North–south asymmetry in solar activity: predicting the amplitude of the next solar cycle

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ABSTRACT

Using Greenwich and Solar Optical Observing Network sunspot group data obtained during the period 1874–2005, we find that the sums of the areas of the sunspot groups in the $0°$–$10°$ latitude-interval of the Sun's northern hemisphere and in the time-interval of -1.35 yr to $+2.15$ yr from the time of the preceding minimum – and in the same latitude interval of the southern hemisphere but $+1.0$ yr to $+1.75$ yr from the time of the maximum – of a sunspot cycle correlate well with the amplitude (maximum of the smoothed monthly sunspot number) of its immediate following cycle. Using this relationship it is possible to predict the amplitude of a sunspot cycle about 9–13 yr in advance. We predicted 74 ± 10 for the amplitude of the upcoming cycle 24. Variations in solar meridional flows during solar cycles and 9–16 yr variations in solar equatorial rotations may be responsible for the aforementioned relationship, which seems to be related to the 22-yr solar magnetic cycle.

Key words: Sun: activity – Sun: magnetic fields – Sun: rotation – Sun: sunspots.

1 INTRODUCTION

The prediction of the level of solar activity is important because solar activity impact us in many ways (Hathaway, Wilson & Reichmann 1999; Hathaway & Wilson 2004). For example, solar flare activity causes geomagnetic storms that can cripple communication and damage power grids. There is also mounting evidence that solar activity has an influence on terrestrial climate and space weather (Rozelot 2001; Hiremath & Mandi 2004; Georgieva et al. 2005). Many attempts have been made to predict the amplitude of a new sunspot cycle by using data of old cycles, with a belief that the solar magnetic field persists for quite some time (Hathaway et al. 1999). The existence of a statistically significant difference between the levels of solar activity in the northern and the southern hemispheres is shown by several statistical studies for most of the solar activity phenomena (Garcia 1990; Carbonell, Oliver & Ballester 1993). The north–south asymmetry is unusually large during the Maunder minimum (Sokoloff 1994). The existence of a few periodicities in the north–south asymmetry of solar activity is also shown (Javaraiah & Gokhale 1997a; Knaack, Stenflo & Berdyugina 2005). In addition, there are considerable north–south differences in the differential rotation rates and the meridional motions of sunspots (Javaraiah & Ulrich 2006). Helioseismology measurements also show the existence of north–south differences in the solar rotational and meridional flows (Zaatri et al. 2006). Therefore, north–south asymmetry in solar activity is an important physical solar property and it greatly

helps in understanding variations in the solar activity (Sokoloff 1994; Javaraiah & Gokhale 1997a; Knaack et al. 2005). In this Letter we have used this property of a solar cycle to predict the amplitude of the upcoming solar cycle 24.

2 DATA ANALYSIS AND RESULTS

We have used the Greenwich sunspot group data during the period 1874–1976, and the sunspot group data from the Solar Optical Observing Network (SOON) of the US Air Force/US National Oceanic and Atmospheric Administration during 1977 January 1–2005 September 30. We have taken recently updated these data from the NASA web-site of David Hathaway (http://solarscience.msfc.nasa.gov/greenwch.shtml). These data include the observation time (the date and the fraction of the day), the heliographic latitude and the longitude, central meridian distance (*CMD*), the corrected whole spot area (in millionths of solar hemisphere, mh), etc. for each day of the spot group observation (130 mh $\approx 10^{22}$ Mx). In the present analysis we have excluded the data corresponding to the $|CMD| > 75°$ in any day of the spot group life-time. This precaution considerably reduces the errors in the derived results due to the foreshortening effect. In the case of the SOON data, we increase the area by a factor of 1.4. David Hathaway found this correction is necessary in order to have a combined homogeneous Greenwich and SOON data (see aforementioned website of David Hathaway). We binned the daily data into $10°$ latitude intervals, in both the northern and the southern hemispheres, and determined the sum of the areas (*AT*) of the spot groups in each $10°$ latitude interval, separately for the rising and the declining phases of the sunspot cycles 11–23. (It should be noted here that cycle 23 is not

