THE SUN–EARTH CONNECTION IN TIME SCALES FROM YEARS TO DECADES AND CENTURIES

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Abstract. The Sun–Earth connection is studied using long-term measurements from the Sun and from the Earth. The auroral activity is shown to correlate to high accuracy with the smoothed sunspot numbers. Similarly, both geomagnetic activity and global surface temperature anomaly can be linked to cyclic changes in the solar activity. The interlinked variations in the solar magnetic activity and in the solar irradiance cause effects that can be observed both in the Earth's biosphere and in the electromagnetic environment. The long-term data sets suggest that the increase in geomagnetic activity and surface temperatures are related (at least partially) to longer-term solar variations, which probably include an increasing trend superposed with a cyclic behavior with a period of about 90 years.

1. Introduction

The Sun affects the Earth's environment in a variety of ways and on many different time scales: The Solar radiation is the main energy source for the Earth's biosystem and the atmosphere. On the other hand, the interaction between the solar wind particles and electromagnetic fields with the magnetosphere controls the geomagnetic conditions. High-energy cosmic rays have access also to lower parts of the atmosphere; the solar cosmic rays mainly affect the mesosphere at 40–60 km altitude, but the galactic cosmic rays may penetrate down to 10–20 km altitudes (Callis and Lambeth, 1998; Svensmark and Friis-Christensen, 1997). Both the Sun and the Sun-Earth coupling thus vary in time scales that range from much longer than the solar cycle to time scales of only a few minutes.

Examining the long-term (tens of years) changes in the Sun-Earth system is difficult, because it requires homogeneous data sets over very long times. Such long records are available from the Sun in terms of the sunspot number and from the Earth in terms of the geomagnetic indices and land surface temperatures. Quantitative data of the sunspot numbers exist from about 1700, and since Carrington's measurements (1853–1861), also the latitudes of individual sunspots have been recorded (see Greenwich Photoheliographic Results). The global *aa*-index time series that gives a measure of the geomagnetic activity is available since 1868 (Mayaud, 1972), and has been further extended by more than two solar cycles to 1844 using single site observations from Helsinki (Nevanlinna and Kataja, 1993).

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Visual observations of northern lights give a time span of about 500 years for solar-terrestrial relationships (Silverman, 1992; Nevanlinna, 1995).

The fraction of auroral nights follow in general the phase of sunspot cycle: most auroras are seen around the sunspot maximum during the ascending and descending part of the 11-year solar cycle. There have been several anomalous periods when practically no auroras were observed at mid-latitudes (e.g., in Central Europe), where northern lights are rather rare but regular provided solar activity is high (Nevanlinna, 1995). The most famous such period is the Maunder-minimum during 1645−1700. Other such periods occurred during 1790−1825 (Dalton's minimum) and 1900−1910. Magnetic activity (as quantified by the aa-index) and mean sunspot number were also at low level during these periods. These observations support the assumption that, in addition to the 11-year solar cycle, the solar activity has also longer periods (22 years, 90 years), and that these variations are reflected in the geomagnetic conditions at Earth (Gleissberg, 1965; Cliver and Boriakoff, 1996).

The climatic records show a sharp increase of 0.66° in the mean temperature since about 1880 (Parker *et al.*, 1994; Lean *et al.*, 1996; Soon *et al.*, 1996; Solanki and Fligge, 1999; Jones *et al.*, 1999). As this roughly coincides with the industrialization period, one of the key questions has been how much of this change is introduced by anthropogenic causes and what portion can be associated with changes in the solar forcing. Furthermore, the increasing dependence on satellite technology of the present- day society has brought the need to understand and predict the magnetospheric plasma environment, or 'space weather' (Baker, 1998).

Friis-Christensen and Lassen (1991) correlated the long-term temperature variation with the length of the solar cycle, and argued that much of the temperature change can be associated with changes in the solar activity. Lockwood and Stamper (1999) and Stamper *et al.* (1999) substantiated this argument; they deduced a temperature rise of 0.2° caused by variations in the total solar irradiance and coronal source magnetic flux. This result is very similar to that by Lean *et al.* (1995) who compared the Sun at present and during the Maunder minimum to, respectively, cyclic and non-cyclic Sun-like stars.

