SOLAR, VOLCANIC, AND CO_2 FORCING OF RECENT CLIMATIC CHANGES

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Abstract. The climate, as represented by the mean Northern Hemisphere temperature, has shown substantial changes within the past century. The temperature record is utilized as a means of elucidating the relative importance of anthropogenic CO_2 increase, volcanic aerosols, and possible solar insolation variations in externally forcing climate changes. Solar luminosity variations, suggested by observed solar radius variations on an ≈ 80 yr time scale, allow a self-consistent explanation of the hemispheric temperature trends. Evidence for solar influences on the climate is also found on the shorter 11 and 22 yr time scales present in solar activity cycles.

1. Introduction

Climate is of interest both because of its central importance to the human condition and because of its inherent variability. Climate shows significant variations over all periods greater than the defined minimum climatic time scale. What fraction of climatic variance can be ascribed to external forcing as opposed to stochastic internal variation remains a problem of considerable discussion [1].

The motivation for this paper follows the recent findings that the solar radius is variable. Analyses of historical records have suggested a large secular decrease of the solar radius over the last three centuries, although individual studies show somewhat discrepant results [2]. Theoretical models of the Sun have consistently suggested that large changes of solar luminosity would accompany changes of solar radius, although individual studies have varied widely in terms of quantitative predictions [3]. Theory predicts relatively larger variations of solar luminosity compared to radius, although the phase and order of magnitude of the relative changes cannot be reliably specified at present. Of potentially greater significance in the search for solar-climate relationships are the recent findings of periodic variations of the solar radius at ≈ 80 yr and at ≈ 11 yr [4].

The purpose of this paper is to answer two questions. First, given that the solar radius has experienced periodic variations and that simple theoretical models of the Sun predict relatively larger accompanying variations of solar luminosity, can an investigation of the

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This work was completed while the author was a postdoctoral fellow in the Advanced Study Program of NCAR.
Any opinions, findings and conclusions or recommendations expressed in this paper are those of the author and do not necessarily reflect the views of the National Science Foundation.
** The National Center for Atmospheric Research is sponsored by the National Science Foundation.

Climatic Change 4 (1982) 111–131. 0165–0009/82/0042–0111$02.10.
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Earth's climate yield information on the suspected variations of the solar constant? Second, using the assumption that the solar constant may vary significantly, can the inclusion of this external climate forcing function help in obtaining a better understanding of how other external forcings (such as the anthropogenic carbon dioxide greenhouse effect) are influencing the climate? Unfortunately, the above questions are not independent. Given precise knowledge of solar constant variations [5] the second question could be investigated on a much firmer basis. Likewise, accurate knowledge of all other aspects of the climate system would allow use of climate histories and models to answer unambiguously the first question.

I will approach the questions stated above by attempting a simultaneous answer to both. Self-consistency among the various aspects of the problem will be used as the primary criterion of success. Although I will approach the climate modelling in a quantitative fashion, the various results are intended to be interpreted in a qualitative manner as plausibility arguments.

Approaching the solar-climate problem by simultaneously including the known, if poorly specified, external forcings of volcanic aerosols and anthropogenic CO_2 is a necessary step. Previous studies have noted the possible simultaneous influence of volcanic aerosol producing events and assumed cyclic variation of solar luminosity over the 11 yr sunspot cycle [6]. Over the past few centuries the mean recurrence interval of significant volcanic events [7] is comparable to the solar sunspot cycle period. Clearly if volcanic aerosol loadings of the stratosphere cause significant climatic effects [8], then the search for expected solar effects of comparable or smaller magnitude should make allowance for the volcanic effects. Failure to allow for the theoretically and observationally demonstrated volcanic climate effects may partly explain the failure of some recent analyses to detect a significant signal in temperature records at the solar-cycle periods of 11 and 22 yr [9]. However, rhythmic variations of local surface temperature at the solar-cycle period have been claimed using a more sophisticated signal processing technique [10].

The remainder of this article will focus on the ability of various external climate forcing functions to explain consistently aspects of a standard climate record. A simple energy balance climate model will be used to demonstrate the relative importance of assumed solar constant, volcanic aerosol and anthropogenic CO_2 changes in inducing historical climate changes. The results will indicate probable solar-climate forcing on the two time scales of significant solar radius change (11 and 80 yr) and the 22 yr Hale solar magnetic cycle. A further observational and theoretical understanding of the solar forcings will be necessary in order to predict the eventual effects resulting from a rapid increase of atmospheric carbon dioxide.

2. Climate Forcing Mechanisms

I will examine three external climate forcing mechanisms. Although these are the most commonly cited mechanisms, other potentially important processes have been proposed [11]. Anthropogenic carbon dioxide is of primary interest because of its potentially dominating near future influence on climate change. Volcanic aerosol temperature effects have been noted as early as 1784, when Benjamin Franklin attributed the severe winter of 1783–1784 to a universal 'dry fog' covering much of the Earth [12]. The theoretical and observational assessments of climatic change resulting from volcanic explosions have reached a fairly consistent level (6–8). In contrast the literature on solar-climate relationships is vast, of inhomogeneous quality, and contains many opposing conclusions [9, 10, 13].

2.1. *Anthropogenic CO_2 Increase*

The increased burning of fossil fuels is leading to a substantial increase of atmospheric carbon dioxide. Carbon dioxide acts as a frequency dependent thermal trap, allowing solar radiation, which peaks at visible wavelengths, to freely reach the surface, while trapping the infrared radiation emitted from the Earth's surface. The projected increases of CO_2 depend upon rates of fossil fuel usage and feedback processes with the biosphere [14], both of which involve complex and inadequately understood mechanisms. I shall adopt an intermediate projection of CO_2 doubling from 300 ppm in 1925 to 600 ppm in 2045. Sensitivity of the climate to this assumed change will be discussed in the next section from a theoretical viewpoint, and from an observational aspect in the succeeding section.

2.2. *Volcanic Aerosols*

While the theoretical consequences of specified atmospheric aerosol loadings from volcanic events may be reasonably well known [8], the direct historical record of volcanic aerosol loading is, however, only poorly known [7]. In some cases [7] climatic anomalies have been explicitly used to infer a volcanic activity record. Clearly if one wishes to model climate records with volcanic indices, it is important that circularity be avoided by not using a volcanic dust index which has been influenced by a knowledge of climatic changes. Since volcanic events of greater or lesser magnitude occur with a frequency of several per year the reconstruction of volcanic dust indices by climatologists must be viewed with caution as subjectivity may be inadvertently introduced in such a way as to explain a known climate feature. Alternative reconstructions [7, 15] of Northern Hemisphere volcanic dust indices have large discrepancies over the 1940–1960 period of crucial significance for this study. The compilation [15], which has several volcanic events in the time span 1947 to 1960, is much more effective in modelling the Northern Hemisphere temperature record, which shows declining temperatures over the period 1940–1960 (discussed further in the next sections), than the volcanic dust index [7] which does not have events in this period. The Hekla (Iceland, 1947) volcanic event utilized by [15] is not evidenced in either atmospheric transparency records [16] or volcanically induced ice core acidity records [17].

