Can solar variability explain global warming since 1970?

S. K. Solanki and N. A. Krivova
Max Planck Institute for Aeronomy, Katlenburg-Lindau, Germany

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[1] The magnitude of the Sun's influence on climate has been a subject of intense debate. Estimates of this magnitude are generally based on assumptions regarding the forcing due to solar irradiance variations and climate modeling. This approach suffers from uncertainties that are difficult to estimate. Such uncertainties are introduced because the employed models may not include important but complex processes or mechanisms or may treat these in too simplified a manner. Here we take a more empirical approach. We employ time series of the most relevant solar quantities, the total and UV irradiance between 1856 and 1999 and the cosmic rays flux between 1868 and 1999. The time series are constructed using direct measurements wherever possible and reconstructions based on models and proxies at earlier times. These time series are compared with the climate record for the period 1856 to 1970. The solar records are scaled such that statistically the solar contribution to climate is as large as possible in this period. Under this assumption we repeat the comparison but now including the period 1970–1999. This comparison shows without requiring any recourse to modeling that since roughly 1970 the solar influence on climate (through the channels considered here) cannot have been dominant. In particular, the Sun cannot have contributed more than 30% to the steep temperature increase that has taken place since then, irrespective of which of the three considered channels is the dominant one determining Sun-climate interactions: tropospheric heating caused by changes in total solar irradiance, stratospheric chemistry influenced by changes in the solar UV spectrum, or cloud coverage affected by the cosmic ray flux. *INDEX TERMS:* 1650 Global Change: Solar variability; 1620 Global Change: Climate dynamics (3309); 7538 Solar Physics, Astrophysics, and Astronomy: Solar irradiance; 2104 Interplanetary Physics: Cosmic rays; *KEYWORDS:* solar variability, solar irradiance, climate change

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1. Introduction

[2] The debate on the extent to which the Sun affects the Earth's climate was reignited by the work of *Eddy* [1976]. With the recognition of the reality of global warming [e.g., *Houghton et al.*, 1996, IPCC-95] this debate has intensified [e.g., *Friis-Christensen et al.*, 2000; *Wilson*, 2000]. As one part of this debate, a number of studies have sought to find correlations between solar magnetic activity and the temperature of the Earth's atmosphere. Good correlations have been found by, e.g., *Eddy* [1976], *Reid* [1987], *Friis-Christensen and Lassen* [1991], *Lean et al.* [1995], and *Solanki and Fligge* [1998, 1999] on a time scale of decades to centuries. In these cases it is mainly the secular variation of parameters describing solar activity which is of relevance. Exceptions are the recently presented correlation over a solar cycle between the cosmic-ray intensity, which is modulated by the strength of the Sun's interplanetary magnetic field, and the coverage of low-lying clouds [e.g., *Marsh and Svensmark*, 2000] or the presence of a significant 11-year period in cloud cover over the United States in the last century [*Udelhofen and Cess*, 2001].

[3] In spite of these good correlations there have been indications that in recent years the secular variation of solar quantities has decoupled from the evolution of global temperature (solar irradiance [*Solanki and Fligge*, 1998], solar cycle length [*Thejll and Lassen*, 2000], and solar activity indices [*Lean et al.*, 2001]). In the present paper we consider this point more quantitatively.

[4] Various processes have been invoked by which the inconstant Sun can influence the troposphere: (1) changes in the energy input into the Earth's atmosphere through variations in the total solar irradiance, (2) changes in stratospheric chemistry through variations of solar UV irradiance, and (3) changes in cloud cover induced by modulations in the cosmic ray flux produced by variations in the Sun's open magnetic flux. For each of these potential sources it is possible to compute the influence on the Earth's climate [e.g., *Wilson*, 2000; *Cubasch and Voss*, 2000; *Haigh*, 1996; *Shindell et al.*, 2001]. Given the complexity of the climate system, however, such modeling perforce is based on simplifying assumptions, which implies a significant uncertainty in the results. Here we take a complemen-

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tary approach. We assume that the Sun has been responsible for climate change prior to 1970. Specifically, we consider the period 1856–1970. Then, using reconstructions and measured records of relevant solar quantities as well as of the cosmic-ray flux, we estimate which fraction of the dramatic temperature rise after that date could be due to the influence of the Sun. Since our original assumption cannot underestimate the solar contribution to global warming prior to 1970, through the present analysis we should obtain an upper limit on the fraction of the warming due to the Sun also after 1970. The two other simplifying assumptions that enter our analysis are (1) the connection between the relevant solar and terrestrial quantities is linear, and (2) this connection remains unchanged with time (and in particular it is the same prior to and post 1970).

[5] Why distinguish between the time before and after 1970? That year marks the onset of a surge in temperature: global surface temperature since 1970 has risen by the same amount as in the century prior to that [*Parker et al.*, 1995]. Also, with the exponential rise of man-made greenhouse gas concentrations [*Houghton et al.*, 1996], their influence is expected to be largest in recent times so that it is possible for the Sun to have played a much more significant role relative to other drivers at earlier times than now. The year 1970 is thus a choice of convenience rather than necessity.

