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Potential biases in inferring Holocene temperature trends from long-term borehole information

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[1] We use a set of global coupled ocean-atmosphere general circulation (OAGCM) experiments for timeslices over the Holocene from 9K Yr BP onwards to examine differences in Northern Hemisphere Ground Surface Temperature (GST) and Surface Air Temperature (SAT) trends. The model results are driven mainly by the orbitally-forced changes in seasonal insolation, and in particular, the increase in northern hemisphere seasonality in the early-to-mid Holocene. The model reproduces qualitatively presumed past trends in NH temperatures, though it may underestimate their magnitude. For this period, we see on average a significant increase in GST relative to SAT as a result of a competition between the effects of changing seasonal insolation, and the varying extent of insulating seasonal snow cover. The model shows a mid-Holocene peak in annual mean terrestrial Northern Hemisphere GST, but not in annual Surface Air Temperatures (SAT). We conclude that the factors influencing long-term GST trends are potentially quite complex, and that considerable care must be taken in interpreting SAT changes from the GST evidence when there is the possibility of substantial seasonal variation in warmth and snow cover. **Citation:** Mann, M. E., G. A. Schmidt, S. K. Miller, and A. N. LeGrande (2009), Potential biases in inferring Holocene temperature trends from long-term borehole information, *Geophys. Res. Lett.*, *36*, L05708, doi:10.1029/2008GL036354.

1. Introduction

[2] There has been considerable recent interest [e.g., *Huang et al.*, 2000; *Folland et al.*, 2001; *Briffa and Osborn*, 2002; *Mann et al.*, 2003; *Jansen et al.*, 2007] in reconciling estimates of past temperature trends from borehole measurements and other higher-resolution 'proxy' data such as tree-rings and ice cores. As borehole measurements ostensibly reflect past changes in ground temperatures, while other proxy data are generally interpreted as reflecting surface air temperatures, efforts to achieve such a reconciliation have naturally led to a close examination of the correspondence (primarily, in model simulations) between terrestrial surface air temperature (SAT) and ground surface temperature (GST) variations [*Mann et al.*, 2003; *Mann and Schmidt*, 2003; *González-Rouco et al.*, 2003, 2006; *Chapman et al.*, 2004; *Schmidt and Mann*, 2004; *Bartlett et al.*, 2004; *Smerdon et al.*, 2004, 2006].

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[3] While terrestrial SAT variations are generally considered to reflect the impacts of radiative forcing and atmospheric circulation changes, the underlying GST may be influenced by a number of additional factors, including land-surface and soil properties, vegetation, latent heat sources and sinks, and permafrost effects [e.g., *Beltrami*, 1996; *Gosnold et al.*, 1997; *Skinner and Majorowicz*, 1999; *Sokratov and Barry*, 2002; *Steiglitz et al.*, 2003; *Taylor et al.*, 2006]. In the winter and transitional seasons, the effects of insulating seasonal snow cover are of considerable potential importance in determining the relationship between SAT and the underlying GST [*Sokratov and Barry*, 2002; *Stieglitz et al.*, 2003; *Mann and Schmidt*, 2003; *Bartlett et al.*, 2004; *Smerdon et al.*, 2006]. A number of recent studies analyzing the relationships between GST and SAT in climate model simulations have come to conflicting conclusions regarding the implication of these considerations for interpreting past borehole-based GST trends [*Mann and Schmidt*, 2002; *González-Rouco et al.*, 2003, 2006]. Using a simulation of the NASA GISS ModelE driven with observed SST and estimated radiative forcings over the latter half of the 20th century, *Mann and Schmidt* [2002] found that SAT changes explained less than 50% of the spatiotemporal variance in GST changes during the boreal cold-season (Oct–Mar), and a considerably greater 78% of the variance during the boreal warm-season (Apr–Sep), implying a considerably greater sensitivity of GST to warm-season SAT variations. If temperature trends averaged at global or hemispheric scales for different seasons happen to be similar, then this may not lead to a substantial bias in inferring hemispheric-mean mean SAT changes from GST trends. This would plausibly explain why low-frequency variations in annual hemispheric GST and SAT appear to track each other closely in some long-term climate model simulations [*González-Rouco et al.*, 2003, 2006]. However, in the more general situation where large-scale temperature trends may indeed be quite different in different seasons, there is the potential for a sizeable seasonal bias in inferring annual SAT variations from annual GST measurements.

