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Global warming in the context of the Little Ice Age

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Abstract. Understanding the role of volcanic and solar variations in climate change is important not only for understanding the Little Ice Age but also for understanding and predicting the effects of anthropogenic changes in atmospheric composition in the twentieth century and beyond. To evaluate the significance of solar and volcanic effects, we use four solar reconstructions and three volcanic indices as forcings to an energy-balance model and compare the results with temperature reconstructions. Our use of a model representing the climate system response to solar and volcanic forcings distinguishes this from previous direct comparisons of forcings with temperature series for the Little Ice Age. Use of the model allows us to assess the effects of the ocean heat capacity on the evolution of the temperature response. Using a middle-of-the-road model sensitivity of 3°C for doubled CO_2, solar forcings of less than 0.5% are too small to account for the cooling of the Little Ice Age. Volcanic forcings, in contrast, give climate responses comparable in amplitude to the changes of the Little Ice Age. A combination of solar and volcanic forcings explains much of the Little Ice Age climate change, but these factors alone cannot explain the warming of the twentieth century. The best simulations of the period since 1850 include anthropogenic, solar, and volcanic forcings.

1. Introduction

Understanding the role of volcanic and solar variations in climate change is important not only for understanding the Little Ice Age but also for understanding and predicting the effects of anthropogenic changes in atmospheric composition in the twentieth century and beyond. Without knowledge of these external forcing factors we cannot separate out the internal climate variability from the forced variability, so an understanding of long-term internally generated oscillations also depends on an understanding of volcanic and solar forcings and their effects. Because of the limited time span covered by instrumental records, the overall upward trend in both temperature and several forcings, and the uncertainty associated with anthropogenic aerosol forcings, it is difficult to separate the effects of the various factors on recent climate change. Extending our study to climate change before the instrumental period is one way to avoid this problem. By calibrating the volcanic and solar forcings on the preindustrial period, we can then evaluate their role in the warming of the twentieth century and determine the relative role of anthropogenic effects.

In this work we model the climate response to reconstructed volcanic and solar forcings and compare the results with several temperature reconstructions for the past 300-400 years. *Robock* [1979] performed a similar study, which indicated an important role for volcanoes and a minimal role for solar variability. Since we now have several new reconstructions of solar variability, a new ice-core-based index of volcanic aerosol loading [*Robock and Free*, 1996], and a new series of estimated temperatures for the period 1400 to the present [*Bradley and Jones*, 1993] (hereinafter referred to as BJ), we have reexamined the issue using an improved energy-balance model.

The next two sections describe the factors that may have influenced climate change over the past 500 years. In the remainder of the paper we present the model and data used and the results of these experiments.

2. The Little Ice Age

The term "Little Ice Age" (LIA) arose initially from observations that glaciers in Europe and other areas had stopped retreating and were instead growing during several periods within the last 1000 years [*Lamb*, 1977b]. Recent data from tree rings, ice cores, and documentary records from areas outside the North Atlantic have confirmed the existence of cooler global temperatures during the period 1500-1900 than in the past century (BJ). While the times of greatest cooling and the details of decadal variations vary with the region, records from China, Japan, and Australia show overall temperature variations similar to those in the North Atlantic area (see Figure 1). Hemispheric mean temperatures from these data show that the coldest period since 1500 occurred from 1570 to 1730, with the nineteenth century the next coldest. The coldest single decade in this summer series was 1600-1609. The late eighteenth century was relatively warm, as were the early 1500s (but not as warm as the twentieth century). The maximum temperature anomaly from the 1950-1979 mean was -0.7°C. The recent analysis by *Mann et al.* [1998], using many of the same data, shows similar variations.

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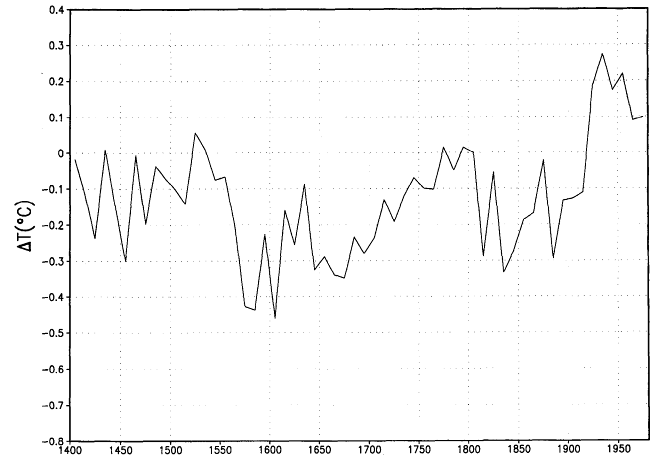

Figure 1. Decadally averaged summer temperature reconstructions from *Bradley and Jones* [1993] (hereinafter referred to as BJ), scaled as annual mean Northern Hemisphere (NH) land temperature departures from the 1860-1959 mean.

Despite the regional variations, these results show the Northern Hemisphere (NH) temperatures were clearly lower during certain periods between 1500 and 1900 than in this century or around 1500. The twentieth century itself exhibits both warm and cool decades as well as a recent warming trend. Explanation of these changes has focused on variations in solar forcing, increased numbers of volcanic eruptions, and internal variability of the climate system, as well as anthropogenic changes in the atmosphere and land surface.

3. Causes of Climate Change on Decadal to Century Scales

3.1. Volcanic Forcing

The basic mechanism by which volcanoes can affect climate is straightforward. An erupting volcano emits sulfur dioxide, which, if the eruption is strong enough, reaches the stratosphere where it forms sulfate aerosol. This aerosol spreads out over the hemisphere or globe (depending on the latitude of the eruption). It reflects solar radiation, cooling the troposphere and the surface, and also absorbs enough solar radiation to produce heating in the stratosphere. After 1-3 years the aerosol falls into the troposphere and is deposited on the surface.

The effects of volcanic eruptions on climate have been the subject of a number of observational studies, summarized by *Robock* [1991]. Many comparisons of time series of eruptions to climate data [e.g., *Humphreys*, 1940; *Bryson and Goodman*, 1980; *Schönwiese*, 1988] suggest some relationship, but the significance varies with the specific data and method used. Recent works relating ice core records to temperature series include *Stuiver et al.* [1995] and *White et al.* [1997]. Two "superposed epoch" studies of the volcano-climate relationship removed the El Niño-Southern Oscillation (ENSO) signal from globally or hemispherically averaged instrumental data and found a significant volcanic cooling of the order of 0.1-0.3°C [*Angell*, 1988; *Mass and Portman*, 1989]. Because the effects of volcanoes are similar in magnitude to ENSO and other internal climate variability, however, the full significance of volcanic effects remains in dispute.

Since volcanic aerosols normally remain in the stratosphere no more than 2 or 3 years, with the possible exception of extremely large eruptions such as that of Toba approximately 71,000 years ago [*Bekki et al.*, 1996], the radiative forcing from volcanoes is interannual rather than interdecadal in scale. A series of volcanic eruptions could, however, raise the mean optical depth significantly over a longer period and thereby give rise to a decadal-scale cooling. Furthermore, it is possible that feedbacks involving ice and ocean, which act on longer timescales, could transform the short-term volcanic forcing into a longer-term effect. As a result, the possible role of volcanoes in decadal-scale climate change remains unclear.

Modeling studies on volcanic effects have been limited until the last few years. Radiative-convective model studies by *Hansen et al.* [1978] and *Vupputuri and Blanchet* [1984] predict cooling at the surface and warming in the stratosphere. Energy-balance models [*Schneider and Mass*, 1975; *Oliver*, 1976; *Bryson and Dittberner*, 1976; *Miles and Gildersleeves*, 1978; *Robock*, 1978; *Gilliland*, 1982; *Gilliland and Schneider*, 1984] have also shown cooling effects for several years after major eruptions. *Schneider and Mass* [1975] and *Robock* [1979] are the only modeling works using volcanic and solar chronologies to investigate periods before the midnineteenth century. Schneider and Mass used a zero-dimensional energy-balance model and found agreement of several large-scale features of their simulations with climate records, but concluded that while volcanoes had a weak relationship to climate, the solar-climate effect was not proven. Robock used a latitudinally resolved energy-balance model with volcanic [*Mitchell*, 1970] and solar forcing (proportional to the envelope of the sunspot number) and found the volcanic forcing explained a much larger share of the temperature variability since 1620 than did the solar series. Both the Schneider and Mass and Robock models used a simple mixed-layer ocean.

