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Deep soil temperature as proxy for surface air-temperature in a coupled model simulation of the last thousand years

F. González-Rouco
Dpto. Astrofísica y CC. de la Atmósfera, Universidad Complutense, Madrid, Spain

H. von Storch
Institute for Coastal Research, GKSS-Research Centre, Geesthacht, Germany

E. Zorita
Institute for Coastal Research, GKSS-Research Centre, Geesthacht, Germany

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[1] The relationship between terrestrial deep soil temperature (TDST) and surface temperature (SAT) at interannual and centennial timescales has been investigated in a simulation of the last millennium with a three-dimensional climate model driven by estimations of historical external forcing. TDST is loosely related to borehole temperature profiles, which have been recently used to reconstruct long term temperature trends in the last centuries. Recently, questions about the validity of boreholes-based reconstructions have been raised. In the simulation, at interannual time scales the connection between TDST and SAT is stable, being stronger in the summer half year than in the winter half year. At long timescales, annual TDSL is a good proxy for annual SAT, and their variations are almost indistinguishable from each other. Both TDSL and terrestrial SAT overestimate the variations of global mean SAT. This may be a source for the disagreement between statistical reconstructions of global SAT and terrestrial borehole measurements. *INDEX TERMS:* 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions. **Citation:** González-Rouco, F., H. von Storch, and E. Zorita, 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, 2003.

1. Introduction

[2] The reconstruction of global or hemispherical SAT variations in the last millennium has been subject of different methodological approaches in the last years [*Jones et al.*, 2001]. Measurements of borehole temperature profiles [*Huang et al.*, 2000] are perhaps the only direct measurements of past temperatures, in contrast to the analysis of other climate proxies, that have to be interpreted in terms of climate anomalies through transfer functions. However, because of heat-diffusion process in the soil column, borehole temperature profiles are believed to be able to yield information on long-term temperature trends only. Furthermore, most of the available borehole measurements are located in terrestrial areas, and doubts may arise that averages calculated from borehole measurements can give a representative picture of global or hemispheric temperatures. Temperature reconstruction of the last centuries based on borehole measurements tend to be much colder than some reconstructions based on tree-ring data or on multiproxy data sets [*Briffa and Osborn*, 2002], although recent reconstructions on extratropical tree-ring chronologies indicate a better agreement with the borehole based reconstructions [*Esper et al.*, 2002]. The validity of all these reconstructions is still a matter of considerable debate. Recently, the validity of the interpretation of borehole temperature profiles has been questioned [*Mann and Schmidt*, 2003]. Apart from other sources of error, such as land-use changes and vegetation cover, it has been argued that the link between soil temperatures and SAT may be stronger in the warm season than in the cold season, due to the insulating effect of snow cover. This effect should be significantly stronger in the continental land masses at middle and high latitudes. Averages of borehole temperature estimations could be then potentially biased towards the warm season temperatures. Also the vegetation cover, therefore the albedo, has a strong seasonal component. A perhaps more disturbing problem may be that the evolution of snow cover and vegetation may have undergone variations along the last centuries, depending of changes in the atmospheric circulation and on moisture content of the atmosphere. This could make the relationship between borehole temperature estimation and SAT unstable in time. Three-dimensional climate model simulations of the last millennium may be useful, not only as a mean of climate reconstruction itself, but also to test the different empirical reconstruction methods [*Mann et al.*, 2003; *Zorita and González-Rouco*, 2002]. The climate simulated by a state-of-the-art model may disagree in certain aspects with the observed climate, but it is a system complex enough to put the several reconstructions methods and their underlying assumptions to a test. In this letter we investigate the relationship between simulated SAT and simulated TDST in a climate simulation of the last millennium with a state-of-the-art coupled climate model driven by historical forcing. Borehole temperature profiles are not simulated in a climate model, so that another simulated variable has to be taken as proxy. The obvious candidate is the soil temperature simulated by the soil submodel of the climate model, as