[6] We now consider the solar data and reconstructions relevant for each of the paths listed above before comparing them with climate records.

2. Total Solar Irradiance

[7] Accurate measurements of the total solar irradiance exist since 1978. Unfortunately, no single radiometer managed to stay operational since then so that the irradiance record for this period is a patchwork made from the measurements of a number of individual instruments, each of which has its own calibration and exhibits a slightly different absolute total solar irradiance. This makes the construction of a composite a delicate affair. It is therefore not surprising that *Willson* [1997] and *Fröhlich and Lean* [1998a] reached different conclusions regarding the secular trend of such a composite. *Willson* [1997] argued that the total solar irradiance increased by 0.036% from the solar activity minimum in 1985 to that in 1996, while *Fröhlich and Lean* [1998a] see no evidence for such an increase.

[8] For the purposes of the present paper we take the standpoint that neither trend can be ruled out so that we use them both when constructing a total solar irradiance record from 1856 to 1999. Since *Willson* [1997] does not actually produce a full composite, we take that of *Fröhlich and Lean* [1998a] and subtract therefrom corrections introduced by *Chapman et al.* [1996] to the ERB/NIMBUS-7 data. These corrections, which amount to a total of 0.63 Wm^{-2}, were imposed by *Fröhlich and Lean* [1998a] but were not taken into account by *Willson* [1997]. These two composites are plotted in Figure 1 (top two curves). Next we need to extend the irradiance record back in time. For this purpose we employ the recent reconstructions of *Solanki and Fligge* [1999] and *Fligge and Solanki* [2000] (the lower two curves in Figure 1) to describe the irradiance for the period before 1979. The two plotted irradiance reconstruction curves are based on different assumptions regarding the secular evo-

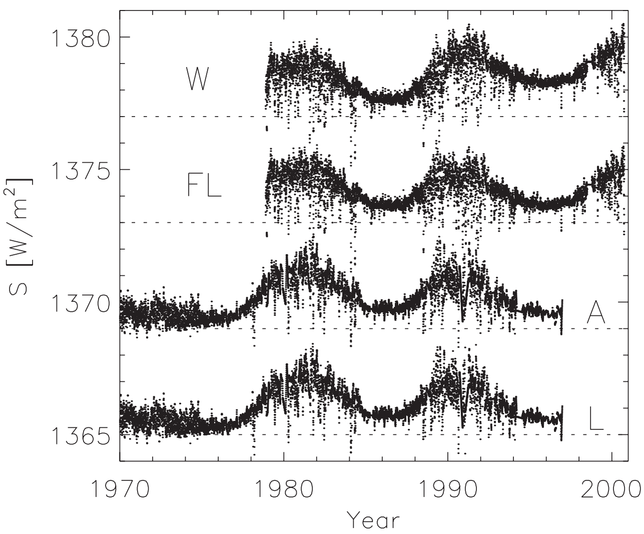

Figure 1. Reconstructed and observed total solar irradiance for the last 3 decades. Cycle length (L) and amplitude (A) based reconstructions and composites of *Fröhlich and Lean* [1998a, 1998b] (FL) and *Willson* [1997] (W) are displaced 0, 4, 8, and 12 Wm^{-2} along the y-axis, respectively.

lution of the irradiance. One follows the cycle length (curve L in Figure 1), the other the cycle amplitude (curve A in Figure 1) (see *Solanki and Fligge* [1999] for details). The true evolution of the irradiance is expected to lie roughly between these curves. In the period plotted in Figure 1 both reconstructions are rather similar but differ substantially at earlier times. This is evident from Figure 2, in which the full total solar irradiance record is plotted after applying an 11-year running mean (reconstructions before 1979, composite of measurements since then). By combining each reconstruction with each composite we obtain four records of total solar irradiance since 1856. Two records each are plotted in Figure 2a (cycle-length based reconstruction combined with the two composites) and Figure 2b (cycle-amplitude based reconstruction combined with the two composites). It can be seen from Figure 1 that the two reconstructions both agree reasonably well with the composite of *Fröhlich and Lean* [1998a] for the period 1978–1997 [*Fligge and Solanki*, 2000; *Solanki and Fligge*, 2000]. Hence if we were to replace the composite by the reconstruction for this period of time it would give almost exactly the same curve in Figure 2 as obtained using the composite of *Fröhlich and Lean* [1998a].

