GEOPHYSICAL RESEARCH LETTERS, VOL. 25, NO. 7, PAGES 1035-1038, APRIL 1, 1998

Solar variability and climate change: Geomagnetic aa index and global surface temperature

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Abstract. During the past ~120 years, Earth's surface temperature is correlated with both decadal averages and solar cycle minimum values of the geomagnetic aa index. The correlation with aa minimum values suggests the existence of a long-term (low-frequency) component of solar irradiance that underlies the 11-year cyclic component. Extrapolating the aa-temperature correlations to Maunder Minimum geomagnetic conditions implies that solar forcing can account for ~50% or more of the estimated ~0.7-1.5°C increase in global surface temperature since the second half of the 17th century. Our analysis is admittedly crude and ignores known contributors to climate change such as warming by anthropogenic greenhouse-gases or cooling by volcanic aerosols. Nevertheless, the general similarity in the time-variation of Earth's surface temperature and the low-frequency or secular component of the aa index over the last ~120 years supports other studies that indicate a more significant role for solar variability in climate change on decadal and century time-scales than has previously been supposed. The most recent aa data for the current solar minimum suggest that the long-term component of solar forcing will level off or decline during the coming solar cycle.

1. Introduction

In the absence of a long-term record of satellite-based measurements of the solar constant, the investigation of solar variability and climate change has been based to a large extent on proxy indicators of solar irradiance. *Eddy* [1976] initiated the modern study of this topic by pointing out that the Maunder Minimum (1645-1715) in sunspot activity corresponded to the coldest excursion of the Little Ice Age (1450-1850). Subsequently, the idea that the Sun could drive climate change was given impetus by correlations between terrestrial temperature and: (a) 11-year averages of sunspot number [*Reid*, 1987], and (b) solar cycle length [*Friis-Christiansen and Lassen*, 1991]. In particular, various authors have noted that solar irradiance proxies and global surface temperatures declined for an interval during the middle of the present century while the concentration of greenhouse gases such as CO_2, which cause global warming, rose monotonically.

In this study, we investigate the usefulness of a new proxy for solar variability and climate change – the time variation of the geomagnetic aa index [*Mayaud*, 1972]. The aa index is a measure of the disturbance level of Earth's magnetic field based on magnetometer observations at two, nearly antipodal, stations in Australia and England. Like the global temperature, the aa index has exhibited a secular increase since ~1900 [*Feynman and Crooker*, 1978]. It is well established that geomagnetic activity is driven by the solar wind. The fact that 11-year averages of the sunspot number and the aa index are highly correlated for the past 150 years [*Cliver et al.*, 1998] indicates that the long-term rise of the aa index is a solar rather than an instrumental or internal (to the Earth) effect.

2. Analysis

Figures 1(a) and (b) contain annual averages of aa and the sunspot number (SSN), respectively, for the last ~120 years. Note that while sunspot numbers return to low values at each solar minimum, aa min-

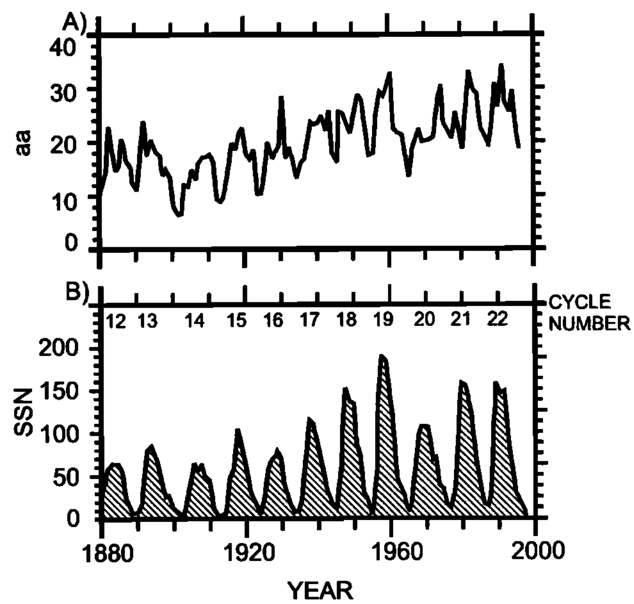

Figure 1. (a) Yearly averages of the geomagnetic aa index, 1880-1996. (b) Yearly averages of the sunspot number (SSN), 1880-1996.

