Solar Activity and Global Warming Revisited

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While in general the changes in surface air temperature follow the changes in solar activity proving the solar influences on climate, in the last few decades solar activity has remained more or less constant while temperature has continued increasing which is a strong argument in favor of anthropogenic influences on climate. In the same period the correlation between solar and geomagnetic activity has decreased, both in the 11-year cycle and on secular time scale. The solar activity index commonly used for long-term studies is the sunspot number as it has the longest data record. But sunspots reflect only the solar activity originating from closed magnetic field regions. The regions of open magnetic field - coronal holes, sources of high speed solar wind and drivers of recurrent geomagnetic activity, are not accounted for in the sunspot index. It appears that in the last decades the impact of coronal holes has increased which can be explained by the increasing tilt of the heliospheric current sheet. This increased tilt means that the Earth encounters two high speed streams from coronal holes per solar rotation and higher geomagnetic activity. On the other hand, the tilt of the heliospheric current sheet is related to the galactic cosmic rays modulation, and galactic cosmic rays are considered key agents mediating solar activity influences on terrestrial temperature. Therefore, using the sunspot number alone as a measure of solar activity leads to the underestimation of the role of solar activity for the global warming in the recent decades.

Introduction

The long-term increase in the globally averaged yearly mean temperatures (the so-called “global warming”) registered in the 20th century has raised the question “what part, if any, of the observed changes can be attributed to human influence and what part, if any, can be attributed to natural phenomena?”. The conclusion reached in the Synthesis Report “Climate Change 2001” of the Intergovernmental Panel of Climate Change is that “most of the warming observed over the last 50 years is attributable to human activities” (http://www.ipcc.ch/). In the above cited document, “natural phenomena” are considered solar variability and volcanic activity. In the present paper we are dealing with one of these natural phenomena – the solar variability.

Sunspot number and global temperature

The most popular index of solar activity is the International sunspot number. It was introduced in 1848 by Rudolph Wolf who devised a daily method of estimating solar activity by counting the number of individual spots and groups of spots on the Sun. Wolf’s sunspot number R is computed as $R = k(10g+s)$, where g is the number of sunspot groups on the solar disk, s is the total number of individual spots in all the groups, and k is a variable scaling factor that accounts for observing conditions and the type of telescope. Daily averaged values of R are available since 1818, monthly averages since 1749, yearly averages since 1700, and a reconstruction of the yearly averages based on sunspot groups – since 1610 [1]. The years of sunspot minima and maxima along with the estimated sunspot numbers in the maxima have been reconstructed since 649 BC based on auroras and naked eye observations of sunspots [2]. This is the solar activity index with the longest data record, so it is only natural to use sunspot numbers when studying long-term phenomena like climate change, though it may not be the most appropriate index.

In Fig.1 the global temperature anomalies (deviations from the values in the base period 1961-1990) from the Climatic Research Unit [3] are compared to the International sunspot number. The data points are the “climatic normals” used for the evaluation of climate changes – that is, the temperature anomalies averaged over 3 full decades, for example 1901-1930, 1911-1940, etc. [4]. It is clearly seen that while in the beginning of the period global temperature closely follows the variations in sunspot numbers, in the last decades sunspot numbers begin decreasing while the temperature continues increasing. This has provided solid arguments in favor of the anthropogenic impact on the global warming (e.g. [5]).

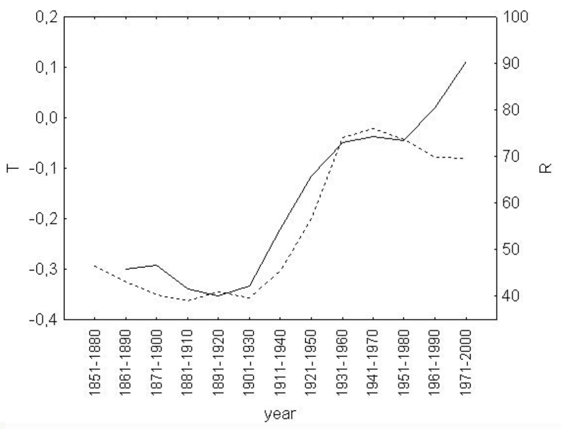

Fig.1. Global temperature anomalies T (solid line) and International sunspot number R (broken line) for the period 1856-2000; climatic normals.

