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Short-Term Period Variation of Relative Sunspot Numbers *

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Abstract We use wavelet transform to analyze the daily relative sunspot number series over solar cycles 10–23. The characteristics of some of the periods shorter than ∼ 600-day are discussed. The results exhibit not only the variation of some short periods in the 14 solar cycles but also the characteristics and differences around solar peaks and valley years. The short periodic components with larger amplitude such as ∼27, ∼150 and ∼360-day are obvious in some solar cycles, all of them are time-variable, also their lengths and amplitudes are variable and intermittent in time. The variable characteristics of the periods are rather different in different solar cycles.

Key words: Sun: sunspots — short-term period — methods: data analysis — wavelet

1 INTRODUCTION

Many periodic and quasi-periodic components of solar activity have been widely and intensively researched, especially the most prominent ∼11-year period. The amplitude of variation is much weaker in some short periods than in the ∼11-year period. For some indices of solar activity, such as solar flares, proton event, sunspot number and sunspot area, F10.7 flux, solar magnitude and variation of photospheric magnetic flux, some short-term periods or parts of them, have been found in different time spans, so it is important to investigate these short-term periods for an understanding of the characteristic of solar activity.

Regarding short periods around or shorter than 1-year, a ∼154-day periodicity was found after Rieger et al. (1984) found the periodicity in gamma-ray flares. Since then, the periodicity was discovered in H-alpha flares (Ichimoto et al. 1985), and was confirmed in hard X-ray, gamma-ray flares (Dennis 1986) and proton flares (Bogart & Bai 1985; Bai & Sturrock 1987; Bai & Cliver 1990). Gabriel et al. (1990) reported the occurrence rate of solar proton events during 19–21 cycles, and pointed out that the 154-day period was prominent when all the cycles are combined, and was prominent in cycles 19 and 21, but was rather weak in cycle 20. These results were consistent with the presence of similar periodicities between 152 and 155 days in major solar flares, the 10.7cm radio flux (F10.7) and the sunspot number (Rz). The period was regarded as a fundamental characteristic of solar activity (Gabriel et al. 1990; Bai & Sturrock 1991; Carbonell & Ballester 1992). After that, a few authors investigated the Rieger-type periodicities for different solar activity indices (Oliver & Ballester 1995; Ballester et al. 2002; Özgüç et al. 2003; Ballester et al. 2004; Kane 2005; Ataç et al. 2006).

In addition, some other periodic and quasi-periodic components of solar activity have been reported, such as the periodicities of ∼25, ∼50-day (Bogart & Bai 1985; Gabriel et al. 1990; Bai & Sturrock 1993;

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Bai 1994, 2003), ∼73-day (Özgüç & Ataç 1994), ∼85-day (Oliver & Ballester 1995; Bai 2003; Joshi et al. 2006), and ∼1.3-year (Prabhakaran et al. 2002; Krivova & Solanki 2002). These periodicities were found to be time-variable in some solar cycles, and some of their amplitudes are weak in individual cycle.

At present, the ∼ 150-day periodicity has been adequately studied and discussed, while the other periodicities need to be analyzed further for a fuller understanding. In the present paper, we use the technique wavelet transform to study the long records of daily relative sunspot numbers from 1849 to 2006, and investigate the temporal characteristics and differences around solar maximum and minimum epoch of cycles 10 to 23.

2 DATA AND ANALYSIS

2.1 Data

In this paper, we use the daily Wolf relative sunspot numbers (SSN) series published by NOAA *(ftp://ftp.ngdc.noaa.gov /STP/SOLAR_DATA /SUNSPOT_ NUMBERS/)*. The available data are unbroken since 1849, and we analyze the data from 1849 January 1 to 2006 November 30, that is, from the declining portion of the 9th cycle to the 23rd solar cycle.

2.2 Wavelet Analysis

In the Fourier analysis, sine and cosine functions are used for the Fourier transform which extends along the whole length of the given time series and the resulting spectrum indicates the average power. However, Fourier analysis cannot describe adequately non-stationary time series with abrupt variation. An alternative method applicable to non-stationary data is the wavelet analysis, in which a wavelet is multiplied with the given time series to produce a wavelet transform. For the wavelet transformation, the mother wavelet is always compactly supported, satisfying the 'admissible condition', $\int_{-\infty}^{\infty} \psi(x)\, dt = 0$, so that it has a good local character in both the time and frequency domains. Wavelet transformation provides an adjustable time-frequency window, shows the changes of frequency with time, and so is a powerful tool for time series analysis.

