NORTHERN HEMISPHERE TEMPERATURE VARIABILITY FOR THE PAST THREE CENTURIES: TREE-RING AND MODEL ESTIMATES

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Abstract. We compare Northern Hemisphere energy-balance-model temperature calculations to an annual temperature reconstruction based on 20 tree-ring width records from latitudinal and elevational treeline sites in northern North America, Scandinavia, Siberia and Mongolia for the past three centuries. The energy-balance model uses three primary forcings; solar, volcanic, and anthropogenic trace gas and aerosol variations. Several different parameterizations of the forcings are compared. The best agreement ($r = 0.8$) is found when the annual reconstruction is compared to a version of the model using (1) the Dust Veil Index of Lamb, (2) a solar parameterization which includes the length of the solar cycle, and (3) anthropogenic forcing. The implication is that all three forcings are important in explaining the temperature variations. The general similarity in low-frequency trends between the two independently-derived time series supports the validity of both the model estimates and the tree-ring reconstruction.

1. Introduction

The present length of instrumental record is insufficient to assess the relative importance of various forcing functions on the earth's climate system. The 100+ year Northern Hemispheric temperature record (Hansen and Lebedeff, 1987), for example, can only be compared to one full Gleissberg sunspot cycle (80–90 yr) (Friis-Christensen and Lassen, 1991). Longer climate records developed from proxy data can extend the time period available for analysis and can also be used to evaluate how temperature trends during the recent interval of possible anthropogenic change compare to those of prior centuries. Both paleo-reconstructions and model simulations of large-scale temperature variations can yield important information regarding climate variability on longer time scales. High-resolution climatic reconstructions have been based on tree-ring data, ice core records, sediment analyses, and/or other paleodata (e.g., Jacoby and D'Arrigo, 1989; Overpeck et al., 1997; Mann et al., 1998). Model simulations can be based on parameterization of forcings such as solar variations, volcanic influences, and trace gas/aerosol

variations over several centuries. The validity of both types of time series should be tested by intercomparisons among reconstructions, among models, and between reconstruction and model estimates. In an effort to provide such validation, we present a comparison of a tree-ring based annual temperature reconstruction for the Northern Hemisphere with an energy-balance model (EBM) simulation based on solar, volcanic and anthropogenic forcings. Such comparisons will aid in testing and improving the climate models and forcing estimates, enhancing their value as realistic estimators of climatic variations and as predictive tools.

The development of large-scale reconstructions of temperature from proxy records dates back to Groveman and Landsberg (1979). They combined tree-ring and other proxy and historical data to estimate annual Northern Hemisphere temperatures back to 1579. Jacoby and D'Arrigo (1989) developed annual (Jan.–Dec.) reconstructions of Arctic and Northern Hemisphere temperatures for 1671–1973, based on 11 tree-ring width records from temperature-sensitive latitudinal treeline sites that extended over 90° longitude across North America. D'Arrigo and Jacoby (1993) improved on this coverage, using 20 tree-ring series from northern North America, Scandinavia and northwestern Russia in a modified reconstruction of Arctic temperatures. The low-frequency trends in the latter reconstruction, using nine additional records, were very similar to those developed in Jacoby and D'Arrigo (1989).

We previously described some qualitative correspondence between our annual reconstructed temperatures and noted climatic events ascribed to specific forcings (Jacoby and D'Arrigo, 1989; D'Arrigo and Jacoby, 1993). For example, the reconstructions indicated colder temperatures around the time of the Maunder sunspot Minimum from 1645–1715 (Eddy, 1976), and in the early-mid 1800s. The latter was a period of elevated volcanic activity and, initially, low sunspot levels (Grove, 1988). Warmer temperatures were reconstructed during the mid-20th century period of enhanced solar activity (Lean et al., 1995) and generally over the past century of increasing trace gases (Houghton et al., 1996).

Another reconstruction, of Northern Hemisphere summer temperature, is based in part on our tree-ring records from northern North America, as well as additional proxy and historical data (Bradley and Jones, 1993). It generally shows similar trends to those seen in Jacoby and D'Arrigo (1989) and D'Arrigo and Jacoby (1993). The Bradley and Jones (1993) reconstruction is of decadal resolution, unlike the annual reconstructions based on tree-ring data alone (Jacoby and D'Arrigo, 1989; D'Arrigo and Jacoby, 1993). Mann et al. (1998) used an augmented data set from Bradley and Jones (1993) to produce an annual hemispheric reconstruction. Overpeck et al. (1997) developed a summer-weighted annual Arctic temperature reconstruction back to A.D. 1600 based on multiple proxies, including the above treeline tree-ring data. These reconstructions also show similarities to time series of the three primary climatic forcings: solar, volcanic and anthropogenic, as listed above.