Sunspot number and geomagnetic activity

The correlation between the long-term variations in the sunspot number and geomagnetic *aa*-index evolves in a way similar to the correlation between the sunspot number and surface air temperature: up to the period 1941-1970 practically all of geomagnetic activity increase can be explained by the increase in solar activity, and in the last three decades sunspot numbers decrease while geo-magnetic activity continues increasing (Fig.2). Geo-magnetic activity can hardly be attributed to anthropogenic influences, and the two figures look very much alike so probably there is some common factor influencing both correlations.

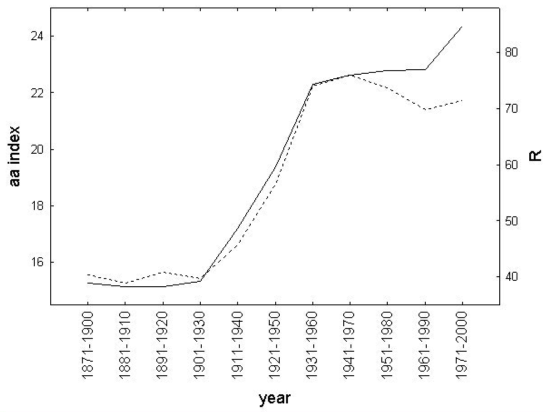

Fig.2. aa-index of geomagnetic activity (solid line) and International sunspot number R (broken line) for the period 1856-2000.

Mechanisms for solar influences on climate

Three main groups of mechanisms have been proposed to explain how changing solar activity can influence climate:

1) variations in the total solar irradiance leading to variations in the direct energy input into the Earth's atmosphere. The composite record of total solar irradiance [6] shows variations of about 0.1% in the 11-year cycle. However, the evaluated long-term variations are much higher [7];

2) variations in the solar UV irradiance causing variations in stratospheric chemistry and dynamics [8]. Model experiments demonstrate that the increase in solar activity which is much higher for lower wavelengths, leads to changes in the tropical convective cells, consequently of the general atmospheric circulation and climate [9];

3) variations in solar wind modulating cosmic ray flux which affects stratospheric ozone and small constituents [10] and/or the cloud coverage [11], and thus the transparency of the atmosphere.

Of these three solar activity agents possibly influencing climate, the first two ones (total and spectral solar irradiance) can be well approximated by the sunspot number. Sunspots are embedded in solar active regions which are regions of strong magnetic fields with closed field lines geometry (magnetic flux tubes). The brightness of the flux tubes (and hence the solar irradiance) depend on the magnetic field strength which also determines the number of sunspots, so there is a linear relationship between sunspot number and irradiance [12].

The third factor (solar wind modulating galactic cosmic rays) has three principal components: co-rotating high-speed streams (HSS's), slow solar wind, and transient structures (coronal mass ejections – CME's). Coronal mass ejections occur when flux tubes become unstable and erupt. The number and velocity of the solar wind streams associated with CME's follow the sunspot cycle [13], so the sunspot number can be considered a good measure of the solar wind originating from closed magnetic field regions. The high speed solar wind comes from coronal holes. These are open magnetic field regions with low plasma density, hence dark in X-ray images, and this was the feature allowing finally to identify them when X-ray telescopes were first flown above the atmosphere. Before that they were known as the "M-regions" – sources of recurrent geomagnetic activity with no visible from the Earth solar feature [14], and they are in no way related to the sunspot number while the slow wind is known to be associated with the highly structured and highly variable streamer belt [15]. None of them can be approximated by the sunspot number.

Solar drivers of geomagnetic activity

Geomagnetic storms can be caused by two main solar sources - long lived, such as polar coronal holes - sources of HSS's related to recurrent geomagnetic activity, and sporadic or short lived, such as solar flares and disappearing filaments, related to CME's and sporadic geomagnetic activity [16]. Richardson et al. [17] found that the most intense storms in both sunspot minimum and sunspot maximum are caused by CME's. However, if we look not at the most intense individual storms but at the average geoeffectiveness of the two types of solar drivers, HSS's from coronal holes are on the average more geoeffective (as expressed by Kp-index) than CME's – Fig.3. Moreover, average HSS's are more geoeffective than average CME's at all phases of the sunspot cycle; only in sunspot max CME's are equally effective (Fig.4).

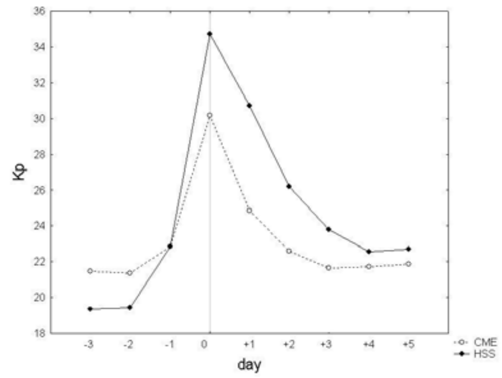

Fig.3. Kp index of geomagnetic activity for high speed solar wind from coronal holes (solid line) and coronal mass ejections (dashed line) in the period 1992-2002.

