

1     **WAVELET ANALYSIS OF THE SINGULAR SPECTRAL RECONSTRUCTED TIME SERIES TO STUDY**  
2     **THE IMPRINTS OF SOLAR-ENSO-GEOMAGNETIC ACTIVITY ON INDIAN CLIMATE**

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14     **ABSTRACT**

15     To study the imprints of the Solar-ENSO-Geomagnetic activity on the Indian Subcontinent, we  
16     have applied the Singular spectral analysis (SSA) and wavelet analysis to the tree ring  
17     temperature variability record from the Western Himalayas. Other data used in the present  
18     study are the Solar Sunspot Number (SSN), Geomagnetic Indices (aa Index) and Southern  
19     Oscillation Index (SOI) for the common time period of 1876-2000. Both SSA and wavelet  
20     spectral analyses reveal the presence of 5-7 years short term ENSO variations and the 11 year  
21     solar cycle indicating the possible combined influences of solar-geomagnetic activities and  
22     ENSO on the Indian temperature. Another prominent signal corresponding to 33-year  
23     periodicity in the tree ring record suggests the Sun-temperature variability link probably  
24     induced by changes in the basic state of the earth's atmosphere. In order to complement the  
25     above findings, we performed a wavelet analysis of SSA reconstructed time series, which agrees  
26     well with our earlier results and increases the signal to noise ratio thereby showing strong  
27     influence of solar-geomagnetic activity & ENSO throughout the entire period. The solar flares  
28     are considered responsible for causing the atmospheric circulation patterns. The net effect of  
29     solar-geomagnetic processes on the temperature record might suggest counteracting  
30     influences on shorter (about 5–6 y) and longer (about 11–12 y) time scales. The present  
31     analyses suggest that the influence of solar activities on the Indian temperature variability  
32     operates in part indirectly through coupling of ENSO on multilateral time scales. The analyses,  
33     hence, provide credible evidence for tele-connections of tropical pacific climatic variability and

34 Indian climate ranging from inter-annual-decadal time scales and also suggest the possible role  
35 of exogenic triggering in reorganizing the global earth-ocean-atmospheric systems.

36 **Key words:** *Geomagnetic activity, Western Himalayas, Sunspot Number, SOI index, Singular*  
37 *spectral analysis, Wavelet spectrum, Coherency.*

38

### 39 **1. Introduction:**

40 Several recent studies of solar/geomagnetic effects on climate have been examined on both  
41 global as well as on regional scales (Lean and Rind, 2008; Benestaed and Schmidt, 2009; Meehl,  
42 2009; Kiladis and Diaz 1989; Pant and Rupa Kumar 1997; Gray et al. 1992; Wiles et al. 1998; Friis  
43 and Svensmark 1997; Rigozo et al. 2005; Feng et al. 2003; Tiwari and srilakshmi 2009; Chowdary  
44 et al. 2006, 2014; Appenzeller et al. 1998; Proctor et al. 2002; Tsonis et al. 2005; Freitas and  
45 Mclean 2013). The Sun's long-term magnetic variability caused by the sunspots is considered as  
46 one of the primary drivers of climatic changes. The short-term magnetic variability is due to the  
47 disturbances in Earth's magnetic fields caused by the solar activities and is indicated by the  
48 geomagnetic indices. The Sun's magnetic variability modulates the magnetic and particulate  
49 fluxes in the heliosphere. This determines the interplanetary conditions and imposes significant  
50 electromagnetic forces and effects upon the planetary atmosphere. All these effects are due to  
51 the changing solar-magnetic fields, which are relevant for planetary climates including the  
52 climate of the Earth. The Sun-Earth relationship varies on different time scales ranging from  
53 days to years bringing a drastic influence on the climatic patterns. The ultimate cause of solar  
54 variability, at time scales from decadal to centennial to millennial or even longer scales has its  
55 origin in the solar dynamo mechanism. During the solar maxima, huge amounts of solar energy  
56 particles are released, thereby causing the geomagnetic disturbances. The 11 years solar cycle  
57 acts as an important driving force for variations in the space weather, ultimately giving rise to  
58 climatic changes. It is, therefore, imperative to understand the origin of space climate by  
59 analyzing the different proxies of solar magnetic variabilities. Another important phenomenon  
60 is El Nino-Southern Oscillation (ENSO), which associated with droughts, floods and intense  
61 rainfall in different parts of the world. The strong coupling and interactions between the  
62 Tropical Ocean and the atmosphere play a major role in the development of the global climatic

