International Journal of the Physical Sciences Vol. 5(7), pp. 1040-1049, July 2010
Available online at http://www.academicjournals.org/IJPS
ISSN 1992 - 1950 ©2010 Academic Journals

Full Length Research Paper

Spectral analysis of solar variability and their possible role on global warming

N. El-Sayed Aly

Department of Physics and Chemistry, Faculty of Education, Alexandria University, Egypt.
E-mail: naglaa_aly_2000@yahoo.com.

Accepted 29 June, 2010

In this study, the effect of solar variability on global warming has been studied. This enables us to understand the existence of solar variability effects on temperature. Monthly, four components that may be closely associated with the climate have been studied, which are geomagnetic activity index aa, solar sunspot number Rz from 1868 - 2008, global surface temperature (GST) from 1880 - 2008 and total solar irradiance TSI from 1978 - 2003. The clear 11-year variation was found in Rz, TSI and aa due to the variation of solar activity, while the 21.3 year variation was found only in GST. It is related to the changes in the polarity of main solar magnetic field, in which the obtained result demonstrates that the interplanetary magnetic field (IMF) effect is more powered on GST. It is believed that the solar and anthropogenic greenhouse forcing are roughly equal contributions to the rise in global temperature during the recent years. Finally, the power law index (n) for Rz and TSI have a higher value than aa and GST. However, this indicates that the modulations of PSD of Rz and TSI are higher than the PSD of the others.

Key words: Geomagnetic induction, total solar irradiance, global warming.

INTRODUCTION

The sun is the chief driving force of the terrestrial atmospheric processes. Hence, any variations in atmospheric processes are attributed to variation in solar radiation and its modulation by the earth's orbital motion. However, the observed variations cannot be explained fully by the variation in solar radiation. Some of these variations have been attributed to cosmic rays of both galactic and solar origin. It is interesting to note that energy input by cosmic rays in the earth's atmosphere is about 10^{-9} times that of solar energy and hence it is unlikely that cosmic rays could influence the atmosphere processes (Devendraa and Singh, 2010). Observation evidences show that the total cloudiness and precipitation reduce when cosmic ray fluxes in the interplanetary space and the atmosphere decreases (Forbush decrease) (Veretenenko and Pudovkin, 1994; Pudovkin and Babushkina, 1992; Miroshnichenko, 2008). Further, diverse reconstructions of past climate change revealed clear associations with cosmic ray variations recorded in cosmogenic isotope archives (Kirkby, 2007). For example, the 1690 - 1700 decade was the coldest during the last 1000 years and during the period that ^{10}Be concentration had the largest peak. The variation in ^{10}Be is a signature of changes in cosmic ray flux. Global temperature and ^{10}Be concentration have opposite trends. Sevenmark (2000) plotted a magnitude of change in ^{10}Be concentration and change in temperature during the period of Maunder minima and earlier periods, which might have been the principal cause of the ‘little’ ice age (Kirkby, 2007; Lean et al., 1992). During the Maunder minima, the absence of strong magnetic field region on the surface of the sun might have affected the solar wind flow and hence modified the characteristic features of cosmic rays incident on the earth`s atmosphere.

Kirkby (2007) had presented an association of high galactic cosmic ray (GCR) flux with cooler climate and low GCR flux with a warmer climate. Ionization produced by cosmic rays in the troposphere and stratosphere produces ultrafine aerosols which may act as cloud condensation nuclei (Yu and Turco, 2001; Tinsley et al., 2000; Tripathi and Harrison, 2002; Tinsley, 2004). The aerosol layers have also significant effect on the earth's atmosphere heat balance through scattering of solar beam in the forward direction and hence effective reduction in solar constant (Dickinson, 1975). The short lifetime (~ few days) of aerosols in the troposphere results in significant spatial and temporal variations in aerosol particle concentration, size and composition. The high variability leads to one of the largest uncertainties of anthropogenic climate forcing. The variation in aerosol in the lowest few kilometers of the atmosphere leads to local turbulent fluctuations of space charge density which impose a time-varying electric field. This electric field at times may be comparable in magnitude to the electric field maintained by global thunderstorm activity and thus affects the global electric circuit (Rycroft et al., 2000; Rycroft and Fullekrug, 2004; Siingh et al., 2007; Siingh et al., 2008). It has been suggested that the global warming may result in enhanced convective activity of thunder-storm and in turn increased thunderstorm production on a global scale (Markson and Price, 1999). The temperature during the last century on the earth's surface was increasing by ~ 0.6 (Hansen et al., 1999). However, its effect on lightning is not yet quantified. Stozhkov (2002) had suggested two mechanisms for heating, namely, solar influence on the weather and climate and the influence of human activities on the atmospheric processes (such as greenhouse effect). Researchers attributed the increase in global temperature (GT) to the rise in green house effect caused by the increase of carbon dioxide emitted by the earth's surface (Rahmstorf et al., 2004), while others attributed global warming to the decrease of the sulfate aerosols (kristánsson et al., 2002). Lean et al. (1995) have calculated the correlation between surface temperature of Northern hemisphere and solar irradiance (reconstructed from solar indices) from 1610 to 1994 and showed the coefficient to be 0.86 in the pre-industrial period from 1910 to 1800. Extending this correlation, they have suggested that solar forcing may have contributed about half of the observed 0.6°C surface warming since 1860 and one third of warming since 1970. The remaining change in global temperature during the pre-industrial period may be due to cosmic rays forcing and other natural processes. Lockwood et al. (1999) found that the total magnetic flux, leaving the sun and driven by the solar wind, has risen by a factor 2.3 since 1901, leading to the global temperature, which has increased by 0.5°C.

Several physical quantities that vary with the magnetic activity of the sun and which may affect the global climate have been identified. These are: (a) the total solar irradiance (TSI), which is the value of integrated solar energy flux over the entire spectrum, arriving to the top of the terrestrial atmosphere at the mean sun-earth distance (the astronomy unit, AU). Changes in total solar irradiance lead to changes in heat input of the lower atmosphere. Relatively, recent measurements of solar irradiance have shown the sun's output to vary by about 0.1% on decadal times scales (FrÖhlich and Lean, 1998), which is sufficient to account for a solar-induced global average temperature change of about 0.1 K (Wigley and Raper, 1990); (b) solar ultraviolet radiation, which varies by several percent over a solar-cycle. The hypothesis is that changes in the ozone concentrations and heating the stratosphere, where the ultraviolet radiation is absorbed, coupled dynamically to the lower atmosphere (Haigh, 1996) and (c) galactic cosmic rays. These effects are modulated by long-term solar magnetic activity, by changes in the source of galactic cosmic rays and in the earth's magnetic field (Sharma, 2002; Shaviv, 2002; Courtillot et al., 2007).

