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Propagation of linear surface air temperature trends into the terrestrial subsurface

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[1] Previous studies have tested the long-term coupling between air and terrestrial subsurface temperatures working under the assumption that linear trends in surface air temperature should be equal to those measured at depth within the subsurface. A one-dimensional model of heat conduction is used to show that surface trends are attenuated as a function of depth within conductive media on time scales of decades to centuries, therefore invalidating the above assumption given practical observational constraints. The model is forced with synthetic linear temperature trends as the time-varying upper boundary condition; synthetic trends are either noise free or include additions of Gaussian noise at the annual time scale. It is shown that over a 1000 year period, propagating surface trends are progressively damped with depth in both noise-free and noise-added scenarios. Over shorter intervals, the relationship between surface and subsurface trends is more variable and is strongly impacted by annual variability (i.e., noise). Using output from the FOR1 millennial simulation of the GKSS ECHO-G General Circulation Model as a more realistic surface forcing function for the conductive model, it is again demonstrated that surface trends are damped as a function of depth within the subsurface. Observational air and subsurface temperature data collected over 100 years in Armagh, Ireland, and 29 years in Fargo, North Dakota, are also analyzed and shown to have subsurface temperature trends that are not equal to the surface trend. While these conductive effects are correctly accounted for in inversions of borehole temperature profiles in paleoclimatic studies, they have not been considered in studies seeking to evaluate the long-term coupling between air and subsurface temperatures by comparing trends in their measured time series. The presented results suggest that these effects must be considered and that a demonstrated trend equivalency in air and subsurface temperatures is inconclusive regarding their long-term tracking.

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1. Introduction

[2] Analyses of terrestrial borehole temperature profiles have provided robust estimates of multidecadal to centennial temperature changes at the Earth's surface for several hundred years prior to widespread meteorological observations. These analyses provide robust records of low-frequency changes in the temperature at the Earth's surface during the last millennium [*Cermak*, 1971; *Huang et al.*, 2000; *Harris and Chapman*, 2001; *Beltrami*, 2002a, 2002b; *Beltrami et al.*, 2005; *Pollack and Smerdon*, 2004; *Pollack et al.*, 2003; *Beltrami and Bourlon*, 2004; *Bodri and Cermak*, 2007; *González-Rouco et al.*, 2009]. Analyses of the subsurface thermal regime also have contributed to the overall assessment of the thermodynamics of climate change through efforts to estimate the continental subsurface heat content and its role in the overall energy balance of the climate system [*Beltrami et al.*, 2002; *Beltrami*, 2002a, 2002b]. Characterization of the continental subsurface heat content is also useful for assessing the adequacy with which General Circulation Models (GCMs) take into account and distribute energy among the major climate subsystems [*Levitus et al.*, 2001; *Beltrami*, 2002a; *Beltrami et al.*, 2006; *Hansen et al.*, 2005; *Huang*, 2006; *Bindoff et al.*, 2007; *Stevens et al.*, 2007, 2008; *MacDougall et al.*, 2008, 2010]. These collective endeavors therefore have made a fundamental understanding of the relationship between air and ground temperatures, particularly on time scales spanning decades to centuries, an important goal for the rigorous interpretation of geothermal climate signals [*Outcalt and Hinkel*, 1992; *Baker and Ruschy*, 1993; *Hinkel and Outcault*, 1993; *Osterkamp and Romanovsky*, 1994; *Beltrami*, 1996, 2001; *Baker and Baker*, 2002; *Bartlett et al.*, 2004; *Frauenfeld et al.*, 2004; *Bartlett et al.*, 2005; *Schmidt et al.*, 2001; *Beltrami and*

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Kellman, 2003; *Lin et al.*, 2003; *Stieglitz et al.*, 2003; *Smerdon et al.*, 2003, 2004; *Hu and Feng*, 2005; *Smerdon et al.*, 2006; *Nicolsky et al.*, 2007; *Demetrescu et al.*, 2007; *Smerdon et al.*, 2009; *Cey*, 2009].

[3] Paleoclimatic interpretations of geothermal data customarily assume that surface air temperature (SAT) and ground surface temperature (GST) are coupled over long time scales. SAT and reconstructed GST histories from inversions of borehole temperature profiles have been shown to compare favorably during their period of overlap [*Huang et al.*, 2000; *Harris and Chapman*, 2001; *Beltrami and Bourlon*, 2004; *Pollack and Smerdon*, 2004; *Pollack et al.*, 2005]. In efforts to further investigate the robustness of GST and SAT coupling over these longer time scales, some researchers have also compared temporal trends in SAT with trends in subsurface temperatures at site-specific locations, using observational records that span several years or decades. These studies have often proceeded with the assumption that demonstrations of equivalent trends in air and subsurface temperatures are a validation of the assumption that borehole inversions of temperature profiles yield robust estimates of past air temperature trends. Comparisons between SAT and GST reconstructions are, however, fundamentally different than the comparison of the trends in SAT time series and those in subsurface temperatures measured at specific depths. In the former comparison, a subsurface temperature-versus-depth profile is inverted to yield an estimate of historical temperature changes at the ground surface, taking the physics of conductive heat transport processes directly into account. In the latter comparison, temperature signals at a given depth are continuous in time and have been filtered by thermal transport processes, thus requiring an accounting of these processes before surface temperature trends and those measured at depth can be correctly compared.

