Solar Cycle Signature in Decadal Variability of Monsoon Precipitation in China

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Abstract

Monthly high-resolution land surface precipitation data from 1901 to 2006 associated with sunspot number (SSN) data is investigated for the relationship between summer precipitation in China and the decadal solar variability. Generally, on a national scale, precipitation is poorly correlated with SSN. However, in many regions, the long-period (>8 years) variability in summer precipitation is significantly (at $>95\%$ confidence level) correlated to SSN. Absolute value correlation coefficient can exceed 0.48 (at $>99\%$ confidence level) in some regions. If only the decadal (9–13 years) precipitation component is considered, the correlation becomes stronger with a maximum (minimum) correlation coefficient of 0.73 (–0.73) (at $>99.9\%$ confidence level). Considering that the decadal component is the most important factor among precipitation's low-frequency signals in the high correlation areas (because it explains more than 50% of the precipitation's low-frequency variance), it can be concluded that solar variability seems to dominate the long-period variation of summer precipitation in these areas. Furthermore, in these high correlation areas, temporal variation patterns in the power spectrum of summer precipitation is similar to that of SSN, strongly suggesting that there is a very likely physical link between solar variability and precipitation in these regions. More convincing and direct evidence shows the significant difference of low-level monsoon flow between high and low solar activity years, which may cause the higher precipitation rate for high, rather than low, solar activity years in central China.

1. Introduction

A number of studies apparently indicate correlations between solar variability and climate change, especially on decadal scales (e.g., Hoyt and Schatten 1997; Herman and Goldberg 2005). However, how much the climate system is influenced by solar variability has long been a subject of controversy (Rind 2002; Li et al. 2003; Lean 2010; Wang 2010). The variation of total solar irradiance (TSI) takes only 0.1% for one solar cycle which may contribute 0.1°C temperature fluctuation (Foukal et al. 2006; Benestad and Schmidt 2009), which is much less than the overall warming trend

of 0.74°C from 1906 to 2005 (IPCC, Fourth Assessment Report 2007). The subtle variability in TSI prevents researchers from easily distinguishing the temperature variation possibly due to solar activity. In comparison to temperature, the more obvious variability in precipitation may benefit from the search for the solar cycle signatures in the climate system.

The existence of sunspot cycle imprints in rainfall distribution can be considered probable even though the cause-effect relationships are still obscure (Jagannathan and Bhalme 1973). Since Herschel (1801) found that the relationship between sunspot and rainfall indirectly dominate the prices of wheat in London, many efforts have been put into exploring the linkage between terrestrial rainfall and solar variations. In recent years, from a global point of view, some significant correlations on precipitation were revealed and proved that solar forcing is important, even more so than other forcings (Currie 1996b; Sud et al. 2002; Lambert et al. 2004; Meehl et al. 2009; Liu et al. 2009; Wasko and Sharma 2009).

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Table 1. The years of maximum (MAX) and minimum (MIN) of SSN from 1901 to 2006.

MAX	1905	1917	1928	1937	1947	1957	1968	1979	1989	2000
MIN	1901	1913	1923	1933	1944	1954	1964	1976	1986	1996

Fig. 1. The upper panel of (a): monthly mean precipitation rates (monthly mean to annual mean precipitation) averaged over 26°–34°N along 115°E from 1901 to 2006; the lower panel of (a): a time-latitude cross section along 115°E of difference (contours) between composites of monthly precipitation in MAX and MIN and significant correlations (shaded) between monthly precipitation and corresponding annual SSN during the 106 years. (b) Significant simultaneous correlations (shaded) between June precipitation in China and corresponding annual SSN during the 106 years. Significance tests are based on Monte Carlo approach.

