



## Evidence of Higher-Order Solar Periodicities in China Temperature Record

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**Abstract**—We examine here a 2000-year-long record of surface air temperature from China using powerful spectral and statistical analysis techniques to assess the trend and harmonics, if any. Our analyses reveal statistically significant periodicities of order  $\sim 900 \pm 50$ ,  $\sim 480 \pm 20$ ,  $340 \pm 10$ ,  $\sim 190 \pm 10$  and  $\sim 130 \pm 5$  years, which closely match with the known higher-order solar cycles. These periodicities are also similar to quasi-periodicities reported in the climate records of sedimentary cores of subarctic and subpolar regions of North America and North Pacific, thus attesting to the global signature of solar signals in temperature variability. A visual comparison of the temperature series shows that the nodes and antinodes of the underlying temperature variation also match with sunspot variations. We also compare the China temperature (CT) with temperature of northern and southern hemispheres of the past 1000 years. The study reveals strong correlation between the southern hemispheric temperatures and CT during the past 1000 years. However, the northern hemisphere temperature shows strong correlation with CT only during the past century. Interestingly, the variations in the correlation coefficient also have shown periodicities that are nearly identical to the periods observed from CT and higher-order solar cycles. We suggest that the solar irradiance induces global periodic oscillations in temperature records by transporting heat and thermal energy, possibly through the coupling of ocean–atmospheric processes and thereby reinforcing the Sun–ocean–climate link.

**Key words:** Temperature, solar cycle, ocean–atmospheric conveyor belt, spectral analysis.

### 1. Introduction

Evidences suggest that climate/temperature variations follow the sunspot cycles on global and regional scales. There are flurry of papers and tremendous renewal of interest amongst the

researchers to understand the mechanisms of solar effect on global temperature/climate variability. However, this issue is important and debated for a long time either because of lack of unbiased long-term temperature data and/or appropriate technique for analysis. At present, a large amount of temperature and climate proxy records are available from the different archives. Most of the proxy data sets decoded from various sources, such as corals, lacustrine sediments, ice cores, etc., serve as indicators for past climate change and solar activity. Spectral analyses of these proxy time series of climate variability facilitate identifying the long-term trends and periodicities. Apparently, these trends and quasi-periodicities render the link of climate variability with some internal and external physical processes. We, however, still lack a fundamental mechanistic understanding to uphold firmly a particular view on the causal link between solar activity and climate/temperature.

Several studies have reported a possible link between terrestrial climate change and solar variability on decadal to centennial scales (STUIVER 1980; FROLICH and LEAN 1998; LEAN and RIND 1999; NESMERIBES and FERREIRA 1993; BOND *et al.* 2001; KERR 2001). The solar radiation alters the terrestrial temperature and thereby drives the climate dynamics. Although the variability in the external solar radiation is considerably less (0.1 %), the change in the UV spectral radiation even at this small change in total solar irradiance could possibly increase the terrestrial temperature by altering ozone concentration in the stratosphere and upper troposphere. Researchers have noticed a significant 11-year cyclic relation between the terrestrial temperature variability and fluctuations in the instrumentally observed solar irradiance associated with the variation in the number of sunspots. In addition to this 11-year cyclic mode of solar

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variability, there are several higher-order cycles in the solar variability, which could possibly alter the terrestrial temperature or climate at the same periodicities (STUIVER 1980; SONETT 1984; SARNTHEIN *et al.* 2003; HU *et al.* 2003; TIWARI 2005; TARICCO *et al.* 2014).

Although several researchers have demonstrated the signature of solar cycles and quasi-periodic sub-harmonics in solar frequency bands from the spectral analyses of non-sinusoidal/abrupt climate and temperature records, there have been some apprehension in accepting the evidence of periodicity. The main questions have been regarding the statistical reliability and stability of these spectral peaks in the climate and temperature records and physical mechanism. In the present study, we investigate the centennial-scale solar periodic forcing on 2000-year-long proxy-reconstructed record of CT data (GE *et al.* 2013) using singular spectral analysis and other spectral methods. We also compare the CT variations with northern and southern hemispheric proxy-reconstructed temperatures to assess the hemispheric forcing on CT during past 1000 years. Finally, we discuss the results with different perspectives and unprejudiced sensibility to promote the scientific temper on this conjectural issue. This is crucial for unswerving interpretations of the present and future evaluation of solar activity link to global climate.

## 2. Source of the Data

We analyse here the proxy-reconstructed record of China temperature (CT) for a period spanning over 0 C.E. to 2000C.E. (GE *et al.* 2013). According to GE *et al.* (2013), the CT is reconstructed using partial least square regression method with 10-year time resolution from the temperature data of relatively high confidence levels from five selected regions of China, namely northeast (NE), central east, southeast (SE), northwest and Tibet Plateau. The five regions were selected because of their geographic location and temperature characteristics from 1961 to 2007. The real-time observations from Chinese Meteorological Administration for the period 1851–1950 were used to standardize CT data (LIN *et al.* 1995). TANG *et al.* (2009) have subsequently updated the

above standardized data. As documented in HAO *et al.* (2011), the data from NE and SE regions extended up to 2000 years using historical records of warm/cold spells. GE *et al.* (2013) have listed different temperature proxies from various studies and have discussed in detail about resolution, variance, core sites and period of measurements and reconstruction. Thus, the data used in the present study (GE *et al.* 2013) is one of the most reliable temperature records available.