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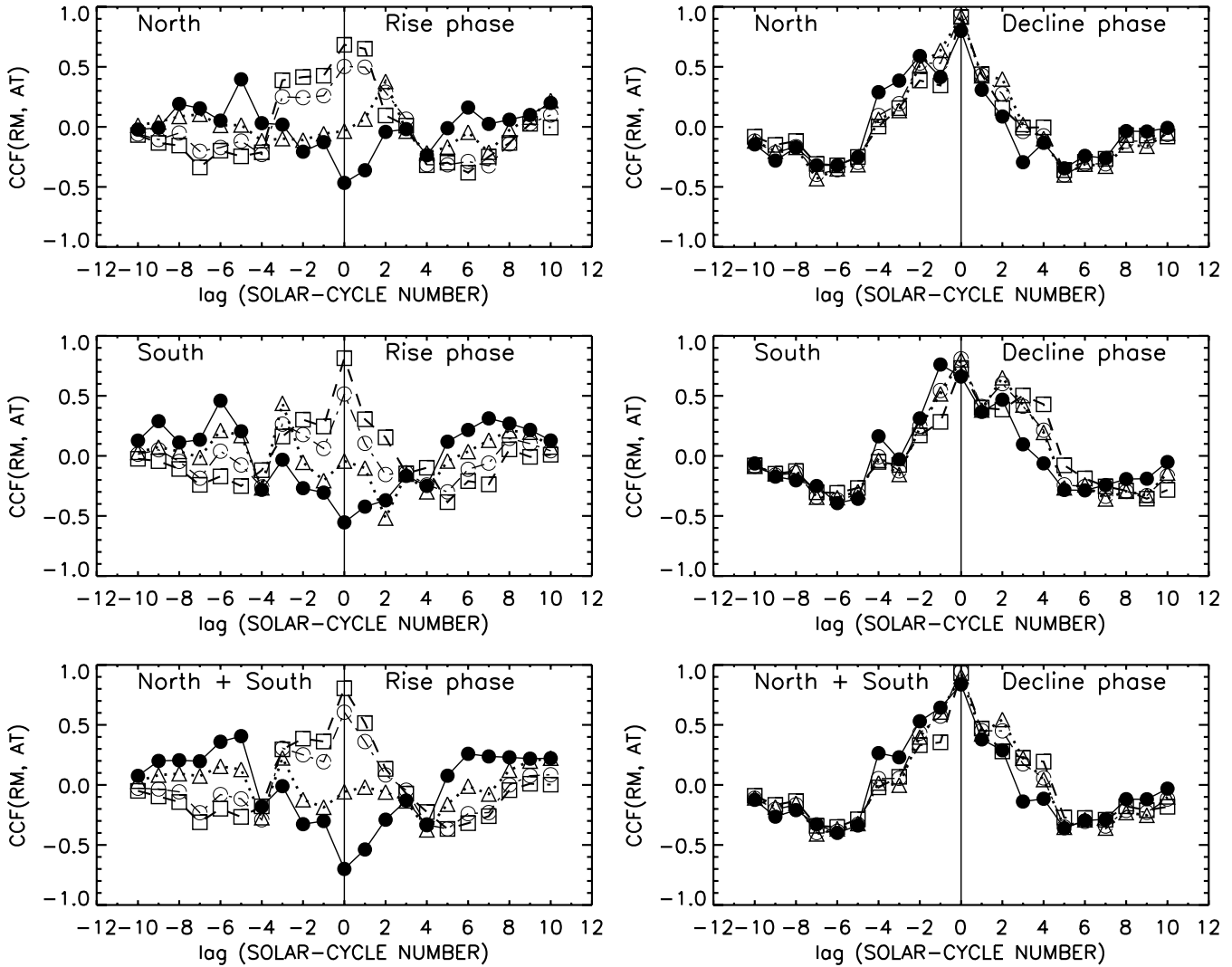
Figure 1. Plots of the *CCF(RM, AT)* verses lag during the rising and declining phases of solar cycles 12–13. A positive value of lag indicates that *RM* leads *AT*. The filled circle, solid curve, the triangle, dotted curve, the square, dashed curve and the open circle, dash–dotted curve represent *CCF(RM, AT)* in the latitude intervals 0°–10°, 10°–20°, 20°–30° and in whole disc, respectively.

