SOLAR ASYMMETRY AND SUN-EARTH CONNECTIONS

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ABSTRACT

The effect of solar activity on climate depends on the North-South solar activity asymmetry: the correlation between solar activity and a number of meteorological elements has opposite signs for predominantly more active Northern or Southern solar hemispheres. We find that the two hemispheres rotate differently, and show that the interplanetary magnetic field at the Earth's orbit is related to the differential rotation of the more active hemisphere. One feature that is persistently different in the two solar hemispheres is the prevailing magnetic helicity, which is carried to the Earth by magnetic clouds preserving the helicity of the source region of their origin. We show that the reaction of the atmosphere to the arrival of magnetic clouds depends on the helicity of the clouds.

1. INTRODUCTION

Many authors have reported correlations between different meteorological elements and solar activity parameters, but the problem of solar activity influences on climate on different time scales remains one of the most controversial problems in solar-terrestrial physics. One of the main reasons is that, for one and the same meteorological element, both positive and negative (and sometimes missing) correlations have been found (i.e. [1], and the references therein). If the sign of the correlation changes randomly, this would be a serious reason to doubt the very existence of such a relation. Moreover, none of the proposed mechanisms for solar-climatic influences explains such a change in the way in which solar activity affects climate.

2. SUNSPOT ACTIVITY AND TEMPERATURE

A compilation of all published results, and a study of all available climate records from meteorological stations worldwide has shown that the correlation between the surface air temperature and sunspot activity in the 11-year solar cycle depends on the period studied and not on the location, and changes sign in consecutive secular (Gleissberg) solar cycles – Fig. 1. Moreover, it has been noted that the sign of the correlation depends on solar activity asymmetry, being positive when the Northern solar hemisphere is predominantly more active, and negative when more active is the Southern hemisphere. This implies a secular variation of solar activity asymmetry [2]. The same conclusion has been reached based on the phase change of the semiannual variation of geomagnetic activity [3].

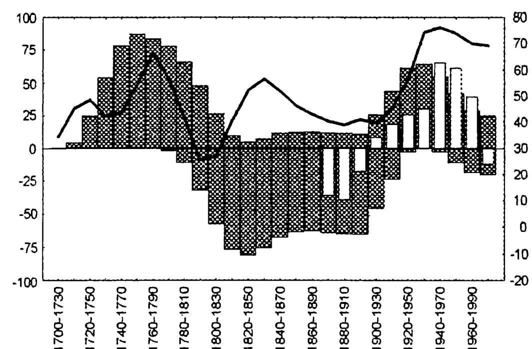

Fig. 1. Correlation between sunspot activity and surface air temperature in the 11-year solar cycle. Dark bars - percentage of meteorological stations worldwide with statistically significant positive or negative correlations, along the positive and negative Y-axis, respectively; Solid line - secular solar cycle; White bars - North-South solar activity asymmetry [2].

3. QBO AND SOLAR-CLIMATIC RELATIONS

A similar dependence has been noticed of the correlation between sunspot activity and climate on the phase of QBO – the quasibiennial oscillation of equatorial stratospheric winds. Statistically significant correlations between solar variability and atmospheric elements from the ground to the top of the stratosphere are obtained if the data is grouped according to the phase of QBO, with the sign of the correlation depending on the QBO phase and on the location [4]. However, in some locations, a change in the sign of the correlation is observed around 1970 – Fig. 2 [5]. This is the period when the sign of solar activity asymmetry changes, and in some locations the sign of the correlation between sunspot activity and surface air temperature also changes (see Fig. 1).

Proc. ISCS 2003 Symposium, 'Solar Variability as an Input to the Earth's Environment', Tatranská Lomnica, Slovakia, 23-28 June 2003 (ESA SP-535, September 2003)

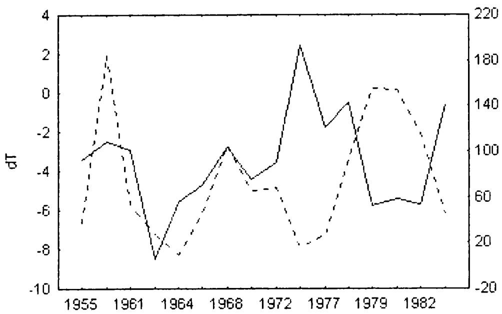

Fig.2. Surface air temperature in Prague (solid line) and sunspot numbers (dotted line) for QBO>0.

