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The Long-term Behavior of the North – South Asymmetry of Sunspot Activity

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Abstract A new index, the cumulative difference of sunspot activity in the northern and southern hemispheres, respectively, is proposed to describe the long-term behavior of the North – South asymmetry of sunspot activity and to show the balance (or bias) of sunspot activity in the two solar hemispheres on a long-term scale. Sunspot groups and sunspot areas from June 1874 to January 2007 are used to show the advantage of the index. The index clearly shows a long-term characteristic time scale of about 12 cycles in the North – South asymmetry of sunspot activity. Sunspot activity is found to dominate in the southern hemisphere in cycle 23, and in cycle 24 it is predicted to dominate still in the southern hemisphere. A comparison of the new index with other similar indexes is also given.

Keywords Sunspots, statistics · Solar cycle, observations

1. Introduction

Solar-activity indexes vary over the solar disk, and various activity indexes cannot be considered to be symmetrical between the solar northern and southern hemispheres (Atac and Ozguc, 1996, 2001, 2006; Carbonell, Oliver, and Ballester, 1993; Gigolashvili, 2003; Knaack, Stenflo, and Berdygina, 2004, 2005; Li *et al.*, 2002; Temmer *et al.*, 2001, 2006). The North – South asymmetry of solar activity has been the subject of many studies carried out using different features of solar activity (for details, see Ballester, Oliver, and Carbonell, 2005). Some of the most important indicators of solar activity considered in

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these studies have been sunspot numbers, sunspot group numbers, sunspot areas, the numbers of flares, the flare index, filaments, (active) prominences, radio bursts, solar γ-ray bursts, coronal holes, CMEs, photospheric magnetic fields, faculae, the monochromatic and K coronae, the solar wind, and green corona intensity (Badalyan *et al.*, 2005; Bai, 1990; Ballester, Oliver, and Carbonell, 2005; Gigolashvili *et al.*, 2005; Javaraiah, 2003; Jevtic, Schweitzer, and Cellucci, 2001; Joshi and Joshi, 2004; Joshi and Pant, 2005; Joshi, Pant, and Manoharan, 2006; Kane, 2005a, 2005b; Li, Schmieder, and Li, 1998; Li *et al.*, 2000, 2003; Oliver and Ballester, 1994; Ozguc, Atac, and Rybak, 2003, 2004; Temmer, Veronig, and Hanslmeier, 2002). These solar activities have indicated that the North – South (N – S) asymmetry of solar activity is a real phenomenon and not due to random fluctuations. Summaries of the study on the hemispheric asymmetry of solar activity include those of Vizoso and Ballester (1990), Verma (1993), Li, Schmieder, and Li (1998), Li *et al.* (2002), and Carbonell *et al.* (2007).

The N – S asymmetry of solar activity shows obvious cyclical behavior (Walmeier, 1957; Verma, 1993; Duchlev and Dermendjiev, 1996; Li, Yun, and Gu, 2001; Li *et al.*, 2000). Three groups of periods can be distinguished: long periods of about 100 years, medium periods of one to three solar cycles, and short periods of one to five years (Duchlev and Dermendjiev, 1996; Chang, 2008). For long periods, Walmeier (1957) obtained a period of about 80 years in the variation of the asymmetry of sunspot activity between the northern and southern hemispheres. Vizoso and Ballester (1990) and Atac and Ozguc (1996) found that every four cycles the slope of the straight-line fitting of the N – S asymmetry values changes its sign, suggesting one kind of eight-cycle periodic behavior in the N – S asymmetry of solar activity. Combining data of seven solar activity phenomena spanning 14 solar cycles, Verma (1993) obtained a trend of a long-term characteristic time scale of about 110 years through studying the variation of the dominant hemispheres with solar cycles. Duchlev (2001) found a long-term period of about 11 solar cycles in the filament asymmetry variation by using the cumulative index for the filament N – S asymmetry. Li, Yun, and Gu (2001) inferred that a long-term hemispheric variation of 12 cycles should exist through investigating the cumulative counts of sunspot group numbers for the northern and southern hemispheres. Li *et al.* (2002) also found that every four cycles the slope of the straight-line fitting of the N – S asymmetry values changes its sign and clarified that the dominant hemispheres of solar activity regularly vary with sunspot cycles, suggesting a long-term characteristic time scale of about 12 cycles in the N – S asymmetry of solar activity. Long periods are uncertain since they are commensurable with the longest time series studied of the N – S asymmetry of solar activity, and some authors (Newton and Milson, 1955; Duchlev and Dermendjiev, 1996) prefer to treat long-term variations in the N – S asymmetry of solar activity as a trend.