TABLE I

Site information of northern tree-ring chronologies used to reconstruct Northern Hemisphere temperature (see also Figure 1). With the exceptions marked, all data are from sampling by the Tree-Ring Laboratory at Lamont-Doherty Earth Observatory. NWT = Northwest Territories, MB = Manitoba, QB = Quebec, LB = Labrador, NWY = Norway, FNL = Finland, SIB = Siberia, TAR = Tarvagatay Mts. Species key: PCGL = *Picea glauca*, LALA = *Larix laricina*, THOC = *Thuja occidentalis*, PISY = *Pinus sylvestris*, LAGM = *Larix gmelina*, PISB = *Pinus sibirica*

	Site	Lat.	Long.	Elev.	Species	Years
North America		*N*	*W*	*M*		
1. 412	Alaska	67 56	162 18	126	PCGL	1515–1977
2. Arrigetch	Alaska	67 27	154 03	732	PCGL	1586–1975
3. Sheenjek	Alaska	68 38	143 43	808	PCGL	1580–1979
4. Silvertip	Alaska	62 33	142 20	1020	PCGL	1513–1992
5. TTHH	Yukon	65 00	138 20	914	PCGL	1459–1975
6. Mack Mt.	NWT	65 00	127 50	1370	PCGL	1626–1983
7. Coppermine	NWT	67 14	115 55	215	PCGL	1428–1977
8. Hornby	NWT	64 02	103 52	160	PCGL	1491–1983
9. Churchill[a]	MB	58 43	094 04	80	PCGL	1650–1988
10. Cape	QB	56 10	076 33	90	PCGL	1663–1982
11. Ft. Chimo[a]	QB	58 22	068 23	46	LALA	1650–1974
12. Gaspe	QB	48 35	065 55	305	THOC	1404–1982
13. Saltwater Pond	LB	56 31	061 55	150	PCGL	1602–1988
Scandinavia[a]		*N*	*E*			
14. Lofoten	NWY	68 29	016 02	200	PISY	1485–1978
15. Pyhatunturi	FNL	67 00	027 15	260	PISY	1655–1983
16. Sompio	FNL	68 45	027 15	325	PISY	1560–1983
17. Morgammaras	FNL	68 45	026 30	300	PISY	1536–1983
18. Suojanpera	FNL	69 19	028 08	140	PISY	1532–1983
Russia						
19. Taymyr	SIB	72 30	105 09	150	LAGM	1490–1995
Mongolia						
20. High Pass	TAR	48 18	098 56	2420	PISB	1465–1994

[a] Fort Chimo and all the Scandinavian chronologies are based on data from H. Fritts and K. Briffa respectively. Some Churchill samples were provided by P. Scott.
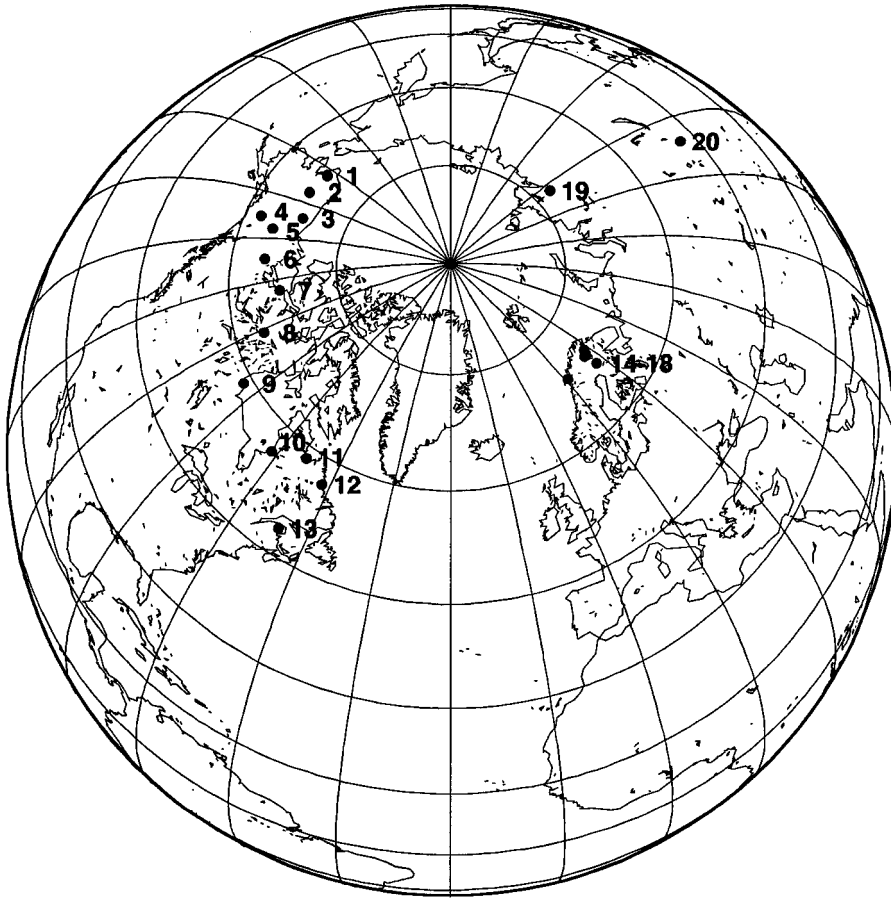
Figure 1. Map of Northern Hemisphere showing locations of 20 tree-ring sites used in this study. See Table I for site and chronology information.