For a certain application, a particular shape or mother wavelet is chosen, for the present paper the Morlet wavelet is used. The continuous wavelet transformation is given by

$$W(a,b) = a^{-\frac{1}{2}} \int f(x)\psi^{*}\Big(\frac{x-b}{a}\Big)\, \mathrm{d}x\,, \tag{1}$$

where ψ is the inner product of the Gaussian and cosine function, a the scale parameter and b a position parameter (Torrence & Compo 1998; Han & Han 2002a, b; Le 2004).

In the following we discuss short periodicities of solar activity and focus on their time-variation characteristics. The time scale of the wavelet transform is selected as from 8-day to 600-day, so that we can check not only the 150-day period but also that of ∼13.5-day, 1.3-year and so on. The result for the sunspot numbers of all the solar cycles and their scale-average time series are shown in Figure 1. In the figure we find the characteristics of short-term periods.

Figure 1(a) is similar to the results of Rybák et al. (2003), in which we may find: (1) Around the maximum of solar activity, the high frequency components exist obviously, and with larger energy density, the periods have larger amplitude. (2) Generally, the amplitude of high frequency components is larger in cycles of stronger activity. (3) Over such a time span, the amplitude of the ∼27-day period is larger than the other periods. (4) Some of the periods longer than ∼50-day are highly intermittent and their characteristic of time-variation is more obvious.

Figure 1(b) exhibits the scale-averaged characteristic corresponding to the contour map of 1(a). Because of the presence of periodicities of ∼27-day, ∼50-day, ∼150-day, ∼360-day and ∼1.3-year, we selected the scale ranges, 25–30-day, 40–60-day, 130–180-day, 310–400-day and 450–500-day. Most of their characteristics are similar to the wavelet power spectrum, e.g., their amplitude is relatively high around maximum solar activity, and is low near the minimum. However, it demonstrates more clearly that the amplitude varies with time in different scale range, and the amplitude is not always higher when the SSN is larger. For example, on the scale range from 130 to 180 days, the averaged amplitude in cycles 21 and 23 is larger than that in cycles 18 and 19, although the SSN is the largest in maximum in cycles 18 and 19. This characteristic is

