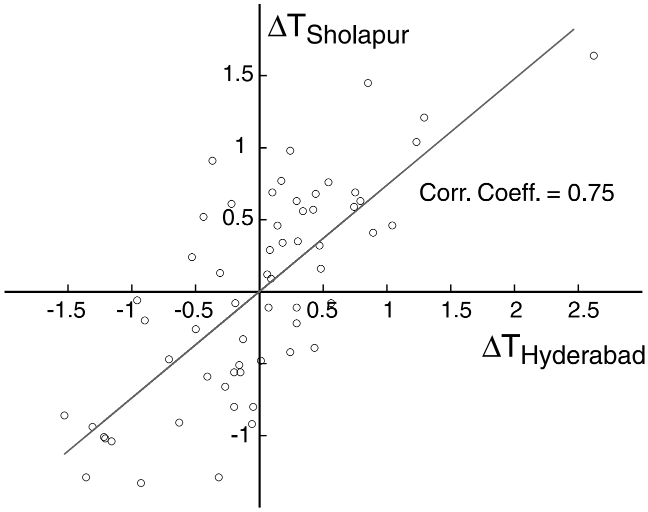

Figure 7. Comparison between monthly temperature residuals (ΔT) for a pair of stations, Hyderabad (HYD) and Sholopur (SHO), in the Interior Peninsula for a five year period 1998–2002. The stations are separated by 250 km. A temperature residual is defined as the temperature difference between the observed mean monthly temperature for a month in the five year period 1998–2002 and the average temperature for that month over the entire time series.

this purpose is the temperature difference between the mean annual temperature for a particular year in the time series and temperature for that year fitted by the series-long trend to the data. For the most recent monthly data, a temperature residual is defined as the temperature difference between the observed mean monthly temperature for a month in the five year period 1998–2002 and the average temperature for that month over the five-year time series.

[24] Figure 7 shows a comparison between monthly temperature residuals for a pair of stations, Hyderabad (HYD) and Sholopur (SHO) in the Interior Peninsula for the period 1998–2002. The stations are separated by ~200 km. The monthly temperature residuals generally vary from −1.6 to +1.8°C and are strongly correlated with a correlation coefficient of 0.75. If, for example, we have a data gap for HYD but complete data at SHO for a particular month, we use a linear regression (Figure 7) to determine the best relation between HYD and SHO temperature residuals and use that relation to infill for missing data at HYD. A complete monthly data set can then be used to create mean annual temperatures.

[25] In a very small number of cases we have used the same infill protocol to replace data. Replacement is only considered when the meteorological data file of annual or monthly mean temperatures seems to suffer from data transcription or other errors that result in temperature shifts that are not credible. For example, in the East Coast climate province in the year 1996, three stations Nellore (NEL), Vishakapatnam (VIS), and Masulipatnam (MAS) have reported mean annual temperatures that are at least 3.5°C below the trend for that decade. Because the average interannual fluctuation for the entire time series is only 0.3°C (standard deviation 0.6°C), and no other stations in the province show similar low temperature residuals for that year, we judge the 1996 values for those three stations to be in error. We have replaced their 1996 mean temperatures by infilling as if there were a data gap for that year. There are only 6 cases in the 2778 station-years of data in the meteorological data file, and so the replacement process has little effect on the data processing with respect to climate change. The replacement process, however, yields a self consistent and credible data set for illustration and inter-station comparison.

[26] Figure 8 shows the infilled meteorological data for 28 stations in south India (locations in Figure 1) for the period 1901 to 2006. Temperature trends computed as linear regressions to the data are also shown next to each station with the trend given in units °C /100 years. A histogram of the trends is given in Figure 9. The mean SAT trend for south India is 0.57 ± 0.2 (95% confidence limit) °C/100 years; the median SAT trend is 0.6°C/100 years, not different from the mean. Twenty three of the stations have warming trends between 0.2 and 1.6°C/100 years; the mean and standard deviation for these stations alone are 0.7 and 0.3°C/100 years respectively. The warming outlier in the south Indian meteorological stations is Hyderabad (HYD) with a warming trend of 2.3°C/100 years, but that trend is calculated for a truncated time series of only 1951 to 2002. Hyderabad is one of the largest south Indian cities in the Interior Province and has experienced rapid growth and expansion in the last half century; the SAT record may be influenced by an urban heat island effect. The four stations that show cooling in the last century are Pune (PUN), Baramati (BAR), Raichur (RAI), and Bellary (BEL), all in the northwest part of the Interior Peninsula. PUN and BAR are adjacent stations, as are RAI and BEL, suggesting that the climate cooling is geographically extended and coherent, at least for that part of south India. It may be a coincidence that 4 out of 28 meteorologic stations show cooling trends, the same percentage as the 11 of 75 borehole sites that exhibit cooling trends in their reduced temperature profiles.