Modeling of volcanic effects with dynamics include an early zonally averaged dynamic climate model [*MacCracken and Luther*, 1984] and general circulation model (GCM) studies by *Hunt* [1977], *Hansen et al.* [1988, 1992, 1997], *Rind et al.* [1992], *Pollack et al.* [1993], and *Graf et al.* [1993]. As with observational studies, however, the details of the volcanic response are often difficult to separate from the models' internal variability. *Robock* [1979] and *Schneider and Mass* [1975] remain the only climate modeling studies dealing with volcanic forcing for the LIA time period.

3.2. Solar Variability

Many observers have been struck by the coincidence of the apparent solar activity minima in the fifteenth and nineteenth centuries with periods of cooler temperatures, and numerous studies of solar-climate relationships exist [*e.g.*, *Eddy*, 1976; *Reid*, 1991; *Hoyt and Schatten*, 1997]. Recent work pointing out a close resemblance between the length of the solar cycle and the instrumental temperature record [*Friis-Christensen and Lassen*, 1991] (herinafter referred to as FCL) and new satellite evidence regarding contemporary solar variability [*Willson and Hudson*, 1991; *Willson*, 1997] have prompted renewed interest in the subject [*Kelly and Wigley*, 1992; *Schlesinger and Ramankutty*, 1992; *Hoyt and Schatten*, 1993; *Lean et al.*, 1995; *Cubasch et al.*, 1997; *Reid*, 1997].

Lean et al. [1995] computed correlations between their solar index and the *Lamb* [1970] volcanic dust veil index (DVI) and BJ decadal temperatures for 1610-1980 and found the solar index well correlated but the DVI poorly correlated with temperatures. *Crowley and Kim* [1996] also found good correlations of solar indices with temperatures using the *Lean et al.* [1995] and *Hoyt and Schatten* [1993] solar indices. On the other hand, zero-dimensional energy-balance work using solar and anthropogenic forcings [*Kelly and Wigley*, 1992; *Schlesinger and Ramankutty*, 1992] concluded that solar variability as modeled by FCL could account for a large proportion of the temperature variation from 1850 to the present but would imply a climate feedback factor more than twice as large as that indicated by GCM and observational studies.

Atmospheric GCM modeling [*Lean and Rind*, 1994; *Nesme-Ribes et al.*, 1993] has suggested that a long-term solar output decline of 0.5% during the LIA could have produced temperatures 1.0-1.5°C lower than present means. A recent transient simulation with an atmosphere-ocean GCM (AOGCM) forced with the *Hoyt and Schatten* [1993] solar reconstruction [*Cubasch et al.*, 1997] gave a temperature change of 0.5°C from a 0.3% solar irradiance change. These studies indicate that observed variability of total solar irradiance during the past 20 years [*Willson and Hudson*, 1991; *Willson*, 1997] is insufficient to explain observed temperature changes by its direct tropospheric effect. Two theories have therefore been suggested to support a causal relationship between solar change and climate change. One is that long-term solar variability is substantially larger than that observed in the short term. Following the first approach, on the basis of observations of non-cycling stars [*Lockwood et al.*, 1992], *Lean et al.* [1995] have estimated a possible decrease of up to 0.3% for activity minima such as the Maunder minimum in the seventeenth century [*Lean et al.*, 1992]. Others [*Nesme-Ribes et al.*, 1993; *Baliunas and Soon*, 1995; *Zhang et al.*, 1994] have suggested a decline in total solar irradiance of 0.4-0.6%. The recently observed 0.036% increase in solar minimum radiation between cycles 21 and 22 [*Willson*, 1997] provides additional support for this position. The size of this variability cannot be dependably estimated, however, without an established theory explaining solar activity, and all of the above estimates are speculative.

The second theory is that the climate is more sensitive to solar variability due to amplification mechanisms not previously included in models, such as the effect of changing UV radiation on the dynamics of the stratosphere or the effect of changes in the electrical properties of cloud particles [*Tinsley*, 1994; *Svensmark and Friis-Christensen*, 1997]. The variability of solar radiation in the ultraviolet is 1-2 orders of magnitude higher than the variability over all frequencies [*Lean*, 1991]. Recent GCM work suggests that differential heating of the tropics and winter pole in the stratosphere due to increased UV radiation could change the stratospheric circulation and indirectly cause significant changes in surface climate [*Haigh*, 1994, 1996; *Rind and Balachandran*, 1995; *Balachandran and Rind*, 1995]. This hypothesis, if proven, would greatly increase the plausibility of the arguments for solar influence on climate change. Since evidence exists for possible solar variability of up to 0.5%, the Sun must be included in any assessment of climate change over the past 600 years.

3.3. Anthropogenic Forcing

Human civilization may have affected climate by increasing amounts of "greenhouse gases" such as carbon dioxide and methane in the atmosphere by introducing additional aerosols into the air, by altering the ozone chemistry of the stratosphere, or by changing the surface characteristics of the Earth through deforestation and agriculture. Although anthropogenic climate effects are generally thought of as a twentieth-century phenomenon, human activities such as deliberate biomass burning and deforestation have been going on for a long time and could have had significant regional, if not global, effects in earlier times [*Robock and Graf*, 1994; *Holdsworth et al.*, 1996]. As many past climate records come from the same places that would have been affected by human activities, they may reflect these changes, even if the anthropogenic activities did not have a large global effect. Since we had no estimates of the extent of any such anthropogenic forcings before the industrial era, however, we limited our consideration of anthropogenic effects to those resulting from emissions of radiatively active trace gases and aerosols during the industrial era.

3.4. Internal Variability

Many climate models exhibit irregular oscillations roughly similar to those found in the climate record even when the models are not subjected to any variation in forcings. These changes are referred to as "internal variability" of the climate system and can arise from chaotic dynamics of the atmosphere, the ocean, or the coupled atmosphere-ocean system. The Geophysical Fluid Dynamics Laboratory coupled ocean-atmosphere model shows variability on a roughly 50-year timescale with global mean amplitudes of less than 0.1°C [*Stouffer et al.*, 1994]. The Max Planck Institute (MPI) coupled AOGCM [*Hegerl et al.*, 1996] and simpler models [*Stocker and Mysak*, 1992; *Hasselmann*, 1976; *Robock* 1978, 1979; *Wigley and Raper*, 1990] also show decadal- or longer-scale variability. An analysis of temperature observations, adjusted to remove an estimated anthropogenic trend, shows oscillations with global amplitude of 0.19°C and a 65 to 70 year period, centered on the North Atlantic [*Schlesinger and Ramankutty*, 1994]. *Mann et al.* [1995] found a similar result in proxy records from preindustrial times. The oscillations shown in the AOGCMs and observational studies do not, however, appear to be large enough to account for the full range of observed climate variability [*Stouffer et al.*, 1994; *Kim et al.*, 1996; *Mann and Park*, 1996]. This suggests that Little Ice Age climate changes were due at least in part to external forcing such as volcanoes or solar variations.

4. Model and Experiments

We used an upwelling-diffusion energy-balance model of the type originated by *Hoffert et al.* [1980]. This version is an adaptation of the model used for climate projections in the first Intergovernmental Panel on Climate Change (IPCC) reports [*Bretherton et al.*, 1990; *Mitchell and Gregory*, 1992] and described by *Wigley and Raper* [1987, 1992], and was kindly provided by T. Wigley. It includes four "boxes" at the surface: NH land, NH ocean, Southern Hemisphere (SH) land, and SH ocean (Figure 2). The atmosphere is reduced to a single layer with temperature response, including the water vapor, cloud, and other feedbacks, determined by the climate sensitivity parameter. The ocean in each hemisphere is simulated using a single column with 39 equal levels below a mixed layer whose depth is

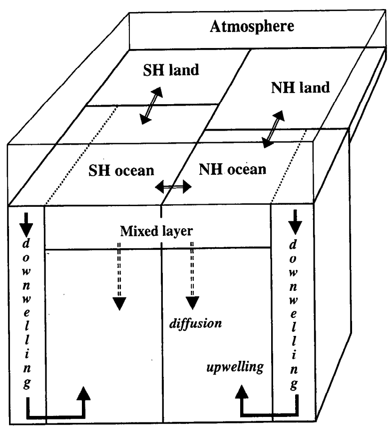

Figure 2. Geometry of the upwelling-diffusion energy-balance model. See text for further explanation. Adapted from Figure 9 of *Houghton et al.* [1997].

specified by the user. Downwelling is assumed to occur at polar latitudes in each hemisphere, and upwelling and diffusion are assumed to occur in the rest of the ocean. We used vertical diffusivity of 1.0 $cm^2 s^{-1}$, upwelling velocity of 4 m yr^{-1}, mixed layer depth of 90 m, and π (the ratio of downwelling water temperature to mixed layer temperature) of 0.2. The model's climate sensitivity is determined by the user as a parameter. We repeated our experiments for three values of sensitivity corresponding to equilibrium temperature changes of 1.5°, 3.0°, or 4.5°C for a doubling of CO_2, spanning the range of plausible sensitivities [*Mitchell et al.*, 1990]. Additional runs with alternative parameter settings indicate that the uncertainty due to model parameters other than the climate sensitivity is less than the uncertainty from varying climate sensitivity.

