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Repeat temperature measurements in boreholes from northwestern Utah link ground and air temperature changes at the decadal time scale

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[1] Borehole temperature profiles provide a record of ground surface temperature (GST) change at the decadal to centennial time scale. GST histories reconstructed from boreholes are particularly useful in climate reconstruction if changes in GST and surface air temperature (SAT) are effectively coupled at decadal and longer time periods and it can be shown that borehole temperatures respond faithfully to surface temperature changes. We test these assumptions using three boreholes in northwestern Utah that have been repeatedly logged for temperature over a time span of 29 years. We report 13 temperature-depth logs at the Emigrant Pass Observatory borehole GC-1, eight at borehole SI-1 and five at borehole DM-1, acquired between 1978 and 2007. Systematic subsurface temperature changes of up to 0.6°C are observed over this time span in the upper sections of the boreholes; below approximately 100 m any temperature transients are within observational noise. We difference the temperature logs to highlight subsurface transients and to remove any ambiguity resulting from steady state source of curvature. Synthetic temperature profiles computed from SAT data at nearby meteorological stations reproduce both the amplitude and pattern of the transient temperature observations, fitting the observations to within 0.03°C or better. This observational confirmation of the strong coupling between surface temperature change and borehole temperature transients lends further support to the use of borehole temperatures to complement SAT and multiproxy reconstructions of climate change.

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1. Introduction

[2] Borehole temperature-depth profiles contain important information about the Earth's changing surface temperature [*Lachenbruch and Marshall*, 1986; *Pollack and Chapman*, 1993; *Pollack and Huang*, 2000; *Beltrami*, 2002; *Harris and Chapman*, 2005]. For one-dimensional, conductive heat transfer, a surface temperature variation in time,

$$T(z = 0, t) = F(t), \tag{1}$$

creates transient curvature in the subsurface temperature profile, with the subsurface temperature response being governed by the diffusion equation

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

where T is temperature, z is depth, t is time, and α is thermal diffusivity. The diffusion of the surface temperature variation into the subsurface is scaled by thermal diffusivity. A surface temperature change at time zero is largely captured within a depth called the thermal length, l,

$$l = \sqrt{4\alpha t}, \tag{3}$$

at a subsequent time t. Because the thermal diffusivity of rocks is about 1×10^{-6} m^2 s^{-1}, the majority of the past 100 years of surface temperature change is stored within the upper 113 m of the Earth; the majority of the last 1000 years of surface temperature change is captured in the uppermost 350 m. Careful analysis of curvature in the upper few hundred meters of a temperature-depth profile, therefore, can be used to reconstruct surface temperature change over the past millennium [e.g., *Huang et al.*, 2000; *Harris and Chapman*, 2001; *Pollack and Smerdon*, 2004].

[3] Equation (2) posits that for a homogeneous half-space, the rate of change of temperature at any depth is proportional to the transient curvature in the temperature-depth profile at that depth. Because the Earth is not a homogeneous half-space, phenomena and processes other than a changing surface temperature can also cause curvature in

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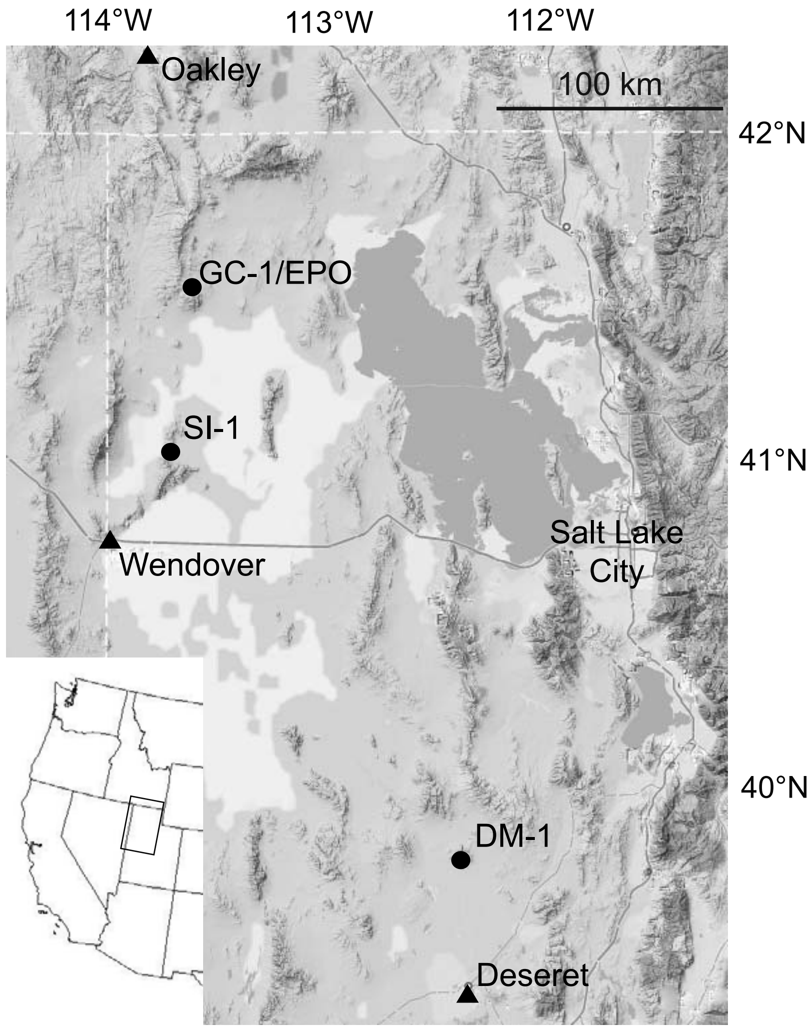

Figure 1. Location map of northwestern Utah, showing borehole sites (circles) and meteorological stations (triangles) used for comparisons between ground and air temperatures. Meteorological stations are from the U.S. Historical Climatology Network [*Menne et al.*, 2009].

temperature-depth profiles. Steady state source of curvature include: subsurface thermal conductivity variation, radioactive heat production, refraction due to topography, and by differential solar insolation due to variations in slope and azimuth. Transient source of curvature include: changes in GST due to surface air temperature (SAT), spatial changes in surface temperature around the borehole caused by temporal variations in albedo, nonisothermal groundwater flow [e.g., *Beck*, 1982; *Chisholm and Chapman*, 1992; *Lewis and Wang*, 1992; *Harris and Chapman*, 1995], precipitation [*Bartlett et al.*, 2004], and other microclimatic effects. *Chisholm and Chapman* [1992] and *Harris and Chapman* [1995] explore the magnitude of many of these effects quantitatively. While most studies of climate change inferred from borehole temperature profiles attempt to select sites that minimize these nonclimatic sources of borehole temperature profile curvature, it is often difficult to partition curvature between steady state and transient sources of curvature. Much of the ambiguity in interpreting borehole temperature-depth curvature can be removed by measuring the transient effect directly.

