JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 103, NO. B4, PAGES 7371-7383, APRIL 10, 1998

Geothermics and climate change
2. Joint analysis of borehole temperature and meteorological data

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Abstract. Long-period ground surface temperature variations contained in borehole temperature-depth profiles form a complementary climate change record to high-frequency, but noisy surface air temperature (SAT) records at weather stations. We illustrate the benefits of jointly analyzing geothermal and meteorological data for two regions in Utah where both high-quality temperature-depth measurements and century long SAT records exist. Transient temperature-depth profiles constructed from SAT time series reproduce in considerable detail borehole transient temperature-depth profiles. Typical rms differences between these transient temperature profiles are less than 13 mK. The analysis yields a preobservational mean (POM) temperature, a parameter describing the long-term mean surface temperature prior to the onset of SAT measurements (i.e., prior to the 20th century). The average POM for these two regions is 0.6° ± 0.2°C cooler than the 1951-1970 average SAT, suggesting that 20th century warming represents a real and significant departure from 19th century surface temperature values. In certain cases, borehole temperature profiles might be used as an independent check on long-wavelength adjustments made to SAT data.

1. Introduction

In the companion article [*Harris and Chapman*, this issue] (subsequently called paper 1), we used borehole temperature-depth anomalies at a number of sites in Utah to reconstruct ground surface temperature (GST) histories. The temperature-depth profiles were analyzed in terms of a functional space nonlinear least squares inversion [*Shen and Beck*, 1991, 1992]. The primary benefit of this algorithm is that the functional form of the solutions are left unspecified and that resolution in the recent past, the period of time for which GST histories and surface air temperature (SAT) records overlap, is increased relative to the simple functions used in previous interpretations [*Chisholm and Chapman*, 1992; *Harris and Chapman*, 1995]. In paper 1, we paid particular attention to the resolution of this method and emphasized that while the temperature resolution is quite good, the temporal resolution drops off rapidly as a function of time in the past.

The purpose of this paper is to document how transient borehole temperature-depth profiles can be combined with surface air temperature (SAT) records to take advantage of the high-frequency content of the SAT record in the recent past and the low-frequency content of transient borehole temperatures in the more distant past. This complementary approach can strengthen the confidence that each signal is responding to similar surface warming and leads to greater insights into the nature of surface temperature variations.

Paper number 97JB03296.
0148-0227/98/97JB-03296$09.00

At the outset, it is important to recognize differences between the signal of surface warming contained in SAT records and in borehole temperature profiles.

1. The most important difference for our purposes arises from the different nature of heat transfer in the two systems. Air temperature responds rapidly to convective heat transfer in the atmosphere, whereas subsurface rock temperature responds slowly by conductive heat transfer to surface temperature variations in the vicinity of the borehole. The frequency content of the two signals is therefore very different.

2. SATs are discrete measurements, either at specific times of the day or daily maximum and minimum points. These discrete measurements are combined into average daily, monthly, and annual temperatures. Borehole transient temperatures, in contrast, integrate the surface temperature continuously in time.

3. Air temperature measurements have been made at a few observing stations since 1750. However, comprehensive coverage is restricted primarily to this century. In western and southeastern Utah, SAT records have been kept since the late 1800s in selected weather stations and broadly since 1911. Because rocks have a low value of thermal diffusivity, the upper 300 m of the Earth contains a thermal memory of surface temperature variations that extends farther into the past than SAT records.

4. Not only is the frequency and temporal content different, but the magnitudes of average temperatures are also different. It is well known that in continental climates, ground temperatures are warmer than air temperatures [e.g., *Chang*, 1958; *Powell et al.*, 1988]. This is simply a result of the ground absorbing more solar radiation than the atmosphere. All of

these factors lead to important differences between the nature of retrievable signals, such that simply overlaying GST solutions on SAT time series is not appropriate.

Differences in vegetation, solar radiation as a function of terrain, rainfall and cloud cover can have pronounced effects on the mean annual GST [*Lewis and Wang*, 1992; *Putnam and Chapman*, 1996], and it is important to use results from geothermal climate change observatories to assess whether the slow evolution of these effects can rival the effects of changes in air temperatures (SAT record) that have been observed. Variations in the offset between the ground and air temperatures through time are difficult to ascertain, but progress is being made at sites where air and ground temperatures are being measured simultaneously [*Putnam and Chapman*, 1996; *Baker and Ruschy*, 1993]. Detailed investigations of the tracking between air and ground temperatures at the same site and of how surface ground temperature changes propagate into the subsurface where they are later measured in borehole temperature-depth logs are underway [*Putnam and Chapman,* 1996; *Gosnold et al.*, 1997], but the detailed tracking of ground and air temperatures over years to decades requires more time.

Several studies have shown that synthetic temperature-depth profiles computed by using SAT records at nearby weather stations as forcing functions successfully reproduce borehole temperature perturbations [*Lachenbruch et al.*, 1988; *Chisholm and Chapman*, 1992; *Harris and Chapman*, 1995, 1997]. These studies show that borehole temperature perturbations have the potential to track long-term trends in surface temperature, and once tracking of ground and air temperature changes are demonstrated for a region, geothermal data can be integrated with SAT time series to complement the direct record of temperature change at the Earth's surface.

After a simple interpretation of the SAT data, we emphasize the complementary nature of SAT and borehole transient temperatures. Correlations between these two signals suggest that both are responding to a similar signal of surface warming. For time periods in the recent past in which coverage of the two signals overlap, a complementary analysis can be used to either support the validity of both signals or highlight potential problems. In the more distant past, prior to the advent of the instrumental record, analysis of borehole temperature records can be used to establish a reference frame for interpreting contemporary SAT trends of warming or cooling.

2. Meteorological Data

Meteorological data used in this study are drawn from the U.S. Historical Climatology Network (HCN) [*Easterling et al.*, 1996]. The HCN data set contains monthly mean, maximum, and minimum temperatures as well as total precipitation for approximately 1200 stations distributed across the contiguous United States. By design, stations comprising the HCN have a relatively long temperature time series, a predominantly undisturbed environment around the meteorological site, and limited station relocations [*Easterling et al.*, 1996]. These data have been inspected [*Easterling et al.*, 1996] and are used in studies of regional contemporary climate change [e.g., *Karl et al.*, 1994]. The HCN data set contains raw SAT (SAT_{raw}) observations, SAT data adjusted for time-of-observation biases (SAT_{tob}), and SAT data adjusted for both time-of-observation biases and nonclimatic biases (SAT_{ncb}). Time-of-observation biases result from different observation schedules and are adjusted using an empirical model based on individual stations throughout the United States [*Karl et al.*, 1986]. Nonclimatic biases due to instrument changes, data gaps, and station relocations are adjusted based on deviations of data from the 20 closest neighbors [*Karl and Williams*, 1987]. Because the meteorological stations used in this study are located near rural communities (populations < 1500 people), we do not assess potential urban heat-island biases.

