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SOLAR-DRIVEN CLIMATIC VARIABILITY ON EARTH

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FINAL REPORT

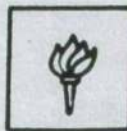
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## APPLICATION OF SOLAR MAX ACRIM DATA TO ANALYSIS OF SOLAR-DRIVEN CLIMATIC VARIABILITY ON EARTH

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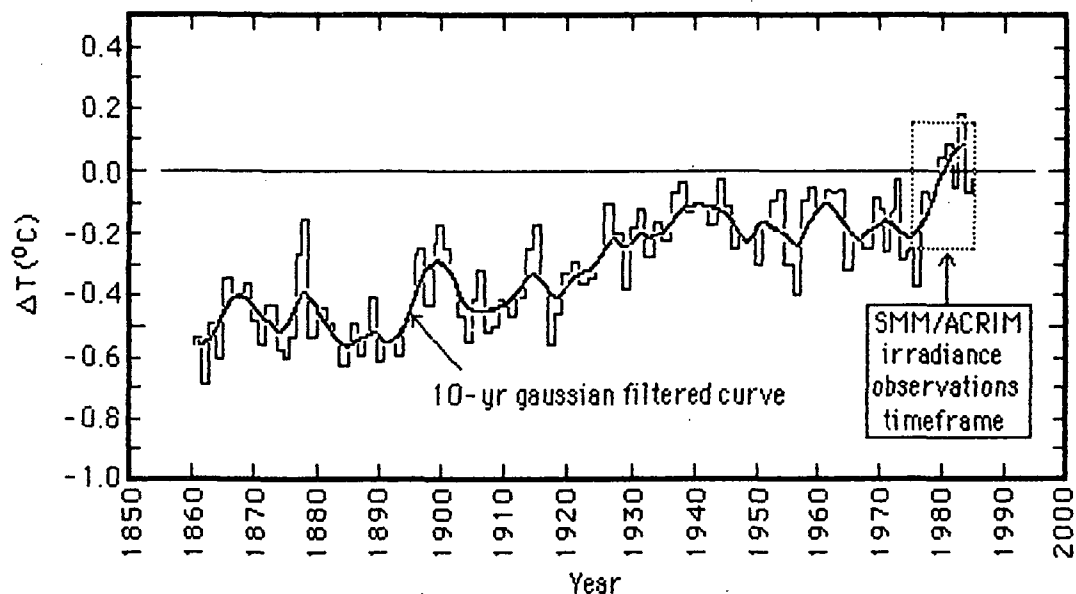
Abstract. Terrestrial climatic effects associated with solar variability have been proposed for at least a century, but could not be assessed quantitatively owing to observational uncertainties in solar flux variations. Measurements from 1980-1984 by the Active Cavity Radiometer Irradiance Monitor (ACRIM), capable of resolving fluctuations above the sensible atmosphere  $< 0.1\%$  of the solar constant permit direct albeit preliminary assessments of solar forcing effects on global temperatures during this period. We computed the global temperature response to ACRIM-measured fluctuations from 1980-1985 using the NYU transient climate model including thermal inertia effects of the world ocean; and compared the results with observations of recent temperature trends. Monthly mean ACRIM-driven global surface temperature fluctuations computed with the climate model are an order of magnitude smaller, of order  $0.01^{\circ}\text{C}$ . In contrast, global mean surface temperature observations indicate an  $\sim 0.1^{\circ}\text{C}$  increase during this period. Solar variability is therefore likely to have been a minor factor in global climate change during this period compared with variations in atmospheric albedo, greenhouse gases and internal self-induced oscillations. It was not possible to extend the applicability of the measured flux variations to longer periods since a possible correlation of luminosity with solar annual activity is not supported by statistical analysis. The continuous monitoring of solar flux by satellite-based instruments over timescales of 20 years or more comparable to timescales for thermal relaxation of the oceans and of the solar cycle itself is needed to resolve the question of long-term solar variation effects on climate.

## INTRODUCTION

Global climatic change is thought to arise primarily from four factors (Hoffert and Flannery, 1985): (i) variations in solar luminosity; (ii) variations in planetary albedo associated with changing amounts of aerosols or dust, surface reflectivity and cloudiness distributions; (iii) variations in amounts of infrared absorbing gases in the atmosphere ( $H_2O$ ,  $CO_2$ ,  $O_3$ , and various trace gases); and (iv) internal nonlinear feedbacks between elements of the climate system. This report will focus on what can be learned from direct satellite measurements of solar irradiance fluctuations from 1980-1984 about the contribution of solar variability to the global surface temperature history of the Earth.

