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Evidence for the effect of sunspot activity on the El Niño/Southern Oscillation

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HIGHLIGHTS

- The solar activity period, are determined in the El Niño 3 area index time series.
- ENSO is negatively/positively correlated with SSN when SSN is large/small.
- Strong ENSO is inferred to be taken place in decade(s) to come.

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ABSTRACT

The El Niño No. 3 area index (5°S∼ 5°N, 150°W∼ 90°W) and yearly sunspot number (SSN) from 1408 to 1978 are used to investigate the influence of solar activity on the El Niño/Southern Oscillation (ENSO), through periodicity analysis, cross wavelet transform (XWT), cross correlation and ensemble empirical mode decomposition (EEMD) analyses. The solar activity period, the Hale period, and the Gleissberg period are determined in the El Niño index time series, but of weak statistical significance. Cross correlation analysis of the index with SSN, and that of its low-frequency components decomposed by EEMD clearly indicate that solar activity may take effect on the ENSO, and such an impact should undergo an accumulation procedure (phase delay). XWT also indicates the existence of the impact. It is found that the index is negatively correlated with SSN when SSN is large during a certain long-term interval, and positively when SSN is small. Strong El Niño is inferred to be taken place in decade(s) to come.

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1. Introduction

The interaction between ocean and atmosphere has a direct effect on the climate and weather environment where we are living. El Niño and La Niña, together called the El Niño/Southern Oscillation (ENSO), are the cycle of warm and cold temperatures, as measured by sea surface temperature, SST, of the tropical central and eastern pacific ocean. The ENSO refers to these warmer or cooler than normal ocean temperatures, and it can affect weather patterns around the world by influencing high and low pressure systems, winds, and precipitation (Trenberth and Hoar, 1996; Fedorov and Philander, 2000; Guilyardi et al., 2009; Merryfield, 2006; Meehl et al., 2006; Lenton et al., 2008; Wittenberg, 2009; Collins et al., 2010). The ENSO accompanied by high air pressure in the western pacific and low air pressure in the eastern pacific may bring much needed moisture to a region while causing extremes of too much or too little water in others. The ENSO is the strongest signal of inter-annual climate variation of the atmosphere-sea system in the tropical pacific. In order to better understand the characteristics, causes and forecast of the ENSO numerous studies including index, intensity, mechanism, and prediction have documented a rich pattern of climate variation and oscillation (Huang et al., 1998; Cobb et al., 2003; Romero-Centeno et al., 2003; Guilyardi et al., 2009; Yeh et al., 2009; Khider et al., 2011; Gushchina and Dewitte, 2011).

The characteristics and causes of the ENSO get a lot of attention, especially the impact factor responsible for it. The ENSO is large-scale changes in atmospheric circulation connected with long-term anomalies of atmospheric parameters, that affects the climate over a great part of the globe on inter-annual to decadal and centennial time-scales. Little is known about the factors determining the long-term variability of these phenomena. The solar activity cycle of 11 years has been found in the analyses of the earth climate data, and solar activity is inferred to be an external factor that should affect

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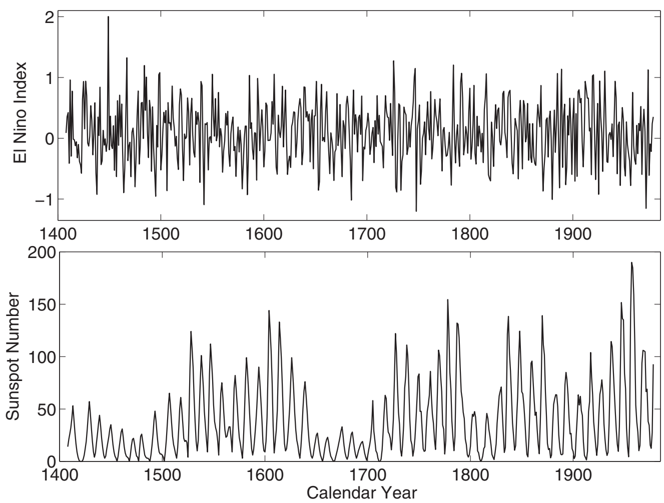

Fig. 1. Top panel: the yearly sunspot number from 1408 to 1978, which is from Nagovitsyn (1997). Bottom panel: the El Niño No. 3 area index from 1408 to 1978, which comes from D'Arrigo et al. (2005).

