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Air-ground temperature coupling and subsurface propagation of annual temperature signals

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[1] Borehole-based reconstructions of ground surface temperature (GST) have been widely used as indicators of paleoclimate. These reconstructions assume that heat transport within the subsurface is conductive. Climatic interpretations of GST reconstructions also assume that GST is strongly coupled to surface air temperature (SAT) on timescales of decades and longer. We examine these two assumptions using records of SAT and subsurface temperature time series from Fargo, North Dakota; Prague, Czech Republic; Cape Henlopen State Park, Delaware; and Cape Hatteras National Seashore, North Carolina. The characteristics of downward propagating annual temperature signals at each site clearly indicate that heat transport can be described as one-dimensional conduction in a homogeneous medium. Extrapolations of subsurface observations to the ground surface yield estimates of annual GST signals and allow comparisons to annual SAT signals. All annual GST signals are modestly attenuated and negligibly phase shifted relative to SAT. The four sites collectively demonstrate that differences between annual GST and SAT signals arise in both summer and winter seasons, in amounts dependent on the climatic setting of each site. *INDEX TERMS:* 1645 Global Change: Solid Earth; 1875 Hydrology: Unsaturated zone; 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 3367 Meteorology and Atmospheric Dynamics: Theoretical modeling; *KEYWORDS:* heat transport, air-ground termperature coupling, paleoclimate

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1. Introduction

[2] Present-day measurements of temperature-depth profiles in terrestrial boreholes have been used extensively to reconstruct ground surface temperature (GST) histories over a large range of spatial and temporal scales (for a review, see *Pollack and Huang* [2000]). Global and hemispheric reconstructions of GST histories [*Huang et al.*, 2000; *Harris and Chapman*, 2001; *Beltrami*, 2002a; *Pollack and Smerdon*, 2004], assembled from hundreds of borehole measurements worldwide, have become important elements in the current ensemble of paleoclimate reconstructions [*Overpeck*, 2000; *Beltrami and Harris*, 2001; *Folland et al.*, 2001; *Beltrami*, 2002b; *Huang*, 2004]. GST reconstructions, inter alia, have added to the debate regarding the amount of decadal to centennial variability represented in estimates of millennial temperature changes at the Earth surface [*Dahl-Jensen et al.*, 1998; *Huang et al.*, 2000; *Broecker*, 2001; *Briffa et al.*, 2001; *Harris and Chapman*, 2001; *Beltrami*, 2002a, 2002b; *Briffa and Osborn*, 2002; *Esper et al.*, 2002; *Mann and Hughes*, 2002; *Mann*, 2002; *Mann et al.*, 2003a, 2003b; *Pollack and Smerdon*, 2004; *Rutherford and Mann*, 2004]. This debate is motivated, in part, by the fact that GST reconstructions indicate a net hemispheric or global warming of approximately 1.0 K from AD 1500–2000 [*Huang et al.*, 2000; *Harris and Chapman*, 2001; *Beltrami*, 2002a; *Pollack and Smerdon*, 2004]. This magnitude of warming contrasts with some proxy-based estimates of surface air temperature (SAT) histories that suggest lesser amounts of warming in the Northern Hemisphere during the same period [*Mann et al.*, 1998, 1999; *Crowley and Lowery*, 2000; *Briffa et al.*, 2001; *Esper et al.*, 2002; *Briffa and Osborn*, 2002; *Mann and Jones*, 2003]. The possible explanations for these differences are many: variable target seasons and regions associated with each reconstruction data set; potential biases in proxy-based reconstructions due to methods and/or models [e.g., *Briffa et al.*, 2001; *Esper et al.*, 2002; *Rutherford et al.*, 2003; *Trenberth and Otto-Bliesner*, 2003; *Zorita et al.*, 2003; *Esper et al.*, 2004];

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uncertainties regarding the strength of coupling between climate and proxy indices [e.g., *Briffa et al.*, 2001; *Pauling et al.*, 2003]; and decoupling between air and ground temperatures and deviations from the simple conductive model assumed in borehole-temperature inversion methods [*Beltrami*, 2002b; *Harris and Chapman*, 2001; *Mann and Schmidt*, 2003; *Smerdon et al.*, 2003; *Mann et al.*, 2003b; *Chapman et al.*, 2004; *Schmidt and Mann*, 2004; *Pollack and Smerdon*, 2004].

[3] In this paper, we address two principal issues specifically relevant to borehole-based reconstructions of GST: (1) these reconstructions derive from inversions of temperature-depth profiles that assume heat transport in the subsurface can be modeled as one-dimensional conduction in a homogeneous medium; and (2) interpretations of GST reconstructions as representations of SAT history are based on the assumption that long-term changes in GST, i.e., changes on decades, centuries or longer, are closely coupled to changes in SAT at equivalent periods. It is therefore important to examine these two assumptions in order to fully understand reconstructed GST signals and their relationship with traditional proxy-based reconstructions of SAT.