[4] Direct observation of the transient temperature field in a borehole temperature profile has a second important consequence. If there is a meteorological station at the borehole site, or reasonably close, then the linkage between changes in the surface air temperature (SAT) with time and changes in the subsurface temperature-depth profile can also be evaluated. How strongly coupled are ground surface temperature (GST) histories to changes in SAT? Such a test is the basis of using borehole temperatures to reconstruct climate change and for comparing the results of borehole studies with SAT changes and also proxy temperature changes over longer periods.

[5] At the annual to decadal scale coupling between SAT and GST has been investigated through comparisons between meteorological data and shallow soil thermistors [e.g., *Putnam and Chapman*, 1996; *Smerdon et al.*, 2004, 2006; *Bartlett et al.*, 2006; *Stieglitz and Smerdon*, 2007]. Related studies include model simulations which parameterize relevant processes at the ground surface to simulate interactions between the atmosphere and subsurface [e.g., *González-Rouco et al.*, 2003, 2006, 2009], comparisons between atmospheric models and observed borehole tem-

Table 1. Geothermal Information for Borehole Sites[a]

Borehole	Latitude	Longitude	Elevation (m)	Γ (°C km^{-1})	T_o (°C)	K (W m^{-1} K^{-1})	Heat Flow (mW m^{-2})
GC-1	41°32′	113°42′	1756	31.03	10.65	3.14	97
SI-1	41°02′	113°47′	1332	40.54	13.93	2.28	92
DM-1	39°44′	112°36′	1524	31.64	14.22	3.01	95

[a]Γ is the average thermal gradient, and T_o is the average surface temperature intercept based on linear fits to the data below 100 m for all temperature logs. K is the thermal conductivity.

perature profiles [*Beltrami et al.*, 2006; *Stevens et al.*, 2008], and comparisons between hemispheric averages of SAT and borehole temperature data [*Harris and Chapman*, 2005; *Harris*, 2007].

[6] In spite of the importance of direct observation of borehole temperature transients, the slow rate of temperature change combined with the difficulty of maintaining access to sites over more than decades has resulted in only a few studies of repeat borehole temperature measurements [*Chapman and Harris*, 1993; *Majorowicz and Safanda*, 2005; *Safanda et al.*, 2007; *Kooi*, 2008]. *Chapman and Harris* [1993] used the differences between repeat borehole temperature logs from northwest Utah to show that subsurface temperature transient can be determined and steady state sources of curvature can be eliminated. More recent studies by *Majorowicz and Safanda* [2005], *Safanda et al.* [2007], and *Kooi* [2008] echo the findings of *Chapman and Harris* [1993], as well as show that multiple temperature-depth logs from individual boreholes can decidedly resolve uncertainty between SAT and GST coupling.

[7] In this study we report direct observations of transient temperatures in three boreholes from northwest Utah. Observations include repeated temperature logs collected over a 29-year time span. At one borehole, site GC-1, we use a collocated meteorological station (Emigrant Pass Observatory, EPO), established in 1993, to investigate fine-scale coupling between air and ground temperatures. We first isolate the transient temperature field in each borehole and then quantitatively compare variations in these temperature logs with variations in SAT from nearby meteorological stations. This study extends the time span of observations and expands the number of sites used in the earlier work of *Chapman and Harris* [1993].

2. Borehole Temperature-Depth Profiles

[8] Boreholes at Grouse Creek (GC-1), Silver Island (SI-1), and Desert Mountain (DM-1) (Figure 1) were drilled in

Table 2. Logging Years and Numbers of Borehole Logs Used in Analysis[a]

Borehole	Year	Number of Logs	Γ (°C km^{-1})	T_o (°C)	ΔT_b (°C)	Notes
GC-1	1978	1	31.19	10.63	0.105	5 m spacing
	1990	1	31.08	10.65	0.012	1 m spacing
	1992	3	31.24	10.62	0.007	
	1993	4	31.19	10.63	0.010	
	1994	3	31.04	10.65	−0.020	small diameter pipe
	1995	3	30.88	10.68	0.027	
	1996	3	31.03	10.66	−0.026	
	1998	1	30.54	10.73	0.042	
	2000	3	31.03	10.66	−0.028	
	2002	3	31.05	10.65	−0.031	
	2004	2	31.04	10.65	−0.030	
	2005	1	31.06	10.65	−0.029	
	2007	2	31.09	10.65	−0.039	
	Ave		31.03	10.65		
SI-1	1978	1	41.92	13.72	0.088	5 m spacing
	1990	1	40.55	13.93	0.004	1 m spacing
	1992	3	40.44	13.94	−0.007	
	1994	4	40.26	13.95	−0.014	
	1995	3	40.44	13.94	−0.011	
	1996	3	40.32	13.96	−0.023	
	1997	3	40.30	13.96	−0.012	
	2007	2	40.11	13.99	−0.026	
	Ave		40.54	13.93		
DM-1	1978	1	31.69	14.20	0.125	5 m spacing
	1990	1	31.81	14.20	−0.026	1 m spacing
	1992	3	31.69	14.23	−0.015	
	1997	3	31.63	14.24	−0.023	
	2007	1	31.40	14.26	−0.061	
	Ave		31.64	14.22		

[a]Γ is the thermal gradient, and T_o is the surface temperature intercept based on linear fits to the data below 100 m. ΔT_b is the shift applied to the temperature logs assuming the bottom hole temperature is constant. The average values at the bottom of each log set are used to reduce the data after applying the temperature shift.