[4] Examining changes in climate associated with earth-orbital forcing back through the early Holocene (i.e., roughly the past 9,000 years) provides an excellent test case for investigating such issues in greater generality. Over this time frame, associated annual global mean radiative forcing changes are minimal, as appear to have been any associated global mean temperature changes [*Kitoh and Murakami*, 2002; *Jansen et al.*, 2007]. Seasonal and latitudinal radiative forcing changes, however, were sizeable. The best available evidence indicates a cooler tropics, and warmer mid- and high-latitude summers during the early and especially mid-Holocene (i.e., roughly 6K BP) [*Jansen et al.*, 2007]. Evidence for mid- and high-latitude winter

change is indeterminate. Decreased winter insolation should have favored colder conditions during the early and mid Holocene. It is possible however that land-surface feedbacks favoring increased forest cover at mid- and high-latitudes might have offset the radiatively-induced cooling. Using the "CLIMBER" intermediate complexity climate model with mid-Holocene radiative forcing, *Ganopolski et al.* [1998], for example, suggest that the poleward expansion of forest associated with a warmer, longer growing season could have led to a terrestrial Northern Hemisphere mean SAT warming during the mid-Holocene of roughly 0.4°C in winter compared to a modern pre-industrial control. Combined with an estimated 2.5°C SAT Northern Hemisphere warming in summer, they deduce a modest but non-zero 1.2°C SAT warming in the annual mean. Note that the seasonal differential in temperature trends (2.1°C) is large compared to the estimated annual mean change (1.2°C).

[5] Recent borehole-based reconstructions of millennial-scale GST changes back through the early Holocene [*Huang et al.*, 2008, hereinafter referred to as HPS08; see also *Huang et al.*, 1997, hereinafter referred to as HPS97 (hereinafter the two collectively referred to as HPS)] estimate, for example, a roughly 2 ± 0.3°C peak GST warming for the mid-Holocene compared to modern pre-industrial conditions (this average represents the uniform mean over a predominantly extratropical Northern Hemisphere land spatial sample). By comparison with the model-estimated SAT changes described above, this is suggestive that the GST changes may preferentially be reflecting warm-season conditions. Here, we address these issues by examining the relationships between SAT, GST (and the role of snow cover trends) in a set of snap-shot simulations of a coupled atmosphere-ocean general circulation climate model ("AOGCM") spanning the past 9000 years forced with estimated orbital insolation, greenhouse gases and ice sheet topography changes.

2. Model Simulations

[6] We use the GISS ModelE Coupled OAGCM. The horizontal resolution of the model is 4° × 5° and the atmosphere has 20 layers in the vertical. The ocean model has the same horizontal resolution and 13 layers in depth. The model specification is described more fully by *Schmidt et al.* [2006] and *Hansen et al.* [2007]. Features of relevance to this paper are as follows: The land surface model consists of 6 soil layers of varying thickness (for a total depth of 3.5 meters) with separate calculations for bare and vegetated ground fractions [*Rosenzweig and Abramopoulos*, 1997] with vegetation type and fraction fixed at present day observations [*Matthews*, 1984]. The snow model is a 3-layer formulation which allows for a varying snow-covered fraction and water percolation [*Lynch-Stieglitz*, 1994]. The snow masking depth for albedo is a function of the vegetation type.

[7] We define GST as the temperature of the uppermost soil layer (averaged over the relative fractions of vegetated and bare soil), SAT as the surface air temperature (defined as being 10m above the surface in this model, though our results are insensitive to the precise definition since we are looking only at differences over time), and SNC is the mean snow cover fraction in the grid box (mean snow depth also co-varies closely with SNC at seasonal timescales).