In this study, a new index, the cumulative difference of sunspot activity in the northern and southern hemispheres, respectively, is proposed to describe the long-term behavior of the N – S asymmetry of sunspot activity. The index can clearly show the long-term cyclical trend of the N – S asymmetry of sunspot activity.

2. The Long-term Behavior of the North – South Asymmetry of Sunspot Activity

2.1. Data

The observational data of sunspot groups come from the augmented Royal Greenwich Observatory (RGO) data set, which is available at its Web site (http://solarscience.msfc.nasa.gov/greenwch.shtml). (The RGO data set extends from 1874 to 1976; thereafter, the observations are from NOAA.) The data set comprises sunspot groups during the period of June

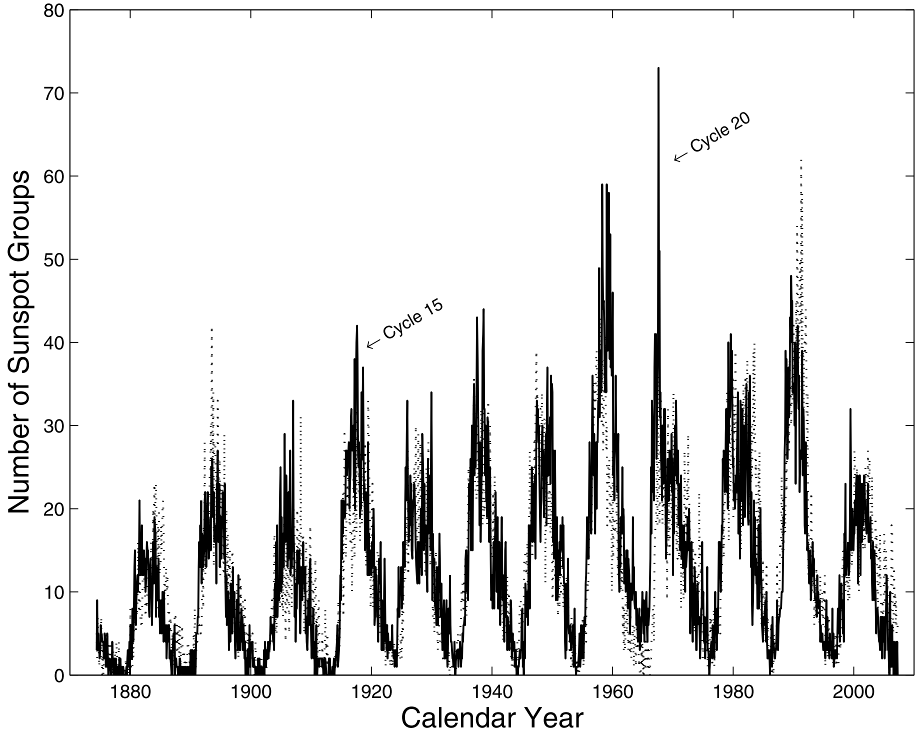

Figure 1 The monthly number of sunspot groups in the northern (solid line) and the southern (dotted line) hemispheres from June 1874 to January 2007, corresponding to late cycle 11 through cycle 23.

