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Volcanic Dust, Sunspots, and Temperature Trends

A calculated global surface temperature history has some similarities to known temperature histories.

Stephen H. Schneider and Clifford Mass

Many possible causes of climatic change have been postulated over the years (*1*). The most deterministic of these causes are labeled external, since they are not themselves thought to be influenced by the climatic state. Small variations in the earth's position relative to the sun, variations in the total flux of solar radiation reaching the earth's orbit (the solar "constant"), volcanic eruptions that periodically inject dust into the stratosphere, or changes in the composition of the atmosphere or the characteristics of the earth's surface due to human activities are examples of such external causes.

On the other hand, fluctuations in climate might also result from internal exchanges of energy between the large reservoirs—the atmosphere, oceans, and ice masses—which collectively comprise the climatic system. Lorenz (*2*) termed the possible existence of some internal causes of climatic change or self-fluctuations in the climatic system "almost intransitivity." To what extent the statistics of the actual climatic system can be attributed to internal or external causes, or to a combination of these, is perhaps the chief open question in climate theory (*3*).

Our purpose in this article is to examine quantitatively the extent to which two often proposed external causes of climatic change, volcanic dust and variations in the solar constant correlated with variable sunspot activity, might account for the general patterns of surface temperature variation since A.D. 1600. We examine the consequences in a simple climatic model of the assumptions that these proposed external causal factors are forcing the climatic system. Similarities between our computed surface temperature patterns since 1600 and the observed patterns should not be quickly interpreted as indicating that the external factors explain the observed record; instead, they only demonstrate that these factors may have contributed to the shape of the record. Such correlations, however, indicate the need for (i) a program to measure solar variability with instruments capable of resolving to a few tenths of a percent the time history of the sun's output, (ii) an increased and quantitative inquiry into the effects of volcanic dust on radiative heating rates and motions in the atmosphere, (iii) an improved reconstruction of the global surface temperature history, (iv) improved physical parameterizations that will permit refined modeling studies of the sensitivity of the surface temperature to changes in external factors, and (v) an examination of the predictability of volcanic (and solar) activity.

Heating Parameterizations

Sunspots. Solar variability is a controversial, yet often invoked hypothesis to explain climatic changes (*4*). To date, no long-term record of the total flux of solar radiation reaching the earth's orbit has been compiled from an extraterrestrial platform. Many attempts have been made to measure the solar constant (which we will henceforth call the solar parameter, S), and the difference between individual measurements often exceeds the stated accuracy of each measurement. Furthermore, many of these data were taken within the earth's atmosphere, which increases the chance that the record was contaminated by fluctuations in atmospheric turbidity. Thus, the report of the Study of Man's Impact on Climate concluded that our precise knowledge of the solar parameter was insufficient for climatic theory and modeling and recommended that it be determined to an absolute value of "better than ± 0.5%, and that the spectral distribution of solar radiation from 1800 Å to 40,000 Å" be determined "to a few percent" (*5*, p. 87).

However, two well-known studies, by a group at the Smithsonian Astrophysical Observatory (*6*) and a Soviet group (*7*), have related the solar parameter to the number of sunspots. The findings of both groups suggest that the value of S increases with sunspot number, but eventually reaches a maximum and subsequently decreases. Kondratyev and Nikolsky's result (*7*), for example, suggests that S is more than 2 percent lower for no sunspot activity than for moderate activity (an annual average sunspot or Wolf number $N \approx 80$), and decreases again to near its value at $N = 0$ for high activity ($N \approx 200$). The validity of this controversial relationship, which was derived from balloon measurements in the atmosphere, is not in question here (*8*). However, the potential climatic consequences of such a large variation in S, if it occurred, is sufficiently compelling to warrant testing the relation $S(N)$. To do this we infer from the time history of N a time history of S, which we then use as input into a simple climatic model based on energy balance to compute a time history of surface temperature T_s. The consequences for a climatic model of accepting $S(N)$ is thus demonstrated. Kondratyev and Nikolsky get good agreement with the relation (attributed to Ångstrom)

$$S(N) = 1.903 + 0.011N^{1/2} - 0.0006N \quad \text{cal cm}^{-2}\,\text{min}^{-1} \qquad (1)$$

The variation of N has been recorded for many years by astronomers and is given in

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Fig. 1a, which is the source of $N(t)$ values used for model forcing. The sunspot numbers before 1710 shown by the solid line are from Eddy (*9*), and those shown by the dashed lines are our interpolations between Eddy's data. Thus, temperatures computed for dates before about 1650 are also interpolations. The data between 1710 and 1960 are from Waldmeier (*10*), those between 1961 and 1975 are from the Solar Geophysical Data prompt reports (*11*), and the projection for 1975 to 1989 (dotted line) is from Sleeper (*12*). Combining $N(t)$ from Fig. 1 with Eq. 1 gives the time history of the modulation of S by sunspot activity, $\Delta S_s(t)$, which is part of the input to the climate model. The remarkable feature of Fig. 1a is the relative absence of spots from about 1650 through about 1700, the so-called Maunder minimum. Eddy (*9*), who has delved into rare book collections to uncover accounts of astronomers at that time, concludes that the Maunder minimum may well be an indication of the absence of sunspots, not simply a dearth of measurements.