[8] We analyzed a series of eight simulations of the model spanning the early Holocene through modern pre-industrial. Simulations were centered at 9, 6, 5, 4, 3, 2, 1, and 0K BP (0K BP corresponds to 1880 Greenhouse Gas Concentrations and AD 2000 orbital forcing). Each simulation was run for 500 model years for equilibration, with the final 100 years used to calculate seasonal climate statistics. The forcings applied to the model were the variations in well-mixed greenhouse gases, earth orbital-related top-of-the-atmosphere insolation [*Berger and Loutre*, 1992] and greenhouse gas changes [*Schmidt et al.*, 2004]. At 9 kyr BP we additionally had a change in sea level of 40 meters [*Fairbanks*, 1989] (though no changes were made in coastlines or land elevation) and included the remnant Laurentide ice sheet [*Licciardi et al.*, 1998].

3. Analysis

[9] For purposes of comparison with the HPS GST estimates, we defined a model domain of analysis representing the terrestrial extratropical Northern Hemisphere region containing the preponderance of borehole geothermal heat flux profiles used by HPS, comprising all land gridboxes within North America between 28N and 60N and within Eurasia between 32N and 76N (see Figure 1 for spatial distribution). We eliminated from consideration a small number of gridboxes which exist as exposed land in certain simulations but not others (e.g., gridboxes covered by the Laurentide Ice Sheet at 9K BP). For each retained gridbox, we calculated mean monthly GST, SAT, and SNC, and three month (DJF, MAM, JJA, SON) and annual (Jan–Dec) means. Northern Hemisphere means were calculated as uniform averages of quantities over all gridboxes to emulate as closely as possible the HPS spatial averaging procedure, though a proper areal averaging yielded nearly identical estimates (see auxiliary material).[1] To facilitate model-data comparison, we adopt the convention that GST and SAT anomalies are zero during a modern, pre-industrial reference period (defined by the '0K' simulation). For comparison, late 20th century Northern Hemisphere land temperatures are increased by just under 1°C relative to this baseline.

[10] The key finding of our analysis is that there is a sizeable, and seasonally variable difference between GST and SAT trends in the simulations, which tends to increase in time back through the mid and/or early Holocene (Figure 1). For the boreal winter, spring, and autumn, the maximum change in the NH mean GST-SAT difference is roughly +0.5°C (which occurs at 9K BP), +0.3°C (at 6K BP), and 0.8°C (at 9K BP) respectively. For summer, the NH mean differences are negligible. Positive GST-SAT differences are especially pronounced in the subtropical regions during the boreal winter, and the mid-latitude and sup-polar regions in autumn and spring (Figure 1).

[11] These differential seasonal trends in GST vs. SAT can be understood in terms of the increased insulation of the ground surface provided by increased seasonal snow cover extent (similar trends are found for domain integrated snow

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL036354.