[4] One way in which the basic tenets of borehole-based reconstructions have been investigated involves the comparison of shallow (<10 m depth) subsurface temperature measurements with SAT and other meteorological conditions over multiyear time intervals [e.g., *Baker and Ruschy*, 1993; *Putnam and Chapman*, 1996; *Beltrami*, 2001; *Beltrami and Harris*, 2001; *Zhang et al.*, 2001; *Baker and Baker*, 2002; *Beltrami and Kellman*, 2003; *Smerdon et al.*, 2003]. These analyses assess how air temperature and other meteorological conditions generate and influence the downward propagating subsurface temperature signal. Such investigations are important because the ground surface and the underlying first few meters of the subsurface are where meteorological conditions influence a wide variety of physical, chemical and biological processes. Given that the downward propagating temperature signal is ultimately established at or near the ground surface, these processes could perhaps lead to departures from the simple conductive model assumed in GST reconstructions and to a weakening of the coupling between GST and SAT. Studies of air and ground temperature relationships at specific sites can provide valuable insights into the influence of meteorological conditions on the subsurface temperature signal, and accordingly have relevance for large-scale reconstructions of GST.

[5] This paper investigates heat transport in shallow subsurface environments and air-ground temperature coupling, using data from observational sites at Fargo, North Dakota; Prague, Czech Republic; Cape Henlopen State Park, Delaware; and Cape Hatteras National Seashore, North Carolina. These sites represent variable climatic settings and different subsurface environments. Our investigation progresses in the following manner: (1) we demonstrate, with observational data, that heat transport in shallow subsurface environments can be effectively characterized on annual timescales as one-dimensional conduction in a homogeneous medium; (2) we use the well-known solution of the heat conduction (thermal diffusion) equation to extrapolate subsurface temperature measurements to the ground surface, and thereby determine the annual GST signal that is driving downward propagating temperatures; (3) we quantify differences between annual GST and SAT signals; and (4) we establish a conceptual framework for understanding how these differences are generated by seasonal meteorological conditions. Our approach is based on methods described by *Smerdon et al.* [2003] (hereinafter referred to as SPEL) and expands on the use of a conductive theoretical framework to quantify differences between GST and SAT arising from meteorological conditions. This framework, when applied widely, will ultimately help to quantify differences between GST and SAT in time and space.

2. Data

[6] Principal information about the observational sites and data sets at Fargo, North Dakota; Prague, Czech Republic; Cape Henlopen State Park, Delaware; and Cape Hatteras National Seashore, North Carolina are listed in Table 1. The Fargo data and site have been described by *Schmidt et al.* [2001] and in SPEL. Subsurface temperatures from Prague were measured in a 40-m borehole drilled in October 1992 on the campus of the Geophysical Institute of the Czech Academy of Sciences. Most of the depths there have been monitored by two thermistors, and the temperatures reported are the average of the two measurements. Temperature measurements were taken 7 times each day at the following times: 0250, 0650, 0950, 1350, 1650, 2050, and 2350 local time (LT). SAT at a mast height of 2 m was also measured at the same times. Precipitation records were obtained from the Czech Hydrometeorological Institute. We use data from the Praha-Libus station (50°00.5′N, 14°26.9′E) that include rain-equivalent precipitation, snowfall, and depth of snow cover measured every day at 0700 LT.

[7] *Wehmiller et al.* [2000] describe the acquisition of subsurface temperatures at Cape Henlopen and Cape Hatteras and the characteristics of these sites. SAT was not observed at the two sites, thus necessitating the use of records collected from nearby locations at similar elevations. We use daily SAT records, obtained from the National Climatic Data Center, at Lewes, Delaware (38°46′N, 75°08′W), and Hatteras, North Carolina (35°16′N, 75°33′W). These stations are approximately 5 and 20 km away from the Cape Henlopen and Cape Hatteras subsurface observatories, respectively. The offsite daily SAT observations correlate well with near-surface measurements of temperature at the subsurface observatories ($r = 0.91$ and 0.93 at Cape Henlopen and Cape Hatteras, respectively).

2.1. Data Aggregation and Interpolation

[8] All of the data in this study have been aggregated into mean daily temperatures from multiple daily measurements. The Fargo, Prague, Cape Henlopen, and Cape Hatteras mean daily temperatures were estimated from twenty-four, seven, five, and five measurements per day, respectively. Gaps in the time series of mean daily temperature occur when all or some of the measurements from a given day are missing. The gaps in the Prague, Cape Henlopen, and Cape Hatteras records vary in length from 1 to 105 days and are not coincident in time at every depth in any given data set.

Table 1. Principal Information for the Observational Sites

Site	Latitude	Longitude	Observational Interval	Observational Depths,[a] m
Fargo, North Dakota	46°54′N	96°48′W	1 Sept. 1980 to 31 Aug. 1999	0.01, 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.8, 1.0, 1.25, 1.5, 1.75, 2.0, 2.5, 3.0, 3.7, 4.7, 5.7, 7.7
Prague, Czech Republic	50°02.5′N	14°28.7′E	5 Jan. 1994 to 3 Dec. 2002	0.0, 0.05, 0.1, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0, 7.5
Cape Henlopen, Delaware	38°46.4′N	75°05.7′W	8 Feb. 1997 to 31 Jan. 2002	0.25, 0.5, 1.0, 2.0, 3.0
Cape Hatteras, North Carolina	35°15.2′N	75°32.0′W	6 Feb. 1996 to 1 Feb. 2003	0.1, 0.25, 0.5, 1.0, 2.0, 3.0

[a]The observational depths listed here are the depths of measurement used within this study; some locations have additional measurements at other depths.

Table 2 summarizes the gaps in the three records at each observational depth (see SPEL for a description of gaps in the Fargo record).