This model is very simple and does not attempt to include the many processes that determine climate sensitivity. Instead, it assumes that the climate response is a linear function of the size of the forcing, regardless of the spatial structure or source of the forcing. The true response is probably somewhat greater for negative forcings than for positive [*Budyko*, 1969; *Sellers*, 1969; *Cubasch et al.* 1997] and differs for forcings with strongly differing spatial distributions [*Stenchikov et al.*, 1998]. The model also excludes dynamic effects such as the winter warming volcanic response [*Robock and Mao*, 1995] that may affect hemispheric mean results. It is designed not to calculate climate sensitivity but rather to simulate the effect of heat transfer between the surface and the deep ocean on transient climate response over relatively long timescales.

Several comparisons between GCM and energy-balance results have been generally favorable. *Houghton et al.* [1996, 1997] show very similar responses by AOGCMs and the upwelling diffusion energy-balance model for gradual greenhouse gas increases. *Raper and Cubasch* [1996] show a similar comparison for the MPI AOGCM. *Schlesinger and Jiang* [1990] adjusted the parameters of their similar energy-balance model to match the output of their AOGCM for an instantaneous ("step") doubling of CO_2. None of these is completely comparable to the volcanic and solar forcings used in our work. At the time most of our work was done, there were to our knowledge no coupled AOGCM runs using solar or volcanic forcings that could be used for comparison. (Recently, the MPI model has been used with the *Lean et al.* [1995] solar forcing since 1600 [*Cubasch et al.*, 1997].)

The other way to validate the model, in principle, is by direct comparison with observations. Unfortunately, it is probably not possible to separate the effects of long-term external forcings from the noise, or internal variability, in the observed climate record with enough precision to validate the model directly. Comparisons using short-term forcings have been favorable. The model's response to the seasonal cycle has been compared with the real world in the process of calibrating the model's exchange of heat between land and ocean. When forced with random high-frequency "noise," these models respond with variability on longer timescales that resembles the observed internal variability [*Robock*, 1978; *Wigley and Raper*, 1990]. *Jain et al.* [1995] successfully used the same model to simulate uptake of carbon by the ocean, giving the observed variation of CO_2 concentration in the atmosphere and the observed vertical profile of carbon and carbon isotopes in the ocean. In addition to these studies supporting the model's reliability, numerous researchers [e.g., *Kelly and Wigley*, 1992] have used this model to assess the likelihood that solar forcings were the cause of the late-twentieth-century warming trend, and several papers have given analytical solutions for the upwelling-diffusion model [*e.g.*, *Morantine and Watts*, 1990; *MacKay and Ko*, 1997].

The body of research based on this model suggests that it has been generally accepted as a simple model of the effects of ocean heat capacity on the climate system temperature response. While the difficulties of untangling the effects of various external forcings from one another and from the system's internal variability probably preclude direct validation of climate models' response to external forcings, the upwelling-diffusion energy balance model has been accepted as the best alternative to a full AOGCM, and the best model for work involving large numbers of long runs [*Houghton et al.*, 1997]. Given the lack of conclusive validation against long-term responses in the real world, however, the results of this study, like those from current coupled AOGCMs, must be viewed with caution.

The alternative, a coupled ocean-atmosphere GCM, would not be suitable for this work because of the large number of alternative forcing scenarios requiring excessive computer time and because of the difficulty of interpreting the results due to the presence of large internal variability in the GCM outputs. An AOGCM would allow us to examine results for only one climate sensitivity. Furthermore, only a model with a high spatial resolution in the stratosphere would capture the winter warming volcanic response. Given these trade-offs, the energy-balance model is an appropriate choice for this work. Use of this simple physical model gives significantly different results than direct comparison of the forcing series with temperature reconstructions because the model accounts for the time delay in response produced by the heat capacity of the ocean (see section 6.1 below).

We forced this model with each of the volcanic and solar series alone and in combination with estimated forcing from anthropogenic gases and aerosols. In additional runs, we also combined volcanic, solar, and anthropogenic forcings. The time step used was 0.1 year. The model runs begin in 1400 and end in 1990, and the results are given as end-of-year temperatures. Since the BJ temperatures are NH values based on proxy data from land, we used decadal averages of the modeled NH land temperatures for comparison. We also used the annual values for comparison with instrumental data [*Jones et al.*, 1986; *Jones and Briffa*, 1992] and proxy data [*D'Arrigo and Jacoby*, 1993].

5. Data

5.1 Volcanic Eruptions

We used three indices of volcanic aerosol loading to force our model (see Table 1 and Figure 3). Ideally, such an index would be proportional to the effect of the volcanic aerosols on the Earth's radiative balance, would be based solely on objective physical evidence, and would not rely at all on inferences from climate effects. Unfortunately, all of the indices existing before *Robock and Free* [1995] fall short for one or more of these reasons. The first such index, *Lamb*'s [1970, 1977a, 1983] dust veil index (DVI), is based on historical reports of eruptions, optical phenomena, radiation measurements, temperature information, and estimates of the volume of ejecta, and as originally formulated contains much subjective information and relies on climate effects to evaluate the size of eruptions. The volcanic explosivity index [*Newhall and Self*, 1982; *Simkin et al.*, 1981] (VEI) is derived from volcanological estimates of the volume of ejecta from past explosive eruptions and was not intended as a measure of climate forcing. The index is objective and independent of climate data, but does not directly reflect the degree of sulfate loading of the stratosphere. *Robock and Free* [1995] describe these and two other newer indices and introduce a fifth, the ice core volcanic index (IVI), based on ice core data. The IVI is a combination of acidity and sulfate ion data from ice cores, processed to remove low-frequency trends.

For this study we modified the indices from those presented by *Robock and Free* [1995]. Because it was based on data from Arctic ice caps, the original NH IVI overestimated the

Table 1. Forcings

Name	Basis	Reference	Beginning Year
		Volcanic Forcings	
IVI	ice core data	*Robock and Free* [1995]	1400
VEI	geological evidence	*Simkin and Siebert* [1994]	1400
DVI	historical records	*Lamb* [1970, 1977a]	1500
		Solar Forcings	
Lean	sunspot number	*Lean et al.* [1995]	1610
Hoyt	cycle length and other	*Hoyt and Schatten* [1993]	1700
FCL	length of solar cycle	*Friis-Christensen and Lassen* [1991]	1750
KW	length of solar cycle	*Kelly and Wigley* [1992]	1750

IVI, ice core volcanic index; VEI, volcanic explosivity index; DVI, dust veil index.

significance of high-latitude eruptions, especially those in Iceland, which are likely to contribute large amounts of tropospheric aerosols to ice cores from Greenland. To compensate for these problems, we reduced the amplitude of peaks attributable to high-latitude NH eruptions by a factor of 2 [*Zielinski,* 1995] and reduced Icelandic eruptions by another factor of 2. We also modified the DVI from *Lamb* [1970] to eliminate explicit reliance on temperature data. For the VEI time series, we used 3^{VEI} rather than 10^{VEI} (the form used in our previous work) to reduce the excessive range of forcing values. These modifications are discussed further in the appendix to this paper. Results for runs using the earlier versions of these indices are given by *D'Arrigo et al* [1999].

None of the three indices is given in units of optical depth or W m^{-2}. In creating a volcanic index for the period 1850 to the present, *Sato et al.* [1993] assigned a value of 0.125 (at wavelength 550 nm) for the maximum optical depth following Krakatoa, based on a review of the meager observational data available for that period. This makes Krakatoa similar in climatic forcing to Pinatubo. Since many of our ice core records end before El Chichón, we were unable to make a direct calibration between our index and the observed optical depths of recent eruptions. In the absence of better information, we adjusted the series to give an optical depth of 0.125 for Krakatoa (1883) and then used a multiplier of 3.0 W m^{-2} for each 0.1 of optical depth, based on radiative transfer calculations by *Harshvardhan* [1979] and *Lacis et al.* [1992].

5.2. Solar Variations

Figure 4 shows the four solar forcing series used in this study, also listed in Table 1. The *Lean et al.* [1995] solar series (hereinafter referred to as Lean) is a combination of a short-term part derived from monthly or yearly group sunspot numbers (plus information from solar images, for years after 1874) and a long-term portion proportional to the average of the group sunspot number over each 11-year cycle. The *Hoyt and Schatten* [1993] series (hereinafter referred to as Hoyt) is a combination of several indicators of solar activity, including sunspot number, cycle length, cycle decay rate, and, after 1874, rotation rate and fraction of penumbral sunspots. These two series are given in terms of W m^{-2}. The *Friis-Christensen and Lassen* [1991] reconstruction (hereinafter referred to as FCL) is based on changes in the length of the 11-year solar cycle, and the *Kelly and Wigley* [1992] series (hereinafter referred to as KW) is an alternative calculation also based on length of the solar cycle but using a different filter for the data.