4. EARTH ROTATION RATE FLUCTUATIONS AND ATMOSPHERIC CIRCULATION

An important element of climate is atmospheric circulation, and long-term changes in atmospheric circulation have been supposed to be connected, either as a cause or as a consequence, to long-term changes in Earth`s rotation rate [6, 7]. If the Earth/atmosphere system can be regarded as a closed one, from the conservation of angular momentum it follows that when the westerly zonal winds strengthen, the Earth's rotation rate must decrease. Indeed, this relation has been demonstrated [6, 8], but for the 20[th] century only, because of data limitations. A study of proxy records of atmospheric circulation reveals that its correlation with Earth's rotation rate changed sign in the same period in which both solar activity asymmetry and the correlation between solar activity and surface air temperature changed sign– Fig. 3 [9].

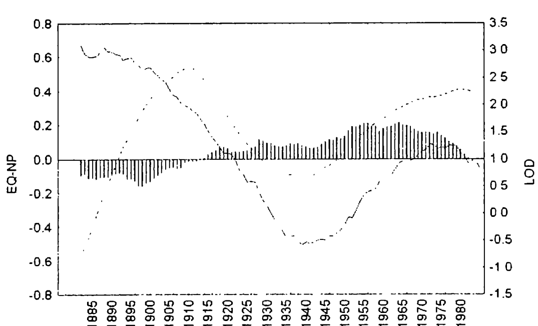

Fig. 3. Decadal changes in the zonality of the atmospheric circulation in the Northern hemisphere presented by the equator-pole temperature contrast (EQ-NP) in degrees Celsius - solid line, and in the variations in the length of the day (LOD) in milliseconds - dashed line. The vertical bars present the North-South solar activity asymmetry. Note that LOD scale is reversed to represent variations in Earth rotation rate.

This means that on decadal time-scales the Earth-atmosphere system is not closed. Neither the changes in atmospheric circulation could be considered the reason for the changes in the Earth's rotation rate, nor vice versa, they are either both governed by some external factor, or an external factor governs the interaction between them. The decadal variations in the Earth's rotation rate are strongly correlated to the North-South asymmetry of solar equatorial rotation Aa, both showing dominant periodicities at about 47 years – Fig. 3 [9].

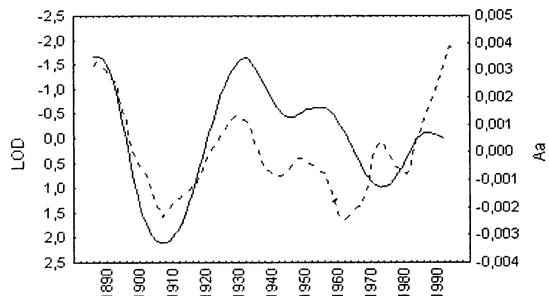

Fig.4. Decadal changes of the variations in the Earth's rotation rate (length of the day LOD, reversed scale - solid line) and the North-South asymmetry of solar equatorial rotation Aa (dashed line).

The same periodicity has been found in the Earth's electromagnetic core-mantle coupling torques [10]. Processes in the core and the mantle are considered one of the possible mechanisms for the excitation of LOD fluctuations [11], and the main driving force for the geomagnetic field variations [12, 13]. The variations in LOD and in the geomagnetic field are closely connected [13, 14]. A dominant peak of 51 years has been found in both the variations of the geomagnetic dipole moment and the fluctuations of the Earth's rotation rate matching the corresponding peak of 47 years in LOD and Aa, with a coherence between the two of above 0.99 [15].

5. SOLAR AND GEOMAGNETIC ACTIVITY

While the long-term trends in geomagnetic activity closely follow the secular variations in sunspot activity, the connection between them on shorter time-scales is less obvious. Between 1868 and 1982, geomagnetic aa index was becoming less correlated and more out of phase with sunspot numbers Rz in the 11-year solar cycle. The characteristic period with which varies the correlation between Rz and aa has been shown to be again about 50 years [16]. Fig. 5 compares the long-term variations in the correlation between sunspot and geomagnetic activity to the long-term changes in North-South solar activity asymmetry. The correlation between Rz and aa is high for strongly negative solar asymmetry - i.e., when the Southern solar hemisphere is more active than the Northern one. With increasing relative impact of the Northern hemisphere to the total solar activity, the correlation decreases.

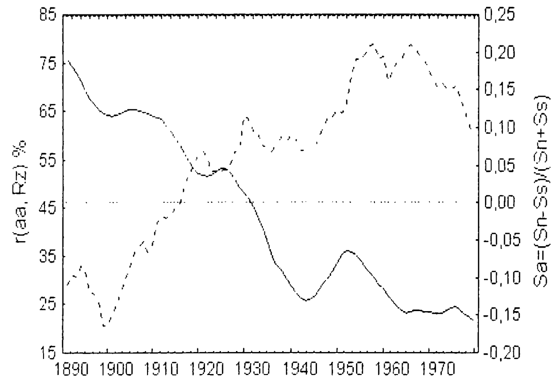

Fig. 5. Long-term changes (31-year running means) of the correlation between solar and geomagnetic activities - solid line - and North-South solar activity asymmetry - dashed line [9].