63 system. The El Nino events generally recur approximately every 3-5 years with large events  
64 spaced around 3-7 years apart. The ENSO phenomena have shown huge impact on the Asian  
65 monsoon (Cole et. al., 1993), Indian monsoon (Chowdary et al. 2006, 2014) as well as globally  
66 (Horel and Wallace 1981; Barnett 1989; Yasunari 1985; Nicholson 1997). In particular, the El  
67 Nino, solar, geomagnetic activities are the major affecting forces on the decadal and  
68 interdecadal temperature variability on global and regional scales in a direct/indirect way (El-  
69 Borie et al, 2010; Gray et al., 2010). Recent studies (Frohlich and Lean 2004; Steinhilber et al.  
70 2009) indicate the possible influence of solar activity on Earth's temperature/climate on multi-  
71 decadal time scales. The 11 year solar cyclic variations observed from the several temperature  
72 climate records also suggest the impact of solar irradiance variability on terrestrial temperature  
73 (Budyko 1969; Friis and Lassen 1991; Friis and Svensmark 1997; Kasatkina et al. 2007). The bi-  
74 decadal (22 years) called the Hale cycle, is related to the reversal of the solar magnetic field  
75 direction (Lean et al. 1995; Kasatkina et al. 2007). The 33 year cycle (Bruckener cycle) is also  
76 caused by the solar origin, but it is a very rare cycle (Kasatkina et al. 2007). The 2–7 years ENSO  
77 cyclic pattern and its possible coupling process is the major driving force for the temperature  
78 variability (Gray et al. 1992; Wiles et al. 1998; Mokhov et al. 2000; Rigozo et al. 2007, Kothawale  
79 et al. 2010). El-Borie and Al-Thoyaib, 2006; El-Borie et al., 2007 and El-Borie et al, 2010 have  
80 indicated in their studies that the global temperature should lag the geomagnetic activity with a  
81 maximum correlation when the temperature lags by 6 years. Mendoza et. al., 1991 reported on  
82 possible connections between solar activity and El Nino's, while Reid and Gage (1988) and Reid  
83 (1991) reported on the similarities between the 11-year running means of monthly sunspot  
84 numbers and global sea surface temperature. These findings suggest that there is a possibility  
85 of strong coupling between temperature-ENSO and solar-geomagnetic signals.

86 Several studies have been carried out to understand the climatic changes of India in the  
87 past millennium using various proxy records e.g. ice cores, lake sediments, glacier fluctuations,  
88 peat deposits etc. There is a lack of high-precision and high-resolution palaeo-climatic  
89 information for longer time scale from the Indian subcontinent. Tree-ring data is a promising  
90 proxy to retrieve high resolution past climatic changes from several geographical regions of  
91 India (Bhattacharyya et al. 1988; Bhattacharyya et al. 1992; Hughes, 1992; Bhattacharyya and

92 Yadav, 1996; Borgaonkar et al. 1996; Chaudhary et al. 1999; Yadav et al. 1999; Bhattacharyya  
93 and Chaudhary, 2003; Bhattacharyya et al. 2006; Shah et al. 2007) It has been noted that tree-  
94 ring based climatic reconstructions in India generally do not exceed beyond 400 years records  
95 except at some sites in the Northwest Himalaya. Thus, a long record of tree-ring data is needed  
96 to extend available climate reconstruction further back to determine climatic variability on sub-  
97 decadal, decadal and century scale. However, non-availability of older living trees in most of the  
98 sites is hindering the preparation of long tree chronology. In a previous study (Tiwari and  
99 Srilakshmi, 2009), we have studied the periodicities and non-stationary modes in the tree ring  
100 temperature data from the same region (AD 1200-2000). To reveal significant connections  
101 among the Solar-geomagnetic-ENSO 'triad' phenomena on tree ring width in detail for the  
102 period from 1876-2000, we have applied here the Singular spectral analysis (SSA) and the  
103 wavelet spectral analysis for Sunspot data, geomagnetic data (aa index), Troup Southern  
104 Oscillation Index (SOI) and the Western Himalayas tree ring data. Here our main objective is to  
105 employ wavelet-based analysis on SSA reconstructed time series to find out the evidence of the  
106 possible linkages, if any, among ENSO–solar-geomagnetic in the Indian temperature records.