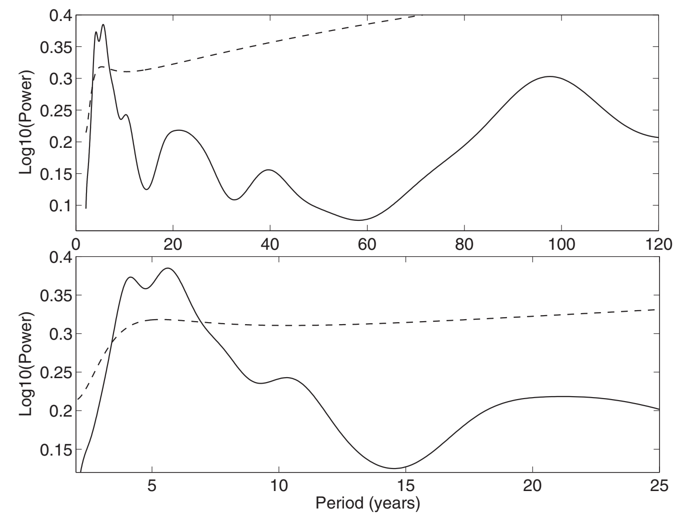

Fig. 2. Top panel: the global wavelet power spectrum (the solid line) of the El Niño index and its 95% confidence level (the dashed line). In order to display well, the spectral power is taken the logarithm of 10). Bottom panel: same as the top panel, but shown is just the period scale of 2–25 years.

the ENSO (Labitzke and Van Loon, 1988; Tinsley et al., 1989; Friis-Christensen and Lassen, 1991; Boberg and Lundstedt, 2002; Thejll and Lassen, 2002; Gleisner and Thejll, 2003; Soon et al., 2014; Zhang and Feng, 2015; Zhao and Feng, 2015). Further, some studies have revealed a good correlation, up to the last decades, between the ENSO and solar activity, though the mechanism is still controversial. This article will investigate the influence of solar activity on the ENSO with the El Niño index at the area 3 (5°S∼5°N, 150°W∼90°W) used.

2. Influence of solar activity on the ENSO over the past 500 years

2.1. Data

The El Niño No. 3 area index (5°S∼5°N, 150°W∼90°W) from 1408 to 1978 is given by Cook (2000) and shown here in Fig. 1. The El Niño No. 3 area index covers most of the Middle East Pacific Ocean around the equator where the El Niño signal is the most prominent (Cook, 2000). The name of the data set is the Niño 3 Index Reconstruction, and its registration number is 2000-052 in the World Data Center paleoclimate (WDC PALEO CONTRIBUTION SERIES). D'Arrigo et al. (2005) have examined past ENSO variability using this data. Their results indicated that the reconstruction is well verified and captures the dominant spectral properties in the instrumental record for the classical ENSO bandwidth. Thus, it is considered to be a valid expression of ENSO variability.

Yearly sunspot number (SSN) at the same time interval as the above data is from Extended time series of Solar Activity Indices (ESAI) web site (http://www.gao.spb.ru/database/esai/). ESAI have extended the ordinary lengths of some traditional indices of solar activity, such as sunspot number to study solar magnetic field variations and their influence on the earth (Nagovitsyn, 1997).

2.2. Periodicity analysis for ENSO

In interdisciplinary studies, investigating a periodical signal and/or finding periodicity of signals are ordinary and classical methods to research their relationship. For example, the period of about 11 years is generally believed to be originated from the Sun, if it is determined in one subject of the sun-earth system, then the subject is inferred to be related to solar activity (Tinsley et al., 1989; Friis-Christensen and Lassen, 1991; Thejll and Lassen, 2002; Boberg and Lundstedt, 2002; Gleisner and Thejll, 2003; Kerr, 2005; Wang et al., 2005; Meehl et al., 2009; Wasko and Sharma, 2009; Soon et al., 2011; Soon and Legates, 2013; Soon et al., 2014).

Firstly, the periodicity of the El Niño No. 3 area index is analyzed by the continuous wavelet transform, and the mother wavelet is the Morlet wavelet (dimensionless frequency $\omega_0 = 6$) (Torrence and Compo, 1998; Li et al., 2004). Fig. 2 shows the global wavelet power spectrum of the index. The ENSO has periods of about 4.15, 5.63, 10.32, 21.20, 39.74, and 97.64 years, and the periods of 4.15 and 5.63 years are statistically significant at the 95% confidence level. These two statistically significant periods may correspond to the 3∼7 years oscillation of ENSO (D'Arrigo et al., 2005). The 10.32-year period corresponds to the well-known solar activity cycle, although it is not statistically significant at the 95% confidence level. The period of 21.20 years may correspond to the Hale magnetic cycle, and the 39.74-year period, seemingly its multi-period (2 times). The period of 97.64 years should be the Gleissberg cycle of the Sun (Gao et al., 2008; Li et al., 2011; Feng and Li, 2014; Feng et al., 2016).

