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Phase analysis of sunspot group numbers on both solar hemispheres *

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Abstract Cross-correlation analysis and wavelet transform methods are proposed to investigate the phase relationship between the monthly sunspot group numbers in the solar northern and southern hemispheres. It is found that (1) the monthly sunspot group numbers in the northern hemisphere begin two months earlier than those in the southern one, which should lead to phase asynchrony between them but with a slight effect; (2) the Schwabe cycle length for the monthly sunspot group numbers in the two hemispheres obviously differs from each other, and the mean Schwabe cycle length of the monthly sunspot group numbers in the northern hemisphere is slightly larger than that in the southern one; (3) the monthly sunspot group numbers in the northern hemisphere precede those in the southern hemisphere during the years of about 1874–1927, after which, the southern hemisphere leads the northern hemisphere in the years 1928–1964, and then the northern hemisphere leads in time till the present.

Key words: methods: data analysis — Sun: activity — Sun: sunspots

1 INTRODUCTION

It has been generally accepted that activities on the Sun exhibit a complex spatial evolutionary behavior. Solar activities in the northern and southern hemispheres are highly synchronous, forming the famous “butterfly diagram” (Carrington 1858; Maunder 1913, 1922). However, solar activities have been found to be sightly asynchronous between the northern and southern hemispheres in recent studies (Ponyavin & Zolotova 2004; Zolotova & Ponyavin 2006, 2007a,b; Donner & Thiel 2007; Li 2008, 2009; Zolotova et al. 2009, 2010; Li et al. 2008, 2009a,b, 2010a,b; Deng et al. 2011a). The north-south asynchrony of dynamical processes is an important topic for understanding the origin and evolution of active regions on the Sun and their various manifestations in the solar corona (Zolotova & Ponyavin 2006, 2007b). Furthermore, the north-south asynchrony brings about hemispheric asymmetry of solar activities (Li et al. 2009a; Deng et al. 2011a, 2012). Therefore, interest in phase asynchrony of solar activities in the two hemispheres has considerably grown.

It is well known that the Sun displays dissipative nonlinear behavior. Approaches using linear analysis, such as cross-correlation analysis and Fourier transform, may generate artifacts when they

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are applied to analyze real-world processes (Zolotova & Ponyavin 2007b; Li 2008; Li et al. 2008, 2010a). Currently, many advanced approaches using nonlinear analysis, such as those involving the wavelet transform methods, cross-recurrence plots (CRPs) and so on, are widely used to study the nonlinear behavior of solar activities. Over the last few years, there have been many applications with approaches of nonlinear analysis in scientific research, and they have been demonstrated to have unprecedented prowess in revealing hidden physical meanings in data (Frick et al. 1997a,b; Grinsted et al. 2004; Ma et al. 2009; Johnson 2010; Gao et al. 2011, 2012; Xie et al. 2012; Li et al. 2008, 2009b, 2010a; Li & Liang 2010; and references therein).

Following the rising interest in the study of hemispheric asynchrony in solar activities, the aim of this paper is to study the phase asynchrony of the monthly sunspot group numbers in the northern and southern hemispheres by means of linear and modern nonlinear techniques. The layout of this paper is as follows. Shown in Section 2 are the data used and the approaches employed in this work. The results are revealed in Section 3. Finally, the main conclusions and discussions are shown in Section 4.

2 DATA AND METHODOLOGY

2.1 Data

The observational data of sunspot group numbers used in the present study come from the Royal Greenwich Observatory data set, which can be downloaded from the website[1]. The data set is comprised of sunspot groups during the period from 1874 May to 2010 December, which covers from solar cycle 12 to the beginning of solar cycle 24. Based on this data set, a new data set was generated, in which every sunspot group was counted once, even though it was recorded several times in the old data set because it was observed during several days when it passed through the solar disk (Li et al. 2002). Using the new data set, Figure 1 shows the monthly sunspot group numbers in the northern and southern hemispheres, respectively, during the time interval from 1874 May to 2010 December. The figure indicates that the sunspot group numbers vary with time in the two hemispheres in different ways. The two data series never peak at the same time, implying that there is a phase asynchrony between the monthly sunspot group numbers in the two hemispheres.