The amplitude of the Lean data is based on a comparison of the Sun's Ca II emission with that of noncycling Sun-like stars, assuming the Sun's behavior during the Maunder minimum was similar to that of these stars. The choice of magnitude for the

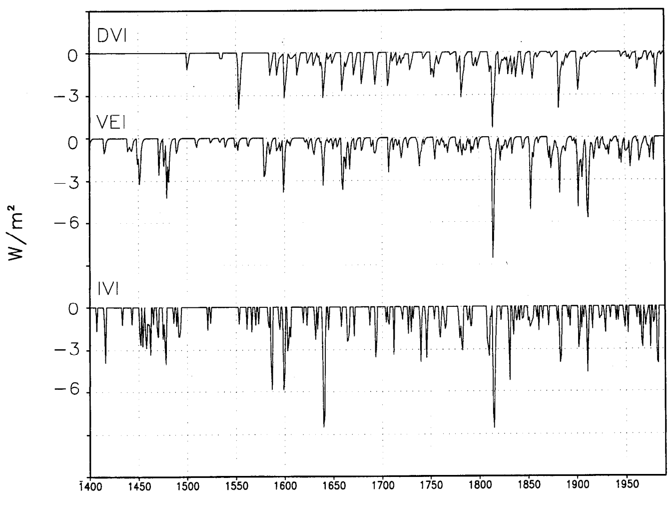

Figure 3. Volcanic indices used as forcings for NH.

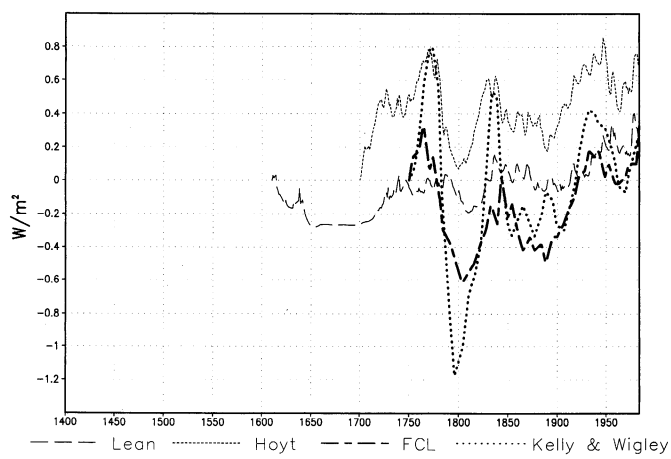

Figure 4. Solar reconstructions used as forcings.

Hoyt series comes in part from Lean's analysis. These series have overall ranges of about 0.6 and 0.9 W m^{-2} respectively, but the Hoyt series has twice the variability of the Lean series in the period before 1850 and less thereafter. The FCL and KW series do not have an amplitude assigned by the authors and must be multiplied by an arbitrary factor to give a forcing in W m^{-2}. Previous work has found optimal fits between model results and instrumental temperatures with factors of -0.2 to -0.8, depending on the anthropogenic forcing assumed [*Schlesinger and Ramankutty*, 1992]. For the results given below, we used a factor of -0.4, giving a forcing change of 0.8 W m^{-2} for FCL and 1.5 W m^{-2} for KW from the low around 1800 to the peak in the early twentieth century. The KW amplitude is slightly larger than the maximum solar variability hypothesized by *Baliunas and Soon* [1995] and *Nesme-Ribes et al.* [1993].

5.3. Anthropogenic Gases and Aerosols

For greenhouse gas forcings, including CO_2, CH_4, N_2O, and CFCs, we adopted the approximate concentration histories used by *Raper et al.* [1996]. The input values for 1990 for CO_2, methane, and chlorofluorocarbons are similar to those adopted by the IPCC [*Houghton et al.*, 1995]. For sulfate aerosol we took 1990 values of -0.5 W m^{-2} for direct forcing and -0.8 W m^{-2} for indirect (cloud) forcing and a concentration history proportional to the emissions history of *Dignon and Hameed* [1989]. The forcing due to increased CO_2 begins in 1765. Before that date, we assume anthropogenic forcing was negligible in the global or Northern Hemisphere mean. Figure 5 shows the anthropogenic forcing history we used. Greenhouse gas forcings are assumed equal for both hemispheres and both land and sea. Aerosol forcings are distributed 90% on land and 10% over the ocean, with 80% in the NH and 20% in the SH.

The anthropogenic forcing is not significant for the analysis of temperatures before 1800 but is essential to an understanding of climate change in the twentieth century. The results for this modern period can be expected to depend somewhat on the level of anthropogenic aerosol effects [*Kelly and Wigley*, 1992; *Schlesinger and Ramankutty*, 1992], which are still very uncertain. Since the primary focus of this work is on earlier time periods, we have not attempted to analyze the dependence of results in this century on uncertainties in anthropogenic aerosol effects.

5.4. Temperature

For comparison to our model results we used the reconstruction of Northern Hemisphere decadal mean summer temperatures from 1400 to the present by *Bradley and Jones* [1993] (Figure 1), derived from observations and proxy records such as tree rings and ice core melt records. This series has a minimum between 1550 and 1600 which is around 0.7°C lower than the mean temperature for 1950-1980 and additional colder periods in the late 1600s and the early 1800s. Since our model does not have a seasonal cycle, we translated the BJ summer temperatures to annual mean equivalents by comparing the maximum range of BJ proxy temperatures for 1860-1980 with the range of decadally averaged annual mean NH land temperatures from the instrumental record [*Jones et al.*, 1986; *Jones and Briffa*, 1992] (hereinafter referred to as Jones), giving a conversion factor of 0.3°C for each BJ standard deviation unit. The BJ paper had an error in averaging which underestimated the summer temperature variations [R. Bradley, personal communication, 1997], but our procedure automatically adjusts for this.

BJ has some shortcomings as a representation of LIA temperatures: It has decadal mean rather than annual resolution, it is calibrated to summer rather than annual temperatures, and it does not include any data from ocean or tropical areas. Because it is a summer series, it arguably will show greater volcanic effects than those present in annual temperatures due to the presence in annual records of the volcanic winter warming effect [*Robock and Mao*, 1995]. The omission of ocean temperatures is not critical for our analysis because our comparison is to land rather than global mean model temperatures. The analysis presented by BJ indicates that despite the omission of tropical data, the regions used in the BJ reconstruction were adequately representative of NH mean temperatures. Furthermore, comparison with the *Mann et al.* [1998] reconstruction shows that the BJ series is reasonably representative of LIA temperatures.

We also compared the model outputs with the Jones yearly instrumental temperatures from 1854 to the present and with Northern Hemisphere temperatures from 1681 to 1968 reconstructed from high-latitude tree ring density data by *D'Arrigo and Jacoby* [1993] and *D'Arrigo et al.* [1999]. Some of the D'Arrigo and Jacoby data were used by BJ in their reconstruction. The series used here includes data from two new areas in Alaska and Mongolia.

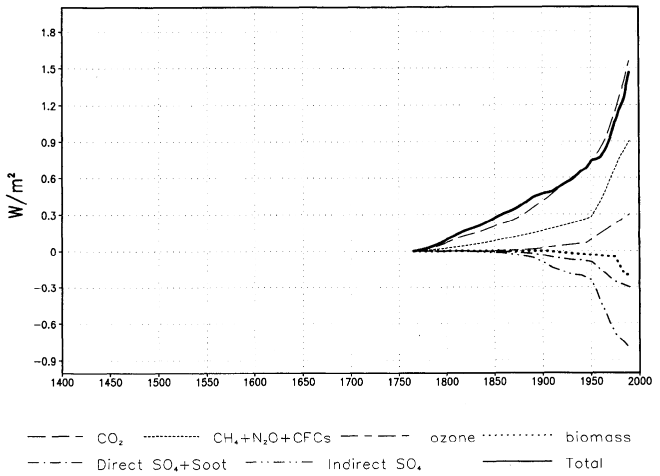

Figure 5. Anthropogenic gases and aerosol forcings.