## GLOBAL TEMPERATURE HISTORIES AND SOLAR VARIABILITY

Considerable effort has been expended in recent years to describe the temperature history of the Earth from instrumental records over the past century. Figure 1, after Wigley *et al.* (1986), shows one of the most recent



**Figure 1 .** Global mean surface temperatures: 1861-1984 (Wigley *et al.*, 1986).

reconstructions of surface temperature anomalies (relative to the year 1980) extending 125 yr back in time. The yearly averaged data and the

10-yr gaussian filtered (smoothed) curve are based on area-weighted averages of both land and sea records. Sea Surface Temperature (SSTs) are from the corrected Comprehensive Ocean Atmosphere Data Set (COADS) including SSTs back to the sailing ship era corrected for the transition from the "bucket" to the water inlet temperatures of steamships. 1980-1984 temperatures are from NOAA observations adjusted for compatibility with earlier data.

The dotted box in Figure 1 indicates the timeframe when direct irradiance measurements from the ACRIM instrument onboard the Solar Maximum Mission satellite are available (Willson, 1985). As discussed shortly, such space-based irradiance observations are necessary for an accurate assessment of solar variation effects on surface temperature. This temperature data trends upward at a rate of  $\sim 0.5$  °C/century, perhaps associated with the fossil fuel greenhouse effect, but it also exhibits considerable variability on interannual to 10-yr timescales. The main question addressed here is the relative contribution of solar variability to the variance of this signal.

Several modeling studies have appeared in recent years which aim at explaining such surface temperature records in terms various driving mechanisms (Schneider and Mass, 1975; Robock, 1978, 1979; Hansen et al., 1981; Gilliland, 1982; Gilliland and Schneider, 1984). All of these to some extent allow for a significant effect from solar luminosity variations. Paradoxically, the contribution to the temperature signal of variations in the "solar constant" -- superficially, the most easily understood of these mechanisms -- remains controversial. Despite longstanding proposals that solar variability had a significant impact on climate over the past 100 years, some recent assessments dispute this strongly (Pittock 1978, 1983). In a recent Soviet study Budyko et al. (1986) claim carbon dioxide and other greenhouse gases, visible albedo and internal variability are the dominant factors in the hundred year record. Indeed, they assert categorically that, "hypotheses about an essential influence of all other external natural factors [including solar variability] are either explicitly untrue or proved by nothing". Interestingly, direct measurements of solar irradiance from satellites which might resolve the issue one way or another have not yet been incorporated in transient climate models.

Surface-based radiometers can only measure variations in the solar constant to an accuracy of 1-2% owing to uncertainties in atmospheric scattering and absorption (Newkirk, 1983). For a typical climate sensitivity parameter of (Hoffert and Flannery, 1985)  $\beta \equiv S_0 \partial T / \partial S \approx 100 \text{ }^\circ\text{C}$ , an uncertainty of  $\Delta S / S_0 \sim \pm 1\text{-}2\%$  corresponds to an uncertainty in the effect of solar variations on global temperature anomalies of  $\Delta T \approx \beta \Delta S / S_0 \approx \pm 1\text{-}2 \text{ }^\circ\text{C}$ . This is significantly greater than the variance of the instrumental global temperature record from all physical mechanisms over the past 100 years (Jones et al., 1982, 1986), indicating ground-based measurements have inadequate resolution to assess the solar fluctuation effects on climate. Present-day radiometer technology can measure solar irradiance with to a precision of  $\pm 0.002\%$ , and a long-term accuracy better than 0.1% (Willson, 1984). This is the range needed for solar variability studies, but it is necessary to get these detectors above the sensible atmosphere to employ their capabilities for long-term monitoring. Applications to understanding climatic change have therefore been a major motivation of recent solar flux monitoring programs from spacecraft.

Recent years have seen the beginnings of extraterrestrial long-term solar monitoring programs, starting with the Earth Radiation Budget (ERB) instruments onboard the NIMBUS 6 and 7 satellites (Hickey et al., 1981), and more recently with the Active Cavity Radiometer Irradiance Monitor (ACRIM) onboard the Solar Maximum Mission (SMM) satellite (Willson et al., 1981; Willson and Hudson, 1981; Willson, 1984).

### **SOLAR VARIABILITY TIMESCALES**

Solar irradiance fluctuations are conveniently classed by their characteristic timescale  $\tau_s$  as (Newkirk, 1983): short-term ( $1 \text{ day} < \tau_s < 1 \text{ yr}$ ), solar cycle ( $1 \text{ yr} < \tau_s < 11 \text{ yr}$ ), long-term ( $11 \text{ yr} < \tau_s < 500 \text{ yr}$ ), secular ( $500 \text{ yr} < \tau_s < 10^5 \text{ yr}$ ) and solar evolutionary ( $10^5 \text{ yr} < \tau_s < 10^{10} \text{ yr}$ ). The extent to which these irradiance fluctuations influence terrestrial climate depends the thermal response time  $\tau_r$  of the Earth's climate system compared to  $\tau_s$ . Surface temperature response times of the Earth are dominated by the thermal inertia of the upper ocean ( $4 \text{ yr} < \tau_r < 100 \text{ yr}$ ; Hoffert et al., 1980). When  $\tau_s \ll \tau_r$  irradiance fluctuations

absorbed by the system are strongly damped by oceanic thermal inertia; they occur too fast to be felt by the climate system unless their amplitude is very large. When  $\tau_s \gg \tau_r$  the system is in a "slowly-varying" near steady state which changes on the same timescale as the forcing  $\tau_s$ .