The highly relativistic particles that have direct access to the lower atmosphere may act as nucleation centers and hence affect cloudiness and the mean temperature (Svensmark and Friis-Christensen, 1997). The flux of these galactic cosmic rays is also modulated by the solar activity, the particles have easier access to the inner heliosphere during low solar activity. Cosmic rays also provide evidence for very long-term solar change, causing isotopes like ^{10}Be and ^{14}C to be deposited in ice sheets (Beer *et al.*, 1998). These mechanisms mean that long-term solar variability has direct effects on the Earth's biosphere as well as on the near-Earth space environment.

In this paper, we investigate the variations in these couplings over time scales that are longer than the well-known 11-year solar cycle variations. We first discuss the direct measurements of the sunspots, auroral occurrence, geomagnetic activity, and surface temperatures that are available from the past 150 years and their interrelationships. We then discuss other, more complete data sets that are available during much more limited periods, and how these can be extended using the existing long-term measurements to cover longer time periods. We summarize our present understanding of the intercoupling of the particle and radiative effects in the Sun-Earth coupling.

2. Long-Term Observations of the Sun–Earth System

The top panel of Figure 1 shows a comparison of the geomagnetic activity (*aa* index and its Helsinki extension 1844–1999) and sunspot number (R) during 1700 –1999. It is evident that the geomagnetic activity generally follows the sunspot activity with two activity maxima, one during the rising solar activity and another during the declining phase of the solar cycle (Gonzales *et al.*, 1990; Gorney, 1990). There is a general rising trend in both the sunspot cycle strength and in the geomagnetic activity during 1900–1995. Data from the past few years (1995–2000) indicate that the maximum may have been reached and a decrease in general level of activity might follow (Cliver *et al.*, 1998).

In order to examine the longer-term behavior, the second panel of Figure 1 shows the sunspot data smoothed over 45 years. The data set clearly shows a periodicity of about 90 years (Gleissberg, 1965; Sonett, 1982; Feynman, 1988) together with a rising tendency especially in the minimum values. When we superpose a curve of the mean magnetic activity smoothed over 45 years, from 1840 until 2000, it is clear that the geomagnetic activity presents similar 90-year periodicity. Again, the observations would indicate that the maximum is reached and that the trend will be toward decreasing activity in the next decades to come.

The next two panels show a comparison of the sunspot number with the annual number of auroral nights. The auroral data is adopted from global statistics of visual observations by Fritz (1873) and Legrand and Simon (1987). The third panel shows the activity smoothed over the 11-year solar cycle, whereas the bottom panel shows the same data smoothed over half of the Gleissberg cycle (45 years). The auroral data follow the sunspot variations to many details in both plots, which also demonstrates the good quality of the old visual observational data. Furthermore, comparison of the annual number of auroral nights and geomagnetic activity gives correlation coefficients typically greater than 0.8 (Legrand and Simon, 1987; Nevanlinna, 1995) indicating a close coupling between the auroral occurrence and geomagnetic activity. As the generally increasing trend is present also in the auroral data, it can be assumed to hold also for the geomagnetic indices, where the data series do not yet cover several 90-year cycles.

In addition to the systematic tendency for increasing peak cycle heights since the 1840s in the sunspot data, the mean latitude of sunspots in each hemisphere has increased by about 3° since early 1900’s (Pulkkinen *et al.*, 1999). Thus, on average,