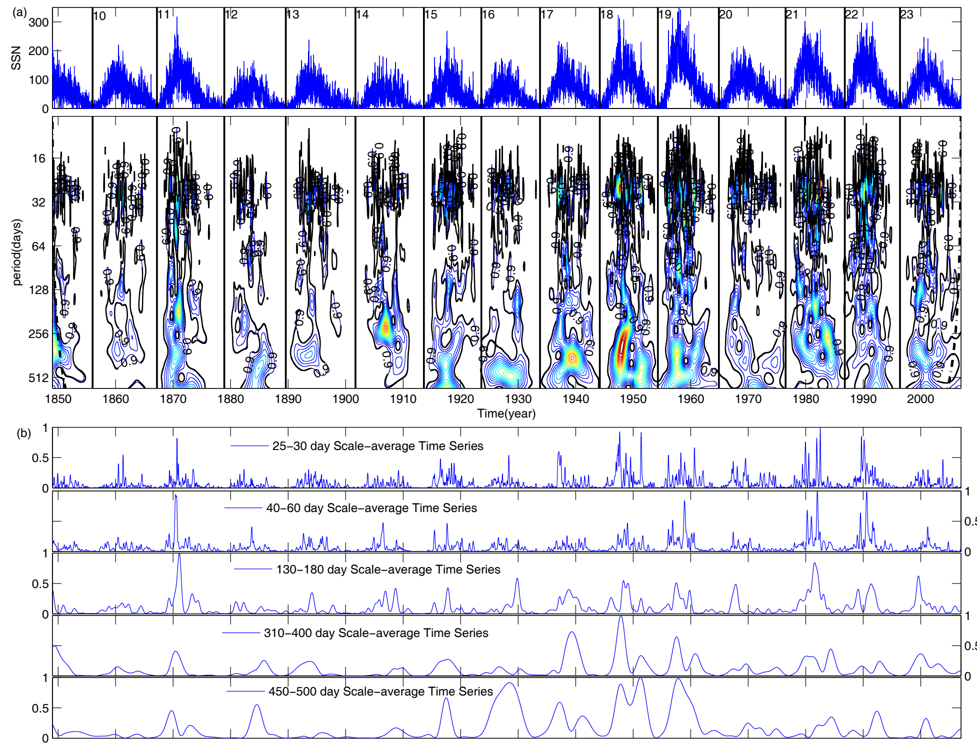

Fig. 1 Wavelet transformation of SSN of cycles 10–23. (a) Upper panel shows the original time series, the black vertical lines mark the minimum epochs of solar activity, and the cycle number is marked on top. The lower panel is a contour map of the local wavelet power spectrum, the y-axis is log period and the x-axis is time. The wavelet power is normalized by the variance of the time series to give a measure of the power relative to white noise (dash-dotted line indicates the cone of influence and the darkest solid contour shows the 90% significance level). (b) Normalized scale-average time series with range of 25–30-day, 40–60-day, 130–180-day, 310–400-day and 450–500-day, respectively.

also present in the scale ranges of 25–30-day and 40–60-day. In solar cycles 15–19, the averaged amplitudes of scale range from 310 to 400 days and from 450 to 500 days are relatively larger, compared to the other cycles, while the amplitudes of other scale ranges in these solar cycles are not so prominent. All the above mentioned seem to indicate that the periodic components make different contributions to the variation of the SSN.

Around the minimum of each solar cycle, the contour map in Figure 1(a) is not distinct, because the power is small compared to the maximum epoch. To study the short-term period characteristic of solar cycle around the peak and valley epochs, we give the separate contour maps in panels (a) to (n) of Figure 2. The peak portion is defined to consist of half of the rising phase and half of declining phase on either side of the peak of the given cycle, and the valley portion is defined as half of the declining phase of one cycle plus half of the rising phase of the next cycle. The left panels refer to the valley portion and the right, the peak portion. As in Figure 1(a), the original time series of SSN is shown above the wavelet transformation map in each panel. Since the time span we covered is from the declining portion of cycle 9 to the peak portion of cycle 23 ($\sim$1852–2003.5), there is no edge effect.

The figure shows clearly the characteristic features of the valley portions, and that the result of the wavelet transformation of sunspot numbers is rather complicated in that the periodic components are different from one cycle to the next. The detailed features will be discussed in next section.

