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Models of solar irradiance variability and the instrumental temperature record

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Abstract. The effects of decade-to-century (Dec-Cen) variations in total solar irradiance on global mean surface temperature T_s during the pre-Pinatubo instrumental era (1854-1991) are studied by using two different proxies for the irradiance and an energy-balance climate model. Irradiance anomalies based on solar-cycle length (CL) and solar-cycle decay rate (CD) proxies can account for most of the warming observed up to 1976, but anthropogenic forcing is needed to explain the subsequent sharp increase in T_s. The time series of CL-solar and anthropogenic radiative forcing resemble each other; this similarity makes it difficult to separate their effects in the instrumental T_s record. The CD-based irradiance values reflect heuristically intensity variations in photospheric turbulence; this proxy allows one to obtain more tightly constrained values of both solar variability and terrestrial climate sensitivity from the instrumental T_s record.

Introduction

Variability of the total solar irradiance W is a potentially important contributor to changes in global mean temperatures on time scales longer than a few years. Striking correlations between the instrumental T_s record, extending back nearly a century and a half, and observable solar features, such as the amplitude and length of the sunspot cycle, have suggested that solar variations may indeed have a strong impact on decade-to-century (Dec-Cen) changes in global mean surface temperature T_s [*Reid*, 1997, and references therein]. In the absence of a convincing physical link between these observed solar features and W, however, the role of solar variability in the terrestrial climate record is difficult to quantify [e.g., *Kelly and Wigley*, 1992 (henceforth *KW*)]. We examine here the implications of some simple physical assumptions regarding the origin of Dec-Cen irradiance variability for the way it might affect the instrumental T_s record.

Models of Solar Variability

Variations on the order of 0.1% in W have been detected within a solar cycle by satellite-borne radiometers [e.g., *Willson and Hudson,* 1991] and successfully modeled in terms of observable photospheric features [e.g., *Pap et al.*, 1994; *Lean et al.*, 1998]. While their effects may be detectable in records of land surface and ocean temperatures [e.g., *Stevens and North*, 1996; *White et al.*, 1997; *Lawrence and Ruzmaikin*, 1998], these subdecadal fluctuations are too small to account for a significant fraction of the 0.6 °C increase in T_s recorded over the last century [*Wigley and Raper*, 1990; *Jones et al.*, 1994; *Solanki and Fligge*, 1998]. Cycle-to-cycle irradiance variability is most plausibly linked to longer-period variations in the intensity of convective heat transport from the solar interior to the photosphere [e.g., *Baliunas and Jastrow*, 1993; *Hoyt and Schatten* 1993, 1997], which may be detectable through their concomitant effects on observable solar features. In particular, *Hoyt and Schatten* [1993] argue that more intense convection leads to a more rapid decay of individual sunspots and a shorter solar cycle, and thus can account for the apparent (inverse) correlation between cycle length and irradiance in the sun as well as in sunlike stars [e.g., *Baliunas and Soon*, 1995].

We investigate here the implications of this assumption for solar effects on the instrumental temperature record. To do so, we use simplified models for cycle-to-cycle irradiance variations and the response of the Earth's mean surface temperature T_s to net radiative forcing. Variations $F(t)$ in the convective transport of heat to the photosphere from its mean are modeled as proportional to the decay rate of the solar cycle, defined as the reciprocal of the time interval between the epochs of a solar cycle maximum t_M and the subsequent minimum t_m:

$$F_1(t_m) = k_1 / (t_m - t_M) ; \qquad (1)$$

k_1 is an unknown proportionality constant. The convective anomaly F_1 for a cycle is defined as occurring at the time t_m of solar minimum, when the photospheric features associated with irradiance variations within a cycle are largely absent [e.g., *Lean et al.*, 1998].

For comparison with previous studies [e.g., *KW*; *Schlesinger and Ramankutty*, 1992], we also consider a formulation in which the convective heat flux anomaly is modeled as inversely proportional to the cycle length, defined as the interval between successive minima:

$$F_2(t_{m+1/2}) = k_2 / (t_{m+1} - t_m) ; \qquad (2)$$

here k_2 is an unknown proportionality constant, and the convective anomaly F_2 is defined at the time $t_{m+1/2}$ which is midway between the epochs of successive minima t_m and t_{m+1}.