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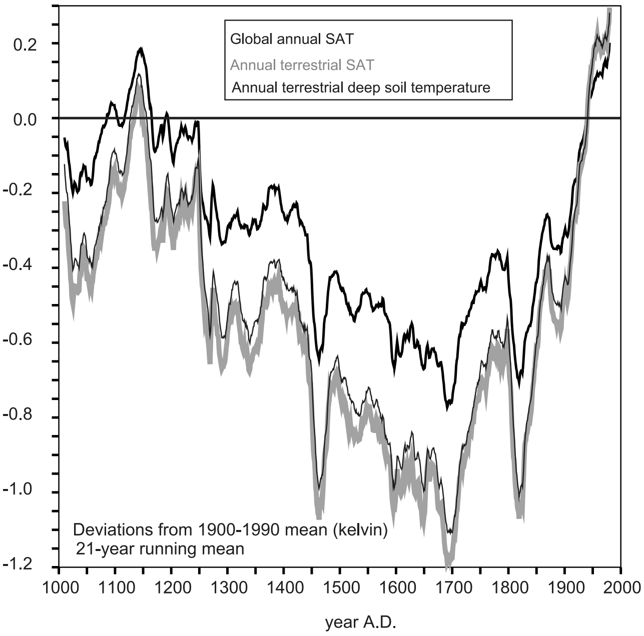

Figure 1. Simulated anomalies of the global annual SAT, annual terrestrial SAT and annual terrestrial deep soil temperature.

in [*Mann et al.*, 2003]. Here the deep soil temperature will be considered. In this analysis only the hypothesis dealing with the coupling between deep soil temperature and SAT can be tested, all other sources of error that are related to the estimation of global SAT from real borehole temperature profiles, such as estimation of heat diffusion parameters, measurements error, etc., can not ne considered. However, other relevant aspects, such as the representativity of terrestrial sampling for the estimation of global means, can be easily included in the analysis.

2. Climate Simulation

[3] The global climate model ECHO-G [*Legutke and Voss*, 1999] consists of the spectral atmospheric model ECHAM4 and the ocean model HOPE-G, both developed at the Max-Planck-Institut of Meteorology in Hamburg). The ECHAM4 model has a T30 resolution (approx. 3.75° × 3.75°) and 19 vertical levels. The horizontal resolution of the ocean model HOPE-G is about 2.8° × 2.8° with a grid refinement in the tropical regions. A constant flux adjustment was applied to avoid climate drift. The model was driven by estimations of three past external forcing factors: solar variability, atmospheric greenhouse gas concentrations, and radiative effects of stratospheric volcanic aerosols, in the period 1000–1990 AD, derived from the estimations provided by *Crowley* [2000]. The soil model is divided into five layers with levels at depths of 0.06 m, 0.32 m, 1.23 m, 4.13 m and 9.83 m. Temperature at the deepest level as been used in this analysis as deep soil temperature. This submodel is an extension of the *Warrilow et al.* [1986] model. The vegetation type is fixed to present conditions. Precipitation in form of snow, snow accumulation. snow melting, infiltration and run-off are simulated. The coupled model ECHO-G has been previously used for studies of natural climate variability, [e.g., *Grötzner et al.*, 1998].

3. Results

[4] The simulated annual global SAT (Figure 1) shows a period of temperatures roughly as warm as today around 1100 A.D. (the Medieval Optimum), a subsequent cooling trend until around 1850 A.D. (the Little Ice Age) punctuated by deeper temperature minima at around 1450 A.D., 1700 A.D., and 1820 A.D., coincidental with known minima of the solar output or periods of more frequent volcanic eruptions (the Spoerer, Maunder and Dalton minima, respectively). Subsequently, the model simulates a steep temperature increase up to the end of the simulated period. The level of cooling in the Little Ice Age and in the shorter-lived temperature minima is larger than in most empirical reconstructions to date, but is quite in agreement with other ongoing climate simulations with the HadCM3 model of the Hadley Centre for Climate Research [*Widmann and Tett*, 2003]. To clarify these discrepancies between models and empirical reconstructions will require further research and is not the scope of this note.