The meteorological stations, climatic divisions, and borehole sites used in this analysis are shown in Figure 1. The seven climatic divisions within Utah primarily follow drainage divides and represent areas of relative climatic homogeneity. Hanksville, Blanding, Moab, Green River, Thompson, and Bluff lie within region VII of the state meteorological division. These SAT records start around 1911 except for Moab which starts in 1890 and Bluff which starts in 1875. Deseret, Modena, and Wendover lie within region I of the state meteorological division and have SAT records starting around 1900. Figure 2 shows paired SAT time series (SAT_{tob} and SAT_{ncb}) plotted as departures from the 1950-1971 mean value. While this data set includes temperature values through 1994, in anticipation of making comparisons between these time series and the borehole temperature-depth profiles, we truncate the time series at 1978 in western Utah and 1980 in southeastern Utah (the respective

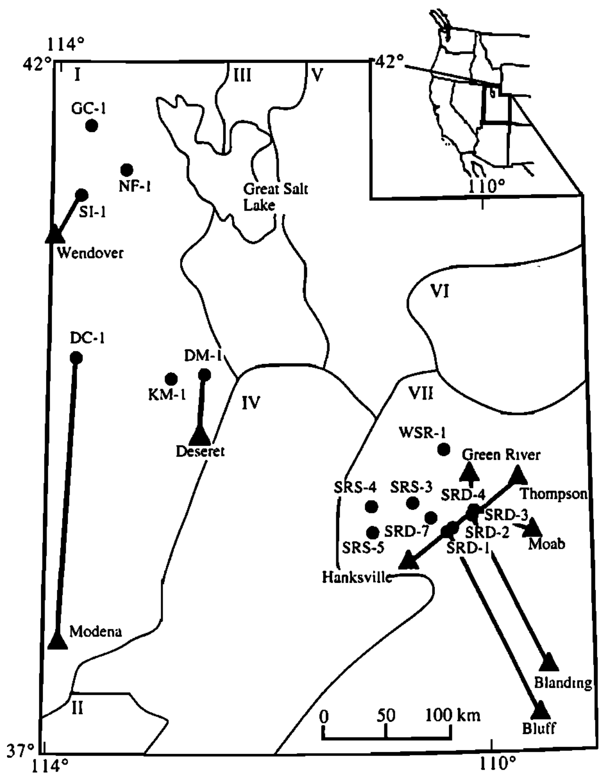

Figure 1. Location map showing boreholes (circles) and meteorological stations (triangles) used for climate reconstruction. Meteorological stations are from the Historical Climatology Network (HCN). Preferred ties between meteorological stations and borehole sites are indicated. Bold curves show climatic divisions in Utah which follow drainage divides and are thought to represent areas of relative climatic homogeneity.

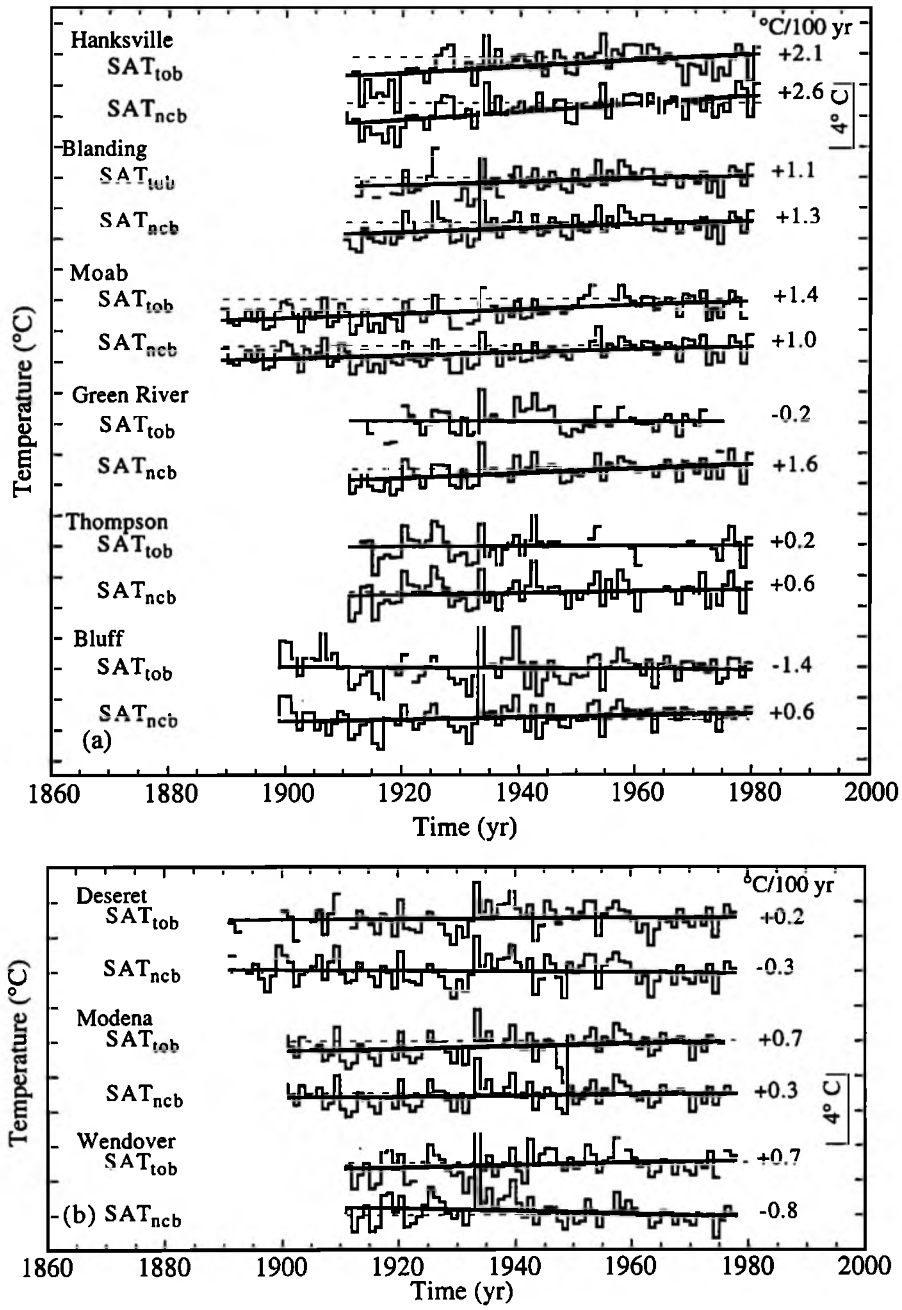

Figure 2. Mean annual surface air temperature (SAT) data for HCN stations in (top) southeastern and (bottom) western Utah. Data are plotted as departures from 1950 - 1971 mean (dashed lines). SAT_{tob} is time series adjusted for time-of-observation bias, and SAT_{ncb} is time series adjusted for both time-of-observation bias and nonclimatic biases. Relative temperatures are used to avoid overlap. Solid lines show linear fit to the data, with the slopes in units of °C/100 yr.

years of borehole logging). Gaps in the SAT time series indicate less than 12 monthly mean temperatures are available for that particular year. The stations used in this study are predominantly coop stations and are not of the highest quality. However, coop stations such as these represent the majority of stations comprising the HCN, and as climate studies become more regional, more of these types of stations are likely to be used.

Linear fits to these time series (Figure 2) serve to highlight overall warming or cooling trends in the data. For each station in western Utah, linear fits to the SAT_{tob} series indicate greater warming than the SAT_{ncb} series. The SAT_{tob} data show an average warming of 0.5° ± 0.3°C/100 yr, whereas the SAT_{ncb} time series show an average cooling of 0.3° ± 0.6°C/100 yr. In southeastern Utah, the differences between SAT_{tob} and SAT_{ncb} data are not as consistent or large; some NCB adjustments increase the 100 year trend while at other stations these adjustments decrease the 100 year trend. On average, the SAT_{tob} data show a warming trend of 0.7° ± 1.0°C/100 yr, while the SAT_{ncb} data show a greater trend of 1.3° ± 0.8°C/100 yr.