[4] It is widely accepted that the effect of conductive heat transport on propagating temperature signals is a process by which the amplitudes of high-frequency oscillations are attenuated with depth more quickly than low-frequency oscillations [*Carslaw and Jaeger*, 1959]. This concept is illustrated by considering a harmonic surface temperature function of the form $T(t) = T_o + \cos(\omega t + \epsilon)$ where ΔT is the amplitude of the temperature oscillation, T_o is the surface temperature mean, ω is angular frequency, ϵ is the relative phase of the surface oscillation, and t is time. The resulting temperature at any depth is given by

$$T(z,t) = T_o + \Delta T e^{-z\sqrt{\frac{\omega}{2\kappa}}} \cos\left(\omega t - z\sqrt{\frac{\omega}{2\kappa}} + \epsilon\right), \qquad (1)$$

where κ is the thermal diffusivity of the subsurface and z is depth, positive downward. It is clear from this equation that the exponential decay of harmonic signals with depth is proportional to the frequency of the surface temperature oscillation, namely signals with higher frequencies decay more rapidly with depth than those with lower frequencies. Although climatic surface temperatures do not generally vary as perfect harmonic signals, any time series can be expressed as a linear combination of harmonic signals and thus equation (1) can be used to understand the selective attenuation of high-frequency signals relative to lower-frequency signals with depth in the terrestrial subsurface.

[5] Perhaps less appreciated is the fact that oscillations are also phase shifted with depth by an amount dependent on the period of oscillation [*Geiger*, 1965; *Smerdon et al.*, 2003, 2006; *Beltrami and Kellman*, 2003; *Demetrescu et al.*, 2007], which can be clearly seen in the second term of the cosine argument in equation (1). The result of these period-dependent phase shifts is that temperature signals are incoherent with depth relative to the surface signal; that is, the relative phases of periodic oscillations in temperature signals at depth have changed relative to the surface signal. It is thus expected that these effects, and those associated with amplitude attenuation, will alter the propagation of trends into the subsurface by amounts that depend on the magnitude of the trend, the thermophysical properties of the subsurface and the time over which the trends are measured.

[6] Despite these theoretical considerations, it is common in the literature to assume that air and subsurface temperature trends should be equal. For example, in one highly cited investigation into the relationship between air and ground temperature trends from meteorological records collected in eastern Minnesota, *Baker and Ruschy* [1993] demonstrated that the air temperature trend and the subsurface temperature trend at 12.8 m depth were essentially equal for the period of observation, prompting them to deduce that air and ground temperature trends are strongly coupled on multidecadal time scales.

[7] Here we use a one-dimensional conductive model to investigate the behavior of propagating trends in the subsurface. We use different combinations of synthetic trends and Gaussian noise to drive the conductive model and demonstrate the theoretical propagation of trends with depth over time intervals of decades to centuries. We also drive the model with output from the GKSS ECHO-G FOR1 General Circulation Model (GCM) simulation [*González-Rouco et al.*, 2003] to complement our synthetic experiments. Finally, we analyze existing air and subsurface temperature records from the Armagh Observatory, Ireland [*García-Suárez and Butler*, 2006], and from the Fargo Station, North Dakota [*Schmidt et al.*, 2001; *Smerdon et al.*, 2003, 2004, 2006]. Collectively, our results provide theoretical and observational evidence that invalidate the assumption that trends in SAT time series and those measured at specific depths within the subsurface should be equivalent, even under conditions in which subsurface temperatures faithfully record long-term changes in surface conditions.

2. Methodology

[8] Our method for investigating the propagation of linear trends into the subsurface uses a one-dimensional heat conduction model. In all simulations, we use a homogeneous subsurface temperature profile of 0°C as the initial condition and all surface temperature forcing series are input as departures from the 0°C value. The thermal homogeneity of the initial profile therefore assumes a constant thermal history prior to the beginning of the surface temperature forcings that we impose. The importance of prior thermal histories with respect to characterizing subsurface temperature trends is addressed in the context of our later analysis and discussion. Our simulations also do not take into account other factors that have been shown to influence the subsurface

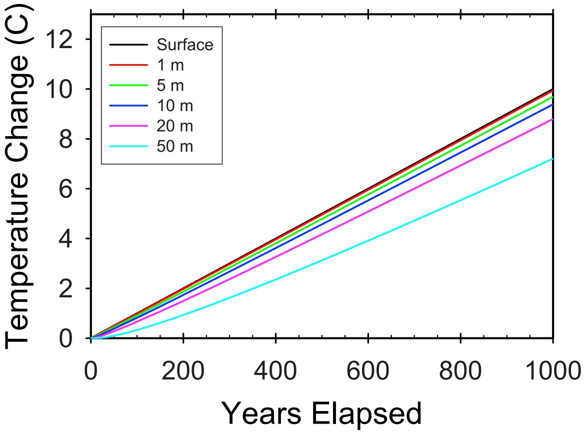

Figure 1. Conductively modeled subsurface trends over a 1000 year simulation interval using an upper boundary condition comprising a trend of 1K/century.

thermal regime. These include factors such as soil moisture [*Lin et al.*, 2003], albedo, snow cover [*Goodrich*, 1982; *Sokratov and Barry*, 2002; *Stieglitz et al.*, 2003; *Bartlett et al.*, 2004, 2005; *Zhang*, 2005], vegetation cover [*Bense and Beltrami*, 2007; *Davin et al.*, 2007; *Hamza et al.*, 2007], and vertical variation of thermal properties or physical and biological processes that take place at or near the air-ground interface [*Pollack et al.*, 2005; *Stieglitz and Smerdon*, 2007; *Ferguson et al.*, 2006; *Ferguson and Beltrami*, 2006]. Nevertheless, a purely conductive model is adequate to assess the impacts of the conductive transport of heat on propagating linear trends and to subsequently evaluate the implications for comparisons between trends measured in SATs and those at specific depths in the subsurface.