Detailed theoretical models (Pollack *et al.* and Hansen *et al.* [8]) of the radiative effects due to various components of volcanic aerosols suggest that sulfuric acid based particulates are much more important than dust particles in changing the radiative energy balance. Fortunately, an objective record exists of the atmospheric content of sulfuric acid based particulates [17]. The acidity trace from Greenland ice cores [17] will not of course represent a perfect record of climatically significant stratospheric aerosol loadings. The acidity trace should contain the component representing stratospheric penetration of aerosols on a hemispheric scale, since the dispersion time scales within the stratosphere are shorter than typically assumed residence times. However, climatically insignificant traces from nearby volcanic events and tropospheric transport could contaminate the ice core record. Hammer [17] compares the acidity trace with commonly used dust veil indices [7] and discusses the degree to which the acidity trace represents hemispheric distributions.

The presence of the added aerosols increases the effective albedo through reflection of sunlight incident on the stratosphere and thus leads to a cooling effect. The particulates also block emitted infrared radiation, but the albedo effect is generally larger [8]. I will assume that the acidity record from Greenland ice cores [17] is an objective and direct measure of volcanically induced radiative blocking for the Northern Hemisphere.

2.3. *Solar Luminosity Variations*

Variations of the solar luminosity with sunspot number have long been suggested in the literature, but are based on meager amounts of questionable data [18]. The suggested variations are such that the solar luminosity first rises with increasing sunspot numbers and then declines at the highest sunspot numbers. Short time scale observations with the *Solar Maximum Mission* satellite have suggested an inverse correlation between sunspot projected areas and the solar luminosity [19]. Extrapolation of the results over short time scales ($\lesssim$ one year) to possible variations over a full sunspot cycle need not be valid, as larger underlying luminosity variations on the long time scale may exist.

For the purposes of this study I shall assume that a possible long term variation of solar luminosity accompanies the established variation of solar radius at ≈ 76 yr [4]. The amplitude and phase of the luminosity variation will be fixed by modelling an observed climate record. The long term radius variation is anticorrelated with the 'Gleissberg cycle' of roughly 80 yr [20] which modulates the amplitude of the 11 yr sunspot cycle. The solar radius variation at ≈ 11 yr is also anticorrelated with sunspot number [4]. I assume that the 11 and 76 yr solar radius variations may arise from independent causal mechanisms and will thus allow for the possibility of different luminosity-radius relationships at the two time scales. Figure 1 shows the solar radius variation at ≈ 76 yr and the external forcing functions related to volcanic aerosols and carbon dioxide discussed above. The amplitudes of the volcanic aerosol and CO_2 effects will also be independently fixed by the modelling process.

3. Climate Model and Observed Temperature Record

3.1. *Energy Balance Climate Model*

In order to compare a climate record with changes expected from known or suspected

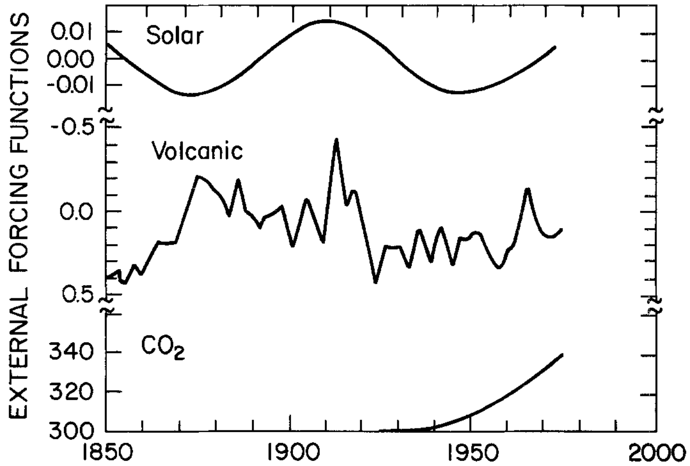

Fig. 1. From top to bottom the external forcing functions of solar radius variations (bandpass filtered at 76 yr) in percent of solar radius, volcanic aerosols (acidity record from Greenland ice core, Ref. [17], low-pass filtered with a 1.7 yr half-width Gaussian) in equivalent solar constant perturbation in percent as determined by the standard model – see Table I, CO_2 at 300 ppm before 1925 increasing to a projected 600 ppm by 2045.

external forcings, a simple climate model is needed which relates an observable quantity (surface temperature) to the external influences. A simple, but nontrivial, climate model adequate for this study is a globally averaged two-box energy balance model [21]. The upper box is an averaged ocean mixed layer, atmosphere and land surface, whose climatic state is represented by the temperature T_U. The lower box is an averaged deep ocean represented by T_L. The energy balance of the two layers may be written as

$$R_U \frac{\mathrm{d}T_U}{\mathrm{d}t} = Q(1-\alpha) - F_{IR} - \frac{c_w}{\sigma_R} \dot{V}(T_U - T_L) \tag{1}$$

$$R_L \frac{\mathrm{d}T_L}{\mathrm{d}t} = \frac{c_w}{\sigma_R} \dot{V}(T_U - T_L). \tag{2}$$

Thermal inertias of the upper and lower boxes are

$$R_U = \frac{c_w}{\sigma_R} V_U; \qquad R_L = \frac{c_w}{\sigma_R} V_L. \tag{3}$$

where c_w is the volumetric heat capacity of water, σ_R is the global surface area, V_U is the water equivalent upper box volume and V_L is the deep ocean volume. The upper box temperature is determined as an energy balance of external solar heating Q, moderated by the albedo α, an energy loss due to infrared emission F_{IR}, and communication with the lower box via the mixing rate $\dot{V}$. The infrared emission is parameterized as [22]

$$F_{IR} = A + B(T_U - 273). \tag{4}$$

Following [21 and 23] the deep ocean ventilation rate is set as $\dot{V} = V_L/\tau$ with $\tau = 550$ yr. The lower box temperature is determined only by exchanges with the upper reservoir. (Numerical values used for Equations (1–4) are: $Q = 342.5$ Wm^{-2}, $\alpha = 0.3$, $A = 212.3$ Wm^{-2}, $B = 1.83$ Wm^{-2} K^{-1}, $c_w = 4.1858 \times 10^8$ Jm^{-3} K^{-1}, $\sigma_R = 5.11 \times 10^{14}$ m^2, $V_U = 44.6 \times 10^{15}$ m^3, $V_L = 840 \times 10^{15}$ m^3).

The depth of the upper box averaged over the full Earth is taken to be 87 m. The lower box has a volume about 19 times greater than V_U. The two boxes have response time scales differing in proportion to their volumes. As discussed in [21] a climate perturbation occurring on time scales of a few years or less will affect only the upper box, while perturbations on decadal time scales will also affect the lower box. The response to CO_2 doubling illustrates the effect of the two-box system. At the time of the assumed CO_2 doubling in 2045 a model initially in equilibrium and with CO_2 forcing given as [21] $\Delta A = -2.88 \times 10^{-4}$ Wm^{-2} (age $-$ 1925)^2, experiences $\Delta T_U = 1.72$ K, and $\Delta T_L = 0.11$ K. The equilibrium response to doubled CO_2 is $\Delta T_U = \Delta T_L = 2.26$ K. At 1980 the transient responses for standard CO_2 forcing are $\Delta T_U = 0.32$ K, $\Delta T_L = 0.01$ K.