1874 to the present (January 2007) and will be updated monthly; the period corresponds to late cycle 11 through cycle 23. In the following, we use the data to count the monthly number of sunspot groups in the northern and southern hemispheres, respectively; these are shown in Figure 1. The figure clearly shows that sunspot groups occur unevenly in the two solar hemispheres.

The monthly mean northern and southern sunspot areas form June 1874 to January 2007 used in the present study come also from the RGO data set and are available at the Web site. As studied by Li *et al.* (2002), Ballester, Oliver, and Carbonell (2005), and Carbonell *et al.* (2007), the monthly mean values of sunspot areas are also asymmetrically distributed in the two solar hemispheres.

2.2. The Long-term Behavior of the N – S Asymmetry of Sunspot Activity

To characterize the N – S asymmetry of solar activity, it is traditionally normalized to the solar activity present in both the solar hemispheres and defined as follows: Asymmetry $= (\mathrm{NO_N} - \mathrm{NO_S})/(\mathrm{NO_N} + \mathrm{NO_S})$, where $\mathrm{NO_N}$ and $\mathrm{NO_S}$ stand for the values of the solar activity indicators considered corresponding to the northern and southern hemispheres, respectively. Sometimes the absolute N – S asymmetry of solar activity is used and defined as $\Delta = \mathrm{NO_N} - \mathrm{NO_S}$ (Ballester, Oliver, and Carbonell, 2005; Temmer *et al.*, 2006; Zolotova and Ponyavin, 2006; Carbonell *et al.*, 2007; Donner and Thiel, 2007; Zolotova and Ponyavin, 2007). On the basis of the normalized N – S asymmetry of solar activity, Duchlev (2001) proposed an index, the cumulative index of asymmetry, to describe the long-term behavior of the N – S asymmetry of solar activity. This index was similarly defined as $A_c = (NO_N - NO_S)/(NO_N + NO_S)$, but NO_N and NO_S stand for the *cumulative* value of the solar activity indicators considered corresponding to the northern and southern hemispheres, respectively, and from the beginning of the considered period for each time point within the period. Here, similarly to what was done by Duchlev (2001), on the basis of the absolute N – S asymmetry of solar activity, a new index, the cumulative difference (CD) of solar activity in the northern and southern hemispheres, respectively, is proposed and defined as $CD = NO_N - NO_S$, where NO_N and NO_S stand for the *cumulative* value of the solar activity indicators considered corresponding to the northern and southern hemispheres, respectively, and from the beginning of the considered period for each time point within the period. In the present study, NO_N and NO_S concretely represent the monthly numbers of the northern and southern hemispheric sunspot groups correspondingly, or the monthly mean northern and southern hemispheric areas of sunspots correspondingly, and accumulated from the beginning (June 1874) of the data period for each time (here each month) within the period. The cumulative difference of sunspot activity in the northern and southern hemispheres was illustrated by Li, Yun, and Gu (2001) and Temmer *et al.* (2006), but it was accumulated within a solar cycle. Here the new index is accumulated within more than 12 cycles to show the long-term behavior of the N – S asymmetry of sunspot activity.

Shown in Figures 2 and 3 are the cumulative difference of the monthly numbers of northern and southern hemispheric sunspot groups and that of the monthly mean northern and southern hemispheric areas of sunspots, respectively. The difference between the CD value of sunspot activity at the beginning and at the end time of a cycle, respectively, represents a net difference of hemispheric sunspot activity in the whole cycle and thus can be used to show a dominant hemisphere of sunspot activity in the cycle. As the two figures show, *i*) the two CD lines are both forming a cosine profile, and thus a long-term hemispheric variation of at least 12 cycles is inferred to exist; *ii*) the difference of the two CD values at the beginning and at the end time of cycle 23 is negative, and thus in the present cycle sunspot activity is found to dominate in the southern hemisphere, and in cycle 24 sunspot activity is predicted to dominate still in the southern hemisphere, because the lines tend to go down in the cycle; *iii*) the absolute cumulative difference of sunspot activity in a cycle usually peaks at the maximum of the cycle, seemingly suggesting a cyclic behavior of about one cycle length; and *iv*) for the first several cycles, sunspot activity is relatively weak, and the cumulative difference is relatively small, but for the last several cycles, sunspot activity has been relatively strong, and the cumulative difference relatively large, and thus the cumulative difference of sunspot activity in a cycle seemingly becomes large with the increase of sunspot activity amplitude in the cycle.

