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Solar activity–climate relations: A different approach

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ABSTRACT

The presentation of solar activity–climate relations is extended with the most recent sunspot and global temperature data series. The extension of data series shows clearly that the changes in terrestrial temperatures are related to sources different from solar activity after ~1985. Based on analyses of data series for the years 1850–1985 it is demonstrated that, apart from an interval of positive deviation followed by a similar negative excursion in Earth's temperatures between ~1923 and 1965, there is a strong correlation between solar activity and terrestrial temperatures delayed by 3 years, which complies with basic causality principles. A regression analysis between solar activity represented by the cycle-average sunspot number, SSN_A, and global temperature anomalies, ΔT_A, averaged over the same interval lengths, but delayed by 3 years, provides the relation $\Delta T_A \sim 0.009\ (\pm 0.002)\ SSN_A$. Since the largest ever observed SSN_A is ~90 (in 1954–1965), the solar activity-related changes in global temperatures could amount to no more than $\pm 0.4\,^{\circ}$C over the past ~400 years where the sunspots have been recorded. It is demonstrated that the small amplitudes of cyclic variations in the average global temperatures over the ~11 year solar cycle excludes many of the various driver processes suggested in published and frequently quoted solar activity–climate relations. It is suggested that the in-cycle variations and also the longer term variations in global temperatures over the examined 135 years are mainly caused by corresponding changes in the total solar irradiance level representing the energy output from the core, but further modulated by varying energy transmission properties in the active outer regions of the Sun.

1. Introduction

At this time there are intense ongoing discussions as well as extensive observational and modeling efforts to disclose whether anthropogenic activities have marked influence on Earth's climate characterized, for instance, by the average global temperature. However, the question of the influence from solar activity remains important and unresolved. Here, the term "solar activity" relates to changes in the state of the Sun and its output of importance to the Earth.

For many solar activity types it is now possible to obtain a long-time record. The magnetic fields embedded in the solar wind influence the level of galactic cosmic radiation (GCR) received by the Earth. Direct measurements of the CGR level have been made with a high degree of reliability by neutron monitor systems around the world for the past 50 years and by less certain measurements for almost a century. The solar wind intensities have been recorded directly by in-situ spacecrafts since the measurements by Pioneer 6–8, launched during 1965–1967, and indirectly by the geomagnetic signatures, e.g., expressed in the aa index, through around 150 years. Similarly, the solar UV- and X-ray levels have been monitored directly by fairly precise measurements from space through around 40 years and indirectly and continuously through monitoring of their proxy, the 10.7 cm solar radio wave emissions, through more than 60 years. For many solar activity parameters it is thus possible to make reliable correlations with the occurrences of sunspots used as the most imminent indicator of the solar activity level. Then, using the varying sunspot number as a proxy, the relations between specific solar activity parameters and the Earth's climate can be pursued over longer spans of time than possible on the basis of direct measurements.

Consequently, we may examine the causal relationships for climate effects where a specific cause related to solar activity is postulated. This group comprises climate effects related to global electric fields and currents generated by the solar wind and its embedded magnetic field (e.g., Burns et al., 2007; Tinsley et al., 2007); variations in the atmospheric circulation or ozone content related to solar UV- and X-ray levels, solar high-energy protons and radiation belt electrons (e.g., Labitzke and van Loon, 1997; Hood, 1997; Haig, 2001; Erlykin et al., 2010); variations in cloud cover caused by changes in cosmic radiation (e.g., Pudovkin and Veretenenko, 1995; Svensmark and Friis-Christensen, 1997;

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Svensmark, 2000; Shea and Smart, 2004); increased atmospheric vorticity at solar wind sector changes (Wilcox et al., 1973).

For the total solar energy output the situation is different. The measurement of spectral solar irradiance (SSI) (Lean, 2000; Harder et al., 2009; Foukal et al., 2006) and total solar irradiance (TSI) (Pap and Fröhlich, 1999), which also includes solar astrometry measurements (Thuillier et al., 2005; Boscardin et al., 2009; Emilio et al., 2010), are very complicated and the precise calibration of the TSI level to the degree required for climate studies is extremely difficult (e.g., Krivova and Solanki, 2008). Thus, presently archived TSI data may provide a fair impression of the relative variation over a short span in time, for instance, a single solar cycle, whereas the trend over a longer span of time is rather uncertain (e.g., Lean et al., 1995; Mendoza, 2005; Lean, 2000; Fröhlich, 2009).

With causality and correlation studies we cannot prove any specific theory correct; however, if a proposed solar activity–climate mechanism fails to comply with causality principles, it can be rejected. For the processes referred to above, the variations in the appointed parameter, for instance, the level of galactic cosmic radiation, corresponds closely to the cyclic variation in sunspot number. It will be argued below that such variable parameters could not possibly be the dominant cause of the observed relation between solar activity and global temperatures. Furthermore, many of the presented processes have a causality problem since it appears that major changes in solar activity follow (not precede) corresponding changes in Earth's climate. To resolve the causality problem some of the presentations resort to using excessive averaging of the solar activity parameter in order to shift the timing.