The precisely reconstructed data show four alternating warming and cooling patterns (phases/spell) during the intervals of AD 1–AD 200, AD 551–AD 760, AD 951–AD 1320 and AD 201–AD 350, AD 441–AD 530, AD 781–AD 950 and AD 1321–AD 1920, respectively, relative to the 1851–1950 climatological database. Among these, the temperatures of AD 981–AD 1100 and AD 1201–AD 1270 periods are analogous to those of the present warm period with  $\pm 0.28$  °C to  $\pm 0.42$  °C, however, with uncertainty at the 95 % confidence interval (GE *et al.* 2013). A visual inspection of the data apparently shows long-term temperature warming and cooling reversals separated by approximately 210–240 years and 450–500 years, which are intermittently superimposed onto the long-term temperature trend.

The abrupt temperature variability including decadal to centennial-scale changes in the CT are considered to be influenced by a wide range of factors such as solar activity (LEAN and RIND 1999; HU *et al.* 2003), oceanic forcing through ENSO (BANHOLZER and DONNER 2014; CHOWDARY *et al.* 2014) and anthropogenic effects (KAUFMANN and STERN 1997; ESTRADA *et al.* 2013). We mention, however, that 10-year resolution (averaging) of the data will have impact on the smaller cycles, such as ENSO (ocean and atmospheric coupling) and high-frequency solar signals and monsoonal temperature variability. Hence, we examine these data for detecting higher-order periodicities using the modern techniques of spectral analysis. Among these multiple causative factors, we pay more attention here on the solar influence because of its relative importance as compared to the other forcing mechanisms reported from the different temporal and spatial proxy records (BOND *et al.* 2001; SHINDELL *et al.* 2001; HU *et al.* 2003; WEBER *et al.* 2004; FOUKAL *et al.* 2006; TARICCO *et al.* 2014). The sunspot number data used in this

study was taken from SOLANKI *et al.* (2004). In addition to the above, we use temperature data from the Northern and Southern Hemispheres for the past 1000 years published by NEUKOM *et al.* (2014) in this study to evaluate the hemispheric correlations with CT.

### 3. Method of Analyses

We employ here singular spectral analysis (SSA) (VAUTARD *et al.* 1992; GOLYANDINA *et al.* 2001, GHIL *et al.* 2002; SERITA *et al.* 2005; TIWARI and RAJESH 2014; TIWARI *et al.* 2014) for analysing the above data. The SSA is a powerful tool to identify unknown and/or partially known dynamics of data series from noisy background in terms of principal component analysis. Appropriate selection of window length is a crucial step in the singular spectrum analysis (PATTERSON *et al.* 2011; HASSANI *et al.* 2013). The window length equal to the maximum of the classical limit of the data  $N/2$  should be appropriate for precisely resolving the principal components. The number of dynamical components present in the data should also be much smaller than  $N/2$  while dealing with the large data set. In such cases, selection of the optimal window length, which is smaller than the data  $N/2$ , would reduce the computational cost. The estimated weighted correlation among the different principal components using a specific window length would help us to verify the resolvability.

Following GHIL and TARICCO (1997), we calculate the weighted correlation to know the separability of the principal components at the respective window lengths using the following equation:

$$W_c = \frac{(PC_1, PC_2)_w}{\|PC_1\|_w \cdot \|PC_2\|_w}, \quad (1)$$

where  $\|PC_i\|_w = \sqrt{(PC_i, PC_i)_w}$ , and  $(PC_1, PC_2)_w = \sum_{k=1}^N w_k \cdot PC_{1k} PC_{2k}$ .

$$w_k = \min\{k, L, N - k\}.$$

The components are said to be well resolved, if the factor  $W_c$  is close to zero.

In addition to the SSA method, we also use Lomb (LOMB 1976) and short time fourier transform (JACOBSEN and LYONS 2003) based spectral method in

the present study to confirm the credential of our results. The Lomb spectral analysis is robust for analysing the paleo-reconstructed time series, even sampled at unequal intervals. The short time Fourier transform method is useful to verify the stationarity behaviour of the spectral content observed from the spectrum. Finally, we estimated the confidence intervals of data, eigenvalues and spectral content using bootstrap statistics (EFRON and TIBSHIRANI 1986).

### 4. Results and Discussion

The temperature variability record of China displayed in Fig. 1 shows a composite response of various physical processes. Hence, we applied the SSA method to decompose the data into its interpretable consistent principal components using the window length 50 [i.e.  $50 \times$  sampling interval (10) = 500 years]. The raw data shown in Fig. 1 was subjected to SSA using the multiple window lengths of 25, 40, 50 and 60. We have computed weighted correlation ( $W_c$ ) between all possible pairs of principal components at the above window lengths using Eq. 1 (Fig. 2a). One can see from Fig. 2 that the weighted correlation of the first nine components with the other components is almost zero for window lengths 50 and 60. However for the window length 25 and 40 (Fig. 2a), the value of  $W_c$  is greater than zero and hence the separability is poor. This implies that the selection of window length  $\geq 50$  is appropriate for the present analysis and will ensure better results and would not entail any artefacts in the reconstructed signal.