Solanki (2002) and Le Mouel et al. (2005) claimed a good correlation between geomagnetic field changes, solar irradiance and global temperature. Vieria and da Silva (2006) reported a cooling effect of ~18 Wm^{-2} in the inner region of the southern hemisphere magnetic anomaly (SHMA). They also reported that correlation between net radiative flux and GCR increases in the inner region of SHMA. The presence of SHMA involves stronger cosmic ray cloud interaction in the lower field region and enhances cooling, whereas in the outer region, weaker cosmic rays/ cloud interaction leads to less cooling or heating effect. Recently, Courtillot et al. (2007) showed a connection between climate and geomagnetic filed variations at various time-scales (secular variation ~10 - 100 years, historical and archeomagnetic changes ~100 - 5000 years and excursion and reversals~10^3 - 10^6 years). However, the involved mechanism is not known.

The effect of solar activity parameters upon global temperature changes have also been the concern of researchers (Lassen and Friis-Christensen, 2000; El-Borie et al., 2007). However, indices of geomagnetic disturbances measure the response of energetic solar eruptions that actually affect the earth. Geomagnetic activity seems to be the possible link through which the solar activity controls the earth's climate (Landschiedt, 2000; Shah and Mufti, 2005).

However, there is much need to refine the study’s under-standing of key natural forcing mechanisms of the climate, including solar irradiance changes, in order to reduce uncertainty in its projections of future climate change. The aim of this work is study the possible role of some solar variability parameters such as the aa geoma-gnetic index, the sunspot number and the total solar irradiance in global temperature changes. The study compared the power spectral density (PSD) of the Rz, aa and TSI with that of the continuous records of the GT in order to get a closer look at a possible connection between them.

RESULTS AND DISCUSSION

The used data are the global surface temperature (GST) measurements(http://www.ncdc.noaa.gov/oa/climate/research/anomalies/anomalies.html) provided by the National Climate Data Center via the National Oceanic and Atmospheric Administration, USA, during the period (1880 - 2008). In addition, we have used the aa geomagnetic activity index and the smoothed sunspot numbers Rz provided by the WDC for Solar - Terrestrial

Physics (http://www.wdcb.rssi/stp/online_data.en.html) via Russian Academy of Sciences Geophysical Center, from 1868 to 2008. Furthermore, the total solar irradiances (TSI) from 1978 to 2003, which were obtained from The National Geophysical and Solar-Terrestrial Data Center (http://www.ngdc.noaa.gov/stp/SOLAR/solarirradiance.html) have been selected.

Different preliminary treatments are applied to the data before performing any analysis. So, gaps were linearly interpolated. When the sample data include spurious trends or higher order polynomial components with a wavelength longer than the record length $T_r = N\Delta t$, the most common technique for trend removal is to fit a low-order polynomial to the data using the least squares procedures. However, long term trends were performed.

A series of power spectral density (PSD) have been performed. The (PSD), describe how the power of a signal or time series is distributed with frequency. Here, power can be the actual physical power, or more often, for convenience with abstract signal, it can be defined as a squared value of the signal. This instantaneous power (the mean or expected value of which is the average power) is then given by:

$$P = S(t)^2 \quad (1)$$

The PSD, which is the Fourier Transform of the normalized autocorrelation function of lag τ, R (τ) of the signal, can be treated as a stationary random process.

$$S(f) = \int_{-\infty}^{\infty} R(\tau) e^{-2\pi f \tau} d\tau \quad (2)$$

The power of the signal in a given frequency band can be calculated by an integration over the positive and negative frequencies,

$$P = \int_{F_1}^{F_2} S(f)df + \int_{-F_2}^{-F_1} S(f)df \quad (3)$$

The power spectral density of a signal exists if and only if the signal is a wide-sense stationary process. If the signal is not stationary, then the autocorrelation function must be a function of two variables, so no existing, but similar techniques may be used to estimate a time-varying spectral density. Fast Fourier Transformations (FFT) have been used to yield the power spectral density (PSD). The results were smoothed using the Hanning window function. This is necessary since most of the disturbed features will completely disappear, while the significant peaks are clearly defined. Nevertheless, the particular window chosen does not shift the positions of the spectral peaks.

Figure 1 (a, b) displays the time profile of the 5-month running averages for the total solar irradiance (1978 – 2003) and the sunspot number (1868 - 2008). Before 1979, there are no direct measures of solar irradiance; however, sunspots have been counted for many hundreds of years. Direct satellite measurements of solar total irradiance from 1978 - 1992 indicate an amplitude of variation of ~ 0.14% during one sunspot cycle, approximately in phase with the changes in surface magnetic activity (Soon et al., 1996). Under the assumption that the solar irradiance changes are due to the magnetic field, the variations of total solar irradiance is roughly proportional with the sunspot cycle at the solar surface (Usoskin et al., 2005). This agrees with Figure 1. Solar irradiance varies during the Schwabe cycle because bright solar faculae and dark sunspots modulate the sun`radiation. Both faculae and sunspots are magnetic phenomena that occur more frequently during times of higher solar activity. At the visible wavelengths that dominate the total solar radiative output, the facular emission close to the maximum solar activity exceeds the corresponding sunspot deflect by a factor of 1.5, causing a net total irradiance increase. Facular emission becomes increasingly larger than sunspot darkening at shorter UV wavelengths, which also vary in phase with solar activity (Lean et al., 1995).

Figure 2 (a and b) is same as Figure 1, for the aa geomagnetic index (1868 - 2008) and global temperature GT (1880 - 2007). Plot 2a shows that geomagnetic activity (aa index) has changed similarly to other measurements of solar activity, which indicate an increase in the early part of the 20th century, followed by a little overall change in the second half of the 20th century. These results are of interest, because changes in geomagnetic activity are thought to influence the number of cosmicrays that strike the earth (http://www.brighton73.freeserve.co.uk/gw/solar/solar.htm).