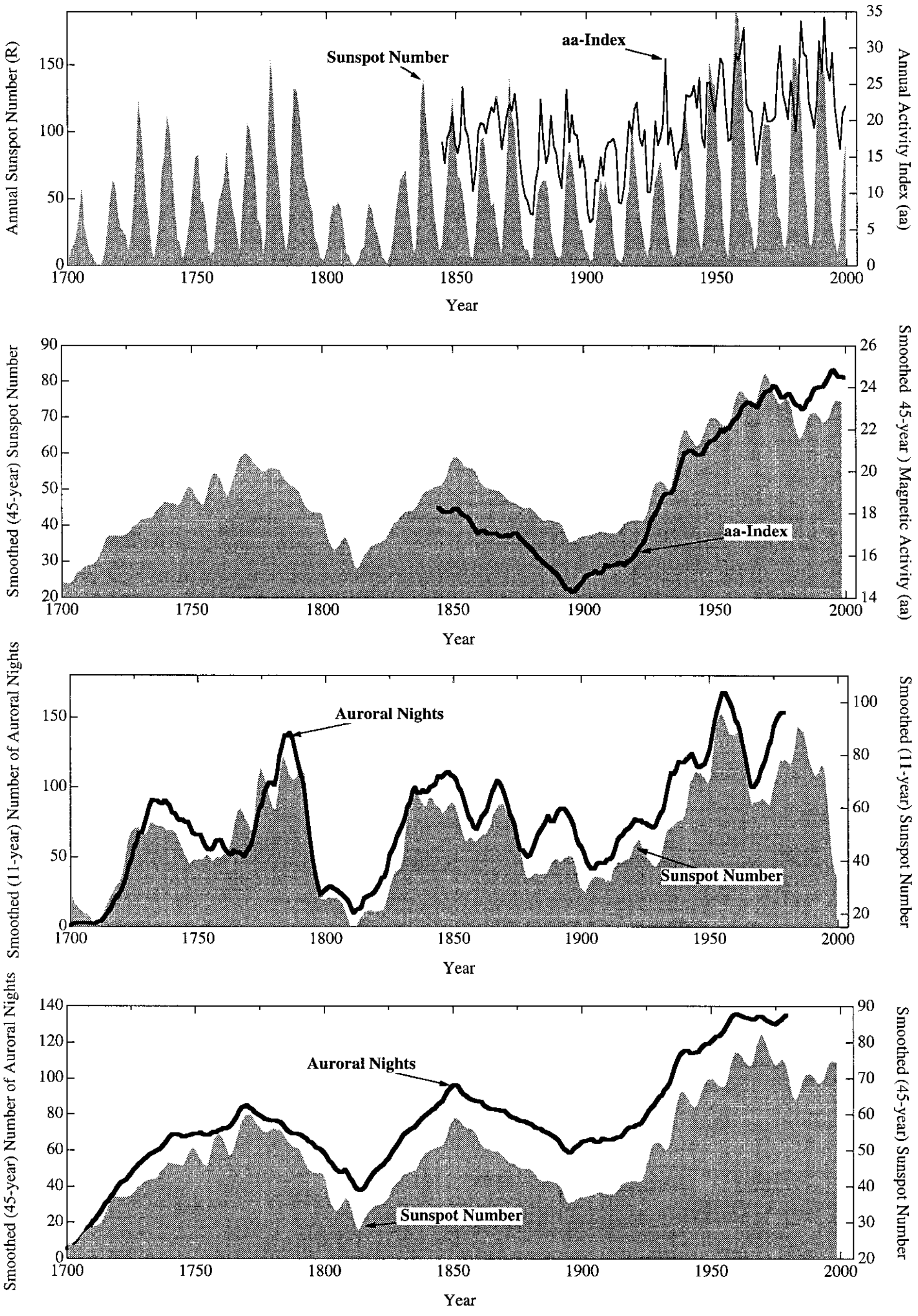

Figure 1. Comparison of solar and geomagnetic activity. From top to bottom: Annual sunspot numbers (shaded) and *aa* index (black). 45-year smoothed sunspot number and 45-year smoothed *aa*-index. 11-year smoothed sunspot number and 11- year smoothed number of auroral nights. 45-year smoothed sunspot number and 45- year smoothed number of auroral nights.

the sunspots today reside further away from the equator, which reflects changes in the large-scale solar magnetic field configuration. Furthermore, the solar magnetic equator as deduced from the sunspot data shows a sinusoidal behavior with a period of about 90 years and amplitude of about 1.3° (Pulkkinen *et al.*, 1999).

There is strong evidence that the sunspot maximum value correlates well with the geomagnetic activity condition (as measured eg, by the *aa*-index) at the preceding minimum (Hathaway *et al.*, 1999), which provides a technique for predicting the sunspot maximum with a lead time of 3–4 years. In the top panel of Figure 2 we have applied this approach for predicting the mean sunspot latitude during an entire sunspot cycle. The mean values of *aa* at the sunspot minimum year during 1844–1996 have been offset by half of the solar cycle length (5.5 years). The solid line shows the actual measured sunspot latitudes as means over the solar cycle (Pulkkinen *et al.*, 1999). The figure clearly illustrates the good correlation between the sunspot latitude variation with the minimum of magnetic activity during each sunspot cycle. In addition to the long-term (90-year) trend, the two data sets also show similar cycle-to-cycle variability before 1920. It is interesting to note that whereas the magnetic activity already shows a decreasing trend during the past two solar cycles, the latitude variations do not yet reveal that decrease.