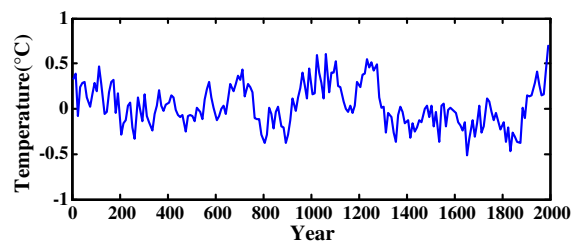


Figure 1  
Raw data of China temperature from 0 to 2000 AD

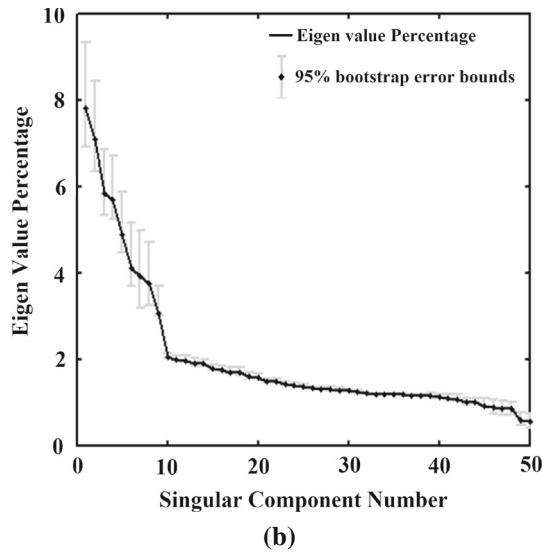
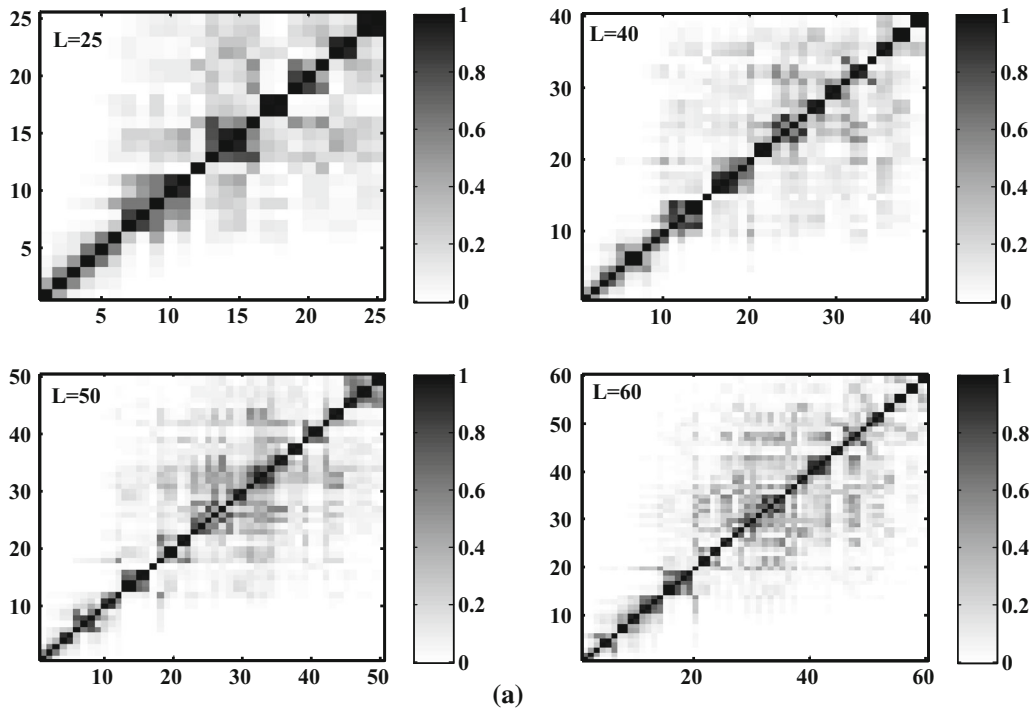


Figure 2

**a** Weighted correlations computed at four different window lengths ( $L = 25, 40, 50$  and  $60$ ) using Eq. 1. **b** Singular spectrum of China temperature record

The singular spectrum shown in Fig. 2b clearly depicts the contribution/variance of independent eigen/principal processes. One can notice from the singular spectrum that the first ten principal components together contribute  $\sim 48\%$  of the total variance. Figure 3a shows the first ten individual

principal components (PC1–PC10). Evidently, these first ten components representing clear trend and quasi-periodic variations are the major contributors to the process. The results from the spectral analysis of all the individual PCs also show the consistency of these cycles (Table 1). The longer cycle may

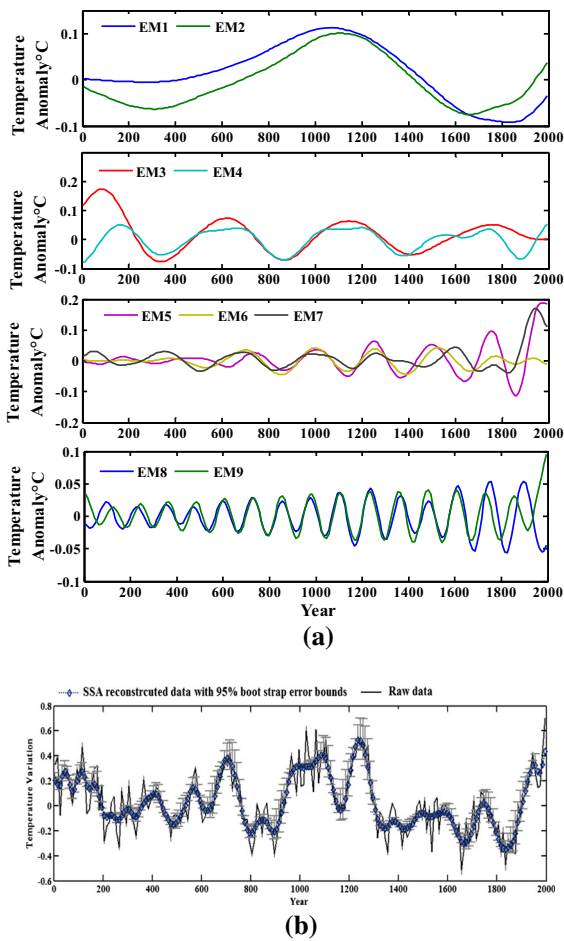


Figure 3

**a** First nine SSA-reconstructed eigenmodes (EM)/principal components of China temperature data series (Refer to Table 1 for eigenvalue percentages of individual components). **b** China temperature reconstructed from first nine eigenmodes/principal components using SSA along with *error bars* computed using bootstrap method and original data