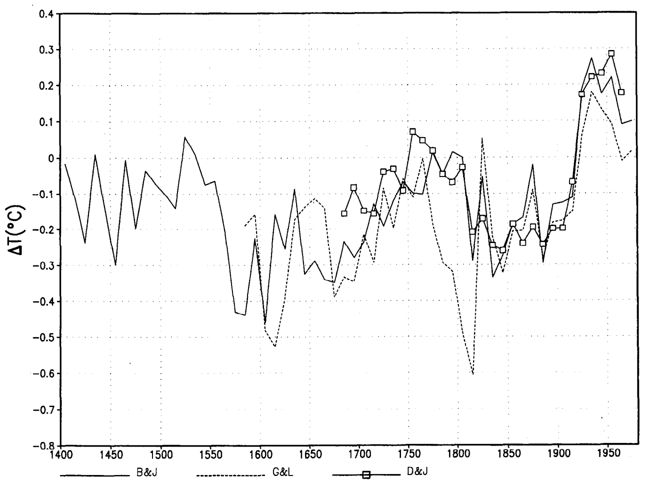

Figure 6. Comparison of decadally averaged temperature reconstructions from BJ, *Groveman and Landsberg* [1979] and *D'Arrigoand Jacoby* [1993].

Figure 6 compares the BJ, *Groveman and Landsberg* [1979], and *D'Arrigo and Jacoby* [1993] temperature series. The Groveman and Landsberg series was constructed from instrumental records from Europe and eastern North America along with a few tree ring series from Alaska and Scandinavia. After around 1750, the three series agree fairly well on the decadal scale. All show a slow rise in temperature from 1650 to after 1750, with the BJ series reaching a maximum in 1790 while the other two series peak earlier. The consistency between the series after 1750 suggests that these reconstructions are fairly reliable after that date.

6. Results

6.1. Effect of Model on Input Series

The model tends to increase the correlation of the DVI series with temperature and decrease the correlation of the Lean solar series as compared with the work of *Lean et al.* [1995] and *Crowley and Kim* [1996], which compared the temperature reconstructions directly to forcings. Lean et al. found a correlation coefficient of 0.005 between the DVI and the BJ temperatures for 1610-1800, compared with 0.34 for our model results; for their solar reconstruction, the correlation was 0.86, compared with our 0.71. Figure 7 shows the Lean forcing, expressed as the temperature that would result from instantaneous equilibrium, and the model response for two different climate sensitivities. Although the model is simple, the shape of the response in time differs substantially from that of the forcing. The model damps the amplitude of cyclical forcings in the solar series as well as shifting the cycles in time (3-7 years for an 80-year cycle) [*Hoffert et al.*, 1980]. This may reduce correlations with temperature series. For the volcanic forcings, on the other hand, the model extends the 1- to 2-year forcings into decadal-scale coolings, increasing the resemblance to the temperature record. Thus differences between our results and previous work are expected and show the importance of modeling the climate response to possible forcings before assessing their relationship to the temperature record.

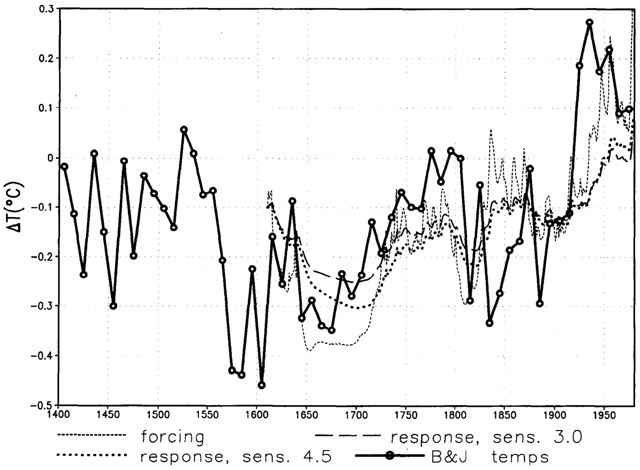

Figure 7. *Lean et al.* [1995] forcing plotted as instantaneous equilibrium temperature response for 4.5°C, compared with corresponding model outputs using climate sensitivities of 3.0 and 4.5°C and BJ decadal average temperatures. The forcing and responses have been shifted down by 0.2°C to facilitate comparison.

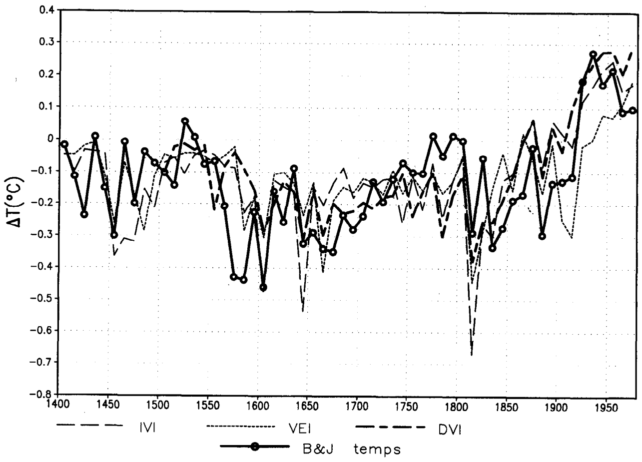

Figure 8a. Decadally averaged NH land model output for combined volcanic and anthropogenic forcings compared with temperatures for climate sensitivity 3.0°C.

6.2. Comparison with BJ Decadal Temperatures

6.2.1. Runs forced with volcanic aerosols. Figures 8a and 8b show decadal average model results for volcanic plus anthropogenic and volcanic-only forcings, for climate sensitivity of 3.0°C for a doubling of CO_2. Although volcanic forcing typically occurs on a 1- to 3-year timescale, examination of these figures shows clear decadal- and longer-scale variations in the temperatures simulated using volcanic indices. These variations have amplitudes comparable to or greater than the variability of the BJ temperature record. These simulations demonstrate that volcanic aerosols can in theory produce significant decadal and longer-scale effects.

The match between volcanic effects and actual proxy temperature reconstructions for the LIA is less clear. Table 2 shows correlations between model runs and the BJ temperature series. While the IVI and DVI results are well correlated with temperatures for 1610-1980, they are not well correlated before 1800. VEI model runs are poorly correlated for all time periods. These correlations vary substantially depending on the part of the LIA chosen, as illustrated in Table 2.

Comparing the volcanic results with temperatures in Figure 8, we see that in the early part of the LIA, the volcanic series

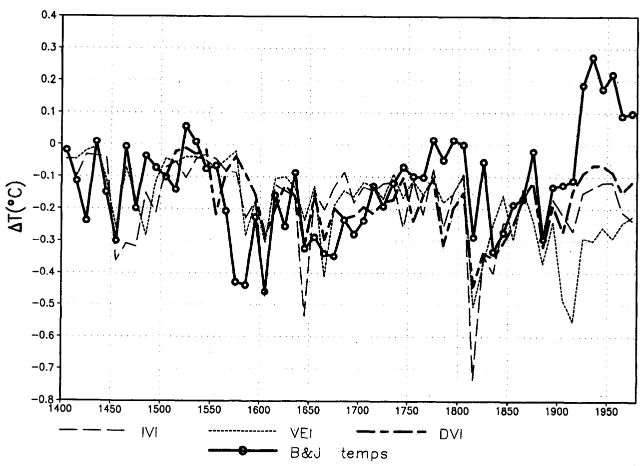

Figure 8b. Same as in Figure 8a but for volcanic forcings without anthropogenic forcings.

Table 2. Correlations of Model Outputs with *Bradley and Jones* [1993] Temperatures for Sensitivity of 3.0°C for $2xCO_2$

	1610-1800	1610-1980	1800-1980	1700-1850
IVI	0.23	(0.35)	(0.61)	(0.53)
VEI	0.45	-0.02	0.17	0.39
DVI	0.34	(0.66)	(0.85)	(0.58)
Lean	(0.71)	(0.67)	0.59	0.11
Hoyt	0.62*	(0.62)*	(0.68)	0.18
FCL		0.55*	(0.72)	0.25*
KW		0.36*	0.48	-0.02*
GHG			(0.63)*	0.70

Numbers in parentheses are significant at the 95% confidence level. GHG, anthropogenic greenhouse gases and aerosols.

* Results from Hoyt forcings begin at 1700; results from FCL and KW begin at 1750.

capture many of the decade-to-decade changes well, but do not explain the drop in temperature around 1560-1570. Many of the decadal temperature oscillations, particularly from 1650 to 1750, are in the opposite direction with respect to the volcanic model results (*e.g.*, 1620, 1630, 1670, 1680, 1710, and 1720 for DVI). The volcanic series account for the changes of the nineteenth century decadal-scale patterns fairly well, but show excessive cooling from Tambora in 1815 and do not account for the strong cooling in the 1830s in the BJ reconstruction. Since 1850, the runs with IVI or DVI and anthropogenic forcings show a fairly good match in amplitude as well as shape.