The change in magnitude (and sign in western Utah) of these linear trends indicates that the adjustments for nonclimatic biases are large and have important implications for interpretations of contemporary climate change. Like our GST solutions (paper 1), these 100 year trends also indicate variability between stations. We will show that the SAT data from southeastern Utah are generally consistent with the borehole GST solutions in that both show recent warming, while in western Utah the SAT_{tob} data are more consistent with our GST solutions than SAT_{ncb}. We return to this point after a quantitative comparison of transient temperature profiles and SAT time series.

3. Comparing Geothermal and Meteorological Records

Although ground surface temperature (GST) histories can be reconstructed from borehole temperature profiles (paper 1), these histories cannot be compared directly with SAT histories. GST reconstructions are products of the Earth's heat conduction filter, and thus to make a comparison between reconstructed GST and SAT we must consider the SAT record as an input function and pass it through the same filter. We can then compare synthetic temperature-depth transients calculated from SAT data with borehole transient temperatures. A good correlation between the synthetic transient and the borehole transient would provide strong evidence that borehole temperatures are tracking air temperatures.

A synthetic transient temperature-depth profile $T_r(z)$ can be computed by expressing a SAT time series as a sequence of N individual step functions of amplitude ΔT_i and time prior to the borehole temperature measurement τ_i, [*Carslaw and Jaeger*, 1959],

$$T_r(z) = \sum_{i=1}^{N} \Delta T_i \operatorname{erfc}\left(\frac{z}{\sqrt{4\alpha\tau_i}} \right), \qquad (1)$$

where erfc is the complementary error function. The initial surface temperature, however, must be determined; we set this to a long-term or preobservational mean (POM) temperature, written explicitly in terms of the first-step change in temperature, $\Delta T_l = (T_l\text{-POM})$. The POM represents a weighted average of surface temperatures prior to the onset of the SAT record at τ_l. Just as transient borehole temperatures are defined relative to the surface temperature intercept T_o changes in SATs can be defined relative to a POM. Investigations into the resolution of GST histories show that for times prior to 100 years ago high-frequency information is lost due to diffusion [*Clow*, 1992], and there is little harm in parameterizing the time before these SAT's (i.e., prior to about 1880 for Utah stations) in terms of a single average temperature. Indeed, our GST solutions (paper 1, Figures 2c and 3c) show that not much information is lost from the average GST histories by adopting this approach.

We use the long-wavelength sensitivity of borehole transient temperatures to determine the POM. Specifically, we search for a POM value that minimizes the misfit between the borehole transient temperatures and synthetic transient temperatures computed from the SAT record. This technique is illustrated in Figure 3 for the HCN station at Wendover paired with a borehole site, Silver Island SI-1, 30 km to the northeast (Figure 1). Departures from the 1951-1970 annual mean SAT_{tob} record at Wendover are shown in Figure 3a; this time series is used as a forcing function to compute a synthetic transient temperature-depth profile. Gaps in the SAT time series are filled by interpolating between values. Most of these gaps are relatively short, and this technique is a conservative approach that minimizes errors in calculating synthetic transient temperatures. For illustration purposes only, three possible choices of POM, each separated by 0.5°C, are shown and quoted relative to the 1951-1970 mean SAT value. A POM of 0.0°C might represent the minimal long-term warming hypothesis, a POM of -0.5°C would represent a century of warming from a baseline temperature close to temperatures at the beginning of this century, and a POM of -1.0°C would be illustrative of extreme warming. Synthetic transient temperature profiles (solid lines in Figure 3b) are calculated by coupling these particular values of the POM with the SAT data shown and using this combination as a forcing function at the surface of the Earth. For the highest initial value (POM I) of 0°C, the SAT record is cooler on average for the early part of this century and is manifested in the transient temperature profile as a slight negative anomaly in the depth range 150 to 20 m followed by a positive temperature anomaly produced by the decade of warming to 1978. The synthetic temperature profile visually confirms the null hypothesis of insignificant long-term warming in this scenario. In contrast, for the lowest initial value (POM III) of -1°C, the SAT record is nearly always warmer than this long-term average, and the transient temperature profile is positive throughout its entire depth range. An intermediate initial value (POM II) of -0.5°C produces an intermediate transient.

The synthetic curves computed from SAT data can be compared to field geothermal observations, even though air and ground temperatures have a variable offset from site to site, because we are isolating the transients in both data sets. Thus Figure 3b shows the comparison of synthetic transient profiles for POMs I, II, and III with a single borehole transient (SI-1) by matching the model and observed transients at a depth of 150 m (i.e., the bottom of the hole). Note the attenuation of the high-frequency SAT fluctuations; air temperature variations of almost 4°C in the annual means are damped to a few tenths in the subsurface temperature variations. Among the simulations shown, POM II clearly matches the SI-1 reduced temperature profile (solid circles) most closely, and surface temperature histories I and III are definitely eliminated by this comparison. In practice, we sweep POM space at 0.01°C intervals; the inset to Figure 3b shows sensitivity of the misfit between the borehole and synthetic transient temperature profiles to the choice of long-term mean. A sharp trough in the misfit diagram indicates that the POM is a robust temperature estimate. Furthermore, the excellent correspondence between the borehole transient temperature profile and the synthetic transient profile (POM II in Figure 3b) in both amplitude and depth, produced with just one free parameter (i.e., the POM), supports our contention that subsurface borehole temperatures can be gainfully combined with meteorological data in climate change studies.

The SAT_{tob} 1951-1970 mean value for Wendover is 11.2°C. As the best fitting POM relative to this mean is -0.5°C, the long-term average or baseline temperature at Wendover prior to 1911 is inferred to be 10.7°C. Although the simple model used here extends that value to infinite time prior to the SAT record, in practice borehole temperature perturbations in the first 160