represent trend in the data. The other stable periods, however, correspond to known higher-order solar periods reported by several researchers (HU *et al.* 2003; TIWARI 2005; SONETT 1984). Hence, we have reconstructed the data using the first nine principal components to analyse further for long period solar cycles (period >100 years.), if any, in the temperature record (Fig. 3b). Figure 3b also shows 95 % confidence intervals with respect to raw data estimated using 1000 bootstraps. The resulting reconstruction of the data shows good match with the original data and thereby attests the authenticity of reconstruction. The Lomb spectral analysis (LOMB 1976) of the SSA-reconstructed data shown in Fig. 4a revealed ~995, 482, 312, 234, 193 and 136 years of periodicities. Further, to verify stationary behaviour of these periodicities, we have computed a spectrogram of the SSA-reconstructed data using short-time Fourier transform (JACOBSEN and LYONS 2003). The spectrogram analysis revealed dominant non-stationary spectral powers around ~130, 180 ± 10 and 900 ± 50 years and stationary spectral power almost throughout the record in the period range of 250 ± 30, 500 ± 40 years (Fig. 4b). The above periodicities in a range of 160–1000 years identified in the spectrum of temperature record matching well with the known Suess (SCHOVE 1983) and Eddy solar cycles. The periodicities observed between 50 and 140 years and 160 and 260 years are Gleissberg and Suess/de Vries bands, respectively. The solar periods deduced from the atmospheric carbon (SONETT 1984) also confirm the above periodicities numerically. In a recent work, HU *et al.* (2003) have also reported identical periodicities of the order ~135, 170, 195,

Table 1

*Spectral content of individual SSA-reconstructed principal components (above 95 % confidence level) along with their eigen-percentage in brackets*

Principal component number	Spectral content [period (years)]	Principal component number	Spectral content [period (years)]
1 (9.25 %)	1592 (trend)	6 (3.65 %)	170, 148, 134
2 (7.77 %)	995, 612, 468	7 (3.41 %)	170, 148, 132
3 (5.65 %)	497, 300	8 (3.23 %)	227, 178,137
4 (4.95 %)	442, 300	9 (3.1 %)	173, 131, 121
5 (4.74 %)	468, 234, 204	10 (2.42 %)	89, 65, 57