6.2.2. Runs forced with solar reconstructions. The Lean series results give distinctly better correlations with temperature for 1610-1800 than do the volcano runs (Table 2). (The other solar series [Hoyt, FCL and KW] are not available over all of this time period.) From 1700-1850, the Hoyt and Lean solar results are not well correlated with temperatures. In the nineteenth century (not shown) the solar series are negatively correlated with temperatures. For 1800-1980, the DVI correlates better with the BJ temperatures than do any of the solar series.

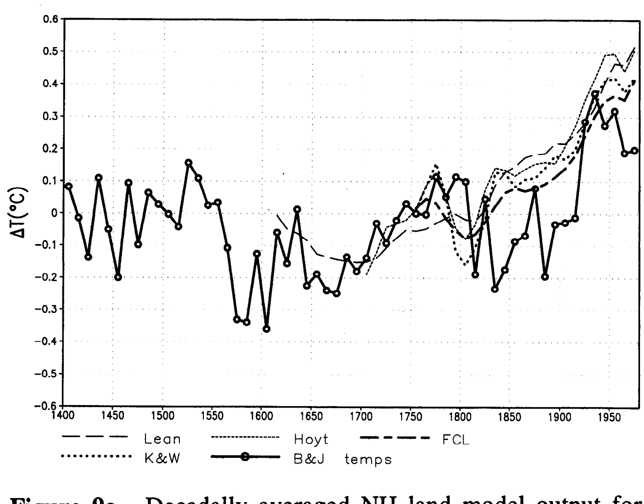

Figure 9a. Decadally averaged NH land model output for combined solar and anthropogenic forcings compared with BJ temperatures for climate sensitivity 3.0°C. The *Hoyt and Schatten* [1993] output was shifted down by 0.2°C to facilitate comparison.

Comparing the series visually from Figure 9, the Lean solar series gives the correct overall trend from 1610 to 1800 but essentially no interdecadal variability. The nineteenth century climate record is dominated by cold decades beginning in 1810, 1830, and 1880, but the solar results do not give unusually cold periods in the 1830s or the 1880s. In general, the solar series account better for the long-term trends than for the 10- to 50-year scale.

Although the solar results show equal or better correlations with temperature in comparison with the volcano runs for some time periods, the amplitude of the responses for a moderate climate sensitivity is in most cases far too small to account for the variability of LIA temperatures. For sensitivity of $3.0°C/2xCO_2$, the Lean reconstruction shows only about one half the cooling of the temperature series in the Maunder Minimum period 1610-1750. The Hoyt series (beginning in 1700) comes closer to matching the BJ amplitudes, but still falls at least 0.1°C short in the nineteenth century. The only solar run to match the size of the reconstructed temperature changes from 1750 to 1850 is KW, where we have used a forcing of approximately 0.6% change in the solar constant; this series does not extend back far enough to model the larger changes from 1530 to 1600.

After 1850, instrumental data give a more reliable temperature record and allow comparison on an annual rather than decadal average basis. We discuss comparisons of results with the Jones instrumental data below.

6.2.3. Runs using combinations of solar, volcanic and anthropogenic forcings. Figures 10 to 12 show results for combinations of all three types of forcings. The combination of the DVI, Lean, and anthropogenic forcings gives the best correlation (0.78) for the time period 1610-1980 (see Table 3), accounting for 60% of the variance in temperature; for 1610-1800, however, only 45% is attributable to the combined forcings. The DVI-Lean-anthro correlations for 1610-1980 and 1800-1980 are not significantly better than the correlations for the DVI with anthropogenic forcings. For times before 1800, however, addition of solar series improves correlations substantially beyond the figures for volcanic forcings alone.

While none of the single-forcing results is significantly correlated with temperatures for all three periods (1610-1800, 1610-1980, and 1800-1980), the combinations give significant correlations for all three time periods. Because the solar responses are small relative to the volcanic responses, the combinations of all three types of forcing look a lot like the volcanic+anthro figures. The results are generally 0.1°-0.2°C too cold from 1750 to 1840 and too hot thereafter by a similar

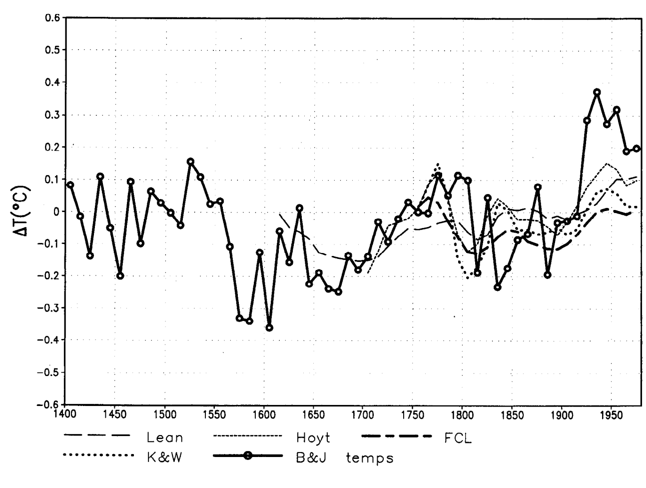

Figure 9b. Same as in Figure 9a but for solar forcings alone.

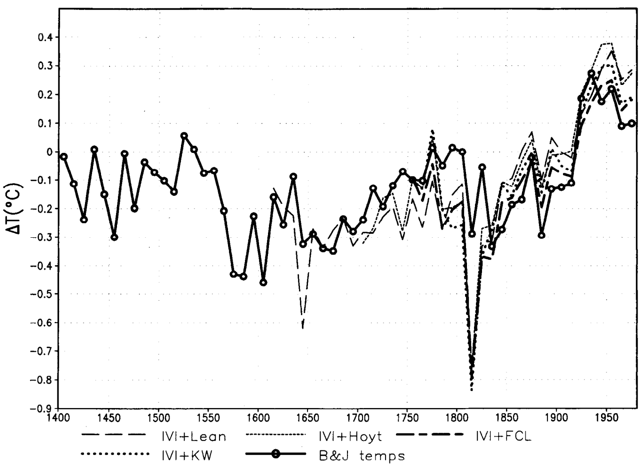

Figure 10. Decadally averaged NH land model outputs from combined ice core volcanic index (IVI), solar, and anthropogenic forcings, compared with BJ temperatures for climate sensitivity 3.0°C. Note change in temperature scale from Figures 8-9. The *Hoyt and Schatten* [1993] output was shifted down by 0.2°C to facilitate comparison.

amount. Results with volcanoes look more like the proxy temperatures than do results without them because they introduce more realistic amounts of interdecadal variability.

6.3. Comparison With Annual Instrumental Temperatures

We also compared the yearly model outputs with the Jones instrumental temperatures for NH land. Figure 13a shows 5-year running means of these temperatures and selected model outputs combining volcanic and anthropogenic forcings, from 1854 to 1980. The output from VEI forcing is much too cool in 1900-1920, suggesting that the VEI may overstate the size of the forcing from the 1902 eruptions and Katmai in 1912. The model outputs using the DVI and IVI follow the long-term trend better but do not simulate many of the intradecadal temperature changes well. For example, instrumental temperatures fell sharply at the beginning of the 1880s, but modeled temperatures in volcanic simulations did not fall until after the Krakatoa eruption in 1883.

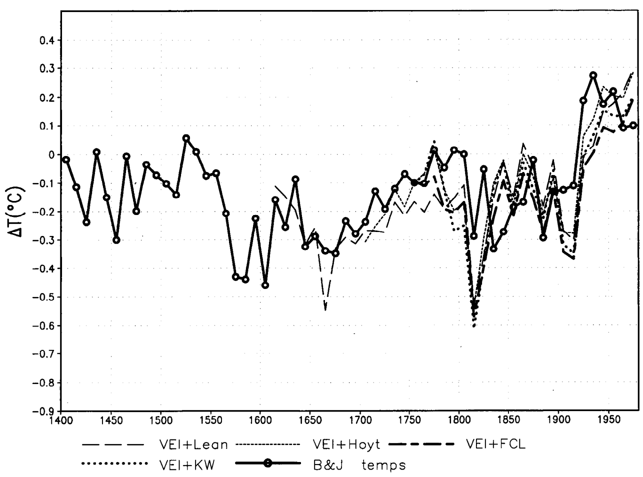

Figure 11. Same as in Figure 10 but for volcanic explosivity index (VEI).