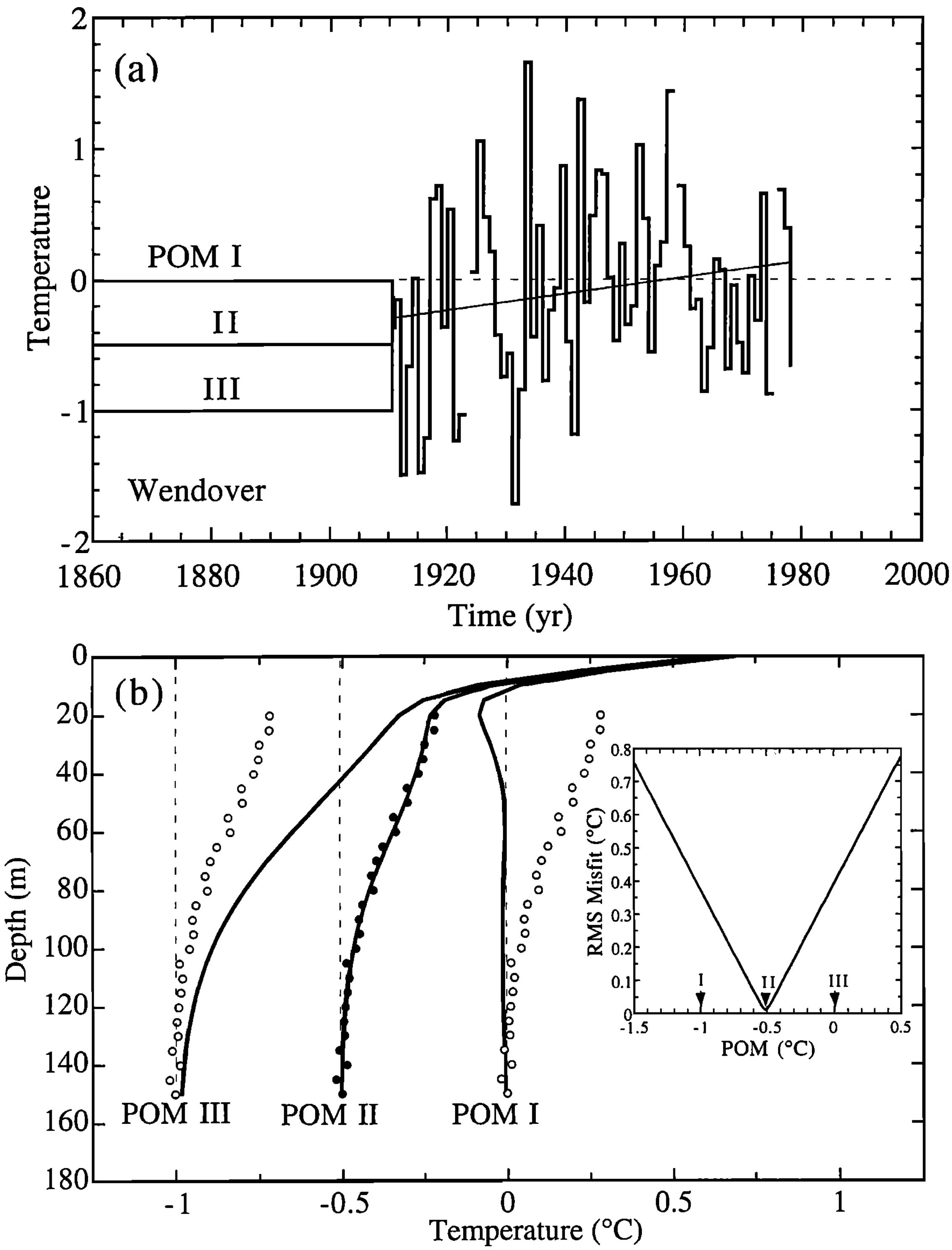

Figure 3. Determining the preobservational mean (POM). (a) Mean annual departures of SAT_{tob} data for Wendover for the period 1911-1978; dashed line is 1950-1971 mean. Linear fit to data is also shown. Horizontal lines marked POM I, II, and III show three different choices of POM. The surface air temperature data coupled with a particular choice of POM are used as a forcing function to compute synthetic temperature perturbations below. (b) Temperature perturbation for SI-1 (circles). Three synthetic transient temperature-depth profiles constructed using SAT data from Wendover coupled with a corresponding choice of POM are shown. Temperature perturbations are plotted relative to POM. Inset shows rms misfit as a function of the POM and illustrates the best fit for POM II.

Table 1. Root Mean Square Misfits Between Meteorological Stations and Reduced Temperature Profiles for Western Utah

	Meteorological Stations			
Boreholes	Wendover	Deseret	Modena	Average (s.d.)
GC-1	25	20	44	30 (10)
NF-1	14	21	7	14 (6)
SI-1	5*	16	12	11 (4)
DC-1	14	30	7*	17 (10)
DM-1	14	6*	30	17 (10)
KM-1	30	40	13	28 (11)

Entries are rms misfits, in milliKelvins, between a borehole transient temperature profile and a synthetic temperature profile computed from the SAT time series.
* Preferred ties.

m depth range are most sensitive to the first 100 years prior to observations, that is, the 19th century mean temperature. If a 50 mK (i.e., 5 times rms noise level of 9 mK) misfit between borehole and synthetic temperature-depth anomaly is considered significant, then this method of combining borehole temperatures and SAT data is capable of estimating 19th century average temperature to better than 0.1°C.

Ties between other meteorological stations and borehole sites are evaluated by computing the rms misfit for the best POM. In western Utah, where all the boreholes are the same depth, the entire transient temperature profile is used to calculate the rms difference. In southeastern Utah, however, where the boreholes have variable depths, the rms difference is calculated to a depth of two thermal lengths $l = 2\sqrt{4\alpha\tau_1}$, where τ_1 is the time of the first annual mean for that particular meteorological station. This gives results that are not biased toward deeper boreholes.

Because the HCN includes SAT time series containing the raw data, data adjusted for time-of-observation biases, and data adjusted for nonclimatic biases, we performed comparisons with all three time series. In southeastern Utah, we found that SAT_{ncb} gave consistently smaller misfits than either of the other two time series, whereas in western Utah, SAT_{tob} gave consistently better fits. Comparisons between borehole data and SAT_{tob} in western Utah and for borehole data and SAT_{ncb} in southeastern Utah are given in Tables 1 and 2, respectively. The nature of the borehole site - meteorological station ties and a selection of preferred ties are examined first.

Tables 1 and 2 show that it is generally, but not always, possible to produce good fits (rms misfit ≤ 13 mK) between synthetic transients and reduced temperatures for paired sites. Table rows indicate how well a particular transient temperature profile correlates with SAT time series from individual meteorological stations. For each borehole (with the notable exception of GC-1, WSR-1, and SRS-5), we are able to find good fits to meteorological stations. A large average rms misfit as well as the lack of a good fitting pair may indicate that a particular temperature-depth profile might not be reflecting surface temperature trends and therefore is suspect. For example, this calculation demonstrates that, on average, rms misfits between borehole WSR-1 and each of the other meteorological stations are greater than 2 standard deviations from the mean of the other ties, affirming that WSR-1 is probably not tracking surface warming. This calculation supports the decision to reject this borehole from the calculation of the average GST (paper 1, Figure 3c). With the exception of borehole SRS-5, all other boreholes have at least one good tie to a meteorological station (rms ≤ 13 mK). We therefore reject borehole SRS-5 as well. Columns indicate how well individual meteorological stations correlate with boreholes. A poor fit in this case might indicate that a particular time series is suspect. For each of these calculations, we were able to find a good fit to at least one temperature-depth profile; we retain all of the meteorological stations. Although there is not a good match between these meteorological stations and borehole GC-1, other evidence strongly suggests that borehole GC-1 is tracking surface temperature variations [*Chapman and Harris*, 1993; *Putnam and Chapman*, 1996].

Preferred ties are shown in Figure 1, and the rms magnitudes of these ties are indicated by asterisks in Tables 1 and 2. In a few cases, we did not select the minimum misfit but chose a combination of small rms misfit and proximity (e.g., Thompson was tied to SRD-3 instead of SRS-3). It is gratifying that ties giving the minimum rms misfits are, in most cases, also the shortest. Plots of rms misfit between meteorological stations and temperature-depth profiles as a function of distance separating the sites being compared do not yield a clear correlation. This is possibly because of the relatively limited areal extent of the data set as well as a relatively small sample.