The ensemble empirical mode decomposition (EEMD) can extract weak signal features of a time series. And then, we decompose the El Niño No. 3 area index using the EEMD method (Wu and Huang, 2009), and consequently, nine Intrinsic Mode Functions (IMFs) are obtained, which are shown in Fig. 3. The 11- and 22-year periods of solar activity can possibly appear only in the first five IMFs, and then the periodicity of the first six IMFs are analyzed at the followings.

The continuous wavelet transform is also utilized to investigate the periodicity of the first six IMF components, and their global wavelet power spectra are shown in Fig. 4. IMF 1 has the period of about 3.89 years, and that is statistically significant at the 95% confidence level. It may correspond to the 3 ∼ 7 years oscillation of ENSO, thus this component should reflect the intrinsic property of the El Niño phenomenon. IMF 2 has the period of 7.58 years which is statistically significant at the 95% confidence level. IMF 3 has the period of about 17.17 years, which is statistically significant at the 95% confidence level. IMF 4's possible period is 25.63 years, statistically significant at the 95% confidence level, therefore this component should reflect main influence of solar activity of the 22 year period on ENSO. IMF 5's possible periods are 52.67 and

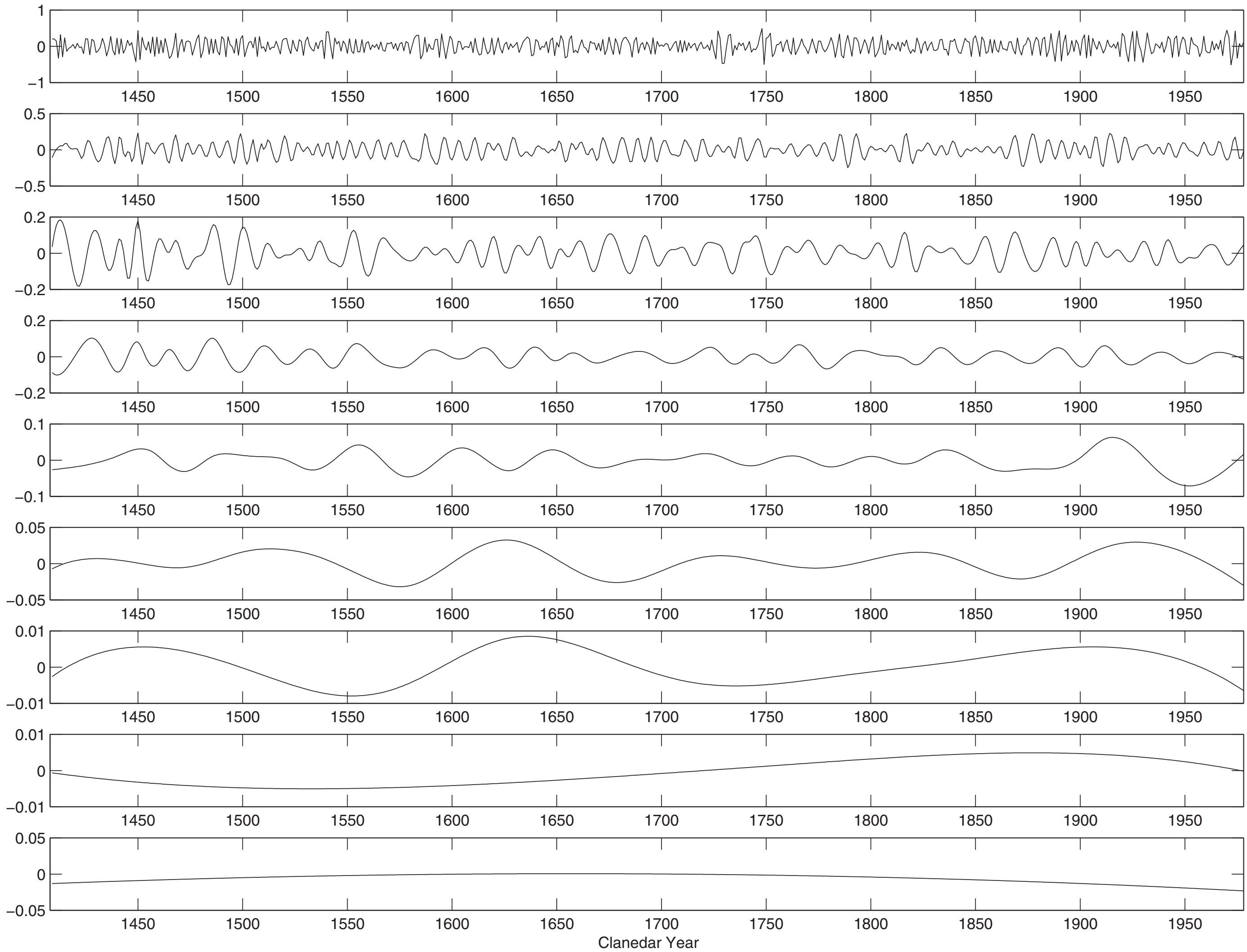

Fig. 3. Intrinsic Mode Functions (IMFs) of the El Niño index, decomposed by the EEMD.

86.67 years, and 52.67 years are statistically significant at the 95% confidence level. IMF 6's possible period is 101.41 years, which is statistically significant.

2.3. Relation of ENSO with sunspot number

The cross correlation coefficient (CC) of the El Niño No. 3 area index with SSN are calculated changing with their relative phase shifts. At first, CC of the two time series is calculated at no relative phase shift. Next, one series is shifted by one year with respect to the other, meanwhile the unpaired data points are deleted, and CC is calculated in this case at the shift of one year. Such a procedure is repeated