4. Combined Analysis of Borehole and Meteorological Data

[27] Our analysis of borehole temperatures in terms of a ramp change yielded average warming amplitude of 0.9°C initiated ~127 years ago. The warming rate from that analysis is ~0.7°C/100 years, which is not significantly different from the value of ~0.6°C/100 years calculated from meteorological data. Thus the rate of surface ground warming in south India is comparable to surface air warming, indicating that the ground is effectively tracking temperature change above the ground, an observation made elsewhere [*Chisholm and Chapman*, 1992; *Harris and Chapman*, 1997].

[28] We now exploit the tracking of air and ground temperatures further by combining our borehole temperature and meteorological data in a hybrid analysis. A SAT time series is used as a driving function at zero depth to produce a synthetic transient temperature-depth profile $T_{RSAT}(z)$ at a time corresponding to borehole temperature log, noting that an initialization temperature is required for the calculation. That initialization temperature was termed the pre-observational mean (POM) temperature by *Harris and Chapman* [1997] because it is the average, long-term temperature for the Earth's surface prior to start of the SAT observations. For a

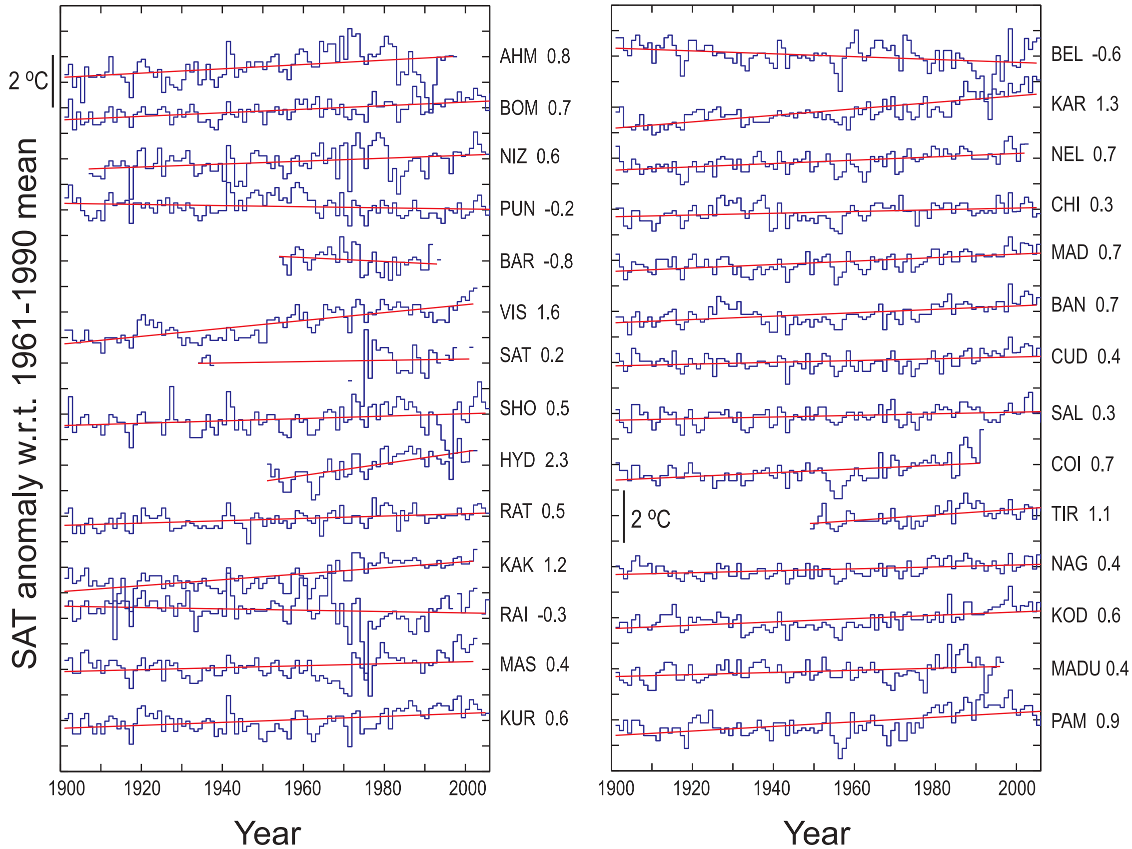

Figure 8. SAT time series for 28 individual meteorological stations in south India. The SAT data are shown as annual departures from the 1961–1990 mean temperature. Solid line shows the best linear fit to the data on each plot. The station names and the corresponding SAT trends (in °C/100 y) are shown next to the plots.

