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LONG-TERM VARIATIONS OF POLAR MAGNETIC FLUX OF THE SUN AND TERRESTRIAL CLIMATE

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ABSTRACT

We calculated the area of polar zones of the Sun, A_{pz}, occupied by unipolar magnetic field on H_α synoptic magnetic charts, following Makarov (1994), from 1878 to 2000. We found a gradual decrease of the annual latitude of the high-latitude zone boundaries of the global magnetic field of the Sun at the minimum of activity, Θ_{2m}, from 53° in 1878 down to 38° in 1996, yielding an average decrease of 1.2° per cycle. We found that the area of polar zones of the Sun A_{pz} has risen by a factor of 2 during 1878-2000. The area of the unipolar magnetic field at high-latitudes A_{pz} may be used as a new index of magnetic activity of the Sun. We compared A_{pz} with the geomagnetic index $< aa >$ and Wolf number W(t). A temperature difference of about 1.3° between the Maunder Minimum and the present time was deduced. We have found that the highest latitude of the polar zone boundaries of the large-scale magnetic field during very low solar activity reaches about 60°. It is supposed that the Θ_{2m} - latitude coincides with the latitude where $\partial_r \omega = 0$, with $\omega(r, \theta)$ being the angular frequency of the solar rotation. The causes of the waxing and waning of the Sun's activity in conditions like Maunder Minimum are discussed.

Key words: solar cycle: magnetic field; polar magnetic flux; geomagnetic activity; Maunder Minimum.

1. INTRODUCTION

Recently it was argued that the average strength of the magnetic field of the Sun has doubled in the last 100 years from an analysis of the geomagnetic $< aa >$ index, Lockwood et al. (1999). This index depends on the magnetic flux of the Sun and is defined as a result of measurements of the geomagnetic field every 3 hours, Mayaud (1972). A long-term growth of the solar magnetic flux concerns a change of the global warming and increase of the temperature on the Earth (Wilson (1997); Cliver et al. (1998a); Cliver et al. (1998b); Kocharov et al. (1995); Callebaut et al. (2000)). Secular changes on a time-scale about centuries were observed too. The Maunder Minimum in the second half of the 17th century is an excellent example. Naturally, a global warming at present is connected with industrial aspects, too. It is well established that geomagnetic activity is driven by the solar wind, Mayaud (1972). Near sunspot minimum activity there are two distinct solar wind regimes: slow and medium-speed wind flowing from the coronal streamer belt that encircles the equator, and fast wind from the polar coronal holes, Legrand & Simon (1989); Wang et al. (2000). The $< aa >$ index is connected with the high-latitude component of the magnetic field and with polar coronal holes. In the present paper we discuss long-time variations of the area of polar zones of the Sun A_{pz}, occupied by unipolar magnetic field and the geomagnetic $< aa >$ index during 1878-2000. We shall touch upon the question how the Sun enters and leaves the Maunder Minimum.

2. OBSERVATIONAL DATA

In the absence of a long-term record of magnetograph measurements of the solar magnetic field the investigation of polar activity of the Sun in the last 120 years has been based on the latitude-time distribution of unipolar areas of the large-scale magnetic field of the Sun during 1878-2000. The neutral line pattern of the large-scale magnetic fields can be derived with greater accuracy than can be inferred from magnetograms especially in the regions of weak fields and polar zones, Duval et al. (1977); Makarov et al. (2001). At present these H_α charts represent ready material for investigating global properties of large-scale magnetic fields for 12 solar cycles. The synoptic charts show that the polarity of the large-scale magnetic field for any longitude alternates in sign at several latitudes between the equator and the poles. We measure the latitudes of the filament band in every 20° longitude zone and average them over one rotation. High Θ_{2m} and middle Θ_{1m} latitude are the boundaries of predominant polarity of the magnetic field, which were detected Makarov & Sivaraman 1989; Callebaut & Makarov 1992; Makarov & Tlatov 1999. One may add Θ_{0m}, which is situated at the equator where new boundaries are generated.