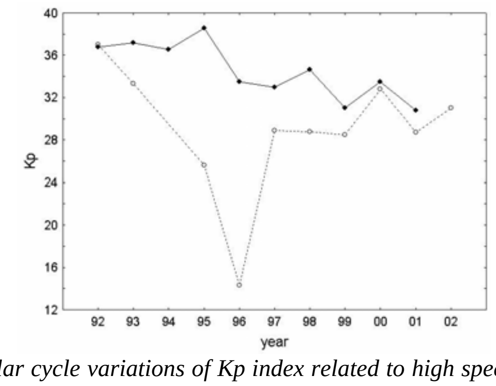

Fig.4. Solar cycle variations of Kp index related to high speed solar wind from coronal holes (solid line) and coronal mass ejections (dashed line).

These figures are in agreement with the results of Richardson et al. [18] who found that:

- mean aa index doesn't follow the sunspot number

- CME-related aa doesn't follow the mean aa (r=0.306)

- HSS-related aa is highly correlated to mean aa (r=0.79)

The explanation can be that *aa* index is sensitive to the solar open flux which determines the mean B in the solar wind "quasi-stationary" structures (slow solar wind and HSS's), while CME-related B doesn't correlate with either the open flux or the mean B in the solar wind [18]. We should remind here that there is a direct relation between Kp and aa-indices [19]: Kp, available since 1938, is a 3-hour planetary index measured as deviations from the quiet day values in 13 geomagnetic observatories between 44 degrees and 60 degrees northern or southern geomagnetic latitude. The ap index is derived from the Kp index, while the aa index is a reconstruction of the ap index since 1868 from only two stations, one in the Northern and one in the Southern hemisphere (recently a still longer reconstruction has been offered derived from measurements since 1840 in only one station – Helsinki [20]). When comparing long-term trends in solar and geomagnetic activity, the geomagnetic activity index usually studied is aa since it has the longest record, and for the same reason the sunspot number is used as the solar activity index with the longest record. However, this comparison is not correct. This is in fact a comparison not between "solar activity" and "geomagnetic activity", but between solar closed and open magnetic flux or, to be more precise, between solar closed flux and the amount of solar open flux reaching the Earth.

Evolution of the correlation between solar and geomagnetic activity

Kishcha et al. [21] examined the 23-year (in order to eliminate the solar cycle variation and the even-odd cycle differences) running correlation between *aa*-index and sunspot number, and found a linear decreasing trend, with a quasi-periodicity of 45-50 years superposed on it. They supposed that the cause of the variations in the solar-geomagnetic activity correlation could be the variation in the time delay of the geomagnetic indices relative to the sunspot number. Further, they speculated that, dividing solar activity into sporadic (related to CME's and hence to sunspots) and recurrent (related to high-speed solar wind from coronal holes), we can even neglect the sporadic sunspot related activity when comparing with the annual geomagnetic activity indices.

Echer et al. [22] confirmed that the correlation between geomagnetic and solar activity has decreased since the end of the 19th century, and the lag between them has increased, and supposed that the probable cause of the correlation decrease seems to be related to the *aa* index dual peak structure. The second *aa* peak related to the high-speed streams seems to have increased relative to the first one related to sunspot (coronal mass ejections) activity, the probable cause being that open solar magnetic field structures (coronal holes) have increased their activity relative to the closed (sunspot-related) solar magnetic field structures. The open flux in sunspot min and on the declining phase resides in polar coronal holes, and in sunspot max – in small low latitude holes near active regions [23]. So it maybe that the polar coronal holes have increased leading to increased open magnetic field flux and consequently increased geomagnetic activity. Indeed, Makarov et al. [24] calculated the area of polar zones of the Sun, and found that the annual minimum latitude of the high-latitude zone boundaries of the global magnetic field of the Sun at the minimum of activity had decreased from 53 in 1878 down to 38 in 1996, consequently the area of polar zones of the Sun, occupied by unipolar magnetic field at the minimum activity, has risen by a factor of 2 during 1878-1996 [24]. However, this doesn't explain the change in the correlation between sunspot number and *aa*-index.