surface temperature history composed of n individual step changes of amplitude ΔT_i and time t_i^* before the borehole measurement, the transient temperature profile $T_{RSAT}(z)$ at the time of measurement is given by [*Carslaw and Jaeger*, 1959]

$$T_{RSAT}(z) = \sum_{i=1}^{n} \Delta T_i erfc\left(\frac{z}{\sqrt{4\alpha t_i^*}}\right). \quad (4)$$

[29] In practice, the POM step is determined by finding the value that minimizes the misfit between the reduced temperature profile and the synthetic transient temperature profile computed from the SAT record [*Harris and Chapman*, 1997].

[30] We compare the average borehole reduced temperature profile (to a depth of 500 m) for south India with the synthetic transient temperature profile constructed using the average SAT time series. We sweep a large POM space (−5 to +5°C) at 0.01°C intervals. The best fitting POM corresponds to a temperature 0.6 ± 0.1°C lower than the 1961–1990 mean SAT for south India. The results of the comparison are shown in Figure 10. The figure also shows the sensitivity of the misfit between the borehole and synthetic transient temperature profile to the choice of POM. A sharp trough in the misfit diagram indicates that the POM is a robust temperature estimate. For comparison, Figure 10 also shows two other POM-SAT models differing by 0.2°C from the best fitting POM-SAT model, corresponding to POM values −0.4°C and −0.8°C relative to the 1961–1990 mean SAT, and synthetic temperature profiles produced by these models.

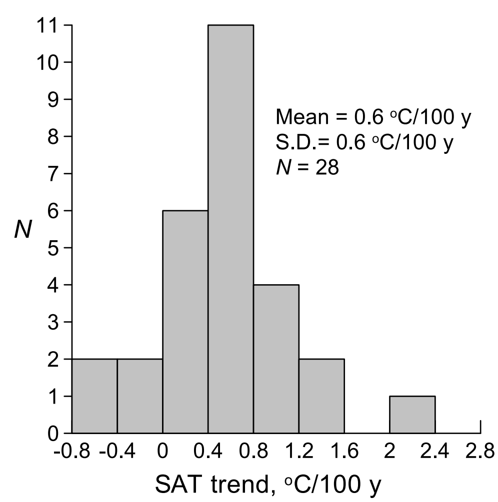

Figure 9. Histogram showing the distribution of SAT trends in °C/100 y obtained from analysis of 28 meteorological station records in south India.