Volcanic dust veils. Volcanic dust veils have been proposed as an external cause of climatic change primarily because they can screen out (scatter and absorb) several percent of the direct solar beam, thereby preventing some of the solar energy from reaching the lower atmosphere. We mimic this effect on solar radiation by defining a relationship between increases in volcanic dust concentrations and effective decreases in the solar parameter, which is scaled proportional to the dust increase. The "dust veil index," compiled and tabulated by Lamb (*13*) from a combination of historical accounts and direct measurements of volcanic contributions to the stratospheric aerosol, is used here as given in Fig. 1b. Again, we are not attempting to comment on the validity of such an approach to the reconstruction of volcanic dust concentrations, but rather are interested in how this time series of volcanic dust concentrations might influence the time series of computed surface temperature patterns.

We use the observations from Mauna Loa Observatory in Hawaii to scale Lamb's dust veil index against $S(t)$. Observations at Mauna Loa show that the transmission of direct solar radiation dropped sharply, by nearly 2 percent, after the eruption of Mount Agung in Bali in 1963 (*14*). Since most of the extinction of direct solar radiation is scattered downward, it reaches the lower atmosphere in any case. We assume that only 25 percent of the extinction of the direct beam should be used for determining the equivalent decrease in solar parameter, ΔS_D, due to volcanic dust. (Note that we are referring here to downward scattering and not to forward scattering—in the direction of the incident solar beam—for which somewhat more than 75 percent would be assumed to reach the lower atmosphere.) Since Agung's eruption decreased direct transmission ≈ 2.0 percent, we scale the dust veil index so that its value for Agung (160 in Lamb's relative units) is equivalent to a 0.5 percent decrease in the solar input at the top of the lower atmosphere. (This scaling includes time variations in S attributed to sunspots.) This 0.5 percent value for Agung is in good agreement with the calculated values of Coakley and Grams (*15*).

Modeling the influence of stratospheric dust veils on climate by an equivalent decrease in S is reasonable as a first-order approximation to the influence of a stratospheric aerosol on the radiative input to the lower atmosphere (*16*). However, several other mitigating or enhancing effects are possible. Probably the most significant additional effect would be an increase in downward infrared (IR) radiation at the tropopause, which would tend to offset somewhat the cooling effect of a stratospheric aerosol on the lower atmosphere. The effect of a dust veil on the downward IR radiation can be broken down into (i) an increase in the IR opacity of the stratosphere due to the dust, and (ii) a change in stratospheric temperature traceable to changes in the net heating by visible and IR radiative fluxes in the stratosphere. Whereas the first effect would always tend to increase the downward IR (and thus offset the cooling below the dust layer), the second could act either to increase or decrease it, depending on whether the perturbed radiation field tended to heat or cool the stratosphere. Unfortunately, the warming or cooling is a complicated function of the wavelength-dependent absorption and backscattering coefficients of the