The 2b plot illustrates substantial month-to-month variability of global temperature, as well as, coherent long-term change over the period 1880 to 2008. The time interval based on the coverage of both pre-industrial and fast industrial growth era was witnessed in this period. We notice that, the global temperature had a tendency to increase almost steadily for more than hundred-year ago, around the year 1880.

In Plot 2 (a and b), the studied period has been divided, according to the state of GST, into three main periods (1880 - 1940; 1940 – 1970 and 1970 - 2008). The major features are:

[1] During the period 1880 - 1940 (1st warming region), the aa magnitudes are low or moderate. In addition, there are only two significant peaks in 1892.17 and 1930.33. Concomitantly to these peaks, global temperatures showed a sustained warming after the first peak till the year of 1901.83. The two considered peaks occurred slightly before the solar activity cycle 13 (1889 - 1901) and in the declining phase of cycle 16 (1923 - 1933), respectively. In addition, the temperatures increased

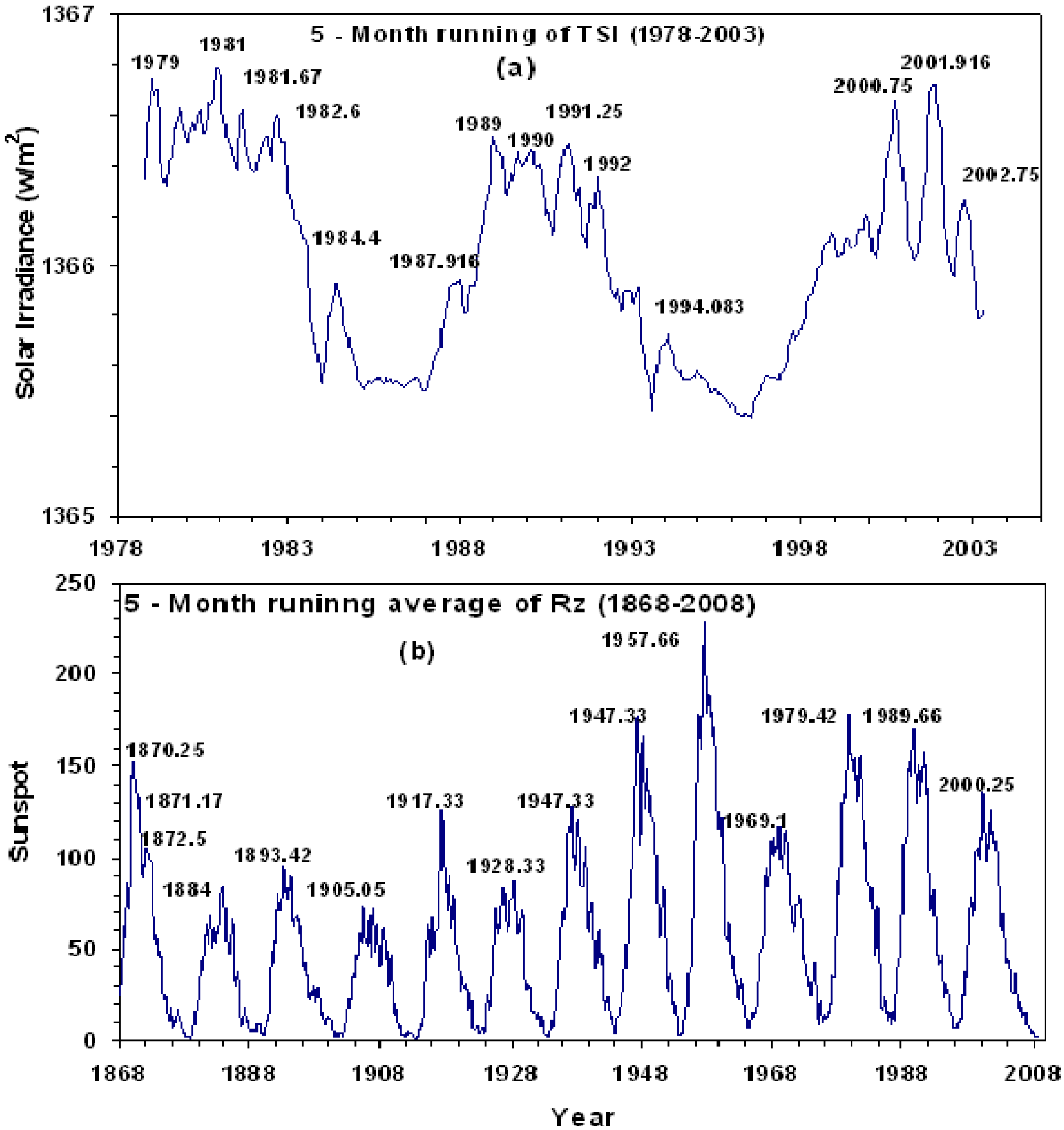

Figure 1. 5-month running average of TSI (panel a) and Rz (panel b).

after-the second peak to the year of 1931.66. These increases were observed later by 1.33 - 9.66 years. In contrast, remarkable strong variations in aa magnitudes were observed earlier by 6 - 7 years (El-Borie et al., 2007). Landsheidt (2000) showed that global temperature lags the aa index by 4 - 8 years and concluded that future change in global temperature may be read from the leading aa data. Generally, the aa maxima had an irregular pattern and two aa maxima were observed, that is (double peaked modulations), one closer to the maximum solar activity period and the other in the descending phase (Kane, 1997; El-Borie, 2001a, b). It is believed that the first peak is caused by coronal mass ejections, whereas the second peak is caused by geomagnetic disturbances due to the coronal-hole fast streams, which are more frequent in this part of each cycle (Richard et al., 2000). In some cycles (1985 - 1996), the geomagnetic aa have three peaks structure. The first peak is before or in the solar maximum and the other two are in the descending phase of the solar activity cycle.