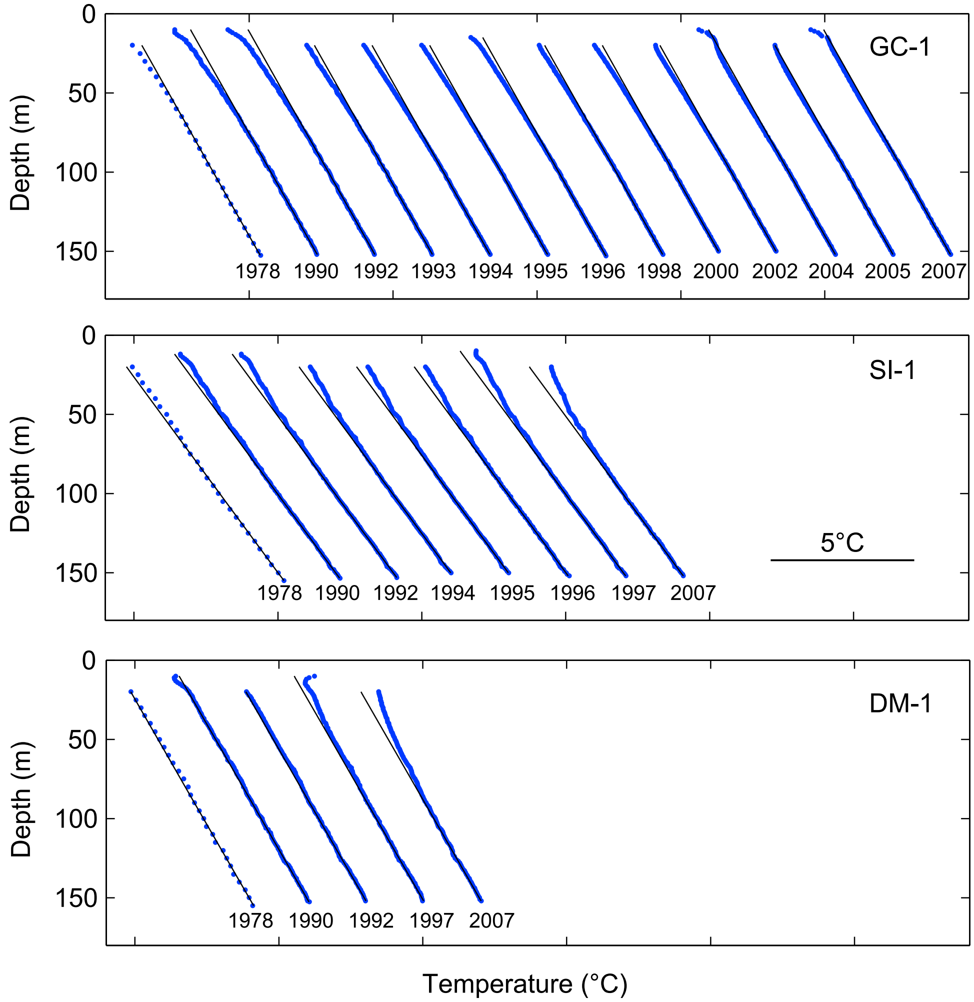

Figure 2. Temperature-depth profiles collected between 1978 and 2007 from boreholes (top) GC-1, (middle) SI-1, and (bottom) DM-1. Plots are offset to avoid overlap. Temperature-depth profiles are averaged when multiple logs were collected during the same field campaign (Table 2). Also shown is the background thermal gradient (solid lines) determined from the data below 100 m.

1978 as part of a heat flow investigation of the northern Basin and Range tectonic province in the western United States [*Chapman et al.*, 1978]. These boreholes were specifically located in granitic plutons with subdued terrain to minimize disturbances due to rock heterogeneity and topography and to minimize possible disturbances from groundwater flow. Each borehole was drilled to a depth of 152 m and cased with 64 mm inner diameter PVC pipe. The annulus was back filled with a slurry of drill cuttings. The bottoms of the casings were capped and the pipes were filled with water to stabilize the measuring environment and facilitate temperature logging.

[9] Borehole GC-1 is located in northwestern Utah at the southern edge of the Grouse Creek Mountains (Figure 1). The environment surrounding GC-1 is classified as desert. The jet stream brings storms from the Pacific Northwest to northern Utah, and much of the roughly 30 cm annual precipitation at the site comes in the form of snow [*Bartlett et al.*, 2006]. Borehole SI-1 is located on the western flank of the Silver Island Mountains on the west side of the Great Salt Lake. This range is surrounded by playa, salt and mud flats from remnants of higher stands of the lake. Precipitation is low in the area as evidenced by the desert conditions and salt flats. Borehole DM-1 is located near the eastern edge of the Great Basin. Grasses and occasional sagebrush on the generally flat and low-lying basin dominate the semiarid desert environment, giving it a more steppe-like setting.

[10] Temperature-depth profiles from these boreholes were originally measured in 1978 at a logging interval of 5 m (temperature-depth data are provided in the auxiliary material).[1] Thermal conductivities (Table 1) were made on rock chips returned to the surface during drilling and are relatively uniform with depth [*Chapman et al.*, 1978]. A changing focus in geothermal studies from heat flow to climate change caused us to relog the boreholes in 1990, decreasing the depth interval of temperature measurements from 5 to 1 m to improve resolution of any possible climatic signal [*Chisholm and Chapman*, 1992]. Starting in 1992

[1]Auxiliary materials are available in the HTML. doi:10.1029/2009JB006875.

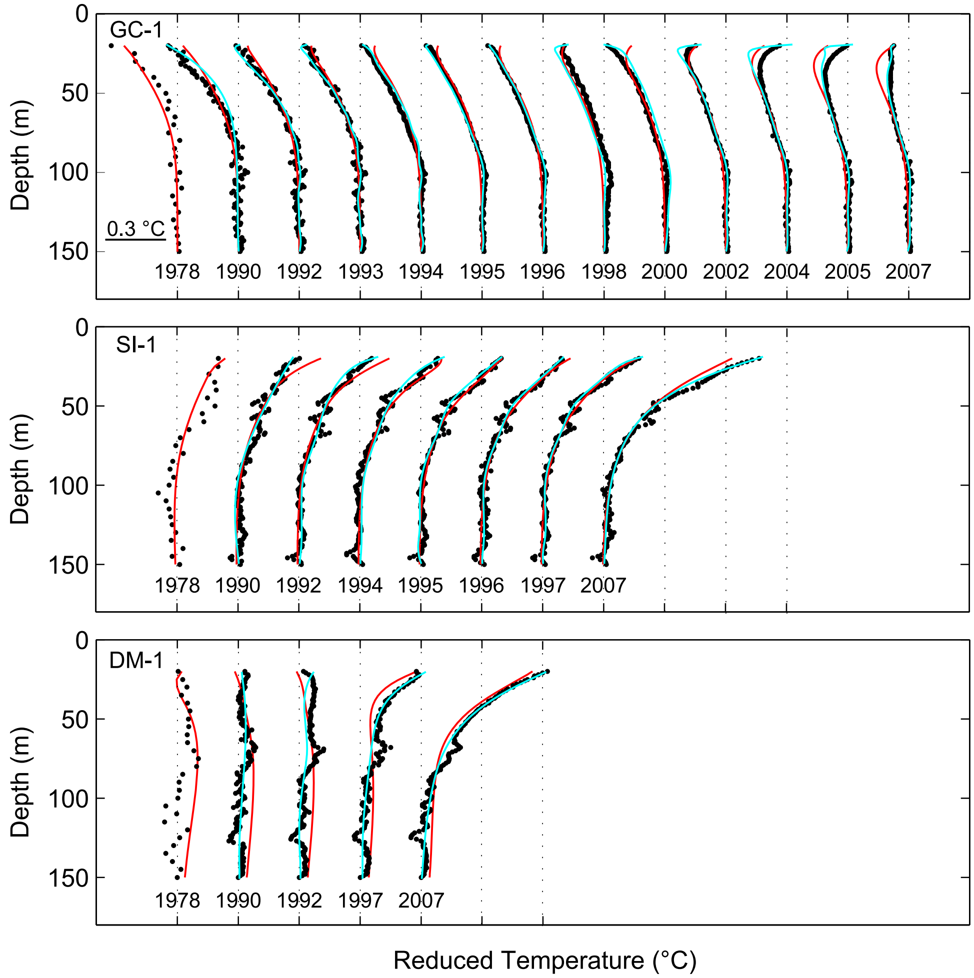

Figure 3. Reduced temperatures (dots) for boreholes (top) GC-1, (middle) SI-1, and (bottom) DM-1. Cyan lines show the previous log forward continued in time assuming a linear change in surface temperature. Red lines show synthetic transient temperature profile constructed from the associated meteorological station data: EPO for GC-1, Wendover for SI-1, and Deseret for DM-1.

multiple logs within the same field session were measured and averaged (Table 2) with the aim of reducing noise from random temperature fluctuations within the borehole [*Chapman and Harris*, 1993; *Harris and Chapman*, 2007]. A waiting time of about 12 h between logs ensured that the thermal conditions in the borehole had equilibrated from disturbances caused by the previous log.