2. Data and Methodology

We have made additional improvements in our tree-ring-based reconstructions relative to D'Arrigo and Jacoby (1993) (Table I, Figure 1). A revised version of our Northern Hemisphere temperature reconstruction was developed for more direct comparison with the hemispheric-scale energy-balance model used for this study. Three new tree-ring series are used in the present reconstruction (Table I). All of these new tree-ring data sets were processed using standard techniques (Cook and Kairiukstis, 1990). The chronologies of ring-width indices were developed using conservative standardization methods to preserve low-frequency temperature response, similar to the methods used in previous studies (Jacoby and D'Arrigo, 1989; D'Arrigo and Jacoby, 1993). Standardization is a process used to reduce the effects of age and size in tree-ring data to help clarify the climatic response (Cook

TABLE II

Calibration and verification statistics for Northern Hemisphere temperature reconstruction model (Fritts, 1976; Cook and Kairiukstis, 1990): R_a^2 is the variance described adjusted for loss of degrees of freedom due to the regression

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Full calibration period: 1880–1973: $R_a^2 = 67\%$.

Early calibration period: 1880–1935, verification 1936–1973: $R_a^2 = 57\%$,

Spearman correlation coeff. 0.41, Reduction of error 0.77.

Late calibration period: 1936–1973, verification 1880–1935: $R_a^2 = 19\%$,

Spearman correlation coeff. 0.75, Reduction of error 0.34.

One possible cause of the low R_a^2 for the 1936–1973 calibration is that the

warmer temperatures during this interval reduced the climatic stress on the trees.

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and Kairiukstis, 1990). One new tree-ring record is from a mesic site at elevational timberline in the Tarvagatay Mts. of Mongolia, filling a considerable gap in data coverage for northern latitudes (Jacoby et al., 1996). The low-frequency trends in the Mongolian record are strikingly similar to (and are well correlated with) the D'Arrigo and Jacoby (1993) reconstruction at $r = 0.71$. The second tree-ring record (Silvertip) is from a mesic elevational treeline site in the Wrangell Mountains of southeastern Alaska. The third new chronology is from a mesic site on the Taymyr Peninsula, Siberia, location of the northernmost trees on the globe. This chronology replaces those used previously for this region.

The resulting data set of 20 tree-ring chronologies was entered into principal components analysis (PCA). The PCA was performed on the period of overlap with the instrumental data (1880–1973). The results of this PCA were applied to the entire tree-ring record which extends from 1671 to 1973, the common period for all the chronologies. The first four eigenvector scores had eigenvalues more than one and were retained for further analysis (Cook and Kairiukstis, 1990). These four sets of scores (for lag years $t - 1$, t and $t + 1$) were used as candidate predictors in principal components regression (Cook and Kairiukstis, 1990). The forward and backward lags are appropriate because tree growth can be influenced by prior-year's climate (Fritts, 1976; Kramer and Kozlowski, 1979) and because different regions can lead or lag large-scale temperature shifts (Jacoby and D'Arrigo, 1989). Those predictors found to be statistically significant at the 95% level were retained in the regression model (these were: eigenvector 1, $t-1$, t and $t+1$; and eigenvector 2, $t - 1$ and t). The resulting reconstruction (1671–1973) accounts for 67% of the variance in annual Northern Hemisphere temperature departures (Hansen and Lebedeff, 1987) for 1880–1973, compared to 59% in the previous reconstruction for the same interval (Jacoby and D'Arrigo, 1989). Calibration and verification statistics (Fritts, 1976; Cook and Kairiukstis, 1990) for the recent model are comparable to or somewhat improved over the previous version (Table II).