The shorter-term behavior of the correlation between Rz and aa shows a pronounced periodicity of 22 years exactly matching the Hale magnetic cycle, while the dominant periodicity in solar activity asymmetry is 15.7 years, close to the 16-17 year periodicity in the IMF direction and solar coronal holes variations [17] – Fig.6.

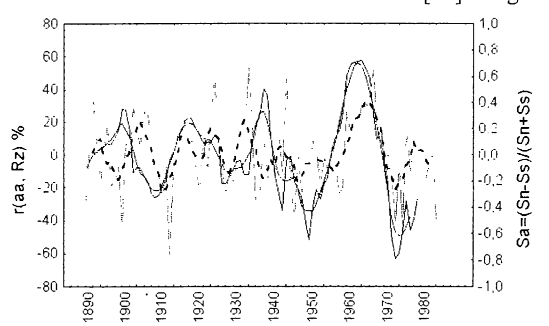

Fig. 6. Short-term (31-year moving averages subtracted) variations in the correlation between solar and geomagnetic activities r(aa, Rz) - thin solid line, and North-South solar activity asymmetry Sa - dotted line, along with their 5-year smoothed values - heavy solid line and dashed line, respectively [9].

6. PERIODICITIES IN SOLAR ROTATION AND INTERPLANETARY MAGNETIC FIELD

A possible physical cause for the change in the correlation between aa and Rz can be the difference in the long-term variations in the total photospheric magnetic field and closed flux determining the sunspot activity, and solar open magnetic flux whose extension, the interplanetary magnetic field (IMF), is responsible for the geomagnetic variations [18].

The different behavior of the interplanetary magnetic field originating from the Northern and Southern solar hemispheres has been shown for solar cycles 20 and 21 [19], and confirmed for cycles 21, 22 and the current part of cycle 23 [20]. An important element of the solar dynamo which is responsible for the solar magnetic field is the solar differential rotation. It has long been known that the two solar hemispheres rotate at different rates [21, 22], but the time variation of the rotation difference between the northern and the southern hemispheres as well as its phase relative to the activity cycle still remains unclear.

We use A and B coefficients in the standard formula of solar differential rotation

$$\omega(\lambda) = A + B\sin^2\lambda$$

calculated from GPR - Greenwich Photoheliospheric Results [23] for the two solar hemispheres, An, As, Bn and Bs, respectively, for the period 1881-1974 [24]. As the variables are of different orders of magnitude, before computing the FFT we first standardize them.

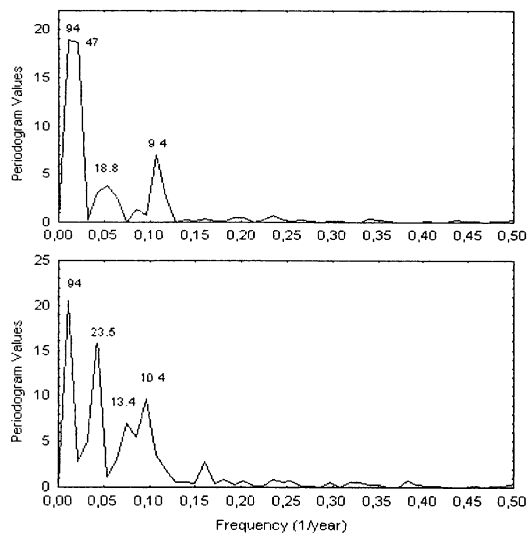

Fig.7. FFT spectra of An (upper panel) and As (lower panel).

In the upper and lower panel of figure 7, the FFT spectra of An and As are presented, respectively. The 47-year periodicity observed in Aa and in Earth rotation fluctuations, as well as the 18.8-year periodicity matching the ≈17 year one in the IMF directions and coronal holes asymmetries and present also in Sa, are only seen in An and not in As. On the other hand, the ≈11-year solar cycle period and the ≈22-year Hale cycle are only found in As and not in An.

As a whole, there is no good correspondence between the rotation in the two solar hemispheres. While there is some weak though statistically significant correlation between the equatorial rotation rates (r=0.36 with

$p<0.05$), there is absolutely no correlation between the latitudinal gradients in the two hemispheres, Bn and Bs. The correlation coefficient is only 0.06.