The 100 year instrumental global temperature record embraces short to long period irradiance fluctuations, and requires a transient atmosphere/ocean climate model to include effects of oceanic thermal inertia (Hoffert and Flannery, 1984). These models normally require as drivers solar irradiance time series extending beyond a solar cycle to fully analyze the climate system's response. Since the era of space-based monitoring of solar irradiance is scarcely a decade old, it might seem at first glance that transient climate analysis is premature. We will show however that measurements made thus far contain enough information to set limits on the surface temperature response to the irradiance fluctuation effect in the 1980-1984 timeframe.

#### **SPACE-BASED IRRADIANCE MEASUREMENTS AND SOLAR ACTIVITY**

Apart from short-duration NASA sounding rocket and Skylab experiments (Eddy, 1979), continuous data sets of solar flux measured from above the atmosphere are mainly from the NIMBUS 6 and 7 ERB satellite experiments, launched in mid-1975 and late-1978, respectively; and from the Solar Maximum Mission ACRIM instrument on orbit since early 1980 (Willson, 1984). Some problems with other instruments on "Solar Max" were corrected in orbit in April 1984 by astronauts from the ill-fated Space Shuttle Challenger, but a fairly continuous ACRIM record exists from 1980 to date.

The ERB/NIMBUS 6 was a simple detector comprised of a blackened flat plate attached to a thermopile incapable of electrical self-calibration: It relied on prelaunch calibrations to relate its observations to SI units ( $\text{W}/\text{m}^2$ ), and had too wide a field of view to resolve the solar disk to better than  $4^\circ$ . Willson (1984) estimates ERB/NIMBUS 6 measurement uncertainties of  $\Delta S/S_0 \sim 0.2\%$  -- too large for reliable estimates of irradiance fluctuation effects on climate. The ERB radiometer on the follow-on NIMBUS 7 launched in late 1978 is a superior detector capable of



self-calibration. But the most accurate irradiance monitoring in space to date is from the self-calibrating SMM/ACRIM, with a long-term accuracy estimated by Willson (1984) as  $\Delta S/S_0 < \pm 0.1\%$ . In a flight test, three ACRIM sensors agreed to within 0.04% of their average result. The precision of the data, about  $\pm 0.002\%$ , is higher than its accuracy. The time resolution of ACRIM raw data samples ( $< 1$  s) is much shorter than what is required for climate analysis, so some level of averaging is needed for data analysis.

While speculations on sunspot effects on irradiance climate have been made for hundreds of years (Lamb, 1972), the SMM/ACRIM data permit realistic assessments for the first time of correlations between irradiance and solar surface features observable from the Earth's surface (Hoyt and Eddy, 1982; 1983). The most studied features are sunspots -- dark, cool regions on the sun's visible surface, or photosphere, whose numbers have varied with an approximately 11.2 year cycle since they have been observed continuously by telescope since the early 17th Century (Eddy, 1979). Indices of sunspot activity include the so-called Wolf daily sunspot number,  $N_W$ , and the number of daily sunspot groups,  $N_G$ . The number of sunspots/group is of the order of 10 (Hoyt and Eddy, 1983);  $N_G \sim N_W/10$ . The Zurich sunspot number, which is dominated by the number of sunspot groups, is also used.

The various sunspot indices tend to trend together; approaching a maximum when 100 or more individual spots are found on a solar hemisphere at one time; and a sunspot minimum, or quiet sun, when few or none are seen for months at a time. The last sunspot maximum was in 1980 -- hence the term Solar Maximum Mission (SMM) for the sun-observing satellite launched that year. It turns out to be important for assessing possible sunspot correlations that ERB/Nimbus 7 was monitoring irradiance two years before the 1980 maximum when ACRIM measurements began, after which an overlapping record is available.

In analyzing the early ACRIM data, Willson *et al.* (1981) focused on short-time solar irradiance fluctuations over the first 153 day period in 1980. The major new finding from early ACRIM data was that reductions in solar constant as much as  $\Delta S/S_0 \sim - 0.2\%$  were found over timescales of



5-8 days as sunspot groups passed over the solar disk. This short-term anticorrelation is opposite in sign to the usual assumptions made by climate modelers that long-term luminosity variations are positively correlated with sunspots (Robock, 1979). Physical models for the short-term irradiance deficit are based on the idea that the "dark" sunspots create a temporary a blockage emerging solar flux, which must be reradiated over timescales of a month or more (Hoyt and Eddy, 1982). We show next that short-term anticorrelations of irradiance with sunspot groups may reverse in sign on monthly timescales when the five year ACRIM record is used.