We compare this reconstruction to simulated temperatures based on an up-welling-diffusion EBM similar to that used in previous studies (Hoffert et al., 1980; Wigley and Schlesinger, 1985; Kelly and Wigley, 1992), and described in Free (1996) and Free and Robock (1998). The model consists of 4 boxes at the surface, representing NH land, NH ocean, SH land and SH ocean, and a 40-level upwelling-diffusion ocean. Water from the mixed layer near the surface is assumed to sink at the poles and then rise in the lower latitudes with a prescribed upwelling velocity. Temperature changes at the surface are also transmitted to the deep ocean by diffusion from the mixed layer. This formulation is intended to simulate the effect of the deep ocean on surface temperature responses. The model variables are perturbations from an assumed initial equilibrium state, that is, at $t = 0$ all the temperatures are set at 0.0 K. In any case, the effects of different initial conditions disappear after about 50 years. The SH and NH are distinguished by the differing proportions of land and ocean in each and by differences in some forcing series between NH and SH. Our comparison is to the temperature responses of the NH land box of the model.

An earlier EBM was compared to the Groveman and Landsberg (1979) reconstruction from 1620–1975 (Robock, 1979). In that study, the best result was obtained with volcanic dust forcing alone, using Lamb's Dust Veil Index (Lamb, 1970). Neither the expression of the solar constant as a function of the envelope of the sunspot number, nor increasing trace gases (through 1975) improved those model comparisons (Robock, 1979). Previous studies have compared simulated temperatures derived from simple models to the instrumental temperature record for the past century (e.g., Hansen et al., 1981; Schonwiese, 1984). General Circulation Model (GCM) temperature simulations have also been made using prescribed individual climate forcings (e.g., Graf et al., 1993; Rind and Overpeck, 1994). However, GCM simulations based on input from multiple forcings for the pre-instrumental period are still in progress (D. Rind, pers. comm.). Simpler models such as EBMs have the advantage that multiple integrations and forcing combinations can be more readily evaluated, and that the EBMs do not have the noise or internal variability of GCMs. Rind (1996) notes in detail the uncertainties in prescribing the magnitude of potential forcings and the correct climate sensitivity for both EBMs and GCMs in such studies. Empirical approaches to evaluation of the impacts of climatic forcings also have their advantages and disadvantages (e.g., Mann et al., 1998).

We evaluated three volcanic indices in the present model (Table III): the Dust Veil Index (DVI, Lamb, 1970, 1977, 1983), the Volcanic Explosivity Index (VEI, Newhall and Self, 1982; Simkin and Siebert, 1994), and a combined Ice Core Volcanic Index (IVI) (Robock and Free, 1995, 1996). Although the DVI has been criticized for using climatic information in its compilation, removal of the temperature-based information did not significantly alter the results in modeling (Robock, 1981; Robock and Free, 1995). The VEI also has limitations, since it is an index of explosivity and not necessarily of sulfate aerosol input (Robock and

TABLE III

Correlation coefficients of model results with Northern Hemisphere (NH) annual temperature reconstruction for three time intervals: 1767–1973 (common to all runs), 1671–1973 (longest possible interval), and 1767–1880 (longest common interval for pre-instrumental period). For 1671–1973, correlations in parentheses are computed between the model runs and the first principal component of the tree-ring data (see text). Model results are also compared with NH instrumental temperatures for 1880–1973. The correlation between the reconstruction and instrumental NH temperatures for 1880–1973 is $r = 0.82$. Comparisons for 1767–1973, 1671–1973 and 1880–1973 are all statistically significant at the 0.01 level