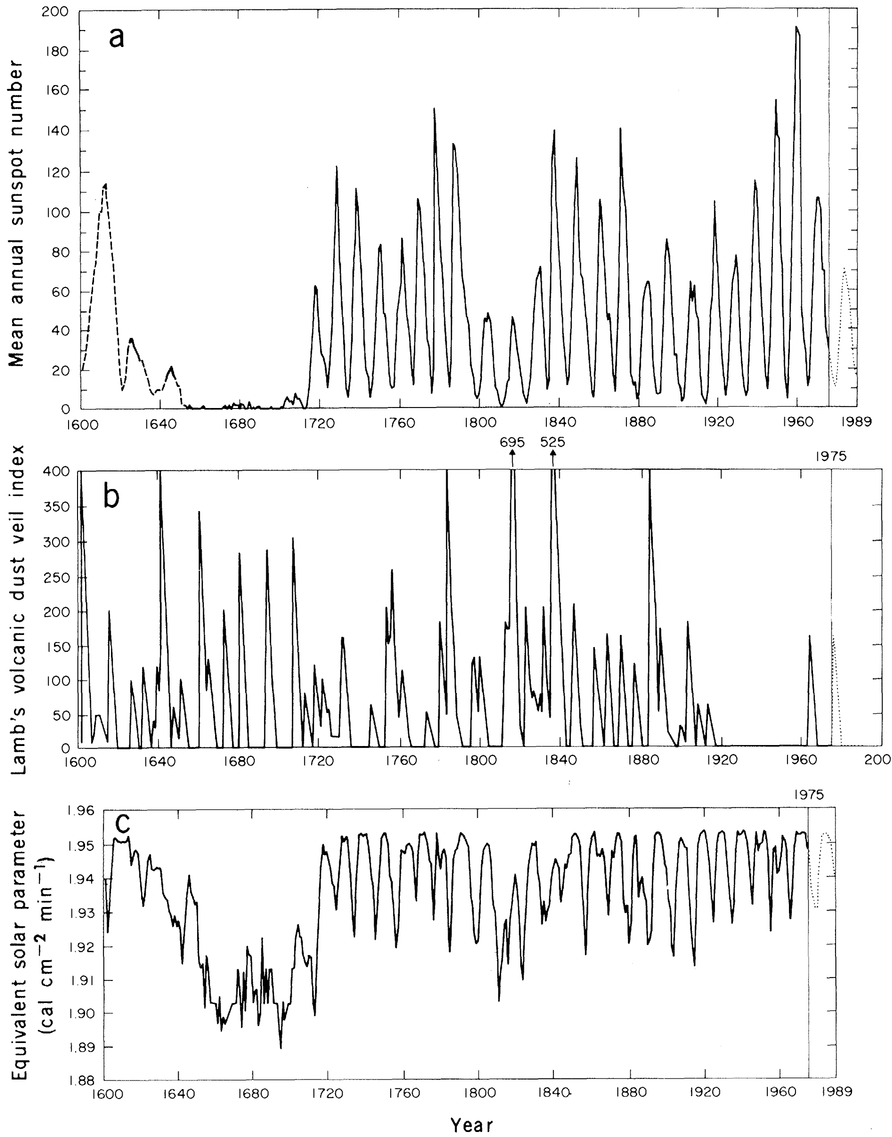

Fig. 1. Input forcing to the model calculations. (a) Mean annual sunspot (Wolf) numbers versus time (see text for sources). (b) Volcanic dust veil index of Lamb (*13*). (c) Combination of sunspot and dust variability into a time-varying record of solar parameter variation $S(t)$ (see text).

particles, the particle size distribution, the optical depth of the aerosol layer, the vertical distribution of the aerosol concentration, the vertical temperature and humidity profiles of the atmosphere, the zenith angle of the sun, and even the albedo of the lower atmosphere. It is possible that a particular dust veil could have opposite effects on stratospheric temperature at different latitudes or seasons.

In the past few years measurements of the composition and optical properties of stratospheric aerosols have been made, and very recently some of these have been used in horizontally averaged vertical column radiative models [see (*3*) for a discussion of climatic models] to estimate the influence of stratospheric aerosols on visible and IR radiation fluxes. Results of Coakley and Grams (*15*) and Harshvardhan and Cess (*17*) suggest that while IR effects tend to offset the surface cooling effect of a dust veil, the cooling effect is dominant. Therefore, we consider that our attempt to include the effects of dust veils in our forcing function $S(t)$ by an equivalent decrease in solar parameter $\Delta S_D(t)$ is a reasonable first-order parameterization. However, we have included this somewhat lengthy discussion of possible offsetting mechanisms to emphasize that such a simple parameterization may not be valid for all volcanic dust veils or where conditions are not globally averaged. Furthermore, the dynamical response of the stratosphere to aerosol-induced changes in its temperature structure could produce alterations to stratospheric motions that might have (positive or negative) feedback effects on the temperature structure of the lower atmosphere. We suspect that such feedback effects would be secondary to the radiative effects, but point out that our simple energy balance modeling approach does not include them.

Combining ΔS_s and ΔS_D we have

$$S(t) = \Delta S_s(t) + \Delta S_D(t) + S_0 \qquad (2)$$

where S_0 is for $N = 0$. The total effect $S(t)$, shown in Fig. 1c, is used as input data to the climate model.

Climate Model: Sensitivity to Energy Inputs

The sensitivity β_s of the global surface temperature to changes in solar parameter is defined as

$$\beta_s = S_0 \frac{\partial T_s}{\partial S} \qquad (3)$$

Various values for β_s can be obtained by using different physical and mathematical models to compute the relationship between T_s and S. The simplest approach, however, is to use not T_s but the planetary radiative equilibrium temperature T_p. Then the planetary radiation balance relation

$$\sigma T_p{}^4 = \frac{S}{4}(1 - \alpha)$$

where α is the earth's albedo and σ is the Stefan-Boltzmann constant, can be used to estimate the sensitivity

$$\beta_p = S_0 \frac{\partial T_p}{\partial S}$$

For mean earth conditions ($\alpha \approx 0.3$ and $T_p \approx 255°$K), $\beta_p \approx 65°$K. That is, a 1 percent decrease in S would lower T_p by 0.65°K. But, the global surface temperature T_s is about 287°K, and its sensitivity to changes in S depends on the changes in absorbing gases in the earth's atmosphere that might occur simultaneously with changes in T_s. In the one-dimensional radiative-convective model of Manabe and Wetherald (*18*) it is assumed that the relative humidity of the earth's atmosphere is nearly constant, and this assumption leads to an estimate $\beta_s \approx 120°$K, nearly double the estimate for β_p (see appendix).