[11] Temperature-depth profiles from the three boreholes taken over a span of 29 years are shown in Figure 2. To account for instrument (thermistor, resistance meter) drift over the nearly three decades and small uncertainties in depth, the temperature data for each log are shifted by a small amount so that bottom hole temperatures are constant for all logs at each borehole (Table 2). Each temperature shift is typically less than a few 10s of millikelvin and improves the consistency of the lower portion of each temperature profile. The lower portion of each temperature log exhibits a constant thermal gradient, consistent with the observed uniform thermal conductivity and constant heat flow. We define a background thermal regime and surface temperature intercept at each site in terms of a linear fit to data below a depth of 100 m (Table 1). These parameters are based on the entire set of temperature logs for each borehole. The repeated temperature logs cover a period of 29 years that corresponds to a thermal length of approximately 60 m. The choice of 100 m as the start of the fitting depth represents a trade-off between starting below recent climatic effects and using as much data as possible to obtain a robust gradient fit [*Chisholm and Chapman*, 1992]. The average surface temperature intercepts (Table 1) are appropriate for this geographic latitude, elevation, and climatic setting. Heat flow at the three sites computed as the product of the thermal gradient and thermal conductivity, is 97, 96, and 95 mW m^{-2}, appropriate for the Basin and Range tectonic setting [*Chapman et al.*, 1978]. The observation that the thermal gradient and surface temperature intercept are consistent with the tectonic and geographic setting adds confidence that heat transfer at these sites is dominantly conductive.

[12] The upper portion of each borehole (<100 m) shows systematic departures from the background thermal regime and these departures change with time between 1978 and 2007. To highlight these departures we compute reduced temperature profiles for each log by removing the average

Table 3. Amplitude of Temperature Changes Between 1978 and 2007.

	Amplitude of Linear Trend (°C)	
Borehole	From Temperature-Depth Profiles[a]	From SAT Data[b]
GC-1	0.9 ± 0.2	1.1 ± 0.1
SI-1	0.7 ± 0.3	0.7 ± 0.1
DM-1	0.7 ± 0.3	1.2 ± 0.1

[a]Amplitude of linear trend that minimizes the misfit when the 1978 temperature profile is forward continued into the 2007 temperature profiles. See text for details.

[b]Amplitude of best fitting trend to SAT data between 1978 and 2007. Uncertainties are 95% confidence limits.

thermal gradient and surface temperature intercept. By using the average thermal gradient and surface temperature intercept to compute reduced temperatures, each log is reduced to the same datum. Results are shown in Figure 3 and the reducing parameters are tabulated in Table 1. The reduced temperatures plotted on an expanded scale display coherent patterns, as well as instrumental and geologic noise.

[13] Several features of the reduced temperature logs merit discussion. In general the bottom portion of each reduced temperature profile is relatively constant with near zero reduced temperatures indicating that the fitting depth starting at 100 m is appropriate. Close inspection of the bottom third of reduced temperature profiles at GC-1 shows a conspicuous fine structure with an amplitude of approximately 0.03°C and a characteristic length of 4 m. This scatter is also evident in the 1978 log, but at reduced resolution because of the 5 m measurement spacing. Similar but somewhat larger amplitude fine structure is observed in the reduced temperature logs for both SI-1 and DM-1. *Chisholm and Chapman* [1992] and *Chapman and Harris* [1993] postulated that the fine structure was caused by convective instabilities in the borehole, thermal conductivity changes, groundwater flow in either the borehole or the granite, or small depth offsets. Starting in 1992 multiple temperature logs at each borehole were collected during each field campaign to understand this structure better. If the variations were random in space or time, averaging and stacking logs should diminish these oscillations. Instead the small temperature irregularities remained a persistent pattern demonstrating that they are stationary in time and space.

[14] In 1993, after measuring the temperature logs at GC-1 we installed a small diameter pipe (2.54 cm ID) inside the casing and attached convective baffles to the outside of the inner pipe. The 1994 and subsequent logs show that the oscillations are greatly reduced suggesting that the oscillations were the result of convection in the borehole. *Harris and Chapman* [2007] summarized several lines of evidence to suggest that the fluctuations were the result of stationary convection, and may be due to heterogeneities in the borehole diameter or less likely thermal properties of the rock that establishes any convection in space.

[15] The second feature meriting discussion, and more salient to this paper, is the uppermost portion of each reduced temperature profile. At GC-1, reduced temperature values are negative indicating surface cooling relative to the background thermal regime prior to 1978. With time, the magnitudes of the reduced temperature become less negative consistent with recent warming. In contrast to GC-1, reduced temperature profiles at SI-1 and DM-1 are positive in the upper reaches of the borehole and show similar changes over the 29 year time span between 1978 and 2007. At 20 m the reduced temperature at both sites increases approximately 0.6°C during this period, from 0.15°C to 0.75°C in the case of SI-1 and from 0°C to 0.65°C at DM-1. During this same period the anomaly shifts downward by approximately 20 m from ~70 to ~90 m. The pattern of reduced temperatures at all three boreholes is consistent with ongoing and persistent surface warming.

[16] To test if these patterns of reduced temperature are quantitatively consistent with surface temperature variations we forward continue each log into the following log (cyan line, Figure 3). In this procedure we use a Laplace transform on the current log and, in an iterative procedure, find the linear trend that produces the minimum misfit when this log is forward continued and compared the following log [*Harris and Chapman*, 2005]. The Laplace transform uses the first log as the initial condition so that a reference temperature does not need to be used. In this manner the 1978 log is forward continued into the 1990 log, the 1990 log is forward continued into the 1992 log, and so on. This forward continuation modifies the temperature observations according to the diffusion equation in two ways. High wave number variations are attenuated and because each linear change is positive, anomalous temperatures have greater magnitude at greater depths relative to the original profile. The assumption of a linear change in surface temperature is the most conservative scenario that incorporates a changing surface condition. In general the fits at long wave numbers are very good. It is interesting to note that the high wave number oscillations in the lower part of the reduced temperature profiles are effectively diffused away over periods of 1 and 2 years, for example as shown by the 1990, 1992, and 1993 logs at GC-1 and their forward continuation, or the high wave number variations between approximately 40 and 60 m in borehole SI-1. Unfortunately, because in most cases logging starts at a depth of 20 m, below the penetration of the high-amplitude annual wave, we do not have great sensitivity to the magnitudes of the linear trends and a range of trends fit the data equally well. However, all linear trends indicate ongoing surface warming. To explore sensitivity over the full time period of repeat logs, we forward continued the initial logs into the most recent logs to estimate the linear change in surface temperature. The amplitude of the temperature change computed from best fit linear trends between 1978 and 2007 are 0.9, 0.7 and 0.7°C, at GC-1, SI-1, and DM-1, respectively (Table 3). The amplitude of each linear trend is the same within uncertainties consistent with their geographic settings and proximity. Sensitivity is improved and root mean square (RMS) misfits are 0.01, 0.03, and 0.03°C for boreholes GC-1, SI-1, and DM-1, respectively. The low RMS misfit suggests that the departures from the background thermal regime can be understood in terms of a changing surface temperature condition. The negative reduced temperatures at GC-1 are puzzling (Figure 3), but this analysis indicates that over the period for which we have repeated temperature logs, each borehole site shows the same magnitude of warming. The difference in the GC-1 repeat temperature profiles relative to SI-1 and DM-1 is the initially cool state.