2.3. Statistical Test for the Cumulative Difference

Student's *t*-test is a suitable statistical test for a noninteger and dimensional time series (Carbonell *et al.*, 2007). In the present study, it is used to test the statistical significance of the cumulative difference of the monthly numbers of northern and southern hemispheric sunspot groups and that of the monthly mean northern and southern hemispheric areas of sunspots. A CD value of a solar index at a certain time is actually the difference of the solar northern and southern hemispheric cumulative index, and it is accumulated from the beginning to the certain time of the CD series; thus "a certain time point" of a CD series is actually the "deadline point" to which the series is accumulated. Therefore, testing the statistical significance of a CD value at a certain time is actually equivalent to testing the

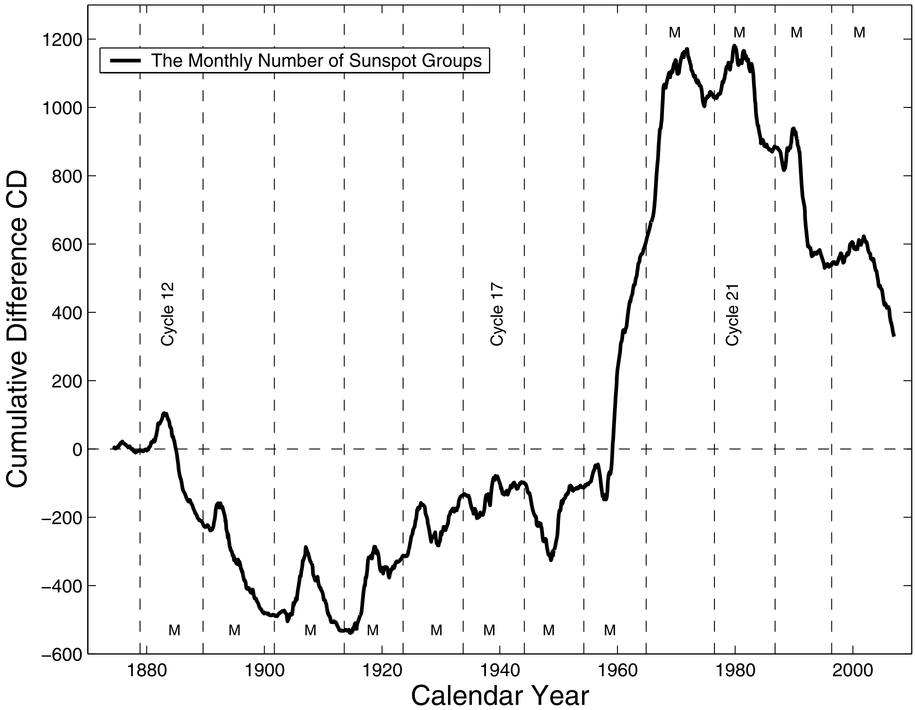

Figure 2 The cumulative difference (CD) of the monthly number of northern and southern hemispheric sunspot groups. The vertical dashed lines represent minima of sunspot active cycles, and M denotes maxima of sunspot active cycles.

statistical significance of a distribution of the CD series from the beginning to the time point (deadline point) of the CD series; "a certain time point" of a CD series determines a span of the CD data that is utilized to test the statistical significance. Figure 4 shows the calculated Student's *t*-test values varying with the span of the CD data used. The tabulated Student's *t*-test values at the 95% probability level are also shown in the figure to help us judge the statistical significance of the CD series. The calculated values periodically fluctuate around the tabulated-value line, suggesting a long-term period of about 12 cycle lengths should exist in the CD series. When a CD series systematically moves from a dominant solar hemisphere of statistical significance to the other dominant solar hemisphere of statistical significance, a time interval of the CD series with statistical insignificance should appear. The calculated line may reflect the periodical variation of solar dominant hemisphere.