[9] To create records with equal time steps of 1 day, we interpolate through all gaps in each time series. Gaps shorter than 10 days are linearly interpolated. Gaps larger than 10 days are bridged by "average interpolation," after linear interpolations of the shorter gaps are complete. Average interpolation fills each day of a gap with the average daily temperature from an ensemble of years that do not contain the gap. The interpolated SAT time series from each site are shown in Figure 1 along with examples of interpolated subsurface time series. Shaded regions in Figure 1 denote where gaps larger than 10 days occur in each record.

2.2. General Climate and Subsurface Characteristics

[10] Table 3 shows the general climatic conditions at each of the four sites. The SAT and subsurface temperatures in Figure 1 further illustrate site-to-site differences between observed surface and subsurface conditions. Mean annual SAT ranged from 5.8°C at Fargo to 18.1°C at Cape Hatteras. Winter temperatures increase from a minimum at Fargo to a maximum at Cape Hatteras. All sites registered periods of subzero SAT except Cape Hatteras (only 3 days registered mean subzero SAT during the five years of analyzed data at Cape Hatteras). Subsurface freezing is evident at Fargo in the 0.2 m time series, and to a lesser extent in the Prague 0.1 m time series. Cape Henlopen and Cape Hatteras show no evidence of ground freezing at 0.25 m.

[11] Precipitation also spans a range of conditions at the four sites. Annual amounts of rain-equivalent precipitation range from 52 to 115 cm per year. Cape Hatteras recorded no snow cover in excess of 2.5 cm during the period of observation whereas Fargo averaged 123 cm of annual snowfall between 1981 and 1999 and 96 days with snow cover in excess of 2.5 cm from 1981 to 1995. The two other

Table 2. Record of Gaps in the Prague, Cape Henlopen, and Cape Hatteras Temperature Records[a]

Observational Depth	Number of Missing Days	Gaps Larger Than 10 Days	Percent Missing From the Record
Prague, Czech Republic (2529 Total Days in the Analyzed Interval From 1 January 1996 to 3 December 2002)			
Air (2 m)	444	8	17.6
0	383	4	15.1
0.05	393	5	15.5
0.1	387	5	15.3
0.5	385	4	15.2
1.0	380	4	15.0
1.5	384	4	15.2
2.0	420	4	16.6
2.5	410	4	16.2
3.0	385	4	15.2
4.0	415	5	16.4
5.0	367	4	14.5
7.5	390	5	15.4
Cape Henlopen, Delaware (1819 Total Days in the Analyzed Interval From 8 February 1997 to 31 January 2002)			
Air (2 m)	52	1	2.9
0.25	418	2	23.0
0.5	58	3	3.2
1.0	58	3	3.2
2.0	82	3	4.5
3.0	35	2	1.9
Cape Hatteras, North Carolina (1822 Total Days in the Analyzed Interval From 22 January 1997 to 17 January 2002)			
Air (2 m)	427	6	23.4
0.1	43	2	2.4
0.25	42	2	2.3
0.5	42	2	2.3
1.0	43	2	2.4
2.0	42	2	2.3
3.0	111	2	6.1

[a]See *Smerdon et al.* [2003] for a tabulation of gaps in the Fargo record.