[9] In a homogeneous semi-infinite, source-free half space the temperature, T, at depth z due to a time varying surface temperature change is governed by the one-dimensional heat diffusion equation [*Carslaw and Jaeger*, 1959]. The temperature anomaly at depth z, due to a step change in surface temperature T_0, as dictated by the solution of the one-dimensional heat diffusion equation, is

$$T(z,t) = T_0 \mathrm{erfc}\left(\frac{z}{2\sqrt{\kappa t}}\right), \tag{2}$$

where erfc is the complementary error function. The time evolution of any arbitrary surface temperature history therefore can be approximated by a series of step changes at the surface [*Beltrami et al.*, 1992; *Beltrami and Mareschal*, 1992], such that the induced temperature anomalies at depth z are given by

$$T_t(z) = T_i(z) + \sum_{k=1}^{K} T_k \left[\mathrm{erfc}\left(\frac{z}{2\sqrt{\kappa t_k}}\right) - \mathrm{erfc}\left(\frac{z}{2\sqrt{\kappa t_{k-1}}}\right)\right], \tag{3}$$

where $T_i(z)$ represents the initial temperature profile. Equation (3) represents a general form of what is known as the forward problem; that is, the boundary condition is known and the subsequent subsurface perturbations can be calculated as a function of time. In contrast, the inverse problem, common in borehole paleoclimatology, consists of estimating the time-varying boundary condition from a temperature-versus-depth profile measured at a specific moment in time [*Huang et al.*, 2000; *Mareschal and Beltrami*, 1992; *Beltrami et al.*, 1997].

3. Analysis and Results

3.1. Noise-Free Linear Increase in Surface Temperature

[10] We initially force the conductive model described in equation (3) with a noise-free linearly increasing surface temperature as the time-dependent upper boundary condition. The model was driven over a period of 1000 years, using 1 year increments that increase the temperature at the surface at a rate of 1K/century. The assumed homogeneous thermal diffusivity in these experiments was 10^{-6} m^2/s. The upper boundary condition and the resulting subsurface temperatures are shown in Figure 1. As expected, the propagation of the surface trend is reduced as a function of depth.

[11] Results from this simulation agree with the analytic solution to the one-dimensional heat diffusion equation for a linearly increasing surface temperature function [*Carslaw and Jaeger*, 1959],

$$T(t,z) = mt\left[\left(1 + \frac{z^2}{2\kappa t}\right) erfc\left(\frac{z}{2\sqrt{\kappa t}}\right) - \frac{z}{\sqrt{\pi \kappa t}} e^{\frac{-z^2}{4\kappa t}}\right], \tag{4}$$

where m is the rate of temperature change at the surface. Differentiating equation (4) with respect to time gives the rate of temperature change,

$$\frac{\delta T(z,t)}{\delta t} = m \mathrm{erfc}\left(\frac{z}{2\sqrt{\kappa t}}\right), \tag{5}$$

which yields analytic rates that directly compare to the trends in Figure 1 with the discrete solution in equation (3). Equation (5) demonstrates that the rate of change at the surface is preserved at depth as time approaches infinity: surface and subsurface trends will eventually be equivalent if the trend in the surface signal is invariant over very long time intervals, the required duration of which depends on

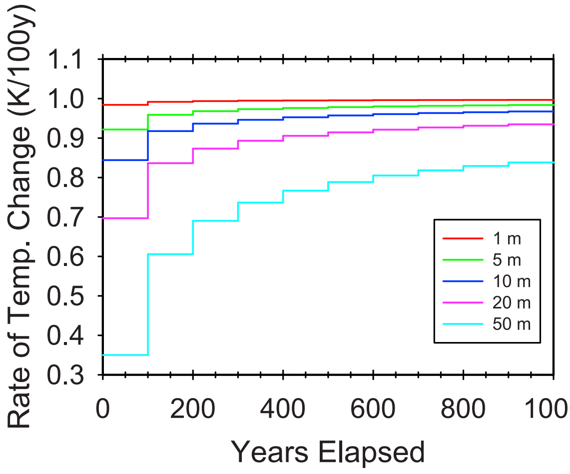

Figure 2. Centennial rates of temperature change at indicated depths for an upper boundary condition comprising a noise-free linear surface temperature increase of 1K/century.

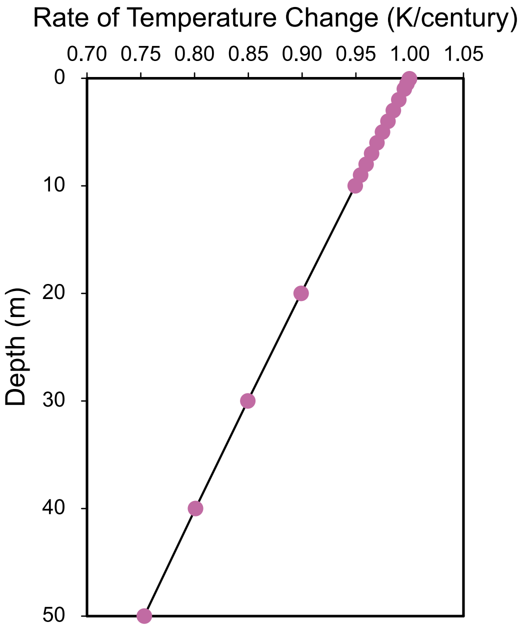

Figure 3. Rates of temperature change as a function of depth calculated over the full 1000 year simulation interval using an upper boundary condition comprising a noise-free linear surface increase of 1K/century; calculated trends decrease linearly with depth.