yet complete. The data are available for about 9 yr of this cycle. In case of cycle 11, the data are available for the last 4 yr.)

We determined cross-correlations between *AT* and amplitude of cycle (*RM*). We have taken the values of *RM* (which is the largest smoothed monthly mean sunspot number), and the epochs of maxima (*TM*) and the preceding minima (*Tm*) of cycles 12–23 from the website, ftp://ftp.ngdc.noaa.gov/ STP/SOLAR_DATA/SUNSPOT_NUMBERS. Fig. 1 shows the cross-correlation function, *CCF(RM, AT)*, in different latitude intervals (a positive value of lag indicates that *RM* leads *AT*). In this figure it can be seen that, except for *AT* during the declining phases of the cycles and in 0°–10° latitudes intervals of both the northern and the southern hemispheres, for each of the remaining cases (viz. *AT* in 10°–20° and 20°–30° latitude intervals during the declining phases of the cycles and in all the latitude intervals during the rising phases of the cycles) the corresponding *CCF(RM, AT)* has a weak peak at *lag* ⩾ 0. This suggests that in all these latitude intervals *AT* and *RM* variations are approximately in the same phase or that *RM* leads *AT*. In case of *AT* during the declining phases of the cycles, in 0°–10° latitude interval of the southern hemisphere

the *CCF(RM, AT)* has a well-defined peak (value 0.76) at *lag* = −1, suggesting that *AT* leads that of *RM* by about 5–10 yr. In the same latitude interval of the northern hemisphere, the *CCF (RM, AT)* is found to be having a broad peak with two humps (values 0.8 and 0.6) at *lag* = 0 and *lag* = − 2, suggesting that *AT* leads *RM* by about 5–25 yr. These results indicate that *AT* can be used to predict *RM*.

There exist a number of short-term periodicities, from a few days to a few years, in both the solar activity and the solar rotation (Bai & Sturrock 1993; Javaraiah & Komm 1999; Knaack et al. 2005). The amplitude of such a periodicity varies greatly during a solar cycle. Therefore, there is a possibility that *AT* in 0°–10° latitude intervals of the northern and southern hemispheres during some short intervals having strong correlations with *RM*. With this hypothesis we determined the maximal values of correlations between *AT* of cycle *n* and *RM* of cycle *n* + 1 in the following way, where *n* = 12, . . . , 22 is the cycle number. First we determined the values of *AT* in the intervals which were chosen arbitrarily around the epochs of the maxima and the preceding minima of the cycles. The *AT* determinations are repeated by increasing or decreasing the lengths of the

Table 1. The maximum (*RM*) and the minimum (*Rm*) amplitudes (the largest and the smallest smoothed monthly mean sunspot numbers) of the solar-cycles 12–23 and the sum of the areas of spot groups (*AT*, normalized by 1000) in the intervals $Tm^* = Tm + (-1.35\ to\ 2.15)$ and $TM^* = TM + (1.0\ to\ 1.75)$, where *TM* and *Tm* represent the maximum and the preceding minimum epochs of the solar cycles, respectively.