3.2. *Standard Climate Record*

In order to make use of a simple globally averaged energy balance climate model, as described above, a correspondingly simple climate record is required. Ideally a global temperature record extending over the past two centuries, for which all the external forcing functions are known, would be used. Regional records of temperature exist covering the last two centuries. It is, however, important that the record used represent at least a hemispheric mean. The most uniform large scale temperature records available are compilations of the mean annual Northern Hemispheric temperature since 1881. Several such compilations showing good agreement exist. I have adopted the mean of two recent compilations [24] as the standard temperature record. The two compilations have a linear correlation coefficient of 0.96. Although these [24] are considered the best available mean climate indicators covering about one century the data sets are far from uniform. The fraction of the Northern Hemisphere, after division into a discrete grid, for which data were available increased by a factor of three from the early to latter parts of the compilation. Therefore the reliability of the record degrades considerably for the earlier portions. The reliability of records for the Southern Hemisphere, which could be incorporated to yield global means, is much poorer than that for the Northern Hemisphere. I have therefore decided to use only the Northern Hemisphere temperature records. The numerical values of constants appearing in Equations (1)–(4) are based upon global averages, changing to areas and volumes, etc. appropriate to just the Northern Hemisphere would not significantly alter the results of this paper. The mean Northern Hemisphere temperature following the smoothing with a 1.7 yr (half-width) Gaussian low-pass filter can be seen in Figure 2. The low-pass filtering is used to remove the effects of high frequency weather anomalies which may bias yearly means, the resulting filtered record represents climate variations with time scales longer than about three years. The conclusions to be presented below are not sensitive to this low-pass filtering.

4. Determination of Relative External Climate Forcings

Given a standard climate record over the period 1881–1975 and a simple climate model, the object is to determine in a consistent manner the relative importance of various assumed external forcings in producing the observed temperature record. The external forcings of increasing CO_2 variable volcanic aerosols and a variable solar luminosity will be consistently evaluated as follows. Given the basic forcing functions of Figure 1 the variance between the observed temperature record and the temperature series of T_U generated by a time integration of Equations (1)–(4) will be minimized in a least squares sense by adjusting representative forcing parameters. The parameters to be used in conjunction with the separate forcing functions are: (1) A_C – a scale factor to multiply the assumed standard CO_2 response. $A_C = 1.0$ would yield a transient CO_2 temperature increase of 0.32 K by 1980 and 1.72 K by the assumed doubling in 2045. The least squares determined A_C will thus represent the ratio of the observationally determined greenhouse effect relative to that of a standard theoretical model. (2) A_S – a scale factor to multiply the solar radius forcing function. $A_S \equiv (\mathrm{d}\ln L_{\odot})/(\mathrm{d}\ln R_{\odot})$ – the inverse of W [3]. (3) P_S – a phase shift factor giving the lag in years that the luminosity variation follows the radius variation. (4) A_V – a scale factor (units are percent equivalent radiative variations for standard model to be described below) to multiply the ice core acidity trace [17], which is assumed to represent the volcanic aerosol forcing function. (5) P_V – a phase shift factor giving the lag in years that the volcanic aerosol extinction follows the acidity trace.

The solar and volcanic forcing terms are both incorporated as relative perturbations to the external heating source Q in Equation (1). The CO_2 greenhouse forcing enters as a change in the constant term in the infrared emissivity [Equation (4)]. The climate modelling proceeds as: (1) Start with climate model in equilibrium ($T_U = T_L = 288$ K). (2) Decide on subset of the five least squares climate parameters to be fit. (3) Integrate the climate model [Equations (1)–(4)] forward in time, adjusting the external forcing parameters in order to minimize the variance between the modelled temperature and the mean Northern Hemisphere record over 1881–1975.

The results of various model integrations may be found in Figure 2 and Table I. The first integration (A of Figure 2 and Table I) assumes only CO_2 greenhouse and volcanic aerosol variations as external climate forcings. With only volcanic and CO_2 forcing (three free parameters) the model fit is fairly good. In particular the model explains 77% of the original variance and the observed and model records have a linear correlation of 0.88. The model shows the long term rise of Northern Hemisphere temperatures from ≈1900 to 1940 due to a decreased volcanic activity over the 1920 to 1960 interval.

There are two serious problems with this model. First, the fall off of Northern Hemisphere temperatures over the 1940 to 1960 interval is not accounted for. The second and more serious problem is that the CO_2 forcing is found to be less than 10% of its theoretically predicted value. Although the lack of volcanic activity over the 1920–1960 time span can account quite well for the 1920–1940 temperature rise, the continued lack of activity until 1963 requires that the CO_2 effect be insignificant. These model results

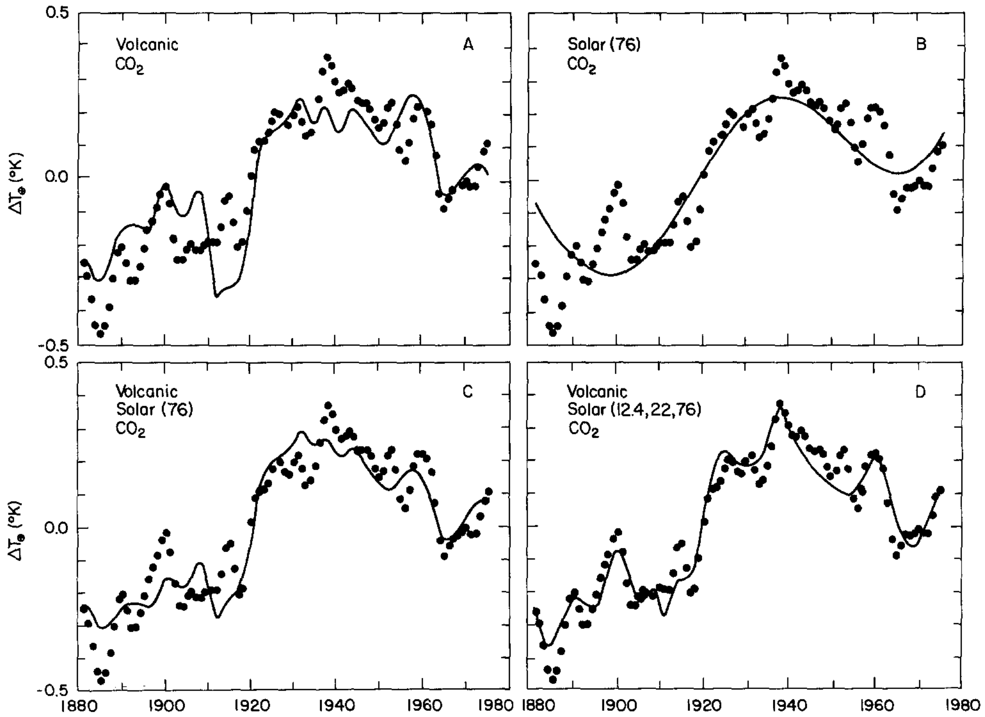

Fig. 2. Climate models (solid curve) with various assumed external forcings fitting the observed Northern Hemisphere temperature record [24]. The observational record (●) has been smoothed with a 1.7 yr half-width Gaussian low-pass filter.