the thermophysical properties of the subsurface. For thermal diffusivities representative of the terrestrial subsurface, this time interval is on the order of several hundred thousand years. Under realistic constraints, modern observations that seek to characterize decadal and century-long trends can therefore reasonably be assumed to have persisted for much shorter time intervals, and therefore relationships between surface and subsurface trends will not be dictated by the limiting behavior of equation (5) as t goes to infinity. Note also that while equation (5) is suitable for our experiments, we use equation (3) in subsequent experiments that add noise to the annual values of surface temperature trends. This noise level is a quantity readily inferred from existing meteorological data, and thus much simpler and intuitive than noise additions to the magnitude of annual trends that would be required by equation (5).

[12] The rates of temperature change in 100 year intervals for the time series plotted in Figure 1 are shown in Figure 2 and illustrate increases in these rates at each depth over the duration of the simulation period. The rates of change at multiple depths for the entire 1000 year period are shown in Figure 3 and demonstrate an overall linear decrease in the trends as a function of depth. This general behavior is as expected from equation (5), where the solution describes a reduction in the surface trend with depth for finite time periods that is described by the complementary error function. Note, however, that the decrease illustrated in Figure 3 is only quasi-linear because the complementary error function governs the decrease in trend with depth and the convergence of trends over very long time intervals. Over deep enough depth ranges, or for different thermal diffusivities, the curvature of the complementary error function will be evident in the trend behavior with depth. Or over long enough time periods, the trends will converge at all depths. Nevertheless, over the depth ranges and time intervals considered herein, and given the realistic value of thermal diffusivity that we have adopted, the character of trend attenuation with depth can be considered nearly linear.

3.2. Monte Carlo Experiment With Gaussian Noise

[13] Section 3.1 investigated perfect trends containing no annual variability. Annual variations affect estimates of both surface and subsurface temperature trends; the effects on trends in the subsurface are depth dependent because the propagation of the annual variations are diffused conductively from the surface downward. In the context of our trend analysis, we therefore consider the annual variations as

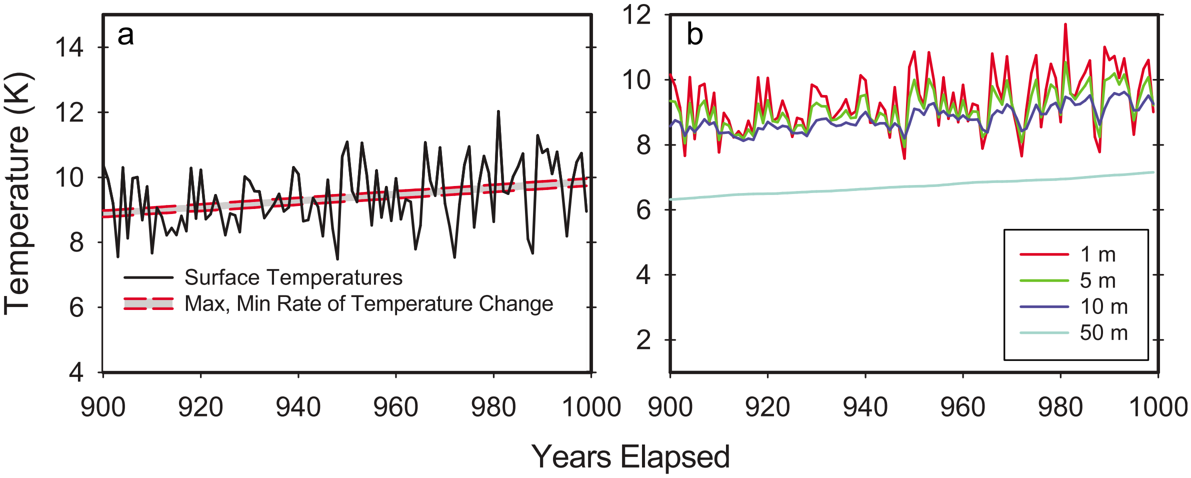

Figure 4. (a) Surface and (b) subsurface temperature time series during the last 100 years of a 1000 year simulation using the conductive model and an upper boundary condition comprising a linear trend of 1K/century and Gaussian noise with zero mean and 1K standard deviation. Both the maximum and minimum lines of best fit are shown for the upper boundary condition.