107

## 108 **2. Source and Nature of Data:**

109 The data analyzed here includes the time series of (1) Smoothed Sunspot number for solar  
110 activity (2) Geomagnetic activity data (aa indices) (3) Troup Southern Oscillation Index (SOI) for  
111 the study of El Nino-Southern Oscillation called ENSO (4) Western Himalayan temperature  
112 variability record. All the data sets have been analyzed for the common period of 125 years  
113 spanning over 1876-2000. The monthly sunspot number data has been obtained from the  
114 Sunspot Index Data Center [http:// astro.oma.be/SIDC/](http://astro.oma.be/SIDC/). The Troup SOI data is obtained from the  
115 Bureau of Meteorology of Australia, <http://www.bom.gov.au/climate/>. The data for  
116 geomagnetic activity, aa Index, was provided by the National Geophysical Data Center, NGDC,  
117 (<http://www.ngdc.noaa.gov/stp/GEOMAG/aastar.shtml>). The aa index is a measure of  
118 disturbances level of Earth's magnetic field based on magnetometer observations at two, nearly  
119 antipodal, stations in Australia and England. In recent studies, the tree ring proxy climate  
120 indicators are being used for extracting information regarding past seasonal temperature or

121 precipitation/drought based on the measurements of annual ring width. The detailed  
122 description of the data has been presented elsewhere (Yadav et. al., 2004). A brief account of  
123 the data pertinent to the present analysis, however, is summarized here. The tree ring data  
124 being analyzed here is one of the best temperature variability records (1876 to 2000) of the  
125 pre-monsoon season in the Western Himalayas available. The mean temperature series is  
126 obtained from nine weather stations including both from high and low elevation areas in the  
127 Western Himalayas. Temperature variability history is based on widely spread pure Himalayan  
128 cedar (*Cedrus deodara* (Roxb.) G. Don) trees and characterizes all the sites with almost no  
129 ground vegetation and thereby minimizes individual variation in tree-ring sequences induced by  
130 inter tree competition (Yadav et. al., 2004). The mean chronological structure is based on in  
131 total 60 radii from 45 trees in total, statistical feature of which show that the chronology is  
132 suitable for dendro-climatic studies back to AD 1226 (Yadav et. al., 2004).

133

134 **3. Methods applied:** To analyze the temporal series and to find the climatic structure, we have  
135 here three methods: Principal component analysis (PCA), Singular Spectral analysis (SSA) and  
136 wavelet analysis.

137 **3.1. Principal component analysis (PCA):** As a preliminary analysis, we have applied the  
138 Principal component analysis (PCA) to the data sets for the reduction and extraction of  
139 dimensionality of the data and to rate the amount of variation present in the original data set.  
140 The purpose to apply the PCA is to identify patterns in the given time series. The new  
141 components thereby obtained by the PCA analysis are termed as PC1, PC2, PC3 and so on, (for  
142 the first, second and third principal components), and are uncorrelated. The different PCs  
143 capture part of the variance and are ranked depending on their corresponding percentage  
144 variance.

145

146 **3.2. Singular spectral analysis:** The Singular Spectrum Analysis (SSA) method is designed to  
147 extract as much information as possible from a short, noisy time series without any prior  
148 knowledge about the dynamics underlying the series (Broomhead and King, 1986; Vautard and  
149 Ghil, 1989; Alonso et. al., 2005; Golyandina et al., 2001). The method is a form of principal

150 component analysis (PCA) applied to lag-correlations structures of the time series. The basic  
 151 SSA decomposes an original time series into a new series which consists of trend, periodic or  
 152 quasi-periodic and white noises according to the singular value decomposition (SVD) and  
 153 provides the reconstructed components (RCs). The basic steps involved in SSA are:  
 154 decomposition (involves embedding, singular value decomposition (SVD)) and reconstruction  
 155 (involves grouping and diagonal averaging). Embedding decomposes the original time series  
 156 into the trajectory matrix; SVD turns the trajectory matrix into the decomposed trajectory  
 157 matrices. The reconstruction stage involves grouping to make subgroups of the decomposed  
 158 trajectory matrices and diagonal averaging to reconstruct the new time series from the  
 159 subgroups.