TABLE I. Externally forced climate models.

External forcings	A_C CO_2 scale factor	A_S Solar (76) scale factor	P_S (yr) Solar (76) phase shift	A_V Volcanic scale factor	P_V (yr) Volcanic phase shift	Variance explained (%)
A. Volcanoes + CO_2	0.09			1.50	−1.95	77
B. Solar (76) + CO_2	1.47	18.63	21.34			73
C. Volcanoes + CO_2 + Solar (76)	0.80	9.84	18.43	1.00	−1.69	87
D. Volcanoes + CO_2 + Solar (76 + 12.4 + 22)[a]	0.82	9.64	18.79	1.00	−1.96	93

[a] Parameters for the short time scale cosine terms are: $P = 12.36$ yr, $\Delta L_{\odot}$ (half-amplitude) = 0.125%, maximum epoch = 1936.6; $P = 21.83$ yr, $\Delta L_{\odot} = 0.093\%$, maximum epoch = 1937.6.

would imply that the anthropogenic CO_2 greenhouse effect is of little significance, even for doubled CO_2.

The second climate model (B of Figure 2 and Table I) assumes only forcing from CO_2 and solar luminosity variations (three free parameters) on a 76 yr cycle following the known radius changes. The model fit here is also quite successful – accounting for 73% of the original variance. Both the 1920–1940 temperature rise and the 1940–1960 temperature decrease are accounted for with this model. The required CO_2 effect is within 50% of the standard theoretical prediction. Obviously the fit with only the assumed long term solar trend and CO_2 does not account for the short time scale structure of the observed Northern Hemisphere temperature record. This model implies a peak to peak $L_\odot$ variation of 0.53%. Such an $L_\odot$ variation might easily have escaped detection over such a long time scale [5].

It is more likely that volcanic aerosol radiative perturbations and solar luminosity variations have acted simultaneously. The third climate model (C of Figure 2 and Table I) includes CO_2 volcanic aerosol and solar luminosity external forcing through a five parameter least squares fit. The climate fit here is much improved over that without either the solar or volcanic forcings as discussed above. The full fit explains 87% of the Northern Hemisphere temperature variance (for time sclaes greater than about three years). The model and observed record correlate at $r = 0.93$. The improved fit (with respect to either A or B of Figure 2) need not imply an increased confidence level, since additional free parameters are used here, fewer degrees of freedom exist. Increased confidence in the validity of this model results from a more consistent (with theory) determination of the CO_2 effect. The large scale features of the observed record (rise to 1940 and subsequent fall) are well matched as are some of the shorter time scale features. The derived peak to peak solar luminosity variation is a very moderate 0.28%, which yields a temperature rise of 0.28 K over the 1900–1940 period. The climate fit shows that the assumed 76 yr variation of $L_\odot$ trails the $R_\odot$ variation by 18.5 yr – almost exactly 90 deg [25]. The climate response introduces a further lag of ≈ 5 yr, therefore the solar radius maximum of ≈ 1911 is followed by an $L_\odot$ maximum in ≈ 1930 and maximum Earth temperature response in ≈ 1935. The volcanic aerosol peak to peak temperature perturbation is 0.40 K. The predicted CO_2 greenhouse effect is fully consistent with simple theory, the transient response for CO_2 doubling in 2045 being 1.37 K and the equilibrium response to CO_2 doubling ≈ 1.8 K.

5. Solar Cycle Climate Influence

As shown above a large (87%) fraction of the variance in the Northern Hemisphere temperature record can be explained using reasonable and objective external forcings due to CO_2 volcanic aerosols and long term solar variability. Now that the smooth long term trends (CO_2 and solar variability) and short term stochastic effects of volcanic aerosols have been modelled, the remaining temperature residuals may be examined for low-amplitude cyclic behavior. The primary external cyclic effects which might be expected to appear in the temperature residuals are: (1) The 11 yr solar sunspot cycle, which also appears as a modulation of the solar radius [4], and has been found in regional temperatures [10]. (2) The 22 yr Hale cycle of solar magnetic reversals, which has also been claimed to appear in Western U.S. droughts [26]. (3) A third possible cycle is at 18.6 yr – the lunar nodal cycle period on which tidal influences may be important [27].

The procedure here is to analyze the Northern Hemisphere temperature residuals, which remain after removal of the best least squares theoretical fit (C of Figure 2 and Table I). The temperature residuals are shown in the upper left panel of Figure 3. The lower left panel of Figure 3 shows the reduction of mean squared residuals with least squares fits of $a \sin (2\pi/P) + b \cos (2\pi/P)$ at a series of generated periods (P). The two strongest reductions occur at 12.4 and 21.8 yr – close to the solar cycle periods of 11 and 22 yr. (The minimum at ≈ 8 yr is probably due to inadequacies in the removal of volcanic aerosol climate perturbations, which happen to generate a signal at this period.) The mean solar radius after removal of the 76 yr cycle and application of 1.7 yr Gaussian low-pass filtering is shown in the upper right panel of Figure 3. The reduction of residuals computed as with the hemispheric temperature is shown in the lower right panel of Figure 3 for the solar radius over 1880–1973. The most prominent reduction for the radii occurs at 12.4 yr. No significant solar radius variation near 22 yr is apparent. The coincidence of primary periodicities at ≈ 12.4 yr in the temperature residual and $\Delta R_\odot$ records suggests a causal link with solar luminosity variations. That similar analyses of both the solar radii and Earth temperature residuals yield signals at 12.4 yr is considered more significant than the precise period of these signals. It remains possible that the periodicity at 12.4 yr results from analysis of a periodicity at ≈ 11 yr with complicated time dependence of successive amplitudes. The claimed 12.4 yr periodicity may be simply related to the canonical 11 yr sunspot cycle.

The Northern Hemisphere temperature residuals and solar radii as plotted in Figure 3 have a maximum linear correlation of $r = 0.38$ with the temperature trailing radii about one year. Since the climate system introduces about a two year lag for radiative changes on a cyclic 12.4 yr time scale, the inferred solar luminosity variations, which force the Earth's temperature variations, are nearly in phase with the solar radius variations. The phase and amplitude relationships of $\Delta R_\odot$ and the temperature residuals at 12.4 yr may be examined by application of a bandpass filter [28]. Figure 4 shows the results of bandpass filtering the temperature residuals and $\Delta R_\odot$ with a 12 yr filter. The results are not sensitive to the exact filter used. The dates of sunspot cycle maxima are also indicated in Figure 4. There is a strong tendency for the dates of radius and temperature minima to coincide with dates of sunspot maxima. The only discrepancy out of 8 cycles occurs in the 1920s and 1930s where one sunspot cycle is skipped in the temperature record. The solar radius minimum corresponding to the 1937 sunspot peak is very weak – consistent with the apparent skipping of a cycle in the temperature record. Given that both the temperature and radius records are quite noisy and rather short, quantitative interpretations of possible cyclic variations must remain ambiguous.