We now return to adjustments applied to each SAT times series. For our preferred ties in southeastern Utah, average misfits between the transient temperatures and the synthetic transient temperatures are 30, 25, and 9 mK for SAT_{raw}, SAT_{tob}, and SAT_{ncb}, respectively. These misfits illustrate the progression one expects; each succeeding adjustment brings the correlation between the SAT data and the borehole transients

Table 2. Root Mean Square Misfits Between Meteorological Stations and Reduced Temperature Profiles for Southeastern Utah

	Meteorological Stations						
Boreholes	Green River	Thompson	Moab	Hanksville	Blanding	Bluff	Average (s.d.)
SRD-1	7	10	8	16	12	30	14 (8)
SRD-2	17	9	21	20	10	23	17 (5)
SRD-3	17	8*	13	27	12*	26	17 (7)
SRD-4	7*	19	8*	10*	19	46	18 (13)
SRD-7	46	34	41	60	35	11*	38 (15)
SRS-3	11	5	11	20	7	23	13 (6)
SRS-4	23	13	24	32	14	9	19 (8)
SRS-5	37	47	25	29	45	50	39 (9)
WSR-1	90	80	86	100	83	53	82 (14)

Entries are rms misfits in milliKelvins between a borehole transient temperature profile and a synthetic temperature profile computed from the SAT time series.
* Preferred ties.

into better agreement. In western Utah, however, the average rms misfits between the transient temperatures and the synthetic transient temperatures for the best fitting ties are 16, 6, and 21 mK for SAT_{raw}, SAT_{tob}, and SAT_{ncb}, respectively. The rms misfit for SAT_{tob} is 62% smaller than that for SAT_{raw} and is 70% smaller than SAT_{ncb}. This implies that while the time-of-observation bias adjustment improves the correlation between the SAT time series and the transient temperatures, the nonclimatic bias adjustment does not.

We also made comparisons between transient borehole temperatures and synthetic transient temperatures constructed from SAT maximum and minimum annual temperatures. These comparisons showed relatively larger differences relative to the mean annual temperature comparison. These results are not surprising because transient borehole temperatures are an integrated time average of continuous surface temperature variations.

Fits between the transient temperature profiles and the synthetic temperatures calculated from the POM-SAT model are shown in Figure 4. The synthetic models fit the data very well in both depth and amplitude, especially considering there is only one free parameter (the POM offset) in the analysis. Variance reduction in the transient borehole temperature is about 90%.

Figure 5 shows the best fitting POM level, derived by combining borehole and meteorologic data, for each of the nine meteorologic stations being studied. Results are plotted together with the respective SAT time series. Whereas a time-smeared version of these results is available in the geothermal analysis alone, these POM values can be estimated to tenths of degrees Celsius and, more importantly, are referenced directly to the meteorological data temperature scale. These POM values can serve as baseline temperatures for times prior to the instrumental record against which one can judge 20th Century warming or cooling [*Harris and Chapman*, 1997].

The uniformity of the POM offset (i.e., difference between the POM and the 1951-1970 SAT mean) is striking given the variability of the linear trends to the SAT time series in the

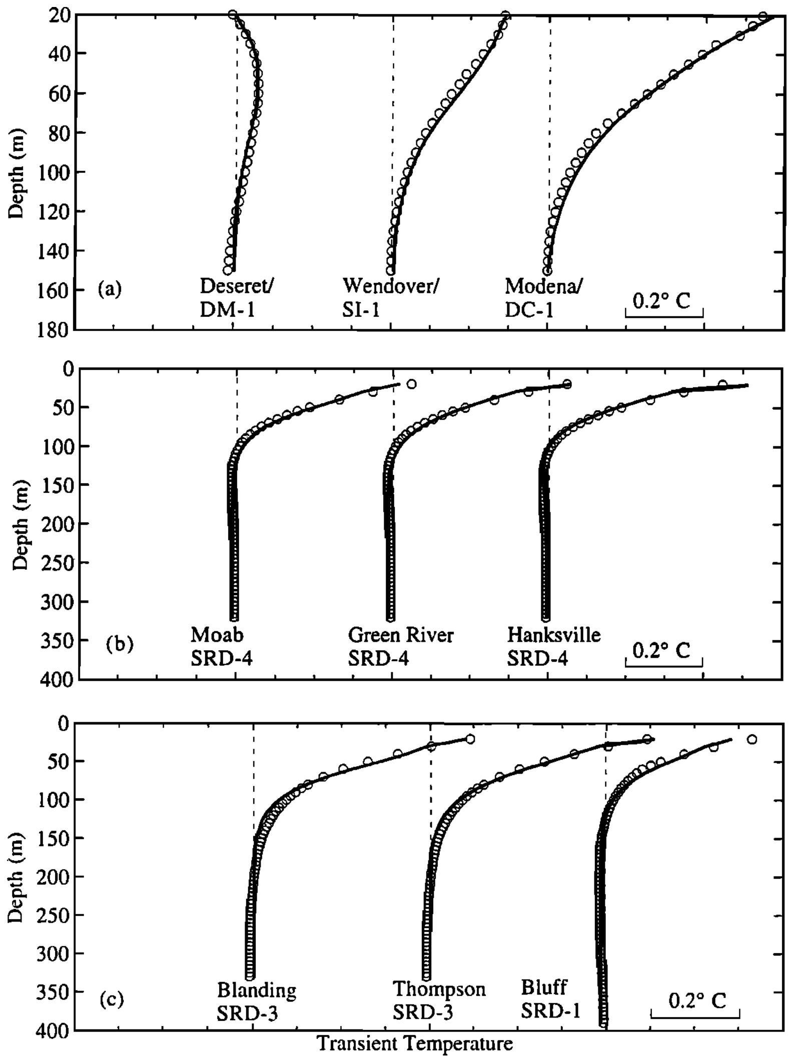

Figure 4. Transient Earth response to POM-SAT models for meteorological stations in Utah. Circles show transient temperature profile computed from functional space inversion. Solid curves show combination of best fitting POM and SAT data. Temperatures are offset to avoid overlap. (a) Ties between meteorological stations and boreholes DM-1, SI-1, and DC-1. (b) Ties between meteorological stations and borehole SRD-4. (c) Ties between meteorological stations and boreholes SRD-3 and SRD-1. Figure 4a shows meteorological stations in western Utah; Figure 4b and 4c show meteorological stations in southeastern Utah.