[2] During the period (1940 - 1970], that is, the global cooling period, the averages of aa showed great fluctuations. These fluctuations in aa are due the to corresponding variations in the solar activities. The maximum solar activity decreased from cycle 11 to 14

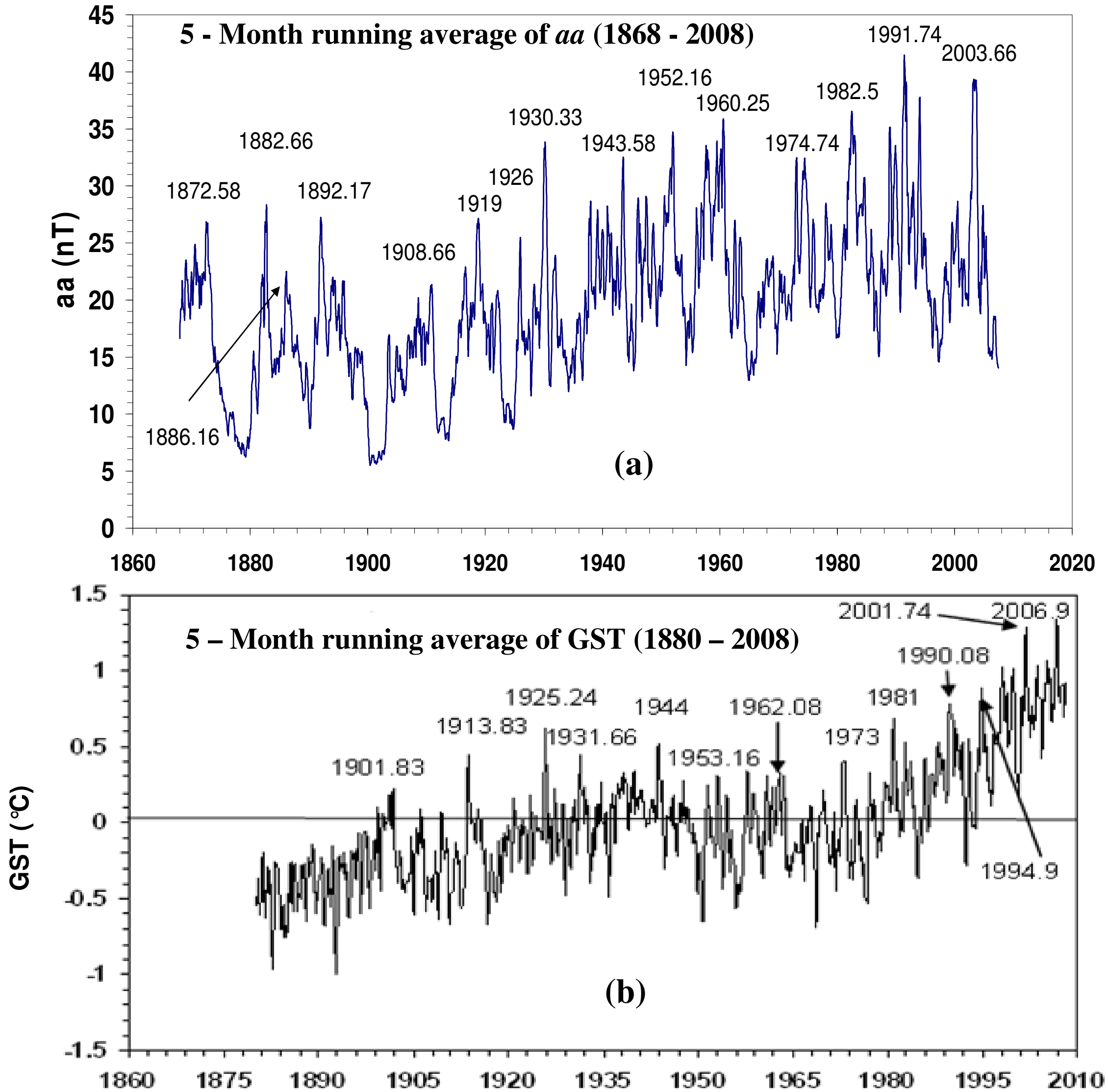

Figure 2. 5-Month running average of *aa* (panel a) and GST (panel b).

(1867 - 1913) and increased thereafter up to cycle 19 (from 1913 - 1964). It decreased considerably in cycle 20 (1964 - 1976) and rose to moderate levels in cycles 21 and 22 (1976 - 1996) and then decreased again in cycle 23 (1996 - 2004).

[3] During the period 1970 - 2008 (the second warming period), in which the increase in GT was faster and smoother than in the first warming region, the aa geomagnetic magnitudes values have greatly increased than the two previous periods (El Borie et al., 2007). The largest peak, over the considered period, was in 1991.74 and the warmest year was 2001.74, which was 10-year apart. The second peak was in 2003.66 and the global warming peak was in 2006.90. For comparison, the separation-time between them was 3.24-year. In other studies (El Boire et al., 2007), the separation- time of both periods was 7years. However, there has been a strong warming trend over the past 50 years. We should notice that, the GT in 1998 was associated with one of the strongest El-Ninos in recent centuries. Generally, there are two classes of physical mechanisms employed to describe the fluctuations in global temperature. The first involves the strong correlations that show the inverse relationship between the strength of interplanetary magnetic field (IMF) and galactic cosmic ray intensity. This factor is correlated with the formation of low cloud cover (Marsh and Sevenmark, 2000). The second involves the strong correlation between the total solar irradiance and low cloud cover (Kristjansson et al., 2002). However, there is a third process that might contribute to global warming.