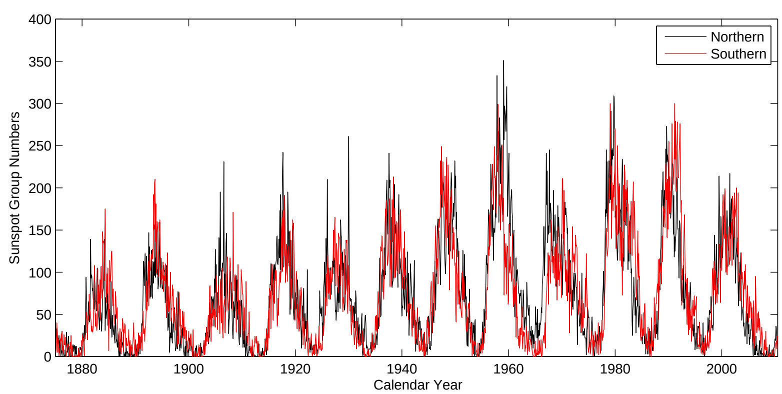

Fig. 1 Monthly sunspot group numbers in the time interval of 1874 May to 2010 December in the solar northern (*black line*) and southern (*red line*) hemispheres.

[1] *http://www.science.nasa.gov/ssl/pad/solar/greenwch.htm*

It should be noted that the sunspot group numbers are introduced by Li et al. (2002) and they are different from the so-called group sunspot numbers defined by Hoyt & Schatten (1998a,b). Both of them can be used to represent long-term solar activity (Hathaway et al. 2002; Ogurtsov et al. 2002; Faria et al. 2004; Li et al. 2005; Li & Liang 2010; Li & Li 2007).

2.2 Methods

2.2.1 Cross-correlation analysis

A cross-correlation analysis (CCA) adopted by Yan et al. (2011) and Deng et al. (2011b) is used to study the phase relationship between the monthly sunspot group numbers in the northern and southern hemispheres. The cross-correlation coefficient between the distributions of the two data series is defined as

$$\mathrm{CC}(\Delta) = \frac{\sum_{i=1}^{n}[N(i) - \langle N\rangle][S(i+\Delta) - \langle S\rangle]}{(n-1)\delta_N\delta_S}\,, \tag{1}$$

where $\langle N\rangle$ ($\langle S\rangle$) and δ_N (δ_S) represent the mean value and standard deviation of the monthly sunspot group numbers in the northern (southern) hemisphere respectively. Positive (negative) Δ means that the time series of the monthly sunspot group numbers in the northern hemisphere leads (lags) those in the southern one. We calculate the cross-correlation coefficients for the leading and lagging shifts between them.

2.2.2 Wavelet transform methods

It is well known that the wavelet transform is a powerful tool for analyzing non-stationary signals and permits the identification of the main periodicity in a time series and the evolution in time of each frequency (Torrence & Compo 1998). The continuous wavelet transform (CWT) is good for detecting the localized and quasi-periodic fluctuations by using the limited time span of the data. Its extensions, the cross-wavelet transform (XWT) and wavelet coherence (WTC), are very useful for examining the relationship in time-frequency space between two time series (Grinsted et al. 2004). They can reveal similarities in the states of the two systems and allow us to study the synchronization or phase difference in two time series (Marwan et al. 2002).

The XWT is an extension of a wavelet transform that reveals their common power and relative phase in time-frequency space between two time series. The XWT of two time series X and Y is defined as

$$W^{XY} = W^X W^{Y*}\,, \tag{2}$$

where $W^X(W^Y)$ is the continuous wavelet transforms of the time series and $*$ denotes complex conjugation. The complex argument arg (W^{XY}) can be interpreted as a local relative phase between X and Y in time-frequency space, namely the phase angle difference of X and Y (Grinsted et al. 2004).