[9] Also plotted in Figure 2 are two temperature records compiled by the Climatic Research Unit of the University of East Anglia, one exhibiting global (Figure 2b) and the other exhibiting Northern Hemisphere (Figure 2a) surface temperatures [*Jones*, 1994; *Parker et al.*, 1995]. Both records have been treated with an 11-year running mean. If one considers the period prior to 1970 there is an excellent correlation between either of the irradiance and the temperature records, with correlation coefficients ranging between 0.83 and 0.97, and the temperature lagging the irradiance by 0 and 11–12 years for the amplitude and length reconstructions, respectively. The correlation coefficients between the solar records

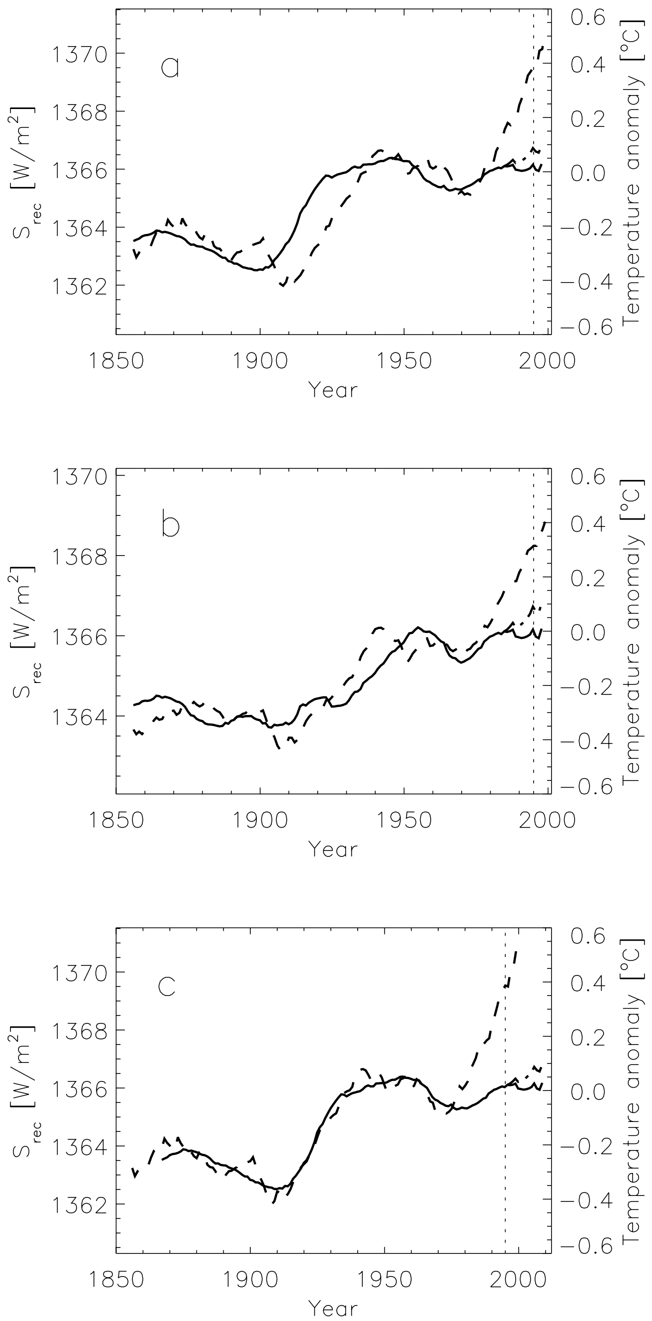

Figure 2. Total solar irradiance and terrestrial temperature versus time. The solid curves prior to 1979 represent irradiance reconstructions ((a) cycle-length based, (b) cycle-amplitude based). From 1979 onward they represent total irradiance measurements ((solid) composite of *Fröhlich and Lean* [1998a, 1998b]; (dot-dashed) composite following *Willson* [1997]). The dashed curves represent Northern Hemisphere (Figure 2a) and global surface (Figure 2b) temperatures. All curves have been smoothed by an 11-year running mean. After the epoch marked by the vertical dotted line the averaging period has been successively reduced. (c) The irradiance curves plotted in Figure 2a have been shifted by 11 years in order to produce the best match with the climate curve (Northern Hemisphere temperature).

and the global temperature are listed in Table 1. The coefficients involving Northern Hemisphere temperatures are very similar and have not been listed for the sake of clarity. In Figure 2c we replot the quantities shown in Figure 2a but after introducing a lag of 11 years to the irradiance curve to improve the match. If the period after 1970 is included the correlation becomes slightly lower, 0.82–0.92, with the higher values now being reached for the irradiance reconstruction based on secular variations proportional to cycle amplitudes combined with *Willson*'s [1997] composite (numbers involving Willson's composite are given in brackets in Table 1). In this case the correlation coefficient actually increases slightly if the period after 1970 is included in the analysis; while in the other three cases it decreases. This decrease is small (0.01–0.02) in the case of the cycle-amplitude based irradiance reconstructions but significant (0.13–0.15) for the cycle-length based ones. Clearly, correlation coefficients provide an indication that the influence of the Sun has been smaller in recent years but cannot be taken on their own to decide whether the Sun could have significantly affected climate, although from Figure 2 it is quite obvious that since roughly 1970 the Earth has warmed rapidly, while the Sun has remained relatively constant. We have therefore also carried out another test in an attempt to quantify this impression.