| Cycle | Minimum | | Maximum | | Latitude Int.: 0°–10° (north) | | Latitude Int.: 0°–10° (south) | |
n	*Tm*	*Rm*	*TM*	*RM*	*Tm**	*AT*	*TM**	*AT*
12	1878.9	2.2	1883.9	74.6	1877.55–1881.05	9.47	1884.90–1885.65	42.11
13	1889.6	5.0	1894.1	87.9	1888.25–1891.75	3.22	1895.10–1895.85	32.64
14	1901.7	2.6	1907.0	64.2	1900.35–1903.85	12.98	1908.00–1908.75	54.64
15	1913.6	1.5	1917.6	105.4	1912.25–1915.75	3.74	1918.60–1919.35	34.58
16	1923.6	5.6	1928.4	78.1	1922.25–1925.75	33.96	1929.40–1930.15	75.96
17	1933.8	3.4	1937.4	119.2	1932.45–1935.95	29.96	1938.40–1939.15	82.01
18	1944.2	7.7	1947.5	151.8	1942.85–1946.35	69.35	1948.50–1949.25	119.65
19	1954.3	3.4	1957.9	201.3	1952.95–1956.45	15.23	1958.90–1959.65	53.01
20	1964.9	9.6	1968.9	110.6	1963.55–1967.05	50.31	1969.90–1970.65	78.28
21	1976.5	12.2	1979.9	164.5	1975.15–1978.65	60.05	1980.90–1981.65	83.53
22	1986.8	12.3	1989.6	158.5	1985.45–1988.95	29.85	1990.60–1991.35	67.48
23[a]	1996.4	8.0	2000.3	120.8	1995.05–1998.55	21.99	2001.30–2002.05	33.58

Notes: [a]indicates the incompleteness of the current cycle 23.

intervals with steps of $\geqslant 0.05$ yr at a time. We find that in the 0°–10° latitude interval of the southern hemisphere, the correlation is maximum and the coefficient of correlation $r = 0.97$ (from 11 data points), in the short (0.75-yr) time-interval just after 1-yr after the time of maximum of each of the cycles 12–23, $TM^* : TM + (1.0\ to\ 1.75)$ (i.e. close to the time of the reversal of polarities of the polar magnetic fields). We also find that in the 0°–10° latitude interval of the northern hemisphere $r = 0.95$ is maximum in the time-interval (3.5 yr) of -1.35 yr to $+2.15$ yr from the preceding minimum of each of the cycles 12–13, $Tm^* : Tm + (-1.35\ to\ 2.15)$. Both these correlations are statistically highly significant, with a >99.99 confidence level (from Student's *t*-test), i.e. the chance of getting these relations from uncorrelated quantities is less than 0.01 per cent. Interestingly, the existence of a 0.75-yr periodicity is known in solar activity (Knaack et al. 2005), and it may be a subharmonic of the well-known Rieger periodicity in solar flare activity (Bai & Sturrock 1993). The existence of a 3.5-yr periodicity in solar activity is also known and this periodicity seems to be more pronounced in the north–south asymmetries of solar activity and surface rotation (Javaraiah & Gokhale 1997a; Knaack et al. 2005). In Table 1 we have given the values of *AT* during Tm^* and TM^*. In the same table we have also given the values of the amplitudes and the epochs of maxima and minima of the sunspot cycles 12–23.

We find the following linear regressions fits between *AT* and *RM* correspond to the correlations above:

$$RM_{n+1} = (1.72 \pm 0.19)AT_n(Tm^*) + (74.0 \pm 7.0), \qquad (1)$$

$$RM_{n+1} = (1.55 \pm 0.14)AT_n(TM^*) + (21.8 \pm 9.6), \qquad (2)$$

where uncertainties in the coefficients are the formal 1σ (standard deviation) errors from the fit. In equations (1) and (2) the slopes are on 9σ and 11σ levels, respectively. That is, they are statistically highly significant. Therefore, the relationship between AT_n and RM_{n+1} is well described by these linear equations. It should be noted here that Tm^* is always associated with the 0°–10° latitude interval in the northern hemisphere, whereas TM^* is associated with the 0°–10° latitude interval of the southern hemisphere (for other combinations, i.e. TM^* with the 0°–10° interval of the northern hemisphere and Tm^* with the 0°–10° interval of the southern hemisphere the values of *r* are found to be mere 0.11 and -0.24, respectively).