2.4. A Comparison of the Two Indexes: The Cumulative Difference and the Cumulative Index of Asymmetry

Duchlev (2001) proposed an index, the cumulative index of asymmetry, to describe the long-term behavior of the North – South asymmetry of solar activity. Shown here in Figures 5 and 6 are the cumulative index of asymmetry for the monthly number of northern and southern hemispheric sunspot groups and that for the monthly mean northern and southern hemispheric area of sunspots, respectively.

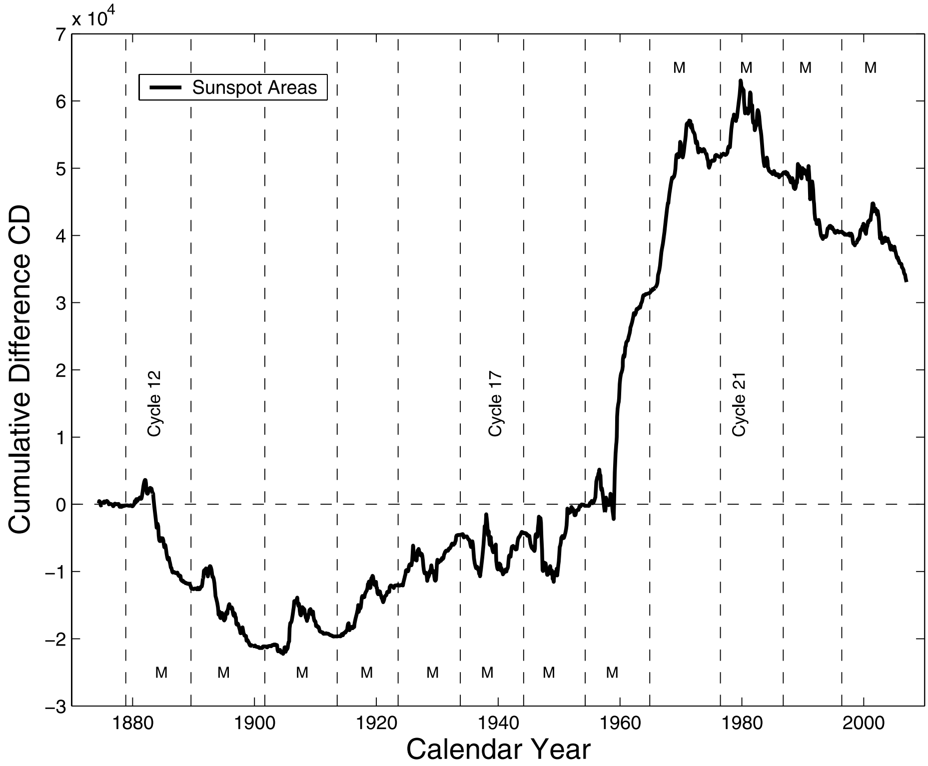

Figure 3 The cumulative difference of the monthly mean northern and southern hemispheric areas of sunspots. The vertical dashed lines represent minima of sunspot active cycles, and M denotes maxima of sunspot active cycles.

As pointed out by Duchlev (2001), the cumulative index of asymmetry A_c allows us to eliminate the fluctuations of a N–S asymmetry in several successive time points. In this way, A_c represents the behavior of the activity balance between the northern and southern solar hemispheres on a long-term scale, and so does the new index CD. As Figures 5 and 6 show, *i*) a long-term hemispheric variation of at least 12 cycles is inferred to exist; *ii*) in the present cycle, cycle 23, sunspot activity is inferred to dominate seemingly in the southern hemisphere; however, in cycle 24 sunspot activity can hardly be predicted to dominate in any hemisphere; *iii*) the absolute A_c peaks at the maximum of a cycle in the first five cycles (cycles 12 to 16); afterward A_c is hardly seen to peak at the maximum of a cycle; and *iv*) as pointed out by Duchlev (2001), the A_c curves are more dynamic in the beginning of a considered period, because in a short initial time interval the cumulative effect is insufficiently effective, but no such large fluctuation is seen for the CD curves in Figures 2 and 3.