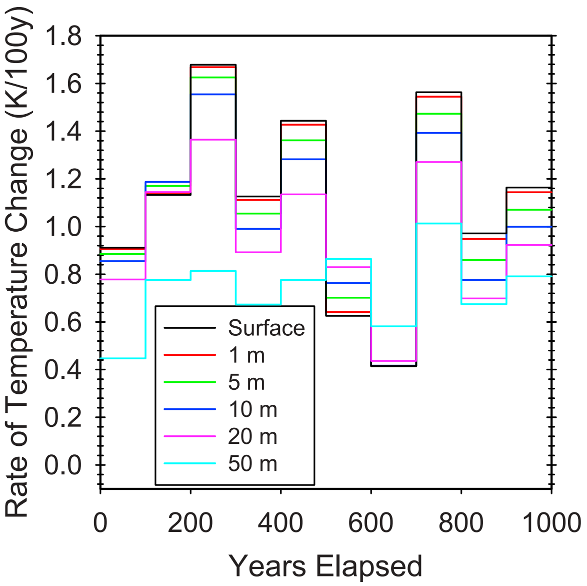

Figure 5. Centennial rates of temperature change in conductively modeled subsurface time series using an upper boundary condition comprising a linear trend of 1K/century and one realization of added Gaussian noise with zero mean and 1K standard deviation.

noise additions to the underlying trend signals. In order to evaluate the effects of these noise additions on the interpretations of surface and subsurface trend comparisons, a single realization of Gaussian noise was added to the SAT forcing function used as the varying upper boundary condition in section 3.1. The chosen noise characteristics (zero mean and 1K standard deviation) are representative of the typical observed variability of annual SAT records at Canadian meteorological stations, for example, the Halifax, Montreal-Mirabel and Calgary International Airports with standard deviations of 0.7, 1.2, and 1.1 K, respectively (Environment Canada National Climate Data and Information Archive, Canadian Climate Normals or Averages 1971–2000, http://climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html). The combined trend-plus-noise time series was used to force the forward model for 1000 years. Both the forcing SAT and subsurface temperature evolution over the last 100 years of the simulation are shown in Figures 4a and 4b, respectively, with the expected amplitude attenuation and phase lag evident in the collection of time series.

[14] The evolution of the rates of temperature change over discrete 100 year intervals along the length of the 1000 year simulation is shown in Figure 5. The addition of noise has a profound impact on the subsurface trends on a centennial scale. Specifically, the presence of noise removes the steady increase in the rate of temperature change as a function of time and also the uniform trend attenuation with depth observed previously for the noise-free case of Figure 2. Relationships between the surface and subsurface temperature trends exhibit varying degrees of damping and amplification over separate centuries and yield no consistent comparisons at these depths. The presence of noise (i.e., annual variability) thus greatly affects the ability to robustly compare trends in observed surface and subsurface time series by masking the observed damping of surface trends with depth shown previously for the noise-free experiments.

[15] In order to obtain statistics on the stability of temperature trends at different depths in the presence of surface temperature variability, we repeated the above noise experiment with a Monte Carlo approach using an ensemble of upper boundary conditions comprising the original trend and 10,000 Gaussian noise realizations of mean zero and 1K standard deviation. Figure 6 shows a quasi-linear relationship between the average rate of temperature change for all realizations and for the evaluated range of shallow depths. The uncertainty ranges in Figure 6 represent 1 standard deviation in the ensemble of trends calculated at each depth. The ensemble mean and standard deviations for each depth are shown for 100 year intervals over the entire 1000 year simulation in Figure 7. These average rates are equal within their uncertainty estimates to the rates found for the noise-free experiments, but also indicate that rates can overlap at any given 100 year interval because of the annual variability in the upper boundary condition.

3.3. Experiments Using GCM Output

[16] We use output from the paleoclimatic simulations [*González-Rouco et al.*, 2003, 2006] of the ECHO-G GCM to further evaluate the propagation of trends in a conductive medium. Three different millennial ECHO-G simulations exist, two forced simulations and one control simulation. The forced simulations, named FOR1 and FOR2 [*González-*

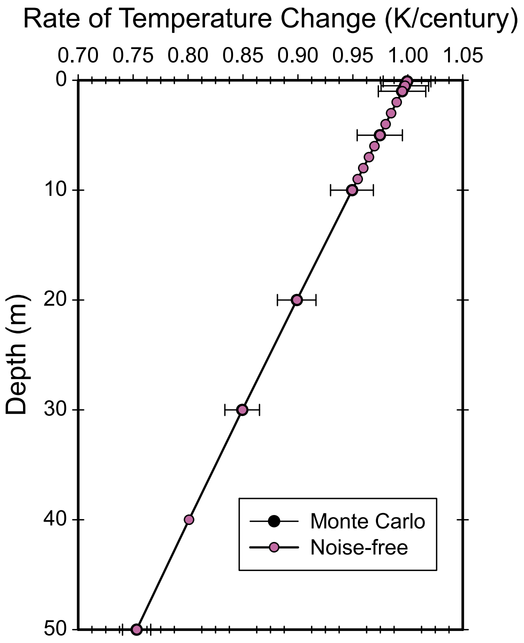

Figure 6. Average rates of temperature change over the 1000 year simulations for the Monte Carlo ensemble containing the 10,000 different Gaussian noise realizations as well as for the noise-free simulation. Values for the Monte Carlo simulation are not visible as they lie directly under those for the noise-free linear increase in surface temperature. The error bars are associated with the Monte Carlo simulation and represent 1 standard deviation in the rates of temperature change.

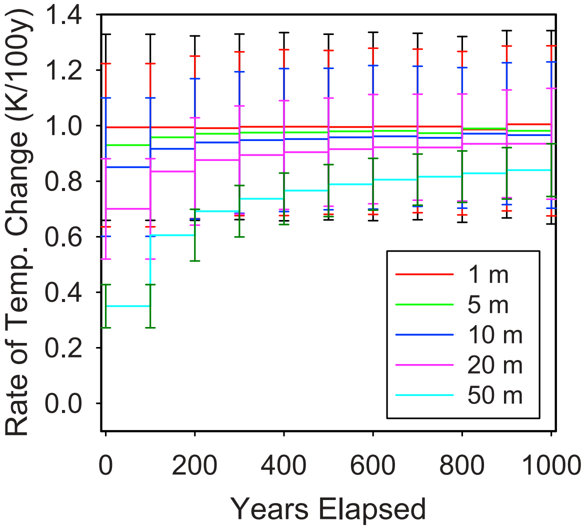

Figure 7. Averaged rate of temperature change over each century for all 10,000 runs of Monte Carlo simulation. Uncertainties correspond to 1 standard deviation in the computed trends over each century for all members of the Monte Carlo ensemble.