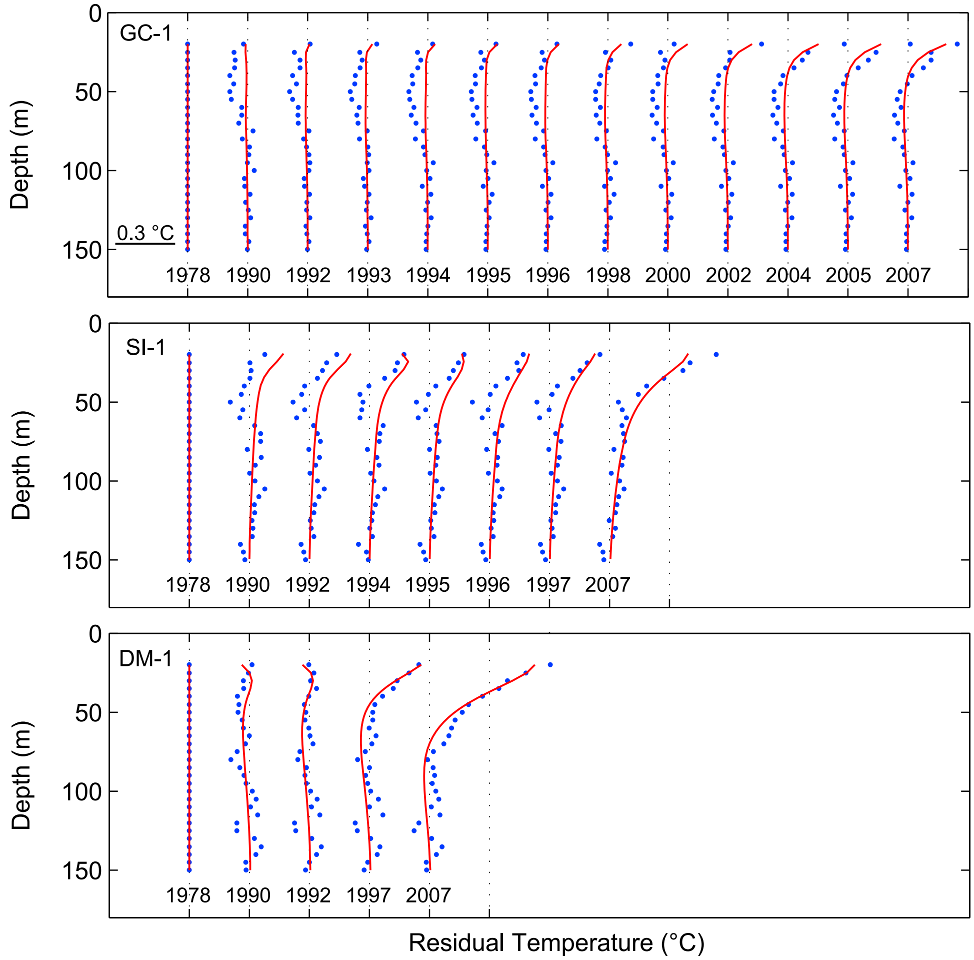

Figure 4. Temperatures differences (circles) relative to the 1978 log. Model fits (red lines) are computed from the associated surface air temperature records, EPO for GC-1, Wendover for SI-1, and Deseret for DM-1.

[17] To isolate subsurface temperature variability between 1978 and 2007 and to remove curvature due to steady state processes we difference the repeated temperature profiles. Figure 4 shows differences between temperature logs for each site relative to the original 1978 log. At GC-1, the temperature difference plot for 1990 shows coherent but small negative temperatures between 25 and 70 m that are a maximum at approximately 40 m depth. While this anomaly is small it is larger than the small fluctuations below 100 m and therefore likely significant. With time this anomaly spreads out and attenuates so that by 2007 it is centered at a depth of approximately 70 m. Starting in approximately 2002 temperature differences above 30 m in GC-1 become positive and increase with time so that by 2007 positive reduced temperatures extend to a depth of approximately 50 m.

[18] Residual temperature variability at SI-1 is considerably larger than at GC-1 particularly in the shallow part of the borehole (Figures 3 and 4). At SI-1 between 1978 and 1990 changes in temperature are small and the fluctuations in the 1990 difference profile may mostly reflect noise (Figure 4). At about 50 m depth a high wave number negative anomaly appears both persistent and stationary in time. This is in the region of high-amplitude variations in the reduced temperature profiles (Figure 3) and is likely due to convection. The sharpness of these anomalies indicates that it is probably not due to climatic variations, and indeed is attenuated in the forward continuation analysis. Small temporal variations in convection may be may be responsible for the persistence of this anomaly. Starting with the 1992 log, shallow temperature differences start to show a coherent trend toward positive values and by 2007 this anomaly extends to about 75 m. This depth extent is consistent with 30 years of warming. At DM-1 trends similar to those observed at SI-1 are present. These differences suggest a stable surface temperature between 1978 and 1992 at DM-1, but by 1997 large temperature differences are present that grow in amplitude and depth through 2007.

3. Surface Air Temperature Records

[19] To understand these transient borehole temperature variations more quantitatively we now turn to meteorological data to test if the observed pattern of subsurface temperature changes are consistent with SAT records. Spe-