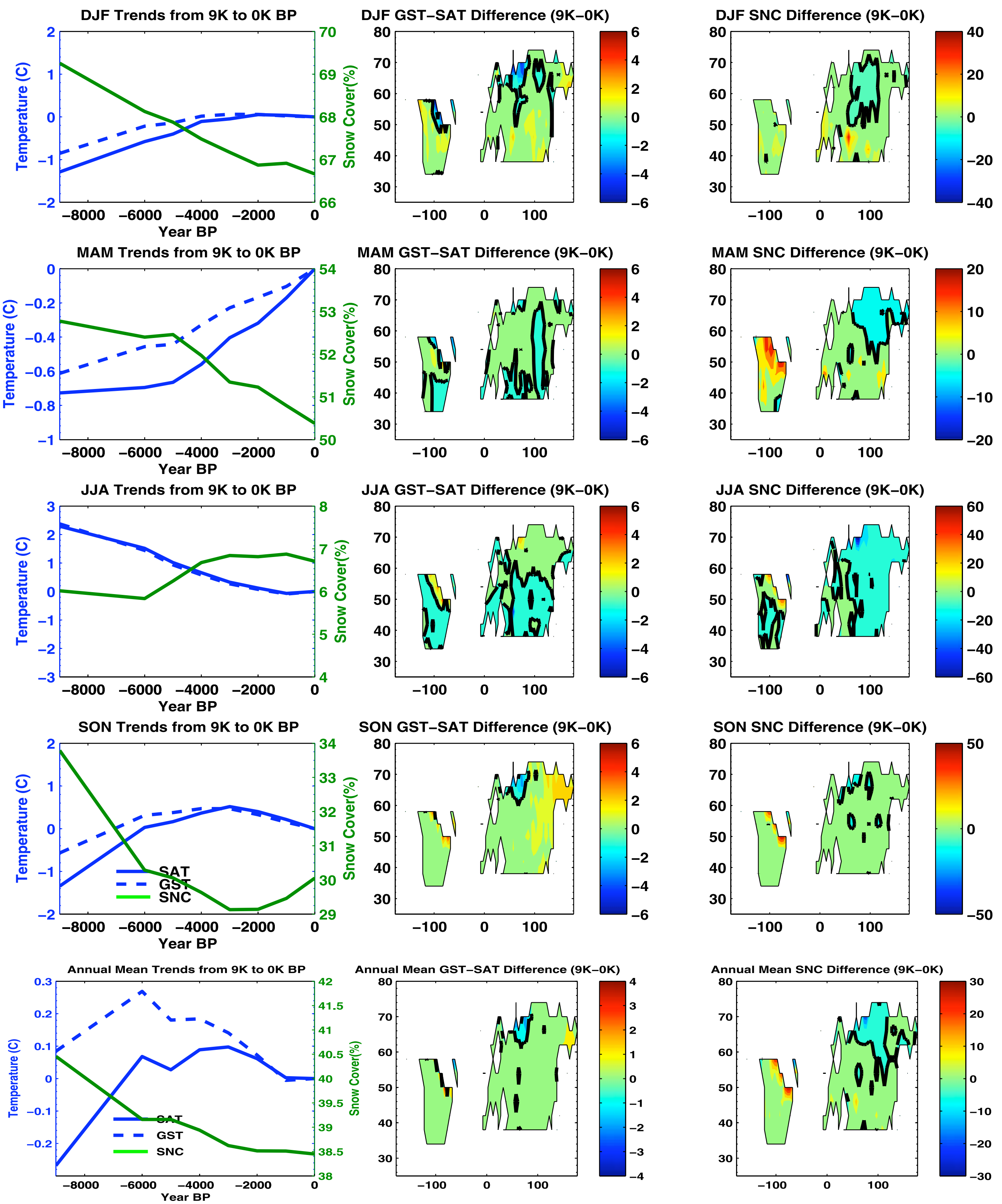

Figure 1. Seasonal and annual Trends. Shown are (left) trends for each season in SAT (solid blue), GST (dashed blue), and Snow Cover (SNC, solid green), (center) the 9K-0K difference in the spatial pattern of GST-SAT, and (right) the 9K-0K difference in the spatial SNC pattern. Annual mean trends are featured in the bottom row. As in Figure 2, the baseline for defining the temperature anomalies is the 0K model simulation (associated with modern pre-industrial boundary conditions as defined in main text).

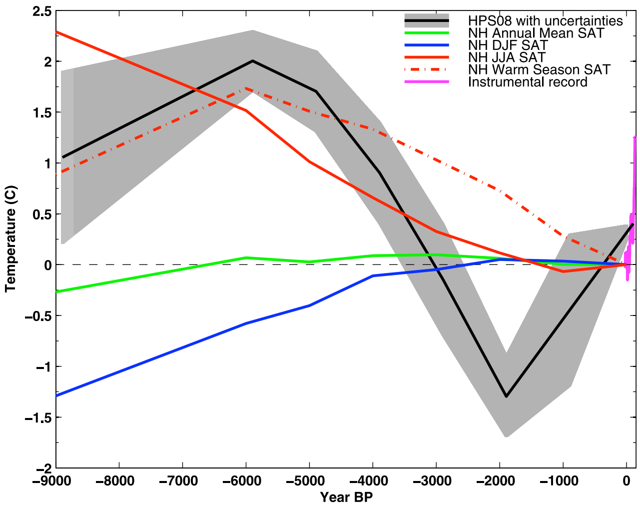

Figure 2. Comparison of HPS08 borehole-estimated Holocene GST trends and model-estimated SAT trends for different seasonal windows. Shown for comparison is the NH instrumental annual mean land surface temperature record from 1850–2007 [*Brohan et al.*, 2006] (note than an 1850–1899 reference period mean is used to correspond approximately to the 0K modern pre-industrial baseline). The borehole-based GST series is centered relative to the instrumental record as in HPS08.

depth—see auxiliary material). We find (Figure 1) that there is a substantial long-term increase in NH mean SNC back through the early Holocene for winter, spring, and autumn. For each of those seasons, there is a corresponding NH mean increase in the GST-SAT offset (Figure 1). The greatest GST-SAT offsets, as expected, are found where there are the most substantial increases (Figure 1) in snow cover (i.e., in the subtropics during winter, and in the mid-latitudes in autumn and spring).