Figure 2 shows monthly averages of the first five years of ACRIM irradiance data. In contrast to the short-term anticorrelation of irradiance with the area of sunspot groups crossing its surface, the monthly mean ACRIM data trends downward along with sunspots since the sunspot maximum in 1980.

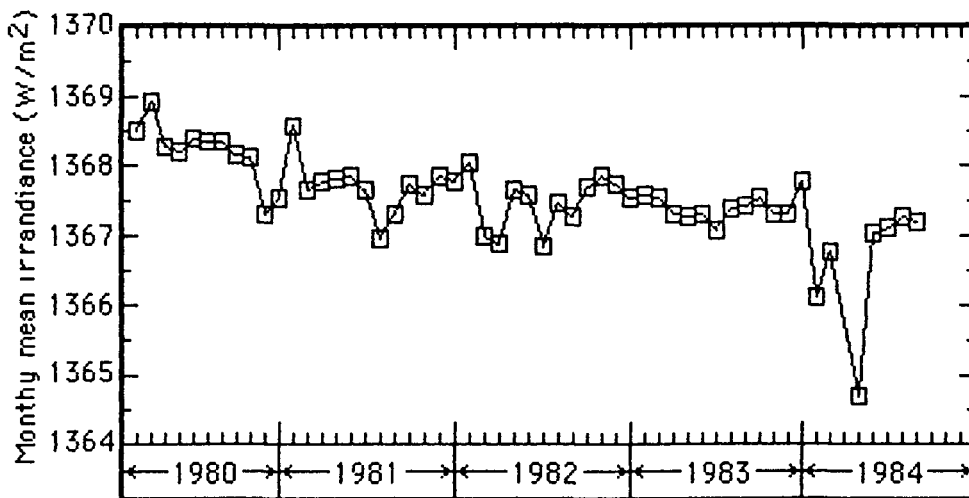


Figure 2 . SMM/ACRIM Irradiance Data : 1980-1984 (Willson, 1985)

Often sunspot numbers alone are often used in irradiance correlations for climate models. For example, Robock (1979) employed the positive correlation  $\Delta S/S_0 \sim + 0.0052 \langle N_W \rangle$  (%) to drive a climate model for the "Little Ice Age" in the northern hemisphere extending back to the Sixteenth Century, where  $\langle N_W \rangle$  is the Wolf sunspot number of the 11-year cycle

smoothed out . We now know however that such relations are based on surface irradiance observations of insufficient accuracy.

Other potentially relevant observables on the solar disk are available for the past 100 years from routine observations published by solar observatories. For example, the sunspot umbra is its dark, central core whose mean brightness is  $\sim 0.25$  of the surrounding photosphere; the penumbra a somewhat less dark region surrounding the umbra with a brightness some  $\sim 0.25$  that of the surrounding photosphere. The relative contrast (brightness - 1) of these zones are  $\sim - 0.25$  for the umbra and  $\sim - 0.75$  for the penumbra. The umbra and penumbra have sharp boundaries and are easily distinguished from each other and from the quiet photosphere. (Hoyt, 1979) has proposed on largely empirical grounds a possible correlation between the umbra/penumbra ratio and the historical northern hemisphere of Jones et al. (1982) surface temperature record from 1881 to 1980. Also distinguishable from the darker photospheric background are irregular, unusually bright patches, or faculae -- "anti-sunspots" emitting energy fluxes higher than the background levels of solar radiation. The mean facular contrast is typically  $\sim + 0.03$  (Hoyt and Eddy, 1982).

Based on corrected area-weighted contributions of light and dark areas on the photosphere, a correlation formula can be written for solar irradiance incorporating projected surface areas of the umbra and penumbra of sunspot groups,  $u_i$  and  $p_i$ , the facular area  $f$ , and a correction factor for photospheric limb darkening  $C(\Theta) = 0.36 + 0.84\cos \Theta - 0.20 \cos^2 \Theta$ , where  $\Theta$  is the angle between the radius vector to the central point of the sun and the line of sight to the spot group (Hoyt and Eddy, 1982):

$$\Delta S/S_0 = + 0.03 f - \sum_{i=1}^{N_G} C(\Theta)(0.75 u_i + 0.25 p_i)$$

This formula can in principle give a net brightening when facular emissions overwhelm the darkening effect of sunspot groups. But when Hoyt and Eddy (1982) applied it to corrected umbral, penumbral and facular areas observed over the past 100 yr spanning 10 solar cycles, the computed irradiance curve still showed minimums during sunspot maxima. It would be interesting if it could be shown unambiguously that an irradiance/solar

activity correlation exist which switches from negative to positive at some timescale associated with the turbulence solar photosphere.