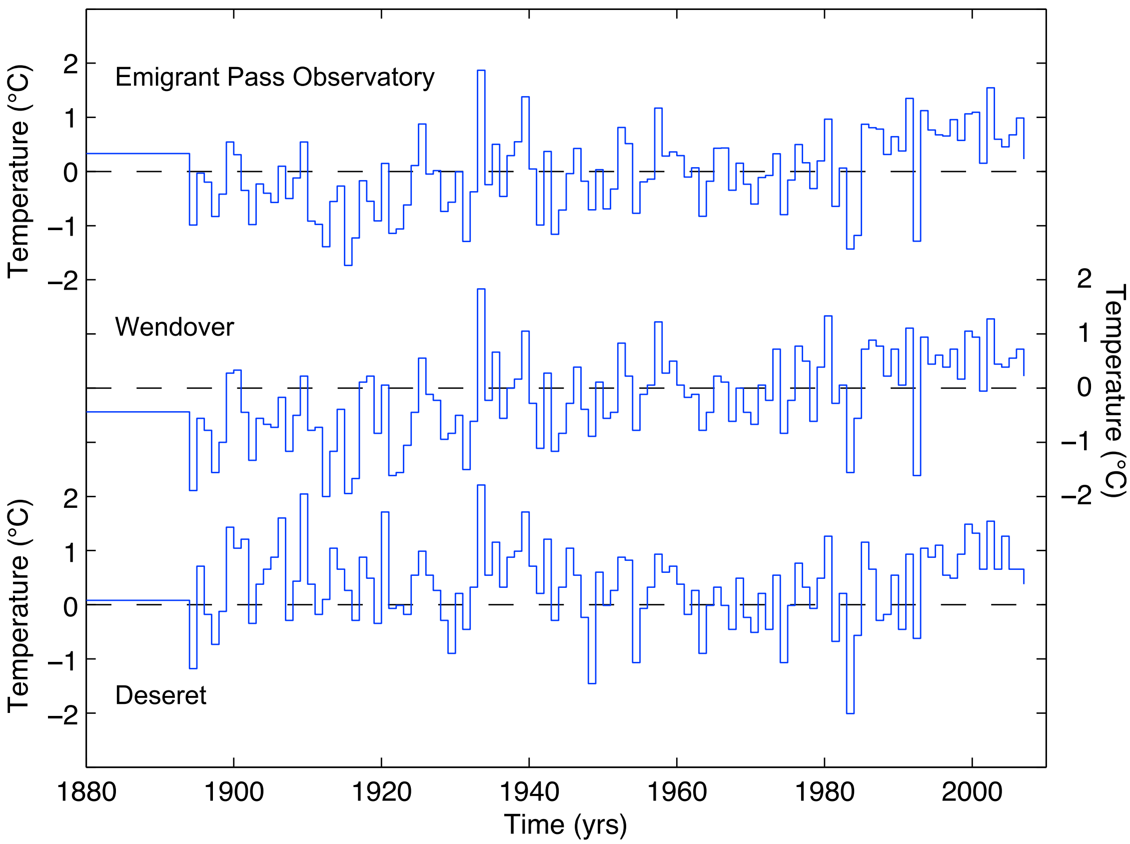

Figure 5. Annual mean surface air temperature (SAT) records for three sites. Data for Wendover and Deseret are drawn entirely from the U.S. Historical Climatology Network used in this study. Data for Emigrant Pass Observatory include a weighted average of annual means from Oakley, Idaho, and Wendover, Nevada, from 1890 to 1993, and the on-site observatory EPO since 1993. Annual means are relative to the 1961–1990 mean temperature.

cifically, we use SAT time series as forcing functions at the ground surface and assess how well they can reproduce both the borehole observations of reduced temperature (Figure 3) and temperature differences (Figure 4).

[20] SAT records reported in this study come from several sources. In the fall of 1993 a meteorological station next to borehole GC-1 (Figure 1) was established. Instrumentation and the first annual cycle of data are reported by *Putnam and Chapman* [1996]. *Bartlett et al.* [2006] analyzed the first decade of data and showed that most variability in shallow (0 to 1 m) ground temperatures could be explained by variations in solar insolation during the summer and the presence or absence of snow cover during winter months. For times prior to 1993 and to fill in data gaps, we use SAT data from U.S. Historical Climatology Network (USHCN) stations at Oakley, Idaho, 79 km to the north and Wendover, Nevada, 93 km to the south [*Karl et al.*, 1990; *Menne et al.*, 2009]. Meteorological stations comprising the USHCN have a relatively long temperature time series, a predominantly undisturbed environment around the site, and limited station relocations. Mean annual departures from these two SATs are conjoined with data from EPO based on weighted averages. Weights are estimated by comparing monthly USHCN data with monthly EPO data over the common period of overlap, 1994 through the present. The best fitting weights are 0.5 for both Oakley and Wendover, likely representing a combination of geographical influences and distance from the EPO site. The composite GC-1 site SAT record uses EPO data where it is present and the weighted average of data from Oakley and Wendover where EPO data is not present (Figure 5).

[21] SAT data used with boreholes SI-1 and DM-1 are from USHCN network stations [*Menne et al.*, 2009]. We compare subsurface temperatures at SI-1 with Wendover, a separation distance of 40 km; subsurface temperatures at DM-1 are compared with Deseret, a separation distance of 50 km. The temperature change amplitude calculated from the linear warming trends between 1978 and 2007 at EPO, Wendover, and Deseret are 1.1, 0.7 and 1.2°C, respectively, and can be directly compared with those obtained from boreholes (Table 3). Like the linear trends fit to the reduced temperature logs in the forward continuation analysis, these linear trends are also approximately the same.

4. Temporal Changes in Subsurface Temperature

[22] For comparison purposes, we produce synthetic reduced temperature profiles for each site by assuming that the SAT time series represents the surface forcing function at each borehole. The SAT series is diffused into the Earth

Table 4. POM and Thermal Diffusivity for Synthetic Temperature Calculations[a]

Borehole	POM (°C)	α ($\times 10^{-6}$ m^2 s^{-1})	RMS (°C)
GC-1	0.33 ± 0.05	0.27 ± 0.06	0.008
SI-1	−0.44 ± 0.03	1.03 ± 0.67	0.008
DM-1	0.08 ± 0.05	1.66 ± 0.67	0.011

[a]POM is the preobservation mean, and α is the thermal diffusivity. Uncertainties are 95% confidence limits. The POM is relative to the 1961–1990 mean temperature.

as a sequence of n individual step functions of amplitude ΔT_i and time prior to the borehole temperature log, τ,

$$T_t(z) = (\mathrm{POM} - T_1)\mathrm{erfc}\left(\frac{z}{\sqrt{4\alpha\tau_1}}\right) + \sum_{i=2}^{n} \Delta T_i \mathrm{erfc}\left(\frac{z}{\sqrt{4\alpha\tau_i}}\right), \quad (4)$$

where the two unknowns are the preobservational mean, POM [*Chisholm and Chapman*, 1992], and the thermal diffusivity, α. The complementary error function is denoted by erfc. The POM is the initial condition corresponding to the long-term mean temperature and represents a weighted average surface temperature prior to the beginning of the meteorological data. In practice it is determined by minimizing the misfit between the SAT record and the reduced temperature profile [*Harris and Chapman*, 2001]. Just as the reduced temperatures are defined relative to T_o, changes in SAT are defined relative to the POM.

[23] Figure 3 shows synthetic borehole temperature profiles produced from SAT data for each reduced temperature log. In general the fits are quite good with synthetic transients fitting both the magnitude and depth extent of reduced temperatures.

[24] The POM associated with the GC-1/EPO comparison is greater than the 1961–1990 annual mean (Table 4) and this combination produces the negative reduced temperatures observed in the logs. By 1990 annual temperatures largely exceed the POM but positive reduced temperatures are still not observed below 20 m, although there is strong evidence of warming temperatures in the upper portion of GC-1 by the late 1990s as shown in by the positive hook in reduced temperatures (Figure 3). The POM associated with the SI-1/Wendover comparison is almost half a degree below the 1961–1990 mean temperature. This relatively low POM produces the strong warming observed in the SI-1 model fits. Finally, the POM associated with the DM-1/Deseret comparison is close to the 1961–1990 mean temperature and accounts for the relatively small reduced temperatures until about 1997 when the annual means are well above the 1961–1990 mean temperature.