Using equations (1) and (2) the amplitudes of the upcoming sunspot cycles can be predicted by about 13 yr and 9 yr in ad-

vance, respectively. The results of the least-square fits are shown in Fig. 2(a). Fig. 2(b) shows the correlation between the simulated amplitudes (*PM*) (simulated using equations 1 and 2) and the observed amplitudes (*RM*) of the cycles 13–23. The correlations between *PM* and *RM* and their levels of significance are the same as those of AT_n and RM_{n+1}.

Using equations (1) and (2) we obtained the values 112 ± 13 and 74 ± 10, respectively, for *RM* of the upcoming cycle 24 (the uncertainty value is 1σ). The latter is more statistically significant than the former. Hence, by using equation (2) the amplitude of a cycle can be predicted accurately about 9 yr in advance. Therefore, we predict 74 ± 10 for *RM* of cycle 24. This is equal to the value predicted by Svalgaard et al. (2005) (see Section 3). The pattern of the mean cycle-to-cycle variation of the simulated amplitudes (*PM*) obtained using equations (1) and (2) is found to strikingly resemble that of *RM* ($r = 0.97$) slightly more. From this we get 93 ± 10 for *RM* of cycle 24. However, the difference between the values obtained from equations (1) and (2) for cycle 24 is significantly large. The mean deviation is at the 2σ level. Hence, we do not suggest the mean value for *RM* of cycle 24. Moreover, from equations (1) and (2) we can get $RM_{n+1} \approx 2.1AT_n(Tm^*) - 0.6AT_n(TM^*)$. [This may be a more appropriate representation, because this includes both terms, $A_n(Tm^*)$ and $AT_n(TM^*)$.] From this relation we get a much smaller value, 57 ± 13, for the amplitude of cycle 24 ($r = 0.95$). It is somewhat closer to the value obtained from equation (2). [The negative sign of the coefficient of $AT_n(Tm^*)$ in the aforementioned relation can be attributed to the opposite polarities of the magnetic fields at Tm^* and TM_{n+1} (in the sunspot latitude belt).]

Each of the values for the amplitude of the upcoming cycle 24 derived above is less than the *RM* of cycle 23. This is consistent with the indication that the level of activity is now at the declining phase of the current Gleissberg cycle (Javaraiah, Bertello & Ulrich 2005). From equations (1) and (2) we can also get $AT_n(TM^*) \approx 1.11AT_n(Tm^*) + 33.6$. [$r = 0.94$, between the simulated and the observed $AT(TM^*)$. Note that the residual is quite large in case of cycle 23.] Hence, the magnetic field at Tm^* may contribute to the field at TM_{n+1} both directly and through influencing the field at TM^*. There is also a suggestion that when $AT_n(Tm^*)$ is zero the $AT_n(TM^*)$ is not always zero. This might have happened during the late Maunder minimum, when sunspot activity is somewhat more pronounced in the southern hemisphere than in the northern hemisphere (see Sokoloff 1994). [The current cycle 23 will be ending soon. Thus,
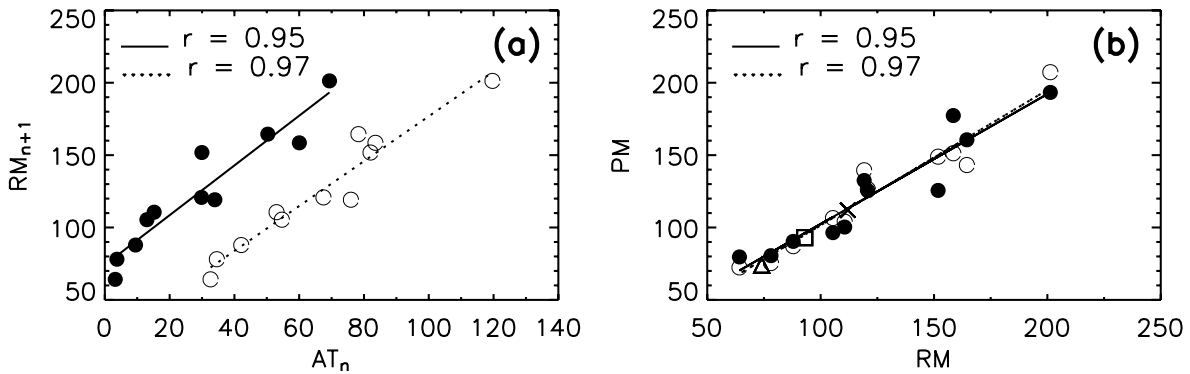
Figure 2. Plots of the correlations (a) between the *AT* (for the values given in Table 1) during the intervals *Tm** and *TM** which correspond to cycle *n* and *RM* of the cycle *n* + 1, and (b) between *RM* and the simulated amplitude *PM* of cycle *n* + 1, where *n* = 12, . . . , 22, is the cycle number. The straight lines represent the corresponding linear relationships. The values of the correlation coefficient (*r*) are also given. The filled circle and the solid line correspond to the *AT* during *Tm**, and the open circle and the dotted line correspond to the *AT* during *TM**. The cross and triangle represent the values for *RM* of cycle 24 obtained using *AT* during *Tm** and *TM**, respectively, and the square represents the corresponding mean value. We predict the value represented by the triangle for *RM* of cycle 24.