again and again with relative phase shift increasing one year by one year (Li et al., 2002). The obtained result is shown in Fig. 5, where the abscissa is shifts of SSN versus the index with backward shifts given minus values. $CC = -0.0544$ at the shift of zero, which is marked as CC_0. But, when SSN is shifted forwards by 9 years, CC reaches the minimum, -0.109 (its absolute value is the maximum), which is marked as CC_9.

The lag-1 autocorrelation coefficient is 0.8472 for SSN, and 0.6173 for the El Niño index, so the two time series are both serially auto-correlated (Ebisuzaki, 1997). In order to test the statistical significance of the CC_0, the block-bootstrap (without any jackknife) method (Kunsch, 1989) is used as the following. The data number of the El Niño index (or SSN) is 571, each of the two whole series is divided into 38 blocks with each block having no data overlapped, and each block (block length) (Palm et al., 2011) includes 15 data points. The rest one data point is divided into the last block, and thus the block has 16 dada points. 35 samples are randomly selected at one time out of the total 38 SSN blocks, and meanwhile the corresponding El Niño index is selected to calculate correlation coefficient (CC'_0) between these two new time series. After 3000 repeats of the above procedure (each time, data are chosen from the original entire data set), 3000 values of CC'_0 are obtained, which are all shown in Fig. 6. If one obtained sample correlation coefficient CC'_0 does not come from the overall correlation coefficient of zero ($\rho = 0$), at the probability level of 95% its t value (in absolute term) should statistically be (Liu, 1996):

$$t = \frac{(CC'_0 - \rho)\sqrt{(n-1)}}{1 - CC'^2_0} > t_{0.05},$$

Therefore,

$$CC'_0 > \frac{t_{0.05}(1 - CC'^2_0)}{\sqrt{(n-1)}} \approx \frac{0.99 t_{0.05}}{\sqrt{(n-1)}}$$

where n is the number of data points, and $t_{0.05}$, the tabulated critical value at the probability level of 95%. Only for 296 of the total 3000 repeats $t > t_{0.05}$, therefore the CC_0 is statistically insignificant.