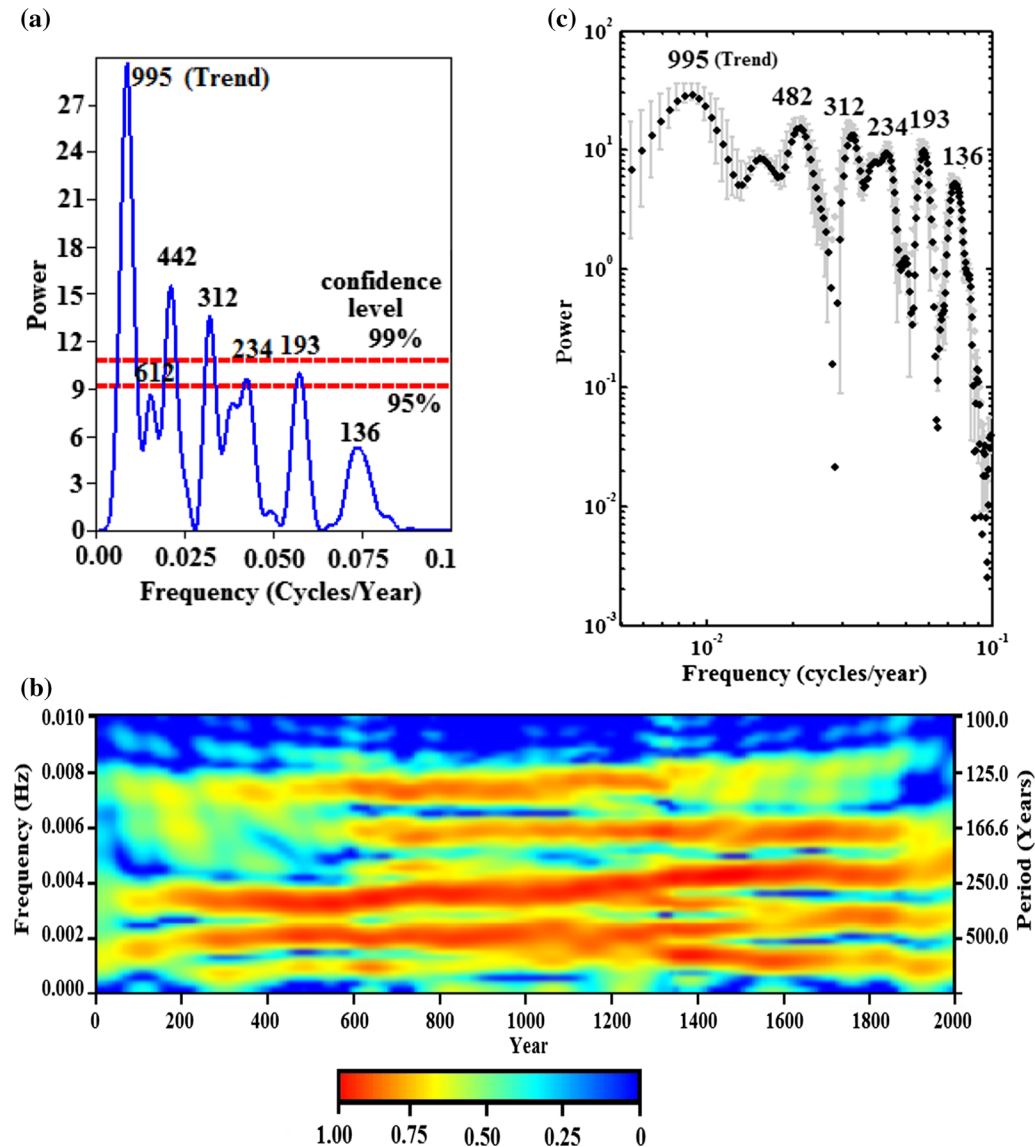


Figure 4

Spectral results of SSA-reconstructed temperature series of China shown in Fig. 3b. **a** Lomb spectrum, **b** spectrogram, **c** Lomb spectrum with bootstrap error bounds for spectral peaks

435, 590 and 950 years in the spectral results of Holocene BSi (biogenic silica) record from Arolik Lake and discussed their link to the known solar cycles. According to Hu *et al.* (2003), the periodicities of  $450 \pm 50$  and  $900 \pm 50$  years are replicable in changes of residual atmospheric  $\Delta^{14}\text{C}$  production associated with solar variation. A comparison between the periodicities obtained from the Lomb

spectra of SSA-reconstructed data and solar periods observed from the proxy-reconstructed solar irradiance data also shows good match and, therefore, may suggest a plausible impact of long periodic solar activity on CT. In addition to the earlier spectral results from the northern hemisphere temperature records, the present result also match with periodicities of the order of 206 and 325 years (TAN *et al.*

2003), 440 and 900 years (MARTÍN-CHIVELET *et al.* 2011) and 178 years (SALZER and KIPFMUELLER 2005). LIU *et al.* (2011) reported statistically significant cycles of period 110, 199, 800 and 1324 years from 2485-year-long proxy temperature record from the central-eastern Tibetan Plateau. HELAMA *et al.* (2010) have noticed periodicities of 225, 135 and 105 years in the multi-taper spectral analysis of tree ring record from Finnish Lapland. We have tabulated all the periodicities identified in our spectral results along with the results of HU *et al.* (2003) and SONETT (1984) for comparison (Table 2). The periodicities observed in the spectral analysis of CT clearly match with the similar periodicities reported from the analysis of atmospheric radiocarbon records (SONETT 1984), Arolik Lake sediments from Alaska, USA (HU *et al.* 2003) and solar irradiance data (SCAFETTA 2012) (Table 2), suggesting their global nature. Further, we have verified the statistical significance of the spectral peaks identified in the Lomb spectrum (PRESS 2007) by computing the bootstrap error bounds (EFRON and TIBSHIRANI 1986). For this, we used 100 bootstrap samples and a running window of 100 years with ten overlapping data points, which further confirm the stability of the above periodicities (Fig. 4c). We, therefore, suggest that the identified periodicities are statically significant and call for physical interpretations. The novelty of the present analyses is that it gives an integrated picture of periodicities corresponding to solar activity and thus further places a strong argument for solar and climate

link through the processes of modulating and/or triggering climate variability.

Further, original and SSA-reconstructed CT data along with decadal sunspot number data (SOLANKI *et al.* 2004) are shown in Fig. 5 for visual comparison. We can observe a good match between temperature lows and solar minimas [Wolf (1280–1340), Sporer (1420–1530), Maunder (1642–1705) and Dalton (1790–1820)] from Fig. 5. This may further emphasize the possible physical link between the solar activity and terrestrial temperature. However, there is some phase lag at certain times between the solar activity and temperature variability, which could be attributed to the temporal accuracy and resolution of data. Thus, the identified periodicities in temperature data and its comparison with sunspot number data may support their link. We have also computed the coherence between the sunspot number data and CT data (Fig. 6). Coherence analysis further suggests a periodic synchronicity between the CT and sunspot number data.

#### 4.1. Comparison with Hemispheric Temperature

Spectral analysis of temperature record for the last five millennia from the Northern Hemisphere has revealed the dominant 330, 250, 110 and 50–80 years periodicities (TARICCO *et al.* 2014), which match well with the periodicities observed in the present analysis of CT data. GE *et al.* (2013) have also suggested the possible Northern Hemispheric forcing on the CT

Table 2

Comparison of periodicities observed in our analysis of CT data with the solar periods identified by Hu *et al.* (2003) from the lake sediment data and Sonett (1984) from atmospheric radiocarbon data

S. No	Periodicities identified in China temperature record (in years)	Periodicities identified by HU <i>et al.</i> (2003) from Arolik Lake sediments	Very long solar periods (SONETT 1984) from atmospheric radio carbon data
1	995	950 [Documented in residual atmospheric <sup>14</sup> C production (STUIVER and BRAZIUNAS 1993)]	962, 890
2	482	590 [Documented in residual atmospheric <sup>14</sup> C production (STUIVER and BRAZIUNAS 1993)]	452
3	312, 234*		252
4	193	195 (de Vries solar cycles of period ~200)	183
5	136	135 (Solar cycle)	134

\*TARICCO *et al.* (2014) have also reported 330, 250 years periods in the Northern Hemisphere temperature