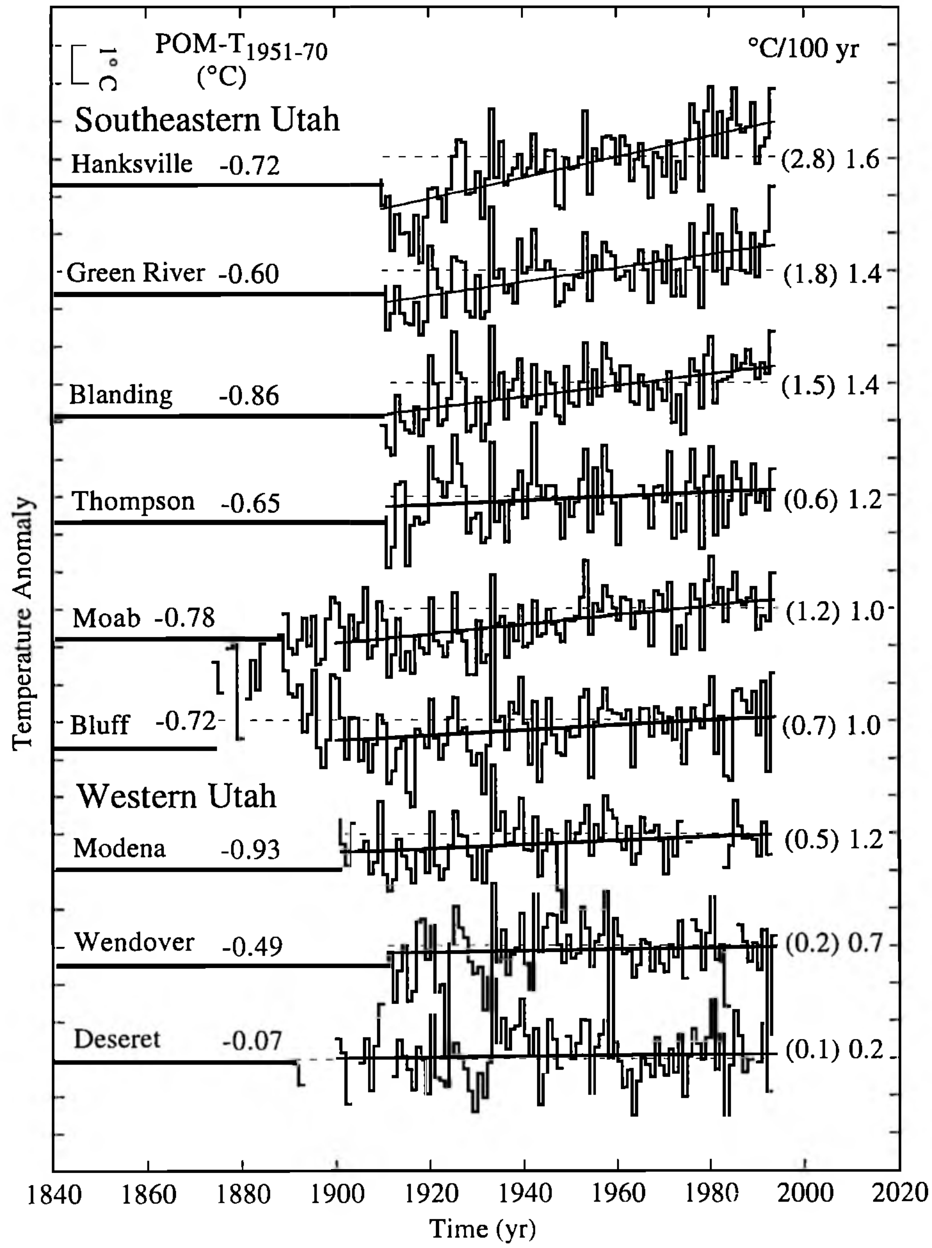

Figure 5. Preobservational mean with SAT time series and linear trends. Top six time series are from southeastern Utah (locations and ties shown in Figure 1) and are adjusted for both time-of-observation bias and nonclimatic biases. Bottom three time series are from western Utah and are adjusted for time-of-observation bias only. Linear century trends based on SAT data alone are also shown. Numerical century trends (°C/100 yr) are computed from SAT data alone (parentheses) and from SAT data constrained by the preobservational mean.

same region (Figure 5). The POM offset for southeastern Utah varies between -0.60°C and -0.86°C with an average of -0.72°C and a group standard deviation of only 0.09°C. In contrast, SAT warming trends at individual stations are highly variable, ranging from +2.8°C per 100 years for Hanksville to +0.7°C per 100 years for Bluff; the group standard deviation is 0.8°C per 100 years. Century-long trends constrained to pass through the POM at the beginning of the SAT record show less variability, with a standard deviation of 0.4°C per 100 years, 50% less than the standard deviation of the linear fits based on SAT data alone. As seen in Figure 5, two HCN stations in southeastern Utah with high apparent temperature change this century (Hanksville and Green River) overestimate the surface temperature change inferred from the combined geothermal meteorological data analysis.

For the small sample in western Utah, the average POM offset is -0.50°C, with a standard deviation of 0.43°C. In this area, two HCN stations with low apparent temperature change (Modena and Wendover) underestimate the surface temperature change this century.

These POM or baseline temperatures preclude that 20th century warming is simply a recovery to normal conditions from an abnormally cool period at the beginning of this century. The POM values also indicate that baseline temperatures in Utah were not much cooler than those prevailing at the turn of the century. For the Utah regions studied and including both the inferred changes to 1951-1970 and subsequent further warming to 1990-1994, the surface temperature has changed about 1°C .

Linking geothermal and meteorologic data thus has provided the following: (1) a good explanation of transient borehole temperatures, suggesting that ground temperatures are tracking air temperatures, and (2) a robust parameter (POM) with relatively tight error bounds that characterizes surface temperatures for times prior to the onset of SATs. Most importantly, this method provides a technique to extend directly the meteorological record of climate change into the past thereby providing a reference frame in which to view contemporary warming.

4. Assessing SAT Data

We now return to the suggestion that high-quality temperature-depth measurements might be used as an independent test of long-wavelength adjustments made to SAT data. For brevity, we focus on the data from western Utah. Figure 6a compares transient temperature profiles at three sites in western Utah with best fitting POM-SAT models for both the SAT_{tob} and SAT_{ncb} time series. As indicated in section 3, both SAT time series provide good fits to the temperature perturbations, although the SAT_{tob} curves have an rms misfit of 13 mK, whereas the SAT_{ncb} curve misfit is 20 mK, 50% higher.

To highlight discrepancies and focus on areas where the borehole or SAT data may be inadequate, we plot (Figure 6b) the difference between the borehole transient temperature profiles and the synthetic transient temperatures based on either the SAT_{tob} data (solid curves) or the SAT_{ncb} data (dashed curves). Note that the overall similarity between the transient temperatures calculated from SAT_{tob} and SAT_{ncb} data, respectively, is strong; they have the same form and show a modest correlation in both magnitude and depth. However, the SAT_{ncb} curve surprisingly predicts transient temperatures that agree less well with observed transient borehole temperatures (shaded area, Figure 6b) than does the SAT_{tob} data.

To move beyond a qualitative assessment of the misfit and toward identifying the long-wavelength components which might be causing the misfit, we model the temperature differences in terms of a "boxcar" event with a surface temperature of magnitude H and a duration extending between time t_1 and t_2 (Figure 7). Because of the process of heat conduction, we can expect only to identify long-wavelength signals and thus do not attempt to interpret high-frequency components. *Lachenbruch* [1994] has developed some "rules of thumb" useful for characterizing a "boxcar" surface temperature event. The depth to the maximum anomalous temperature z_m is related to the average time of the boxcar event t_a through the equation

$$t_a = z_m^2/2\alpha. \tag{2}$$

This is the average thermal length of the two steps comprising the boxcar. The onset of the boxcar surface temperature event is given by

$$t_2 = z_2^2/8\alpha, \tag{3}$$

where z_2 is the bottom of the anomalous temperatures. This equation is based on two thermal lengths or the position where the temperature perturbation is 0.5% of the causal surface temperature change. This depth is near a cusp in the reduced temperature plots as indicated in Figure 7. The end of the boxcar function is then given by $t_1 = t_2 + \Delta t$. The maximum anomalous temperature T_m and the duration of the event Δt can be related to the product $H\Delta t$,