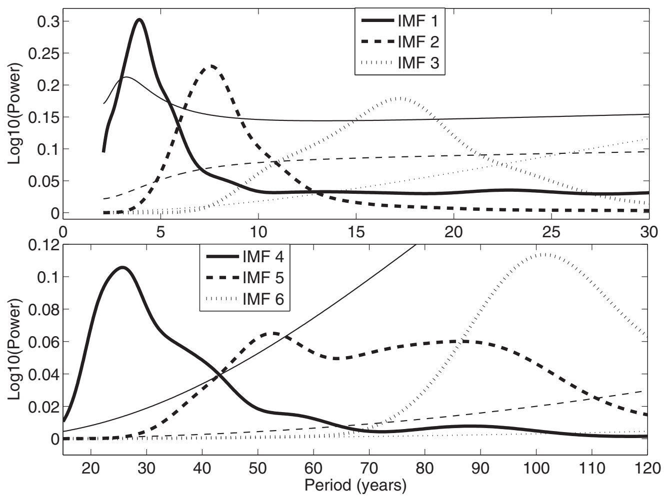

Fig. 4. The global wavelet power spectra (the solid lines) of the first 6 IMFs of the El Niño index and their corresponding 95% confidence levels (the dashed lines). In order to display well, the spectral power is taken the logarithm of 10.

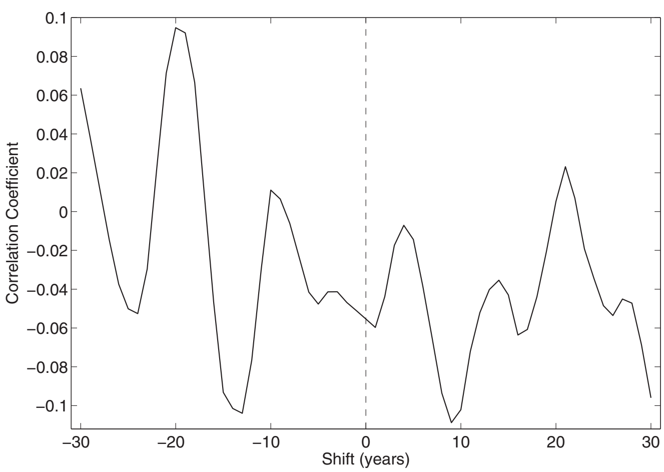

Fig. 5. Cross-correlation coefficient of sunspot number and the El Niño index varying with their relative phase, with negative values representing backward shifts.

In order to test the statistical significance of the CC_9, the block-bootstrap (without any jackknife) method (Kunsch, 1989) is used as well. The SSN series is shifted forwards by 9 years versus the El Niño index, then the unpaired data points are deleted, and the data number of each series is thus 562 (571-9). The two whole series are divided into 40 blocks with each block having no data overlapped, and each block (block length, (Palm et al., 2011)) includes 14 data points. The rest (last two) data points of the two series are divided into their last block, and thus the last block has 16 data points. 37 samples are randomly selected at one time out of the total 40 SSN blocks, and meanwhile the corresponding El Niño index is selected to calculate correlation coefficient (CC'_9) between these two new time series. After 3000 repeats of the above procedure, 3000 values of CC'_9 are obtained, which are all shown in Fig. 6. The corresponding t values of these 3000 CC'_9s are calculated, and for 2883 of the total 3000 repeats, occurring 96.1%, $t > t_{0.05}$, therefore the CC_9 is statistically significant. That is, the CC_9 at the shift of 9 days is statistically significant, suggesting that solar activity could play a part in ENSO. Solar activity's influence on ENSO should be the most remarkable nine years later. That is, the impact of solar activity on the coupled air-sea system of tropical pacific should undergo an accumulation procedure of about 9 years. Or in other word, the response of ENSO may have 9-year delay on solar activity.