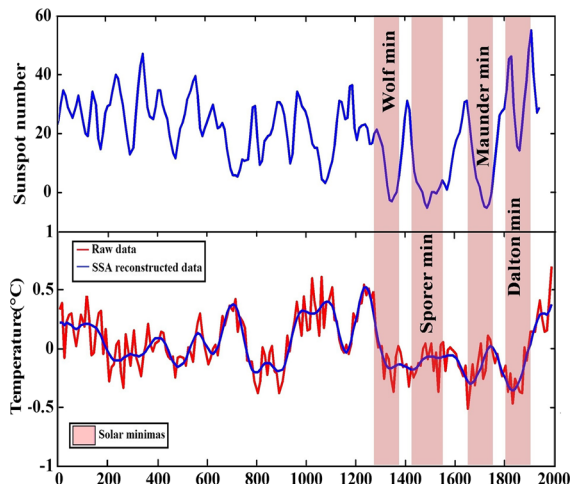


Figure 5

Comparison of sunspot data (top panel) and CT-reconstructed series (bottom panel)

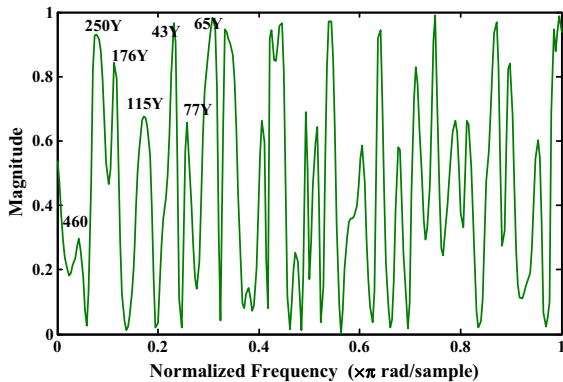


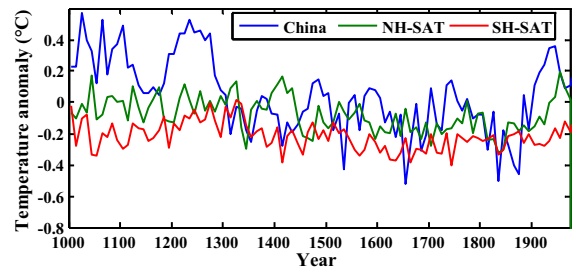
Figure 6

Coherency between sunspot number data and CT

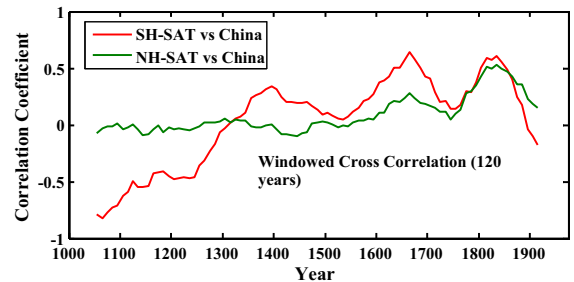
during the last century. To verify the hemispheric forcing on CT, we have performed windowed correlation analysis of the CT data of the past 1000 years with the available Northern Hemisphere temperature (NHT) and Southern Hemisphere temperature (SHT) data (NEUKOM *et al.* 2014) shown in Fig. 7a. The green and red colour line plots in Fig. 7b show the moving window correlation of CT with NHT and SHT, respectively. As we are interested in finding the role of higher-order solar cycles, we have chosen here a 120-year moving window.

One can notice the following features from Fig. 7b.

1. During 1000–1300 AD, the correlation between NHT and CT was nearly insignificant ( $\sim 0$ ),



(a)



(b)

Figure 7

**a** Comparison of CT record of the past 1000 years with Northern (NH-SAT) and Southern (SH-SAT) Hemispheric temperature data, **b** cross-correlation of CT with hemispheric temperatures using a window of 120 years

whereas SHT has shown strong negative correlation with CT, which gradually decreased towards 1300 AD

2. Between 1300 and 1500 AD, SHT has shown positive correlation with CT, whereas NHT has shown negative correlation with CT.
3. After 1500 AD, both NHT and SHT have shown positive correlation with CT. Although both have shown positive correlation with CT, the correlation of SHT with CT is large compared to the correlation of NHT with CT during 1520–1750 AD.
4. The NHT and SHT have shown almost the same positive correlations with CT during 1750–1860.
5. There is an apparent gradual decrease of correlation of NHT and SHT with CT after 1860. Although correlations of NHT and SHT with CT are decreasing, SHT has shown more negative gradient and become negative after 1890. Hence, it appears that the CT is forced by NHT during the last century as suggested by GE *et al.* (2013).



Nevertheless, the Southern Hemisphere has also strongly correlated with the CT until 1890.

Our results suggest the possible impact of internal dynamics from ocean-dominated Southern Hemisphere on CT via coupled ocean–atmosphere circulation. The solar energy stored in the oceans is possibly released into the atmosphere and drives the climate through ocean–atmospheric circulations during low solar activity periods (TIWARI *et al.* 2014). Hence, the ocean–atmospheric circulations could produce periodic changes in the climate with time constants equal to the solar period, however, with some phase lag. Such oceanic forcing is dominant mainly during low solar activity (TIWARI *et al.* 2014). Overall, the correlation studies indicate that the correlation of CT with the Northern Hemispheric temperature is comparatively lower than the correlation with the Southern Hemispheric temperatures during the past 1000 years. This manifests the influence of coupled ocean–atmospheric circulations on CT due to solar-induced variations in the oceanic temperature and pressure in the ocean-dominated Southern Hemisphere.