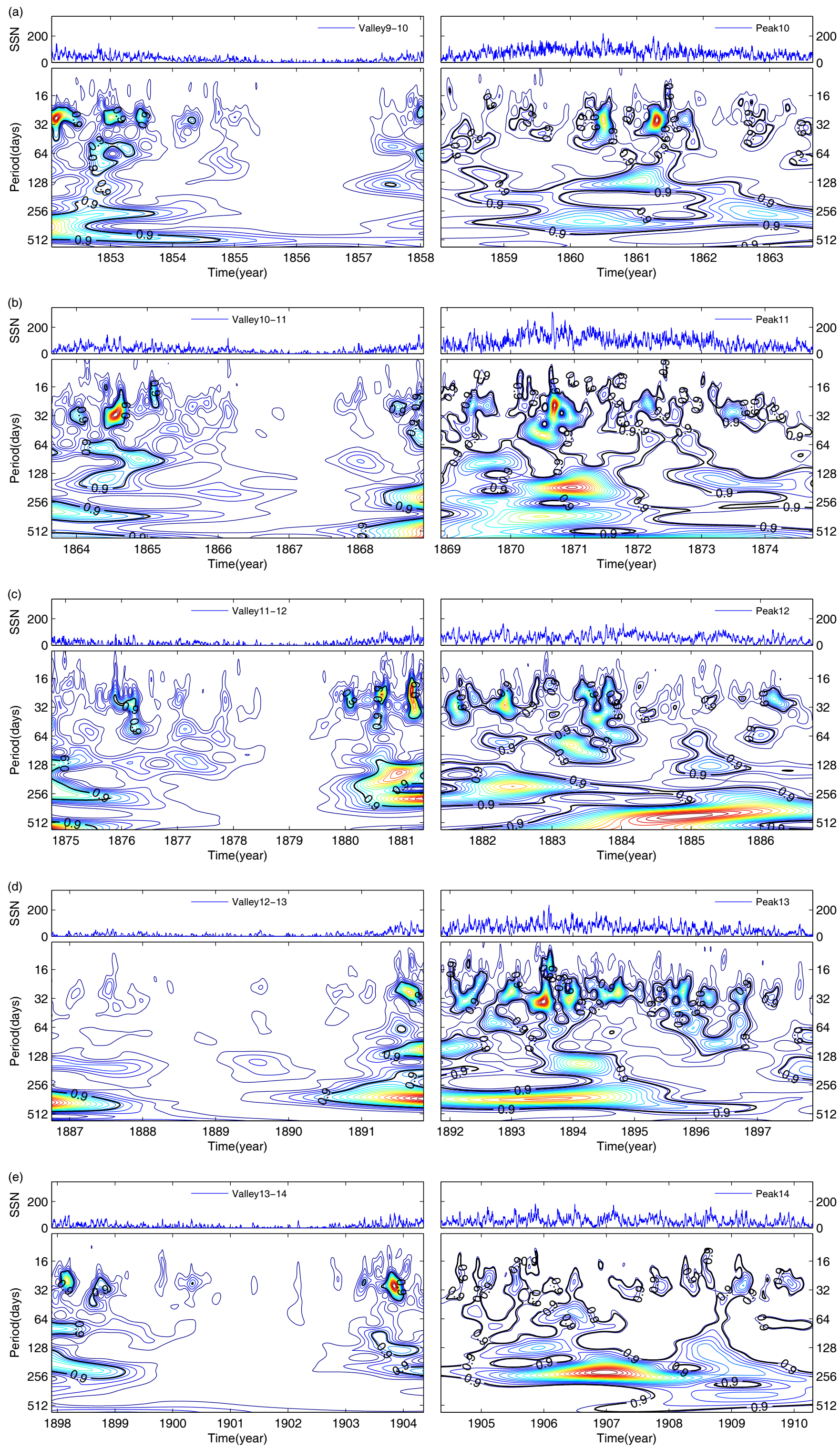

Fig. 2 Wavelet transformation of SSN of cycles 10–23. The left panels show the valley portion and right panels show the peak portion of the cycles. Same wavelet transform parameters as in Fig. 1(a).