A phase *cosine* fit to the bandpass filtered $\Delta R_\odot$ of Figure 4 yields: P = 12.47 yr, half-amplitude = 0.085 arc sec (0.009% of $R_\odot$), maximum radius in 1937.0. Using the climate model [Equations (1)–(4)] to infer a sinusoidal $\Delta L_\odot$ best generating the filtered temperature residuals (middle panel of Figure 4) yields: $P = 12.40$ yr, half-amplitude = 0.12%, maximum luminosity in 1936.7 [29]. The remarkable coincidence of parameters representing the solar radius and Earth temperature residuals must be taken as strong prima facie evidence for a solar-climate connection, especially since $L_\odot$ variations are a

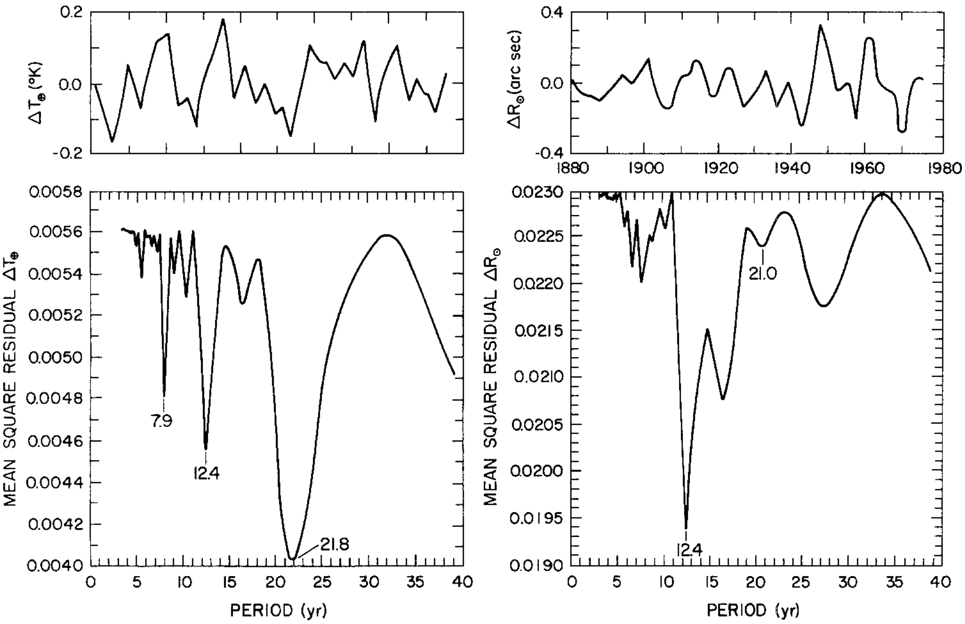

Fig. 3. Northern Hemisphere temperature residuals in the upper left panel after removing model fit with volcanic, solar (76) and CO_2 forcings (C of Figure 2). Lower left panel shows reduction of squared residuals following least squares fit of sin and cos at a series of assumed periods. Upper right panel shows solar radii after subtraction of the 76 yr term (see Figure 1). Lower right panel shows the squared residuals spectrum for the solar radius variations.

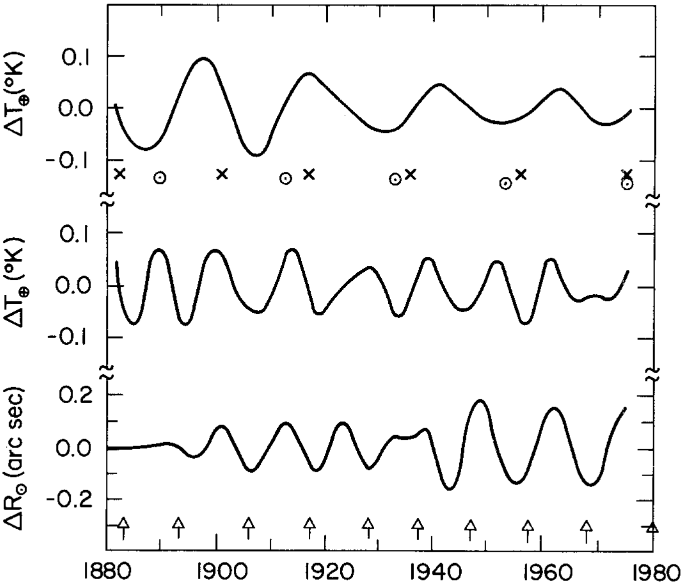

Fig. 4. Upper panel shows bandpass filtered Northern Hemisphere temperature residuals at 22 yr (see Figure 3 for plot of residuals). Middle panel shows the temperature residuals after application of a 12 yr bandpass filter. Solar radii filtered at 12 yr are shown in the lower panel. Dates of sunspot maxima are indicated by (↑), dates of Western U.S. drought maxima [26, 31] are indicated by (*X*), and fiducial dates [26] for the 22 yr double sunspot cycle are indicated by (⊙).

potential direct causal mechanism for both the $R_\odot$ variations [3] and Earth temperature variations.

At a period of 22 yr the solar radius does not show significant variation [4], however, the Hale double sunspot cycle has averaged 21.85 yr for the four cycles between 1889.4 and 1976.8 [26]. A climate model fit to the bandpass filtered (at 22 yr) temperature residuals of Figure 4 yields: P = 21.94 yr, half-amplitude (of $L_\odot$) = 0.09%, maximum luminosity in 1937.8. The dates of the Hale magnetic cycle and maxima of the 22 yr drought cycle [26] are also indicated in Figure 4. The temperature minima lead the Hale cycle by an average 3.0 ± 1.6 yr with no evident phase slippage. The drought cycle maxima average only 18.8 yr over this interval and show no consistent relationship with the 22 yr cycle of hemispheric temperature residuals. It may be that the 22 yr drought cycle amplitudes are modulated by solar influences [26], while the basic cycle length is set by tidal influences [27].

The 12.4 and 22 yr cycles found in the hemispheric temperature residuals are independent. Removal of one or the other cycle from the record has little effect on the other suspected periodicity. The parameters representing the 12.4 and 22 yr cycles may also be found with least squares cosine fits to the unfiltered temperature residuals yielding: P = 12.42 yr, half-amplitude = 0.12% and maximum $L_\odot$ at 1936.9; P = 21.74 yr, half-amplitude = 0.094%, maximum $L_\odot$ in 1937.5. A climate model fit with simultaneously applied external forcings of CO_2, volcanic aerosols, long term solar, and sinusoids near 12.4 and 22 yr (11 free parameters) is given as D in Figure 2 and Table I. The model explains 93% of the temperature variance with a linear correlation of $r = 0.966$.

One could, with some validity, argue that fitting 11 least squares parameters to a climate record of 95 yr after smoothing with a low-pass filter is a case of over-determination. I am not attempting to argue the statistical significance of the above models, but merely that all of the included external forcings are plausible. This is a sensitivity study of several assumed external forcing mechanisms for which representative parameters are simultaneously estimated by fitting an observed record. To the extent that detailed theory and observations exist concerning solar variations [2–4, 29] volcanic aerosol induced climate effects [8], and the CO_2 greenhouse effect [21, 30] the model results claimed above are all consistent.