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Paper number 98GL00499.
0094-8534/98/98GL-00499$05.00

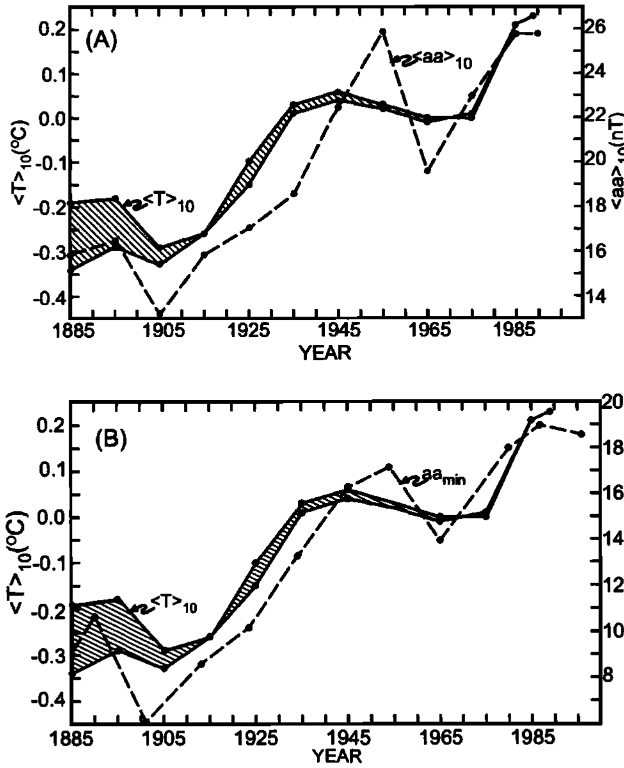

Figure 2. (a) Comparison of decadal averages of the geomagnetic aa index ($< aa >_{10}$) and Earth's surface temperature ($< T >_{10}$) from 1880-1990. (b) Comparison of solar cycle minimum values of the geomagnetic aa index (aa_{min}) and ($< T >_{10}$) from 1880-1990.

ima reflect the long-term level of solar activity revealed by cycle-averaged sunspot numbers or by the envelope of peak sunspot numbers. Since ~1900, the increase of the aa baseline from solar minimum to solar minimum has been so pronounced that geomagnetic minima in recent cycles have higher annual aa averages than the aa maximum of cycle 14 in ~1910. *Cliver et al.* [1998] have shown that solar cycle averages of aa and SSN are highly correlated ($r = 0.96$). Thus, following *Reid's* [1987] demonstration of a correspondence between 11-year running averages of SSN and terrestrial temperature, one would expect a similar correspondence between aa and temperature. This correspondence is shown in Figure 2(a), where we used the global temperature reconstruction of *Parker et al.* [1994] which gives decadal averages of surface temperature ($< T >_{10}$) from 1881-1990, relative to average temperatures from 1951-1980. Those authors used different areal averaging techniques and various sets of coverage criteria for input data to give several tables of temperature values. In Figure 2(a), the shaded area represents, to first order, the range of values encompassed by their various data handling prescriptions as given by columns 1 and 4 (Globe) in their Table 2. The aa and temperature profiles show several points of similarity, the most significant being the general rise to mid-century followed by the dip to a minimum in ~1970 and the increasing values of the last 20 years. On the negative side, the peak in the temperature record at mid-century leads that in the aa curve.