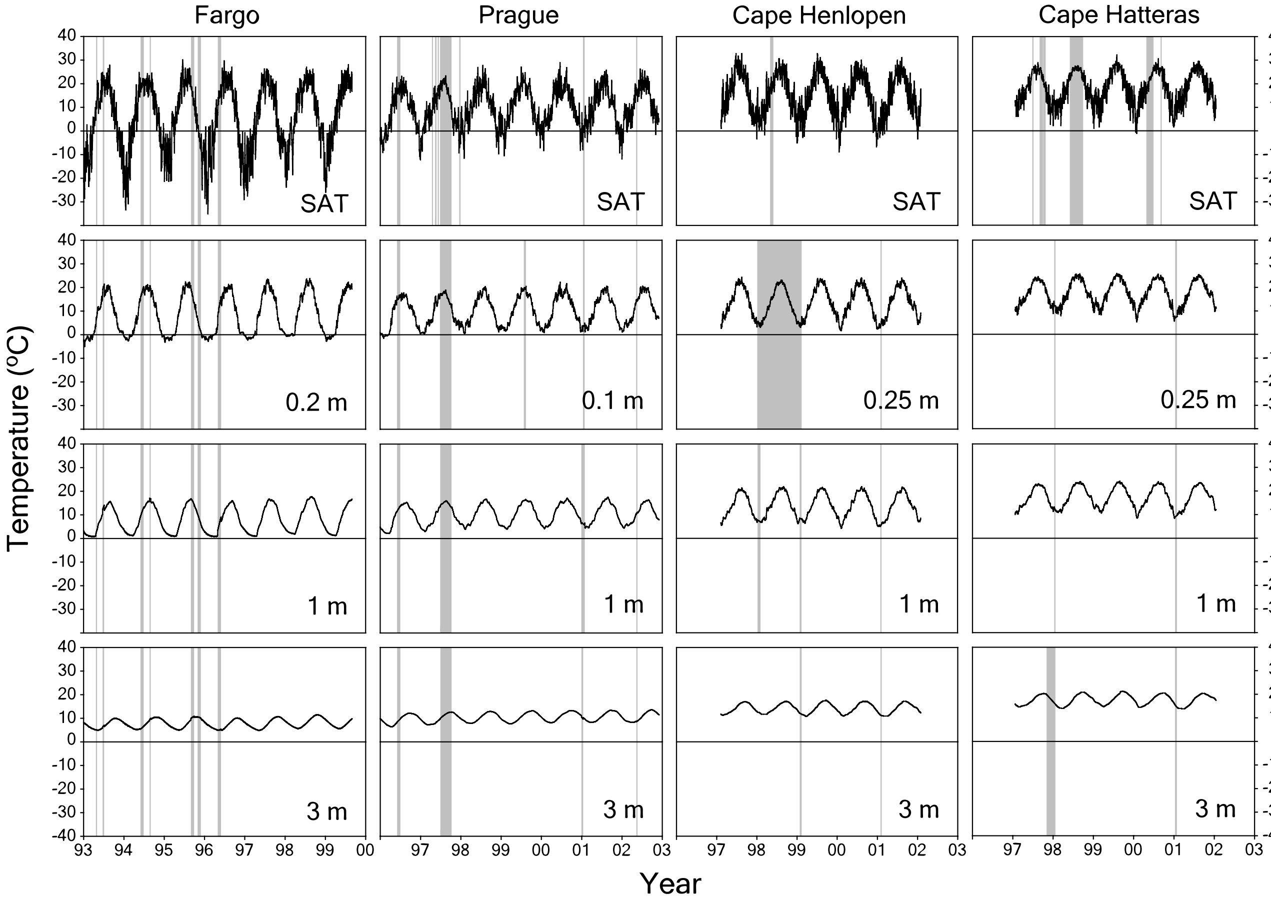

Figure 1. Interpolated SAT time series and subsurface temperature time series at various depths measured at Fargo, North Dakota; Prague, Czech Republic; Cape Henlopen State Park, Delaware; and Cape Hatteras National Seashore, North Carolina. The interpolated time intervals are shorter than the total observational time periods given in Table 1. Also note that the Fargo record spans a different time period from that of the other three sites. The total record used by *Smerdon et al.* [2003] extends back to 1980 and is fully displayed in that study (here we show only a portion of the record for the purpose of comparison). Shaded regions in each plot comprise gaps longer than 10 days that have been interpolated using the average interpolation method described by *Smerdon et al.* [2003].

locations have mean annual snowfall and snow cover days that fall within the range defined by the Cape Hatteras and Fargo sites.

[12] A variety of subsurface characteristics and vegetation are also represented. Fargo and Prague are both grassy sites underlain by several meters of soil. Subsurface characteristics at Fargo are further described by *Schmidt et al.* [2001]. The upper 4 m of the Prague site are soil and loose material with low thermal conductivity (1.7–2.0 W $m^{-1}K^{-1}$), underlain by siltstone/shale bedrock with gradually increasing thermal conductivity. Below a depth of 10 m the thermal conductivity is approximately 3.2 ± 0.2 W $m^{-1}K^{-1}$ and

Table 3. General Climatic Conditions at the Observational Sites

Site	SAT Mean,[a] °C	SAT Range, °C	Mean Annual Rain-Equivalent Precipitation,[a] cm	Mean Annual Snowfall,[a] cm	Mean Annual Snow Cover Days[a]
Fargo, North Dakota	5.8 (1981–1989, 1991, 1993–1998)	−35 to 35	52 (1981–1994, 1997–1999)	123 (1981–1995, 1997–1999)	96 (1981–1995)
Prague, Czech Republic	9.9 (1996, 1998–2001)	−10 to 25	53 (1990–2002)	31 (1990–2002)	35 (1990–2002)
Cape Henlopen, Delaware	15.0 (1998–2001)	−5 to 30	115 (1996–2001)	31 (1996–2000)	not available
Cape Hatteras, North Carolina	18.1 (1997–2001)	0 to 30	112 (1996, 1999, 2001)	0 (1996–2001)	0 (1996–2001)

[a]Numbers given in parentheses are the years used to calculate the annual means shown.

fairly uniform. Thermal diffusivities have also been measured; values of approximately 0.4×10^{-6} m^2s^{-1} characterize the uppermost strata at the site, and a range of 0.79–0.90×10^{-6} m^2s^{-1} is typical for depths below 10 m. The Cape Henlopen and Cape Hatteras sites are both partially shaded in maritime forest environments, with subsurface media comprising well-drained dune sand. The diversity of subsurface characteristics and climates represented by this collection of sites thus provides an opportunity to test the conductive behavior of the subsurface and the relationship between annual GST and SAT signals under variable conditions.

3. Annual Signal Transport in the Subsurface

[13] It is well known that there are many processes active at or near the ground surface that influence heat transfer in the shallow subsurface [e.g., *Goodrich*, 1982; *Lewis and Wang*, 1992; *Gosnold et al.*, 1997; *Zhang et al.*, 2001; *Kane et al.*, 2001; *Sokratov and Barry*, 2002; *Lin et al.*, 2003]. Downward propagating temperature signals are affected by vegetation, snow, subsurface freezing and thawing, evapotranspiration, water infiltration and subsurface migration of water as liquid or vapor on timescales of minutes, hours, days, and seasons. These factors primarily have short-term influences on heat transfer in the subsurface, particularly at intradaily timescales. Here, however, we specifically address heat transfer on annual timescales.