NH model	NH recon.		NH temps.	
	1767–1973	1671–1973	1767–1880	1880–1983
Single forcing				
VEI	0.24	0.22 (0.20)	0.27	0.47
IVI	0.25	0.18 (0.15)	0.14	0.33
DVI	0.70	0.61 (0.57)	0.58	0.74
LEAN	0.59	0.45 (0.45)	–0.34	0.63
KW[a]	0.50	0.51 (0.44)	0.21	0.82
HOYT[a]	0.70	0.65 (0.56)	0.22	0.80
FCL[a]	0.74	0.73 (0.66)	0.48	0.82
ANTHRO[a]	0.61	0.61 (0.61)	–0.71	0.66
Multi-Forcing				
VEI-LEAN-ANTHRO	0.42	0.41 (0.41)	0.15	0.60
VEI-KW-ANTHRO	0.44	0.41 (0.41)	0.20	0.66
VEI-HOYT-ANTHRO	0.50	0.46 (0.45)	0.20	0.68
VEI-FCL-ANTHRO	0.43	0.41 (0.41)	0.21	0.65
IVI-LEAN-ANTHRO	0.52	0.48 (0.46)	–0.05	0.61
IVI-KW-ANTHRO	0.56	0.51 (0.48)	0.05	0.65
IVI-HOYT-ANTHRO	0.59	0.56 (0.53)	0.04	0.69
IVI-FCL-ANTHRO	0.56	0.51 (0.48)	0.06	0.65
DVI-LEAN-ANTHRO	0.76	0.68 (0.67)	0.28	0.77
DVI-KW-ANTHRO	0.80	0.74 (0.71)	0.41	0.81
DVI-HOYT-ANTHRO	0.82	0.74 (0.71)	0.41	0.80
DVI-FCL-ANTHRO	0.81	0.74 (0.72)	0.44	0.80

[a] Note however that HOYT begins in 1700; FCL and KW both begin in 1751; ANTHRO effect presumed to begin in 1767.

Free, 1995). The IVI is a direct measure of acidity or sulfate concentration from several ice cores. The values include contamination by other sources of sulfate besides volcanism, and overemphasize high-latitude eruptions, such as Katmai in 1912. Averaging of the ice core data from various locations reduced this last noise effect (Robock and Free, 1995). The IVI, although constructed for the period since A.D. 453, is not considered useful for delineating climate forcing by explosive volcanic eruptions prior to around A.D. 1200 in the Northern Hemisphere (Robock and Free, 1996).

Four indices of solar activity were compared for this exercise (Table III). Both the FCL (Friis-Christensen and Lassen, 1991) and KW indices (Kelly and Wigley, 1992) are based on the length of the solar cycle. The HOYT parameterization is based on a solar irradiance model which also incorporates the length of the solar cycle, as well as the normalized decay rate and mean level of solar activity (Hoyt and Schatten, 1993). The LEAN series is composed of calculations of solar irradiances based on sunspot numbers and recent satellite observations (Lean et al., 1995). Good agreement was found overall between the Lean et al. (1995) estimates of solar activity and the Bradley and Jones (1993) temperature reconstruction on the decadal scale ($r = 0.86$) (Lean et al., 1995). However, correspondence was relatively low during the 19th century, when there were several major volcanic events. There is at present an incomplete understanding of solar variability and how the related physical processes influence earth's climate (e.g., Lean et al., 1995).

The trace gas/aerosol parameterization (ANTHRO, which includes tropospheric aerosols, Table III) is that specified in the International Panel on Climate Change Report (IPCC) (Houghton et al., 1996) for projections of future greenhouse warming. There is an assumed sensitivity of $3.0\,°C$ for doubled CO_2 based on the mean value from the IPCC report described in Houghton et al. (1996). See Free (1996) and Free and Robock (1998) for additional details on the model and parameterizations.

The time series of tree-ring reconstruction and climate model output can be considered to be independent, as the former is based on measured tree-ring widths, whereas the latter are derived from quantification of volcanic phenomena, solar measurements and/or laws of physics and radiation, and estimation and measurement of trace gases and aerosols. The tree-ring data are calibrated by linear regression (after PCA) with recorded temperatures. The climate model has a sensitivity based on the physics of GCMs. These calibrations set the range of variations into comparable degrees Celsius, however the temporal variations of each type of series are inherent in their independent derivation.