### 5. Conclusion

We studied here long periods of solar forcing on CT using multiple statistical and spectral methods. The eigenvalue analysis of the CT record reveals ~48 % contribution of the total variance of the centennial scale variation derived from the first ten principal components. The multiple spectral and statistical analyses of the temperature record revealed periodicities of the order of 136, 193, 234, 482 and 995 years. The periodicities identified from the SSA-reconstructed data match well with the known solar cycles. The CT data and its SSA-reconstructed output also agree with the variations in the sunspot number data within the limit of resolution and reconstruction errors. Hence, we conclude that the long period of solar forcing was one of the dominant drivers of temperature on CT record over the past 2000 years.

The correlation study between the Southern and Northern Hemispheric temperature with CT suggests that the Northern Hemispheric forcing on CT was

only during the last century. Further, we have also shown strong negative or positive correlation of CT with Southern Hemispheric temperature variability during 1000–1300 AD and 1300–1890 AD, respectively. This long-term forcing may be due to the variation in solar radiative forcing on the Northern and Southern Hemispheres coupled with the ocean–atmospheric circulation system.

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### REFERENCES

- BANHOLZER, S. & DONNER, S. (2014). *The influence of different El Nino types on global average temperature*. Geophysical Research Letters., doi:10.1002/2014GL059520.
- BOND, G., KROMER, B., BEER, J. *et al.*, (2001). *Persistent Solar Influence on North Atlantic Climate during the Holocene*. Science, 294, 2130–2136.
- CHOWDARY, J. S., JOHN, N., GNANASEELAN, C. (2014). *Interannual variability of surface air-temperature over India, impact of ENSO and Indian Ocean Sea surface temperature*. Int. J. Climatol., 34, 416–429.
- ESTRADA, F., PERRON, P., MARTINEZ-LOPEZ, B. (2013). *Statistically derived contributions of diverse human influences to twentieth-century temperature changes*. Nature Geoscience, 6 (12), 1050–1055.
- EFRON, B., TIBSHIRANI, R. (1986). *Bootstrap methods for standard errors, confidence intervals, and other measures of statistical accuracy*. Statistical science, 54–75.
- FOUKAL, P., FRÖHLICH, C., SPRUIT, H., WIGLEY, T. M. L. (2006). *Variations in solar luminosity and their effect on the Earth's climate*. Nature, 443, 161–166, doi:10.1038/nature05072.
- FROLICH, C. & LEAN, J. (1998). *The sun's total irradiance cycles, trends and related climate change uncertainties since 1976*. Geophys. Res. Lett., 97, 7579–7591.
- GE, Q., HAO, Z., ZHENG, J., SHAO, X. (2013). *Temperature changes over the past 2000 yrs in China and comparison with the Northern Hemisphere*. Climate of the Past., 9, 507–523.
- GHIL, M., ALLEN, M. R., DETTINGER, M. D. *et al.*, (2002). *Advanced spectral methods for climatic time series*. Rev. Geophys., doi:10.1029/2000RG000092.
- GHIL, M. & TARICCO, C. (1997). *Advanced Spectral Analysis Methods*. In Past and Present Variability of the Solar-Terrestrial System: Measurement, Data Analysis and Theoretical Models. Cini Castagnoli G, Provenzale A (Eds.), SocietÀ Italiana di Fisica, Bologna, & IOS Press, Amsterdam.
- GOLYANDINA, N., NEKRUTKIN, V., ZHIGLJAVSKY, A. A. (2001). *Analysis of Time Series Structure: SSA and Related Techniques*.