Binomial smoothing of the solar record can considerably alter its climatic impact, depending on the associated bandwidth [*KW*], and requires adjustment near the end of the series where the filter extends beyond the available span of data. We choose instead to model the effect of convective heat-flux variability on W in terms of a first-order autoregressive (AR-1) process:

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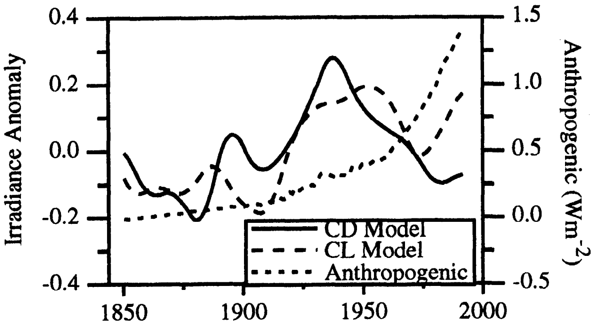

Figure 1. Time series of radiative-forcing terms used to drive the climate model. Irradiance anomalies derived from solar-cycle decay rate (CD) and solar-cycle length (CL) proxies are shown in arbitrary units (left ordinate). Anthropogenic forcing is shown in Wm^{-2} (right ordinate), relative to its value in 1850; runs starting from 1765 (not shown) with anthropogenic forcing have nearly identical temperature variation during the instrumental era.

$$dw/dt + w/\tau = k\,F(t)\,; \qquad (3)$$

here w is the solar irradiance anomaly, $W = W_0 + w$, $F(t)$ is the anomalous convective heat transport derived from either the cycle decay-rate (CD) model (Eq. 1) or the cycle length (CL) model (Eq. 2), and k is an unknown proportionality constant. The relaxation time $\tau \sim L^2/\nu$ in Eq. (3) for the convective anomaly was estimated *a priori* by choosing the kinematic eddy viscosity ν of the convective zone near the lower limit of a plausible range [$\nu \sim 10^{12} - 10^{13}$ cm^{2}sec^{-1}, cf. *Zeldovich et al.* 1983] and the length scale L as the depth of the convective zone (about 1/3 of the solar radius); this yields $\tau = 12.6$ yr.

Irradiance anomalies w were calculated using *Lassen and Friis-Christensen's* [1995] epochs for t_m and t_M (their Tables 1 and 2), and 1996.6 as the epoch of the last minimum [cf. *Wilson et al.*, 1998]. Due to the linearity of the AR-1 process, the proportionality constants k_1 and k_2 in Eqs. (1) and (2) can be combined with the constant k in Eq. (3) into a single unknown scaling factor for each of the resulting irradiance curves, which are plotted in Fig. 1 in arbitrary units. The CL model essentially reproduces earlier Dec-Cen irradiance parameterizations based on the solar-cycle length [see, e.g., Fig. 1 of *KW*]; in particular, a clear upward trend over the course of the instrumental era is evident. The CD model produces a distinctly different irradiance profile, however, showing a sharp irradiance increase between 1880 and 1937, with a subsequent decrease to values below the 140-year average. The implications of these characteristics of the modeled solar irradiance for Sun-climate relations are explored next.

Global Mean Temperature Response

We computed the response of the global mean surface temperature T_s to changes in radiative forcing by applying a simplified version of the upwelling-diffusion energy-balance climate model described by *Wigley* [1995]. In our version no distinction is made between land and ocean or northern and southern hemispheres, enabling us to minimize the number of assumptions required and the complications arising from the regionally heterogeneous nature of anthropogenic forcing [cf. *Schneider*, 1994; *Cox et al.*, 1995].