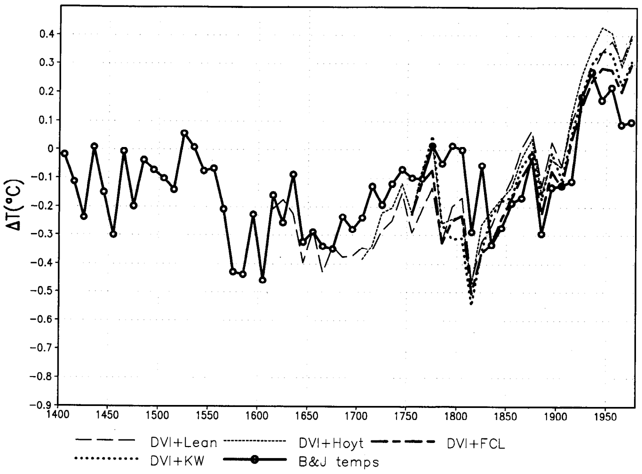

Figure 12. Same as in Figure 10 but for dust veil index (DVI).

Similarly, none of the model runs duplicates the peak in temperature around 1940. These discrepancies may be the result of ENSO events or other unforced variability of the climate system. Despite these shortcomings, the combined model results using the DVI or IVI with anthropogenic and solar forcings match the overall shape and magnitude of the instrumental record fairly well.

The figures suggest that the volcanic forcings account better for short-term variability and the solar forcings account better for for long-term variability. Since volcanic forcings occur at subdecadal timescales and the solar forcings hypothesized here are primarily long term, one might expect that the decadal averaging required for comparison with the BJ temperatures would reduce the correlations of volcanic results and increase those of solar results. In fact, because of the presence of high levels of natural variability at the year-to-year scale, even a basically high-frequency forcing like volcanic aerosol produces results that are better correlated with temperatures at decadal or longer scales than at interannual scales.

Table 3. Correlations of Model Runs Forced by Combinations of Volcanic and Solar Forcing.

	1610-1800	1610-1980	1800-1980	1700-1850
IVI and Lean	(0.57)	(0.75)	(0.75)	0.48
IVI and Hoyt	0.52*	(0.76)*	(0.80)	0.48
IVI and FCL	0.09*	(0.76)*	(0.79)	0.43
IVI and KW	0.10*	(0.71)*	(0.74)	0.33
VEI and Lean	(0.70)	(0.70)	(0.62)	0.25
VEI and Hoyt	0.63*	(0.70)*	(0.70)	0.29
VEI and FCL	-0.31*	(0.65)*	(0.67)	0.25
VEI and KW	-0.11*	(0.59)*	0.62	0.13
DVI and Lean	(0.68)	(0.78)	(0.81)	0.47
DVI and Hoyt	0.58*	(0.79)*	(0.84)	0.44
DVI and FCL	0.05*	(0.79)*	(0.85)	0.41
DVI and KW	0.07*	(0.74)*	(0.80)	0.25

All runs also include anthropogenic forcing. Numbers in parentheses are significant at the 95% confidence level.

* Results from Hoyt forcings begin at 1700; results from FCL and KW begin at 1750.

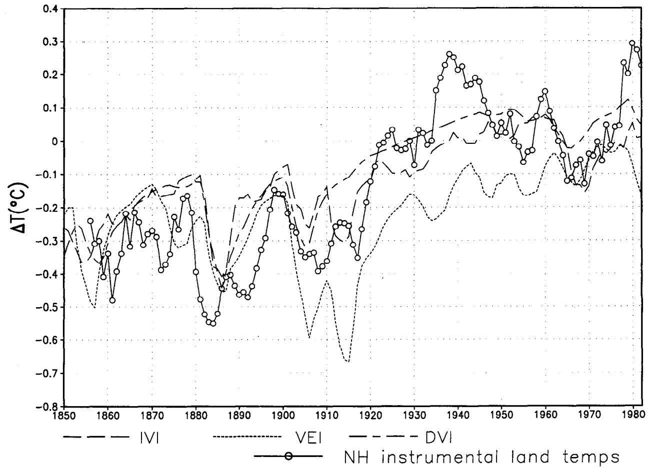

Figure 13a. Five-year running means of NH land model results for volcanic forcings with anthropogenic forcings, compared with instrumental land temperatures (climate sensitivity 3.0°C). Model outputs have been shifted down by 0.2°C to adjust for the difference in base period between the observations and results.

All runs without anthropogenic forcings (Table 4) are significantly correlated with the Jones NH land temperatures from 1880 to 1980, but the IVI and VEI are substantially less well correlated than the other runs. Significant correlations remain even when the series are linearly detrended, for all outputs except VEI and Lean. The detrended DVI results and Hoyt results have similar correlations (0.44), while the FCL and KW results are slightly better (0.50). The combination of DVI, KW, and anthro produces essentially the same correlation as KW alone. These correlations give little basis for distinguishing between possible external forcing explanations for the temperature changes of the twentieth century.

Figure 13b shows 5-year running means of Jones instrumental temperatures compared to model outputs using solar forcings alone, for sensitivity of 3.0°C. The observed temperatures

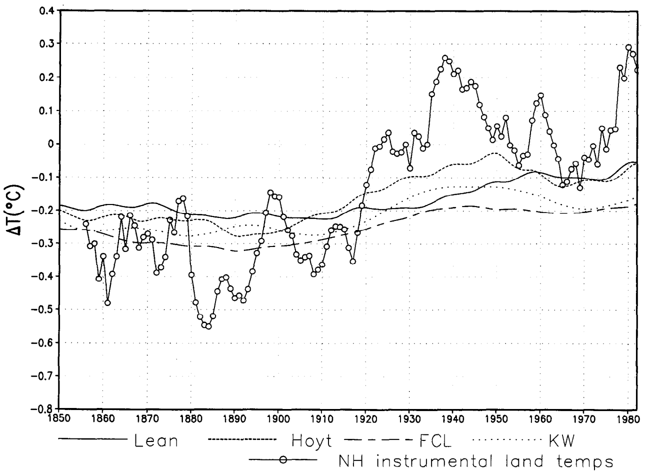

Figure 13b. Same as for Figure 13a but for solar forcings alone. *Lean et al.* [1995], *Kelly and Wigley* [1992], and *Friis-Christensen and Lassen* [1991] runs have been shifted down by 0.2°C, and *Hoyt and Schatten* [1993] runs have been shifted down by 0.4°C, to adjust for the difference in base period between the observations and results.

Table 4. Correlations of Model Output with *Jones et al.* [1986] and *Jones and Briffa* [1992] Instrumental Data, 1880-1980

	Before Detrending	Linearly Detrended
IVI	(0.35)	(0.32)
VEI	(0.29)	0.14
DVI	(0.62)	(0.39)
Lean	(0.56)	-0.04
Hoyt	(0.72)	(0.44)
FCL	(0.74)	(0.51)
KW	(0.73)	(0.51)
GHG	(0.63)	0.14
IVI and Lean	(0.62)	(0.31)
IVI and Hoyt	(0.69)	(0.42)
IVI and FCL	(0.67)	(0.39)
IVI and KW	(0.66)	(0.41)
VEI and Lean	(0.51)	0.14
VEI and Hoyt	(0.60)	0.26
VEI and FCL	(0.56)	0.21
VEI and KW	(0.56)	0.24
DVI and Lean	(0.71)	(0.41)
DVI and Hoyt	(0.74)	(0.49)
DVI and FCL	(0.74)	(0.47)
DVI and KW	(0.75)	(0.50)

Combinations of solar and volcanic forcing also include anthropogenic forcings. Numbers in parentheses are significant at the 95% confidence level. GHG, anthropogenic greenhouse gases and aerosols.

increase by roughly 0.8°C from the low point in the 1880s to the peak of the 1930s, but the solar series show not much more than 0.1°C change. At a high-end climate sensitivity of 4.5°C, the Lean solar series still rises less than 0.2°C, less than 25% of the observed increase. If the size of the Lean forcing were doubled, corresponding to a change of 0.5% in solar forcing, the resulting temperature increase for a climate sensitivity of 4.5°C would still be less than 0.3°C from 1880 to 1960. Furthermore, if the same climate sensitivity is used with our assumed anthropogenic forcing, the result is much larger than the observed temperature increase of the last 100 years, making this sensitivity assumption unlikely unless solar and greenhouse forcings produce dramatically different climate responses.

While the correlations between the alternative model runs and temperatures are too similar to provide a basis for choosing among possible forcings, the amplitudes of the model results show that given our assumptions about the size of solar forcing, solar forcing alone is insufficient to explain twentieth-century climate warming and that anthropogenic forcings are the most likely explanation.