As pointed out by Duchlev (2001), the basic shortcoming of the A_c index is connected with the problem of an initial point. It is necessary to have an initial time interval elapsed before the accumulating method works effectively. For this reason the behavior of the plotted A_c curve is affected by different initial times within his method. An A_c curve is shifted forward in time in relation to actual moments of the long-term variation of a North–South asymmetry. For the CD index, different initial time points just make the whole CD curve shift vertically upward or downward, thus eliminating the problem of an initial point.

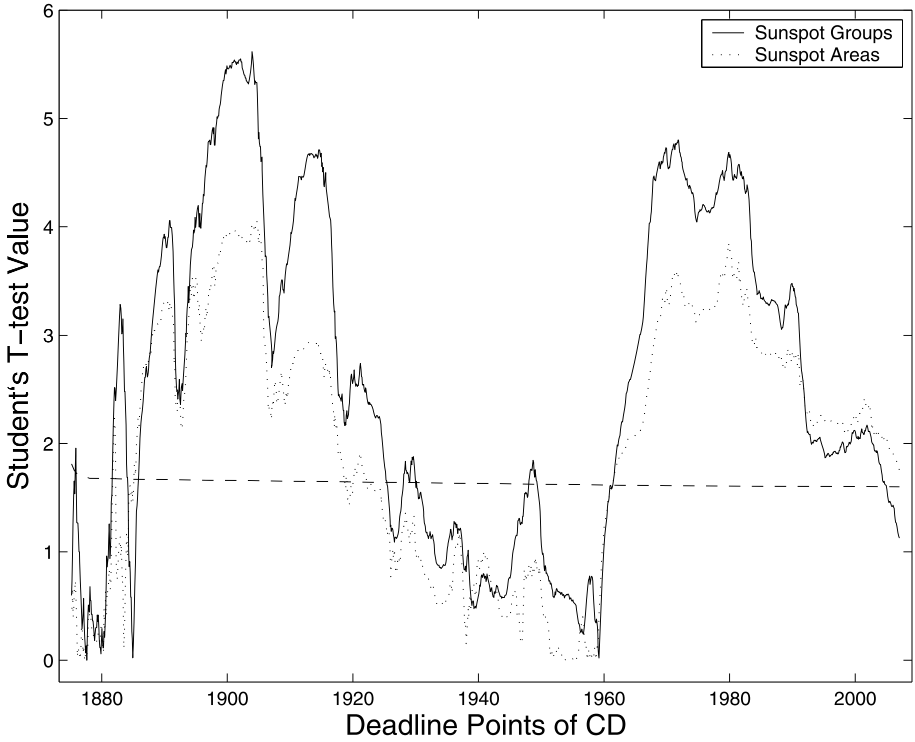

Figure 4 The calculated Student's *t*-test values of CD distribution for the monthly number of northern and southern hemispheric sunspot groups (solid line) varying with data span (the deadline time point of the CD data) and those for the monthly mean northern and southern hemispheric areas of sunspots (dotted line). The dashed line is the tabulated Student's *t*-test values at 95% probability level.

As more and more cycles elapse, the A_c index gets closer and closer to zero, because its denominator ($NO_N + NO_S$) becomes larger and larger. That is, the method of the A_c index works less efficiently when more cycles have elapsed. But for the method of CD index, no such problem seems to appear.