As noted, earlier studies compared EBM simulations to instrumental temperatures for the past century (e.g., Schneider and Mass, 1975; Hansen et al., 1981; Schonwiese, 1984), and to proxy data for prior centuries (Robock, 1979). The study described herein builds on the work of Robock (1979) in comparing EBM output to an annual temperature reconstruction extending back several centuries prior to the period of instrumental data. Although the Groveman and Landsberg (1979)

series employed in Robock (1979) is longer than our reconstruction, the geographic coverage by the former is sparse with some inhomogeneities in the earlier part of their record; e.g., there are only three series from 1579–1658 and four from 1659–1706. Similarly, the Bradley and Jones (1993) reconstruction is not homogeneous over the length of record. Our reconstruction is based on the same set of tree-ring data for the entire period. Other recent studies have included comparisons with individual forcings, as in Overpeck et al. (1997). Mann et al. (1998) employed an empirical approach using statistical attribution analysis and multivariate regression to compare forcings to temperature, but did not combine these forcings into one representative series. Our study allows us to relate a reconstruction to multiple forcing time series and a physically-based model. This new comparison also permits comparison with several volcanic and solar indices not available at the time of Robock (1979).

3. Results

Correlations between the reconstruction and the model runs were computed for three intervals (Table III): (1) the years 1767–1973, common to all runs; (2) the longest interval available for each run, dating as far back as 1671 (note, however, that HOYT begins in 1700, FCL and KW begin in 1751 and ANTHRO in 1767), and (3) for the years 1767–1880, the longest common pre-instrumental interval for all runs prior to the positive trend in temperatures beginning around 1880. The best fits ($r = 0.80$–0.82) for the interval 1767–1973 common to all runs are found with the model versions which include the combined DVI and trace gas parameterizations along with either the KW, HOYT or FCL solar inputs, which are similarly derived (Table III, Figure 2). Note that Figure 2 (based on the DVI-FCL-ANTHRO model which had a slightly higher correlation than the KW or HOYT inputs) is plotted back to 1671 although the FCL input does not begin until 1751 and ANTHRO in 1767. Thus the earlier part of the comparison in Figure 2 includes only input from volcanic forcing. The highest correlation previously found by Robock (1979) for comparison of the Groveman and Landsberg (1979) reconstruction with the combined volcanic-sunspot-CO_2 model was 0.45 for 1620–1975. For the individual forcings the best correlations are found with the FCL, HOYT, DVI, ANTHRO, and LEAN parameterizations, in descending order. The correlations for the period before 1880 are considerably lower. Part of the reason for the better correlations post-1880 is the general agreement among the data in upward trends for much of the 20th century. Also indicated in Table III in parentheses are the correlations between model output and the first eigenvector scores of the tree-ring data following PCA for 1671–1973. This comparison shows that the tree-ring data are well correlated with the model time series even without calibration with instrumental temperatures.
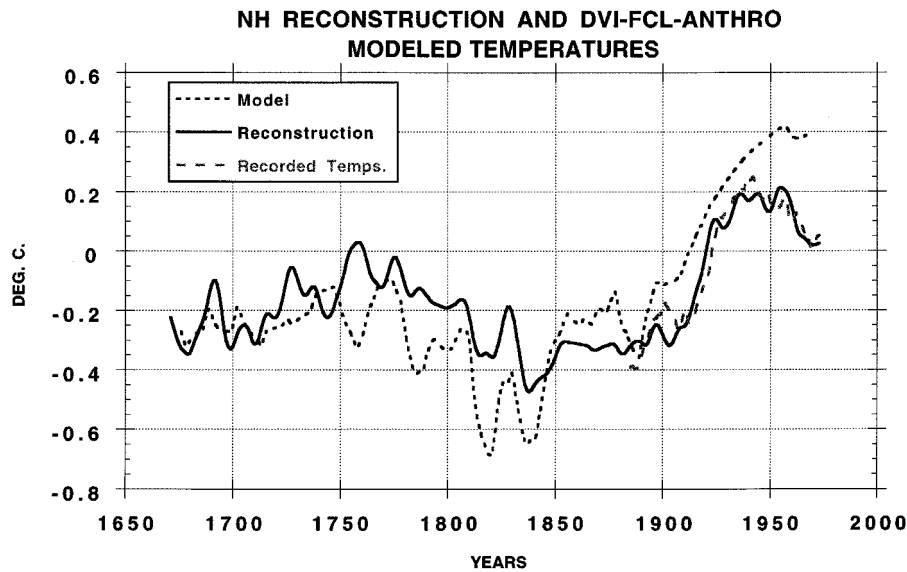
NH RECONSTRUCTION AND DVI-FCL-ANTHRO MODELED TEMPERATURES