From a regional point of view, some studies on the relationship provide plenty of thought-provoking conclusions. The drought cycle in North America (Stockton et al. 1983; Perry 1994; Currie 1996b; Cook et al. 1997), the precipitation in Africa (Currie 1993, 1996b; Verschuren et al. 2000, 2009), Australia and South America (Currie 1996a; Thresher 2002), and monsoon rainfall in India and Arabia (Neff et al. 2001; Burns et al. 2002; Fleitmann et al. 2003; Koder 2004; Bhattacharyya and Narasimha 2005; Ma et al. 2007) all exhibit some coincidence or correlation with the variation in solar activity, especially on decadal or two decadal scales. However, that opposing correlations appear in different regions suggests that the possible modulation of solar activity on precipitation mainly demonstrates regional features other than a global pattern. How to explain the difference of responses of precipitation in different regions to solar variability is a complicated subject.

In China, in the first half of the 20th century, Zhu (1926) and Tu (1936) conducted pioneering research on the connection between the sun and China's climate. Yang (1962), Zhu (1962), Wang (1962) and others extended and promoted research in this subject area and adopted sunspot number into operational weather forecast. Afterward, some valid conclusions were drawn by Chen (1984), Xu (1986) and others on the relation between China's drought/flooding and astronomical factors. In recent years, the increasing accumulation of data and updated methods enhance more studies in this issue (Currie 1995, 1996b; Li 2002; Zhang 2003; Wang 2005). Currie undertook a systematic investigation of solar signal in temperature and precipitation worldwide using maximum entropy spectral analysis and obtained many valuable results. A low pass filter in Chinese dryness-wetness indices was used, and it was found that the solar signal in annual precipitation is statistically

Table 2. The correlation coefficients between SSN and the raw and 8-year low-pass filtered precipitation^a.

Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Whole year
Raw	0.20	0.03	0.18	-0.12	-0.03	0.30	0.06	0.09	0.02	-0.13	0.01	0.09	0.16
Filtered	0.31	0.14	0.39	-0.25	-0.17	0.49	0.10	0.15	-0.00	-0.18	0.07	0.13	0.28

^aNote: 0.19 (0.25) and 0.38 (0.48) denote the 95% (99%) confidence level, for raw and filtered precipitation, respectively (sample number: 106).

Fig. 2. (a) and (c) The standardized time series and (b) and (d) global wavelet spectrums of annual SSN and the HRB June precipitation. (a) and (b) With raw precipitation data, (c) and (d) with 8-year lowpass filtered precipitation data. The test lines in (b) and (d) denote 95% confidence level, using Morlet's wavelet as mother wavelet.

significant in central and northern China (Currie 1995, 1996b). But because the data has only five levels of quantization and only reflects whole-year precipitation situation, it still remains unclear whether the solar signal becomes statistically significant in low-pass precipitation data for each individual month or season. On the other hand, as one of the most important climate factors in China, both the response of the East Asian summer monsoon (EASM) to the solar cycle and the role which plays in the linkage between precipitation fluctuation and solar activity are in lack of a special focus.

In this study, using a high-resolution, large-coverage precipitation data, the connection between solar activity and decadal precipitation variability in China, especially during the EASM onset period, is investigated and rigorously tested to pursue correlations with both statistical and physical significance, and the cause for the

regional difference of precipitation response to solar activity is also discussed.

2. Data

Monthly global land surface precipitation data used in this study is CRU TS 3.0 with $0.5^\circ \times 0.5^\circ$ resolution from 1901 to 2006 compiled by the University of East Anglia Climatic Research Unit (CRU) (Mitchell and Jones 2005). CRU TS 3.0 is reliable based upon observations and is long enough to study decadal and inter-decadal precipitation variations within the past 106 years, i.e., ten solar cycles. Wind data were obtained from NOAA-CIRES 20th Century Reanalysis version 2 Monthly Averages (1871–2008) with a spatial resolution of 2.0° . The yearly mean relative sunspot number (SSN), as the primary proxy of solar activity, is from the NOAA sources

Fig. 3. Significant correlations (shaded) between annual SSN and long period (>8 years) components of June precipitation in China using Monte Carlo test.

(ftp://ftp.ngdc.noaa.gov/STP/SOLAR.DATA).