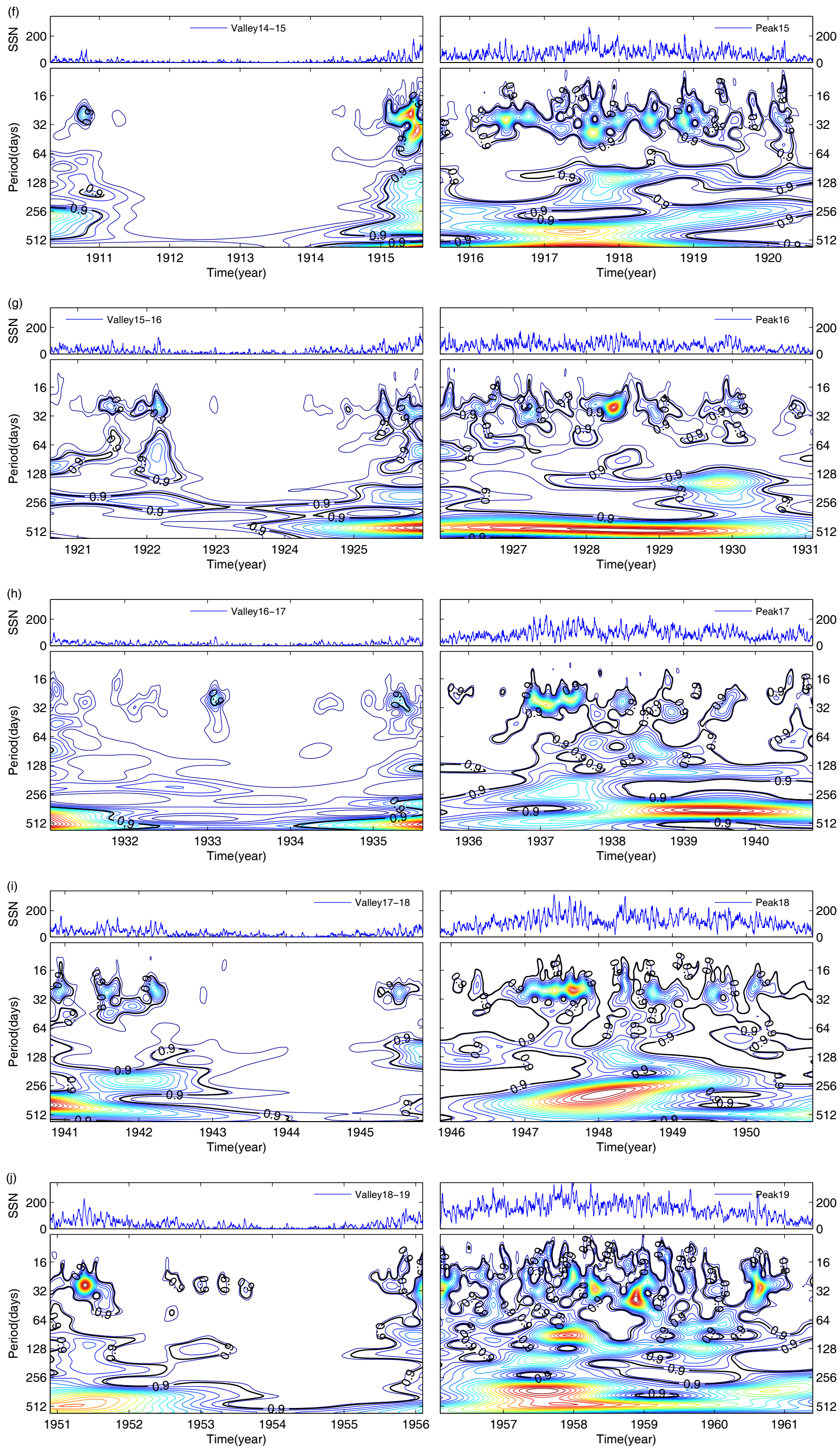

Fig. 2 – Continued.

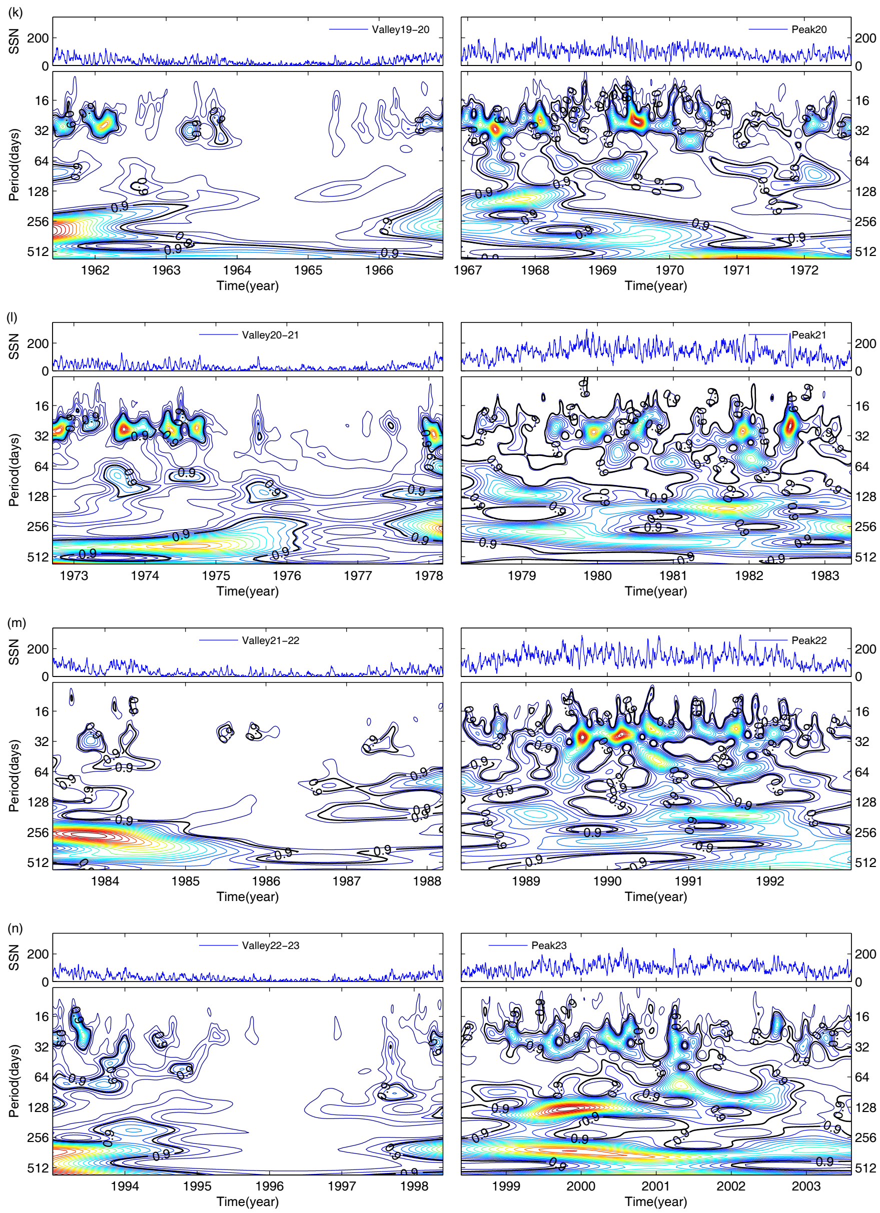

Fig. 2 – Continued.