Figure 2. Comparison of annual Northern Hemisphere temperature reconstruction with model simulation based on combined DVI, FCL (which had a marginally higher correlation than the KW and HOYT parameterizations) and ANTHRO (DFA) forcings for 1671 to 1973. Tree-ring, model estimates, and recorded temperatures are smoothed to emphasize low-frequency trends. The reconstruction is only smoothed with a five-year filter because it already uses $t-1$, t, and $t+1$ in estimating the temperatures. Four of the prominent dips in the model curve are associated with major volcanic events: Laki in 1783, Tambora in 1815, Coseguina in 1835, and Krakatoa in 1883. The model seems to reflect these events more strongly than the tree-ring data. The recorded data (Hansen and Lebedeff, 1987) and hence the reconstruction are based on temperature departures from the mean of the period of 1951 to 1980. The recorded temperature mean was adjusted to the full term mean of the model.

Because the common period for the chronologies ends in 1973, as an exercise correlations were also computed between the model runs and the Mongolian tree-ring record, which shows a very strong similarity to the overall reconstruction and extends through 1990, the last year of the model output. Correlations with the Mongolian chronology were slightly higher for 1671–1990 than for 1671–1973. There is evidence that some trees growing at the northern treeline, previously strongly influenced by temperature, are now showing influence of moisture stress or other growth-limiting factors (Jacoby and D'Arrigo, 1995; Briffa et al., 1997). However, the Mongolian trees and those from some other sites are still responding primarily to temperature. When the model run and the instrumental temperatures are compared through 1989, the model shows the 1960s–1970s cooling and then returns to continued warming, similar to the recorded data. The model continues to overestimate the recent instrumental temperatures, however to preserve the independence of the series we have not adjusted the data or curves at this time.

Correlations computed between the model runs and instrumental Northern Hemisphere temperatures (Hansen and Lebedeff, 1987) for 1880–1973 are con-

sistent with the reconstruction comparisons and likewise indicate the highest correlations with the volcanic DVI; KW, HOYT, and FCL solar indices, and ANTHRO inputs, for both the individual and multiple forcing runs (Table III).

The more recently derived volcanic indices thus do not provide a better model than the DVI of Lamb (1970, 1983), which was also well correlated with the Groveman and Landsberg (1979) reconstruction in Robock (1979; 0.41 for DVI for 1620–1975). Although it might be argued that the DVI incorporates some temperature effects, as mentioned their removal in a previous study did not significantly alter the results (Robock, 1981). It is likely that the DVI is a better index because it reflects direct evidence of sulfate aerosols in the atmosphere: either radiation measurements (after 1883), or information such as that on haze or unusual sunsets. The VEI reflects the volume of material ejected, not strictly the component that ends up as sulfate in the stratosphere, and hence is not as close to the actual climate forcing. IVI has various problems, as noted, inherent in using ice cores as data, which could perhaps be reduced with additional cores and effort. Those solar parameterizations used herein, particularly those which include the length of the solar cycle, do yield much improved model results relative to the earlier solar index used in Robock (1979). The trace gas/aerosols parameterization is well correlated with the instrumental and reconstructed temperatures through 1973. This finding is consistent with that of the Mann et al. (1998) empirical study. Improved simulations will require improved forcing estimates, models and proxy data in order to decrease present uncertainties (Rind, 1996). Other sources of climate variability (thermohaline circulation, the El Niño-Southern Oscillation, land use changes) likely account for some discrepancies between the modeled and reconstructed temperatures.

4. Summary

The agreements in correlations (Table III) and graphical presentation (Figure 2) between the tree-ring reconstruction and climate models support the validity of each as being representative of temperature changes over the past three centuries. The tree-ring reconstruction and the model output are derived independently. The trees are biological entities that can record the effects of thermal variations by the widths of their annual rings. The energy-balance model is based on geophysical indices of volcanic, solar and trace gas/aerosol variations. Our results suggest the combined importance of volcanic and solar activity (particularly as parameterized using the DVI and solar cycle length) to the climate variability of the past several centuries, as well as trace gas/aerosol forcing over the more recent period. Despite limitations inherent in the modeled and reconstructed indices of temperature, the results are a positive step in showing how the comparisons of proxy and modeled climate can contribute to the further understanding of how the climate system is driven.

Acknowledgements

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