[14] The general approach that we use to examine subsurface heat transfer is presented in detail by SPEL and summarized here (for similar and additional discussion, see *Putnam and Chapman* [1996]). We utilize the steady state analytic solution of the one-dimensional heat conduction equation for a simple-harmonic surface temperature signal propagating into a homogeneous half-space [*Carslaw and Jaeger*, 1959]. This theory has been widely applied in soil physics contexts [e.g., *van Wijk*, 1963; *Campbell*, 1977; *Ghildyal and Tripathi*, 1987; *Hillel*, 1998; *Geiger et al.*, 2003]. Our approach is therefore based on well-established principles, which we use to examine subsurface heat transport at annual timescales.

[15] The downward propagation of a harmonic surface temperature signal in a homogeneous, conductive, semi-infinite half-space as a function of time t and depth z is given by $T(z, t) = Ae^{-kz} \cos(\omega t + \varepsilon - kz) + T_0$, where A, ω and ε are the amplitude, angular frequency and initial phase of the surface temperature signal, respectively, and T_0 is the initial mean subsurface temperature. The wave vector k is defined as $k = (\pi/P\kappa)^{1/2}$, where P is the period of oscillation and κ is the thermal diffusivity. A downward propagating harmonic signal will thus be exponentially attenuated in amplitude and linearly phase shifted with depth, both by amounts dependent upon the period of oscillation of the harmonic signal and the thermal diffusivity of the conducting medium. Although the temperature time series at each observational site exhibit many spectral components, we focus on the largest component, the annual oscillation.

[16] The basic characteristics of conductive heat transport are remarkably apparent from a simple visual inspection of Figure 1. High-frequency oscillations about the annual component of the SAT are progressively filtered and are almost completely absent by a depth of 3 m at all sites. The annual subsurface signals are also clearly attenuated and phase shifted relative to SAT signals. We quantitatively test the one-dimensional, homogeneous, conductive model by examining the natural logarithm of amplitude and the phase shift of the annual signals as functions of depth; amplitude and phase information has been extracted using Fourier transforms of each time series. The data and regression lines are shown in Figure 2. Linear models fit the changes with depth of the amplitude and phase data with high fidelity; all coefficients of determination (r^2) lie within the range 0.995–0.999. Table 4 and Figure 2 display the principal results from each analysis and clearly demonstrate that the simple conductive model describes well the heat transfer in the subsurface at these four sites on annual timescales over the observed depth ranges.

[17] To validate our results further, we determine the thermal diffusivity from this analysis of subsurface temperatures, and compare the results with other measurements and estimates. The slopes of the regression lines in Figure 2 enable estimates of the mean thermal diffusivity of the subsurface at each site [*Ghildyal and Tripathi*, 1987]; results are shown in Table 4. The estimated thermal diffusivity at the Fargo site of $0.37 \pm 0.01 \times 10^{-6}$ m^2s^{-1} [*Smerdon et al.*, 2003] compares well with the mean estimate (0.38×10^{-6} m^2s^{-1}) derived from the seasonal and layered model analyses of *Schmidt et al.* [2001]. The value estimated for the Prague site of $0.65 \pm 0.05 \times 10^{-6}$ m^2s^{-1} also falls well within the range of measured diffusivities at the location (see section 2.2). No direct measurements of thermal diffusivities exist for the Cape Henlopen and Cape Hatteras sites.

[18] The results of this section demonstrate that a one-dimensional, homogeneous, conductive model effectively characterizes subsurface heat transport at the four sites. This characterization is on annual timescales and spans several meters of the subsurface. The diversity of meteorological conditions and subsurface characteristics at the four sites supports the wide applicability of the simple conductive model.

4. Assessing Coupling Between Annual GST and SAT Signals

[19] Understanding the coupling of GST and SAT signals is important for assessing how well GST reconstructions represent changes in SAT. Toward this end, the regression results displayed in Figure 2 allow a quantitative assessment of the coupling between annual GST and SAT signals. We estimate the amplitudes and phases of annual GST signals using the surface intercepts of the regression lines (see Table 4 and Figure 2). The amplitudes and phases for the annual SAT signals are extracted using Fourier analyses of the SAT time series; these results are also shown in Table 4. All phase shifts of GST, relative to SAT, are small (4.5–8.5 days). All GST amplitudes are attenuated relative to SAT; percent attenuation ranges from 7.6 ± 2.0% to 22.5 ± 0.7% and is also given in Table 4.

4.1. Seasonal Causes of GST and SAT Differences

[20] There are several seasonal processes that account for the differences between annual GST and SAT at these four sites. Latent heat fluxes within the subsurface occur during