To assess the solar climate link, it is important to know

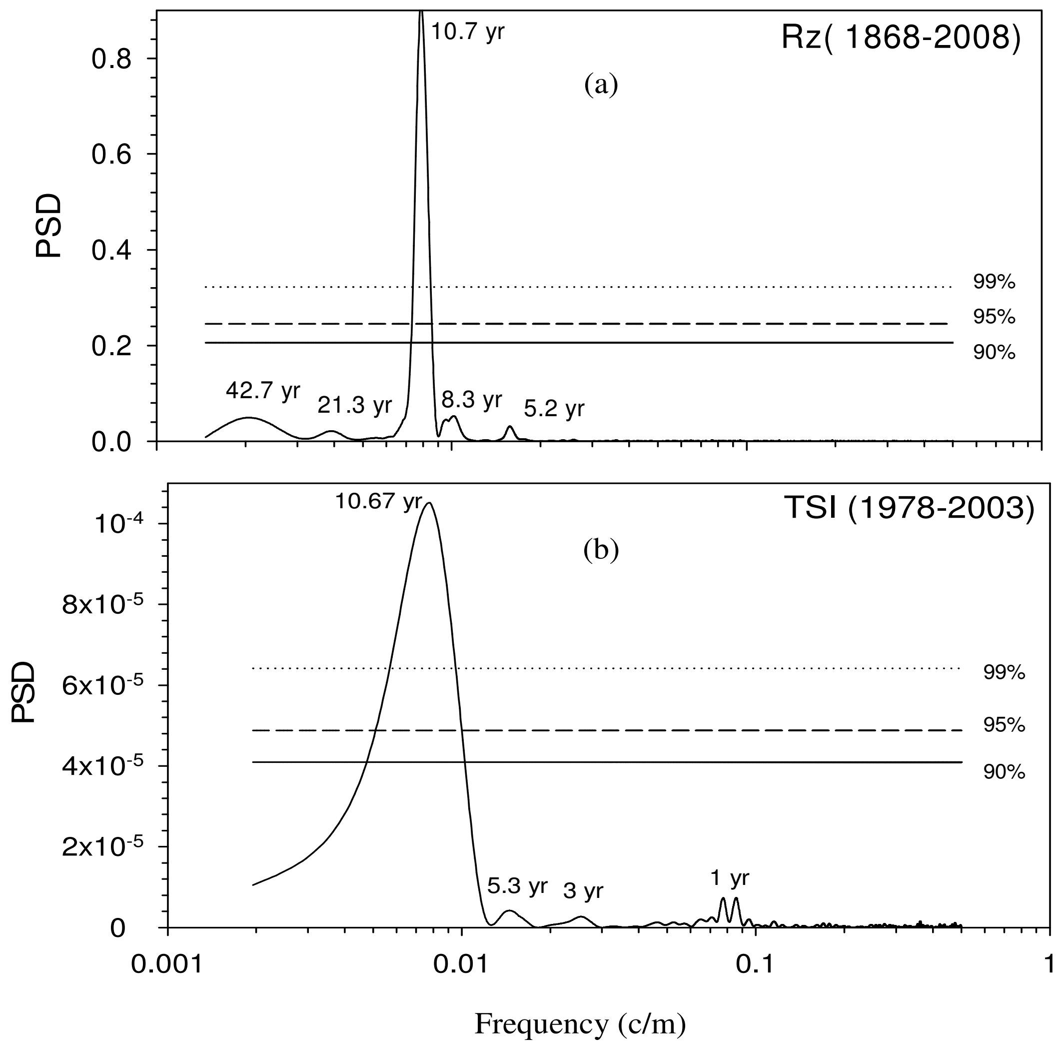

Figure 3. PSD of Rz (panel a) and TSI (panel b). The confidence levels 90, 95 and 99% are shown.

the periodicities involved and their interactions with climate phenomena. A series of power spectral density (PSD) have been performed. Figure 3 (a, b) shows a comparison of the PSD for the Rz (1868 - 2008) and TSI (1978 - 2003), while Figure 4 (a, b) shows a comparison of the PSD for the aa (1868 - 2008) and GST (1880 - 2008). The large amount of the data is the cause of high fluctuations. Numbers are added to assist in determining the relative locations of peaks in years (yrs). The indicated statistical uncertainties (dashed lines) show the 99, 95 and 90% confidence levels. Table (1) lists the existence of significant peaks with the confidence levels. From Table (1), we can conclude that the peak at the 34-year exist only in the aa index at a 99% level of confidence. It should be noted that only GT shows strong 21.3 years periodicity at a 99% significant level. The ~ 22 years variation is due to the polarity of the solar magnetic cycle (Hale cycle). This proves that the (IMF) effect is more powered on GST than the solar activity cycle. The polarity of solar magnetic field may be playing an important role in the mechanism that produces the modulation of cosmic rays and the variation in solar diurnal variation having a 22-year periodicity (Ahluwalia, 1988; Sharma and Yadav, 1993).

The amplitude of solar diurnal variations shows an 11-year variation and the values of amplitude decrease with increasing the median rigidity of stations. Also, the phase of the solar diurnal variations showed a 22-year variation according to the polarity of interplanetary magnetic field (IMF). The phase, during the positive magnetic polarity (directed away from northern solar hemisphere) shows relatively, small change and large decrease in amplitude in the higher rigidity data than during the negative magnetic polarity (directed towards the northern solar hemisphere) (El-Borie et al., 1995). The high-speed solar-wind streams (HSSWS) emanate from both solar