If the positive feedback effect of ice, temperature, and albedo were included β_s could be increased by as much as a factor of 4, and if negative climatic feedbacks were included it might be reduced severalfold (*1, 3*). However, since the uncertainties in the present state of the art cannot resolve even the algebraic sign of all improperly accounted for climatic feedback mechanisms, it is sufficient for our purposes to use the order of magnitude estimates obtainable from a simple global energy balance formula

$$R \frac{\partial T_s}{\partial t} = \frac{S}{4}(1 - \alpha) - F_{IR}{}^{\uparrow}(T_s) \qquad (4)$$

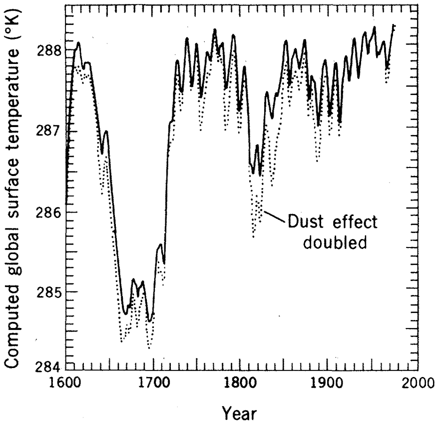

Fig. 2. Global surface temperature computed by the climate model, Eq. 4. The solid curve is for the nominal case where $S(t)$ is given by Fig. 1c, and the dotted curve is obtained by doubling the dust effect while leaving the sunspot effect unaltered.

where R is a planetary thermal inertia coefficient and $F_{IR}{}^{\uparrow}$ is the outgoing IR radiation flux to space written as a function of T_s. An empirical formulation for $F_{IR}{}^{\uparrow}$ derived by Budyko (*19*) and used here is

$$F_{IR}{}^{\uparrow}(T_s) = a + b(T_s - 273) \text{ cal cm}^{-2} \text{ min}^{-1} \qquad (5)$$

where, in these units, $a = 0.289$ and $b = 2.08 \times 10^{-3}$. The coefficient R merely scales the surface temperature response to changes in S, and is chosen on the basis of a water planet with about a 75-m mixed layer (*20*). A simple-centered finite difference solution to Eq. 4 gives

$$T_s(t + \Delta t) = \left(\frac{1}{\frac{R}{\Delta t} + \frac{b}{2}}\right) \left\{ T_s(t)\left(\frac{R}{\Delta t} - \frac{b}{2}\right) + \left(\frac{1 - \alpha}{4}\right)\frac{1}{2} \left[S(t + \Delta t) + S(t)\right] - a \right\} \qquad (6)$$

where Δt is a 1-year time step.

The sensitivity to changes in S of the asymptotic steady-state temperature from Eq. 4 is $\beta_s = 152°$K, which is close to the Manabe-Wetherald value of 120°K (*21*). In the appendix we present an analysis of these temperature-energy sensitivity coefficients, β, and the role of climatic feedback mechanisms in modifying β.

The solution to Eq. 6 with $S(t)$ as input forcing is shown in Fig. 2, with initial conditions T_s (t = A.D. 1600) = T_0, where T_0 is the equilibrium steady-state value of T_s corresponding to $S = S_0$. The solid curve in Fig. 2 shows the temperature evolution for the "nominal case" in which $S(t)$ is as given in Fig. 1c. The dotted curve in Fig. 2 is for a doubling of the dust veil effect while the sunspot influence is left as before. Since much of the sunspot data before 1650 is interpolated between observations, the temperatures in Fig. 2 should also be regarded as interpolations during this period.

Discussion of Results

Despite the uncertainties in the observational records of global surface temperatures, especially before 1880, and the improper modeling or omission of climatic feedback mechanisms, the calculated curves (Fig. 2) are similar in some general features to a number of historical records (Fig. 3, a to d) (*22*). Particularly striking are the "little Ice Age" temperature minimum between 1650 and 1700, the subsequent rise in temperature until about 1800, and the fall and rise to 1880. At this point we can compare Fig. 2 to more accurate instrumental records, such as the well-known work of Mitchell (*23*) (Fig. 3e). Mitchell's records show that not long after the eruption of Krakatoa in the Sunda Strait in 1883, the temperature began to rise; it continued to rise until the middle of the 20th century, after which it fell again (or leveled off in Mitchell's Southern Hemisphere curve). The rise in temperature after 1890 is followed in Fig. 2. The Lamb dust veil index (Fig. 1b) shows that there was negligible volcanic activity between 1915 and 1963 (when Mount Agung erupted). Thus, the "explanation" of the temperature drop indicated in Fig. 2 immediately after 1950 is to be found in Fig. 1a, which shows very high sunspot activity and thus a reduction in S.