A somewhat better correspondence is apparent in Figure 2(b) where we have plotted the global temperature vs. the aa baseline, obtained simply by connecting solar cycle minima of the aa parameter (aa_{min}) in Figure 1(a). Generally, the aa minima occur within a year following SSN minima [*Wilson,* 1990]. The 1980 aa minimum which occurred near solar maximum is a notable exception. We used it in Figure 2(b) because it is lower than the "true" aa minimum between cycles 20 and 21 in 1977. Using the 1980 rather than the 1977 minimum value of aa strengthens the correlation with temperature as can be seen in Figure 3 where the underlying long-term aa component is shaded and the unused 1977 minimum is circled. Figures 4(a) and (b) contain scatter plots of temperature vs. aa corresponding to the curves plotted in Figures 2 (a) and (b), respectively. For Figure 4(b), we used the annual mid-range temperature (T^*_{min}) for each aa minimum year in Figure 2(b). The regression line for Figure 4(a) is

$$< T >_{10} = 0.0391 < aa >_{10} - 0.842 \qquad (r = 0.90) \qquad (1)$$

and that for Figure 4(b) is

$$T^*_{min} = 0.0397 aa_{min} - 0.584 \qquad (r = 0.95) \qquad (2)$$

We can extrapolate (1) and (2) to Maunder Minimum geomagnetic conditions to infer the solar-induced temperature change since ~1650. *Cliver et al.* [1998] have recently used correlations between SSN and aa to deduce both solar cycle averages (~7 nT) and solar cycle minimum values of aa (~0-1 nT) during the Maunder Minimum. Substituting these values into (1) and (2), respectively, implies that $< T >_{10}$ and T^*_{10} were both ~0.77°C below current temperatures (+0.21°C from 1981-1990) during the Maunder Minimum (Figure 4). Estimates for the temperature deficit during the Maunder Minimum (relative to the present) range from ~0.7-1.5°C [*Crowley and North,* 1991; *Lean and Rind,* 1997]. Thus our extrapolations of (1) and (2), taken at face value, indicate that an increase in solar irradiance could account for ~50-100% of the net global warming over the past ~350 years.

Assuming a climate sensitivity of 0.6°C/(Watt/m^2) (a midrange value) indicates an irradiance reduction of 0.54% (~1.3 W/m^2 at the top of the atmosphere) during the Maunder Minimum based on our inferred solar-

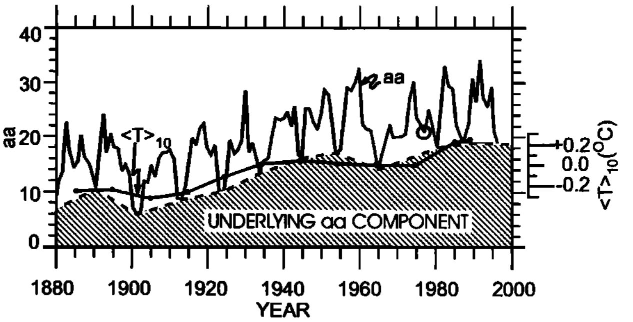

Figure 3. Comparison of the record of geomagnetic activity (aa) and the global surface temperature of the Earth ($< T >_{10}$) over the last ~120 years. Solar cycle minima of the aa index are connected by dashed lines and the underlying component of aa is shaded.