- Chapman & Hall/CRC Monographs on Statistics & Applied Probability, Taylor & Francis.
- HAO, Z. X., ZHENG, J. Y., GE, Q. S. (2011). *Historical analogues of the 2008 extreme snow event over Central and Southern China*. *Clim. Res.*, 50, 161–170, doi:10.3354/cr01052.
- HASSANI, H., HERAVI, S., ZHIGLJAVSKY, A. A. (2013). *Forecasting UK Industrial Production with Multivariate Singular Spectrum Analysis*. *Journal of Forecasting*, 32, 395–408.
- HELAMA, S., MACIAS FAURIA, M., MIELIKÄINEN, K. et al., (2010). *Sub-Milankovitch solar forcing of past climates: mid and late Holocene perspectives*. *Geol Soc Am Bull.*, 122, 1981–1988.
- HU, F. S., KAUFMAN, D., YONEJI, S. et al., (2003). *Cyclic Variation and Solar Forcing of Holocene Climate in the Alaskan Subarctic*. *Science*, 301, 1890–1893.
- JACOBSEN, E. & LYONS, R. (2003). *The sliding DFT*. *Signal Processing Magazine*, 20(2), 74–80.
- KAUFMANN, R. K. & STERN, D. I. (1997). *Evidence for human influence on climate from hemispheric temperature relations*. *Nature*, 388(6637), 39–44.
- KERR, R. A. (2001). *A Variable Sun Paces Millennial Climate*. *Science*, 294, 1431–1433.
- LEAN, J. & RIND, D. (1999). *Evaluating Sun-climate relationships since the Little Ice Age*. *J. Atmos. Solar-Terr Phys.*, 61, 25–36, doi:10.1016/S1364-6826(98)00113-8.
- LIN, X. C., YU, S. O., TANG, G. L. (1995). *Series of average air temperature over China for the last 100-year period*. *Sci Atmos Sinica*, 19, 525–534.
- LIU, Y., CAI, O. F., SONG, H. M., AN, Z. S., LINDERHOLM, H. W. (2011). *Amplitudes, rates, periodicities and causes of temperature variations in the past 2485 years and future trends over the central-eastern Tibetan Plateau*. *Chin Sci Bul.*, 16, 2986–2994.
- LOMB, N. R. (1976). *Least-squares frequency analysis of unequally spaced data*. *Astrophysics and space science*, 39(2), 447–462.
- MARTÍN-CHIVELET, J., MUÑOZ-GARCÍA, M. B., EDWARDS, R. L., TURRERO, M. J., ORTEGA, A. I. (2011). *Land surface temperature changes in Northern Iberia since 4000 yr BP, based on  $\delta^{13}C$  of speleothems*. *Glob Planet Change*, 77, 1–12.
- NESME-RIBES, E. & FERREIRA, E. N. (1993). *Solar dynamic and its impact on solar irradiance and the terrestrial climate*. *J Geophys Res.*, 98(18), 923–935.
- NEUKOM, R. et al. (2014). *Inter-hemispheric temperature variability over the past millennium*. *Nature Clim. Change* 4, 362–367 (2014).
- PATTERSON, K., HASSANI, H., HERAVI, S., ZHIGLJAVSKY, A. A. (2011). *Multivariate singular spectrum analysis for forecasting revisions to real-time data*. *Journal of Applied Statistics* 38, 2183–2211.
- PRESS (2007). *Numerical Recipes* (3rd Ed.). Cambridge University Press. ISBN 0-521-88068-8.
- SALZER, M.W. & KIPFUELLER, K. F. (2005). *Reconstructed temperature and precipitation on a millennial timescale from tree-rings in the Southern Colorado Plateau, USA*. *Clim Change*, 70, 465–487.
- SARNTHEIN, M., VANKREVELD, S., ERLLENKEUSER, H. et al., (2003). *Centennial-to-millennial-scale periodicities of Holocene climate and sediment injections off the western Barents shelf, 75°N*. *Boreas*, 32, 447–461, doi:10.1111/j.1502-3885.2003.tb01227.x.
- SCAFETTA, N. (2012). *Multi-scale harmonic model for solar and climate cyclical variation throughout the Holocene based on Jupiter-Saturn tidal frequencies plus the 11-year solar dynamo cycle*. *Journal of Atmospheric and Solar-Terrestrial Physics*, 80, 296–311.
- SCHOVE, D. J. (1983). *Sunspot Cycles*, Hutchinson Ross Publ Co. Stroudsburg, Pennsylvania.
- SERITA, A., HATTORI, K., YOSHINO, C., HAYAKAWA, M., ISEZAKI, N. (2005). *Principal component analysis and singular spectrum analysis of ULF geomagnetic data associated with earthquakes*. *Natural Hazards and Earth System Sciences*, 5, 685–689.
- SHINDELL, D. T., SCHMIDT, G. A., MANN, M. E., RIND, D., WAPLE, A. (2001). *Solar forcing of regional climate change during the Maunder Minimum*. *Science*, 294, 2149–2152.
- SOLANKI, S. K., USOSKIN, I. G., KROMER, B. et al., (2004). *Unusual activity of the Sun during recent decades compared to the previous 11,000 years*. *Nature*, 437, 1084–1087.
- SONETT, C. P. (1984). *Very long solar periods and the radiocarbon record*. *Rev Geophys.*, 22(3), 239–254.
- STUIVER, M. (1980). *Solar variability and climatic change during the current millennium*. *Nature*, 286, 868–871, doi:10.1038/2868680.
- STUIVER, M., BRAZIUNAS, T. F. (1993). *Sun, ocean, climate and atmospheric  $^{14}CO_2$ : an evaluation of causal and spectral relationships*. *The Holocene*, 3(4), 289–305.
- TAN, M., LIU, T. S., HOU, J. et al., (2003). *Cyclic rapid warming on centennial-scale revealed by a 2650-year stalagmite record of warm season temperature*. *Geophysical Research Letters*, 30, 1617–1620, doi:10.1029/2003GL017352.
- TANG, G. L., DING, Y. H., WANG, S. W. et al., (2009). *Comparative analysis of the time series of surface air temperature over China for the last 100 years*. *Adv Clim Change Res.*, 5, 71–78.
- TARICCO, C., MANCUSO, S., LJUNGVIST, F. C. et al., (2014). *Multispectral analysis of Northern Hemisphere temperature records over the last five millennia*. *Climate Dynamics*, doi:10.1007/s00382-014-2331-1.
- TIWARI, R. K. (2005). *Geo spectroscopy*. Capital-publishing Company ISBN: 81-85589-17-8.
- TIWARI, R. K. & RAJESH, R. (2014). *Imprint of long-term solar signal in groundwater recharge fluctuation rates from Northwest China*. *Geophysical Research Letters*, 41(9), 3103–3109.
- TIWARI, R. K., RAJESH, R., PADMAVATHI, B. (2014). *Evidence for Non-linear coupling of Solar and ENSO signals in Indian temperature during the past century*. *Pure and Applied Geophysics*, doi:10.1007/s00024-014-0929-1.
- VAUTARD, R., YIOU, P., GHIL, M. (1992). *Singular-spectrum analysis: A toolkit for short, noisy chaotic signals*. *Physica D*, 58, 95–126.
- WEBER, S. L., CROWLEY, T. J., VAN DER SCHRIER, G. (2004). *Solar irradiance forcing of centennial climate variability during the Holocene*. *Climate Dynamics*, 22, 539–553.