3. Analysis

3.1 Preliminary statistical correlation analysis

The years of maximum and minimum SSN occurring in each solar cycle from 1901 to 2006 are selected and denoted, respectively, by MAX and MIN (Table 1). Monthly mean precipitation rates (monthly mean to annual mean precipitation) averaged between 26°N and 34°N along 115°E from 1901 to 2006 are shown in the upper panel of Fig. 1a. It is found that in June, the mean precipitation rate is the highest, i.e., the rainfall amount accounting for the largest proportion of total annual rainfall, when rainy season is at its peak in the mid-lower Yangtze River basin and its southern area. The lower panel of Fig. 1a shows the difference between composite monthly precipitation in correspondence with MAX and MIN, and significant correlations between monthly precipitation and annual SSN during the 106 years along 115°E. In June, the difference is most obvious and the area with significant correlation is the largest, and evident positive and negative significant correlation regions exist simultaneously. Considering that these two regions correspond to the time and space when and where the EASM onset, this paper will focus on this temporal and spatial coverage.

There are spatial distributions with significant correlation between SSN and June precipitation, as shown in Fig. 1b. Positive significant correlations are mainly lo-

cated in the Huaihe River Basin (HRB), with the highest correlation being 0.33 in the Hetao area (located in the middle Huanghe River basin). The negative significant correlations are mainly located south of the mid-lower Yangtze River basin, with the most negative correlation -0.30 at the west of the Qinghai-Tibet Plateau. Significant correlation usually denotes that there is an obvious difference in precipitation between in MAX and MIN. The results preliminarily suggest that in some regions of China, the interannual oscillations in June precipitation were either in exact phase or anti-phase with the SSN from 1901 to 2006, but the area of significant correlation is not large.

3.2 Spectrum analysis of unfiltered and filtered data

In June, the beginning of the monsoon season in the HRB, the correlation between the SSN and precipitation is relatively high (see Fig. 1). So, we choose regional-averaged June precipitation in the HRB (105–118°E, 31–35°N) to further our investigation. In June, although the correlation coefficient between the SSN and the HRB precipitation is only 0.30, one can still read in Fig. 2a that the precipitation presents a general coincidence with the SSN on the decadal time scale since the higher frequency precipitation plays the role of noise which reduces the correlation coefficient. Besides, it can be seen from Table 2 that only in June, the correlation coefficient exceeds 0.25 (at 99% confidence level), and for a whole year, the correlation is very weak (0.16).

By decomposing a time series into time-frequency space, one is able to determine both the dominant modes of variability and how those modes vary in time (Torrence and Compo 1998). When using wavelets for feature extraction purposes, the Morlet's wavelet is a good choice since it provides a good balance between time and frequency localization (Grinsted et al. 2004). So through applying wavelet power spectrum analysis (e.g., Torrence and Compo 1998) with Morlet's wavelet as the mother wavelet with regards to rainfall as well as SSN, the spectrum rainfall peaks appear approximately at 4.6, 10.9, 21.8 and 40.7 year with a maximum at 10.9 year, which is very close to the SSN period (10.5 year) (Fig. 2b). However, the maximum in rainfall spectrum does not pass the 95% confidence level. So far, although the raw data hints a possible link between the HRB June precipitation and the SSN, it is still hard to confirm whether the quasi-11-year precipitation signal is 'signal-like' or 'noise-like'.

To remove the dominance of higher frequency rainfall components (for instance, the components probably controlled by ENSO with a typical period of 2~7 years), the signals with periods less than 8 years in rain-

Fig. 4. Variance contributions of 9~13-year components of June precipitation to (a) the total in the raw records and to (b) the low-frequency (>8 years) portion.

Fig. 5. Temporal evolutions of scale-averaged wavelet power for annual SSN and June (a) raw and (b) 8-year lowpass filtered rainfall in the HRB over 9~13-year band. The test lines denote 95% confidence level.

fall data are filtered out. The remainders are now correlated much more closely than unfiltered raw data with SSN variation, and individual monthly correlations increase observably for the most part, such as in January, March, April, June and the whole year maximum value 0.49 for June (Table 2 and Fig. 2c). The wavelet spectrum of the filtered rainfall data shows a convincing quasi-11-year oscillation which significantly passes the 95% confidence level (Fig. 2d).