The WTC can quantify how coherent common oscillatory components of two signals are in time-frequency space. The measure of WTC is defined between two CWTs to find significant coherence even though the common power is low (Grinsted et al. 2004). The WTC is necessary because the wavelet cross-spectrum appears to be unsuitable for significance testing of the interrelation between two processes (Marwan & Kurths 2002; Maraun & Kurths 2004). The WTC of two time series X and Y is defined as

$$R_n^2(s) = \frac{\left|S\left(s^{-1}W_n^{XY}(s)\right)\right|^2}{S\left(s^{-1}|W_n^X(s)|^2\right)\cdot S\left(s^{-1}|W_n^Y(s)|^2\right)}\,, \tag{3}$$

where S is a smoothing operator.

However, the CWT, XWT and WTC suffer from edge artifacts because the wavelet is not completely localized in time. Thus, a cone of influence (COI), in which the transform suffers from these edge effects, is introduced. The COI is defined so that the wavelet power for a discontinuity at the edges decreases by a factor e^{-2} (Grinsted et al. 2004). In our analysis, we employ the Morlet wavelet, which is defined as

$$\Psi_0(\eta) = \pi^{-1/4} e^{i\omega_0 \eta} e^{-\eta^2/2}\,, \tag{4}$$

where ω_0 is the dimensionless frequency and η is the dimensionless time. When using wavelets for the purpose of feature-extraction, the Morlet wavelet (with ω_0 = 6) is a good choice, since it provides a good balance between time and frequency localization (Grinsted et al. 2004).

3 RESULTS

Figure 2 shows the result of the cross-correlation coefficients between the monthly sunspot group numbers in the northern and southern hemispheres in the time interval from 1874 May to 2010 December. The abscissa indicates the shift of the monthly sunspot group numbers in the northern hemisphere with respect to those in the southern one, with positive (negative) values representing forward (backward) shifts. From the figure, the best (positive) correlation, with a correlation coefficient of 0.7543 between the monthly sunspot group numbers in the northern and southern hemispheres, occurs when the former has a forward shift of two months with respect to the latter. From a statistical point of view, the cross-correlation coefficient obtained is highly significant. Therefore, such a phase shift should lead to a slight increase in phase asynchrony between the two.

Figure 3 shows the continuous wavelet power spectra of the monthly sunspot group numbers in the northern and southern hemispheres. There are evidently common features in the wavelet power spectra of the two time series. From the figure, it can be found that the periodic belt of the highest power spectra for both data sets is located around the 11-year periodicity (the Schwabe cycle). Moreover, the periodic belt is reliable because it is above the 95% confidence level.

Figure 4 displays the Schwabe cycle length varying with time for the monthly sunspot group numbers in the northern and southern hemispheres. At a certain time point, the Schwabe cycle length

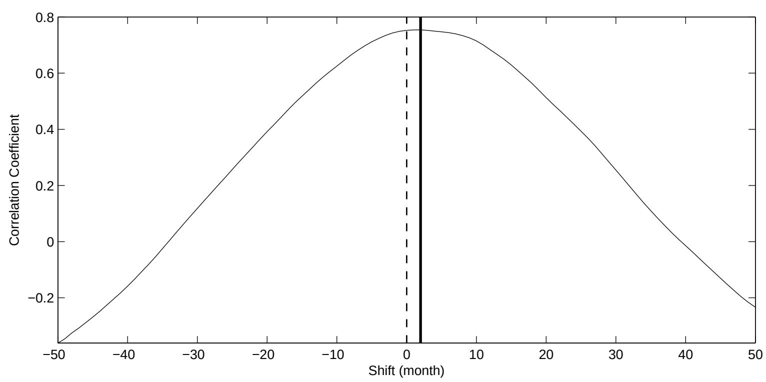

Fig. 2 Cross-correlation coefficients between the sunspot group numbers in the northern and southern hemispheres as a function of shift. The abscissa indicates the shift of the sunspot group numbers in the northern hemisphere with respect to those in the southern one, with negative values representing backward shifts. The cross-correlation coefficients have been smoothed by a 13-point running average method.