[25] It is interesting to note discrepancies between the synthetic and observed transient temperatures. At GC-1 discrepancies are present in the 2004, 2005, and 2007 comparisons (Figure 3). Synthetic profiles show a cooling "bulge" that is associated with the generally low temperatures between approximately 1960 and 1980 at EPO (Figure 5). This feature is not very well captured by the reduced temperatures, although the forward diffusion model with linear surface temperature change does reproduce it well (Figure 3), as do the temperature differences (Figure 4). This discrepancy does not seem to be correlated with either snow or rain events, factors not taken into account with our simple model. It is possible that subtle changes in micrometeorological variables at the site may account for this discrepancy at GC-1. At SI-1 starting in 1990 the shallow portion of the synthetic profile is warmer than the reduced temperature. With time the reduced temperatures become more positive than the synthetic, suggesting that the ground at SI-1 is warming more quickly than the SAT data at Wendover. At DM-1 the synthetic profile fits the reduced temperature profile general shape extremely well at long wavelengths but does not fit short wavelength fluctuations particularly well. Part of these misfits may be due to steady state curvature in the reduced temperature profiles not related to surface temperature change.

[26] The temperature difference logs (Figure 4) avoid complications from steady state processes or effects that cause curvature in temperature-depth profiles. We produce synthetic difference profiles from SAT data by computing diffused versions of the forcing function between 1978 and successive logging times in a single step using,

$$T_{res}(z) = \left[(\mathrm{POM} - T_1)\mathrm{erfc}\left(\frac{z}{\sqrt{4\alpha(\tau 1)_1}}\right) + \sum_{i=2}^{n1} \Delta T_i \mathrm{erfc}\left(\frac{z}{\sqrt{4\alpha(\tau 1)_i}}\right)\right] - \left[(\mathrm{POM} - T_1)\mathrm{erfc}\left(\frac{z}{\sqrt{4\alpha(\tau 2)_1}}\right) + \sum_{i=2}^{n2} \Delta T_i \mathrm{erfc}\left(\frac{z}{\sqrt{4\alpha(\tau 2)_i}}\right)\right], \quad (5)$$

where the terms in the first set of brackets refer to the 1978 log and terms in the second set of brackets refer to the second log. We explicitly show this equation to emphasize that while each temperature difference (ΔT_i) prior to 1978 is the same, the weights change slightly because of the difference in time prior to the respective logs, either $\tau 1$ or $\tau 2$. At GC-1 and SI-1 the modeled differences show a monotonic warming trend consistent with general warming trends in the SAT forcing function relative to the 1961–1990 mean temperatures (Figure 4). At Deseret there is a sharp step in warming at about 1995 and this is manifested in the modeled difference as a strong warming trend. These plots show that in general ground temperatures at GC-1 and DM-1 between 1978 and 2007 have kept pace with warming at their associated surface air temperature sites, while ground temperatures at SI-1 appear to be warming more quickly than those at Wendover.

[27] Finally, we investigate the sensitivity of our solutions to the two free parameters POM and α. Figures 6a–6c show the RMS misfit comparisons between reduced temperature (Figure 3) at each borehole, GC-1, SI-1, and DM-1 and the synthetic profile computed from its associated SAT record; Figures 6d–6f show results for the temperature difference plots (Figure 4) and the synthetic profile differences. In all cases the models fit the data within an RMS value of 0.02°C. In general, the fits are most sensitive to the POM and relatively insensitive to thermal diffusivity (Table 4). The optimum thermal diffusivity at SI-1 and DM-1 are close to 1×10^{-6} m^2 s^{-1}, a default value in many geothermal studies of climate change. At GC-1, the best fitting thermal diffusivity is 0.3×10^{-6} m^2 s^{-1}. *Bartlett et al.* [2006] estimated the thermal diffusivity at GC-1 based on daily tem-