Is 0.49 statistically significant? Because filtered data and unfiltered time series have different degree of freedom (DOF), more vigorous statistical tests based on the Monte Carlo approach are applied to demonstrate the statistical significance. In this paper, correlation

coefficients between the SSN and 5000 independently and normally distributed random series (106 samples in each series, the same as SSN), and correlations between the SSN and their filtered data (>8 years) are all calculated 40 times, respectively. For each time, according to sort of absolute values of these correlations, a threshold value table of correlations is acquired, and their mean values are assumed the final threshold values of correlation coefficients, and their standard deviations reflect their stability and astringency. The results show that the threshold value and standard deviation of correlation at 99% confidence level is 0.482 and 0.009, respectively, and correspondingly effective DOF decreases to 26. Therefore, 0.49 is indeed statistically significant at 99% confidence level.

3.3 Correlation analysis of the filtered data

These results encourage us to check if there is also similarly good correlation in other regions. The same method of low-pass filtering and Monte Carlo testing approach are applied to June precipitation all over China, and then the simultaneous correlation coefficients between the SSN and filtered June precipitation in China are shown in Fig. 3. In some regions the long-period (>8 years) of variability in precipitation is significantly (at >95% confidence level) correlated to the SSN. The correlation coefficients exceed 0.48 (at >99% confidence level) in some regions with the highest value of 0.56 in central China (107.75°E, 32.25°N) and most negative value of -0.48 in southern China (117.25°E, 27.25°N). In different regions, the correlativity is likely to be different, and main positive and negative correlation zones seem to be alternately distributed on both sides of the Yangtze River, that is to say, the Yangtze

Fig. 6. (a) 106-year (1901–2006) mean June 700 hPa vertical velocity (shaded, units: Pa s^{-1} , negative values denote upward vertical motion) and horizontal wind (vector arrows, units: m s^{-1}). (b) Mean difference of June 700 hPa vertical velocity (shaded, units: Pa s^{-1}) and horizontal wind (vector arrows, units: m s^{-1}) between in the HSY and the LSY (in areas surrounded by thick short dash contours, the difference of vertical velocity is significant at 5% significance based on Monte Carlo test). Thick contours in (a) and solid/long dash contours in (b) denote 106-year and HSY/LSY mean southerly velocity of 0 m s^{-1} , respectively. The rectangles in both (a) and (b) outline the HRB.

River is an important boundary. Moreover, if only the decadal precipitation component is considered (i.e., by 9~13-year bandpass filtering), the correlation becomes stronger with a maximum correlation coefficient of 0.73 and a minimum of -0.73 (figure omitted) (the threshold value of correlations at 99.9% confidence level is 0.70

using Monte Carlo test).

3.4 Variance contributions

Although the correlation is significant in many regions, the result is flawed in one aspect: the variance contribution of decadal signals to the data was not inves-

tigated. Thereby, the variance contributions of 9~13-year signals to the total and to the long-period components of precipitation data are calculated (Fig. 4). In some regions where the high correlation coefficient exists, the 9~13-year component generally contributes only 15% to the total variance of raw rainfall (Fig. 4a), but more than 50% to that of the low-frequency (>8 years time scale) (Fig. 4b), which indicates that the decadal component is the largest among low-frequency precipitation signals in the high correlation regions, e.g., in central China, dominating its long-period (>8 years) variation.

4. Discussion

The analysis demonstrates that the decadal fluctuation of summer precipitation in some monsoon regions of China is significantly correlated to SSN variation. However, good correlation still exists only as a statistical phenomenon and one cannot necessarily conclude that there is essential physical links between the precipitation and solar activity. This can be carefully investigated by checking whether the temporal behavior and spectral power of precipitation's decadal component is phase-locked with that of SSN. Thus, the temporal evolution of scale-averaged Morlet's wavelet power over 9~13-year band for SSN and precipitation in the HRB are compared (Fig. 5). It is obvious that the wavelet precipitation power (not filtered) varies in phase with that of SSN and the correlation coefficient between them is about 0.91, but the curve of the precipitation wavelet power (thick dashed line) always lies below 95% confidence level (Fig. 5a). Nevertheless, if filtering out the high-frequency values (<8 years), the greater part of the precipitation wavelet curve power (thick dashed line) lies above 95% confidence level (Fig. 5b). The investigation into some other regions with high correlation coefficients in Fig. 3 brings similar results. It means that not only the long period (>8 years) components of June precipitation in China vary in-phase or anti-phase with SSN, but also the wavelet spectral precipitation power has very similar evolution to that of SSN. These results strongly suggest that there are very likely intrinsic physical connections between the 11-year solar cycle and summer precipitation in these regions.