3. Results and Discussion

In the present study, a new index, the cumulative difference of sunspot activity in the northern and southern hemispheres, respectively, is proposed to describe the long-term behavior of the North – South asymmetry of sunspot activity. The cumulative difference of sunspot activity is defined as an absolute northern and southern hemispheric cumulative asymmetry without any normalization. With the use of the observational data of sunspot groups and sunspot areas during the period from June 1874 to January 2007, the following results are obtained: *i*) a long-term hemispheric variation of at least 12 cycles is inferred to exist; *ii*) sunspot activity in cycle 23 is found to dominate in the southern hemisphere, a trend that is predicted to continue into cycle 24; and *iii*) the absolute cumulative difference of sunspot activity usually peaks at the maximum of a cycle, suggesting a cyclic behavior of about one cycle.

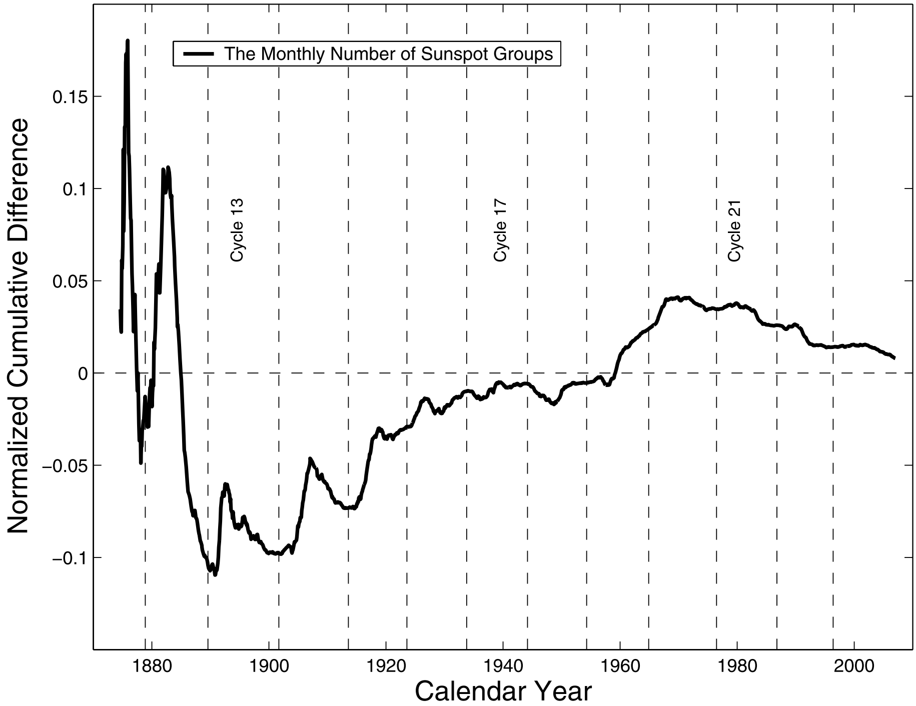

Figure 5 The cumulative index of asymmetry for the monthly number of northern and southern hemispheric sunspot groups. The vertical dashed lines represent minima of active sunspot cycles.

A long-term hemispheric variation of about 12 cycles was obtained by Verma (1993), Duchlev (2001), Li, Yun, and Gu (2001), and Li *et al.* (2002); our findings are in agreement with theirs. Ballester, Oliver, and Carbonell (2005) analyzed the absolute N – S asymmetry of sunspot areas through the discrete Fourier transform and the Lomb – Scargle periodogram. They also found a long-term period of 129.75 years (about 12 cycles), which was regarded as an underlying trend of hemispheric sunspot activity. Verma (1993), Atac and Ozguc (1996), and Li *et al.* (2002) predicted that sunspot activity will dominate in the southern hemisphere in cycle 24, as do our findings.

In the present study, Student's *t*-test is used to test the statistical significance of the cumulative difference of the monthly numbers of northern and southern hemispheric sunspot groups and that of the monthly mean northern and southern hemispheric areas of sunspots, and a long-term period of about 12 cycles length should be inferred to exist in the CD series.