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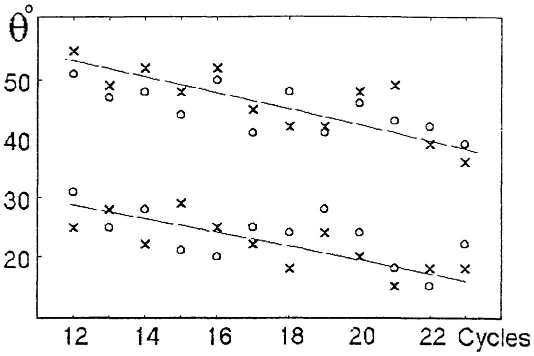

Figure 1. Annual mean latitude of the high-latitude Θ_{2m} (upper part) and low-latitude Θ_{1m} (lower part) zone boundaries of the magnetic field during the minimum activity (x -Northern and o - Southern hemispheres).

3. RESULTS

4.1. The latitude of zone boundaries in 1878-2000.

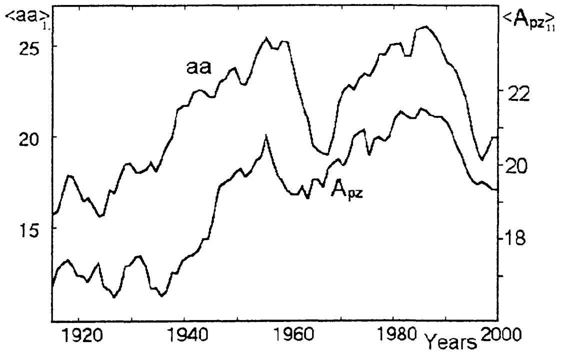

Figure 2. The continuous curve A_{pz} represents the run of mean annual area of unipolar magnetic regions of solar polar caps, averaged with 11-year smoothing for 1915-2000. The upper curve represents the value of the geomagnetic index $< aa >$ averaged with 11-year smoothing.

In Figure 1 we show annual mean latitude of the zone boundaries of the large-scale magnetic field in the minimum activity for N and S hemispheres for 1878-2000, i.e. solar cycle 12-23. These boundaries separate the high and middle-latitude unipolar magnetic fields of the Sun. From Figure 1 one can see that the high-latitude zone boundary (Θ_{2m}), average N and S hemispheres, came nearer to the equator by about 15° during 12 solar cycles. In the Northern hemisphere the latitude (Θ_{2m}) shifted from 55° in 1878 down to 36° in 1996. The similar process was observed in the S-hemisphere, where the latitude (Θ_{2m}) shifted from 51° in 1878 to 39° in 1996. During the 12 cycles the dynamics of the Θ_{2m}-latitude displays the 22-year magnetic cycle of the Sun rather well as pairs of EVEN-ODD 11-year cycles: in an even 11-year cycle the latitude Θ_{2m} is on the average 4° higher than for the subsequent odd one, Makarov 1994. It means, that the area of a polar zone of the Sun occupied by a magnetic field of one polarity varies during a 22-year magnetic cycle. The low-latitude zone boundary Θ_{1m} lowered similarly but less regularly. Nevertheless a correlation between the ODD-EVEN (opposite to Θ_{2m}) cycles is observed. From Figure 1 one can see the general increase of the area of the polar area of the Sun A_{pz}, occupied by the magnetic field of one polarity during a minimum of activity. We calculated the variation of the A_{pz} area during 1878-2000. A spherical segment with an angle of $\pi/2 - \theta$, where θ is the latitude of high-latitude boundary, has relative area S=(1-sinθ)/2 of the complete surface of the Sun. According to Figure 1 the polar caps of the Sun in a minimum of activity had the relative area 0.20 in 1878, and about 0.39 in 1996. It means that the areas, outlined by the latitude Θ_{2m}, increased by a factor 1.95 during more than 120 years. This doubling of the Sun's polar caps, occupied by unipolar magnetic field, corresponds rather well with the increase of the geomagnetic index $< aa >$ in this period, Figure 2. It means, that a doubling of the magnetic flux of the Sun during the past century may be connected, on the whole, with the increase of the magnetic flux from polar caps of the Sun. Indeed, according to (Lockwood et al. (1999)) magnetic flux from the Sun (Fs) was $2.3 \cdot 10^{14}$ Wb in 1901 and it rose to a value of $5.3 \cdot 10^{14}$ Wb in 1992. Thus there was a rise of the solar flux near the Earth by a factor of 2.3. According to Figure 1 (Θ_{2m} = 50° for 1901; Θ_{2m} = 40.5° for 1986; averaged over N and S) the polar cap areas A_{pz} rose by a factor 1.5 during the period 1901-1992. The surface of polar cap with the latitude Θ is S=1/2(1-sinΘ), in units $4\pi R^2$ (πR^2 is more suitable. Hence dS = -1/2cosΘdΘ. With the induction B we obtain for the change in flux parallel to the equator: dF = BcosΘdS. Integrating from $\Theta = pi/2$ to Θ_{2m} under assumption B = const and omitting the factor of proportionality yields