The analyses of the relations between solar activity, as monitored through the sunspot numbers, and Earth's climate represented by the terrestrial temperatures, are divided in two lines. In one line of analyses the sunspot numbers and the terrestrial temperatures are averaged over the length of complete $\sim$11 year solar cycles. The averaging intervals for the temperatures are displaced (by 3 years) to obtain optimum correlation. Otherwise, no further smoothing or shifting is applied to the data. These analyses shall define the long-term relations between the cycle-average parameters and also provide the basis for a discussion of causality problems. In another line of analyses the in-cycle variations in sunspot numbers and terrestrial temperatures are contrasted. This part serves to provide the basis for discussions of the potential interaction mechanisms that might relate global climate to solar activity.

Many investigations have referred to the publications by Eddy (1976), Reid (1987, 1999), and Friis-Christensen and Lassen (1991) (hereafter Eddy76, Reid87, Reid99, and FCL91, respectively) in support of theories of solar activity as the cause of climate changes. Eddy76, Reid87, and Reid99 use the sunspot numbers to characterize solar energy output while FCL91 introduced the Solar Cycle Length (SCL) as a relevant parameter to characterize solar activity based on its inverse correlation with the sunspot number (stronger cycles run faster). The SCL is an interesting parameter and no doubt important for studies of solar physics. However, even now, two decades later, it is not resolved whether it relates to any solar energy output parameter of importance for the Earth. Still, the SCL parameter has been used in further publications (e.g., Lassen and Friis-Christensen, 1995; Thejll and Lassen, 2000). These basic reports are first examined more closely in order to underline the differences from the approach taken here.

2. Solar activity and Earth's climate parameters

A parameter often used to characterize solar activity is the Wolf (1868) Zürich sunspot number ($R=k(10g+s)$). It has been attempted to deduce sunspot numbers from astronomer's reports as early as the 16'th century. Restorations of a continuous series of sunspot numbers have been made back to around 1600 (e.g., Eddy, 1976). The absolute magnitudes of the early sunspot numbers are rather uncertain. From around 1850 the sunspot numbers are considered observationally reliable.

The official index, the "International Sunspot Number", is published daily by the Solar Influences Data Center (SIDC) at the Royal Observatory in Belgium. Series of sunspot numbers are published jointly by SIDC (sidc.oma.be) and by the National Geophysical Data Center (NGDC) at NOAA in Boulder, USA, (ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS). Here we focus on the interval from 1850 to present based on the series of monthly average sunspot numbers provided back to 1749 (sunspot cycle no. 0) and through 2010 (cycle 24). Furthermore, we use the table of (decimal) years of cycle maxima and minima provided by NGDC back to cycle −12 starting year 1610 ending with the sunspot minimum in 2008 at the start of cycle 24. In their definition of times of maxima and minima, NGDC notes: "*When observations permit, a date selected as either a cycle minimum or maximum is based in part on an average of the times extremes are reached in the monthly mean sunspot number, in the smoothed monthly mean sunspot number, and in the monthly mean number of spot groups alone. Two more measures are used at time of sunspot minimum: the number of spotless days and the frequency of occurrence of "old" and "new" cycle spot groups*." The NOAA definition of solar cycles 9–24 is shown in Table 1, which also presents the min-to-min and the max-to-max cycle-average sunspot numbers based on SIDC monthly sunspot numbers.

The Earth's climate could be characterized by some average temperature. It is frequently debated whether the atmospheric or the oceanic temperatures provide the proper measure of Earth's climate. It is also discussed whether northern or southern hemisphere data or global average values are the more representative choice. The present work uses a selection of monthly average temperature anomaly series (base period 1961–1990) provided by the Hadley Centre at the UK Meteorological Office in collaboration with the Climatic Research Unit at the University of East Anglia (Brohan et al., 2006). These data sets are made both on a global basis and for the northern and southern hemisphere separately and further divided into land-surface (*CruTem3gl/nh/sh*), sea-surface (*HadSST2gl/nh/sh*), and combined land-surface/sea-surface (*HadCruT3gl/nh/sh*) temperature data sets. Monthly and yearly average temperatures are provided from 1850 up to 2010. The global combined land-surface/sea-surface temperature *HadCruT3gl* data set is considered the primary data set for the present work, but the northern hemisphere version as well as the global and northern hemisphere versions of the land-surface and sea-surface temperature data sets are considered for consistency. The *HadCruT3gl* (2010) data series is displayed in Fig. 1 along with the SIDC sunspot number. The min-to-min and max-to-max cycle-average values have been marked by square dots and asterisks, respectively. The thin black lines provide simplified sketches of the variations through segments of the temperature and sunspot data.

When the temperature data displayed in the top panel of Fig. 1 are compared to the sunspot data in the bottom panel of the figure, there appear to be similarities; for instance the slowly decreasing, relatively low level in the last half of the 19th century, the rise in the beginning of the 20th century, and the decline past the middle of the century. For the rise in temperature after $\sim$1985, a different forcing mechanism rather than solar activity has arrived at the end of cycle 22, that is, between 1980 and 1986 (e.g., Lockwood and Fröhlich, 2007). Whether this forcing is caused by anthropogenic activities, and if so, whether it is related to the CO^2 concentration in the atmosphere, however intriguing, is not the subject here. In the present analysis the data from cycle