3 DISCUSSION AND CONCLUSIONS

The time-variable characteristics of short-term periods of SSN are well demonstrated by the results of wavelet analysis, as shown in Figures 1 and 2. We have the following conclusions:

1. Globally, an extremely intermittent behavior of the power spectrum is shown at all periods. The amplitude of periodicity is larger during the epochs of maximum solar activity, and is smaller during the minimum epochs.
2. Differences exist in the length and amplitude of the periods for different solar cycles, and are sometimes more evident in some periods.
3. The ∼27-day period is present in almost all the solar cycles, even in the minimum times. This periodicity is more prominent and stable than the other short periodicities, especially in some solar cycles,

e.g., the length of the periodicity varies roughly between 23 and 36 days in cycle 15, 21–34 days in cycle 16, 24–35 days in cycle 18, and 23–33 days in cycles 20 and 22. Bai (2003) found a periodicity of 33.5 days in the flare occurrence during cycle 23, which periodicity might have resulted from a length change in the $\sim$27-day periodicity. The same periodicity was also looked into in the solar radio flux at seven frequencies by Zięba et al. (2001), who showed that the 26-day period was more prominent in the rising phase than in the minimum during 1996–1999. Özgüç et al. (2004) reported that the modulation of the flare index due to the 27-day solar rotation was more pronounced during the declining portion of the solar cycle than during the rising portion in 1966–2002. If we examine both valley portion and peak portion in Figure 2, we see that the period around 27-day in SSN appears intermittently in whole time span. Compared with the 27-day period, the intermittent character in the other periodicities is more obvious.

4. The $\sim$50-day period is scattered: there is a relatively continuous appearance in cycle 16, around the maximum of cycle 19 and in the declining portion of cycle 21. The $\sim$80-day periodicity appeared in the maximum and declining portion of cycle 12, in the declining portion of cycle 13, around the maximum of cycle 19, and during the rising and declining portion of cycle 22, when this component was also found in the sunspot area (Oliver & Ballester 1995) and in the X-ray flare index (Joshi & Joshi 2005). For cycle 23, Joshi et al. (2006) expressed the view that the southern hemisphere showed a strong periodicity of about 85 days in SSN and sunspot area, and in the last panel of Figure 2, changes of length of the periodicity are exhibited.
5. The $\sim$154-day period, which was discovered by Rieger et al. (1984) in the occurrence of high-energy flares, has been well studied, and the result in Figure 2 shows that its appearance in the solar cycles is highly intermittent. It is more prominent in the maximum and declining portions of cycle 16, the rising portion and maximum of cycle 17 and 22. There also are some periodic components around 154-day, such as the span of 130–180-day in cycle 10 and in the maximum of cycle 21, the 128–172-day in declining portion of cycle 12 and the $\sim$130-day periodicity, which reported by Bai (2003) with solar flare occurrence and Joshi & Joshi (2006) with SSN, is also time-variable.
6. It is remarkable that the about 1-year periodicity is more continuous in some solar cycles if we disregard the amplitude of the periodicity, such as in cycles 10 and 20, the rising portion of cycle 13, and the maximum epochs of cycles 17, 19 and 21. Especially, in the declining portion of cycle 22 and the whole cycle 23, the $\sim$1-year periodicity with range of 310–400 days lasted almost 14 years, although the amplitude varied in the interval. Also, in the early part of the data, a $\sim$240-day periodicity is relatively continuous in the maximum years of cycle 14 and the whole cycles 15–16.
7. Regarding the 1.3-year periodicity which many authors have studied, Krivova & Solanki (2002) showed it to be most prominent during the years 1920–1965 (about solar cycles 16–19), but if we examine it in detail, we find it most stable just in cycle 16, and it has a variable length and amplitude in the other cycles.

Our results show that it is difficult to give an exact value or span of each short-term periodicity due to their time-variable characteristics. This might be the main reason that some authors found fluctuations with different periodic length in the solar activity indices in different time intervals. These phenomena indicate that the solar activity is very complicated and the problem of solar periodicities is still open and needs to study deeply. Wavelet analysis exhibits both stable and intermittent periodicity components, and so is useful for a better understanding of the nature of solar activity. To combine with other indices of solar activity to examine these complicated phenomena is necessary in future work.

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