$$F = 1/2(\pi - \sin 2\Theta_{2m}) \qquad (1)$$

For the ratio between 1901 and 1992 we now obtain 1.8. In reality the flux from the cap to Θ_{2m} and the region between Θ_{2m} and Θ_{1m} are opposite and part of them neutralize each other. So in reality we may have to use a polar cap, which does not extend up to Θ_{2m} and this will increase the ratio of the flux somewhat, but probably not up to 2.31. Another small increase in the ratios of the surfaces and flux may be obtained by using the averages of Θ_{1m}, instead of its minimum Θ_{2m}: then some 3° have to be added to the values of Θ_{2m}, decreasing the areas a bit, but increasing the ratios. The remaining part may be attributed to an increase of the magnetic field strength. However, we may agree that there was an increase, on the whole, of the value of the polar cap areas and a minor increase of the field.

4.2. Correlations between $< aa >_{11}$, $< A_{pz} >_{11}$, and $< W >_{11}$-index.

In Figure 2 we show changes of $< aa >_{11}$ index and polar cap areas of the Sun, occupied by unipolar magnetic field $< A_{pz} >_{11}$ during 1878-2000. From Figure 2 it is seen that both indexes change practically simultaneously during the last 120 years. This is connected with the formation of new polar coronal holes that are responsible for strengthening the so-

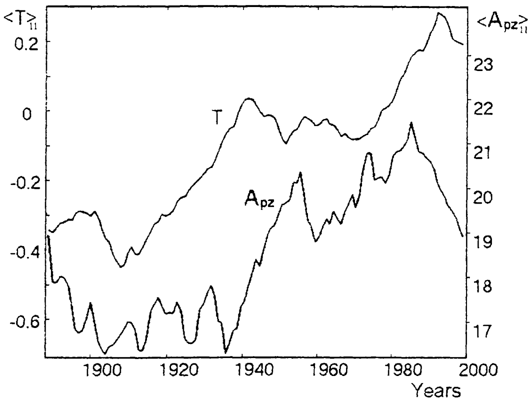

Figure 3. Comparison of the Sun's polar cap area occupied by unipolar magnetic field $< A_{pz} >_{11}$ and the variation of the global surface temperature of the Earth $< T >_{11}$ over the last 120 years for 1880-2000.

lar wind and correspondingly the geomagnetic index $< aa >$. Below are shown the correlations based on "11-year" averages of the Sun and the geomagnetic activity. The regression lines are

$$< aa >_{11} = 0.19 < W >_{11} + 8.1; \qquad (r=0.93) \qquad (2)$$

$$< A_{pz} >_{11} = 0.16 < W >_{11} + 9.3; \qquad (r=0.82) \qquad (3)$$

$$< A_{pz} >_{11} = 0.84 < aa >_{11} + 22.5; \qquad (r=0.82) \qquad (4)$$

$$< A_{pz} >_{11} = 60.8(1 - \sin\Theta_{2m}); \qquad (5)$$

It was noted that the Mount Wilson observations of polar faculae for the a time span of about 80 years do not show a long-term variation of the cycle averaged number of polar faculae, Sheeley (1991); Makarov & Makarova (1996). Polar faculae numbers may be considered as an index of the polar magnetic field. It may be interpreted that the intensity of polar magnetic field did not change in this period. This suggests the conclusion that the long-term increase of the magnetic flux from the Sun and of the $< aa >$ index is caused essentially by growth of the area of polar caps of the Sun.