Similarly, the magnetic activity can be correlated with the global temperature change. The bottom panel of Figure 2 shows a good correlation between the magnetic activity and the global temperature anomaly (taken from Friis-Christensen and Lassen, 1991). The similarities of the curves in both panels of Figure 2 would indicate that all three processes (solar activity, geomagnetic activity, and climatic changes) have the same causal origin in the Sun's temporal variability.

3. Space-Era Observations of the Sun and the Solar Wind

The solar wind density, velocity, and interplanetary magnetic field (IMF) intensity and direction are the main controlling factors of the solar wind–magnetosphere coupling. These parameters have been measured since the early space era, and quite reliable and detrended data set has been constructed beginning from 1963 in the OMNI data set available at NSSDC. The most important drivers of geomagnetic and auroral activity are the solar wind magnetic field intensity, solar wind velocity (or pressure), solar wind electric field (as computed from $\mathbf{E} = -\mathbf{V} \times \mathbf{B}$), and the ϵ parameter ($\epsilon = 10^7 v B^2 l_0^2 \sin^4(\theta/2)$, Perreault and Akasofu (1978). E_Y is thought to be proportional to the electric field which, during periods of southward IMF when dayside reconnection is in progress, penetrates to the magnetosphere and enhances magnetospheric convection. On the other hand, the ϵ parameter gives the average energy per unit time (or power) with which solar wind energy is transferred from the solar wind into the magnetotail. Typical numbers leading to geomagnetic activity are a $E_Y \sim 2$ mV m^{-1} and $\epsilon = 10^{11}$ W for a time period lasting for about 1–2 hours.