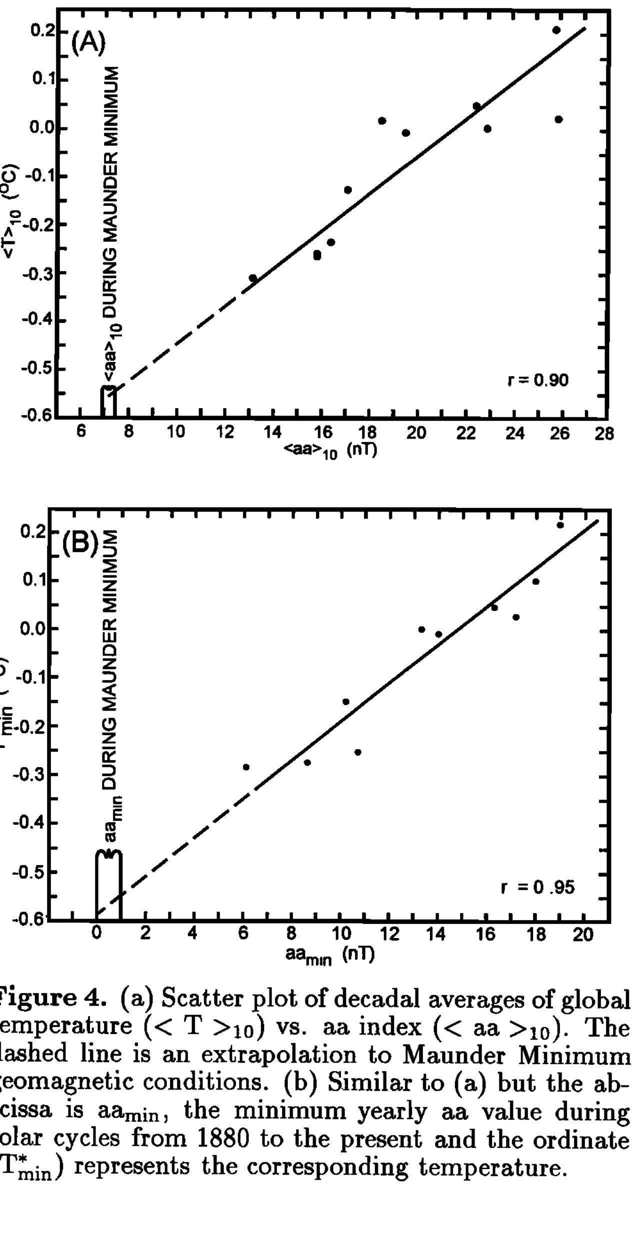

Figure 4. (a) Scatter plot of decadal averages of global temperature ($< T >_{10}$) vs. aa index ($< aa >_{10}$). The dashed line is an extrapolation to Maunder Minimum geomagnetic conditions. (b) Similar to (a) but the abscissa is aa_{min}, the minimum yearly aa value during solar cycles from 1880 to the present and the ordinate (T^*_{min}) represents the corresponding temperature.

induced temperature decrease of 0.77°C. In comparison, *Lean et al.* [1992] obtained an irradiance reduction of 0.24% from an extrapolation of a relation between Ca II emission and satellite-based irradiance measurements to assumed Maunder Minimum conditions. A range of values (0.2-0.6%) encompassing our inferred 0.54% reduction was obtained by *Zhang et al.* [1994] from observations of brightness and magnetic activity variations in solar-type stars. A slightly greater decrease of ~0.65% was recently calculated by *Reid* [1997] under the assumption that the temperature during the Maunder Minimum was ~1°C cooler than at present.

We qualify our results by noting that they are obtained from a correlative study based on a small number of samples. Our analysis does not take into consideration other known drivers of climate change such as anthropogenic greenhouse-gas warming or cooling by volcanic aerosols. The unaccounted-for presence of greenhouse-gas warming in our calculation will overstate the importance of solar forcing derived from (1) and (2), resulting in artificially-high estimates of irradiance and solar-driven temperature changes since the Maunder Minimum.

3. Discussion

The correlation we find between the aa baseline and terrestrial surface temperature suggests the existence of a long-term (low-frequency) component of solar irradiance that tracks the average level of geomagnetic (sunspot) activity. In this view, the absence of pronounced 11-year temperature fluctuations (related to the unshaded area under the aa curve in Figure 3), is attributed to the damping effect of the thermal inertia of the oceans. *Wigley and Raper* [1990] have shown that such damping can reduce the impact of even a relatively strong solar cycle with ~0.1% peak-to-peak irradiance variation [*Willson and Hudson,* 1991] to a barely detectable temperature signal (~0.02°C). Thus it is the slow variation of the underlying solar signal, as revealed by the aa_{min} time history, rather than the 11-year cycle in either aa or sunspots that shows up most strongly in the temperature record.

The fact that the aa index at solar minimum retains a value proportional to its flanking sunspot maxima, rather than falling to near zero values like the sunspot number, is thought to be a reflection of the interchange of poloidal and toroidal (sunspot) magnetic fields via the solar dynamo [*Babcock,* 1961]. Differential solar rotation transforms poloidal fields at solar minimum to toroidal fields of the subsequent sunspot maximum. Thus a large (small) peak SSN for a solar cycle implies strong (weak) poloidal fields and high (low) geomagnetic activity at the preceding sunspot minimum. The point we wish to make here is that the aa index provides evidence for a long-term (low-frequency) component of solar variability that persists through sunspot minimum and may therefore affect Earth's climate.