4.3. The latitude zone boundaries during the Maunder Minimum

The nature of the solar wind during very low sunspot activity like the Maunder Minimum remains uncertain. High correlation between the solar activity (Wolf numbers) and the geomagnetic $< aa >$ index assumes an extrapolation of the observed solar wind variations to the Maunder Minimum condition. Here we use the correlation between the geomagnetic $< aa >_{11}$ index and polar cap areas $< A_{pz} >_{11}$ to obtain an estimate of the latitude of the high-latitude zone boundary Θ_{2m} in the Maunder Minimum. Using "11-year" average of index we obtained

$$< aa >_{11} = 1.2 < A_{pz} >_{11} - 3.0 \qquad (6)$$

$$\sin\Theta_{2m} = -0.014 < aa >_{11} + 0.96 \qquad (7)$$

According to Cliver et al. (1998a) the mean level of geomagnetic activity during the Maunder Minimum (1645-1715) was approximately a third of that observed for recent solar cycles ($< aa >_{11} = 6.9$-7.5 nT vs 24 nT). Using these estimates one can find that the polar cap areas of the Sun $< A_{pz} >_{11}$ correspond to the value of $\Theta_{2m} \approx 60°$ in Maunder Minimum. Thus we expect that Θ_{2m} oscillates between some upper limit, say 60°, and some lower limit, $< 38°$ (its present value). A deep minimum like the Maunder Minimum may correspond to an extremum of Θ_{2m}. In the cycle 23 the value of $< A_{pz} >_{11}$ corresponds to the latitude $\Theta_{2m} = 38°$. This value is not far from the latitude $\approx 37°$, $\partial_r\omega = 0$, with $\omega(r,\theta)$ the angular frequency of the solar rotation.

The Sun has a central uniformly rotating sphere($\partial_r\omega = 0$ and $\partial_r\theta = 0$) to which two "conical blades" ($\Theta_{2m} = 37°$) are attached, where $\omega(r,\theta)$ has the same value. These "conical blades", one in each hemisphere, extend from the uniformly rotating sphere to the solar radius. They separate the polar sectors, where $\partial_r\omega < 0$, from the equatorial sectors, where $\partial_r\omega > 0$. These sectors correspond respectively with the polar faculae and sunspot regions. The separation between those sectors, $\partial_r\omega = 0$ corresponds with Θ_{2m}. Hence this yields an additional link between the large-scale unipolar field, sunspot cycle and polar faculae cycles. The large-scale regions pass from the sunspot region to the polar faculae region and take their "rest" at Θ_{2m} during minimum activity at the separation between both, where $\partial_r\omega \approx 0$. Figure 1 clearly show that Θ_{2m} is steadily decreasing during the last 120 years. We advance the hypothesis that the "conical blades", where Θ_{2m}=0, have the same evolution as they are presumably the cause of Θ_{2m}. Clearly this must bear consequences for the sunspot and polar faculae phenomena, including the deep minima. Thus the layer in the convection zone, where $\partial_r\omega = 0$, decreases too from some upper limit in latitude 60°. However the difference Θ_{2m} - Θ_{1m} is about 21° and remained roughly the same during the last 120 years. For Θ_{1m} we have not a clear link with $\omega(r,\theta)$. Supposing that Θ_{1m} - Θ_{0m}, where Θ_{0m} = 0° (new boundaries are generated at the equator), should not drop below 21°, (i.e. the same difference as Θ_{2m} - Θ_{1m}) then Θ_{1m} is at present at its low minimum. The coming cycles may be rather particular, may be at the verge of a new deep minimum. However, as now Θ_{2m} reaches its minimum value instead of its maximum, the coming deep minimum may have a different character. Any-way, we suggest that the causes of the waxing and waning of the Sun's activity like in the Maunder Minimum are connected with pole ward and equator ward migration of the "conical blade", where $\partial_r\omega = 0$. In the preceding we have considered Θ_{2m} for each cycle as a rather stable value.