[5] Figure 1 also shows the evolution of the SAT and TDST averaged over terrestrial grid points. The evolutions of these variables are roughly similar to that of the global annual SAT, although the magnitudes of the variations are stronger. This is probably due to the larger heat capacity of the upper ocean layers. This figure indicates that in the world simulated by the climate model, and at long time-scales, global annual TDST is a good proxy for terrestrial global annual SAT, but that TDSL, as well as terrestrial SAT, tend to overestimate the global SAT variations. The overestimation at the peak of the LIA is of the order of 50%. These conclusions can also be reached from the results of a twin simulation with a slightly different version of the model ECHO-G starting in year 1550 A.D. (not shown).

[6] Is this behaviour extrapolable to the warm and cool season separately? To answer this question we turn our attention to the evolution of the temperatures in terrestrial extratropical areas in the Northern Hemisphere (most borehole measurements are located in extratropical land masses, [*Huang et al.*, 2000]. Figure 2 shows the time series of TDSL and SAT in the winter months (December to February), summer months (June to August) and the annual mean. In the summer months the evolution of both temperatures is almost indistinguishable, indicating that there is a strong coupling between both variables. In contrast, in the winter months TDST is systematically warmer than the SAT. This warm bias is probably due to the fact that in winter the heat loss from the deep soil is hindered by snow cover or frozen soil layers, whereas in summer heat flux from the atmosphere can penetrate more easily into the soil [*Mann and Schmidt*, 2003]. The largest differences between TDST and SAT in the simulation are found in the more intense minima within the Little Ice Age (Spoerer, Maunder and Dalton) and these differences can reach values of about 0.5 Kelvin. In the annual mean these differences are much reduced. At interannual time scales the coupling between TDSL and SAT is different in the summer and winter months. The coupling at grid-point level is systematically higher in summer than in winter, but it tends to be stable along the

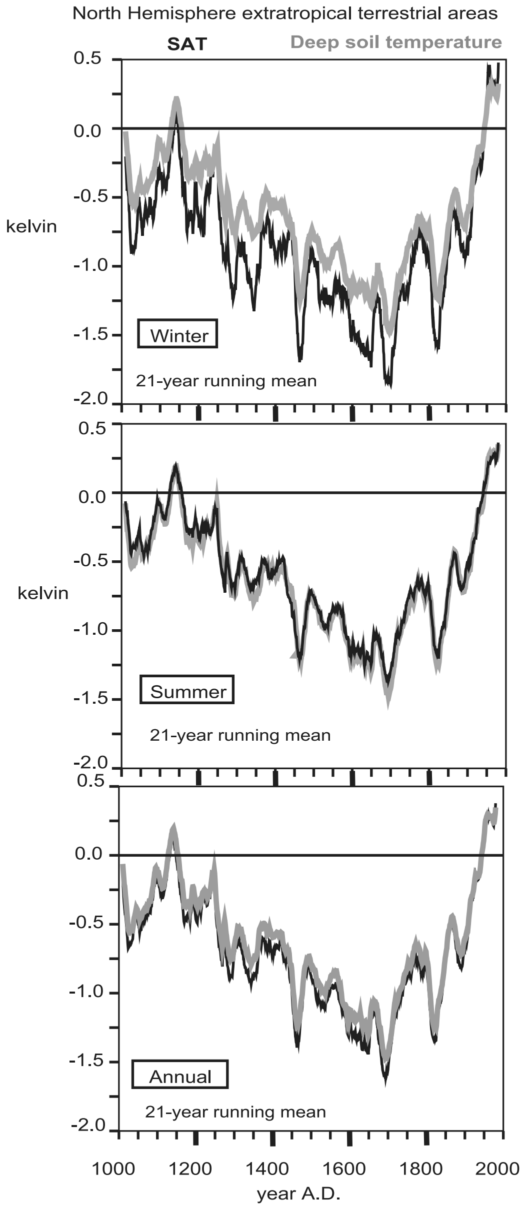

Figure 2. Simulated anomalies of the extratropical terrestrial North Hemisphere TDSL and SAT in (a) winter (December–February), (b) summer (June–August) and (c) annual mean.