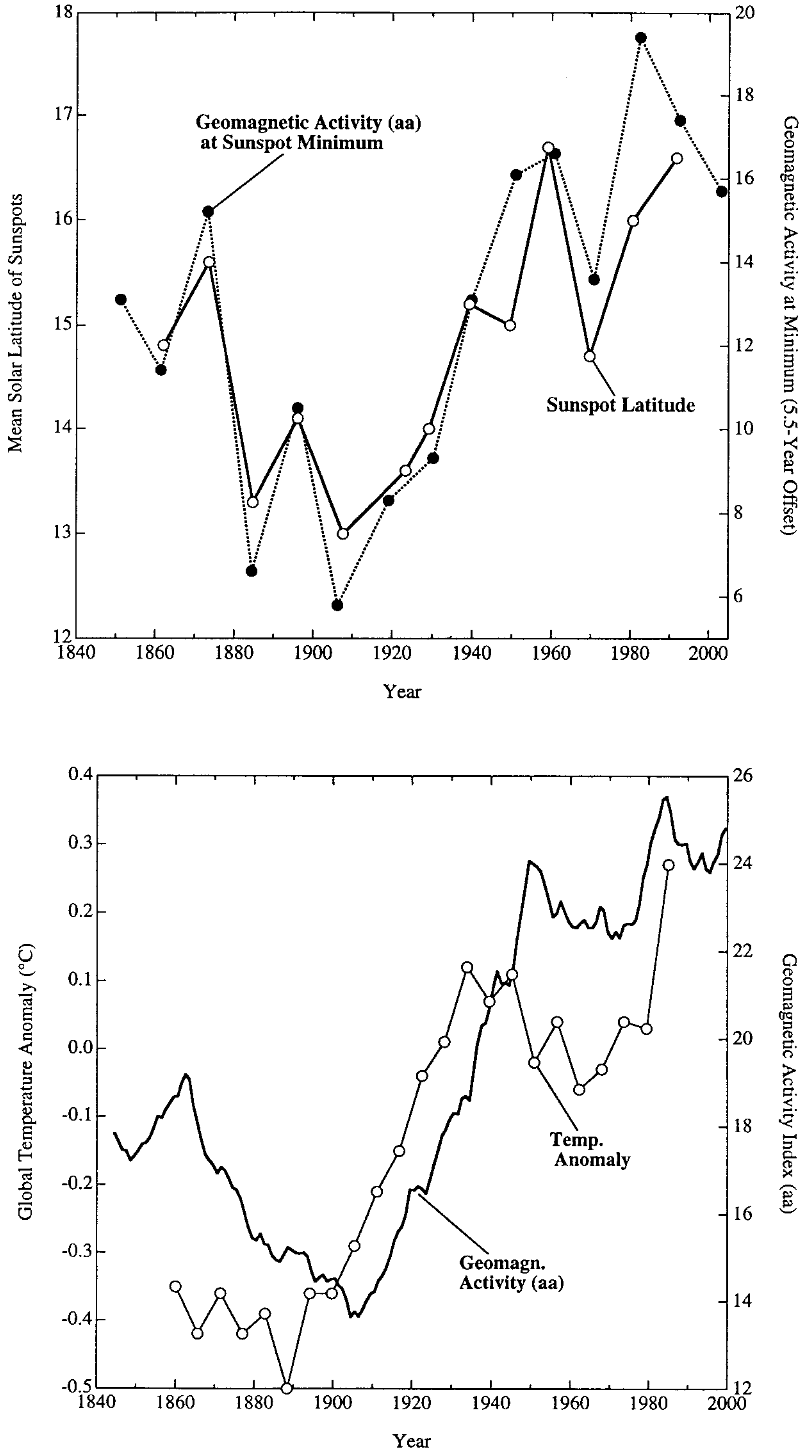

Figure 2. (Top) Solar cycle minimum of geomagnetic activity index *aa* (solid line) and solar cycle mean latitude of sunspots (dotted line). (Bottom) Solar cycle minimum of geomagnetic activity index *aa* (solid line) and solar cycle mean of the global temperature anomaly.