If the dust effect is doubled the rise in temperature from 1890 to about 1950 is more pronounced, as is the subsequent cooling between 1963 and about 1968. We doubled the dust effect to show the relative importance of dust and sunspots in the computed temperature history. Suppose, for example, that Kondratyev and Nikolsky's relation was qualitatively correct but that the magnitude of the difference in S for $N = 0$ and $N = 80$ was considerably less than 2.5 percent of S (*8*). This would amplify the relative effect of dust, although it would reduce the magnitude of the computed temperature variations considerably, diminishing the computed cooling after 1950 as well as reducing the little Ice Age cooling before 1700. However, we could then assume that the ice-albedo-temperature positive feedback mechanism was operative in Eq. 4, which would increase β_s significantly and restore the magnitude of the temperature variations. Although we recognize that in the present state of climatic theory β_s can only be estimated within a wide range about the "no-feedback" value of 150°K (and thus we cannot rule out the possibility that $\beta_s > 150°K$), we are hesitant to try to improve the fit of our calculations to the observations by "tuning" the model—that is, using various combinations, within the uncertainties in present knowledge, of $S(N)$, β_s, and scaling factors for ΔS_D versus $S(t)$. With so many parameters to vary one could fit almost anything to anything, and our chief purpose here is to try to show the consequences for computed surface temperatures of accepting a set of assumptions and observations already in the literature.

Returning to Fig. 2, although a best-fit curve drawn through either the solid or the dotted lines would (even with the present assumptions) produce a curve strikingly similar to Mitchell's observations (Fig. 3e), we have not drawn such a curve in order to emphasize the high degree of short-term fluctuation that appears on our simulation but does not seem to show up on this observational record. Some implications of this discrepancy are discussed in the next section.

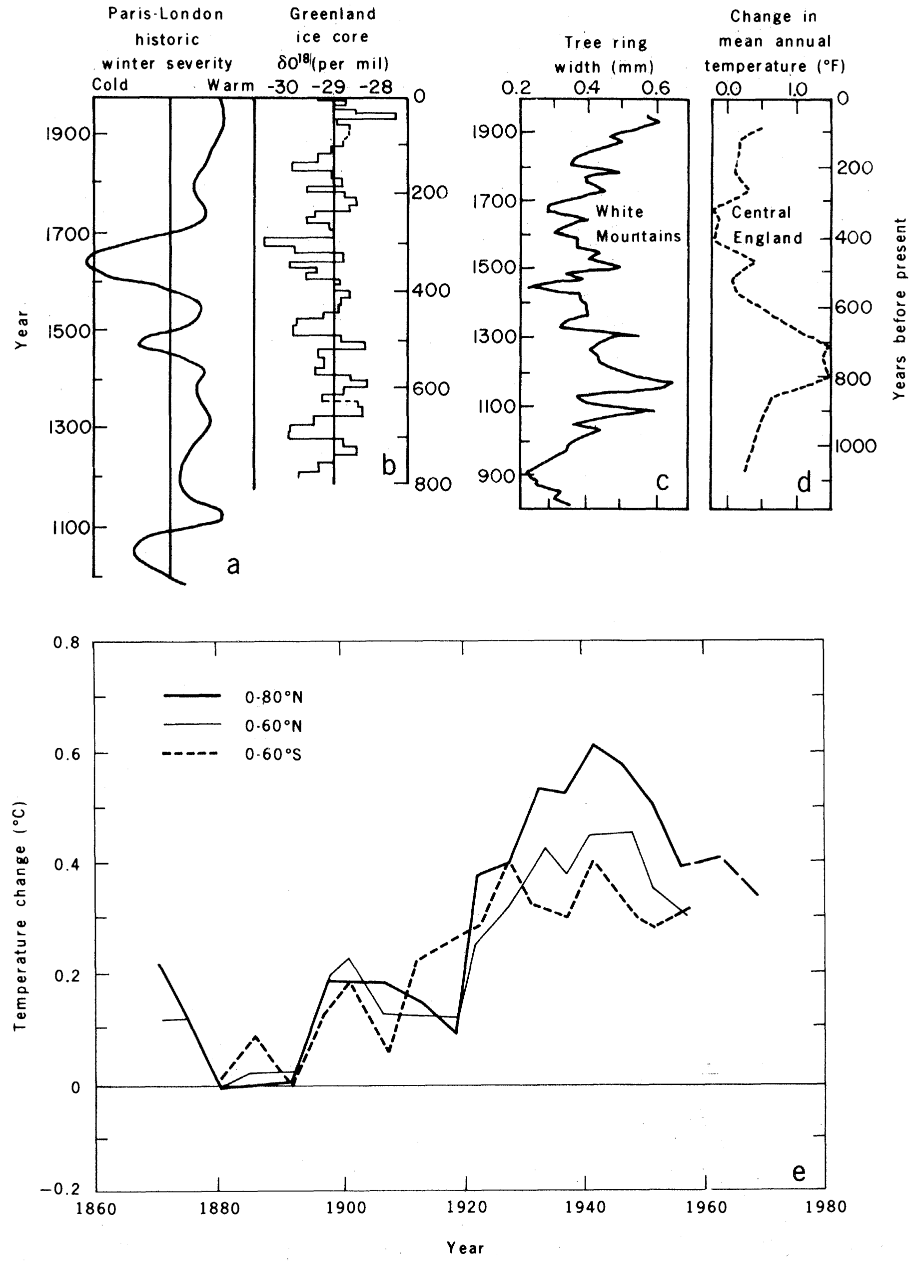

Fig. 3. Measurements of the earth's surface temperature (or records related to temperature). (a) Fifty-year moving average of a relative index of winter severity compiled for each decade from documentary records in the region of Paris and London. (b) Record of $\delta^{18}O$ values preserved in the ice core taken from Camp Century, Greenland. (c) Records of 20-year mean tree growth at the upper treeline of bristlecone pines, White Mountains, California. At these sites tree growth is limited by temperature, with low growth reflecting low temperature. (d) Fifty-year means of observed and estimated annual temperatures over central England. (e) Instrumental records of Mitchell (*23*).