$$H = 4T_m t_a/\Delta t. \tag{4}$$

Table 3 gives the boxcar parameters that yield the shaded regions in Figure 6b, reproducing the misfit between borehole transient temperatures and modeled temperature profiles using SAT_{ncb}. The actual boxcar functions are plotted in Figure 8. To check the efficacy of this model, we compare these boxcars with plots of the nonclimatic bias adjustment. The boxcar "rules of thumb" without further iteration produce signals that fit the long-wavelength adjustments to SAT data well both in sign and in magnitude. Because of the asymptotic nature of heat diffusion, the magnitude of the boxcars is better determined than the timing of the event. The dominant nonclimatic bias adjustment for Deseret, Modena, and Wendover is a positive temperature change of 0.24°, 0.22°, and 0.70°C, respectively. Likewise, the boxcars functions inferred independently for these stations have similar magnitudes, matching the nonclimatic bias adjustment within 0.04°, 0.02°, and 0.3°C, respectively. Additionally, the timing of the boxcar events corresponds generally to the onset time of the nonclimatic bias correction, agreeing with the inferred boxcar events to within 13, 4, and 1 years for Deseret, Modena, and Wendover, respectively. As this example suggests, comparing synthetic transient ground temperatures calculated from SAT time series with the transient component of borehole temperature-depth profiles can indicate the consistency between the two data sets, and has the power to indicate time intervals and magnitudes of SAT data or borehole data that may need to be checked. Thus while the anomalous temperatures are quite small, the geothermal technique has adequate resolving power for these purposes at least in our test region.

Why might the nonclimatic bias correction not work for HCN stations in western Utah? This correction is based on a statistical correlation between a candidate station and its 20 nearest neighbors. The denser the network surrounding a candidate station is, the closer the neighbors are and the more likely the climate will be correlated between stations. The HCN stations we have investigated in western Utah lie in the most sparsely sampled area in the United States [*Karl and Williams*, 1987, Figure 1]. Further, the weather is poorly correlated in the basin and range of the intermountain west [*Briffa and Jones*, 1993]. Thus the network characteristics are less than ideal for this type of adjustment.

There are, of course, uncertainties associated with temperature perturbations. If both sets of HCN data disagreed, it would, in general, not be possible to state that either the temperature-depth data or the HCN data represents more correct values than the other. However, this type of analysis is able to highlight problem areas either in the borehole data, SAT data (and adjustments), or both. It is important to note that the borehole method is most suitable for aiding in long-wavelength adjustments and may provide a means of checking longer-wavelength corrections applied to SAT data. While it is dangerous to extrapolate one example globally, we believe that

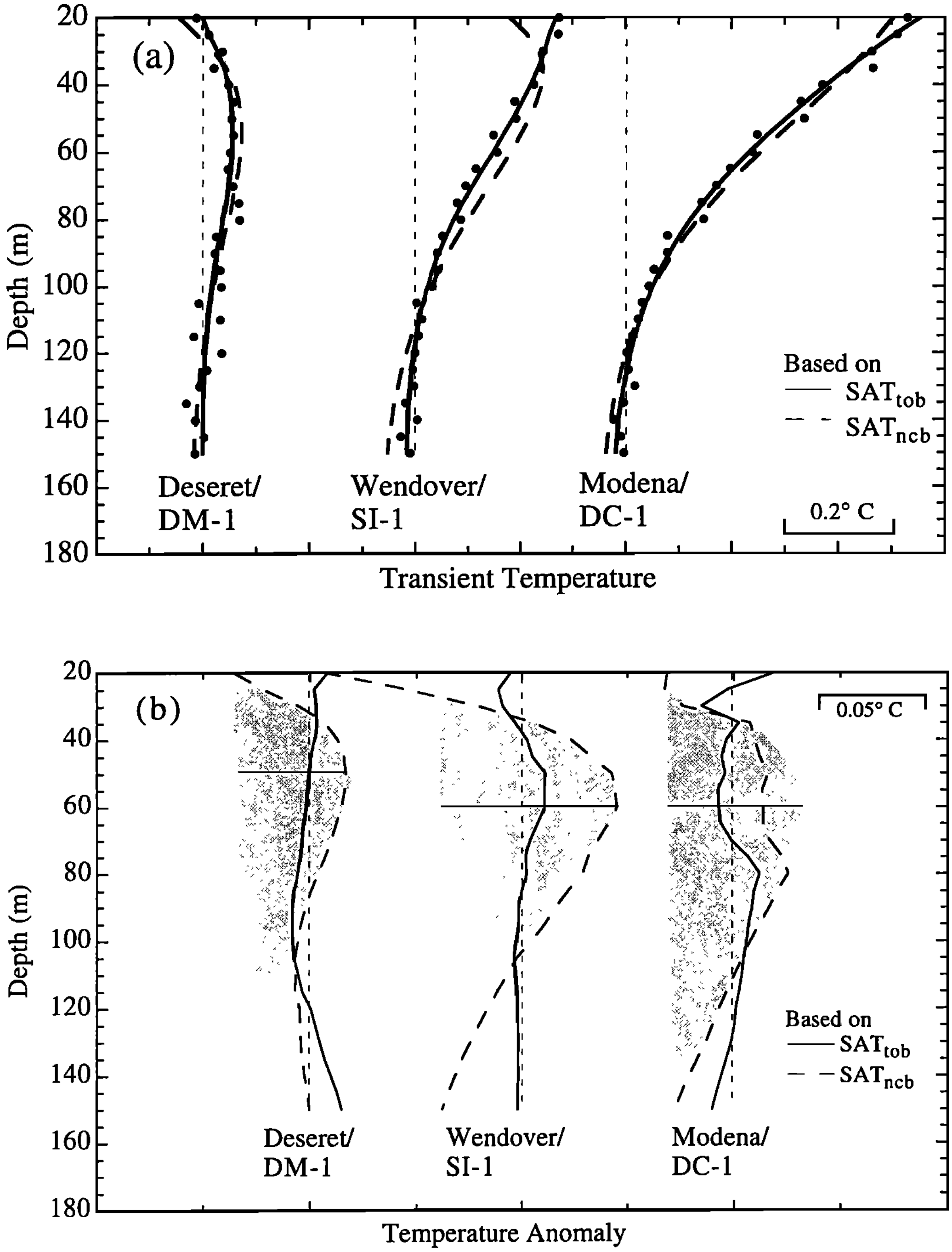

Figure 6. Comparison of transient temperatures computed from SAT-POM models for western Utah. (a) Transient temperatures for boreholes DM-1, SI-1, and DC-1 (circles) with synthetic transient temperature profiles calculated from SAT_{tob} (solid curve) and SAT_{ncb} (dashed curve) and best fitting POM. Model parameters are given in Table 3. (b) Anomalous temperatures calculated as the difference between transient temperature profiles and synthetic transient temperature profiles computed from SAT_{tob} (solid curve) and SAT_{ncb} (dashed curve) data. In each case, the transient profile computed using SAT_{tob} fits the modeled transient temperatures better than SAT_{ncb}. Thin vertical dashed line corresponds to zero anomalous temperature. The shaded area represents the anomalous temperatures interpreted in terms of a boxcar event. Thin horizontal line depicts the depth of the maximum anomalous temperature and its magnitude.

comparing meteorological and geothermal data sets in this manner can build confidence in both data sets. Indeed, our point is not to suggest that the NCB correction is not warranted but to illustrate the advantages of combining SAT data with transient borehole temperatures and to suggest that results of contemporary climatic studies incorporating both types of data are likely to yield more robust results than studies using only one type of data.