The hemispheric temperature deviations resulting from application of the individual climate forcings (D of Figure 2) are shown in Figure 5 and summarized in Table II. The largest external forcing effect over the interval 1881–1975 was that of volcanic aerosol radiative perturbations. Volcanoes produced a peak to peak hemispheric temperature variation of 0.4 K with minimum in ≈ 1912 and maximum ≈ 1930–1960. The peak to peak equivalent solar constant perturbations for the volcanic aerosols is 0.84%. Solar luminosity variations on a 76 yr time scale produce the second largest effect with a peak to peak temperature variation of 0.27 K (minima ≈ 1895, 1970, maximum ≈ 1933) caused by peak to peak $L_\odot$ changes of 0.28%. The model climate system damps perturbations on short time scales – the $L_\odot$ perturbation at 22 yr is 25% smaller than at 12.4 yr, yet the temperature response at 22 yr is 17% larger than that at 12.4 yr. Radiative fluctuations at 10 yr produce smaller temperature responses by about a factor of three with

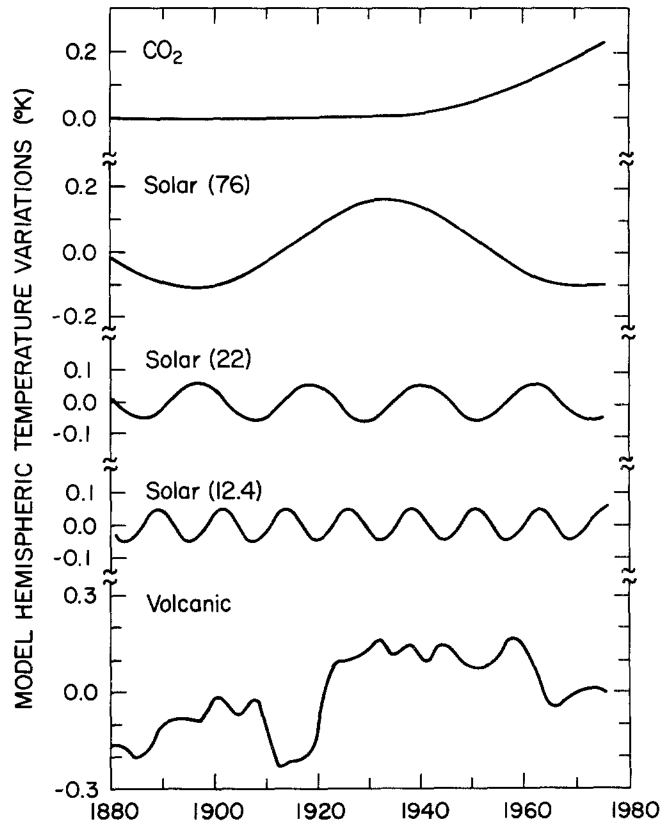

Fig. 5. Model hemispheric temperature variations for (from top) CO_2 76 yr solar variation, 22 yr solar variation, 12.4 yr solar variation, and volcanic aerosols. These are the individual components of the model of panel D – Figure 2.

TABLE II: Individual temperature components

External forcing	$\frac{1}{N-1}\sum_{x=1}^{N}(T_i - T_i)^2$	$\frac{1}{N-1}\sum_{x=1}^{N}\lvert(T_i - \bar{T}_i)\rvert$	$T_{max} - T_{min}$
CO_2	0.004	0.049	0.226
Solar (76)	0.010	0.088	0.272
Solar (22)	0.002	0.036	0.112
Solar (12.4)	0.001	0.031	0.096
Volcanoes	0.015	0.105	0.403

respect to fluctuations of the same amplitude at 80 yr.

Taking the analysis one step further, it is interesting to note that a signal near 18.6 yr appears very weakly in the hemispheric temperature residuals after removal of all the external forcings (as in D of Figure 2) discussed above. The upper panel of Figure 6 shows the mean squared residuals of the full climate model fit obtained with *sin* and *cos* least squares fits as in Figure 3. The minima at 8 yr is present as before, but having removed the signals at 12.4 and 22 yr the second most prominent feature appears at 18.6 yr. The lower panel shows the residuals and the result of bandpass filtering at 19 yr [28]. A *cosine* fit to either the raw residuals or the bandpass filtered record yields P = 18.3 yr, half-amplitude = 0.025 K, maximum temperature in 1933. The mean period between the maxima or minima in Figure 6 is 18.6 yr. This marginal result for a periodicity at 18.6 yr is considered interesting only because it is in agreement with an independent theoretical prediction based on changing sea surface temperatures in response to the tidal variations at 18.6 yr [31]. The epochs of Western U.S. droughts [26] are also indicated in Figure 6 and trail maxima of the 18.6 yr temperature variation by a very uniform 4 ± 1 yr. This tends to support the contention, based on a longer data series, that the 18.6 yr period of the lunar nodes is important in driving regional effects such as the Western U.S. drought [27, 31]. The amplitude of the 18.6 yr temperature term is an order of magnitude smaller as a hemispheric mean, than as a regional term [27]. This is

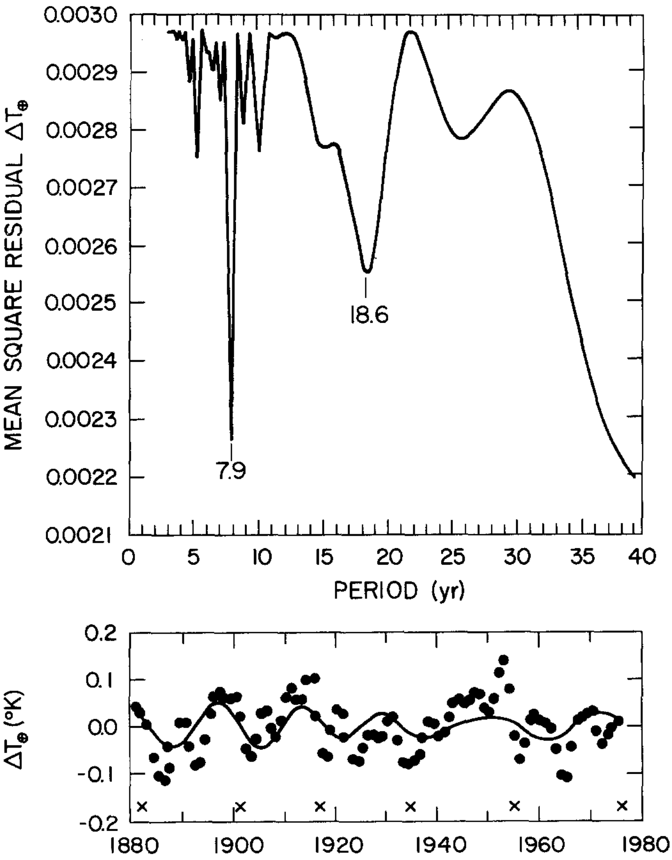

Fig. 6. Upper panel shows mean square residuals as reduced by sin and cos least squares fitting at generated periods for the residuals resulting from the full climate fit (D of Figure 2). Lower panel shows the temperature residuals (●) and the results of bandpass filtering at 19 yr (solid curve). Dates of Western U.S. drought maxima [26] are indicated by (X).

also consistent with the simple theory by Bell [31], which predicts opposing effects in the Pacific and Atlantic, leading to partial cancellation in averages over latitude. The 22 yr term on the other hand appears most prominently in a hemispheric temperature record, which supports the contention that this is a solar induced phenomenon.