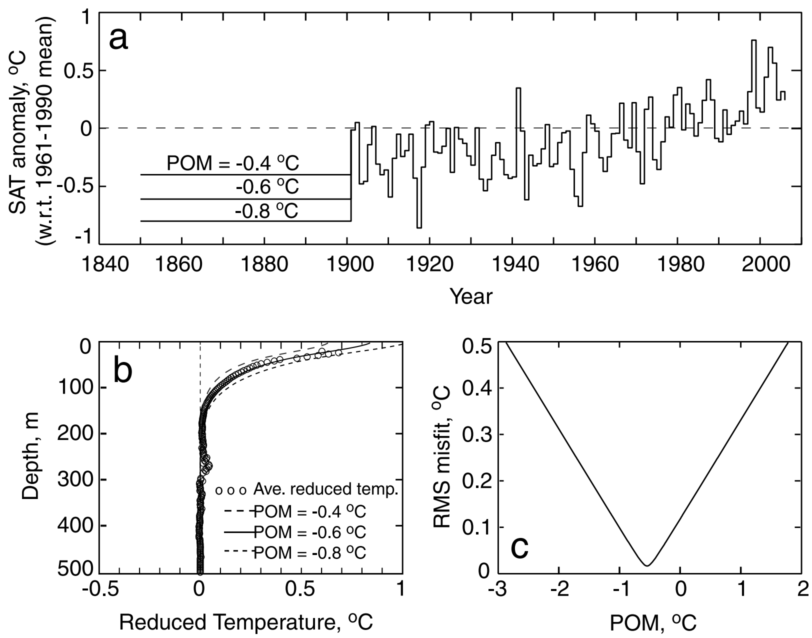

Figure 10. Determination of a pre-observational mean (POM) temperature for south India. (a) Mean SAT anomalies for the 28 weather station ensemble in south India. Zero corresponds to the 1961–1990 mean. Horizontal lines illustrate three possible choices of POM. (b) Synthetic temperature-depth profiles for the three POM-SAT scenarios shown in Figure 10a, along with the subsurface temperature-depth profile obtained by averaging the set of borehole reduced temperature profiles of the present study. The best fitting POM-SAT scenario corresponds to a POM 0.6°C lower than the 1961–1990 mean SAT. (c) Plot of RMS misfit as a function of the POM illustrating that the inferred POM is quite robust.

[31] Availability of annual meteorological data until 2006 permit an analysis of total warming from the baseline temperature representing an average 18th and 19th Century temperature to the current decade. The past two decades have been warm in India, as for most of the globe. Relative to the 1961–1990 mean temperature, SAT annual averages for south India from 1995 through 2006 are 0.149, 0.038, 0.317, 0.761, 0.176, 0.140, 0.442, 0.698, 0.562, 0.245, 0.317 and 0.242°C. Over a 10 year window from 1995 to 2005 centered on the year 2000, the average SAT warming relative to the 1961–1990 mean is 0.35°C. Thus the hybrid POM-SAT method suggest that total surface warming in south India from the early 1800 s to 2000 is $\sim$0.95°C (0.6 plus 0.35°C).

5. Discussion

[32] The 75 new sites from south India constitute a significant contribution to the previously available global archive of borehole temperatures used for climate reconstructions [*Huang et al.*, 2000]. *Harris and Chapman* [2001] noted that the global collection in fact was heavily biased toward sites in the northern hemisphere concentrated between 30° and 60° latitudes; these data for south India and the data for other parts of India reported in *Roy et al.* [2002] correct some of that geographical bias (Figure 11).

[33] The data for south India span 7 degrees of latitude. The magnitudes of the ramp temperature changes inverted from borehole temperatures (Table 1) are shown in Figure 12 for one-degree latitude bands. The average temperature change amplitude is 1.2°C in the southernmost bin (8–9°N) and varies only between 1.0°C and 1.3°C over eight degree latitude range. In southern India there seems to be no discernible changes with latitude that might be associated with a general latitudinal amplification of warming or regional climate change effects.

[34] This borehole temperature study extends the knowledge of surface temperature change obtainable from surface air temperatures (SAT) alone. The value added in combining borehole temperature data to traditional meteorological data for south India is illustrated in Figure 13. From SAT information alone one can deduce the standard 30-year mean datum, in this case the 1961–1990 mean illustrated by

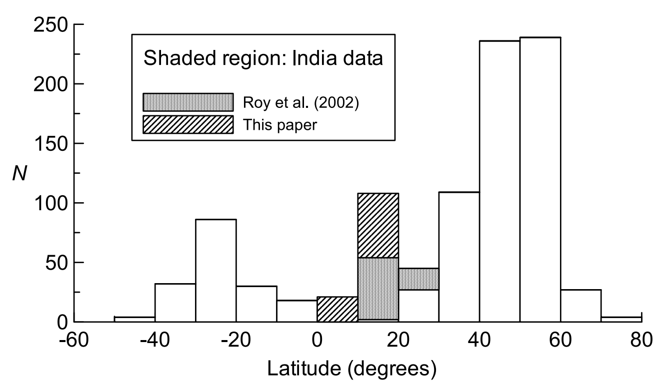

Figure 11. Histogram of the global latitudinal distribution of borehole sites used for past climate change analyses. The shaded regions show the latitudes for India data analyzed in the study of *Roy et al.* [2002] and the present study.