[10] In Figure 2 we have scaled the irradiance such that the magnitudes of the temperature and irradiance variations are similar between 1856 and 1970. To be precise, we minimize the χ^2 between irradiance and temperature prior to 1970. This implies converting irradiance into temperature using a linear regression. When determining the χ^2 we also allowed the irradiance curve to be shifted in time (see Figure 2c), since a time-lag between solar output and the reaction of the ocean-atmosphere system is conceivable. This is a "maximum" scaling in the sense that it illustrates the case in which the Sun is the overwhelming contributor to the temperature fluctuations up to this date. This means that for the period 1970–1999 in this scaling a direct comparison between the irradiance and temperature records provides an estimate of the maximum contribution of the Sun to climate change in the last three decades. In Table 1 we list the standard error of estimate, s ($s^2 = \chi^2/N$, where N is the number of data points), values obtained by comparing the four possible irradiance records (values for *Willson*'s [1997] composite are given in brackets) with the global temperature record. Consider for the moment just the columns headed "4 Wm^{-2}" (see next paragraph for more details). According to Table 1, s^2 increases by a factor between 1.8 and 19 when the period 1970–1999 is included in the computation. This significant increase is indicative of the much poorer correspondence between solar irradiance and climate since 1970.

[11] The irradiance curves plotted in Figure 2 are based on an increase in the 11-year averaged total irradiance since the Maunder minimum of 4 Wm^{-2} following *Solanki and Fligge* [1999]. This quantity is relatively uncertain, with values between 2 Wm^{-2} and 8 Wm^{-2} being quoted in the literature on the basis of stellar observations and their comparison with the Sun. Since the change in irradiance since 1978 is known (within the uncertainty given by the two composites), the amplitude of the irradiance changes since that time is fixed, irrespective of the amplitude before

Table 1. Standard Error of Estimate, s, and Correlation Coefficient, r_c, for the Total and UV (λ < 3000 Å) Irradiance Records Compared With the Global Surface Temperature

	Length-Based Irradiance Reconstruction				Amplitude-Based Irradiance Reconstruction			
	4 Wm^{-2}		2 Wm^{-2}		4 Wm^{-2}		2 Wm^{-2}	
	<1970	<1999	<1970	<1999	<1970	<1999	<1970	<1999
				Total				
lag	12		12		0		0	
s^2	0.001	0.019 (0.019)	0.001	0.020 (0.019)	0.005	0.012 (0.009)	0.005	0.015 (0.010)
r_c	0.97	0.83 (0.83)	0.96	0.82 (0.83)	0.85	0.88 (0.92)	0.83	0.85 (0.91)
				UV				
lag	12		11		0		0	
s^2	0.001	0.017/0.017	0.001	0.016/0.017	0.004	0.011/0.012	0.004	0.012/0.013
r_c	0.97	0.85/0.85	0.96	0.86/0.85	0.87	0.89/0.88	0.86	0.88/0.87

that epoch. A larger increase between 1700 and 1978 would thus lead to a stretching of the scale for the irradiance change prior to 1978 in Figure 2 but not from 1979 onward. In this case solar total irradiance variations can be responsible for an even smaller part of the temperature rise after 1970.

[12] If, however, the secular irradiance change between 1700 and 1978 was less than 4 Wm^{-2}, the scaling would change in the opposite direction and it is conceivable that the Sun has provided a bigger contribution to global warming since 1970 than suggested by Figure 2. To set an upper limit on this contribution we need to find a lower limit to the secular increase in irradiance since 1700. There are various threads of argument favouring a value of at least 2 Wm^{-2}. The first is based on the comparison of Ca II H and K core emission from the Sun and Sun-like stars. For example, *Lean et al.* [1992, 1995] and *White et al.* [1992] obtain 0.24% of 1368 Wm^{-2} = 3.3 Wm^{-2} for the increase in the 11-year averaged total irradiance and *Zhang et al.* [1994] between 2.5 and 8 Wm^{-2}. Finally, *Lean et al.* [2001] find that long term changes in the Sun's chromospheric emission since the Maunder minimum may exceed recent solar cycle amplitudes by as much as a factor of two, which translates into an irradiance increase of at least 2.6 Wm^{-2}. Another argument is based on the secular evolution of the Sun's open magnetic flux [*Lockwood et al.*, 1999] and its good correlation with irradiance. *Lockwood and Stamper* [1999] deduce therefrom that the solar irradiance has increased by 1.65 Wm^{-2} since 1901. Extrapolating back to the Maunder minimum, when the Sun's open magnetic flux was almost zero [*Solanki et al.*, 2000] we obtain approximately 2.5 Wm^{-2}. Based on different arguments other authors have proposed a much larger increase (4–5 Wm^{-2} by *Hoyt and Schatten* [1993]; 6.8 Wm^{-2} by *Nesmes-Ribes and Manganey* [1992]).