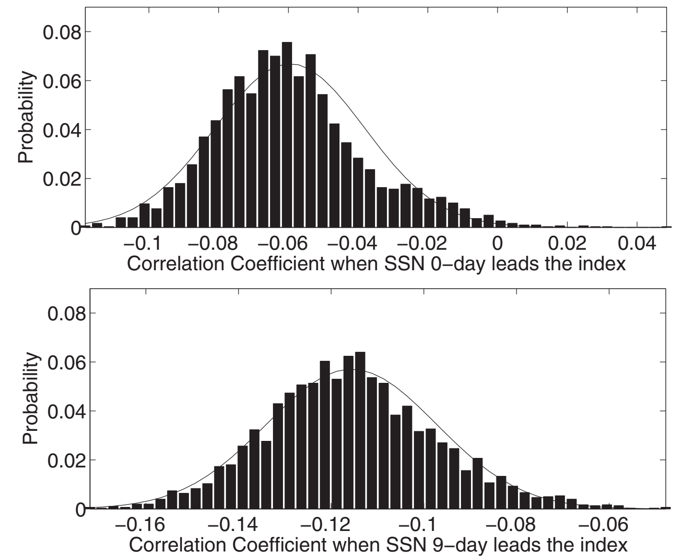

Fig. 6. Top panel: correlation coefficient *CC* between SSN and the El Niño index at their relative phase shift of 0 day. The two whole series are divided into 38 blocks, and each block includes 15 data points. The last data point is divided into the last block. 35 samples are randomly selected at one time out of the total 38 SSN blocks, and meanwhile the corresponding El Niño index is selected to calculate *CC*s. Such a procedure is repeated 3000 times, and resultantly, 3000 points are plotted in this panel. Bottom panel: correlation coefficient *CC* between SSN and the El Niño index at their relative phase shift of 9 day. The SSN series is shifted forwards by 9 years versus the El Niño index, then the unpaired data points are deleted, and thus two new series are obtained. The two whole series are divided into 40 blocks, and each block includes 14 data points. The last two data points is divided into the last block. 37 samples are randomly selected at one time out of the total 40 SSN blocks, and meanwhile the corresponding El Niño index is selected to calculate *CC*s. Such a procedure is repeated 3000 times, and resultantly, 3000 points are plotted in this panel.

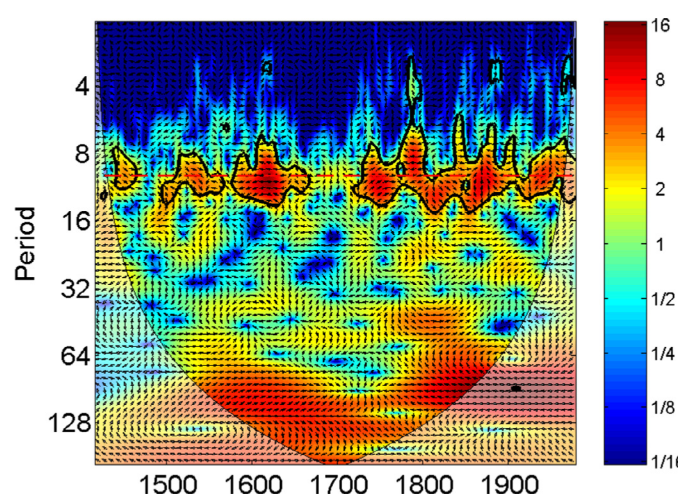

Fig. 7. The Cross-wavelet spectra of sunspot number and the El Niño index. The thick black contours indicate the 95% confidence level, and the region below the thin line indicates the cone of influence. The relative phase relationship is shown as arrows with in-phase pointing right, anti-phase pointing left, and the former leading the latter by 90° pointing straight up.

Then the local power spectrum of SSN with the El Niño No. 3 area index is calculated with the cross wavelet transform method (XWT) used, which is shown in Fig. 7. In Fig. 7, the relative phase relationship of SSN vs the El Niño No. 3 area index is shown as arrows with in-phase pointing right, anti-phase pointing left, and the former leading the latter by 90° pointing straight up. The cor-

Table 1
Correlation coefficients between the El Niño index and SSN at different time intervals.

Time interval	Time span (years)	Correlation coefficient	Statistical significance
1408–1481	74	0.4934	High
1482–1504	23	−0.7335	High
1505–1545	41	0.3445	High
1546–1572	27	−0.2739	Low
1573–1607	35	0.2517	Low
1608–1636	29	−0.5341	High
1637–1671	35	0.6702	High
1672–1715	44	−0.5343	High
1716–1750	35	−0.2531	Low
1751–1776	26	0.5868	High
1777–1805	29	−0.4253	High
1806–1857	52	0.4224	High
1858–1914	57	−0.4721	High
1915–1944	30	0.2128	Low
1945–1954	10	0.8404	High
1955–1978	24	−0.2043	Low