Another interesting feature of Fig. 2 is the rise in computed global surface temperature beginning about 1968, since there is widespread belief that the earth's surface temperature has been cooling since the 1950's. Thus, either (i) the sunspot–volcanic dust mechanism we have been using is incomplete or wrong, (ii) the "cooling trend" is not global (as are the calculations on Fig. 2), (iii) some other mechanism has been operating in addition to those we have modeled, (iv) the sensitivity of our model to changes in $S(t)$ is wrong, (v) our thermal coefficient R is too low, or (vi) we don't really have a statistically significant record of global surface temperatures with which to compare Fig. 2.

Finally, we used Sleeper's extrapolation (*12*) of sunspot activity to the year 1989 to "forecast" a temperature pattern for a volcano-free period [except for the eruption of Mount Fuego in Central America in late 1974, whose effect on $S(t)$ is assumed equivalent to that of Mount Agung]. It is well known that human input of carbon dioxide into the atmosphere is increasing exponentially and, using Broecker's (*24*) table for the projected CO_2 effect to the year 1989, we find that CO_2 warming dominates the surface temperature patterns soon after 1980, but that superimposed on that warming is a very strong temperature minimum between 1976 and 1981. These results are shown in Fig. 4, where the solid line is the same as the solid line on Fig. 2 up to 1975, but because of the expanded scale shows the short-term oscillations more clearly, and the dotted line includes the CO_2 effect (*25*). More thorough discussions of the uncertainties in present estimates of CO_2 effects on climate are given in (*26*).

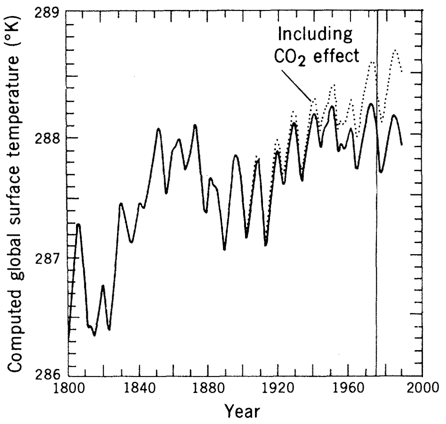

Fig. 4. Global surface temperature computed by the climate model. The solid line is for the nominal case given by Fig. 1c, and the dotted curve includes the added effect of increasing atmospheric CO_2 (*24*). The calculations for 1975 to 1989 are not based on actual observations, of course, but are extrapolations (see text) given only to show the consequences for a climatic model of accepting a set of assumptions about possible external causes of climatic change.

Conclusions and Perspective

Bryson, among others, has often argued that the rise in temperature to about 1945 could be correlated with a lull in volcanic activity, but that the subsequent fall in temperature might be related to anthropogenic dust increases, Bryson's so-called human volcano (*27*). However, while the results in Fig. 2 are consistent with the first part of his hypothesis, they also show that the downturn in temperature after 1950 can be explained in terms of the extremely high sunspot numbers and Kondratyev and Nikolsky's relation between the solar parameter and sunspot numbers (Eq. 1), although the magnitude of our computed global cooling is rather small in any case. On the other hand, there could be longer-term trends in the solar parameter which we have excluded here, and a host of other possibilities could be invoked to explain the temperature drop, including a spectrum of internal causes. It is difficult to test our results shown in Fig. 2 against observations because no statistically significant *global* record of temperature back to 1600 has been constructed. Thus, the results in Fig. 2 are, at best, no more than in agreement with the most general features—the very cool period before 1700 and the warming to 1950—that seem to recur on nearly all of the few temperature reconstructions we have seen. Finally, the possibility exists that the suggestive correspondence between our computed results and these features of the observed general patterns of temperature variations in the Northern Hemisphere back to 1600 occurred by chance.

We have played down computation of a correlation coefficient between our results and a 400-year record of global surface temperature observations because we do not know what such a global surface temperature record should look like. The four curves we have referred to, Fig. 3, a to d, are not global temperature records, but only local (or regional) time series. In fact, with the possible exception of the recent part of Fig. 3d, they are not even temperature records, but observations of quantities related to temperature. What is the global surface temperature history over the past 400 years? We believe that this question has not been answered with sufficient accuracy to permit much confidence in any correlation between the record and our computations, particularly for the Southern Hemisphere. Nevertheless, all of the records in Fig. 3 (and several others we have seen for the Northern Hemisphere) seem to have a few common features, most notably the strong temperature minimum before 1700 and the rise in temperature through the middle of the 20th century. Since our computed results also evidence these qualitative features, we are motivated to look deeper, both observationally and theoretically.