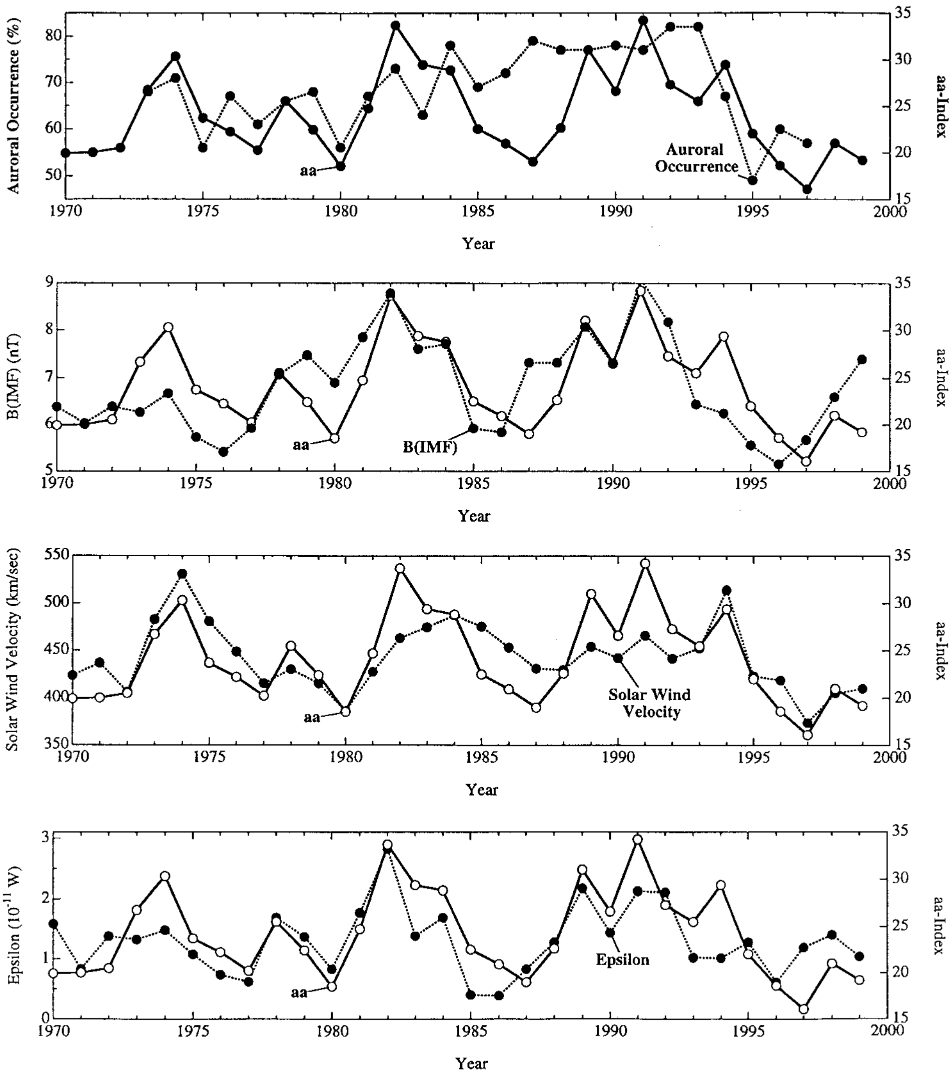

Figure 3. From top to bottom: Geomagnetic activity index *aa* (solid line) and auroral occurrence (dashed line). *aa* index and interplanetary magnetic field intensity (dashed line). *aa* index and solar wind velocity (dashed line). Auroral occurrence and solar wind electric field (solid line) *aa* index and ϵ parameter (dashed line).

Figure 3 shows the correlation of these driver parameters with geomagnetic activity and auroral occurrence during 1970–1999. During this period, all-sky camera measurements from Finland have been quantitatively analyzed to determine the probability for auroral occurrence (see Nevanlinna and Pulkkinen, 1998, 2000, for more details). When both the magnetic field intensity and the solar wind velocity show solar cycle variability, it is not surprising that the same cyclic behavior is seen also in the coupling functions deduced from these parameters. Especially, the ϵ parameter is well-correlated with the *aa*-index. Furthermore, a linear fit to the radial component of the IMF shows that the mean field has risen by about 1 nT in the past 30 years (Lockwood *et al.*, 1999).

The Sun's brightness can be parametrized by the total solar irradiance, which has been monitored by a variety of satellite instruments since 1980. While there is a clear solar cycle variation of about 0.1%, due to problems in calibration between the different instruments it is not clear whether an increasing trend exists: Willson (1995) suggest an increasing trend of about 0.036% per decade, but Frölich and Lean (1998) dispute this result by showing detrended and cross-calibrated data that do not reveal a longer-term increasing trend. The solar cycle variations arise from the combined effects of the increased number of solar faculae and the increased number of sunspots. At the wavelengths that dominate the total radiative output, the increase caused by facular emissions near solar maximum is larger than the decrease from the larger area covered by sunspots, leading to a net increase in the irradiance during high solar activity (Lean *et al.*, 1995).

4. Long-Term Effects at Earth

The interplanetary magnetic field emanates from the Sun, and hence its longer-term variability arises from changes in the amount of magnetic flux crossing the solar corona at a distance where the solar field has become approximately radial. Assuming that variations in the radial field component are small, the total flux threading the source surface is $F_S = 0.5(|B_{\text{radial}}|4\pi R^2)$, where $R = 1$ AU for measurements made in the near-Earth interplanetary space (Lockwood and Stamper, 1999). As the average IMF is well- represented by the Parker spiral theory, the radial component can be found from the total field magnitude.

Lockwood and Stamper (1999) argued that the irradiance measurements show, in each data set independently, a similar dependence of the total solar irradiance of the coronal source magnetic flux. They concluded that there is a linear relationship between the total solar irradiance and the coronal source magnetic flux, and that both effects arise from the magnetic properties of the Sun (Lean *et al.*, 1995).