[13] The final argument for sizable secular trends in irradiance comes from magnetograms [*Harvey*, 1994] and the first physical models to explain a secular variation of the Sun's total magnetic field [*Solanki et al.*, 2002]. Between minimum and maximum of the last three activity cycles the Sun brightened by approximately 1.3 Wm^{-2} [*Fröhlich*, 2000], while the magnetic flux at the solar surface deduced from Kitt Peak synoptic charts tripled [*Harvey*, 1994]. This brightening is the balance between the brightening due to faculae (and the network) and the darkening due to sunspots. The ratio between facular brightening and sunspot darkening over a cycle is roughly 2:1 or smaller [see *Knaack et al.*, 2001]. Thus if the magnetic flux in sunspots at activity maximum were completely in the form of faculae, the irradiance variations over a solar cycle would be at least 3 times as large as currently observed. At activity minimum only bright network and faculae are present, while models of solar open and total flux evolution and the comparison with stars indicate that the solar surface was practically free of magnetic flux at the end of the Maunder minimum. Taking the estimate of *Harvey* [1994] for the total magnetic flux at activity minimum, which is very conservative [*Krivova et al.*, 2002a, 2002b], we obtain that the smallest secular change since the Maunder minimum (i.e., the irradiance at current sunspot minimum minus the irradiance during the Maunder minimum) is 1.5 Wm^{-2}.

[14] To this value we need to add the 11-year average of the change in the cyclic irradiance signal since the Maunder minimum. The 11-year average of the cyclic portion of the total solar irradiance is approximately 0.65 Wm^{-2} for recent cycles. During the Maunder minimum we expect this value to be close to zero. Hence an increase of 0.5 Wm^{-2} from the Maunder minimum to today is a conservative estimate. Adding this to the 1.5 Wm^{-2} rise between Maunder minimum and present-day minimum we find that the 11-year averaged total irradiance increased by at least 2 Wm^{-2} between 1700 (the end of the Maunder minimum) and today.

[15] In Figure 3 we replot the quantities already shown in Figure 2 but with the secular part of the irradiance reconstruction now scaled to give a 2 Wm^{-2} increase of the 11-year average of the total irradiance since the Maunder minimum. Because the irradiance variations since 1970 are not affected by this scaling of the secular trend the reconstruction incorporating *Willson*'s [1997] composite now lies closer to the temperature curve. In Table 1 the cases illustrated in Figures 2 and 3 are summarized under the headings 4 Wm^{-2} and 2 Wm^{-2}, respectively. The table reveals that by far the largest influence on s^2 is produced by including or excluding the period after 1970. This is followed by the type of irradiance reconstruction used (cycle-length based or cycle-amplitude based) and then come the remaining parameters, (1) whether the Northern Hemisphere or the global temperature record is employed (not listed in Table 1), (2) whether the *Fröhlich and Lean* [1998a] or the *Willson* [1997] composite of the irradiance is used, or (3) whether the total increase in irradiance since the Maunder minimum amounted to 4 Wm^{-2} or 2 Wm^{-2}.