It will be particularly important in the future to compare the time spectrum of the computed global surface temperature with observed global surface temperature spectra, keeping in mind that the computed temperatures are truly global averages, while observational records are seriously limited by sparsity of good data over vast regions of the earth's surface. The available observational data are subject to errors at individual stations, and statistical sampling considerations imply that averages of real data incorporate statistical noise levels. Thus, the apparent absence of 11-year fluctuations in observational records of T_s comparable to those computed using Eq. 2 need not necessarily be a refutation of the validity of Eq. 2; it could simply be an indication that the amplitude of the instrumental and sampling errors in a global average taken from a limited number of stations is comparable to the amplitude of computed 11-year fluctuations. In any case, the relative magnitudes of the power spectra and the correlation between both observed and computed time histories need to be evaluated (*28*). Furthermore, it is possible that the earth-atmosphere-ocean system possesses a longer thermal relaxation time than we have assumed here, and this could be an alternative explanation for the smoothing out of short-term power in the observations.

The causes of climatic change are far from explained by this simple exercise; however, the feasibility of external climatic influences contributing significantly to long-term temperature trends is too striking to allow further delay in obtaining a continuous record of high-precision extraterrestrial measurements of solar variability. If a long-term record of external forcing could be obtained (*29*), and if this input were then used in conjunction with a long-term climatic record, the sensitivity, β_s, of the climatic system to external forcing could be obtained implicitly [in much the same way that a "transfer function" can be inferred from knowledge of input and output functions by classical methods of systems analysis (*30*)]. Such a finding would be of great help to those trying to unravel (or at least bound) the response of the real climatic system to changes in external inputs by use of climatic models. Moreover, reducing the uncertainty of β_s has, as argued by Schneider (*31*), benefit beyond its mere scientific interest since β_s gives an indication of how urgent it is for society to deal with the growing burden of thermal pollution and atmospheric carbon dioxide—external climatic forcing functions that are increasingly competing with the natural factors that cause climatic change.

Appendix: Temperature-Energy Sensitivity Analysis

Equation 4 represents the time-dependent energy balance for the earth-atmosphere system. To first order in T, $F_{\rm IR}$ can be written in the form

$$F_{\rm IR} = a_i + b_i T_i \tag{7}$$

When i = p (for planetary radiative equilibrium conditions), $a_i = 0$, and $b_i = \sigma T_p^3$, and when i = s (for surface conditions), $a_i = -0.279$ and $b_i = 2.08 \times 10^{-3}$, as in Eq. 5.

To derive a relationship between the sensitivity parameters β_p and β_s we rewrite Eq. 4 for equilibrium conditions (that is, $d/dt \longrightarrow 0$) and include Eq. 7

$$\frac{S}{4}\ (1-\alpha) = a_i + b_i T_i \tag{8}$$

Differentiating Eq. 8 by T_i, rearranging terms, and multiplying by S_0 gives

$$S_0 \frac{dT_i}{dS} = \frac{1-\alpha}{4}\left(\frac{1}{b_i + T_i \frac{db_i}{dT_i}}\right) S_0 \qquad (9)$$

which is equal to β_i, as in Eq. 3. For i = p Eq. 9 reduces to

$$\beta_p = \frac{1-\alpha}{4}\left(\frac{1}{4\sigma T_p^3}\right) S_0 \qquad (10)$$

and for i = s Eq. 9 becomes

$$\beta_s = \frac{1-\alpha}{4}\left(\frac{1}{b_s}\right) S_0 \qquad (11)$$

Thus

$$\beta_p/\beta_s = \frac{1}{4}\,\frac{b_s}{\sigma T_p^3} \qquad (12)$$

For present conditions $\sigma T_p^3 \approx 1.2 \times 10^{-3}$ cal cm^{-2} min^{-1} and b_s is empirically determined by Budyko to be 2.08×10^{-3} in these units. Thus

$$\beta_p/\beta_s = 0.43$$

which is indicative of the fact that the empirical coefficient b_s implicitly includes the positive feedback "greenhouse" effect of increased atmospheric water vapor that is expected to accompany increased temperatures (*5*). If other climatic feedback processes were included in this analysis, they could be approximated to first order by the coefficient λ, which could be combined with Eqs. 4 and 7 to yield (dropping the subscript i)

$$R\frac{\partial T}{\partial t} = -(b + \lambda)T + Q \qquad (13)$$

where Q amalgamates all inhomogeneous constant terms. If $b + \lambda > 0$, then the solution to Eq. 13 is bounded. If $\lambda > 0$ the new equilibrium value of T resulting from a perturbation in S will be reduced (negative feedback) relative to the case of $\lambda = 0$, but if $\lambda < 0$ a perturbation in S will result in an amplification (positive feedback) of the response in T relative to the $\lambda = 0$ case. If $\lambda + b < 0$ the solution to Eq. 13 becomes unbounded and exhibits unstable behavior (such as a transition to an ice-covered earth). However, it is not yet known to what extent physical processes not included in our simple energy balance equation (Eq. 4) would amplify or dampen the response of T to a perturbation in energy input (*1, 3, 5*). Thus, a primary task of climate theory still remains: determine λ.