Following the approach of *KW*, ensembles of runs were performed starting from an assumed zero temperature anomaly: the climate sensitivity S (defined as the equilibrium increase in T_s for doubled CO$_2$), and solar forcing amplitude I_0 (defined as the difference between the minimum and maximum net irradiance anomaly for the proxy curves in Fig. 1, in Wm^{-2} at the tropopause) were varied from run to run over fixed ranges. The model results for T_s were evaluated in terms of the percentage of variance accounted for in the *Jones et al.* [1994] reconstruction of T_s that spans the pre-Pinatubo instrumental temperature record (1854–1991). Our runs start in 1850, since prior dates for solar maxima needed for the CD irradiance model are less reliable [*Lassen and Friis-Christensen*, 1995]; moreover, due to the limited memory of the climate system, solar forcing prior to this time appears to have little impact on global temperature trends during the instrumental era [*Wigley and Raper*, 1990; *Wigley et al.*, 1997].

Solar-only forcing derived from the CL proxy model can account for at most 55% of variance in the *Jones et al.* [1994] T_s record, for climate sensitivity values ranging up to $S = 5$ °C (Fig. 2a, upper panel); this agrees with *KW's* solar-only results, although they obtain higher variances for larger values of S. Our result was obtained for a net irradiance amplitude of $I_0 = 0.90$ Wm^{-2}, which (assuming a planetary albedo of 30%) corresponds to a variation in the solar "constant" of 0.38% during the last century. *Lean et al.* [1992] used linear regression of solar Ca II (HK) emission with respect to satellite-measured irradiance to estimate the irradiance deficit for a noncycling state (such as the Maunder Minimum, ca. 1700) as 0.24%, which scales to a peak-to-peak variation of ~0.14% during the last century; *Zhang et al.'s* [1994] corresponding estimates, based on brightness changes in a sample of sunlike stars, span a range from about this value to an irradiance change over the last century of ~0.5%.

The amplitude of the CL-solar forcing required to fit the observed T_s record – although consistent with a limited stellar sample – is, therefore, considerably in excess of Dec-Cen variability inferred from the solar HK-irradiance relationship. The simulated T_s variation using our optimal (I_0, S) pair roughly matches the observed record until 1976 (Fig. 2a, lower panel); even with this relatively large solar forcing though, the climate model is unable to capture the subsequent rapid increase which occurred prior to the Pinatubo eruption in 1991.

Anthropogenic forcing was calculated following *Shine et al.* [1990] for the well-mixed greenhouse gases except CO$_2$, for which we used the IS92a history [cf. *Enting et al.*, 1994] with *Hansen et al.'s* [1997] value of 4.19 Wm^{-2} for the adjusted radiative forcing due to doubled CO$_2$. Aerosol effects were assumed proportional to the global annual sulfur emission given by *Lefohn et al.* [1999], and scaled to produce a total radiative forcing of -0.6 Wm^{-2} in 1990; this includes an estimated direct forcing of -0.4 Wm^{-2} [cf. *Schimel et al.*, 1996] and a reduced central estimate for the indirect forcing (i.e. cloud nucleation), whose net effect may actually be near zero (*Lohmann et al.* [1998]; see *Wigley et al.* [1997] for the impact of different sulfate scalings). The addition of anthropogenic forcing to the CL-derived solar irradiance increases the maximum T_s variance accounted for to 72% (Fig. 2b, upper panel), a percentage considerably in excess of *KW's* corresponding result for combined forcing (61%). This greater increase reflects the strong warming present in the most recent

Table 1. Results Using Solar and Anthropogenic Forcing

Solar Model	Irradiance Change	Climate Sensitivity	Solar Contribution to ΔT_s 1910-1940	1854-1991
CL	0.27%	2.1 °C	70%	21%
CD	0.22%	3.0 °C	58%	-3%