Duchlev (2001) proposed an index, the cumulative index of asymmetry, to describe the long-term behavior of the North – South asymmetry of solar activity. The basic shortcoming of the index is connected with the problem of an initial count point, and secondly, the index works with less and less efficiency when more and more cycles have elapsed. To avoid these two defects, we propose a new index. A comparison of the two indexes is carried out in this study, and it is found that the new index can give a dominant hemisphere of sunspot activity in a future solar cycle; however, the previous one cannot. Further, the old index, the cumulative index of asymmetry (its absolute value), peaks at the maximum of a cycle just in the first several cycles of a considered long-term interval; after that it is hardly seen to peak at the maximum of a cycle. As pointed out by Duchlev (2001), his index curve is more

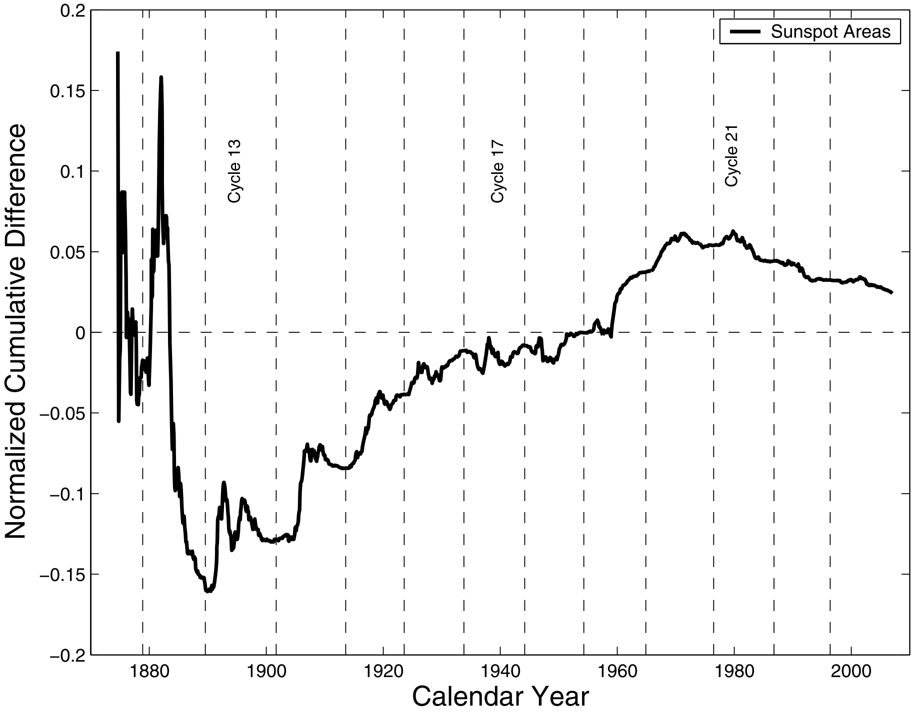

Figure 6 The cumulative index of asymmetry for the monthly mean northern and southern hemispheric areas of sunspots. The vertical dashed lines represent minima of active sunspot cycles.

dynamic in the beginning of the considered period, because in a short initial time interval the cumulative effect is not yet sufficiently effective, but no such large fluctuation appears for the new index. Thus, the proposed new index is necessary, and it is believed to be capable of more and more clearly showing the long-term behavior of the North – South asymmetry of sunspot activity as more and more sunspot cycles have elapsed.

Sunspot activity is characterized by the solar cycle; however, Ballester, Oliver, and Carbonell (2005) found that the solar cycle does not appear in the absolute N – S asymmetry of sunspot activity, because it occurs in the two hemispheres at exactly the same period and in phase. The discrete Fourier transform of the CD series indicates that the solar cycle does not appear in the CD series of sunspot activity. When a hemispheric index is accumulated within a rather long time interval, of course, the period signal of the solar cycle should be weakened. Further, the period signal of the solar cycle in a long CD series becomes weaker if the solar cycle occurs in the two hemispheres at exactly the same period and in phase, because CD reflects hemispheric differences of sunspot activity such as the absolute N – S asymmetry of sunspot activity.

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