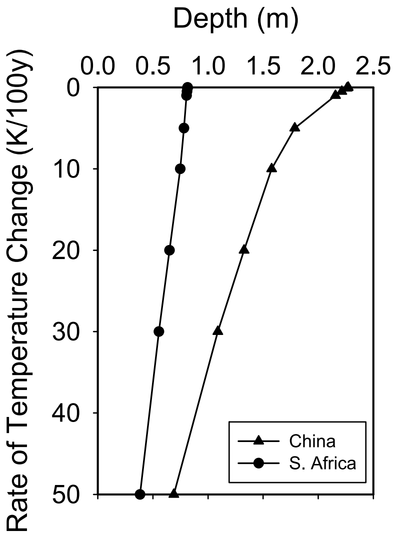

Figure 9. Average rate of temperature change for the last 100 years plotted against depth from conductive simulations using ECHO-G FOR1 surface temperatures from grids in China and South Africa as the upper boundary condition. Values for the surface are included and are shown as 0 m depth.

Rouco et al., 2003, 2006], used identical estimates of solar variability, greenhouse gas concentrations and stratospheric volcanic aerosols, but used different initial conditions. Additional details and model verifications of the ECHO-G simulations are given by *González-Rouco et al.* [2009].

[17] In the following experiments, we use the simulated data from two grid points of the ECHO-G FOR1 simulation as the time varying upper boundary condition of the conductive model. The location of the first point is in China, near the Russian border at approximately 123.75°E 50.1°N. The second grid point is located in South Africa at approximately 30.0°E 24.1°S. These two locations were chosen for their different climates, as China provided a greater variation in temperature than the South African location. ECHO-G surface temperature data for both grid points were used at monthly resolution for 990 years. The annual and smoothed time series are shown in Figures 8a and 8b for China and South Africa, respectively.

[18] For both grid point locations, the upper boundary condition of the forward model was set to the anomalies of the SAT time series relative to their mean over the 990 year interval; similarly, the initial conditions of the forward model were set to the mean temperature of each time series over the entire simulation period. The model was run for the first 890 years as a spin-up in order to eliminate any undesirable effects of the initial conditions and only the last 100 years of the simulation were considered for our experiment. Figure 9 shows the simulated temperature trends in the subsurface using the two ECHO-G time series as the

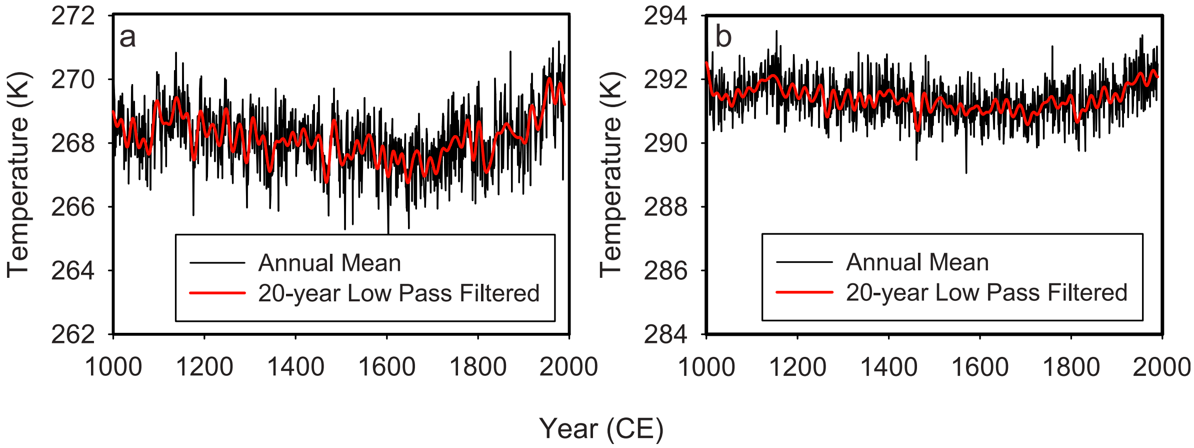

Figure 8. Surface temperatures from the ECHO-G FOR1 simulation taken from (a) China (123.75°E 50.1°N) and (b) South Africa (30.0°E 24.1°S). Annual mean values are shown in black; time series smoothed by a 20 year low-pass filter are shown in red.

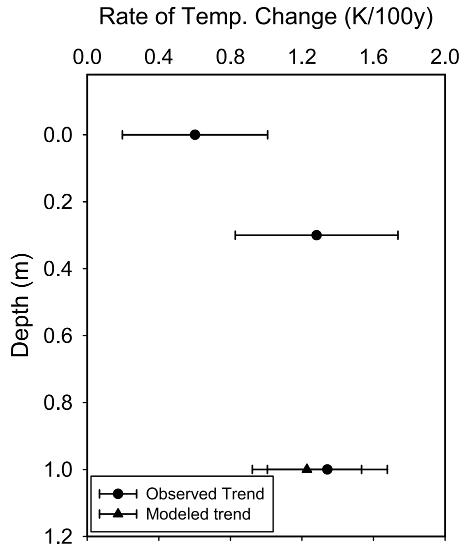

Figure 10. Rates of temperature change for the years 1904–2003 C.E. for various depths from Armagh Observatory, Ireland. Surface values are included as a depth of 0 m.

upper boundary condition. The results illustrate a decrease in the rate of temperature change with depth down to 50 m over the last 100 years of the simulation.