6. Conclusions and Speculations

A long term climate record covering the interval 1881–1975 has been analyzed for the purpose of isolating potential effects resulting from several possible external forcings. The coincidence of independent signals in the mean Northern Hemispheric temperature record with the forcing functions expected from anthropogenic CO_2, solar variations, volcanic aerosols, and possibly lunar tides, suggests that some 95% of the hemispheric temperature record variance on time scales greater than about 2–3 yr [32] may be of external deterministic origin. The inferred temperature variations for the individual external forcings are in good agreement with theory for the cases of volcanic [8] and CO_2 [21, 30] forcing. The variations of hemispheric temperature are consistent with the assumed solar [3–5] and tidal influences [31], although the observations and theory of these potential forcing functions are currently in a rudimentary state of development.

The suggestion of solar-terrestrial influences on time scales of several decades or longer has often been made to explain various climatic events. The correlation of solar activity variations with climate changes on time scales of centuries led to the suggestion that the solar luminosity may vary by $\approx$ 1% on these long time scales [33]. Solar [4, 20] and terrestrial [26, 34] variations on a 70–80 yr time scale are ubiquitous and consistent with the $\approx$ 76 yr variation of $L_\odot$ as proposed above.

I have not tried to argue the statistical significance of individual forcing mechanisms and modelled temperature responses [35]. In relation to this several caveats concerning this work need to be explicitly stated: (1) The mean Northern Hemisphere temperature record [24], while probably the best climate record available, is non-uniform with time and may well contain some subtle systematic errors [6, 8, 24]. (2) The solar radius variation at $\approx$ 76 yr is uncertain by 50% in magnitude and some 10% in period [4]. The $R_\odot$ variation is also of non-uniform quality in the time domain. (3) The theory predicting $L_\odot$ variations following $R_\odot$ variations is in a very crude state [3, 25]. Current solar theory can only be used to claim that if an $R_\odot$ variation exists, then a somewhat larger $L_\odot$ variation (of unspecified phase) is also likely at the same period. (4) The acidity trace from a Greenland ice core [17], used to represent the volcanic aerosol forcing function, has significant errors of measurement. Possible systematic effects such as latitude or longitudinal dependence of volcanic events also make the acidity trace an imperfect record of volcanic activity. It is possible that some climatic feedback could exist in the acidity record through changes of atmospheric circulation and precipitation patterns. (5) The assumed solar signal at $\approx$ 12.4 yr in the temperature agrees with the existence of a similar $R_\odot$ cycle, but a cycle length of $\approx$ 11 yr would have been expected for both. (6) The 22 yr cycle in temperature, although in excellent agreement with the 22 yr double sunspot cycle, is not represented by a detectable variation of $R_\odot$. (7) The climate model [21] used here is extremely crude, e.g. no land/sea or air/surface temperature resolution is included. Many potentially important climate feedback mechanisms may not be properly accounted for in this simple model. (8) Uncertainty exists concerning the history of CO_2 concentrations. (9) Fitting a smoothed 95 yr data base with five different forcing functions (11 parameters) and still seeking information in the residuals may be claimed excessive.

Everyone would agree that the climate is generated by a complicated physical system. Most will agree that many potential external climate forcings exist, although their relative importance is a matter for current debate. Given that perhaps a half-dozen external forcing mechanisms are of potential importance how can one of these, say the suspected 22 yr solar period, be best investigated? Assume that the 22 yr influence is a uniform global forcing of small magnitude such as to yield mean temperature variations of only 0.1 K peak to peak (as found in this study). Would one expect to see a signal of 0.05 K half-amplitude at a period of 22 yr in 55 yr local records with variances exceeding 1 K, and in which known stochastic effects (e.g. volcanic aerosol perturbations) of amplitude 0.1–0.5 K have not been first removed? Probably not. Such a study [9], failing to isolate a significant signal at 22 yr (detection limits were not given), is quoted [13] as being very thorough and implying that a 22 yr influence does not exist. A more reasonable approach is that adopted in this study. Known effects (and long term trends) were first removed from the most uniform hemispheric temperature record available using objective estimates for the assumed forcing functions. The residuals were then analyzed for periodicities. The residuals show the strongest signal at ≈ 21.8 yr, which may be related to a mean solar magnetic cycle length of 21.85 yr over the same interval. The second strongest signal in the residuals was at ≈ 12.4 yr, which corresponds to an $R_\odot$ variation at the same period and phase. With all the caveats acknowledged above a rigorous statistical argument concerning the above periodicities is not possible. However, the coincidence of signals in a standard climate record with suspected external forcings is compelling evidence for a physically significant solar-climate relationship.

Given for the moment that 22, 12.4 and 18.6 yr cycles have existed in the climate of the last century, with magnitudes as claimed above, is this of any practical significance? The largest amplitude is ascribed to the 22 yr cycle at ≈ 0.1 K peak to peak. With local annual cycles of temperature variation being two orders of magnitude greater than this, and long term local variations due to other causes (or internal fluctuations) one order of magnitude larger, the direct temperature effect is obviously of academic interest only. However, it has been argued that the Western U.S. drought cycle correlates significantly with the 22 yr solar cycle [26], the 18.6 yr cycle of lunar tides [27] and more probably a combination of the two [31]. Furthermore the amplitude of the drought cycle has been shown to correlate well with the long term envelope of solar activity [26]. The long term drought cycle amplitude modulation is quite consistently explained by the existence of a 76 yr variation of $L_\odot$ as suggested above. The drought cycle amplitudes (Figure 6 of Ref. [26]) have a linear correlation with the $R_\odot$ variation of $r = 0.66$ with droughts trailing $R_\odot$ by ≈ 25 yr. The 25 yr lag is due to $L_\odot$ trailing $R_\odot$ by ≈ 19 yr with a further small lag introduced by the climate system response. (The above correlation is significant at about the 2% level.) This provides circumstantial evidence that the extent and severity of droughts respond quite sensitively to small changes of long term external forcings – factor of about 2–4 change in areal drought extent [26] of given severity corresponding to hemispheric temperature variations of order 0.5 K. The significance of a Western U.S. drought cycle has been questioned on the grounds that such effects may not exist in other regions of the globe [36].