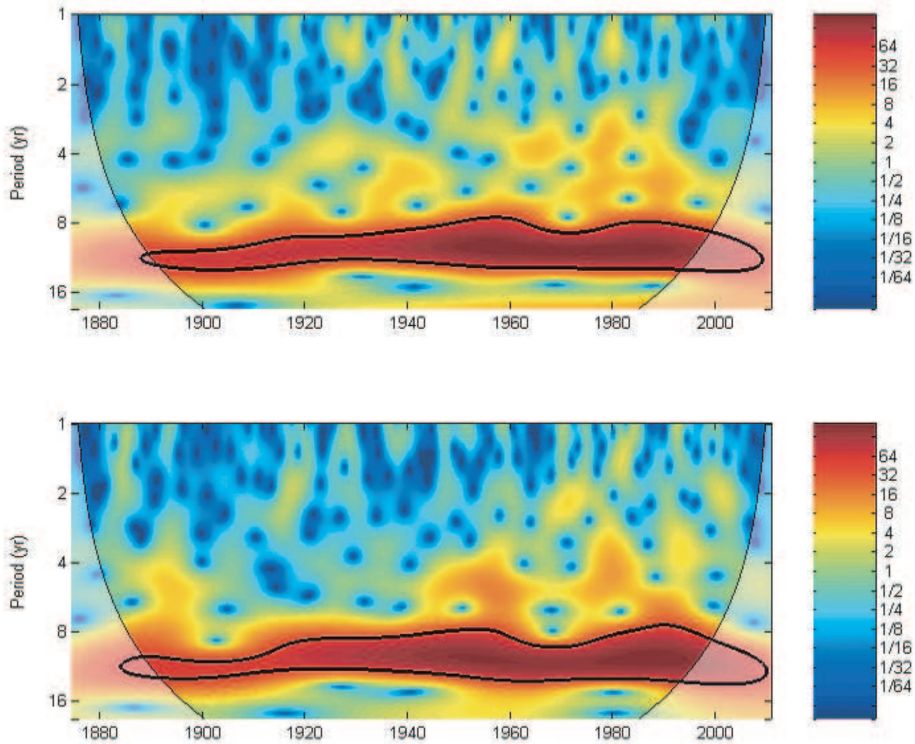

Fig. 3 Continuous wavelet power spectra of the monthly sunspot group numbers in the northern (*top panel*) and southern (*bottom panel*) hemispheres. The thick black contours indicate the 95% confidence level, and the region below the thin black line is the cone of influence (COI) where edge effects might distort the picture.

of the monthly sunspot group numbers in the northern or southern hemisphere has the highest spectral power among all time scales in the local wavelet power spectra (Li et al. 2008, 2009a,b, 2010a; Li & Liang 2010). As the figure shows, (1) the Schwabe cycle length of the monthly sunspot group numbers in the two hemispheres varies from 9.8–11.7 years during the considered time interval; (2) the Schwabe cycle length is longer in the northern hemisphere than that in the southern one in the years of 1884–1950 and 1981–1996, and shorter during the years of 1874–1883, 1951–1980 and 1997–2010. We calculate the mean Schwabe cycle length for the monthly sunspot group numbers in the two hemispheres, and find that the mean Schwabe cycle length is 10.527 years for the northern hemisphere and 10.515 years for the southern hemisphere. The mean Schwabe cycle length is slightly longer in the northern hemisphere because the Schwabe cycle length is longer during most times in the northern hemisphere than in the southern hemisphere. As demonstrated by Zolotova & Ponyavin (2006), if period or frequency of two time series differs from each other, the two are asynchronous. Thus, we infer that the difference between the Schwabe cycle length of the monthly sunspot group numbers in the two hemispheres should also lead to phase asynchrony between them.

To know the phase relationship between the monthly sunspot group numbers in the two hemispheres, and whether the common features of the two time series obtained by CWT are a coincidence or not, the codes provided by Grinsted et al. (2004) are employed to show the XWT between them,