whole simulation, as illustrated in Figure 3. This figure shows the local described variance (correlation squared) between TDSL and SAT, spatially averaged over the Northern Hemipshere, calculated over a moving 50-year window, for summer and winter separately. The described variances in summer and winter vary around 45% and 35%, respectively, with some low-frequency variability. These variations, however, cannot be directly associated with generally warmer or colder climates. Despite the different seasonal coupling between TDSL and SAT in the model, it seems that the main caveat in using TDST as a proxy to global or hemispheric SAT lies in its limited coverage, which does not include ocean areas. The question arises whether this drawback could be corrected by applying a statistical model linking the TDST field as predictor with the mean SAT as target variable. This possibility has been also explored using annual means from the output of this climate simulation. In a simple linear regression model only the spatially averaged TDSL has been considered as predictor for the average SAT:

$$T(t) = a\ dst(t) + \epsilon(t) \qquad (1)$$

where T is the annual North Hemisphere SAT anomalies and $dst(t)$ the TDSL anomalies in the Northern Hemisphere and ϵ are the residuals. Before calibrating the regression model, it has been tested if the the correlation between the NH SAT and NH TDST is stable along the simulation. Figure 4 shows the running correlation between both variables in a 100-year moving window. In general the correlations are high, always higher than 0.6. In the 14th century, however, the correlation clearly drops to its lowest values. The regression model has therefore been calibrated in two different periods, the observational period 1900–1990 A.D and in 1350–1400 A.D. Once the regression parameter has been estimated, the statistical model can be applied to the NH TDST field along the whole simulation, obtaining a pseudo-reconstruction of the North Hemisphere annual SAT, that can be compared with the one simulated by the ECHO model (Figure 4.) The reconstructions are in both cases very close to the values actually simulated by the climate model, indicating that the TDSL could be a potentially a good predictor for NH SAT.

[7] The statistical correction of average TDSL to yield a reliable estimation of average SAT has been, in this case, possible because annual values of both variables are available in the calibration period. This is, however, not the case for borehole temperature profiles. In reality, the estimation of past ground temperatures is hampered by heat diffusion in the soil column, so that only long-term trends, at time scales of centuries, can be derived from the measurements of temperature profiles. A calibration of a statistical model to correct for the terrestrial coverage of the borehole measurements would not be possible in this case, although a correction factor could be, in principle, derived from

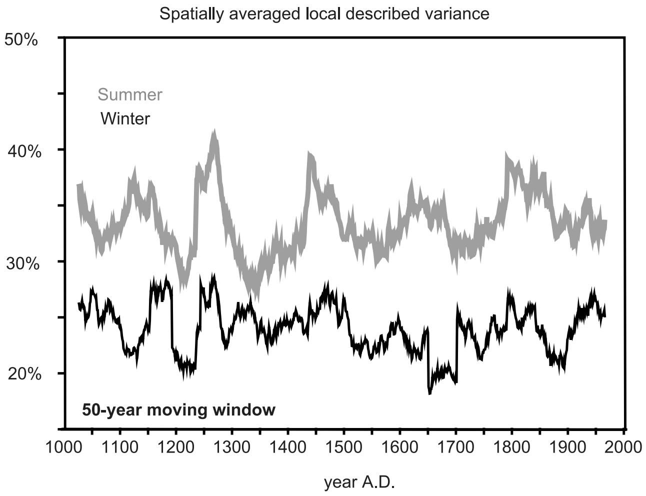

Figure 3. Spatially averaged described variance(correlation squared) between local TDST and SAT in terrestrial areas in the Northern Hemisphere.