Lockwood *et al.* (1999) showed that the *aa* index can be converted to the total magnetic flux leaving the Sun by calibrating it using satellite measurements of the interplanetary magnetic field at 1 AU. They found that the total magnetic flux leaving the Sun has grown by a factor of 2.3 since the turn of the century. Figure 4(a) (after Lockwood and Stamper, 1999) shows the inferred solar source magnetic flux and the sunspot numbers. These results would indicate that there are changes in the solar magnetic field during the past 160 years that display cyclic variation with a period close to the Gleissberg cycle (90 years). Furthermore, using the average relationship between the source flux and irradiance and the geomagnetic data, Figure 4(b) shows the solar irradiance variations from 1868 to present time (after

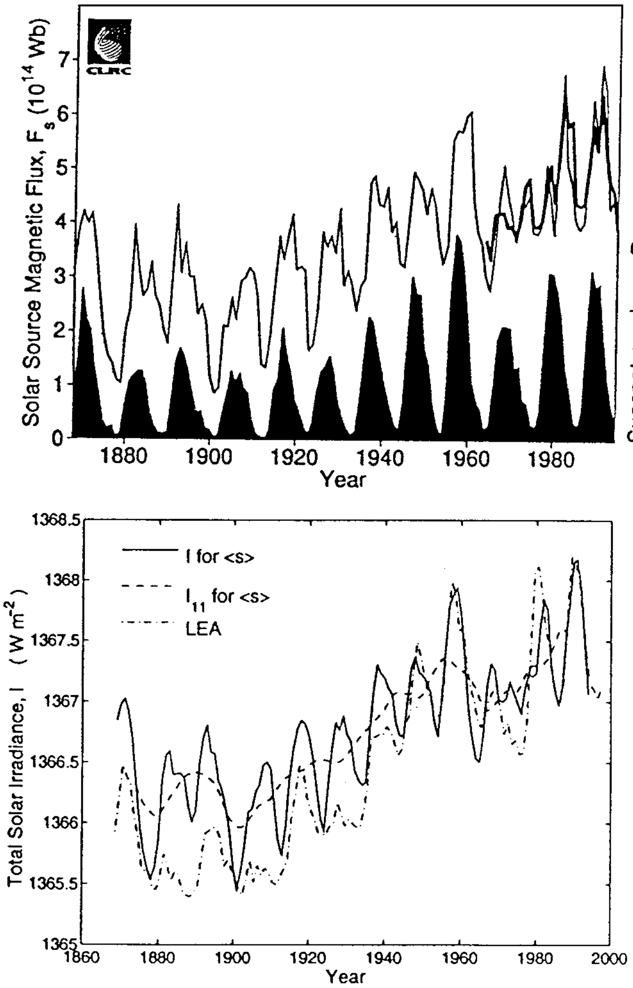

Figure 4. (Top) Annual means of the coronal source magnetic flux as deduced from the *aa* index and sunspot number R. (Bottom) Variation of the total solar irradiance I as deduced from the correlation with the coronal source magnetic flux and the sunspot number *R* (after Lockwood and Stamper, 1999).

Lockwood and Stamper, 1999). Similarly to Figure 4(a), the irradiance variations show strong solar cycle modulation and an increasing trend from the early 1900's until present time.

The results above suggest a rise in the radiative forcing at the top of the atmosphere of 0.3 W m^{-2} (Lockwood and Stamper, 1999), which is about 20% of the effect of anthropogenic greenhouse CO_2 (1.5 W m^{-2} estimated by the Intergovernmental Panel on Climate Change). Using a simple linear relationship between the total solar irradiance and the surface temperature variation, the results indicate a temperature rise of 0.24° since solar cycle 11, when the temperature records