Tables of solar observations from 1874 to 1981 (Hoyt and Eddy, 1982) give in addition to mean values of the number of sunspot groups/day ( $N_G$ ), Wolf sunspot number ( $N_W$ ), as well as the projected and corrected umbral area ( $u$ ), whole spot area ( $w = u + p$ ) and facular area ( $f$ ). Areas are normally given in units of  $10^{-6}$  of the solar disk. R. Gilliland (1985) of the National Center for Atmospheric Research has supplied us with monthly mean values of these parameters from 1980-1984, enabling a analysis over the ACRIM timeframe. Figure 3 shows the variation of monthly of mean of

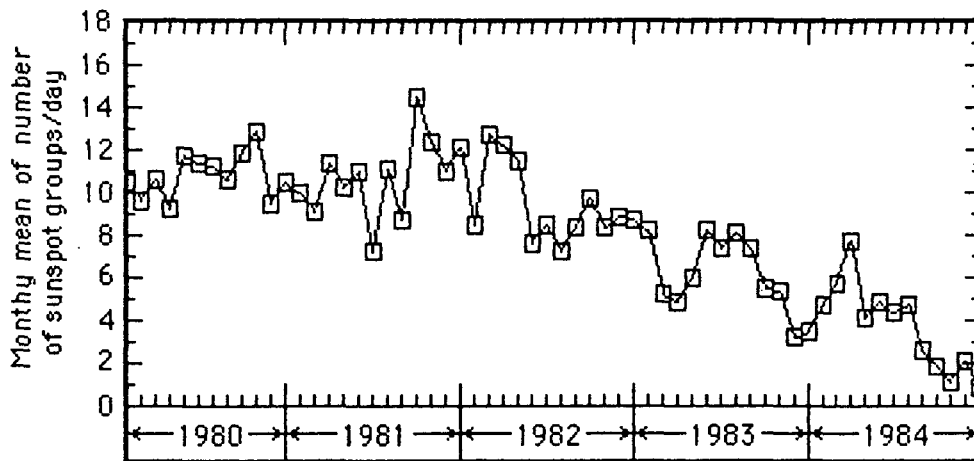


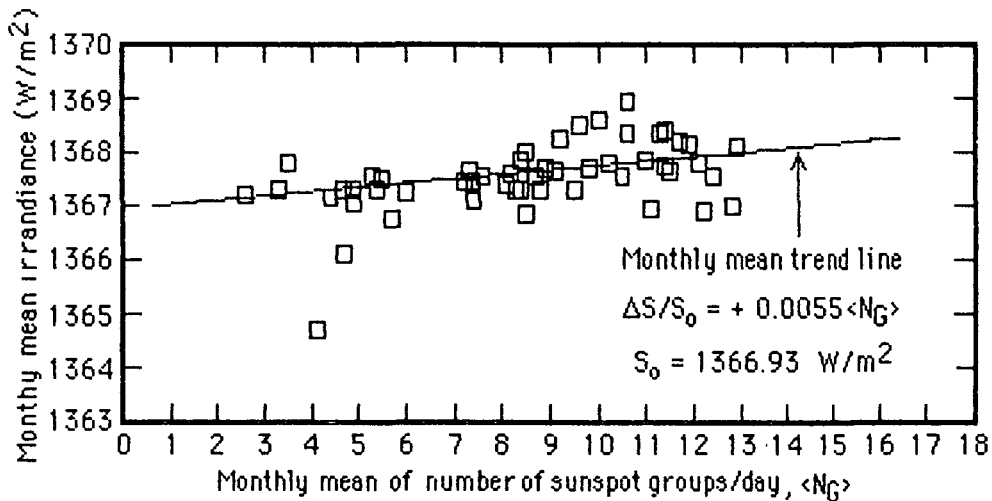
Figure 3. NCAR Sunspot group data 1980-1984 (Gilliland, 1985)

sunspot groups/day,  $\langle N_G \rangle$ , from Gilliland's NCAR data over the same timeframe as the ACRIM data of Figure 1. The downward trend to a minimum in 1985-1986 is quite evident, and will almost certainly be followed by a subsequent rise to the next solar maximum near 1991.

### STATISTICAL ANALYSIS OF ACRIM/NCAR DATA

Figure 4 is a "scatter diagram", in which the ACRIM irradiance of Figure 2 in  $W/m^2$  is plotted against the monthly mean sunspot group number  $\langle N_G \rangle$  of Figure 3. As a first step in statistical analysis the regression line through the data and shown in Figure 3 was computed using a least square best-fit routine. A positive irradiance/group number correlation was found for the

monthly data albeit with appreciable scatter around the trend line. The standard deviation of irradiance was  $\pm 0.56 \text{ W/m}^2$  corresponding to only  $\approx 16\%$  of the irradiance variation predictable by  $\langle N_G \rangle$ . The group, rather than the Wolf, sunspot number was used for consistency with Wilson *et al.*'s (1981) findings on short-term variability.