160 **Step1: Decomposition:**

161 **(a) Embedding:** The first step in the basic SSA algorithm is the embedding step where  
 162 the initial time series change into the trajectory matrix. Let the time series be  $Y = \{y_1, \dots, y_N\}$   
 163 of length  $N$  without any missing values. Here the window length  $L$  is chosen such that  $2 < L <$   
 164  $N/2$  to embed the initial time series. We map the time series  $Y$  into the  $L$  lagged vectors,  $Y_i =$   
 165  $\{y_i, \dots, y_{i+L-1}\}$  for  $i = 1, \dots, K$ , where  $K = N - L + 1$ . The trajectory matrix  $T_Y$  ( $L \times K$  dimensions) is

166 written as:  $T_Y = \begin{pmatrix} Y_1 \\ Y_2 \\ \cdot \\ \cdot \\ Y_K \end{pmatrix} \dots\dots\dots(1)$

167 **(b) Singular Value Decomposition (SVD):** Here we apply SVD to the trajectory matrix  $T_Y$   
 168 to decompose and obtain  $T_Y = UDV'$  called eigentriples; where  $U_i$  ( $K \times L$  dimensions;  $1 < i < L$ ) is an  
 169 orthonormal matrix;  $D_i$  ( $1 < i < L$ ) is a diagonal matrix of order  $L$ ;  $V_i$  ( $L \times L$  dimensions;  $1 < i < L$ ) is  
 170 a square orthonormal matrix.

171 The trajectory matrix is thus written as  $T_Y = \sum_{i=1}^d U_i \sqrt{\lambda_i} V_i^T$ ;  $\dots\dots\dots(2)$

172 where the  $i^{\text{th}}$  Eigen triple of  $T_i = U_i \times \sqrt{\lambda_i} \times V_i^T$ ,  $i = 1, 2, 3, \dots, d$  in which  $d = \max(i: \sqrt{\lambda_i} > 0)$ .

173 **Step 2: Reconstruction:**

174 **(c) Grouping:** Here the matrix  $T_i$  is decomposed into subgroups according to the trend,  
 175 periodic or quasi-periodic components and white noises. The grouping step of the  
 176 reconstruction stage corresponds to the splitting of the elementary matrices  $T_i$  into several  
 177 groups and summing the matrices within each group. Let  $I = \{i_1, i_2, \dots, i_p\}$  be the group of indices  
 178  $i_1, \dots, i_p$ . Then the matrix  $T_I$  corresponding to the group  $I$  is defines as  $T_I = T_{i_1} + T_{i_2} + \dots + T_{i_p}$ . The split of  
 179 the set of indices  $J=1, 2, \dots, d$  into the disjoint subsets  $I_1, I_2, \dots, I_m$  corresponds to the equation  
 180 (3):

$$T = T_{I_1} + T_{I_2} + \dots + T_{I_m}. \quad \dots\dots\dots(3)$$

182 The sets  $I_1, \dots, I_m$  are called the eigen triple grouping.

183 **(d) Diagonal averaging:** The diagonal averaging transfers each matrix  $T$  into a time  
 184 series, which is an additive component of the initial time series  $Y$ . If  $z_{ij}$  stands for a element  
 185 matrix  $Z$ , the  $k$ th term of the resulting series is obtained by averaging  $z_{ij}$  over all  $i, j$  such that  
 186  $i+j=k+2$ . This is called diagonal averaging or the Hankelization of the matrix  $Z$ . The Hankel matrix  
 187  $HZ$ , is the trajectory matrix corresponding to the series obtained by the result of diagonal  
 188 averaging.