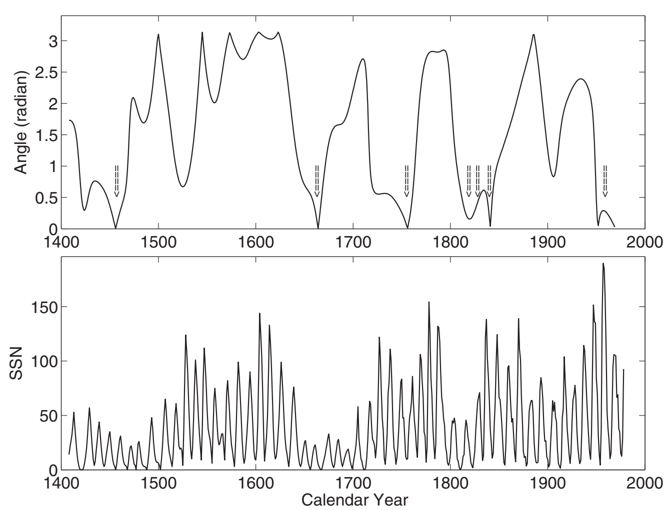

Fig. 8. Top panel: the relative phase angle of the cross-wavelet power spectrum shown as Fig. 7 near the period scale of 10 years. Bottom panel: yearly sunspot number. Down arrows at the top panel correspond well to low sunspot activity shown at the bottom panel.

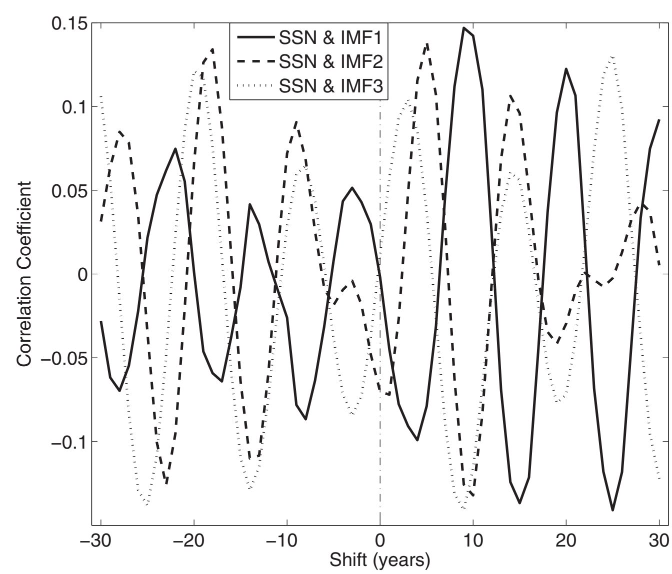

Fig. 9. Cross-correlation coefficient of sunspot number respectively with IMFs 1–3, varying with their relative phase, with negative values representing backward shifts.

relation between SSN and El Niño No. 3 area index clearly shows temporal variation. Areas of statistically significant at the 95% confidence level mainly appear around the period scales of about 11 years, implying the existence of the influence of solar activity on ENSO. However, arrows in the areas point sometimes left, and right sometimes, indicating that such the influence is complex. According to the XWT, *CCs* between the El Niño No. 3 area index and SSN are calculated at different time intervals, which are listed in Table 1. In the last column, "high" means that *CC* is statistically significant at the confidence level of 95% at least, and "low", statistically insignificant. As the table shows, the time intervals of statistical significance, occurring the most (73.6%) of the entire considered period, appear intermittently, and further, during these time intervals ENSO is sometimes positively correlated with SSN, and negatively sometimes. This is the reason why *CC* is not large for the whole considered time interval. Of course, during some time intervals, *CCs* are statistically insignificant. Anyway, in some time intervals, the absolute value of *CC* is over 0.5, especially in 1945 to 1954, *CC* is even as high as 0.8404.

According to the XWT, the relative phase angle around the scale of the 11-year solar activity period at each point of calendar years is extracted, and its absolute value (ϕ) is shown in Fig. 8. When arrows point to right in the XWT, ϕ is 0, and the two time series are positively correlated. When arrows point to left, ϕ is π, and the two time series are negatively correlated. Compared the phase angle with SSN, they present a similar secular trend. That is in particular, the time series of the phase angle seems to be the envelope of the SSN time series. When SSN is large during a certain long-term interval, ϕ is large (close to π), SSN and the El Niño No. 3 area index present a negative correlation during the interval. When SSN is small during an interval, ϕ is also small (close to 0)(as pointing-down arrows marked in Fig. 8), and the relationship between SSN and the index is positive in the meanwhile. Such a changing correlation is inferred to be the reason why the solar activity cycle doesn't appear in IMFs (as shown in Fig. 4).