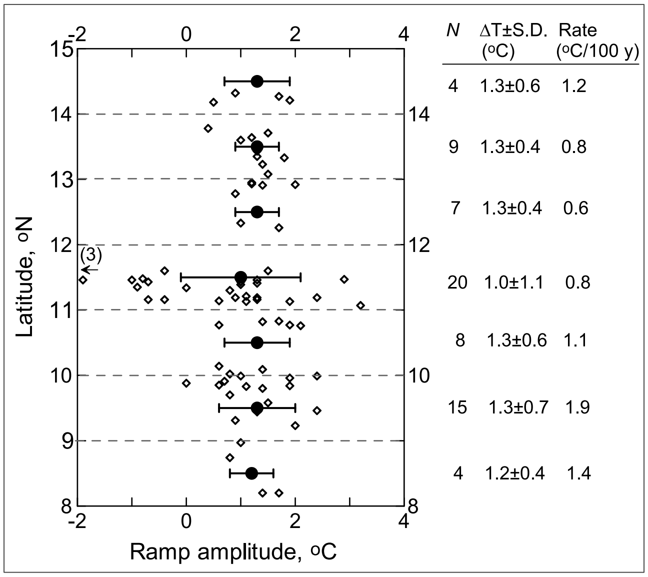

Figure 12. Temperature change (ramp amplitude) versus latitude for 75 south India borehole sites. The latitude range is divided into 1° bins. The average surface ground temperature change (solid circle) and standard deviation (solid lines) in each 1° bin are also shown. Three sites in the latitude bin 11–12°N that show cooling in the range −2.9 to −4.3°C are not plotted but are indicated by an arrow inside the bin. The number of borehole sites, average ramp amplitude (°C) and average rate of change of surface ground temperature (°C/100 y) corresponding to each latitude bin are listed beside each bin. The average shown against the 11–12°N latitude bin does not include the 8 sites in Namagiripettai area that show local cooling attributable to changes in land use (see text). These 8 sites show an average cooling of 1.7 ± 1.8 (SD) °C and a rate of −1.9°C/100 y.

item #1 on Figure 13. One can also calculate a trend for the SAT time series; item #2 on Figure 13 shows that trend of 0.57°C/100 yr plotted to pass through the midpoint of the 1961–1990 mean datum. The warming for the Century is thus partitioned linearly into 0.43°C prior to 1975 (midpoint of 1961–1990) and 0.14°C subsequent to 1975. In the case of south India, SAT temperatures in the last decade depart significantly from the trend and it is appropriate to show that departure by plotting the 1995–2005 mean temperature as a separate feature (item #3 on Figure 13).

[35] Addition of borehole temperature data both extends and complements this picture. Most significantly, the hybrid SAT-POM method provides a baseline temperature for ~1700–1900 against which the current warming phase can be considered. That baseline is 0.6°C cooler than the 1961–1990 mean SAT (item #4 on Figure 13). Finally the borehole temperature inversion, parameterized in terms of a simple ramp change, returned values of 0.9°C amplitude and 127 years duration for the ramp; that result is plotted as a borehole warming trend, item #5 on Figure 13, originating on the baseline temperature and terminating in the year 2000, a median time for the borehole temperature logs (Table 1). It is not surprising that the total warming from the baseline to ~2000 for the SAT data agrees with the borehole warming trend because the borehole temperatures were used to derive the POM. But the method locks both borehole data and SAT data on to the same scale. Studies that use boreholes alone simply determine a rate of ground temperature change and, because there is an offset between ground and air temperatures, superimpose the borehole warming or cooling on a SAT plot with an arbitrary shift.

[36] Figure 13 suggests, however, significant warming in the 19th Century, prior to the observational SAT record. Warming during that period is supported by an entirely independent data set. *Anderson et al.* [2002] have analyzed the abundance of the foraminifera *G. bulloides* in cores from the Arabian Sea. They use an index based on *G. bulloides* abundance as an indicator of monsoon wind speed, in turn related to temperatures in south Asia, to argue for continental warming starting as early as 1600 A.D. with a local minimum between 1800 and 1900 A.D. Although not easily quantified, that inference is consistent with our analysis based on borehole temperatures and meteorological data.

[37] It should be mentioned that all trends and values plotted on Figure 13 have uncertainties, some of them large, which would smear the plotted data. Nonetheless, an image arises from the combined borehole and meteorologic data in Figure 13 that south India has experienced between 0.8 and 1°C of warming above a baseline broadly representative of an 18th and 19th Century mean temperature. That result could not be obtained from meteorologic information alone given the abbreviated SAT time series from 1901 to 2006 A.D.