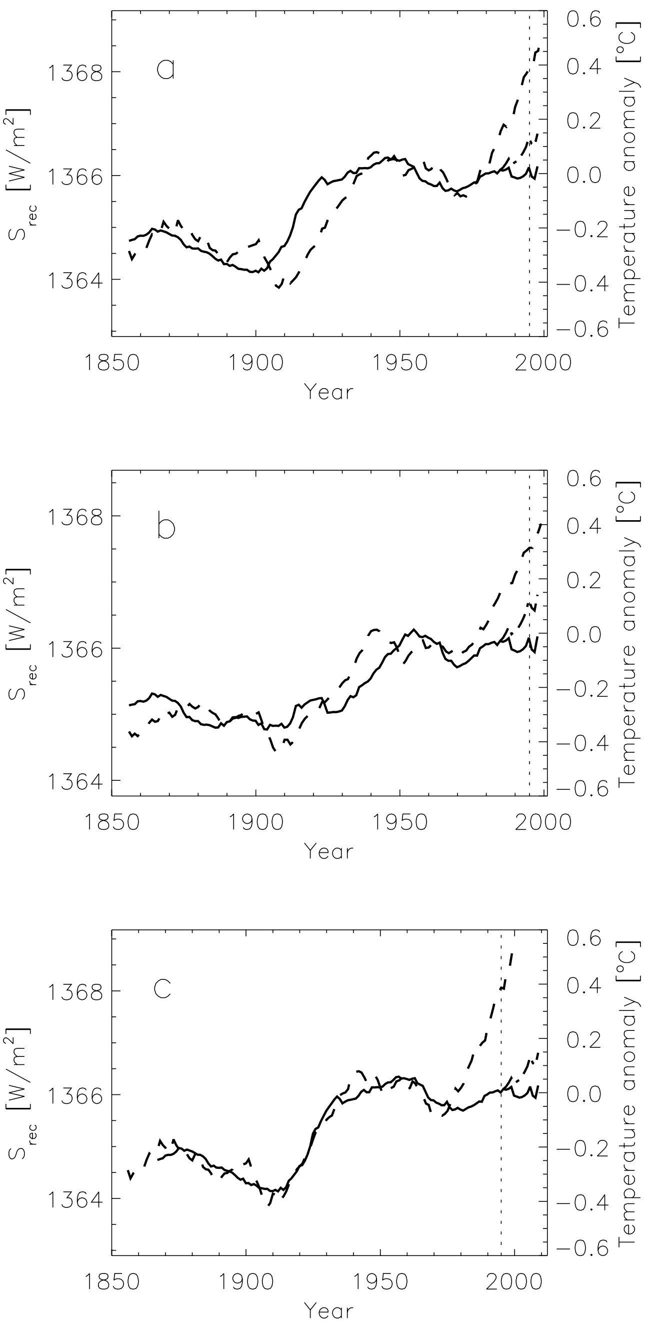

Figure 3. The same as Figure 2 but for irradiance reconstructions with an increase in the 11-year averaged irradiance between 1700 and 1978 of 2 Wm^{-2}.

[16] Note that the various parameters are not independent of each other. For example, whether the cycle-length based or cycle-amplitude based reconstruction is used has a large effect on the change of s^2 produced by including the period 1971–1999. Thus for the cycle-length based reconstruction, s^2 increases by at least a factor of 16 if the last 3 decades are included so that solar total irradiance is expected to have provided a very insignificant contribution to the temperature rise since 1970. Due to the 12-year lag between solar and terrestrial records the secular increase in irradiance shown by *Willson*'s [1997] composite has not had time to significantly affect the climate. This explains why the two composites give such similar results in this case. The situation is different for the cycle-amplitude based reconstruction, in particular when combined with Willson's composite. s^2 only differs by a factor of 1.8 between 1970 and 1999 in this case. One surprising result seen from Table 1 is that unlike the naive expectation outlined earlier in this section, by employing a 2 Wm^{-2} increase in irradiance since the Maunder minimum s^2 increases by a larger amount than if 4 Wm^{-2} is used. From a more careful analysis we found that this difference is produced mainly between 1970 and 1980 when the irradiance deviates more strongly from the temperature in the 2 Wm^{-2} case than for 4 Wm^{-2} (compare Figure 2b with Figure 3b).

[17] A look at Figure 3 reveals that in particular *Willson*'s [1997] composite would suggest a significant solar contribution also in the last decades if the secular variation of solar irradiance follows cycle amplitude and amounts to 2 Wm^{-2} since 1970. Nevertheless, even in this most optimistic case the solar total irradiance variations cannot be responsible for more than roughly half of the steep temperature increase since 1970. This fraction is obtained by comparing the increase since 1970 of the irradiance with that of the global temperature (after both curves have been "normalized" by requiring the χ^2 prior to 1970 to be minimized).

[18] Even this appears excessive for the following reasons. First, model calculations [e.g., *Fröhlich and Lean*, 1998a; *Fligge and Solanki*, 2000] reproduce the composite created by *Fröhlich and Lean* [1998a], but not that of *Willson* [1997] (see, e.g., Figure 1). Second, if the total irradiance increases secularly, the UV irradiance must also increase accordingly. This is not observed (see section 3), in agreement with models of spectral irradiance [e.g., *Fligge and Solanki*, 2000]. See also the discussion in section 5.

3. Solar UV Irradiance

[19] Let us now turn to UV irradiance variations. From the reconstructions of spectral irradiance variations by *Fligge and Solanki* [2000] we deduce that the 11-year UV irradiance closely follows the total irradiance (except for a time-independent factor). Differences arise from the fact that the ratio of cyclic to secular variability is larger in the UV, due to the enhanced brightening of faculae at these wavelengths. Irradiance observations in the UV suffer from insufficient long-term stability of the operating instruments, so that only the Mg II core-to-wing ratio deduced from such data can be used as a reliable proxy of UV irradiance for a sufficient length of time. Such observations are available since November 1978 from the SBUV and SBUV2 instruments on-board the NIMBUS 7, NOAA 9, and NOAA 11 spacecraft (1978–1997) and the SOLSTICE and SUSIM instruments on the UARS satellite (1992–2001). A combined record based on the data sets obtained from these two groups of instruments can be created in two different ways, depending on the calibration used for the NIMBUS 7, NOAA 9, and NOAA 11 data. The calibrations due to *Cebula et al.* [1992] and *Viereck and Puga* [1999] differ only slightly from each other on time-scales of the solar cycle, as can be seen from Figure 4, where both records are plotted (the two upper curves). Figure 4 also displays the