[12] The differential seasonal trends in GST vs. SAT lead to noticeable differences in the long-term trends in annual mean GST and SAT (Figure 1). In particular, annual mean GST in these simulations exhibits a distinct mid-Holocene annual mean warm peak while annual mean SAT shows a broad, mid-to-late Holocene plateau. The GST peak results from the fact that GST cools less than SAT back in time in fall, winter, and spring, while GST and SAT warm similarly back in time in summer. As with the seasonal changes, the greatest GST-SAT differences coincide regionally (Figure 1) with the largest snow cover decreases.

[13] We can approach the problem from an alternative perspective. As discussed earlier, we can view the snow cover insulation effect in terms of a decreased sensitivity of GST to SAT variations during the cold and transitional seasons, i.e., in terms of GST exhibiting a 'warm-season' bias relative to SAT variations. It is therefore interesting to ask what seasonal window of response would best reconcile reconstructed GST trends back through the early Holocene assuming the modeled trends are realistic. We find (Figure 2) that the HPS mean GST reconstruction, including the quite large (+2°C relative to pre-industrial modern mean) mid-Holocene GST peak, could be matched by a late summer/early fall (Aug–Sep) seasonal average of the model NH mean SAT with one notable discrepancy: Between roughly 4K and 1K BP the model runs too warm relative to the GST reconstruction).

[14] There are a number of reasons why the model estimates could themselves be biased. This includes the use of fixed vegetation, since as noted earlier dynamic vegetation changes during, e.g., the mid-Holocene [*Ganopolski et al.*, 1998] could lead to annual mean warming not captured in our simulations, presumably mitigating the snow cover increases found in our study. On the other hand, *Ganopolski et al.* [1998] also find that inclusion of these feedbacks leads to a modest increase in terrestrial winter precipitation, which could lead to an increase in snow cover, and hence the GST-SAT bias isolated in our study. Other potential biases in the simulations are overly stable sea ice (there is some indication that sea ice was more significantly diminished around 9K BP than indicated by the model [*England et al.*, 2008]) and perhaps too low (roughly 2.7°C equilibrium) a 2 × CO_2 climate sensitivity. Coupled model simulations with interactive terrestrial vegetation could provide a better comparison in future work.

4. Conclusions

[15] Analysis of climate model simulations under various forcing regimes provides one potential path towards a better understanding of the complex factors that may influence past GST trends, and their relationship with past SAT trends. Here, we have examined a time interval, the early Holocene through modern pre-industrial, during which paleoclimate evidence and theoretical considerations both indicate the existence of substantial seasonal differences in long-term radiative forcing histories and associated climate trends. In particular, seasonal trends in temperature are likely to have been substantially different, and long-term changes in seasonal snow cover are likely to have been significant. Using a set of climate model simulations that reproduce such long-term Holocene climate trends, we find a substantial difference in the behaviors of annual mean GST and SAT. For example, the simulations reproduce a well defined mid-Holocene peak in annual mean GST (though far smaller in amplitude than that estimated in the long-term borehole-based GST reconstructions) even when annual mean SAT shows no such peak. This feature likely arises from the influence of long-term changes in seasonal snow cover on winter and transitional season GST changes.

[16] There are undoubtedly shortcomings in the simulations that may complicate comparisons with the true course of Holocene climate changes, the most significant of which may be the lack of interactive vegetation changes and an underestimate of Arctic sensitivity. However, the key implications of our results may well be robust to these uncertainties. Our simulations provide a scenario of internally-consistent forced changes in climate which display strong seasonally-specific characteristics leading to differential behavior in hemispheric GST and SAT trends. Since the real world seasonality changes were perhaps even stronger than modeled, we anticipate that the trend differences will persist with more realistic modeling.