6.4. Comparison to other proxy series

Figure 14 shows 5-year running means of model output for Lean forcing, alone and in combination with DVI and anthropogenic forcing, in comparison with *D'Arrigo and Jacoby* [1993] proxy temperatures. From the beginning of the proxy temperatures in 1681 to around 1830, the curves show similar overall trends, rising to maxima between 1750 and 1800 and then

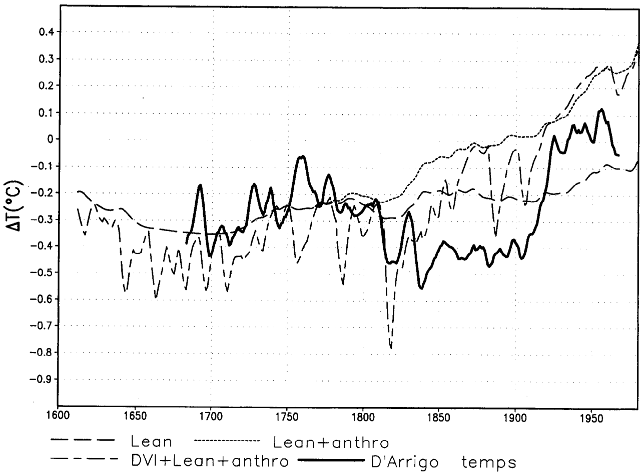

Figure 14. Five-year running means of NH land model results for *Lean et al.* [1995] and combined forcings, compared with proxy temperatures [*D'Arrigo and Jacoby*, 1993].

declining in the first two decades of the 1800s. After 1840 the series diverge, as the model results climb, while the proxy temperatures decline further and then remain roughly stable from 1850 to 1900. The variability of the D'Arrigo and Jacoby temperature reconstruction is noticeably smaller than the model output, particularly after Tambora (1815) and Krakatoa (1883). As with the comparison with the BJ decadal temperature series and the instrumental data, the variability of the solar results is too small to match the temperature changes of the LIA or the twentieth century.

A more detailed comparison of an earlier version of our results with the *D'Arrigo and Jacoby* [1993] temperature reconstruction appears in *D'Arrigo et al.* [1999]. While the details of the correlation results differ, those results are generally consistent with our conclusions based on comparisons with the BJ and Jones temperature series. A principal difference is that the newer version of the IVI used for this work gives better agreement with temperature data than the earlier version.

7. Comparison With Other Work

Kelly and Wigley [1992] and *Schlesinger and Ramankutty* [1992] showed that observed solar variability of around 0.1% was too small to explain temperature changes in the instrumental record without assuming climate sensitivity much larger than that indicated by other evidence. Our results extend their conclusions to the period 1610-1850 and show that the forcing amplitude of 0.24% of solar output hypothesized by *Lean et al.* [1995] is inadequate to account for the LIA or the warming of the twentieth century. A larger amplitude of 0.4% of total solar irradiance would be required to match the cooling of the Maunder minimum period for sensitivity of 3.0°C for doubled CO_2. For a sensitivity of 4.5°C, a solar irradiance change of around 0.3% would be required. To match the larger cooling of the 1500s, however, would require a solar irradiance change of 0.4-0.5% within a period of roughly 50 years.

Some previous analysis may also overstate the likely amplitude of climate response to solar forcing [*Lean and Rind*, 1994; *Crowley and Kim*, 1996; *Nesme-Ribes et al*, 1993]. The temperature dip produced by the Maunder minimum in our (decadally averaged) Lean solar model results is only 0.2°C less than temperatures at the start of the seventeenth century and only 0.3°C below twentieth century maxima, even with a high-end climate sensitivity of 4.5°C. (The equilibrium response to the Lean 0.24% reduction in solar output would be greater than 0.6°C with the high-end climate sensitivity.) The response to even a century-long decline in solar output can be much less than the equilibrium response, and the responses do not scale linearly with climate sensitivity. This is one reason why our results show some solar responses only half or less of the observed climate variability even with the somewhat speculative solar forcing amplitudes chosen by the originators of the forcing series. However, our model may understate the true cooling response to both solar and volcanic forcings because it does not include nonlinear processes such as sea ice feedbacks [see section 4 above]. *Cubasch et al.* [1997] found an approximately 0.5°C transient response in annual mean temperatures to the Hoyt solar forcing estimate using an AOGCM with climate sensitivity of 2.5°C, whereas our model gives about 0.3°C change in decadal averages for the same forcing. Their results suggest that this question needs further examination with a range of climate models to determine the correct sensitivity to solar forcing.

Our results showing a significant role for volcanic forcings are consistent with those of *Robock* [1978] and *Gilliland and Schneider* [1984], but this work indicates a greater role for solar forcings than those authors found. The correlations shown here between volcanic model results and climate proxy records are unlikely to be the results of hidden climate trends in the volcanic data, as suggested by *Crowley et al.* [1993] for the Crete ice core record. The ice-core-based IVI has been constructed so as to exclude all but short-term changes in the underlying data [*Robock and Free*, 1995], and the DVI has been scrutinized to remove all evident reliance on temperature information. Our choice of model parameters is based on independent criteria and the model is not tuned in any way to the historical or proxy climate record.

8. Conclusions

8.1. Implications for the LIA

Contrary to the results of *Lean et al.* [1995] and *Crowley and Kim* [1996], the statistical evidence for solar and volcanic effects on climate is similar in overall strength. The results vary widely with time period, specific solar or volcanic reconstruction, and to a lesser extent, the proxy or observational temperature series used for comparison. Solar responses look better than volcanic responses in correlations before 1800, but their amplitude is too small, and they do not fit nineteenth-century temperatures. The responses to volcanic forcings are big enough, but the fit is not very satisfactory, particularly before 1800. The high correlations seen in direct comparisons of solar forcing series with temperature records for the twentieth century are greatly reduced using model output for earlier time periods, because the model simulates the delaying and damping effect of the ocean on temperature variations. Despite the problems, our results indicate a greater role for volcanic aerosols in past decade-to-century climate than found in some previous work and a lesser, but still significant, role for solar forcing.

8.2. Implications for the Twentieth Century

Solar variability alone is clearly not enough to cause the warming of the twentieth century under our assumptions for forcing size and sensitivity. With a most-likely climate sensitivity of 3.0°C/2xCO_2 and an assumed variability of 0.24%, solar change is unlikely to account for more than 25% of the warming of the past 100 years. Correlations between solar forcings and twentieth-century temperatures are less impressive when a physically based model is used to reconstruct the climate response, and some disappear entirely when the linear trend is removed. Volcanic forcing in combination with anthropogenic changes gives results that correlate with temperature almost as well as do the solar runs, with a much better match in size. Only simulations including greenhouse gas forcing can match the observed temperature rise.

Combinations of solar, volcanic, and anthropogenic forcings can provide a consistent explanation of a portion of temperature changes over much of the last 600 years, but the fraction of total variance accounted for still leaves a significant role for internal variability of the climate system. We cannot afford to ignore any of these sources of climate change if we want to understand the past behavior of the climate system.

Appendix

A1. Adjustments to the IVI

The unadjusted IVI showed the 1912 eruption of Katmai in Alaska as twice as large as El Chichón (see Figure 3). Radiation measurements [*Sato et al.*, 1993] suggest that Katmai was no greater than El Chichón. We therefore adjusted the IVI values for high-latitude eruptions by dividing by 2, following *Zielinski* [1995]. Because the Northern Hemisphere IVI relies heavily on ice core data from Greenland, Icelandic eruptions appear to be overvalued more than other high-latitude signals. The IVI value for the 1783 Laki eruption is roughly 4 times as large as its DVI value. We therefore divided the IVI values for all identifiable Icelandic eruptions by 4 instead of 2. We relied on the VEI and DVI listings to identify IVI signals that were probably made by high-latitude and Icelandic eruptions.

A2. Adjustments to the DVI

Lamb [1970] relied in part on temperature data in assigning amplitudes to volcanic aerosol clouds. His Table 7(b) gives index values excluding those based solely on temperature data, but the remaining values are in some cases still based partially on such data. We identified the eruptions whose values were listed as based partially on temperatures and changed their DVI to a value based solely on the other data listed by Lamb for that eruption.

A3. Adjustments to the VEI

The VEI was constructed as an exponential index of the volume of ejecta from explosive eruptions. Previous work therefore assumed aerosol effects proportional to 10^{VEI} [*Schönwiese*, 1988]. The ice core evidence [*Robock and Free*, 1995] and radiation measurements [*Sato et al.*, 1993] do not, however, support order-of-magnitude differences in the optical effects of, for example, Agung or El Chichón (VEI 5) versus Pinatubo or Krakatoa (VEI 6). The ratios of aerosol optical depths for these eruptions appear to be closer to 1:2 or 1:3 than to 1:10. We chose 3 as a base because the IVI shows Tambora (VEI 7) as approximately 3 times as large as Krakatoa (VEI 6). The VEI index rescaled as 3^{VEI} looks much more like the DVI and the IVI in size distribution than did the previous VEI index based on 10.

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