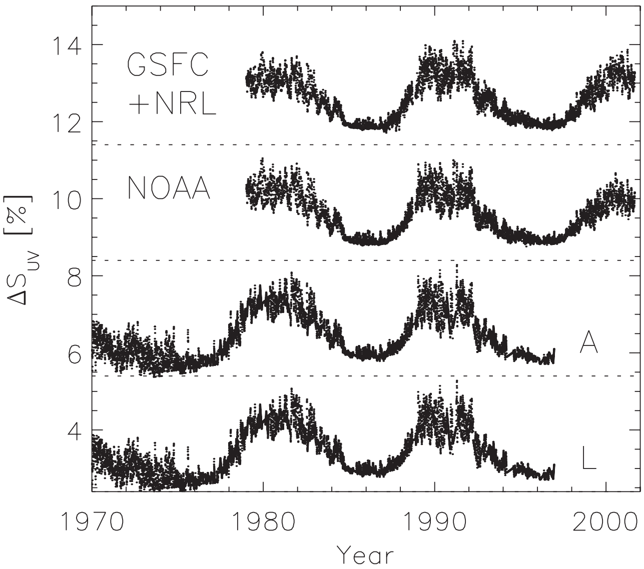

Figure 4. Variation of the UV irradiance for the last three decades. Cycle length (L) and amplitude (A) based reconstructions and the Mg II core-to-wing ratio compiled by NOAA [*Viereck and Puga*, 1999] as well as GSFC and NRL [*Cebula et al.*, 1992] are displaced 0, 3, 6, and 9% along the y-axis, respectively. $\Delta S_{UV} = 0$ corresponds to the Maunder minimum. The Mg II core-to-wing ratio has been scaled to match the modeled UV irradiance variations.

satisfactory match between data and model. For the latter we employed the radiation at wavelengths shorter than 3000Å predicted by the model of *Fligge and Solanki* [2000]. We therefore combine the measured Mg II core-to-wing ratio (1990–2001) with the reconstruction ($\lambda <$ 3000 Å) of *Fligge and Solanki* [2000] for the period 1856–1997 by scaling the former to match the latter during the period 1978–1997. Prior to 1 January 1979 the reconstruction is used; after that date the scaled observations are used. The choice of this date is not critical. We are well aware that the wavelength-integrated irradiance below 3000 Å is a simple, possibly too simple parameterization to describe the solar influence on the chemistry of the middle atmosphere. For example, the gradient with wavelength of the irradiance variability also plays an important role for O_3 chemistry [*Huang and Brasseur*, 1993; *Fleming et al.*, 1995; *Larkin et al.*, 2000; *Rozanov et al.*, 2002]. All the same, we feel the observations are not yet of a quality to warrant a significantly more refined analysis in the context of this paper.

[20] The 11-year average of the UV irradiance record between 1856 and 1999 has a form very similar to the total irradiance, except that the relative change is larger for the UV irradiance. In particular, the 11-year mean is flat since 1975, in agreement with the composite of *Fröhlich and Lean* [1998a] for the total irradiance. If we accept that total and UV irradiance have the same cause, namely changes in the amount and distribution of the magnetic flux at the solar surface [*Unruh et al.*, 1999; *Fligge et al.*, 2000; *Solanki and Fligge*, 2002; *Krivova et al.*, 2003], then this fact provides strong independent support for the composite of *Fröhlich and Lean* [1998a] compared with that constructed following *Willson* [1997]. Since the 11-year mean records of total and UV irradiance are so similar (except for a scaling factor) we refrain from plotting the UV curves separately.

[21] Since neither the model nor the measurements of UV irradiance (according to either calibration) exhibit any significant increase in the last 2 decades, the UV irradiance does not match the rapid increase in temperature since 1970, irrespective of the assumed magnitude of the increase in total irradiance since the Maunder minimum. This is illustrated by the lower half of Table 1, which lists s^2, with s being the standard error of estimate, and correlation coefficients, r_c, obtained from the comparison of UV irradiance with surface temperature. Note that where two numbers are given, the first refers to the NOAA calibration due to *Viereck and Puga* [1999] and the second to the GSFC calibration [*Cebula et al.*, 1992]. Note the striking increase in s^2, by a factor of 2.8–17, when the period 1970–1999 is included. Since the two currently available calibrations agree relatively well with each other, the uncertainty for the trend in the UV irradiance is smaller than for the total irradiance. We estimate that if UV irradiance is the main channel by which the Sun influences climate, then the Sun has contributed less than 30% to the temperature increase since 1970.

4. Cosmic Ray Flux

[22] A third mechanism proposed to affect tropospheric temperature is cloud-cover variations induced by modulations in cosmic-ray flux. These in turn are caused by changes in the Sun's open magnetic field [*Svensmark and Friis-Christensen*, 1997; *Marsh and Svensmark*, 2000]. In this case we are in the fortunate situation that there is a relatively reliable estimate of the evolution of the Sun's open magnetic flux since 1868 [*Lockwood et al.*, 1999; *Solanki et al.*, 2000] as well as of the concentration of the cosmogenic isotope ^{10}Be in Greenland ice [*Beer et al.*, 1990]. Both quantities are closely related to the cosmic ray flux; the first modulates it [*Usoskin et al.*, 2002], while the second is produced by it [*Masarik and Beer*, 1999]. In addition, direct measurements of sufficient quality by the Climax Neutron Monitor (cut-off 3 GV) are available from the University of Chicago since 1953. An overlap of more than 40 years between the open magnetic flux and neutron