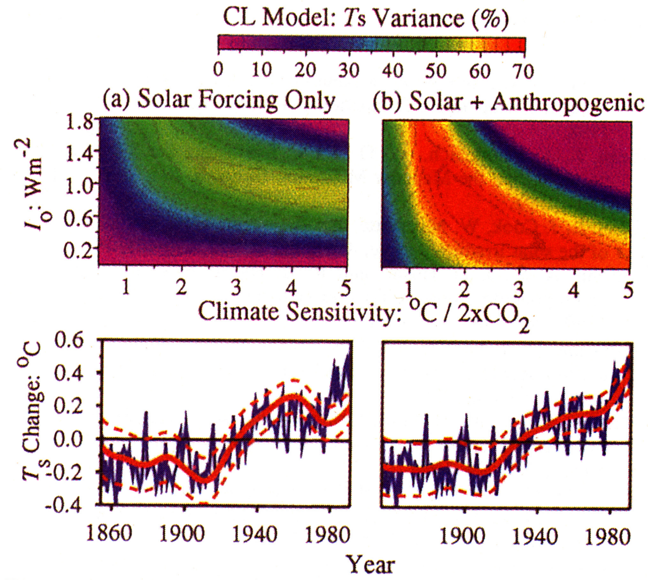

Figure 2. (a) Results of climate simulations using the anomalous irradiance profile given by the solar-cycle length (CL) proxy. The upper panel shows the percentage of variance in the *Jones et al.* [1994] yearly series of global mean surface temperature associated with the simulated T_s series, using the climate sensitivity (S) and solar scaling (I_0) parameters defined by the abscissa and ordinate, respectively. The lower panel shows the corresponding temperature history obtained using the (I_0, S) pair that yields the highest variance; since the climate model simulates only temperature changes, both the simulated and observed series (solid red and blue curves, respectively) have been adjusted to have zero mean over the time interval plotted. The dashed red lines show 2σ confidence intervals derived by *Jones et al.* [1997] for decadal temperature errors, and are plotted to indicate a plausible range of observational deviations from a "perfect" model. (b) as in (a), with the anthropogenic radiative forcing added to the CL solar forcing.

part of our data (Fig. 2b, lower panel) and not included in *KW's* earlier analysis; it lends further support to the idea that this recent warming is not due to solar forcing alone.

The temporal profile of the net anthropogenic forcing (dotted line in Fig. 1) is similar to the solar irradiance profile generated by the CL model (with a correlation coefficient r = 0.57); both show an overall upward trend during the last century. This similarity introduces an ambiguity in the attribution of the observed warming [cf. *Santer et al.*, 1996], which manifests itself in our results as a hyperbolic-shaped region in the I_0-S plane for which the explained T_s variance is close to its maximum value. The red-shaded area in Fig. 2b (upper panel), in particular, shows that the observed T_s record is consistent with relatively large CL-solar variations ($I_0 > 1.2$ Wm^{-2}, or ~0.5% W) during the last century, provided the climate sensitivity is restricted to values below the IPCC range ($S < 1.5$ °C). These results indicate that the recent increase in T_s cannot be explained by CL-derived irradiance alone, but do not rule out a large role for solar forcing in producing the warming observed over the last century.

To examine the dependence of solar-forcing effects on the proxy model for Dec-Cen irradiance variability, we repeated the above calculations using the cycle decay-rate (CD) irradiance profile (solid line in Fig. 1). For the solar-forcing-only experiments, the distribution of associated T_s variance in the I_0-S plane (Fig. 3a, upper panel) is quite similar to that obtained with the CL model, although its magnitude is diminished by about one-half. As for the CL model, the optimal temperature history simulated with CD-solar forcing reproduces the observed T_s variation fairly well until about 1976 (Fig. 3a, lower panel), but fails to capture the subsequent warming. The addition of anthropogenic forcing to the CD irradiance more than doubles the associated T_s variance (Fig. 3b, upper panel) to the same maximum (72%) as obtained with the combined CL forcing; the recent warming is, therewith, quite well captured (Fig. 3b, lower panel). The best-fit solar forcing amplitude (I_0 = 0.52 Wm^{-2}, or 0.22% W over the last century) is roughly consistent with *Lean et al.'s* [1992] estimate of the maximum possible Maunder irradiance deficit. Due to the near "orthogonality" (r = 0.07) of the CD-solar and anthropogenic forcing profiles (cf. Fig. 1), moreover, the subset of (I_0, S) values which is compatible with the observed T_s record forms a more compact region in parameter space than was obtained for the CL irradiance (compare upper panels of Figs. 2b and 3b). The combination of very high values of solar forcing ($I_0 > 1.2$ Wm^{-2}) and very low values of climate sensitivity ($S < 1.5$ °C) found to be compatible with the CL profile is thus effectively excluded by the CD irradiance model.