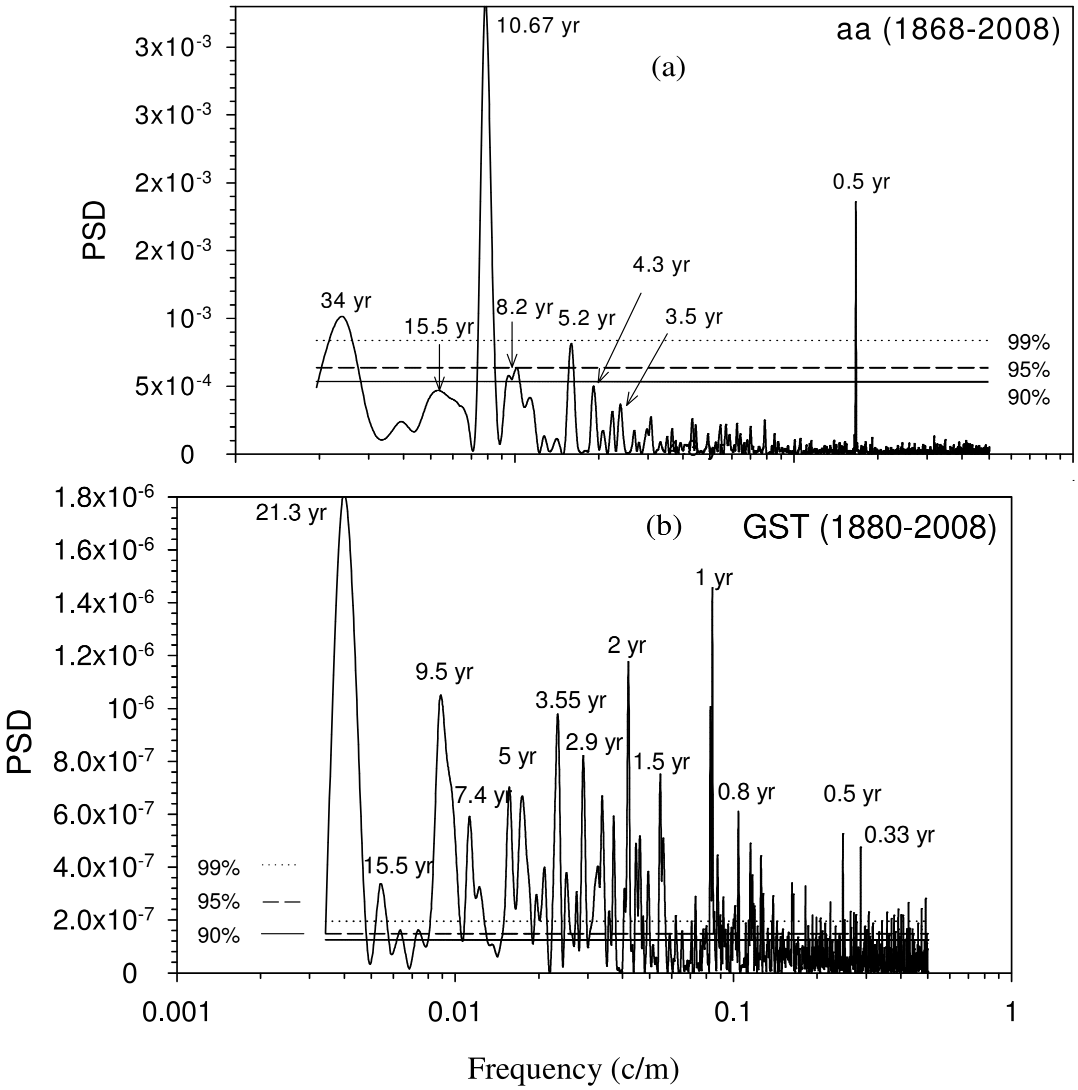

Figure 4. PSD of aa (panel a) and GST (panel b). The confidence levels 90, 95 and 99% are shown.

Table 1. Periods (in years) obtained by FFT spectral analysis for Rz (1868 - 2008), TSI (1978-2003), aa (1868 - 2008) and GST (1880 - 2008).

Periods (years)	Main periods existence/significance			
	Rz	TSI	aa	GST
34	-	-	+/<99	-
21.3	-	-	-	+/<99
10.7	+/<99	+/<99	+/<99	-
15.5	-	-	+/>90	+/<99
9.5	-	-	-	+/<99
7.4 - 8.2	+/>90	-	+/<90	+/<99
5 - 5.2	+/>90	+/>90	+/<95	+/<99
2 - 3.55	-	-	+/>90	+/<99
1 - 1.5	-	+/>90	-	+/<99
0.5 - 0.8	-	-	+/<99	+/<99
0.33	-	-	-	+/<99

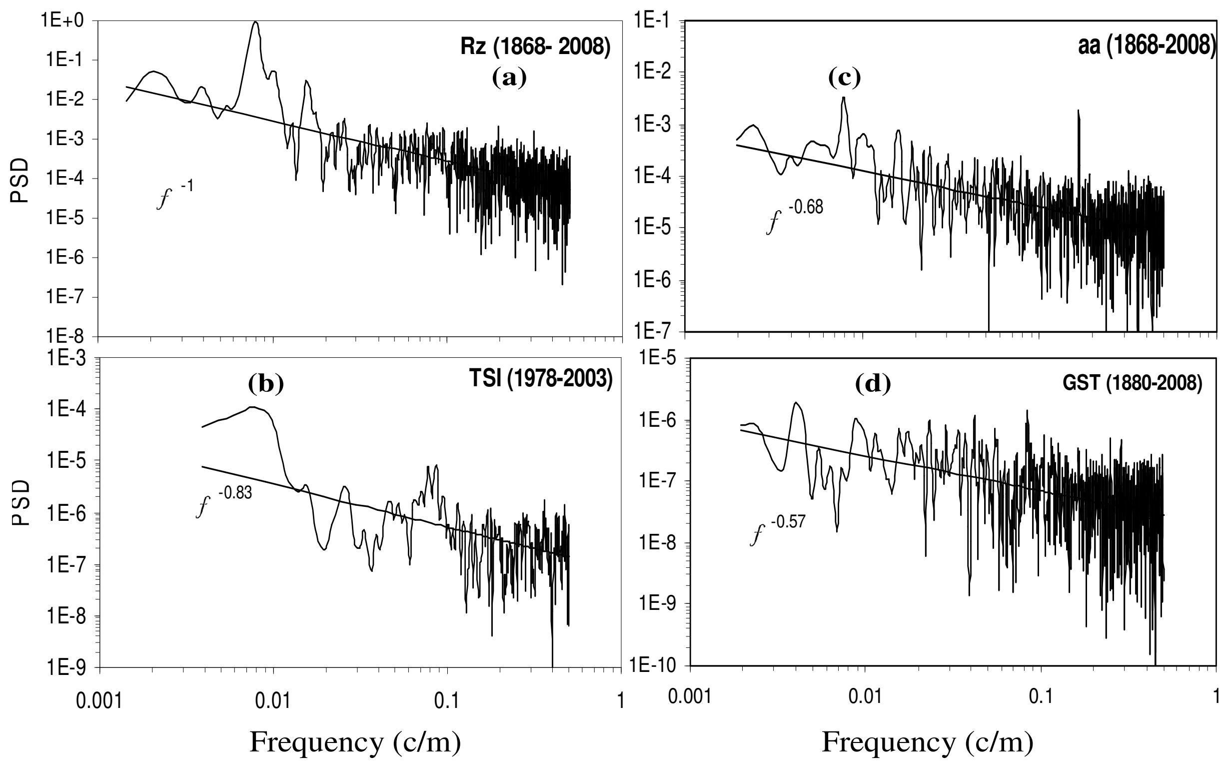

Figure 5. The best-fit line of Rz (panel a), TSI (panel b), aa (panel c), and GST (panel d). The value of power law index (n) is shown.