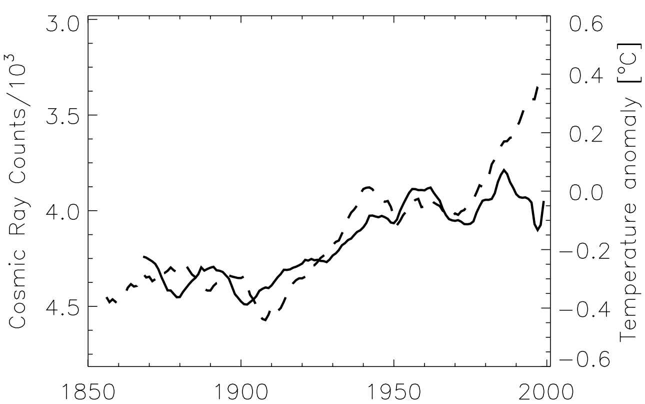

Figure 5. Same as Figure 2b but exhibiting a composite of cosmic ray flux (solid curve, see text) instead of irradiance.

Table 2. Standard Error of Estimate, *s*, and Correlation Coefficient, r_c, for the Cosmic Ray Flux Compared With the Global Surface Temperature

	<1970	<1999
lag	2	
s^2	0.004	0.014
r_c	−0.89	−0.85

monitor data has been used to convert through linear regression the indirect record into cosmic-ray flux for the earlier period. *Lockwood* [2001] found that curves for different hardness factors are proportional to each other so that it is sufficient to consider a single representative value. The Climax data profit not just from the length of the data record, but also yield a slightly higher correlation coefficient compared with other records.

[23] The combined cosmic-ray record (reconstruction up to 1953 and observations thereafter) is plotted in Figure 5 after applying an 11-year smoothing. Also plotted is the global temperature record repeated from Figure 2b. Again, the relative scaling is such that the χ^2 between the solar and terrestrial quantities prior to 1970 is minimized. In this case the two quantities follow each other closely up to 1985, after which they diverge strongly. In Table 2 the s^2 and correlation coefficients are listed for the records between 1856 and 1970 (left column) as well as 1856 and 1999 (right column). The s^2 for the latter period is considerably (roughly a factor of 3) larger. The correlation coefficient once again does not distinguish strongly between the two periods. Table 1 and Figure 5 suggest that changes in cosmic ray flux are also not responsible for more than a small fraction of the temperature rise since 1970. A conservative estimate would be 15% for the full period 1970–1999 (note that the rise in cosmic ray flux between 1970 and 1985 lags temperature and cannot have significantly contributed to it).

5. Conclusions

[24] We have compared records of three solar quantities considered to be candidates for influencing the Earth's climate. We have extended the observed records of these quantities to earlier times by combining them with reconstructions taken from the literature. In all but one case, namely the measured total irradiance record following the intercalibration due to *Willson* [1997], the reconstruction and the data agree relatively well with each other during the period over which they overlap. These combined records of the solar total and UV irradiance as well as the cosmic-ray flux are then compared with climate records. The solar indicators correlate well with the temperature record prior to 1970 (correlation coefficients $\geq$0.83). In the case of total and UV irradiance, although both cycle amplitude-based and length-based reconstructions give highly significant correlations, the correlation due to reconstructions with secular trend following cycle length is higher than that involving cycle-amplitude reconstructions. We have shown that even in the extreme case that solar variability caused all the global climate change prior to 1970, it cannot have been responsible for more than 50% of the strong global temperature rise since 1970 through any of the channels considered here. We believe that even this fraction is too high. Solar total irradiance variations could be responsible for up to 50% of the temperature increase since 1970 only if the intercalibration between different instruments carried out by *Willson* [1997] is correct. The fact that the irradiance reconstruction of *Fligge et al.* [1998] [cf. *Fligge and Solanki*, 2000] agrees far better with the composite of *Fröhlich and Lean* [1998a] than with *Willson* [1997], although the reconstruction was made quite independently of the secular trend in these data, supports the former composite. Note, however, that the Fligge et al. reconstruction is based on combining proxies of facular brightening with different weights. A different choice of weights may well give somewhat different results. The far better agreement of the Fröhlich and Lean composite with the Mg II core-to-wing ratio, the standard proxy of UV irradiance (which also agrees well with the UV-irradiance reconstruction of *Fligge and Solanki* [2000]), also provides strong support for this composite. In view of this and the arguments presented by *Fröhlich and Lean* [1998b] we conclude that the Sun has contributed less than 30% of the global warming since 1970 (unless it is through a channel not considered here).

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N. A. Krivova and S. K. Solanki, Max-Planck-Institut für Aeronomie, 37191 Katlenburg-Lindau, Germany. (natalie@linmpi.mpg.de; solanki@linmpi.mpg.de)