**Figure 4.** ACRIM monthly irradiance data versus NCAR sunspot groups: 1980-1984

More elaborate correlations such as the Hoyt-Eddy (1982) one based on umbral, penumbral and facular areas would presumably do better. But our objective at this point was simply to determine whether a timescale could be found at which the bulk correlation of irradiance with sunspot groups switches from negative to positive from gross statistical analysis -- perhaps arising from re-radiation after some time lag  $\tau_L$ .

To do this we computed the cross-correlation coefficients,  $R$ , which compare deviations about the means of the irradiance and group number time series. A value of  $R = +1$  implies that the relative magnitudes and signs of deviations of one time series can be used to predict the behavior of the second time series; a value of  $R = -1$  implies that deviations in one data set are comparable in magnitude but opposite in sign to the other -- that is, they are anticorrelated. One can predict the behavior of one time series from the other with a confidence level of  $(R^2 \times 100)\%$ . To isolate possible reradiation lags from faculae we introduced a time lag variable  $\tau_L$ , such that  $R^2(\tau_L)$  is the confidence level with which we can predict the behavior

of one time series at time  $t + \tau_L$  from the behavior of the other time series at time  $t$ . The cross-correlation coefficients versus lag time over the 1980-1984 time frame varied smoothly in the range of  $-14 \text{ months} < \tau_L < +14 \text{ months}$ , and exhibited a peak at  $\tau_L \sim 6 \text{ months}$ . Throughout this range the formal predictability was only  $(R^2 \times 100) \leq 25\%$ . An interesting feature of this result was that the cross-correlation coefficients for all lag times were positive, and form a smooth function. This suggests a switchover time for negative to positive correlations is less than a month. However, a longer-term positive correlation with solar activity at any given time is contrary to the predictions of the Hoyt-Eddy (1982) model, and may simply indicate similarities in the long-term trend of the two data sets arising from external factors. These are discussed next.

While we are aware of controversies in the solar physics community whether the secular, downward trend in the ACRIM data set is real or instrumental, we accept it in light of similar findings of solar cooling at about the same rate by the NIMBUS 7 ERB instrument during this period. In the 1980-1984 period both the measured SMM/ACRIM and the measured NIMBUS 7/ERB irradiance data trend downward at a rate of about  $0.01\%/year$  (Willson, 1984). During the same epoch all indices of solar activity, including counts of groups (Fig. 1, middle panel) also decline, since the period embraces the declining phase of an 11-year solar cycle that peaked in late 1979/early 1980. Thus one expects an apparent correlation if possibly accidental positive correlation. The question here is whether this reflects the behavior of the sun over longer timeframes. The answer is problematical because ERB/NIMBUS 7 irradiance values have decreased monotonically since measurements were begun in about 1978, well before the peak of the 11-year activity cycle (Hickey *et al.*, 1981). That is, the NIMBUS data decline more or less monotonically while the sunspot numbers rise to a maximum (1980) and then fall, apparently refuting a straightforward correlation between measured irradiance and any simple sunspot index.

In view of these contradictions and uncertainties we do not believe it is productive at this time to work with correlations for irradiance with surface observables beyond the 1980-1984 timeframe, and focus next on what can be learned from computing the surface temperature effect from a

climate model over the ACRIM period for which a direct space-based irradiance measurement record exists.

### CLIMATE MODEL RESPONSE TO SOLAR FORCING: 1980-1984

The world's oceans exert a kind of "thermal flywheel" effect on all external climatic forcing including solar irradiance fluctuations. To study the influence of ACRIM irradiance data on the response of global mean surface temperature  $T_S(t)$  we used the upwelling-diffusion one dimensional ocean transient climate of Hoffert et al. (1980). Salient features of the model are given below.

A useful reference condition for transient climate studies is the equilibrium temperature,  $T_e$ , corresponding to the instantaneous steady state surface temperature at solar flux  $S$ , planetary absorptance  $a$  and atmospheric carbon dioxide concentration  $c$ . At the reference values  $S_0$ ,  $a_0$  and  $c_0$ ,  $T_0 = T_e$ . An increase in any of the forcing parameters by  $\Delta S = S - S_0$ ,  $\Delta a = a - a_0$  or  $\Delta c = c - c_0$  tends to create a new equilibrium surface temperature

$$T_e(t) = T_0 + \beta_T(\Delta S/S_0 + \Delta a/a_0) + \beta_c \ln(1 + \Delta c/c_0),$$

where  $\beta_T \approx 108$  °C and  $\beta_c \approx 3.6$  °C are climate sensitivity parameters (Hoffert and Flannery, 1985). For a planet with zero thermal inertia,  $T_S(t) = T_e(t)$ . But in the real world the  $T_S(t)$  response is delayed and modified by oceanic mixing and storage in ways which depend on the  $T_e(t)$  forcing.