189 Considering equation (3), let  $X$  ( $L \times K$ ) matrix with elements  $x_{ij}$ , where  $1 \leq i \leq L, 1 \leq j \leq K$ .  
 190 Here diagonal averaging transforms matrix  $X$  to a series  $g_0, \dots, g_{T-1}$  using the formula:

$$g_k = \begin{cases} \frac{1}{k+1} \sum_{m=1}^{k+1} x_{m, k-m+2}^* & 0 \leq k < L^* - 1 \\ \frac{1}{L^*} \sum_{m=1}^{L^*} x_{m, k-m+2}^* & L^* - 1 \leq k < K^* \\ \frac{1}{T-k} \sum_{m=k-k^*+2}^{N-k+1} x_{m, k-m+2}^* & K^* - 1 \leq k < T \end{cases} \quad (4)$$

192 This diagonal averaging by equation (4) applied to the resultant matrix  $X_{I_n}$ , produces time series  
 193  $Y_n$  of length  $T$ . For such signal characteristics, it is essential to examine the time-frequency  
 194 pattern as to understand whether a particular frequency is temporally consistent or  
 195 inconsistent. Hence for non-stationary signals, we need a transform that will be useful to obtain  
 196 the frequency content of the time series/signal as a function of time.

197 An alternative method for studying the non-stationarity of the time series is wavelet  
 198 transform. For non-stationary signals, wavelets decomposition would be the most appropriate

199 method because the analyzing functions (the wavelets function) are localized both in time and  
200 frequency.

201  
202 **3.3. Wavelet spectral analysis:** During the past decades, wavelet analysis has become a popular  
203 method for the analysis of aperiodic and quasi-periodic data (Grinsted et. al., 2004; Jevrejeva  
204 et. al., 2003; Torrence and Compo, 1998; Torrence and Webster, 1999). In particular, it has  
205 become an important tool for studying localized variations of power within a time series. By  
206 decomposing a time series into time-frequency space, the dominant modes of variability and  
207 their variation with respect to time can be identified. The wavelet transform has various  
208 applications in geophysics, including tropical convection (Weng and Lau 1994), the El Niño–  
209 Southern Oscillation (Gu and Philander 1995), etc. We have applied the wavelet analysis to  
210 analyze the non-stationary signals which permits the identification of main periodicities of  
211 ENSO-sunspot-geomagnetic in the time series. The results give us more insight information  
212 about the evolution of these variables in frequency-time mode.

213 A wavelet transform requires the choice of analyzing function  $\Psi$  (called “mother  
214 wavelet”) that has the specific property of time-frequency localization. The continuous wavelet  
215 transform revolves around decomposing the time series into scaling components for identifying  
216 oscillations occurring at fast (time) scale and other at slow scales. Mathematically, the  
217 continuous wavelets transform of a time series  $f(t)$  can be given as:

218 
$$W_{\psi}(f)(a, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} f(t) \psi\left(\frac{t-b}{a}\right) dt \dots\dots\dots(5)$$

219 Here  $f(t)$  represents time series,  $\Psi$  is the base wavelets function (here we have chosen the  
220 Morlet function), with length that is much shorter than the time series  $f(t)$ .  $W$  stands for  
221 wavelet coefficients. The variable ‘ $a$ ’ is called the scaling parameter that determines the  
222 frequency (or scale) so that varying ‘ $a$ ’ gives rise to wavelet spectrum. The factor ‘ $b$ ’ is related to  
223 the shift of the analysis window in time so that varying  $b$  represents the sliding method of the  
224 wavelet over  $f(t)$ .

225 In several recent analyses, complex Morlet wavelet has been found useful for  
226 geophysical time series analysis. The Morlet is mostly used to find out areas where there is high



227 amplitude at certain frequencies. The complex Morlet wavelet can be represented by a periodic  
 228 sinusoidal function with a Gaussian envelope and is excellent for Morlet wavelet may be  
 229 defined mathematically, as follows:

$$230 \quad \psi(t) = \pi^{-1/4} e^{-i\omega_0 t} e^{-t^2/2} \dots\dots\dots(6)$$