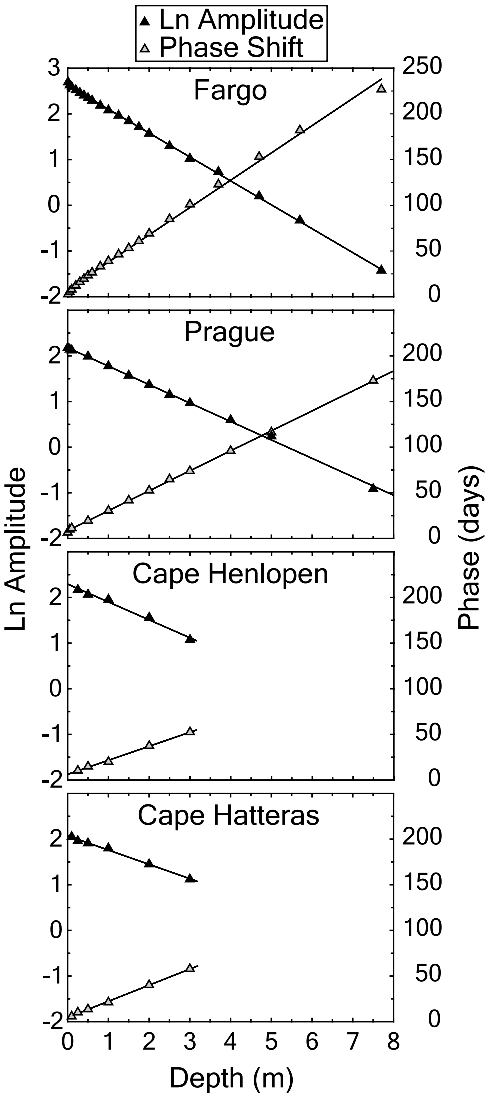

Figure 2. Regression results for annual signals extracted from subsurface temperatures collected at Fargo, North Dakota; Prague, Czech Repulic; Cape Henlopen State Park, Delaware; and Cape Hatteras National Seashore, North Carolina. Linear regressions of the natural logarithm of the amplitudes and the phase shifts (relative to SAT), as functions of depth, yield estimates of mean thermal diffusivities at the sites, as shown in Table 4. The zero-depth intercepts of the regression lines also yield estimates of the amplitudes and phases (relative to SAT) of the annual GST signals; these are also shown in Table 4.

summer via evapotranspiration [e.g., *Lin et al.*, 2003] and during winter via freeze and thaw cycles [e.g., *Kane et al.*, 2001; *Sokratov and Barry*, 2002]. Snow cover also influences temperatures and heat transfer in the subsurface [e.g., *Goodrich*, 1982; *Lewis and Wang*, 1992; *Gosnold et al.*, 1997; *Zhang et al.*, 2001]. These factors generally cause mean daily GST to be cooler/warmer, relative to SAT, in the summer/winter, respectively. The consequences of seasonal differences are therefore manifest as attenuation of annual GST signals, and to a lesser degree as phase shifts, relative to SAT. Quantitative differences between annual GST and SAT signals thus have the potential to be used as a single and straightforward metric through which the dominant meteorological influences on the annual coupling between GST and SAT can be captured.

[21] The results in Table 4 confirm variable seasonal influences on annual temperature signals. Winter effects attenuate annual GST signals by the greatest amount, with attenuation becoming progressively larger as winters become more extreme, i.e., colder temperatures and greater snowfall. Fargo and Prague, for instance, both experienced approximately the same amount of rain-equivalent precipitation during their respective periods of observation (Fargo and Prague measured 52 and 53 cm of mean annual rain-equivalent precipitation, respectively). At Prague, however, much less of the precipitation fell as snow (Prague averaged 92 cm less annual snowfall and 61 fewer days of annual snow cover than Fargo), and the lesser intensity of cryogenic processes at the site, relative to Fargo, is reflected in the reduced GST attenuation observed at Prague. This seasonal interpretation is supported at all four sites, where attenuation diminishes as freezing temperatures and snowfall become less prevalent; Fargo, with the coldest mean annual SAT and the most annual snowfall, registers the greatest amplitude attenuation, while Cape Hatteras, with no significant period of freezing temperatures or annual snowfall, has the least attenuation.

[22] While winter processes clearly play a significant role in the attenuation of GST amplitudes, they are not solely responsible for the effect. The Cape Henlopen and Cape Hatteras sites averaged negligible or no snowfall (the mean snowfall determined from the five years of snowfall data at Cape Henlopen is significantly affected by one large snowfall year; the yearly cumulative snowfalls between 1996 and 2000 were 116.5, 2.5, 0, 7.4, and 27.7 cm). Even in the virtual absence of snow and subsurface freezing, annual GST signals suffered attenuation relative to SAT. This observation is consistent with the premise that summer precipitation reduces daily subsurface temperatures relative to SAT via evapotranspiration [*Lin et al.*, 2003], and consequently increases the amount that annual GST signals are attenuated. Both Cape Henlopen and Cape Hatteras averaged more than twice the amount of annual rain-equivalent precipitation measured at either Fargo or Prague.

4.2. Reconstructed GST and SAT Annual Signals

[23] SPEL reconstructed the annual GST signal at Fargo by referencing amplitude and phase information to an estimated GST annual mean, using the temperature measurement at 1-cm depth to determine the estimate of the mean. This allows a comparison to the annual SAT signal and illustrates the amount that GST attenuation is partitioned into the summer or winter seasons; SPEL demonstrated that most of the GST attenuation at Fargo occurred during the winter. We use the same method to compare annual GST and SAT signals at the Prague, Cape Henlopen and Cape Hatteras sites. The zero-, 25- and 10-cm depths are used to estimate the respective mean GST at Prague, Cape Henlopen and Cape Hatteras.