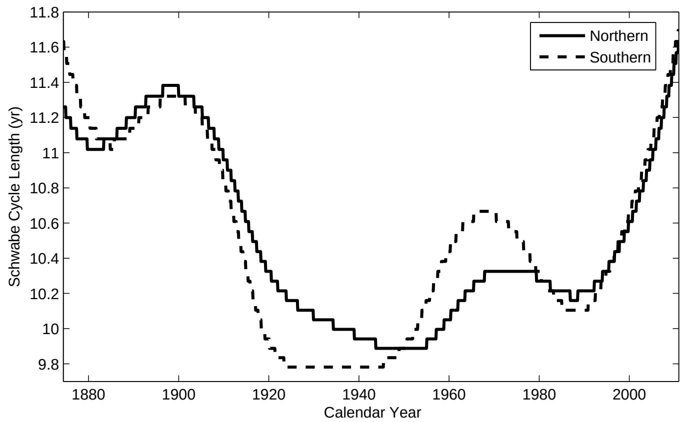

Fig. 4 Schwabe cycle length for the monthly sunspot group numbers in the northern (*solid line*) and southern (*dashed line*) hemispheres.

which are displayed in Figure 5. The relative phase relation is shown by arrows. Arrows point to the right when processes are in phase and to the left when they are in anti-phase. If an arrow points up (down), then the first process lags (leads) the second one.

From Figure 5, the common features found from the individual CWT in Figure 3 are still very clear and their confidence level is also above 95%. The high-frequency components demonstrate a noisy behavior with strong phase mixing because almost all the arrows at high frequencies are randomly distributed. That is to say, the cross-wavelet spectrum displays phase asynchrony of the monthly sunspot group numbers in the two hemispheres in the high-frequency components. In the low-frequency components around the Schwabe cycle belt (8–14 years), the arrows have a small angle with the right direction, pointing down before the year of about 1927, pointing up during the years of about 1928–1964, and pointing down again after that. Thus, the leading hemisphere of the monthly sunspot group numbers is inferred to be the northern one before the year 1927, then the southern one until about the year 1964, and after that returning back to the northern one.

Furthermore, we calculate the average of relative phase angles varying with period between the monthly sunspot group numbers in the two hemispheres, which is shown in the top panel of Figure 6. Here, such a phase angle at a certain period is calculated as the mean value of all phase angles at the period from the beginning to the end of the considered time interval (Li et al. 2008, 2009b, 2010a; Li & Liang 2010). The corresponding standard deviation of the phase angles is also calculated, which is shown in the bottom panel of Figure 6. As the figure shows, the phase angle is less than 11% ($0.36/\pi$) and standard deviation is less than 17% ($0.52/\pi$) of the mean length of the Schwabe cycle at the periodic scales of 8–14 years. These relative phase angles are always positive, indicating that the monthly sunspot group numbers in the northern hemisphere lead those in the southern hemisphere at the periodic scales of 8–14 years. At periodic scales of less than eight years, the relative phase angles fluctuate violently and their standard deviations are very large. By studying the hemispheric asynchrony of sunspot areas, Donner & Thiel (2007) found that the availability of a physically meaningful phase definition depends crucially on the appropriate choice of reference frequencies. Our results are fully consistent with the results of Donner & Thiel (2007).

Because the relative phase angles acutely fluctuate, there are no regular oscillatory patterns in the very small and very large reference periodic scales. Therefore, we focus on periodicities around the Scwabe cycle of 8–14 years as the reference time scales. Based on Figure 5, we calculate the average