However, these results are not enough to induce an inevitable cause-effect relation. The related circulation may provide some clues to the reasoning for the decadal oscillation in precipitation that happened mostly in June in some certain regions. As shown in Fig. 6a, in June, after onset of the low-level southwest monsoon, the EASM usually influences southern China, the Yangtze River basin and a part of the HRB. That is to say, the

HRB usually lies just at the front edge of EASM and the southerly-northerly transition region. However, as shown in Fig. 6b, between high and low solar activity years (denoted by MAX/MIN and one year before and after MAX/MIN, in total 30 years, respectively, and ab. HSY and LSY, respectively), influencing domains of EASM are distinctly different, especially in the HRB. The contours of mean southerly velocity of 0 m s^{-1} are generally more northern and eastern in the HSY than those in the LSY, and there are significant northeastward and upward (light shading) differences in flow over the HRB. Fig. 6b only shows areas with statistically significant differences in vertical motion between in the HSY and the LSY, and in fact, over the HRB, the differences of westerly and southerly are also significant. The results indicate that in the HSY, it is more apt (less likely) to rain than in the LSY in the HRB (southern China).

Therefore, solar activity probably modulates the decadal variability of summer precipitation in some monsoon regions by magnifying or diminishing the role of the EASM. However, further research is needed to be discovered through what physical process solar activity modulates and influences the low-level southwest monsoon.

5. Conclusions

The relationship between solar variability and precipitation is an issue of multi-system interaction, and the regional difference in the relationship is a further complication with regards to the sun-climate relation. Based on a 106-year land surface precipitation data and the corresponding SSN data, the present study can be concluded as:

(1) Poor correspondence exists between the 11-year solar cycle and each individual monthly precipitation in China, and the highest correlation coefficient is only about 0.30, which appears in the HRB in June.

(2) Much higher correlations between SSN and long period (>8 years) / decadal (9–13 years) components of June precipitation can be found in some certain regions of China where absolute values of correlations can even exceed the value of 0.48/0.70 at $>99\%$ / 99.9% confidence level. Meanwhile, it is found that the correlation is positive/negative in the regions to the north/south of Yangtze River. The result is distinct from that of Clayton (1923), in which the annual precipitation MAX is larger than that of the MIN in most regions of China by use of rough observation data from 1860 to 1917.

(3) For June precipitation, the decadal (9~13-year) component is the largest among low-frequency (>8 years) signals in those regions where precipitation is relatively more closely correlated with SSN. For example,

in central China, the decadal component can contribute more than 50% to the variance of low-frequency portion of precipitation.

(4) The wavelet spectral powers of SSN and the decadal precipitation in central China vary in a very significantly in-phase manner throughout most of the 20th century. It strongly suggests likely intrinsic physical connections between the 11-year solar cycle and summer precipitation in these regions.

(5) In the HSY, significant enhancement and northward expansion of EASM contribute to more rainfall in the HRB than in the LSY, which probably results in decadal solar-cycle oscillation in precipitation in the HRB.

Considering the dominant role of decadal components in long period precipitation signals, it is very likely that the solar cycle modulates the decadal variability of summer precipitation in many regions of China, especially in some typical monsoon regions, probably by strengthening or weakening monsoon circulation. Although these results are all basically statistically significant, some important physics mechanism behind the phenomena remains unclear, and thus further investigation is needed to unveil how solar activity can play such an important role in summer precipitation in China.

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