[17] The results of the study could have implications for more recent climate changes over the past few centuries if, as argued elsewhere, forcings and the associated climatic

responses may have been substantially seasonal in nature [e.g., *Jones and Mann*, 2004]. In our simulations, annual mean NH SAT at 9K BP was about 0.3°C cooler than modern pre-industrial SAT (interestingly, this is well within the range of variability estimated over previous centuries, e.g., *Jansen et al.* [2007]). Yet the annual mean NH GST at 9K BP was roughly 0.1°C *warmer*, than during the modern pre-industrial, a discrepancy not only in net magnitude (0.4°C) but in sign. Such a discrepancy would be adequate, for example, to explain discrepancies between borehole-based trends and other proxy reconstructed trends during past centuries [see also *Jansen et al.*, 2007] if seasonal changes were comparable.

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References

Bartlett, M. G., D. S. Chapman, and R. N. Harris (2004), Snow and the ground temperature record of climate change, *J. Geophys. Res.*, *109*, F04008, doi:10.1029/2004JF000224.

Beltrami, H. (1996), Active layer distortion of annual air/soil thermal orbits: Permafrost and past climates, *PermafrostPeriglacial Processes*, *7*, 101–110.

Berger, A., and M. F. Loutre (1992), Astronomical solutions for paleoclimate studies over the last 3 million years, *Earth Planet. Sci. Lett.*, *111*, 369–382.

Briffa, K. R., and T. J. Osborn (2002), Blowing hot and cold, *Science*, *295*, 2227–2228.

Brohan, P., J. J. Kennedy, I. Harris, S. F. B. Tett, and P. D. Jones (2006), Uncertainty estimates in regional and global observed temperature changes: A new data set from 1850, *J. Geophys. Res.*, *111*, D12106, doi:10.1029/2005JD006548.

Chapman, D. S., M. G. Bartlett, and R. N. Harris (2004), Comment on "Ground vs. surface air temperature trends: Implications for borehole surface temperature reconstructions" by M. E. Mann and G. Schmidt, *Geophys. Res. Lett.*, *31*, L07205, doi:10.1029/2003GL019054.

England, J. H., T. R. Lakeman, D. S. Lemmen, J. M. Bednarski, T. G. Stewart, and D. J. A. Evans (2008), A millennial-scale record of Arctic Ocean sea ice variability and the demise of the Ellesmere Island ice shelves, *Geophys. Res. Lett.*, *35*, L19502, doi:10.1029/2008GL034470.

Fairbanks, R. G. (1989), A 17,000-year glacio-eustatic sea level record-Influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation, *Nature*, *342*, 637–642.

Folland, C. K., et al. (2001), Observed climate variability and change, in *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, edited by J. T. Houghton et al., pp. 99–181, Cambridge Univ. Press, Cambridge, U. K.

Ganopolski, A., et al. (1998), The influence of vegetation-atmosphere-ocean interaction on climate during the Mid-Holocene, *Science*, *280*, 1916–1919.

González-Rouco, F., H. von Storch, and E. Zorita (2003), Deep soil temperature as proxy for surface air-temperature in a coupled model simulation of the last thousand years, *Geophys. Res. Lett.*, *30*(21), 2116, doi:10.1029/2003GL018264.

González-Rouco, J. F., H. Beltrami, E. Zorita, and H. von Storch (2006), Simulation and inversion of borehole temperature profiles in surrogate climates: Spatial distribution and surface coupling, *Geophys. Res. Lett.*, *33*, L01703, doi:10.1029/2005GL024693.

Gosnold, W. D., Jr., P. E. Todhunter, and W. L. Schmidt (1997), The borehole temperature record of climate warming in the mid-continent of North America, *Global Planet. Change*, *15*, 33–45.

Hansen, J., et al. (2007), Climate simulations for 1880–2003 with GISS modelE, *Clim. Dyn.*, *29*, 661–696, doi:10.1007/s00382-007-0255-8.

Huang, S. P., H. N. Pollack, and P.-Y. Shen (1997), Late Quaternary temperature changes seen in world-wide continental heat flow measurements, *Geophys. Res. Lett.*, *24*, 1947–1950.

Huang, S., H. N. Pollack, and P.-Y. Shen (2000), Temperature trends over the past five centuries reconstructed from borehole temperature, *Nature*, *403*, 756–758.