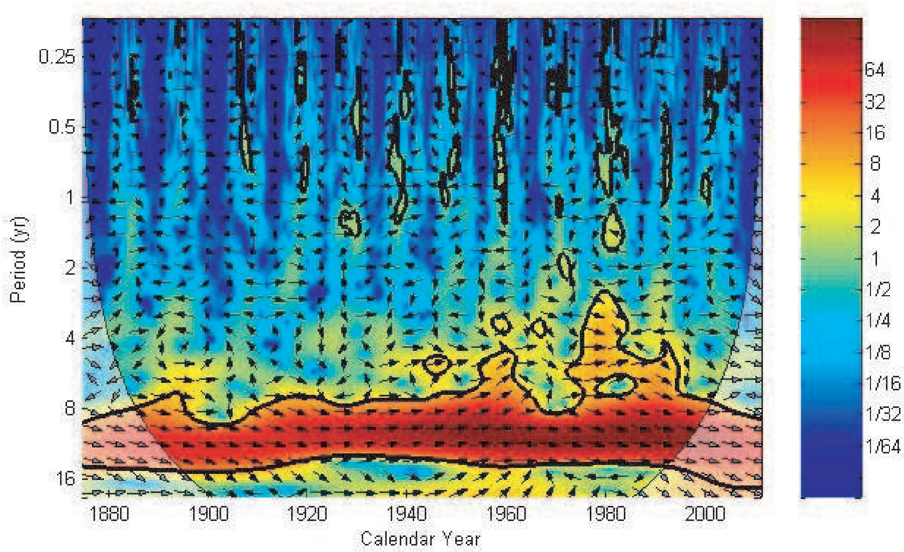

Fig. 5 Cross-wavelet transform of the monthly sunspot group numbers in the northern hemisphere with respect to those in the southern one. The thick black contours indicate the 95% confidence level, and the thin black line is the cone of influence (COI). The relative phase relationship is shown as arrows with in-phase pointing right, anti-phase pointing left, and the former leading the latter by 90° pointing straight down.

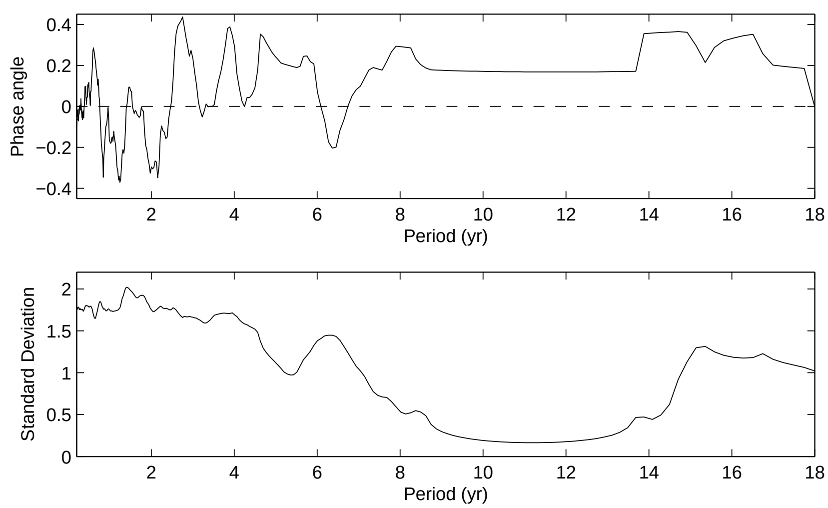

Fig. 6 Phase angles of the monthly sunspot group numbers in the northern hemisphere with respect to those in the southern one as a function of period (*top panel*) and their corresponding standard deviations (*bottom panel*) with the XWT method used. Positive values should be interpreted as the monthly group sunspot numbers in the northern hemisphere leading those in the southern one.

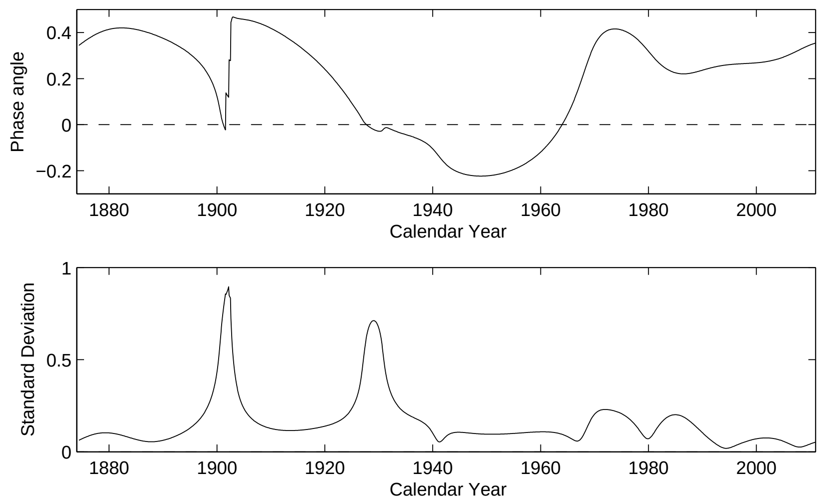

Fig. 7 Average of phase angles by the period scales of 8–14 years varying with time (*top panel*) and their corresponding standard deviations (*bottom panel*) with the XWT method used. Positive values should be interpreted as the monthly sunspot group numbers in the northern hemisphere leading those in the southern one.