[19] The dependency of the trends on depth appears to be qualitatively similar to the findings in our previous experiment shown in Figure 7, but the relationship between the rate of temperature change and depth does not appear linear for China in the first 10 m. The difference is likely caused by the increasing trend in the last several centuries of the temperature time series from the grid point in China. The presence of the trend will be most pronounced in the shallow depths of the simulation, whereas the deeper depths will not yet be strongly affected by the increase. The consequence is the departure from the linear decrease in trends with depth observed for the location in China in Figure 9. Note also that the increasing temperature trend in the latter centuries of the ECHO-G simulation is much less pronounced in the time series from South Africa, and thus explains the absence of deviations from the quasi-linear decrease in trends with depth observed for that location in Figure 9.

3.4. Meteorological Data

[20] We chose two meteorological data sets that contain temporal coverage on the order of multiple decades. Observations from the Armagh Observatory in Armagh, Ireland [*García-Suárez and Butler*, 2006], consist of standard SAT and subsurface temperature measured at depths of 30 cm and 1 m, recorded daily from 1904 to 2003 C.E. We use the monthly mean temperatures at 30 cm and 1 m depths. There are 1200 months of data available, and only 3 months of missing data exist between the years 1946 and 1947 C.E. at 30 cm and 1 month of missing data in 1947 C.E. at 1 m depth. Surface air temperatures were available from 1904 to 2003 C.E. with no missing data.

[21] We also used data from the Fargo Station, North Dakota. Part of these data already have been examined by *Schmidt et al.* [2001] and *Smerdon et al.* [2003, 2004, 2006]. This station's record contains daily air and soil temperature data from the surface down to a depth of 11.7 m since early 1980 C.E. to the present. The analyses contained herein contain an additional decade of data that were not analyzed in the above cited works that is now available at the following Web site: http://www.ndsu.edu/ndsco/soil/farg/farg.htm.

[22] The data from each observational station were used as the upper boundary condition to force the conductive model and produce simulations of the thermal regime of the shallow subsurface at each site. We used the temperatures for the shallowest depth as input rather than the SAT, in order to minimize the effects at the air-ground interface such as snow and vegetation. The nearest depths to the surface were 30 and 5 cm for Armagh Observatory and Fargo Station, respectively. The effective diffusivities for each site were approximated using an annual signal analysis [*Smerdon et al.*, 2003], and estimated to be 2.83×10^{-7} m^2/s and 3.7×10^{-7} m^2/s for the Armagh Observatory and the Fargo Station, respectively.

[23] The trend retrieved from the forward model simulation for the Irish data at 1 m shown in Figure 10 is within the uncertainties of the same trend calculated directly from the meteorological data. This suggests that in the case of Armagh, Ireland, a purely conductive model simulation is sufficient to produce trends similar to those observed. Nevertheless, the data at this location allow only for the simulation of the trends at a single depth; thus it is not possible to ascertain whether this result would hold elsewhere in the subsurface.

[24] The estimates for the observed and simulated rates of temperature change at selected depths for the 29 years of the Fargo station data are shown in Figure 11. Although several of the shallow depth trends overlap with each other, there is a significant difference between the observed and simulated trends below 3 m. Although effects such as the insulation of snow cover have been removed or reduced by using the subsurface temperature record at 5 cm depth as the upper boundary condition in our model simulation, many factors

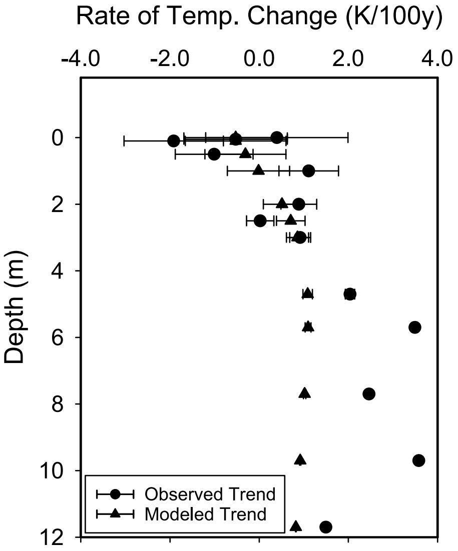

Figure 11. Rates of temperature change for the years 1980–2009 C.E. for various depths from Fargo Station, North Dakota. Surface values are included as a depth of 0 m.

not included in the model affect the real data. These include the variations in thermal diffusivity and moisture content with depth, seasonal freezing, etc. The difference at depths below 3 m could also be explained by the fact that the subsurface temperatures, especially at deeper depths, are affected by the unknown thermal history of the surface and subsurface prior to the beginning of measurements. Our model does not include this history, relying only on initial conditions and the measured surface temperatures as the driving upper boundary condition.