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8. We use the Kondratyev-Nikolsky result for our calculations, but this should not be interpreted as indicating our belief in its correctness. We are not in a position to make such a judgment, but we can compute the consequences in a global climate model of accepting the relationship as valid. Furthermore, it has been suggested that even if these $S(N)$ measurements are relatively accurate, they may really indicate not a variation of S with N, but a variation of upper atmospheric transmission with N, presumably related to the effects of sunspots on the geomagnetic field; the geomagnetic field modulates the flux of galactic cosmic rays, which can affect certain particles and gases in the upper atmosphere. One proponent of such a theory, W. O. Roberts, commented (on an early draft of this article) that "some authors have suggested that this sunspot number versus radiation relationship is due to solar effects on atmospheric transmission with the form of effect as suggested by Kondratyev and Nikolsky. For your modeling purposes this probably doesn't matter," since the variation in transmission would be equivalent to a variation in solar parameter as far as the climate model is concerned.
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20. The thermal inertia coefficient for a 75-m mixed layer is $R = 7500$ cal cm^{-2} °K^{-1} [W. D. Sellers, *Physical Climatology* (Univ. of Chicago Press, Chicago, 1965), p. 242]. Thus, the thermal relaxation time constant of the simple model, Eq. 4, is $\tau = (R/b) = 7500/(2.08 \times 10^{-3})$ minutes $\approx$ 6.9 years.
21. The original Manabe-Wetherald result (*18*) for β_s (= 120°K) was computed with a one-dimensional climate model. A value closer to $\beta_s \approx 200$°K has been computed by these authors using a three-dimensional general circulation model (S. Manabe and R. T. Wetherald, in preparation), as discussed by T. Gal-Chen and S. H. Schneider (*Tellus*, in press).
22. Figure 3, a to d, the climatic records of the past 1000 years, are from: U.S. Committee for the Global Atmospheric Research Program, *Understanding Climatic Change: A Program for Action* (National Academy of Sciences, Washington, D.C., 1975). The original sources are: (Fig. 3a) H. H. Lamb, in *World Survey of Climatology,* Vol. 2, *General Climatology*, H. Flohn, Ed. (Elsevier, New York, 1969), pp. 173–249; (Fig. 3b) W. S. Dansgaard, S. J. Johnsen, H. B. Clausen, C. C. Langway, Jr., in *The Late Cenozoic Glacial Ages*, K. Turekian, Ed. (Yale Univ. Press, New Haven, Conn., 1971), pp. 37–56; (Fig. 3c) V. C. LaMarche, *Science* **183**, 1043 (1974); and (Fig. 3d) H. H. Lamb, *Geogr. J.* **132**, 183 (1966).
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25. The estimates we use for surface temperature increase with increasing CO_2 are from a simple one-dimensional climate model (*18*), and could be altered by the effects of unknown climatic feedback mechanisms.
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28. A preliminary analysis of the correlation between our computed $T_S(t)$ and a dozen long-term temperature records yields the highest value of correlation coefficient ($\approx$ .20) when $\Delta S_S(t)$ is halved and $\Delta S_D(t)$ is doubled. However, none of these instrumental records goes back further than 1698, nor do they constitute a globally averaged record. A correlation coefficient of about 0.5 is obtained, however, between the solid line on Fig. 2 and Fig. 3b.
29. Commenting to us on the importance of obtaining a "valid data base" from which to investigate physical hypotheses of climatic change, H. E. Landsberg remarked that "one reliable observation is worth a thousand models and a million speculations." We are inclined to agree, but nevertheless offer our calculations in the hope that they will encourage those contemplating such measurements to proceed with energy. In this connection, we wish to repeat a comment made privately to us by K. Ya. Kondratyev: "Our conclusions about the interrelationship between the solar 'constant' and Wolf number were made on the basis of the results of about 20 balloon flights. Although we failed to discover any instrumental errors in our results and also think that the error of extrapolation from the altitude of about 30 to 33 km is much smaller than 1 to 2 percent, we cannot believe that our results have climatological significance. They may reflect the existence of short-term 'variation' of the solar 'constant.' Our main conclusion is the need for direct long-term monitoring of the solar 'constant.' "
30. C. R. Wylie, Jr. [*Advanced Engineering Mathematics* (McGraw-Hill, New York, 1960)] discusses the methodology of systems analysis.
31. S. H. Schneider (with L. E. Mesirow) [*The Genesis Strategy* (Plenum, New York, in press)] discusses the relationship between climatic change and the "world predicament."
32. We are grateful to W. O. Roberts, whose frequent pleas for quantitative, physical modeling of possible solar-terrestrial mechanisms motivated us to undertake this study. We also deeply appreciate the prepublication sunspot data provided to us by J. A. Eddy, and comments on an early draft of the article by R. E. Dickinson, W. W. Kellogg, K. Ya. Kondratyev, H. E. Landsberg, and J. M. Mitchell. The National Center for Atmospheric Research is sponsored by the National Science Foundation.