using equation (1), or using the aforementioned relationship between $AT_n(Tm^*)$ and $AT_n(TM^*)$ and equation (2), an approximate prediction can be made for the amplitude of cycle 25 in three years' time.]

3 DISCUSSION

The strength of the preceding minimum is used to predict the strength of the maximum of the same cycle. However, it seems this method works better after 1–2 yr after the start of the cycle, i.e. an accurate prediction is possible only about 3–4 yr in advance. The same is also true for the predictions based on geomagnetic indices as precursor indicators (Hathaway et al. 1999).

The magnetic fields at the Sun's polar regions are important ingredients for a dynamo model (Ulrich & Boyden 2005). The polar field is maximum near the sunspot minimum. Schatten et al. (1978) have used, for the first time, the strength of the polar fields at the preceding minimum of a cycle as a precursive indicator to the strength of the following maximum. Recently, Svalgaard et al. (2005) analyzed the polar fields' data during the four recent solar cycles and predicted a small amplitude, 75 ± 8, for the upcoming cycle 24. Obviously from this method the prediction can be made only about 5 yr in advance. This method seems to be more uncertain and could fail if used too early before the start of the cycle (Svalgaard et al. 2005).

Dikpati, de Toma & Gilman (2006), by simulating the surface magnetic flux using the guidelines of a dynamo model, predicted a large amplitude, 150–180, for cycle 24, i.e. a contradiction to the aforementioned prediction by Svalgaard et al. (2005). This discrepancy implies that the dynamo processes are not yet fully understood, making prediction more difficult (Tobias, Hughes & Weiss 2006).

Using the well-known Gnevyshev–Ohl, or G-O, rule (Gnevyshev & Ohl 1948), it is possible to predict only the amplitude of an odd-numbered cycle (Wilson 1988). This is also not always possible because occasionally (for example, recently by the cycle pair 22,23) the G-O rule is violated. A major advantage of the AT_n–RM_{n+1} relationships above is that using these the amplitudes of both odd- and even-numbered cycles can be predicted. In addition, this new method seems to have a solid physical basis. Interestingly, the *TM** is very close to the epoch when the polar-field polarity reversals take place (Makarov, Tlatov & Sivaraman 2003) and *Tm** is close to the epoch when the magnetic field polarity reversals take place, close to

the equator, i.e. at the beginning of a cycle and continuing through the years of minimum (Makarov, Tlatov & Sivaraman 2001). This suggests that the AT_n–RM_{n+1} relationships are related to the 22-yr solar magnetic cycle. It should be noted here that although sunspot activity is confined to middle and low latitudes, it may be caused by the global modes of the solar magnetic cycle (Gokhale et al. 1992; Juckett 2003).