flares and coronal holes. They occur during different phases of the sunspot cycle and produce different modulation effects in the level of cosmic-ray intensity due to geomagnetic disturbances (Rekha and Mishra, 2009) and in turn on the solar diurnal variations. The resulting decrease in cosmic rays implies that fewer energetic particles penetrated into the lower atmosphere where they may help produce cloud, particularly at high latitudes where shielding by the earth's magnetic field is less. The reduction of clouds, that reflect sunlight, would explain why the global surface temperature gets hotter when the sun is more active (Lang, 2001). The peak at ~10.7 year is existing in Rz, TSI and aa with a 99% significant level. This is a well-known periodicity ~11 years, known as solar activity. The location of 10.7 year peak in TSI and Rz is roughly the same. The 9.5 years variation is shown in GT with confidence level 99%, while aa index and GT show 5 and 5.2 year periodicities with 95 and 99% significances, respectively. A simple explanation for 8.2 - 8.3 year peak in Rz and aa is that it may be related to the formation rate and the magnetic structure of achieving regions in the solar southern hemisphere (McIntosh et al., 1992). We think that 9.5 years in GT is due to the true solar-temperature effect and not related to the 11 year solar activity cycle and the 5 - 7 years peaks that are related to the North Atlantic oscillation (NAO) (Mokhov et al., 2000). Additionally, the TSI spectrum contains a minor peak at 5.3 years and may be attributed to the different paths of the ion particles in heliosphere.

The minor peak at 4.3 years is caused by the dual-peak structure of the geomagnetic activity or by the sector boundary crossings (Prestes et al., 2006) of the achieved regions in the solar. The other striking periodicity is indicated as the period of 9.5 years. It should be noted that the only real feature in the solar power spectra is the ~11 year, which is the standard solar cycle. McIntosh et al. (1992), showed that the southern coronal-hole area power spectra had a distinct peak at 3490 days (9.56 years) and that the solar wind speed structure is closely related to the magnetic topology of coronal holes area. Figure 5 displays the best fit of the PSD f^{-n} for Rz (panel a), TSI (panel b), aa (panel c) and GST (panel d). However, it shows the value of the power law index (n). The study noted that Rz and TSI have a higher value of the power law index than other parameters. This indicates that the modulations of Rz and TSI are higher than the other parameters.

Conclusion

The aim of understanding any relation between the global surface temperature and solar parameters or any periodic variation in the temperature records lies in the practical need to characterize quantitatively those sources of variance that are potential tools for understanding future climate changes. Therefore, the possible role of some solar parameters such as the sunspot number, the aa geomagnetic index and the total solar irradiance in climate variability of global temperature has been investigated. The variations of total solar irradiance are roughly proportional with the sunspot cycle. Results of time series of geomagnetic index aa and global temperature GT revealed that:

1. During the period 1880 - 1940 (1st warming region), the increase of GT were observed later by 1.33 - 9.66 years.
2. During the period (1940 - 1970], which is the global cooling period, the averages of aa showed great fluctuations. These fluctuations in aa are due to the corresponding variations in the solar activities.
3. During the period 1970 - 2008, which is the second warming period, the increase in GT was faster and smoother than in the first warming region. The warmest year was 2001.74, by 10 year apart and the global warming peak was in 2006.90, by 3.24 year apart. Result of time series of TSI and Rz shows that the variations of total solar irradiance are roughly proportional with the sunspot cycle.

Results of spectral analysis revealed strong 21.3 year peak in GST. It is related to the changes in the polarity of main solar magnetic field. This obtained result demonstrates that the interplanetary magnetic field (IMF) effect is more powered on GST. Significant peak at 10.7 year is appearing in Rz, TSI and aa. This is a well-known periodicity ~11-year, known as solar activity.

The power law index (n) for Rz and TSI have a higher value than aa and GST. This indicates that the PSD of Rz and TSI is harder than the PSD of the other parameters.

ACKNOWLEDGMENTS

The author would like to express his appreciation to the National Aeronautic and Space Administration's Goddard Institute for Space Studies (GISS) and to the National Geophysical and Solar-Terrestrial Data Center, Boulder, Colorado, for making data available via www.