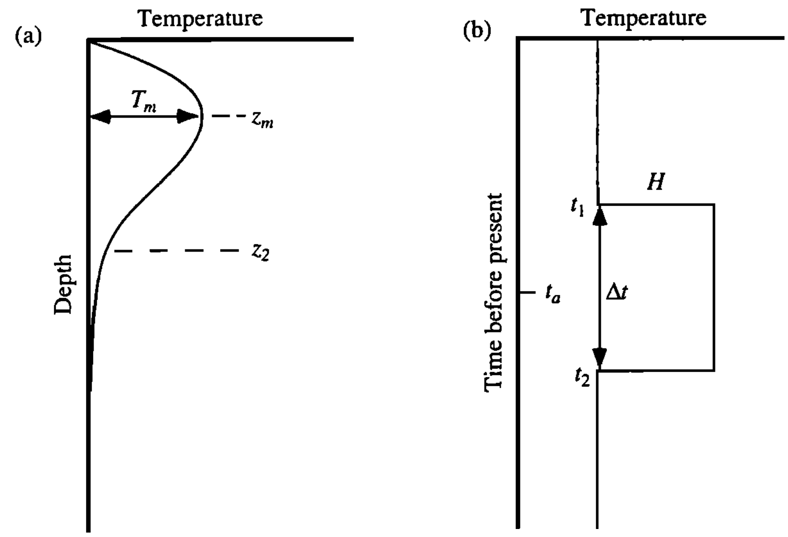

Figure 7. Schematic example and notation used for (a) anomalous temperatures with depth to maximum anomaly z_m, depth to bottom of anomaly z_2, and magnitude T_m. (b) Simple boxcar function representing a surface temperature event of magnitude H (shown at 1/4 size), duration Δt, and average age t_a.

5. Summary

Geothermal temperature-depth data and meteorological surface air temperature data from western and southeastern Utah have been analyzed jointly. This analysis leads to the following observations and conclusions.

1. Air temperature time series are not directly comparable to borehole reduced temperature-depth profiles; air temperatures must be used as an input time series and subjected to Earth's heat conduction filter to compute a synthetic temperature profile for comparison with observations.

2. The SAT series must further be coupled with an estimate of a long-term or preobservational mean (POM) temperature in order to compute the synthetic temperature-depth profile. Computationally, the POM represents an initial condition to the problem; geophysically, it represents a surface temperature averaged over a broad time window prior to the air temperature instrumental record. A POM can be linked directly to a SAT record, for example, to the 1951-1970 mean temperature. Borehole data alone do not allow this resolution because of time averaging.

3. Time series based on a POM and a roughly 100 year SAT record from a weather station reproduces in considerable detail the transient temperature profiles at nearby borehole sites. This observation supports the hypothesis that the Earth's subsurface thermal field contains an accurate record of changing ground surface temperatures and can be related to changing surface air temperatures. We have assumed a constant offset between air and ground temperatures at relevant periods; this assumption requires checking. This comparison, however, also suggested that two of the boreholes (SRS-5 and WSR-1) may not be tracking ground surface temperatures.

4. Average 19th century surface temperatures (prior to the 20th century meteorological observing period) estimated for western and southeastern Utah are -0.50°C and -0.72°C cooler, respectively, than the 1950-1971 surface air temperature means for these regions. The warming to 1990-1994 has been about 1.0°C.

5. We have modeled the misfit between transient borehole temperature profiles and synthetic transient profiles computed using different corrections to SAT data. In western Utah, SAT data adjusted for time-of-observation bias more closely fits

Table 3. Model Parameters

Meteorological Station/ Borehole	POM_{tob}, °C	POM_{ncb}, °C	z_m, m	T_m, °C	t_a, years B.P.*	t_2, years B.P.*	H, °C
Deseret/ DM-1	-0.1	-0.2	55	0.04	47	71	0.2
Modena/ DC-1	-0.9	-0.9	60	0.05	56	88	0.2
Wendover/ SI-1	-0.5	-0.5	60	0.08	56	76	0.4

POM_{tob} and POM_{ncb} are the best fitting preobservational means for ties between SAT_{tob}, SAT_{ncb}, and the borehole data, respectively, z_m is the depth to the maximum temperature anomaly, T_m is the maximum borehole temperature anomaly, t_a is the time of the center of the boxcar event, t_2 is the onset time of the event, t_1 is the end of the event. Δt is the duration, and H is the magnitude of the event.

*Time is with respect to 1978 when the boreholes were logged.

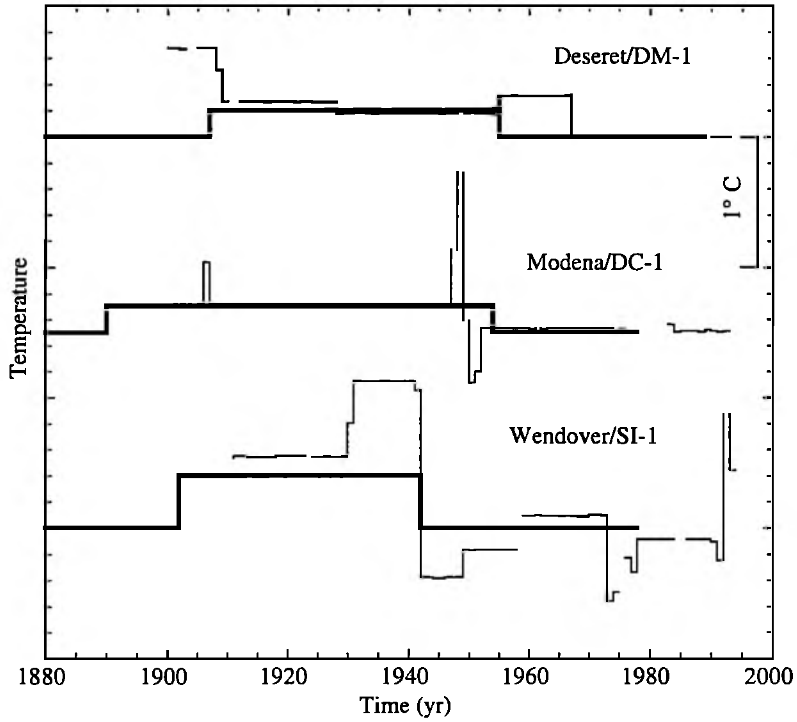

Figure 8. Comparison between nonclimatic bias adjustment made to SAT data for each meteorological station (thin line) and the result of modeling the anomalous temperatures (Figure 6b) as a simple boxcar function are shown (bold line). Relative temperatures are used to avoid overlap.

temperature perturbations from temperature-depth profiles than SAT data adjusted for nonclimatic biases. Simple boxcar temperature-time functions that reproduce the temperature misfits also approximate standard long-wavelength SAT adjustments in time and amplitude. Borehole temperature profiles might be used as an independent check on long-wavelength adjustments made to SAT data.

Acknowledgments. We thank Alan Beck, Paul Shen, and Vladimir Cermak for helpful reviews of this manuscript. This work was supported by the National Science Foundation (EAR-9104292 and EAR-9205031), grant project 92037 of the Czech—U.S. Science and Technology Cooperation Program, and the University of Utah Graduate Fellowship program.

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(Received June 26, 1997; revised October 26, 1997;
accepted November 10, 1997.)