A hint was provided by Mursula and Zieger [25] who studied the long-term evolution of the 13-14 day (half solar rotation) periodicity in solar wind speed. Recurrent geomagnetic activity on the declining phase of the sunspot cycle driven by high speed solar wind can be observed when the Sun's polar coronal holes extend towards the solar equator [26]. If the heliospheric current sheet is tilted enough, the Earth encounters two high speed solar wind streams per solar rotation [27], which leads to exceptionally high geomagnetic activity [28]. The presence of a strong 13-14 day periodicity in the solar wind speed is a signature of two high speed solar wind streams per solar rotation, and hence of a significant tilt of the heliospheric current sheet. The tilt of the heliospheric current sheet varies throughout the sunspot cycle, from nearly 90^o around sunspot maximum to zero around sunspot minimum. Measurements however show that in the recent sunspot minima the tilt is never zero which means that the heliospheric current sheet is indeed tilted relative to the ecliptic [29]. Bravo and Stewart [29] suggested a possible explanation: a small constant relic field inclined to the main solar dipole field and summing to it. However, if this relic field is indeed constant, it can't explain the increased geomagnetic activity due to high speed streams from coronal holes. Mursula and Zieger [25] found that the power of the 13-14 day periodicity was stronger in the last eight solar cycles while in the earlier cycles it was weaker and appeared closer to sunspot maximum – therefore, the tilt of the heliospheric current sheet increased in the recent cycles as compared to the end of the 19th and the beginning of the 20th century.

In [21] it is demonstrated that the correlation between sunspot and geomagnetic activity varies in phase with the solar rotation period. The 45-50 year periodicity in the sunspot-geo-magnetic activity correlation matches the periodicity found in the north-south asymmetry in solar rotation [30], and in the movement of the Sun about the barycentre of the solar system [31]. The same periodicity was found in the Earth's rotation rate [30] and in the electromagnetic core-mantle coupling torques [32] believed to be related to the decadal variations in both the Earth's rotation rate and geomagnetic activity [33]. We could therefore suggest that the changing correlation between sunspot number and geomagnetic activity can be due to the changing inclination of the heliospheric current sheet relative to the solar equator, which in turn can be due to the overall dynamics of the solar system and the movement of the Sun about the solar system barycentre.

What about climate?

As mentioned above, one of the key actors in the proposed mechanisms for solar activity influences on climate is the cosmic rays flux determining, in one way or another, the transparency of the atmosphere and therefore the solar radiation reaching the Earth ([10], [11]). This galactic cosmic rays flux is in turn modulated by solar wind [34], and is highly correlated to the tilt angle of the heliospheric current sheet [35, 36].

Both geomagnetic *aa*-index and surface air temperature are influenced by different agents of solar activity, some of them originating from regions of closed magnetic field geometry (irradiance, flares, coronal mass ejections), others from regions of open field geometry (coronal holes), while sunspot number is an index accounting for only solar activity associated with closed magnetic field regions. If we can suppose that the decreasing correlation between the sunspot number and global temperature on the one hand, and between sunspot number and *aa*-index of geomagnetic activity on the other hand are both due to the increasing importance of solar activity originating from solar regions with open magnetic field geometry not accounted for by the number of sunspots, there should be a good correlation between surface air temperature and *aa*-index. Fig.5 demonstrates this correlation which for the whole period of observation is $r = 0.85$.

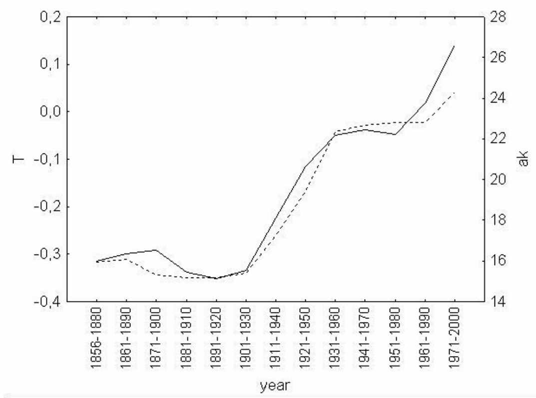

Fig.5. Global surface air temperature and geomagnetic activity.

Summary and conclusion

The long-term correlations of solar activity as measured by the sunspot number to both surface air temperature and aa-index of geomagnetic activity have decreased in the recent decades. But the sunspot number accounts for only solar activity originating from closed magnetic field regions, while high speed solar wind from coronal holes – regions of open magnetic field – is also important for geomagnetic activity and for the modulation of galactic cosmic rays considered a possible mediator between solar activity and climate. We show that these decreasing correlations are due to the increasing tilt angle of the heliospheric current sheet.

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