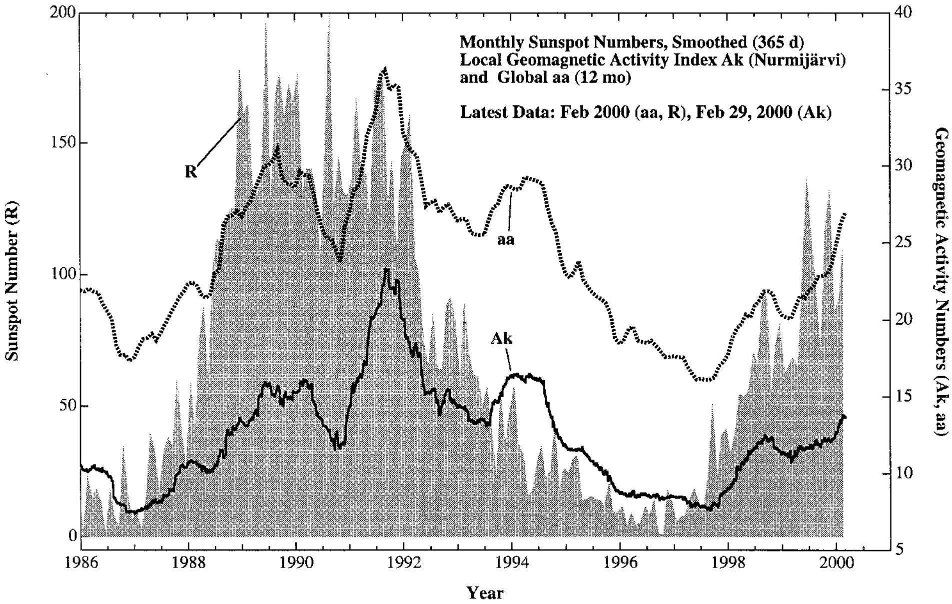

Figure 5. Monthly sunspot numbers smoothed over one year (grey shading), local geomagnetic activity index Ak (Nurmijärvi) (solid line) and global geomagnetic activity index *aa* (dotted line).

show a rise of 0.66° over the same interval (Parker *et al.*, 1994; Lean *et al.*, 1995; Lockwood and Stamper, 1999). These numbers indicate that about a third of the observed temperature increase can be due to effects that are of solar origin (see also Cliver *et al.*, 1998).

5. Discussion

We have reviewed the interconnections between the solar magnetic activity, solar radiative output, geomagnetic activity, auroral occurrence, and global temperature anomalies. We showed that many of these parameters are closely correlated with each other, suggesting a common origin of the effects. We argued, following Lockwood *et al.* (1999), that the irradiance variations can be traced to variability in the long-term solar magnetic activity, which at Earth leads to natural coupling between the geomagnetic and climatic effects.

The future solar activity is therefore of key importance for climatological issues, for space weather issues, and for those who enjoy the auroral displays. Figure 5 shows the solar and geomagnetic activity updated to most recent times available. It is evident from the figure that the activity maximum during solar cycle 23 will be significantly smaller than during the previous cycles: the sunspot numbers are much lower than those predicted, and the geomagnetic activity shows already a decreasing trend with maximum only half of the maximum during solar cycle 22.

The magnetic activity, of course, may peak only during the declining phase of the solar cycle, which is still a few years ahead. On the other hand, the Gleissberg periodicity would suggest that we might be moving to the next period of decreasing solar activity. If this is the case, we might see fewer than expected space weather events causing damage and even loss of spacecraft. In the best case, we might also be able to slow down the global warming when the solar activity would not as strongly add to the anthropogenic changes.

The mean latitude of sunspots on each hemisphere has been rising practically during the entire 20th century and possibly seems to now have reached a maximum. This may be a sign of a strengthening dipole moment of the solar magnetic field, which quite certainly has an effect on the terrestrial magnetic environment. The connection between the sunspot latitude and dipole field intensity is similar to the migration of sunspots during the 11-year cycle: At the beginning of a solar cycle, the dipolar field is quite strong, and generates sunspots at high latitudes. Later in the cycle, the dipole is weaker and the twisted field lines closer to the equatorial regions produce the sunspots there. Thus, the sunspot latitude measurements strongly support the conclusions about the enhancing solar source magnetic flux during the 1900s.

Along with the strength of the dipole moment, the center of mass of sunspots seems to be varying, more systematically, over a period of about 90 years. This can be understood as a result of the oscillation of the quadrupolar mode of the global solar magnetic field as discussed by Pulkkinen *et al.* (1999): when the quadrupolar mode is strongest, it enhances the dipolar field in the other hemisphere and diminishes in the other, resulting in a maximal asymmetry (1.3 deg) in sunspot positions (Pulkkinen *et al.*, 1999).

Resolving these interesting long-term connections between solar magnetic field, sunspots, and geomagnetic activity at the Earth clearly require even longer data series than are available today. For long-term series of solar-terrestrial parameters, like the *aa*-index, it is important to sustain the inherent homogeneity of the recordings for decades and even centuries in order to ensure data reliability. This poses a challenge to the field of solar-terrestrial physics: in addition to development of new advanced measurement technologies, we need to maintain the observatories providing data that make studies like this possible.

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