231 where  $\omega_0$  is a non-dimensional value.  $\omega_0$  is chosen to be 5 to make the highest and lowest  
 232 values of  $\psi$  approximately equal to 0.5, thus making the admissibility condition satisfied. The  
 233 complex valued Morlet transform enables to extract information about the amplitude and  
 234 phase of the signal to be analyzed. Wavelet transform preserves the self-similarity scaling  
 235 property, which is the inherent characteristic feature of deterministic chaos. The continuous  
 236 wavelet transform has edge artifacts because the wavelet is completely localized in time. The  
 237 cone of influence (COI) is the area in which the wavelet power caused by a discontinuity at the  
 238 edge has dropped to  $e^{-2}$  of the value to the edge. The statistical significance of the wavelet  
 239 power can be assessed relative to the null hypotheses that the signal is generated by a  
 240 stationary process with a given background power spectrum ( $P_k$ ) of first order autoregressive  
 241 (AR1) process. (Grinsted et. al., 2004)

$$242 \quad P_k = \frac{1 - \alpha^2}{|1 - \alpha e^{-2i\pi k}|^2} \dots\dots\dots(7)$$

243 where k is Fourier frequency index.

244 The cross wavelet transform is applied to two time series to identify the similar patterns  
 245 which are difficult to assess from a continuous wavelet map. Cross wavelet power reveals areas  
 246 with high common power. The cross wavelet of two time series x (t) and y (t) is defined as  $W^{XY} =$   
 247  $W^X W^{Y*}$ , where \* denotes complex conjugate. The cross wavelet power of two time series with  
 248 background power spectra  $P_k^X$  and  $P_k^Y$  is given as

$$249 \quad D \left( \frac{|W_n^X(s) W_n^{Y*}(s)|}{\sigma_X \sigma_Y} < p \right) = \frac{Z_v(p)}{v} \sqrt{P_k^X P_k^Y}, \dots\dots\dots(8)$$

250 where  $Z_v(p)$  is the confidence level associated with the probability  $p$  for a pdf defined by the  
 251 square root of the product of the two  $\chi^2$  distributions (Torrence and Compo, 1998). The  
 252 wavelet power is  $|W_n^X(s)|^2$  and the complex argument of  $|W_n^X(s)|$  can be interpreted as the local  
 253 phase. The cross wavelet analysis gives the correlation between the two time series as function  
 254 of period of the signal and its time evolution with a 95% confidence level contour. The  
 255 statistical significance is estimated using red noise model.

256 Wavelet coherence is another important measure to assess how coherent the cross  
 257 wavelet spectrum transform is in time frequency space. The wavelet coherence of two time  
 258 series is defined as (Torrence and Webster, 1998)

$$259 \quad R_n^2(s) = \frac{|S(s^{-1} W_n^{XY}(s))|^2}{S(s^{-1} |W_n^X(s)|^2) \cdot S(s^{-1} |W_n^Y(s)|^2)} \dots\dots\dots(9)$$

260 where,  $S$  is a smoothing operator. The smoothing operator is written as  $S(W) = S_{scale}(S_{time}$   
 261  $(W_n(s)))$ , where  $S_{scale}$  denotes smoothing along the wavelet scale axis and  $S_{time}$  smoothing in  
 262 time. Here for the morelet wavelet, the smoothing operator is

$$263 \quad S_{time}(W)|_s = \left( W_n(s) * c_1 \frac{-t^2}{2s^2} \right) \dots\dots\dots(10)$$

$$264 \quad S_{time}(W)|_s = (W_n(s) * c_2 \Pi(0.6s))_n | \dots\dots\dots(11)$$

265 Where  $c_1$  and  $c_2$  are normalization constants and  $n$  is the rectangle function. The factor of 0.6 is  
 266 empirically determined scale decorrelation length of the Morlet wavelet (Torrence and Compo,  
 267 1998). The statistical significance level of the wavelet coherence is estimated using the Monte  
 268 Carlo methods (Grinsted et. al., 2004).