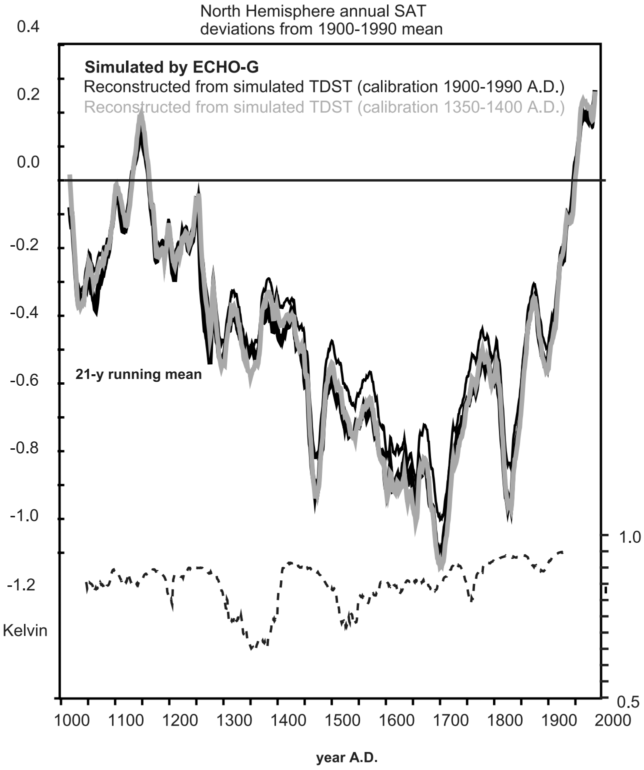

Figure 4. Northern Hemisphere annual SAT as simulated by the model ECHO-G and reconstructed using the terrestrial deep soil temperature as predictor. The regression model has been calibrated in the periods 1900–1990 A.D. And 1350–1400 A.D. with annual values. The running correlation between NH SAT and NH TDST is also shown (dotted line).

climate model simulations and applied to the data set of real measurements.

4. Conclusions

[8] In the climate simulation the coupling at interannual timescales between deep soil temperature and surface air temperatures is weaker in winter than in the summer months, thus supporting the hypothesis put forward by *Mann et al.* [2003]. However, the intensity of the coupling is stable along the simulations. At decadal and longer timescales the differences between TDST and terrestrial SAT in the annual mean are negligible, so that in the model the TDST would be a good proxy for terrestrial SAT.

[9] The question whether borehole temperature profiles are a reliable proxy for global SAT is loaded by many other sources of error (connected to the retrieval algorithm, changes in land use, coverage of the point measurements, the role of changing vegetation cover) that have not been considered here. Our results indicate that even if these problems where solved, the question of the insufficient global sampling (i.e., mostly terrestrial measurements) represent a problem needs to be addressed. However, if the results of the climate model are transferable to the real world, the drawback of a possible seasonal bias or of the influence of other disturbing factors such as snow cover, seems to be of minor importance at decadal and centennial time scales. In the model simulation, the mismatch between terrestrial TDST and global SAT caveat can be overcome by a simple statistical scheme calibrated with interannual values of both variables over roughly several decades to one hundred years. The calibration period does not seem to be critical for this correction. This scheme is, however, not directly transferable to borehole temperature profiles measurements, since they do not provide interannual estimations of ground temperatures.

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F. González-Rouco, Facultad C.C. Físicas, Universidad Complutense de Madrid, 28040 Madrid, Spain. (fidelgr@fis.ucm.es)

H. von Storch, GKSS-Research Centre, Max-Planck-Str. 1, 21502, Geesthacht, Germany. (storch@gkss.de)

E. Zorita, GKSS-Research Centre, Max-Planck-Str. 1, 21502, Geesthacht, Germany. (zorita@gkss.de)