In Figure 8 the FFT spectra of Bn and Bs are presented. The 47-year and the ~11-year periodicities are seen only in the Northern hemisphere, while the dominant 18.8-year periodicity in the Southern hemisphere is much weaker in the Northern one.

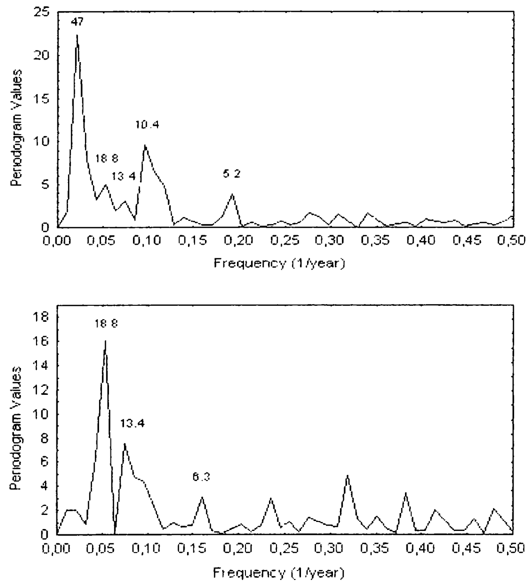

Fig. 8: FFT spectra of Bn (upper panel) and Bs (lower panel).

IMF has been measured directly since the beginning of the satellite era. For the period 1967-1994, we have data for both Bn and Bs coefficients of solar differential rotation derived from Mt Wilson Doppler shift measurements of photospheric line [25], and IMF parameters compiled in OMNI database of the National Space Science Data Center provided through their web-site http://nssdc.gsfc.nasa.gov/omniweb/. The dominant periodicity in the average IMF magnitude in this period is 9.3 years coinciding with the dominant periodicity in Bs, while the dominant periodicity in Bn is 14 years. In this period predominantly more active is the Southern solar hemisphere. I.e., the dominant periodicity in the IMF seems to be the dominant periodicity of the differential rotation of the more active solar hemisphere. To check this result, we compare the periodicities in Bn and Bs to the periodicity of aa index of geomagnetic activity in the periods 1881-1912 when more active is the Southern solar hemisphere, and 1913-1966 with more active Northern hemisphere. In figure 9a, the FFT spectra of aa (respectively of IMF), Bn, and Bs are compared for the first period, 1881-1912, when more active is the Southern solar hemisphere. The dominant periodicity in aa is 16 years matching the dominant periodicity in Bs, while Bn varies with a period of 10.8 years.

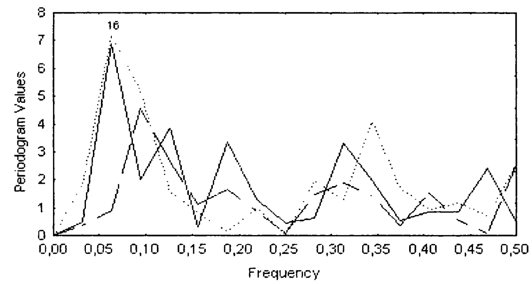

Fig. 9a. FFT spectra of aa-index of geomagnetic activity (solid line), Bn (broken line) and Bs (dotted line) for the period 1881-1912.

In the second period, 1913-1966, more active is the Northern solar hemisphere. The dominant periodicity in aa is 10.8 years. A strong peak at this periodicity is seen in Bn, and no peak in Bs – figure 5b.

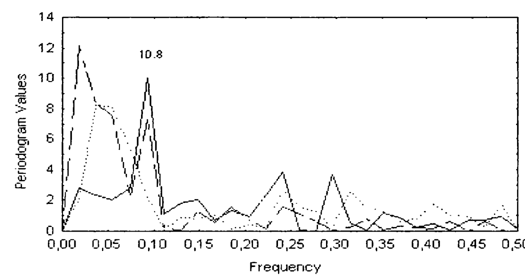

Fig. 9b: The same as figure 9a, for the period 1913-1966.

In the third period, 1967-1994, with more active Southern hemisphere, the dominant periodicity in aa, as in IMF, is 9.3 years, which is the Bs periodicity, while the Bn dominant periodicity is 14 years – figure 5c.

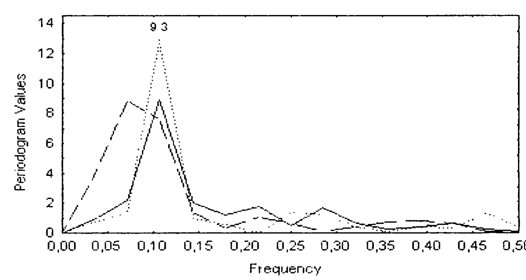

Fig. 9c: The same as figure 9a, for the period 1967-1994.