The relation between the concentration of C^{14} and solar activity is well known. Stuiver & Quay (1980) detected a few periods of very low activity of the Sun: the Maunder Minimum (1645-1715), the Spörer Minimum (1416-1435, 1470-1534), the Wolf Minimum (1282-1342) and, probably, the Oort Mimimum (1010-1050). The mean duration of low activity is about 60 years and the mean length of time between the minima is about 220 years, or about 20 solar cycles. This corresponds to a latitude drift of the zone boundary of 24°. Again this is an indication that the

Sun may be turning soon (in a few cycles?) into a period of low activity with duration of about 60 years. Very low solar activity at the beginning of the XXI century was predicted (Chistyakov (1983); Badalyan et al. (2001)).

4.4. Temperature variations of the Earth from the Maunder Minimum to the present time.

It is known that Earth's surface temperature is correlated with the geomagnetic $< aa >$ index, Cliver et al. (1998a); Cliver et al. (1998b). For the period 1880-2000 we found regression lines

$$< T >_{11} = 0.039 < aa >_{11} - 0.88 \qquad (r=0.82) \qquad (8)$$

$$< T >_{11} = 1.8 - 2.9 \sin\Theta_{2m} \qquad (r=0.75) \qquad (9)$$

We can extrapolate (9) to the Maunder Minimum to infer the solar induced temperature change. We obtained estimates for the temperature deficit during the Maunder Minimum (-1.0°) relative to the present (+0.3°), yielding an increase of 1.3°, Makarov et al. (2001a). Cliver et al. (1998a) estimated an increase of $\approx 0.7° - 1.5°$ in global surface temperature since the second half of the 17th century. Thus, an increase of the Sun's polar cap area occupied by unipolar magnetic field (solar forcing) is correlated to the global warming over the past 350 years besides greenhouse warming, ocean-atmosphere coupling, etc.

4. CONCLUSION

Our analysis indicates that 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 1878-2000. Thus the behavior of the index $< aa >$ in this period and consequently the magnetic flux from the Sun may be explained by an increase of an area of polar caps with roughly the same value of the magnetic field, although the field shows fluctuations, as e.g. an increase during the last 3 cycles. Indeed our analysis shows that the magnetic flux from the Sun increases by a factor of 1.4 since 1964 and it agrees with the observations. But we have found an increase of polar magnetic field strength B_p from the observations of the annual mean number of polar faculae N_{pf} in this period, Makarov & Makarova (1996). The mean polar magnetic field $< Bp >$ has been estimated of 2.5 Gauss in cycle 21 and 4.0 Gauss in cycle 23, i.e. an increase by factor of 1.6. Hence there was an increase of the value of the polar field of the Sun, but on an interval of time of about two to three 11-year cycles. Long-term increase of a magnetic flux from the Sun was mainly caused by growth of the area of polar cap of the Sun occupied by the unipolar magnetic field. We used the correlations between $< aa >$ and $< A_{pz} >$ to estimate the limit latitude of high-latitude zone boundary Θ_{2m} to be about 60°. Its minimum is < 38°. We suggest that Θ_{2m} practically coincides with the "conical blades" where $\partial_r \omega = 0$ and thus that these "conical blades" have a similar oscillatory motion between say 60° and < 38°. It is supposed that deep minima of solar activity may occur when these "conical blades" reach extreme latitudes. This may be an indication that we are approaching a new deep minimum. We estimated an increase of 1.3° in the temperature of the Earth from Maunder Minimum to the present time.

5. ACKNOWLEDGMENTS

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