6. Conclusions

[38] This study of surface air temperatures from meteorological records combined with temperature-depth data from widely dispersed borehole sites in south India lead to the following observations and conclusions:

[39] 1. Temperature-depth profiles from 75 sites in south India add significantly to the 70 sites previously used [*Roy et al.*, 2002] to study ground surface temperature changes in India. As the global archive of borehole sites previously

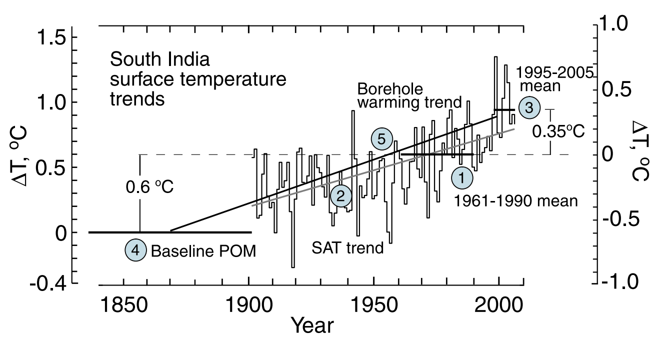

Figure 13. Information obtained about surface temperature change in south India by combining borehole temperatures with SAT data. Numbers on plot refer to: (1) mean SAT datum for the thirty-year period 1961–1990; (2) SAT annual anomalies and trend for the period 1901 to 2006; (3) mean SAT anomaly for the period 1995–2005; (4) POM or baseline temperature representing a mean temperature for the 18th and 19th centuries; (5) average warming ramp determined from inversion of borehole temperatures.

used for climate change studies is biased toward the latitude band 30 to 60°N latitude, these sites also significantly redress the absence of low latitude sites in the data archive.

[40] 2. The south India borehole temperature-depth profiles indicate that the ground surface has warmed by 0.9°C over the past 127 years on average. Temperature change is determined more precisely than the onset time for the warming.

[41] 3. As occurs elsewhere, there is considerable variation in the inferred temperature change from site to site. Although 85% of the sites show distinct warming trends, 11 sites yield surface temperature cooling, possibly associated with irrigation or land use changes. Another 4 sites show warming but the onset of warming precedes the modal warming onset in south India by 150 years.

[42] 4. There is no evidence for a latitudinal change in the degree or onset of warming in the latitude range 8 to 15°N represented by the south India data.

[43] 5. Monthly and annual temperature data have been compiled for 28 meteorological stations over the regions where the new borehole sites exist. A data infill algorithm was developed to create a near-complete data set for the time period 1901 to 2006 A.D. The meteorological data have characteristics seen elsewhere in the world, large interannual variations but overall warming trends. The average warming rate is 0.6°C/100 years but with considerable scatter among individual stations (range −0.8 to +2.3°C/100 years).

[44] 6. Meteorological data have been combined with the borehole data to extract a baseline surface temperature prior to the existence of the observational record (often termed the pre-observational mean temperature or POM). The average POM for south India is −0.6°C relative to the 1961–1990 mean SAT. The variability of the POM among sites is much less than the variability of warming rates determined from meteorological data alone, a result in part from the attenuated temperature effects in the subsurface. Adding the post-1990 warming observed over south India, the total surface warming in south India from the early 1800 s to the early 2000s is ~0.95°C. It appears that significant warming took place prior to the establishment of widespread meteorological stations in southern India in about 1900 A.D.

[45] This south India study involving the geothermics of climate change provides another case study illustrating the benefit of using borehole temperature-depth profiles in combination with meteorological data to analyze multi-century surface temperature change for an important subcontinent on planet Earth.

[46] **Acknowledgments.** We are thankful to CSIR-NGRI, Hyderabad for supporting the acquisition of temperature-depth data in boreholes. In particular, we are grateful to R. U. M. Rao, G. V. Rao, R. Srinivasan and Labani Ray for help with data acquisition. We thank the Department of Science and Technology, Govt. of India for funding "dedicated" heat flow boreholes in south India. The National Data Centre, India Meteorological Department, Pune, provided the surface air temperature data sets. Derrick Hasterok, Mike Davis, A. V. Vyasulu and G. Ravi helped at various stages of the work; Rob Harris provided a thoughtful review of the paper. S.R. is grateful to CSIR for awarding Raman Research Fellowship tenable at the University of Utah and to V. P. Dimri, former Director for encouragement and support during this work. D.S.C. acknowledges the CSIR Distinguished Foreign Scientist award that supported his 2008 visit to NGRI in Hyderabad. Publication of the work is supported by Director, CSIR-NGRI.

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