Reconnection of the magnetic fields of opposite polarities is believed to be the basic mechanism of flare activity. (Priest & Forbes 2000) During *Tm** the magnetic field structure seem to be largely quadrupole nature, which is probably favourable for the production of X-class flares (Garcia 1990). The solar meridional flows transport angular momentum and magnetic field from pole to equator and vice versa, in the convection zone. The motions of spot groups mimic the motions in the convection zone (Javaraiah & Gokhale 1997b; Javaraiah & Komm 1999). The mean meridional motion of sunspot groups is changing from pole-ward to equator-ward rapidly in the $0°$–$10°$ latitude interval of the northern hemisphere and gradually in the same latitude interval of southern hemisphere during *Tm** and *TM**, respectively (see fig. 2 in Javaraiah & Ulrich 2006). These results indicate a participation of the meridional flows in the magnetic reconnection process and the reversals of the polarities of magnetic fields during *Tm** and *TM**. The interceptions of the poleward and the equator-ward meridional flows may be responsible for the quadrupole nature of magnetic fields during *Tm**. It seems that during rising phases of the cycles the flare activity is strong in the northern hemisphere and weak in the southern hemisphere, and this is reversed during the declining phases of the cycles (Garcia 1990). During the rising phases of the cycles the mean meridional velocity of spot groups is equator-ward in the northern hemisphere and pole-ward in the southern hemisphere. During the declining phases of the cycles the velocity is pole-ward in both hemispheres, but the variation is steep in the southern hemisphere, mainly in the $20°$–$30°$ latitude interval (Javaraiah & Ulrich 2006). In view of the above inferences, the north–south asymmetry in solar flare activity may be related to the north–south asymmetry in the meridional flows. The corresponding losses in the magnetic flux in the northern and the southern hemispheres caused by the reconnection processes may have contributed to the north–south asymmetries in solar magnetic field and in sunspot-activity.

The lengths of the intervals between the beginnings of *Tm** and *TM** of a preceding cycle to *TM* of its following cycle vary between

14–19 yr and 8–12 yr, respectively. The corresponding mean values are found to be 16 yr and 9.6 yr, respectively. Similar periodicities exist in both the equatorial rotation rate and the latitude gradient term of the solar rotation determined from the sunspot group data (Javaraiah & Gokhale 1997a; Javaraiah 2005; Georgieva et al. 2005). Therefore, variations in the solar meridional flows during solar cycles and 9–16 yr variations in the solar equatorial rotation may be responsible for the AT_n–RM_{n+1} relationships above.

4 CONCLUSIONS

Using Greenwich and SOON sunspot group data during the period 1874–2005 we find that:

(i) the sum of the areas (AT) of the spot groups in the $0°$–$10°$ latitude interval of the Sun's northern hemisphere during the interval $Tm^* : Tm + (−1.35 \text{ to } 2.15)$ in a cycle is well correlated with the amplitude (RM) of its following cycle, where Tm is the time (in years) of the preceding minimum of the preceding cycle,

(ii) the AT of the spot groups in the $0°$–$10°$ latitude interval of the southern hemisphere during the interval $TM^* : TM + (1.0–1.75)$ in a cycle is also well correlated with RM of its following cycle, where TM is the time (in yr) of the maximum of the preceding cycle,

(iii) using (i) and (ii) it is possible to predict the RM of a cycle about 9–13 yr in advance, respectively,

(iv) we predicted 74 ± 10 for RM of cycle 24,

(v) variations in solar meridional flows during solar cycles and 9–16 yr variations in solar equatorial rotation may be responsible for the relations described in (i) and (ii), which seems to be related to a 22-yr solar magnetic cycle.

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