Therefore, the interplanetary magnetic field at the Earth's orbit which is an extension of the solar coronal field, is the magnetic field of the more active solar hemisphere.

7. SOLAR HELICITY AND THE ATMOSPHERE

One feature is persistently different in the two solar hemispheres – the helicity, or handedness of the magnetic field, which is predominantly negative or left-handed (i.e. counterclockwise when looking at the Sun) in the Northern solar hemisphere, and positive or right-handed in the Southern one [26]. The helicity doesn't change from one sunspot or magnetic cycle to the other, and is carried to the Earth by the magnetic clouds which retain the helicity of the region of their origin [27].

To study the reaction of the atmosphere to the arrival of magnetic clouds with different orientations, we use NCEP CPC stratospheric climate data for polar (80°) temperature, longitudinally averaged zonal wind at 60°, heat flux VT and momentum flux UV between 45 and 75°, from 10 to 70 hPa for the Northern and Southern hemispheres [28]. We compiled a list of 71 magnetic clouds - 30 right-handed (R), and 41 left-handed (L). First we check whether magnetic clouds, irrespective of their handedness, have an impact on the stratosphere. To this end we use Factor analysis - STATISTICA for Windows, Statsoft Inc. (1999). This statistical method is applied to detect structures in variables - to check whether the variables are grouped by one or more factors, i.e. whether they belong to one or more populations. Fig. 10 demonstrates the factor loadings for UV at 30 hPa, North. Three factors are extracted: the days of arrival of magnetic clouds (DAY_0) are "special", and the days before (MINUS_3 to MINUS_1) and after that (PLUS_1 to PLUS_6) – 3 days before to 6 days after the arrival of the cloud, respectively - are clearly in different groups.

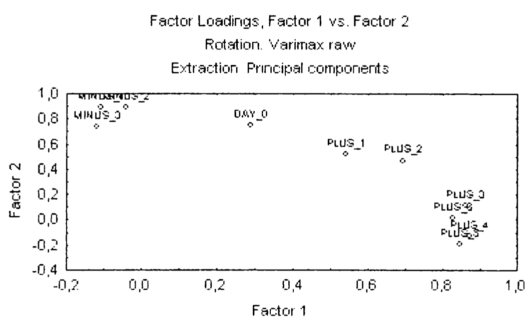

Fig. 10. Factor loadings for UV-30 hPa, from 3 days before to 6 days after the arrival of magnetic clouds.

Effects of magnetic clouds are found in the heat flux and momentum flux, and not in the temperature and zonal winds. No differences in the mean values of the variables are seen when calculated over all cases. However, if the cases are grouped by the phase of QBO, or by the orientation of the magnetic cloud, the difference is obvious. The effects of QBO phase and handedness of magnetic clouds are comparable, and the changes in the heat flux are similar for westerly QBO and right-handed clouds, and for easterly QBO and left-handed clouds (not shown), while for the momentum flux the changes are similar for easterly QBO and right-handed clouds, and for westerly QBO and left-handed clouds – Fig. 11.

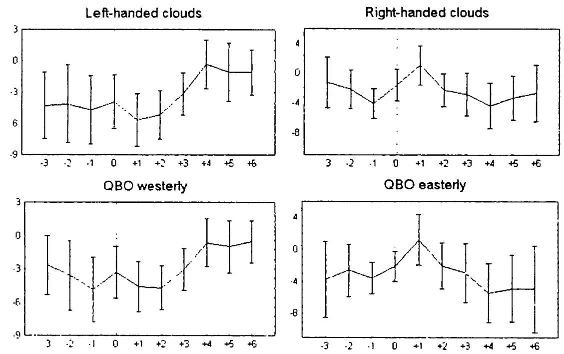

Fig. 11. 30 hPa momentum flux averaged between 45 and 75° C for the days relative to arrival of magnetic clouds, with the data grouped by the handedness of the magnetic cloud (upper panel) or by QBO phase (lower panel).

The statistical significance of the result presented in Fig. 11 is not high, but we believe the effect is real as it present at all pressure levels, and both in the Northern and Southern hemispheres.

8. SUMMARY

The effects of solar variability on climate depend on the North-South solar activity asymmetry. The interplanetary magnetic field at the Earth's orbit originates from the more active solar hemisphere. The North and South solar hemispheres differ in the prevailing helicity which is carried to the Earth by the magnetic clouds. Magnetic clouds change the dynamics of the stratosphere, and their effect depends on both the phase of the quasibiennial oscillation of stratospheric winds, and the handedness of the clouds, i.e. on the solar hemisphere of their origin.

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