4. Discussion

[25] Our numerical simulations make evident that surface temperature trends appear damped with depth when propagating conductively into the subsurface. Over the range of depths considered and using a thermal diffusivity of 10^{-6} m^2/s, this damping is quasi-linear with depth if no annual variability is included in the upper boundary condition. The uncertainties in the rates of temperature change at each depth in the presence of annual variability, however, indicate that this variability can play an important role even on time scales as large as 1000 years. Although an increase in the number of years used to estimate the time series trends reduces the impact of annual variability on the propagation of linear trends with depth, the time intervals for which consistent meteorological data are available are almost exclusively less than a century. While further investigations into the sensitivity of our results to the magnitude of surface trends, the thermophysical properties of the subsurface, the time range of trend calculations and the amplitude of annual variability in the surface temperatures are warranted, the conditions used in our synthetic simulations are reasonable approximations of real-world conditions and constraints.

[26] The findings from the ECHO-G output simulations were consistent with those of the added Gaussian noise cases. The South African grid exhibited a nearly linear trend in slope with respect to depth; however, the Chinese grid contained curvature above 10 m. The reason for this behavior is likely due to increasing temperatures at the end of the interval preferentially affecting the estimates of rates of temperature change at shallower depths.

[27] The observed trends in the meteorological and subsurface data from Armagh Observatory, Ireland, and Fargo Station, North Dakota, demonstrated that neither location contained subsurface temperature trends that decreased regularly with depth. Based on the results from our synthetic experiments, trends estimated over 100 and 29 years can be strongly impacted by annual variability. The propagation of such annual variability – due to a combination of temporal phase shifts and amplitude damping, both as functions of depth – imparts significant variability in the estimated trends and therefore makes it difficult to robustly observe trend propagation with depth.

[28] Despite the significant variability in the observational trend estimates, the simulated trends using observed near-surface temperatures as forcing functions showed some overlap with the observed subsurface trends at both locations. The measured and simulated trends for the single depth at Armagh Observatory agreed within the estimated uncertainties. Similar agreement was observed for the Fargo Station in the near-surface depths, but observed and simulated trends diverged at depths below 3 m. Due to the short time scale at Fargo, it is likely that the thermal history prior to the observational period affects the estimation of temperature trends at depth, with impacts that increase with depth. Because this temperature history is unknown, it is only approximated by the initial conditions of the forward model. This idea is enforced by our synthetic simulations showing that the thermal effects of previous years can play a large role in measured trends. The simulated trends at all depths are also influenced by factors not included in our model such as the vertical variation of the subsurface thermophysical properties, soil moisture, vegetation cover and biological processes taking place in the upper soil layer. Fargo Station also experiences seasonal snow cover and ground freezing that also plays an important role in the propagation of temperature trends within the subsurface. Nevertheless, these effects did not strongly impact a conductive interpretation of annual signal propagation by *Smerdon et al.* [2003], suggesting that the unknown prior thermal history may be the largest impact on the discrepancies between the observed and modeled trends in the Fargo data shown here.

[29] The results found in this study also highlight the need for caution when comparing air and subsurface temperature time series in terms of linear trends. The abrupt changes in trends that were observed both at the end of the interval for the Northeastern China grid and in the Gaussian noise simulations were effectively caused by temperature variations not captured by a linear model. The conductive propagation of these nonlinear variations therefore complicates the analysis and comparison of air and subsurface temperature time series and suggests that additional investigations into coupling and heat transport on multiple time scales of variability are important.

5. Conclusions

[30] The experiments performed herein have illustrated the theoretical behavior of trend propagation in a conductive medium and unequivocally demonstrated that it is incorrect to assume that equivalent trends in surface and subsurface temperatures alone implies that air and ground temperatures track each other on long times scales (it is similarly incorrect to assume that demonstrations of dissimilar trends in such temperatures would alone suggest a long-term decoupling between them). This conclusion implies that it has been incorrect to assume that demonstrations of equivalent trends measured in air and subsurface temperatures [e.g., *Baker and Ruschy*, 1993] provide sufficient characterizations of their long-term relationships. Our experiments have additionally demonstrated the difficulty of estimating trends in observational subsurface temperature data that typically span only a few decades and contain significant annual variability relative to the magnitude of longer-term trends in the data. We have further demonstrated these conclusions using data from the Armagh Observatory, Ireland, and Fargo Station, North Dakota, where the relationships between trends in the measured air and subsurface temperatures were variable and dependent on the depth at which they were measured. Nevertheless, our synthetic experiments suggest that the biggest limitations of these data sets for the trend analyses that we have performed are simply the length of the

periods over which they were measured and the variability that they contain.

[31] A final note is necessary regarding the implications of our results for the field of borehole paleoclimatology. We have demonstrated that conductively propagated temperature trends in subsurface time series vary as a function of depth relative to the surface trend and can be significantly affected by annual variability. The importance of these findings relates principally to whether or not comparisons of trends in surface and subsurface temperature time series are a useful means of investigating a principal assumption of borehole paleoclimatology, namely that reconstructed GSTs can be used as robust estimates of long-term changes in SATs. We have shown that such comparisons of trends are likely of limited value, and at the very least need to take into account the impacts of conductive heat transport in the analysis of subsurface trends. By contrast, analyses of borehole temperature profiles for the purpose of reconstructing GST histories specifically assume that heat propagates within the subsurface conductively and explicitly incorporate the physics of thermal diffusion into the inversion or forward modeling methods used to interpret borehole temperature profiles. Proper accounting of the effects due to the conductive heat transport of temperature trends is therefore included when these profiles are analyzed. Interpretations of paleoclimatic histories inferred from borehole temperature profiles thus are not impacted by the issues that we have addressed in this study.

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