The transient climate model used here computes heat capacity and internal mixing effects on  $T_S(t)$  of an ocean mixed layer of depth  $h \approx 75$  m and thermal relaxation time  $\tau \approx 4$  yr, overlying a deep ocean upwelling at  $w = 4$  m/yr with eddy diffusivity  $\kappa \approx 2000$  m<sup>2</sup>/yr. Considerations leading to these numerical values and to the model itself are discussed in Hoffert et al. (1980). Basically, the evolving surface temperature is given by numerical solution of the differential equation

$$\frac{dT_S}{dt} = \frac{[T_e(t) - T_S]}{\tau} + \frac{1}{h} \left\{ \kappa \frac{\partial T}{\partial z} + w(T - T_p) \right\}_{z=h},$$

where  $T_p$  is the temperature of polar bottom water. The term in brackets in equation describes the rate at which heat is exchanged with the deep ocean at the mixed layer/thermocline interface. If the term is small, then heat is trapped in the mixed layer, and only superficial heating of the oceans needs to occur for climate to re-equilibrate with an altered surface heat balance. If the term is large, then warming of the ocean's surface cannot occur until the ocean warms from top to bottom. To evaluate the complete ocean model in transient evolution, we integrate the  $T_s$ -equation numerically and simultaneously with a coupled upwelling-diffusion model for  $T(z,t)$  in the deep ocean, where  $z$  is depth below the mixed layer.

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left\{ \kappa \frac{\partial T}{\partial z} + w(T - T_p) \right\},$$

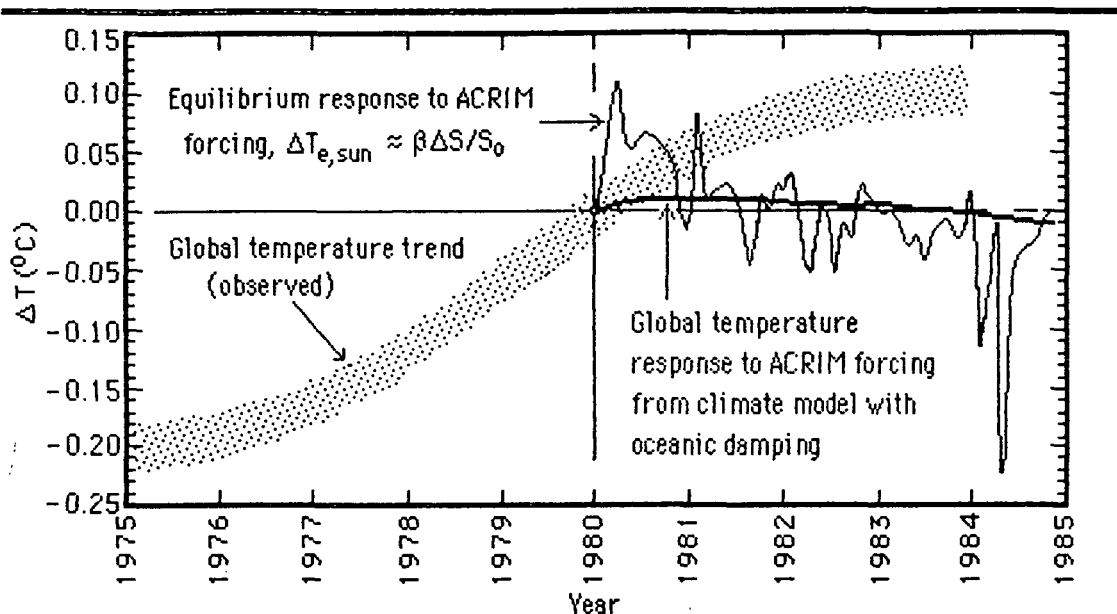
where the bottom boundary condition on this equation is  $\kappa \partial T / \partial z + wT = wT_p$  at  $z = h_d$ . Normally the partial differential equation for the ocean's internal temperature  $T(t,z)$  is solved by finite differences over 40 one hundred meter thick layers between the mixed layer/thermocline interface and the sea floor at  $h_d \approx 4000$  m.

To calculate the irradiance effect from 1980-1984, we forced the system with  $T_e(t) = T_0 + \beta_T \Delta S(t) / S_0$ , where  $t$  is the time from a hypothetical initial state in 1980,  $T_0$  is the 1980 surface temperature, and  $\Delta S(t) / S_0$  is the monthly mean ACRIM irradiance data of Figure 2. The polar sea temperature was held constant at  $T_p = 1$  °C during the run. The initial vertical ocean temperature profile needed to start the calculation was specified by  $T(0,t) = T_p + (T_0 - T_p) \exp(-zw/\kappa)$ : That is, a pre-existing oceanic steady state was assumed in 1980. The surface temperature response is illustrated in Figure 5 by the thick solid line. Also shown is equilibrium temperature forcing and the trend line of actual global surface temperatures from 1975-1985.