[24] The annual GST and SAT signals from the four sites are shown in Figure 3. Most of the attenuation at Fargo occurs in winter, whereas Cape Henlopen and Cape Hatteras

Table 4. Results From Regression Analyses of the Observational Data

Site	r^2 (Amplitude, Phase)	Reconstructed GST Phase Relative to SAT, days	Estimated Thermal Diffusivity, $\times 10^{-6}$ m^2 s^{-1}	Reconstructed GST Amplitude, K	SAT Amplitude, K	Percent GST Attenuation
Fargo, North Dakota	0.999, 0.996	8 ± 1	0.37 ± 0.01	13.8 ± 0.1	17.8 ± 0.1	22.5 ± 0.7[a]
Prague, Czech Republic	0.999, 0.9996	8.4 ± 0.4	0.65 ± 0.05	8.83 ± 0.12	10.1 ± 0.1	12.6 ± 1.5
Cape Henlopen, Delaware	0.994, 0.998	6.2 ± 0.8	0.94 ± 0.09	9.90 ± 0.41	10.8 ± 0.1	8.3 ± 3.9
Cape Hatteras, North Carolina	0.995, 0.999	4.6 ± 0.5	1.04 ± 0.05	7.95 ± 0.14	8.6 ± 0.1	7.6 ± 2.0

[a]This number differs slightly from the number reported in SPEL (21.5 ± 0.5%) because the original number contained a typographical error and because we have now included error estimates in SAT amplitudes that make slightly larger the error associated with percent attenuation estimates.

are attenuated primarily during the summer. This seasonal partitioning of amplitude differences is consistent with the arguments that we have already presented, given the dominant climatic processes at each location: Fargo experienced modest mean annual rain-equivalent precipitation (52 cm), but a significant amount of snow (123 cm of mean annual snowfall; 96 days of mean annual snow cover); Cape Henlopen and Cape Hatteras experienced no subsurface freezing and considerably more precipitation than Fargo (mean annual rain-equivalent precipitation at the two sites was 115 and 112 cm, respectively), but negligible amounts fell as snow. At Prague, the mean annual SAT is warmer than Fargo (9.9°C versus 5.8°C) and the mean annual rain-equivalent precipitation at Prague (53 cm) is approximately equal to that at Fargo, but much less fell as snow (31 cm of mean annual snowfall and 35 days of mean annual snow cover). As a result, attenuation at Prague was less than at Fargo and more balanced between the summer and winter seasons. Shown collectively, the signals displayed in Figure 3 clearly illustrate the variable seasonal effects that can occur in annual GST signals, relative to SAT, in a variety of climatic settings.

5. Discussion

5.1. Subsurface Influences on Downward Propagating Temperature Signals

[25] The GST signals in Figure 3 are not obtained from a measurement exactly at the ground surface. They are derived by extrapolation from many subsurface temperature observations that span several meters of the subsurface, and are arguably the most representative characterization of the surface temperature signal being propagated to greater depths. This extrapolation to the surface of subsurface temperature observations is directly analogous to reconstructions of GST derived from inversions of borehole temperature measurements. In both formulations, i.e., the regression method discussed here and borehole temperature inversions, the reconstructed GST signal is the best estimate of the downward propagating-temperature signal observed below the ground surface at an array of different depths.

[26] Table 4 and Figure 2 clearly indicate that heat transfer in the subsurface can be simply and effectively described as one-dimensional conduction in a homogeneous medium. Small departures from this simple model may occur in approximately the upper meter of the subsurface, but this zone comprises only a small fraction of the several meters that we have characterized. As we have demonstrated, these departures have little consequence for applications of the simple conductive model. The upper meter of the subsurface is, however, where the characteristics of the downward propagating temperature signal are established. Differences between the amplitude and phase of annual GST and SAT signals are thus closely linked to the processes active in the shallow zone beneath the ground surface.

5.2. Implications for Long-Term Coupling Between GST and SAT

[27] With regard to borehole-based reconstructions of GST histories, it is ultimately important to assess the fidelity of coupling between GST and SAT signals over timescales much longer than a year. If the difference between annual GST and SAT signals at a given site is static in time, the constant offset between the two temperatures will have no effect on their relative tracking over centuries or longer; changes in one will be seen as equivalent changes in the other. Differences between GST and SAT are significant, with respect to long-term tracking of the two temperatures, only if the differences change over long time periods. Demonstrating the existence of differences between GST and SAT at short timescales provides no conclusive evidence regarding the presence or absence of long-term systematic biases in GST histories relative to SAT histories.

[28] The signals shown in Figure 3 highlight seasonal effects in both summer and winter seasons that impose competing responses on mean annual GST relative to SAT. Winter and summer attenuation of the annual GST signal cause warming or cooling, respectively, of mean annual GST relative to SAT. At Fargo winter attenuation is dominant and mean annual GST (9.1°C) is warmer than mean annual SAT (5.8°C). In contrast, mean annual GST at Cape Henlopen and Cape Hatteras (13.5° and 17.1°C) is colder than mean annual SAT (15.0° and 18.1°C) because attenuation of GST at the two sites is primarily during the summer. At Prague mean annual GST (10.3°C) and SAT (9.9°C) were very similar, with slightly more attenuation occurring in the winter than the summer. Changes in the differences between the annual GST and SAT amplitudes driven by secular changes in the amount or seasonality of precipitation, for example, would therefore have different effects on the relationship between mean annual SAT and GST at each of the sites.