Next, *CC* of SSN respectively with IMFs 1 to 3 is calculated using the same method as done in Fig. 5, which is shown in Fig. 9. *CC* of SSN with IMF1 is −0.019 at the phase shift of 0 year, peaks to be −0.099 at the phase shift of 4 years, and 0.147 at the phase shift of 9 years. The critical value for the 99.9% confidence level is about 0.135, and the maximum *CC*, 0.147 is significant at the 99.9% confidence level. the block-bootstrap (without any jackknife) method (Kunsch, 1989) is also adopted to test the statistical significance of the maximum *CC*, and it is also significant. Thus, solar activity should take effect in IMF1, and such an impact should undergo an accumulation procedure of about 9 years. That is, the response of the IMF component may appear 9-year delay on solar activity.

Similarly, *CC* of IMF2 with SSN is −0.0070 at the phase shift of 0 year, locally peaks to be −0.072 at the phase shift of 1 year, 0.139 at the phase shift of 5 years, and −0.1321 at the phase shift of 10 years. the maximum value is 0.139 among all absolute *CC* values, implying that IMF2 and SSN are positively related. The block-bootstrap (without any jackknife) method (Kunsch, 1989) is utilized as well to investigate the statistical significance of the maximum *CC*, and the *CC* is significant. Solar activity should thus take effect in IMF2, and such an impact should seemingly undergo an accumulation (phase delay) procedure of about 5 years. By the way, *CC* is −0.1257 at the shift of 9 years, which is also significant.

CC between IMF3 and SSN is 0.0117 at the phase shift of 0 year, peaks to 0.104 at the phase shift of 3 years, and −0.141 at the phase shift of 9 years, whose absolute value is the maximum, implying that IMF3 is negatively correlated with SSN. The block-bootstrap (without any jackknife) method (Kunsch, 1989) is used to probe the statistical significance of the maximum *CC*, and it is significant. Solar activity should thus take effect on IMF3, and such an impact should undergo an accumulation procedure (phase delay) of about 9 years.

3. Conclusion and discussion

Cook (2000) reconstructed the yearly El Niño No. 3 area index of El Niño/Southern Oscillation variability, for the months of December through February of the years 1408–1978. We used this time series to investigate the influence of solar activity on El Niño/Southern Oscillation through periodicity and Ensemble Empirical Mode Decomposition analyses. Intrinsic period of a time series for a certain phenomenon is usually used to understand the cause and to predict the phenomenon. The periods of about 4.15, 5.63, 10.32, 21.20, 39.74, and 97.64 years exist in the El Niño No. 3 area index, and the last four periods are believed to be related with solar activity (Hathaway, 2015). However, just the periods of 4.15 and 5.63 years are statistically significance at the 95% confidence level.

The Ensemble Empirical Mode Decomposition may pick up weak signal of a time series, and the El Niño No. 3 area index is decomposed into nine decomposition components, namely, the so-called intrinsic mode functions (IMFs). Period analyses of these IMFs indicate that the four periods do not appear in the IMFs, but two new periods, 7.58 and 17.17 emerge.

Correlation analyses of SSN are taken respectively with the El Niño index and its first 3 IMFs. *CC* reaches its local maximum when SSN is shifted forwards by 9 years respectively vs the El Niño index, the first IMF, and the third IMF, and the maximum values are all statistically significant. When SSN is shifted forwards by 9 years vs the second IMF, $CC = -0.1257$, which is significant. Thus we infer that solar activity should take an effect on ENSO, and the effect should undergo an accumulation procedure of about 9 years.

The cross wavelet transform (XWT) of yearly sunspot number (SSN) with the El Niño index has been taken, and areas of high communal power mainly appear around the period scales of about 11 years, showing that the decadal-period solar activity is not ruled out as a possible factor to influence on ENSO. However, such the influence is complex and varies with time. Based on the XWT, correlation analyses are taken between SSN and the El Niño index at different time intervals, and time intervals of statistical significance are intermittently. The El Niño index is sometimes positively correlated with SSN, and sometimes negatively. This is inferred to be the reason why *CC* is small for the entire time interval.

When the complex Morlet wave is used to calculate XWT, relative phase of SSN with the El Niño No. 3 area index at a certain time could be calculated from their cross wavelet transform spectrum. Relative phase angle is calculated around the scale of the 11-year solar activity period at each point of calendar years, and it is compared with SSN. The phase angle looks like the envelope of the SSN time series, presenting a similar secular trend like SSN. It is found that SSN and the El Niño index generally present a negative correlation when the Sun is at high activity level for a long time, and a positive correlation when the Sun is at low activity level. Solar activity is inferred to be weak in decades to come (Li et al., 2015), therefore we predict that El Niño/Southern Oscillation should be strong next decades. Time will tell.

Acknowledgments

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