Huang, S. P., H. N. Pollack, and P.-Y. Shen (2008), A late Quaternary climate reconstruction based on borehole heat flux data, borehole temperature data, and the instrumental record, *Geophys. Res. Lett.*, *35*, L13703, doi:10.1029/2008GL034187.

Jansen, E., et al. (2007), Palaeoclimate, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., pp. 433–497, Cambridge Univ. Press, Cambridge, U. K.

Jones, P. D., and M. E. Mann (2004), Climate over past millennia, *Rev. Geophys.*, *42*, RG2002, doi:10.1029/2003RG000143.

Kitoh, A., and S. Murakami (2002), Tropical Pacific climate at the mid-Holocene and the Last Glacial Maximum simulated by a coupled ocean-atmosphere general circulation model, *Paleoceanography*, *17*(3), 1047, doi:10.1029/2001PA000724.

Licciardi, J. M., P. U. Clark, J. W Jenson, and D. R. Macayeal (1998), Deglaciation of a soft-bedded Laurentide Ice Sheet, *Quat. Sci. Rev.*, *17*, 427–448.

Lynch-Stieglitz, M. (1994), The development and validation of a simple snow model for the GISS GCM, *J. Clim.*, *7*, 1842–1855.

Mann, M. E., and G. A. Schmidt (2003), Ground vs. surface air temperature trends: Implications for borehole surface temperature reconstructions, *Geophys. Res. Lett.*, *30*(12), 1607, doi:10.1029/2003GL017170.

Mann, M. E., S. Rutherford, R. S. Bradley, M. K. Hughes, and F. T. Keimig (2003), Optimal surface temperature reconstructions using terrestrial borehole data, *J. Geophys. Res.*, *108*(D7), 4203, doi:10.1029/2002JD002532.

Matthews, E. (1984), Prescription of land-surface boundary conditions in GISS GCM II: A simple method based on high-resolution vegetation data bases, *NASA Tech. Memo. 86096*, NASA, Washington, D. C.

Rosenzweig, C., and F. Abramopoulos (1997), Land-surface model development for the GISS GCM, *J. Clim.*, *10*, 2040–2054.

Schmidt, G. A., and M. E. Mann (2004), Reply to comment on "Ground vs. surface air temperature trends: Implications for borehole surface temperature reconstructions" by D. Chapman et al., *Geophys. Res. Lett.*, *31*, L07206, doi:10.1029/2003GL019144.

Schmidt, G. A., et al. (2006), Present day atmospheric simulations using GISS ModelE: Comparison to in-situ, satellite and reanalysis data, *J. Clim.*, *19*, 153–192, doi:10.1175/JCLI3612.1.

Skinner, W. R., and J. A. Majorowicz (1999), Regional climatic warming and associated twentieth century land-cover changes in north–western North America, *Clim. Res.*, *12*, 39–52.

Smerdon, J. E., H. N. Pollack, V. Cermak, J. W. Enz, M. Kresl, J. Safanda, and J. F. Wehmiller (2004), Air-ground temperature coupling and subsurface propagation of annual temperature signals, *J. Geophys. Res.*, *109*, D21107, doi:10.1029/2004JD005056.

Smerdon, J. E., H. N. Pollack, V. Cermak, J. W. Enz, M. Kresl, J. Safanda, and J. F. Wehmiller (2006), Daily, seasonal, and annual relationships between air and subsurface temperatures, *J. Geophys. Res.*, *111*, D07101, doi:10.1029/2004JD005578.

Sokratov, S. A., and R. G. Barry (2002), Intraseasonal variation in the thermoinsulation effect of snow cover on soil temperatures and energy balance, *J. Geophys. Res.*, *107*(D10), 4093, doi:10.1029/2001JD000489.

Stieglitz, M., S. J. Déry, V. E. Romanovsky, and T. E. Osterkamp (2003), The role of snow cover in the warming of arctic permafrost, *Geophys. Res. Lett.*, *30*(13), 1721, doi:10.1029/2003GL017337.

Taylor, A. E., K. Wang, S. L. Smith, M. M. Burgess, and A. S. Judge (2006), Canadian Arctic Permafrost Observatories: Detecting contemporary climate change through inversion of subsurface temperature time series, *J. Geophys. Res.*, *111*, B02411, doi:10.1029/2004JB003208.

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