Discussion and Conclusions

The relative roles of solar and anthropogenic forcing in producing climate change over the instrumental era, as deduced from the CL and CD experiments, are summarized in Table 1. Simulations using both irradiance models indicate that the steep rise in temperature observed in the early part of the century (1910-1940; see *Ghil and Vautard* [1991] and references therein) was largely caused by Dec-Cen solar variability, consistent with results using other irradiance reconstructions [e.g. *Reid*, 1997; *Wigley et al.*, 1997]. For the warming documented in the full (1854-1991) T_s record, our results agree with previous findings of dominant anthropogenic influence; in fact the CD irradiance slightly offsets the observed warming trend. This leads to an increase in the inferred sensitivity over our CL case by an amount (43%) which is comparable to the sensitivity increase obtained by excluding solar forcing altogether in CL-type response models [cf. *KW*; *Schlesinger and Ramankutty*, 1992]. Results from both irradiance models underscore the inability of solar forcing alone to explain recent temperature increases (Figs. 2a and 3a, upper panels – see also *Marcus and Ghil* [1998], *Solanki and Fligge* [1998] and

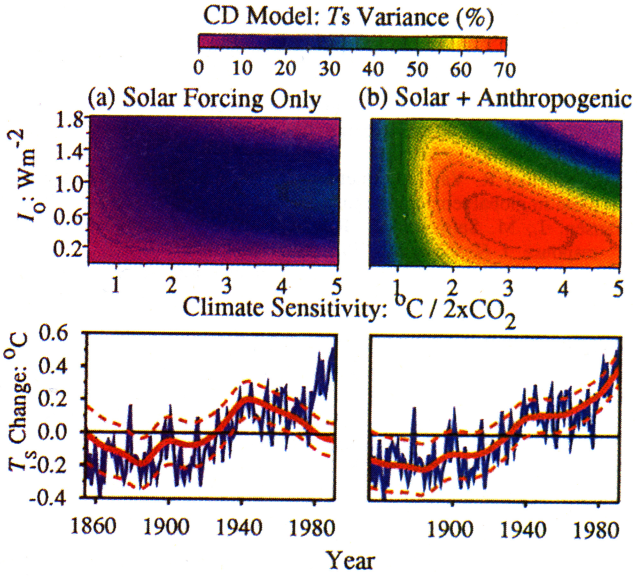

Figure 3. (a) As in Fig. 2a, using the anomalous W profile given by the solar-cycle decay rate (CD) proxy. (b) As in Fig. 3a, with the anthropogenic radiative forcing added to CD solar forcing.

Froehlich and Lean [1998]). The combined CD model, however, provides more robust constraints on plausible values of the climate sensitivity and solar forcing than are obtained with the CL model (Figs. 2b and 3b, upper panels).

Distinct models of long-term irradiance variability can thus lead to significantly different conclusions regarding the role of solar forcing in terrestrial climate change, as well as to fairly different values of the climate system's sensitivity, as inferred from comparisons with the instrumental temperature record. A recent analysis of satellite radiometer data indicates little irradiance change between the last two solar minima [*Froehlich and Lean,* 1998], tending to contradict the increase inferred from solar-cycle length models but roughly consistent with the flatter CD profile. No definitive assessment of the relative merits of the CD and CL irradiance proxies can be obtained from the results presented here, since each (combined with anthropogenic forcing) accounts for the nearly same year-to-year variance (72%) in the pre-Pinatubo instrumental record. We hope that our results will stimulate the development of a robust Dec-Cen solar irradiance model, perhaps incorporating elements of both [cf. *Hoyt and Schatten,* 1993; 1997], and fully based on solar physics.

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