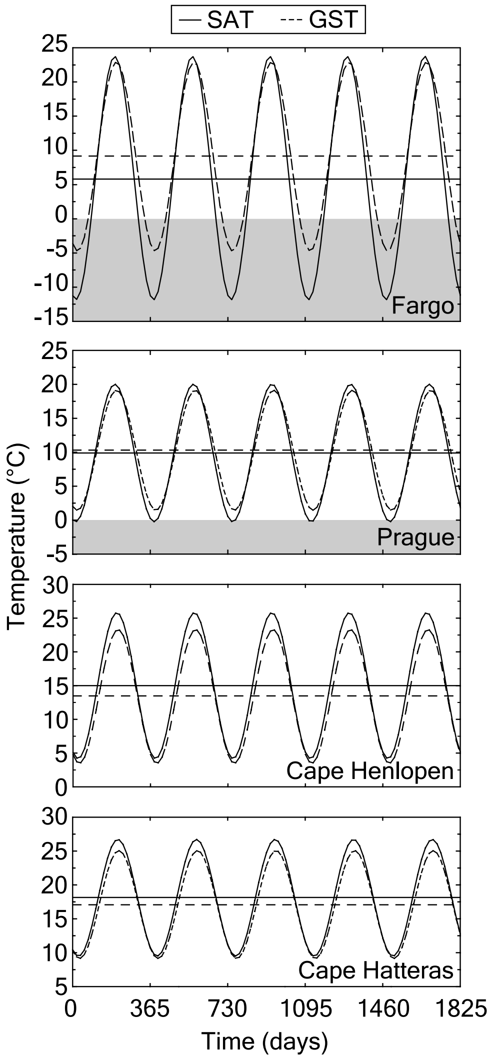

Figure 3. Fargo, Prague, Cape Henlopen, and Cape Hatteras SAT and GST annual signals, respectively, derived from spectral decomposition and extrapolation of amplitude and phase regression analyses. SAT signals have been referenced to their respective means, and GST signals have been referenced to approximate ground surface means using the closest near-surface measurement in each data set. The GST and SAT mean temperatures are shown with dashed and solid lines, respectively. The ordinate in each panel spans different ranges, but each linear scaling is equivalent. Shaded regions represent zones of subzero temperatures.

[29] Some recent critiques of borehole-based temperature reconstructions [*Mann et al.*, 2003b; *Mann and Schmidt*, 2003] have discussed only winter effects on GST and SAT coupling. Using five decades of modeled data, *Mann and Schmidt* [2003] argue that changes in snow cover have imparted winter trends in subsurface temperatures that are not representative of SAT changes. This conclusion, however, has been recently challenged [*Chapman et al.*, 2004] by a reanalysis of the *Mann and Schmidt* [2003] data showing hemispheric SAT and GST to be highly correlated when annual temperatures are assessed, i.e., annual temperatures containing both summer and winter effects. Millennial simulations of air and subsurface temperatures further illustrate the need to consider both winter and summer seasons [*González-Rouco et al.*, 2003] and confirm that variations in air and subsurface temperatures are virtually identical at centennial and longer timescales.

5.3. Spatial Caveats

[30] The results that we present are most representative of midlatitude seasonal relationships between GST and SAT. In the tropics, evapotranspiration is potentially significant year-round, and at high latitudes, in perennially frozen subsurface media, cryogenic effects are dominant. These conditions may influence GST and SAT relationships in ways somewhat different from the midlatitude sites presented here. For example, cryogenic (latent heat) effects may mute annual GST signals at high latitudes during the summer, the season during which the permafrost active layer thaws [e.g., *Hinkel et al.*, 2001]. Effects tied to soil moisture, regardless of latitude, are also dependent on the hydrologic characteristics of the subsurface. The extent to which moisture penetrates and is stored in the subsurface will be determined by the porosity and permeability of subsurface media. This, in turn, will influence the magnitude of latent energy fluxes in summer and winter. For example, areas with low porosity and permeability will be affected much less by evapotranspiration, and therefore daily GST in the summer may be warmer than SAT because of differential absorption of solar energy [*Putnam and Chapman*, 1996]; in such cases, annual GST amplitudes may be larger than SAT amplitudes.

[31] The spatial caveats discussed above underscore the need to consider the spatial distribution of GST and SAT differences, particularly on long timescales. Regional reconstructions of GST are derived from ensembles of boreholes [*Beltrami et al.*, 1997; *Shen et al.*, 1995; *Harris and Chapman*, 2001; *Pollack and Smerdon*, 2004] that reside in an array of climatic settings. If indeed changes in meteorological conditions caused secular differences between GST and SAT from site to site, the consequences for regional GST reconstructions would ultimately be determined by the spatial distribution of these changes.

6. Conclusions

[32] We have analyzed four data sets to examine heat transport in subsurface environments. The annual subsurface temperature signals at Fargo, Prague, Cape Henlopen, and Cape Hatteras all exhibit depth-dependent characteristics that are simply and effectively described by a one-dimensional, homogeneous, conductive model. Each site is representative of different meteorological conditions and subsurface media, and therefore this validation of the simple conductive model supports its wide spatial applicability.

[33] We have also compared annual GST and SAT signals. These comparisons reveal differences in amplitude and phase between the two signals that vary with meteorological conditions. Annual GST signals lag the SAT by negligible amounts (4.6–8.4 days) at all analyzed sites. GST amplitudes are attenuated relative to SAT, ranging from 22.5 ± 0.7% at Fargo to 7.6 ± 2.0% at Cape Hatteras. The amplitude differences are associated with specific seasons, and attenuation is consistent with

the meteorological conditions that are present at each site. These amplitude differences partition into summer and winter seasons and can therefore cause mean annual GST to be either cooler or warmer relative to SAT.

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