It is evident from Figure 5 that for the climate sensitivity parameter used here ( $\beta_T \approx 108$  °C), the ACRIM irradiances correspond to short-period (monthly) fluctuations of equilibrium temperature of  $\sim 0.1$  °C. The longer



term trend over the five included years is cooling, as discussed earlier, whereas the Wigley *et al.* (1986) temperature data indicate a warming. Moreover, the effect of ocean thermal inertia associated with the mismatch of irradiance fluctuation and thermal relaxation timescales tends to damp the solar-driven response to amplitudes at the  $\sim 0.01$  °C level.



**Figure 5 .** ACRIM equilibrium temperature forcing and model response initialized in 1980 compared with blow-up of overlapping 10-yr temperature trend of Figure 1.

While very weak compared to actual surface temperature fluctuations, the response to irradiance variations is interesting insofar as an initial warming is produced, followed by a cooling. This reflects the complex interplay of oceanic mixing and storage to modulate the imposed solar signal. However, it seems clear that the solar effect was quite minor during this period. Since the system is linear, an upper-bound doubling of the climate sensitivity would still produce a small response for the solar component. We therefore conclude that solar variability is unlikely to be an important factor over 5-10 year timescales.

### **IMPLICATIONS FOR TRANSIENT CLIMATE MODELS**

Although we have not attempted to extend the study of irradiance effects

on climate beyond the period of space-based direct ACRIM measurements, such extensions in principle should incorporate only correlations which are grounded in accurate (space-based) observations. For this purpose, the Hoyt-Eddy (1982) correlation seems the most physically-motivated. It produced a 90% correlation with sunspot blocking (10% short-term storage) with ACRIM data over the first year of Solar Max operation (Hoyt and Eddy, 1983). To extend it, one must go beyond mere sunspot numbers; but the corrected umbra, penumbra and facular areas needed are readily available for the past 100 years. This extension was actually done by Hoyt and Eddy (1982).

But the monthly mean deviation in % of solar irradiance computed with the Hoyt-Eddy (1982) sunspot and facular radiation model and observed projected sunspot areas from April 1974-October 1981 shows minimums of order 0.1% during periods of maximum solar activity, albeit with substantial peak-to-peak variability over the 10 cycles in this interval. This anti-correlation of long-term solar activity with irradiance is in the same direction as the short-term blockage effect observed by Willson et al. (1981), but opposite to the five-year trend of the ACRIM and ERB data discussed here. This supports our earlier judgement that extensions to long-term solar forcing scenarios from limited data sets are premature. The apparent lack of an 11-yr cycle correlated with solar activity in the surface temperature record of Figure 1 also support Pittcock's (1979) and Budyko et al.'s (1986) findings that solar fluctuation effects correlated with sunspot cycles are in any event small. Finally, our climate model results suggest a small effect from solar irradiance over the period for which ACRIM data exists because of oceanic damping.

Other solar forcing correlations have been used by transient climate modelers to explain observations with even less justification. We have already referred to the pre-ACRIM positive irradiance/sunspot number correlations used for example by Schneider and Mass (1975) and Robock (1979) in climate models as based on insufficiently accurate observations. Hansen et al. (1981) have used the Hoyt (1979) umbra/penumbra ratio correlation for the solar component to improve predictions by their model of the local peak around 1940 of global temperature (see Figure 1). This correlation has not to our knowledge been tested against extraterrestrial

irradiance measurements; and Hoyt (1979) himself states, " The high cross-correlation between northern hemisphere temperature anomalies and the umbral/penumbral ratio may be a mathematical oddity without physical meaning." More recently, Gilliland and Schneider (1984) modeled the effects of solar forcing in a transient climate model with a sinusoidal term based on assumed solar radius cycle of 76-yr period with phase and amplitude arbitrarily adjusted to fit temperature data. However, their "best fit" of solar forcing to surface temperature histories contradicts satellite observations -- since Gilliland and Schneider (1984) show a rise in solar forcing over the 1980-1984 timeframe when both SMM/ACRIM and ERB/NIMBUS 7 instruments measure declining irradiance trends.

All of these efforts reflect an understandable tendency to explain observational global temperature anomalies in terms of phenomena about which one knows the least. Fortunately, direct space-based observations of solar variability is accumulating rapidly, allowing us weed out unphysical correlations employed in the past to estimate solar luminosity effects on global climate. The (linear) thermodynamic upwelling-diffusion ocean model results discussed here indicate that currently available satellite data is sufficient to rule out a major solar variation effect on surface temperature in the short term, although longer-term effects are still possible. Moreover, we cannot exclude the possibility that nonlinearities in the climate system amplify and modulate imposed forcing in ways not captured by the current linear models (Gaffin *et al.*, 1986). Hopefully, future generations will have the data needed to finally resolve the transient effects of our dynamic sun on climate, as long time-series irradiance monitoring from space becomes an operational fact of life.

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