REFERENCES

Courtillot V, Gallet Y, Le Mouël JL, Fluteau F, Genevey A (2007). Are there connections between the Earth's magnetic field and climate? Earth Planet. Sci. Lett., 253: 328.
Devendraa S, Singh RP (2010). The role of cosmic rays in the Earth's atmospheric processes, Pramana- J. Phys.. 74: 155-158.
Siingh D, Gopalakrishnan V, Singh RP, Kamra AK, Singh S, Pant V, Singh R, Singh AK (2007). The atmospheric global electric circuit: An overview, Atmos. Res., 84: 91-110.
Siingh D, Singh AK, Patel RP, Singh R, Singh RP (2008). Thunderstorms, lightning, sprites and magnetospheric whistler-mode radio waves, Sur Geophys, 29: 499.
Dickinson RE (1975). Solar variability and the lower atmosphere, Bull. Am. Meteorol. Soc., 56: 1240-1248.
El-Borie MA (2001a). Cosmic-ray intensities near the heliospheric current sheet throughout three solar activity cycles, J. Phys. G: Nucl. Part. Phys.. 27: 773.
El-Borie MA (2001b). North-South asymmetry of interplanetary plasma and solar parameters, Il Nuovo Cimento, 24C: 843.
El-Borie MA (2007). Proceedings of the Second Arab International Conference in Physics and Material Science, Alexandria University, Eygpt.
El-Borie MA, Darwish AA, Bishara AA (1995). Cosmic ray solar diurnal variations gradients and the interplanetary magnetic field.In: Proc. 24th Int. Cosmic Ray Conference (ICRC), Rome. 4: 603-606.
FrÖhlich C, Lean J (1998). In New Eyes to see inside the Sun and Stars, FL. Deubner (Ed.), Kluwer Academic Publ., Dordrecht, Netherland, IAU Symp.Proc. Int. Astron. Union Symp., 85: 89.
Haigh JD (1996). The impact of solar variability on climate', Science 272: 981-984.
Kane RP (1997). Quasi-biennial and quasi-triennial oscillations in geomagnetic activity indices, Ann. Geophysica, 15:1581.
Kirkby J (2007). Cosmic rays and climate, Surv. Geophys. 28: 333.
Kristánsson JE, Staple A, Kristiansen J, Kaas E (2002). A new look at possible connections between solar activity, clouds and climate Geophys. Res. Lett., 29: 2107.
Landscheidt T (2000). Solar forcing of El Niño and La Niña. ESA Special Publication, ESA-SP, 463: 497-500.
Lang KR (2001). The Cambridge encyclopedia of the Sun, Cambridge. ISBN 0 521 78093 4 1.
Lassen k, Friis-Christensen EJ (2000). The length of the solar ... European Space Agency, Geophys. Res., 105: 27493.
Le Mouėl JL, Kossobokov V, Courtillot V (2005). On long-term variations of simple geomagnetic indices and slow changes in magnetospheric currents: The emergence of anthropogenic global warming after 1990? Earth Planet. Sci. Lett., 232: 273.
Lean J, Skumanich A, White O (1992). Estimating the Sun's radiative output during the Maunder-minimum. Geophys.Res. Lett. 19: 3195.
Lean MEJ, Han TS, Seidell JC (1995). Impairment of health and quality of life in people with large waist circumference, Geophys. Res. Lett. 22: 3195.
Lockwood M, Stamper R, Wild MN (1999). A doubling of the Sun's coronal magnetic field during the past 100 years, Nature, 399: 437-439.
Marsh ND, Svensmark H (2000). Low Cloud Properties Influenced by Cosmic Rays, Phys. Rev. Lett. 85: 5004.
Mokhov II, Eliseev AV, Handorf D, Petukhov VK, Dethloff K, Weisheimer A, Khvorost'yanov DV (2000). North Atlantic Oscillation: Diagnosis and simulation of decadal variability and its long-period evolution, Izv. RAN, FAO, 36: 605-616.
Markson R, Price C (1999). Ionospheric potential as a proxy index for global temperatures. Atmos. Res., 51: 309-314.
McIntosh PS, Thompson RJ, Willock EC (1992). A 600-day periodicity in solar coronal holes, Nature 360: 322 - 324. doi:10.1038/360322a0.
Miroshnichenko LI (2008). Solar cosmic rays in the system of solar–terrestrial relations, J. Atmos. Solar Terr. Phys., 70-450.
Prestes A, Rigozo NR, Echer E, Vieira LEA (2006). Spectral analysis of sunspot number and geomagnetic indices, J. Atmos. Solar-Terr. Phys., pp. 68-182.
Pudovkin MI, Babushkina SV (1992). Atmospheric transparency variations associated with geomagnetic disturbances, J. Atmos. Terr. Phys., 54: 841.
Rahmstorf S, Archer D, Ebel DS, Eugster O, Jouzel J, Maraun D, Neu U, Schimidt GA, Severinghaus J, Weaver AJ, Zachos J (2004).Cosmic rays,carbon dioxide and climate, Eos, Trans. AGU, 85(4): 38-41.
Rekha A, Mishra RK (2009). Galactic cosmic ray modulation during last four solar cycles utu.fi, Proceedings of 31st ICRC, ĹóDŹ
Richardson IG, Cliver EW, Cane HV (2000). Sources of geomagnetic activity over the solar cycle: Relative importance of coronal mass ejections, high speed streams, and slow solar wind, J. Geophys. Res., 105: 18203.
Rycroft MJ, Fullekrug M (2004). The initiation and evolution of Special,

J. Atmos. Solar-Terr. Phys., 66: 1103
Rycroft MJ, Israelsson S, Price C (2000). The global atmospheric electric circuit, solar activity and climate change stanford.edu. J. Atmos. Solar-Terr. Phys., 62: 1563.
Svensmark H (2000). Cosmic rays and Earth's climate. Space Sci. Rev., 93: 155-166.
Shah GN, Mufti S (2005). "Anti-Podal Geomagnetic Ac- tivity, Sea Surface Temperature and Long Term Solar Variations," 29th International Cosmic Ray Conference, Pune, pp. 101-104.
Sharma N, Yadav R (1993). 23rd Cosmic Ray Confer. Calgary, 3: 625.
Sharma M (2002). Variations in the solar magnetic activity during the last 200,000 years: Is there a Sun-climate connection? Earth Planet. Sci. Lett., 199: 459-472.
Shaviv N (2002). Cosmic Ray Diffusion from the Galactic Spiral Arms, Iron Meteorites, and a Possible Climatic Connection, J. Phys. Rev. Lett., 89: 51102.
Solanki SK (2002). Solar variability and climate change: is there a link? Astron. Geophys., 43: 5.
Soon WH, Posmentier ES, Baliunas SL (1996). Inference of solar irradiance variability from terrestrial temperature changes, 1880-1993: An astrophysical J. 472: 891-902.
Stozhkov YI (2002). The role of cosmic rays in the atmospheric processes, J. Phys. G. Nucl. Part. Phys., 29: 913.
Tinsley BA (2004). Scavenging of condensation nuclei in clouds: Dependence of sign of electroscavenging effect on droplet and CCN sizes, in: Proceedings Int. Conf. on Cloud and Precipitation, IAMAS, Bologna, 18-23: 248.
Tinsley BA, Rohrbaugh RP, Hei M, Beard KV (2000). Effects of Image Charges on the Scavenging of Aerosol Particles by Cloud Droplets and on Droplet Charging and Possible Ice Nucleation Processes. J. Atmos. Sci., 57: 2118-2134.
Tripathi SN, Harrison GR (2002). Enhancement of contact nucleation by scavenging of charged aerosol particles, Atmos. Res. 62(1-2): 57-70.
Usoskin IG, Schüssler M, Solanki SK (2005). Solar activity, cosmic rays, and Earth's temperature: A millennium-scale comparison oulu.fi. J. GeoPhys. Res. 110, A10102, doi:10.1029/2004JA010946.
Veretenenko SV, Pudovkin MI (1994). Cloudiness decreases associated with Forbush-decreases of galactic cosmic rays, Geomag. Aeron., 34:38.
Vieira LEA, da Silva LA (2006). Geomagnetic modulation of clouds effects in the Southern Hemisphere Magnetic Anomaly through lower atmosphere cosmic ray effects, Geophys. Res. Lett. 33:L14802, doi:10.1029/2006GL026389.
Wigley TML, Raper SCB (1990). Climatic change due to solar irradiance changes. Geophys. Res. Lett. 17: 2169-2172.
Yu F, Turco RP (2001). From molecular clusters to nanoparticles: Role of ambient ionization in tropospheric aerosol formation. J. Geophys. Res., 106(5): 4797-4814.