While we hypothesize that the changing aa baseline is somehow related to a long-term irradiance variation on the Sun, there is another possibility and that is that the solar wind itself influences climate. This could occur as a result of cosmic ray modulation and its effects on the global electric circuit and cloud nucleation [e.g., *Tinsley,* 1997; *Svensmark and Friis-Christensen,* 1997]. To date, however, such models have failed to gain wide acceptance, at least in part because of the classic objection that the energy contents of the solar wind and galactic cosmic rays are many orders of magnitude below the Sun's radiative output [*Lean and Rind,* 1997].

Our study suggests that solar variability has contributed significantly to the long-term change of Earth's climate during the past 350 years. The aa-T correlations in Figure 4 indicate that 50-100% of the ~0.7-1.5°C increase in global temperature since the Maunder Minimum was due to solar forcing. As noted above, Earth's climate is affected by a host of phenomena [e.g., *Lean and Rind,* 1997] besides solar variability – greenhouse warming, anthropogenic and volcanic aerosol cooling, effects of ozone, internal ocean-atmosphere couplings, etc. More sophisticated analyses than ours, that take these additional phenomena into account, indicate that the role played by solar forcing, while important, is at the low end of our calculated 50-100% range. *Crowley and Kim* [1996] found that ~30-55% of climate change on decadal to century time scales can be attributed to solar variability while *Lean and Rind* [1997] concluded that about half of the 0.55°C surface warming since 1900 (and only one-third of the warming since 1970) could be attributed to solar forcing. Similarly *Reid* [1997] suggested that solar and anthropogenic greenhouse forcing were roughly equal contributors to the rise in global temperature during the first half of this century.

Even these reduced estimates, however, indicate that the Sun has played a more substantial role vis-à-vis anthropogenic effects in the global warming of this century than has generally been supposed. For example, the Intergovernmental Panel on Climate Change [*Schimel,* 1996] estimated that the change in solar forcing between 1850 and 1990 was only ~0.3 W/m^2 at the top of the atmosphere vs. 1.5 W/m^2 for forcing by anthropogenic CO_2 [cf., *Reid,* 1997]. While acknowledging the importance and threat of such anthropogenic forcing, we are reminded that there is evidence, albeit mixed [*Folland et al.,* 1990; *Crowley and North,* 1991; *Hughes and Diaz,* 1994; *Grove and Switsur,* 1994], for temperatures comparable to present day values during the interval from 900-1250 A.D., well before the industrial age. The latter part (1100-1250 A.D.) of this so-called Medieval Warm Period had inferred solar activity comparable to present levels [*Jirikowic and Damon,* 1994].

The recent aa minima plotted in Figure 3 suggest that the long-term solar component of climate change is leveling off or decreasing. This conclusion can be extended by grouping solar cycles in pairs of even-numbered cycles followed by odd-numbered cycles, e.g., 12-13, 14-15, reflecting the 22-year magnetic cycle on the Sun. For each of the five such pairs of cycles in Figure 1, we note that the yearly aa value of the minimum lying between the even and odd cycles lay on or above a line connecting the aa minima at the beginning and end of the pair. This appears to be a manifestation of the tendency for high speed solar wind streams and recurrent geomagnetic activity to be stronger on the decline of even-numbered solar cycles [*Cliver et al.,* 1996]. The implication is that the geomagnetic minimum between cycles 23 and 24 (in ~2007) will not exceed that of the 1996 geomagnetic minimum (18.6 nT) which itself was slightly lower than the 1987 aa minimum (19.0 nT), and that the underlying trend in solar irradiance will continue to be flat or downward. As of this writing it appears that the average aa value for 1997 will be even lower (~16 nT) than that of 1996. Such a leveling off or decline of the long-term solar component of climate change will help to disentangle its effects from that of anthropogenic greenhouse warming. Our aa-based inference of a flat or declining secular component of solar irradiance contrasts with the results of a recent analysis of satellite-based irradiance measurements by *Willson* [1997] who found an increase of 0.036% for the 1996 solar minimum relative to that of 1986.

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(Received September 5, 1997; revised January 14, 1998; accepted January 19, 1998.)