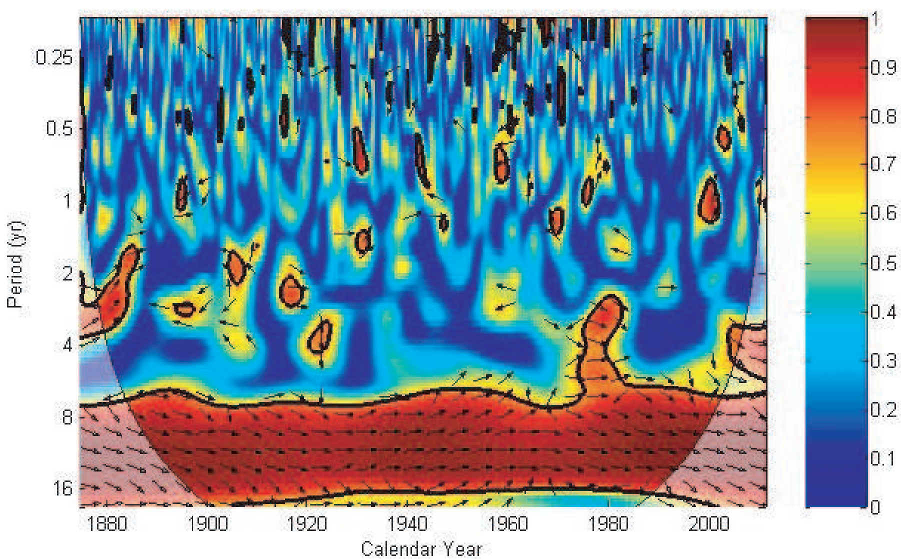

Fig. 8 Wavelet coherence of the monthly sunspot group numbers in the northern and southern hemispheres. The thick black contours indicate the 95% confidence level, and the thin black line is the cone of influence (COI). The relative phase relationship is shown as arrows with in-phase pointing right, anti-phase pointing left, and the former leading the latter by 90° pointing straight down.

of relative phase angles over periodic scales of 8–14 years for all time points of the considered time interval, which is shown in the top panel of Figure 7. Their corresponding standard deviations of the phase angles are also calculated and shown in the bottom panel of Figure 7. The figure indicates that the mean phase angle is positive in the years of 1874–1927 and 1965–2010, and negative during the years of 1928–1964. That is to say, the monthly sunspot group numbers in the northern hemisphere should lead those in the southern hemisphere in the years of 1874–1927 and 1965–2010, and the southern hemisphere leads the northern one in the years of 1928–1964.

Figure 8 shows the wavelet coherence between the monthly sunspot group numbers in the northern and southern hemispheres. Similar to the XWT shown in Figure 5, the wavelet coherence spectrum displays phase asynchrony in the high-frequency components because almost all the arrows at high frequencies are randomly distributed. In the low-frequency components around the Schwabe cycle belt (8–14 years), the arrows have a small angle with the right direction, pointing down before the year of about 1927, pointing up during the years of about 1928–1964, and pointing down again after that. Thus, the leading hemisphere of the monthly sunspot group numbers is inferred to be the northern one before the year 1927, then the southern one until about the year 1964, and after that returning back to the northern one. The results obtained by the WTC confirm the results given by the XWT.

4 CONCLUSIONS AND DISCUSSION

In the present study, with the data of the monthly sunspot group numbers in the time interval of 1874 May to 2010 December, we investigate the phase relationship of the monthly sunspot group numbers in the two hemispheres by means of a linear method (CCA) and nonlinear tools (CWT, XWT and WTC). The CCA simply displays the monthly sunspot group numbers in the northern hemisphere beginning two months earlier than those in the southern hemisphere on the average of the considered time interval. However, the phase shift is so small that no long-term systematic phase shift is statistically acceptable as a first-order effect, as suggested by White & Trotter (1977). Although the phase shift between the two is very small, any phase shift of two time series should certainly bring about phase asynchrony. We should note that such a phase shift is not a major reason which obviously results in asynchrony between the monthly sunspot group numbers in the two hemispheres. Li et al. (2009a) found that the sunspot areas begin one month earlier in the northern hemisphere than in the southern hemisphere, but the phase shift is smaller than that obtained by us. Perhaps the main reason is the different characteristics of their cycles (Li & Liang 2010).