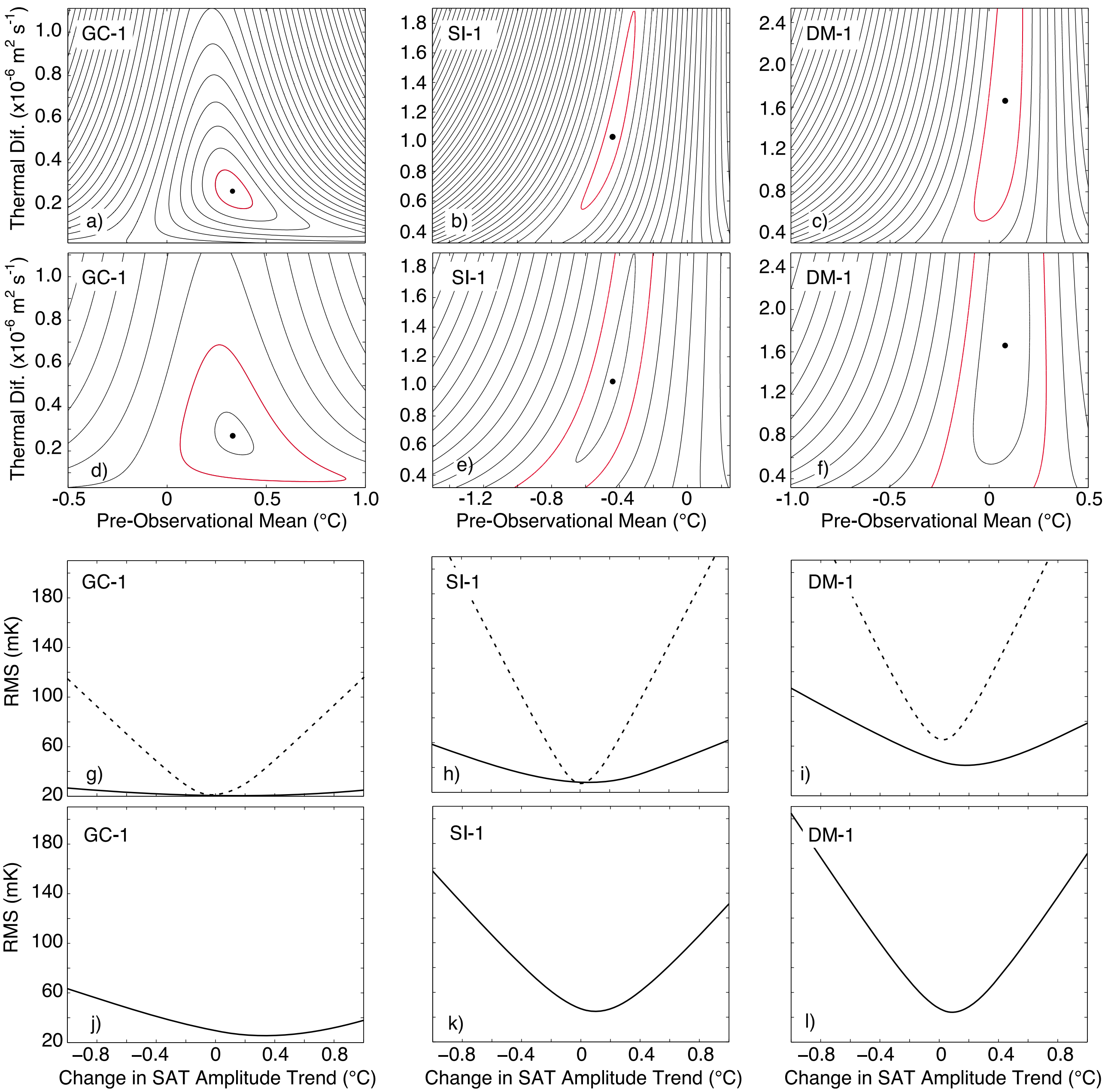

Figure 6. Model sensitivity. (a–c) RMS misfits between reduced temperature profiles and synthetic temperature profiles calculated from SAT data using equation (2). (d–f) RMS misfits between temperature difference profiles and synthetic differences calculated from SAT data using equation (3). The contour interval is 0.04°C, and the inner contour is 0.02 in Figures 6a–6f. The red contour indicates the 95% confidence interval. (g–i) The sensitivity of the model fit between the reduced temperatures and the SAT data to the trend of the SAT data over the entire time series (dashed line) and between 1978 and 2007 (solid line). (j–l) The sensitivity of the model fit between the difference profiles and the SAT data to the trend of the SAT data between 1978 and 2007.

perature series at depth of 0.1 and 1.0 m between 1993 and 2004. They found that the best fitting daily mean thermal diffusivity had a range of 0.78–0.96 × 10^{-6} m^2 s^{-1} with a mean value of 0.88 × 10^{-6} m^2 s^{-1}. Our lower value may be due to a slight depth dependence of thermal diffusivity or surface processes not accounted for in the simple diffusion model [*Pollack et al.*, 2005]. Further, the increased sensitivity of the thermal diffusivity at GC-1 is likely due to the intermediate wave number hook in the shallow subsurface starting about 2002. This added structure increases the sensitivity of the model to the thermal diffusivity.

[28] We show the sensitivity of the reduced temperature profiles to the linear trend in the SAT data by varying the trend of the SAT data over the entire period (Figures 6g–6i). The RMS misfit diagrams indicate (1) that the minimum misfit corresponds to the true SAT amplitude at the 95%

Table 5. Amplitude of the Best Fitting SAT Trend[a]

Borehole	Reduced Temperature Plus Entire SAT (°C)	Reduced Temperature Plus 1978–2007 SAT (°C)	Temperature Differences Plus 1978–2007 SAT (°C)
GC-1	−0.03 ± 0.14	−0.01 ± 0.87	0.35 ± 0.39
SI-1	−0.02 ± 0.08	0.05 ± 0.31	0.10 ± 0.16
DM-1	0.04 ± 0.09	0.19 ± 0.24	0.09 ± 0.12

[a]Values are reported relative to century long trends such that 0°C is equal to the true trend in the SAT series. Uncertainties are 95% confidence limits.

confidence level (Table 5) and (2) that there is good sensitivity to the longest wavelength trend in the SAT series. Both of these observations are consistent with good coupling between air and ground temperatures. The solid lines in Figures 6g–6i show the sensitivity of the SAT time series to its linear trend over the 29-year period for which we have repeated temperature profiles. Using a limited SAT period significantly decreases the sensitivity of the SAT record to the reduced temperature profiles.

[29] Differencing the synthetic transients generated with the SAT records (equation (5)) decreases the sensitivity to the POM and thermal diffusivity (Figures 6d–6f) and increases the sensitivity to the SAT forcing function (Figures 6j–6l) relative to the reduced temperature (solid lines, Figures 6g–6i). In this case we are comparing SAT trends between 1978 and 2007 to temperature differences logged between 1978 and 2007. For our set of repeated logs this time interval is the one in which we have greatest sensitivity. For the 1978–2007 time period the minimum RMS misfits associated with the differenced logs (Figures 6j–6l) are slightly larger than for the reduced temperature profiles but this should not be surprising since these misfits are based on differences. Figures 6j–6l show good sensitivity to the trend during this time interval. In general, the change in best fitting SAT trends are somewhat greater than 0°C at the 95% confidence level suggesting that the differenced profiles indicate slightly greater warming than the SAT records over this time period (Table 5).

5. Discussion

[30] Repeated temperature logs in northwestern Utah demonstrate significant ground warming over a 29-year time period. The three borehole sites show similar warming trends over the 29-year time period, as do the SAT data. Linear warming trends between the boreholes and the meteorological sites are in good agreement (Table 3) and qualitatively suggest coupling. The advantage of repeated temperature logs is the ability to isolate temperature transients within the borehole temperature logs that removes curvature due to steady state processes. A second advantage is increasing sensitivity to SAT records in model fits that provides a more stringent test of ground and air temperature coupling by decreasing sensitivity to the free parameters, the POM and thermal diffusivity.

[31] While model fits between air and ground temperatures are not perfect they are quite good given (1) the distances between boreholes and meteorological stations, (2) the differences of heat transfer in the two systems, convective and radiative, in the atmosphere and conductive in the subsurface, (3) the complexities of processes at the ground surface, and (4) the simplicity of our model (equations (2) and (3)) that casts comparisons in terms of temperature only. Between 1978 and 2007 these models explain 79, 89, and 95% of the variance for GC-1, SI-1, and DM-1, respectively. Part of the reason for the success of this model is that the ground acts as a low-pass filter attenuating high-frequency processes that may be perturbing the relationship between air and ground temperatures. Another reason for the apparently good fits may be the dry desert conditions that characterize these sites with little annual precipitation.

[32] It is interesting to note that the greatest misfit occurs at GC-1 where the borehole and meteorological station are collocated. Because linear trends from GC-1 are similar to those from SI-1 and DM-1, we can rule out anomalous warming at GC-1. Additionally, noise in the borehole temperature measurements at GC-1 is smaller than at SI-1 and DM-1. We attribute the relatively larger misfits between GC-1 and EPO to microclimatological effects that may be due to its location near the northeast edge of the Great Salt Lake. These micrometeorological effects prompted us to install EPO in 1993 and are the subject of ongoing studies.

[33] Repeated temperature logging studies such as this should be expanded to a greater diversity of geographic settings to explore the impact of other processes such as the latent heat of freezing and thawing, and evapotranspiration. These studies could also benefit from a full description of the energy balance at the land surface over decade and longer time scales.

6. Conclusions

[34] Measurement and analysis of repeat temperature-depth logs from three boreholes in northwest Utah lead to the following conclusions:

[35] 1. Temperature measurements at boreholes GC-1, SI-1, and DM-1, made over a 29-year time span provide observational constraints for understanding the relationship between ground and air temperatures. Over the period of observation both ground and air temperatures are warming.

[36] 2. Synthetic temperature profiles calculated from nearby SAT records closely fit observed temperature-depth profiles measured between 1978 and 2007 by matching both the amplitude and pattern of subsurface transient changes. A comparison with forward continued ground temperatures indicates that the observed profiles can be understood in terms of a changing surface temperature.

[37] 3. Differences between temperature logs isolate transient variations in ground temperature that can be ascribed to changes in GST.

[38] 4. Our direct observation of transient temperatures in boreholes, and comparisons between repeated temperature-depth profiles and SAT records offer strong support for using GST histories to complement SAT data and multiproxy reconstructions in climate change studies.

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