In terms of the CO_2 problem, these results suggest that the surface warming due to the greenhouse effect has now been roughly determined and the magnitude is consistent with theoretical predictions [21, 30]. The failure of some previous studies to find the expected effect may be attributed to their interpretation of all climatic variability other than the CO_2 signal to random noise [37]. This study has explained in excess of 90% of the variance in a hemispheric temperature record using a few realistic and objectively specified external forcings including a CO_2 effect determined at $\approx$ 1.8 K for equilibrium CO_2 doubling [38]. A corollary is that, while a temperature minimum in the 1960s–1970s induced by natural external forcings has masked the CO_2 effect, a rising temperature trend from $\approx$ 1980–2000 due to natural external forcing could lead to a future overestimate of the CO_2 effect [39]. Figure 7 shows the standard model temperature fit (D of Figure 2 and Table I) extended from 1800–2000 assuming solar, CO_2 and average (constant) volcanic perturbations past 1975. The extrapolation from 1976–2000 shows a steeper temperature increase than would be expected from CO_2 forcing alone. The 1800–1880 part of the reconstruction is less reliable than 1880–1975 due to a less precise solar radius determination over the earlier period. The temperature extrema from 1800–1860 result from generally reenforcing (and thus inseparable) contributions from solar and volcanic forcing.

The amplitude of the Western U.S. drought cycle, these results imply, could be modulated by long term temperature trends – primarily solar and volcanic induced. The low temperatures of the last two decades result primarily from a minimum of the solar 76 yr cycle. The next temperature maximum resulting from the claimed solar cycle is in about 2010. By 2010 this study predicts a CO_2 induced temperature increase of 0.7 K, which by itself implies a larger excursion from the mean temperature than any found in the historical hemispheric record. The work of Bell [31] predicts that the next drought cycle

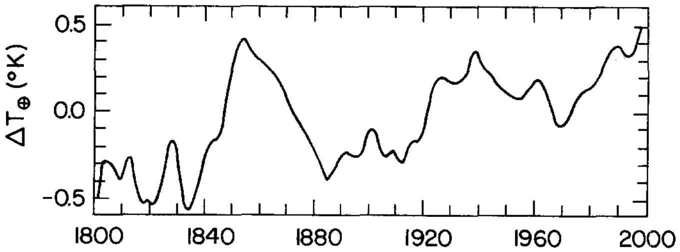

Fig. 7. Model Northern Hemisphere temperature record calibrated over 1881–1975 as in D of Figure 2. Period before 1881 is based on solar and volcanic forcings. Period after 1975 results from extrapolated solar and CO_2 forcing with an assumed mean volcanic aerosol level.

to occur in the 1990s, under either the 18.6 or 22 yr assumptions [26, 27], will be skipped due to opposition of these cycles. If this were the case, with mild climate ensuing to the year 2000, complacency with the possible CO_2 impact might develop. This complacency could be shattered in the drought cycle of about 2010 by the modulating effects of temperatures higher than any in historical times due to combined solar and CO_2 greenhouse effects.

Analysis of possible externally induced climate effects in a regrettably short and noisy record demands that consistent account be taken of the several suspected influences simultaneously. Precise determination of the strong solar forcings made plausible by this study are crucial for the prompt observational detection of CO_2 induced warming. Theoretical effort should be devoted to understanding solar luminosity and radius variations using realistic physical modelling input. Most important for the understanding of climate variations are accurate long term measurements of yearly mean $R_\odot$ (to 0.001%) and particularly $L_\odot$ (to $< 0.05\%$), both of which are now technically feasible.

Acknowledgements

I thank J. Eddy and S. Schneider for many useful comments on an earlier version of this manuscript. I also thank P. Gilman, D. Hoyt, and J. Kasting for helpful comments. J. M. Mitchell, Jr. provided comments on and copies of the studies listed in Ref. [24].

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[3] The solar variability modelling efforts published to date have all relied on unrealistically simple representations of the interactions between convection, rotation and magnetic fields in the solar envelope, which are assumed responsible for producing variability. The modelled solar variability may be most simply represented by the parameter $W = (\mathrm{d} \ln R_\odot)/(\mathrm{d} \ln L_\odot)$, giving the relative radius and luminosity adjustments. For time scales of variability in the 1–1000 yr range published values of W evaluated for the same assumed physical mechanism are: $W = +0.075$ (Sofia, S. *et al.*: 1979, *Science* **204**, 1306) $W = +5.0 \times 10^{-3}$ (Dearborn, D. S. P. and Blake, J. B.: 1980, *Astrophys. J.* **237**, 616) $W = +8.5 \times 10^{-4}$ (Gilliland, R. L.: 1980, *Nature* **286**, 838). From the study by Spiegel, E. A. and Weiss, N. O.: 1980, *Nature* **287**, 616, one may deduce that W is small and negative. Gilliland, R. L.: 1982, *Astrophys. J.* **253**, (in press) has argued that the current and immediately realizable models of solar variability are too crude to allow more than plausibility arguments concerning the value of W, even if consensus should be reached on its numerical value with current techniques.

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same variation which will be more precisely characterized as 12.4 yr in this paper.)

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zone the required radiative energy deficit is quite small. A 0.02% shift of the solar radius (observed half-amplitude of 76 yr cycle) would represent $\gtrsim 7 \times 10^{42}$ ergs if the whole convection zone is lifted. The thermal energy content of the convection zone is $\gtrsim 3 \times 10^{45}$ ergs. The differential rotation and magnetic field energy reservoirs are greater than or of order 10^{40} ergs. A possibly related solar index which trails the radius variation by 90° is the ratio of sunspot umbral to penumbral areas – hypothesized to be associated with changes of $L_\odot$ by Hoyt, D. V.: 1979, *Climatic Change* **2**, 79. The *U/P* ratio and $R_\odot$ variations have a maximum linear correlation coefficient of 0.97 at a 19 yr lag after both have been filtered by an 8 yr half-width low-pass Gaussian filter. Thus at long time scales the *U/P* and $R_\odot$ (shifted 90°) variations are in nearly perfect coincidence. Siquig, R. A. and Hoyt, D. V.: 1980, in R. O. Pepin, J. A. Eddy, and R. B. Merrill (eds.), *Proc. Conf. Ancient Sun*, Pergamon, p. 63, have presented climate simultations using CO_2, volcanic dust index, and *U/P* solar luminosity variations as external forcing functions.

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[32] A full climate fit (as with D of Figure 2) using unsmoothed temperature and volcanic activity records explains 76% of the variance. The model and yearly mean temperature correlate at $r = 0.87$. The resulting parameters are not significantly different from those obtained after applying the low-pass filter. Objections to a procedure accounting for 95% of the variance in a record which is not itself thought to represent reality at that level may reasonably be raised. J. M. Mitchell (seminar at NCAR, April, 1981) maintains that at least 20 to 25% of the variance in the Northern Hemisphere temperature record results from errors such as urban effects and geographically uneven representativeness of the record. The claim that some 95% of the hemispheric temperature record variance may be of external deterministic origin may result from statistical over-specification. On the other hand, the errors of order 25% in the observed record do not imply that only 75% of the variance should be explicable in terms of external forcings, only that until the errors are removed the confidence levels of specific claims must remain correspondingly low. The best way out of the quandary of statistical over-specification is to learn more about the proposed external forcing factors such that they may be included explicitly without removing degrees of freedom from the observational record.

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[35] In a record of only 95 yr the statistical significance of a 76 yr period (solar forcing) obviously will be low. The lack of statistical significance does not in any sense argue that the claimed results are invalid, merely that insufficient data exists for demonstrating formal statistical significance.

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(Received 20 October, 1981; in revised form 5 November, 1981)