The CWTs of the monthly sunspot group numbers in the two hemispheres indicate that the Schwabe cycle length in the northern and southern hemispheres differs from each other in all time points of the whole considered time interval, and the mean Schwabe cycle length is slightly longer in the northern hemisphere than in the southern hemisphere. The two time series are asynchronous if their main periods are different from each other (Zolotova & Ponyavin 2006). Thus, the difference between the Schwabe cycle length of the monthly sunspot group numbers in the two hemispheres should also lead to phase asynchrony between them.

The XWT of the monthly sunspot group numbers in the two hemispheres indicates that the high-frequency components demonstrate a noisy behavior with strong phase mixing and the arrows have a small angle in the low-frequency components around 8–14 years. The leading hemisphere of the monthly sunspot group numbers is inferred to be the northern one before the year 1927, then the southern one until the year about 1964, and after that returning back to the northern one. By calculating the average of relative phase angles over periodic scales of 8–14 years, we find that the mean phase angle is positive in the years of 1874–1927 and 1965–2010, and negative during the years of 1928–1964. An alternate way is explored through wavelet coherence, and the results obtained confirm the results given by the XWT. By studying the phase asynchrony of sunspot areas in the two hemispheres, Li et al. (2009b) found that the northern hemisphere leads in time during the years of about 1874–1926 and 1966–2008, and the southern hemisphere leads in time in the years of 1926–1966. Our results are slightly different from their finding, with the main reason being the different characteristics of their cycles exhibited by the sunspot group numbers and sunspot areas.

Using the wavelet transform methods, we find that the low-frequency components around 8–14 years can be considered a long-term trend and the high-frequency components a stochastic component that is not random but phase modulated (Carbonell et al. 1993, 1994). We suggest that the high-frequency component is a result of imperfect quasi-regular phase and delayed asynchrony. Thus, the low-frequency components around the Schwabe cycle can be used to study the varying relationship of long-term solar activity between the northern and southern hemispheres.

The phase shift obtained by the CCA and the difference of the Schwabe cycle length calculated by the CWT are not the major reason which results in phase asynchrony between the northern and southern hemispheres for the sunspot group numbers (Li et al. 2008). Maybe the high-frequency components of the XWT and WTC are responsible for their strong phase asynchrony of the sunspot group numbers. Actually, although the CCA, XWT and WTC can be used to measure the long-term variation in the hemispheric leadership of solar activity, all these three methods have the disadvantage that they need to consider sequences of data points, causing an averaging of the property being measured (Zolotova et al. 2009). Another useful tool, the so-called CRP approach, is able to compare the timescales of the two data series on a point-by-point basis (Zolotova et al. 2009).

According to the analyzed data series of sunspot group numbers, two significant changes in the predominant leading hemisphere have been detected: the first change occurred in 1928 and the second in 1965. This is to say, the persistence of phase leading in one hemisphere lasts about four solar cycles, and the period of phase asynchrony probably corresponds to the Gleissberg cycle. Li (2009) and Zolotova et al. (2009, 2010) found that an eight-cycle period is inferred to exist in long-term phase shift of hemispheric solar activity. Our results are in agreement with their finding. On the basis of these studies, we are of the view that the phase-leading hemisphere may be the northern hemisphere during solar cycle 24 and that the asynchrony may shift to the southern hemisphere during solar cycle 25. As is known to all, the new solar cycle 24 started on 2008 January 4 in the north, so the northern hemisphere leads in time and dominates in power (Zolotova et al. 2009). The result of this study may be helpful for understanding the long-term solar activity and dynamo models of the Sun which are based on the magnetic fields related to solar active regions. It should be noted that this period still needs to be demonstrated in the future, because only 12 cycles of reliable observational data of the sunspot group numbers have been obtained. It is not long enough to confirm the eight-cycle period.

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