269  
 270 **4. Results and Discussion:**

271 We analyzed the data sets spanning over the period of 1876-2000 using the PCA, SSA and  
 272 wavelet spectral analyses. Figure 1 shows four time series: (1) Smoothed Sunspot number  
 273 representing solar activities; (2) Geomagnetic (aa indices); (3) Troup Southern Oscillation Index  
 274 (SOI) for the study of ENSO and (4) Western Himalayan temperature variability record that are

275 analyzed in the present work. From visual inspection it is apparent from Fig. 1 that both WH  
276 and SOI data show irregular and random pattern, while sunspot numbers have quasi- cyclic  
277 character. Further WH tree ring record also exhibits distinct temperature variability but  
278 nonstationary behavior at different scales. This variability might be suggestive of coupled global  
279 ocean-atmospheric dynamics or some other factors, such as deforestation, anthropogenic, high  
280 latitudinal influence etc (Yadav et. al., 2004).

281 **(Figure 1)**

282 Hence it is quite difficult to differentiate such a complex climate signals visually and difficult to  
283 infer any clear oscillation without the help of powerful mathematical methods. For  
284 identification of any oscillatory components and understanding the climatic variations on  
285 regional and global scale, we have applied the PCA, SSA and wavelet analysis. Figure 2 shows  
286 the principal components (PCs) for the first four eigen triples (PC1, PC2, PC3, PC4) for the given  
287 data sets. Figure 3 shows the power spectra of the principal components (PCs) for the four data  
288 sets shown in figure 2. From the figure 3, it is observed that the power spectra of PC1-4 for the  
289 sunspot data exhibits high power at 124, 11, 4-2.8 years. The presence of high solar signal at  
290 124 years indicates the quasi-stable oscillatory components in the data. The power spectra of  
291 geomagnetic data also shows the presence of strong signals at 124, 10-11, 4-2 years suggesting  
292 a strong link of solar-geomagnetic activity. The power spectra of WH temperature data shows  
293 strong high power at ~62 years, 32-35 years, 11 years, 5 years and 2-3 years suggesting strong  
294 combined influence of global ocean-atmospheric circulation, solar-geomagnetic and ENSO  
295 effects on the Indian climate system. Climate cycles of 50-70 years have been widely reported  
296 in various ocean and atmospheric phenomena (Ogurtsov, et al. 2002, Tiwari, 2005). Schiesinger  
297 and Ramankutt (1994), Minobe (1997) have reported similar 55-70 year inter decadal  
298 oscillations in global mean temperature. Dominant amplitudes corresponding to 62 and 32-35  
299 years periodicities may, therefore, be linked to the Atlantic Multi-decadal Oscillation (AMO) of  
300 ocean -atmospheric circulations. The 11-year peak is well known solar signal while the 2-5 year  
301 periods apparently falls in ENSO frequency band. These results could be better confirmed by  
302 applying the mathematical tools of SSA and wavelet analyses.

303 **(Figure 2 & 3)**

304 To explore the stationary characteristics of these peaks obtained by the PCA, we have applied  
305 the Morlet based wavelet transform approach (Holschneider, 1995; Foufoula-Georgiou and  
306 Kumar, 1995; Torrence and Compo, 1998; Grinsted et. al., 2004). The wavelet spectrum  
307 identifies the main periodicities in the time series and helps to analyze the periodicities with  
308 respect to time. Figure 4 shows the wavelet spectrum for the a) Smoothed Sunspot number for  
309 solar activity (SSN) (b) Western Himalayan (WH) temperature variability record (c) Geomagnetic  
310 activity and (c) Troup Southern Oscillation Index (SOI). From the wavelet spectrum of sunspot  
311 time series (Figure 4a), the signal near 11-year is the strongest feature and is persistent during  
312 the entire series indicating the non-stationary behavior of the sunspot time series. The wavelet  
313 spectrum of SOI (figure 4c) shows strong amplitudes. However, due to non-stationary (time  
314 variant) character of the time series, the observed spectral peaks (power) split in the interval of  
315 2- 8 years. The wavelet power spectrum of the western Himalayan temperature variability  
316 (Figure 4b) reveals significant power concentration at inter-annual time scales of 3-5 years and  
317 at 11 years solar cycle. A dominant amplitude modes is also seen in the low frequency range at  
318 around 35-40 years (at periods 1930-1980) corresponding to AMO cycles. Our result agrees well  
319 with the results of other climate reconstructions (Mann et. al., 1995) from tree rings and other  
320 proxies. The observed variability in AMO periodicity has also been reported in other tree ring  
321 record (Gray et. al., 2004). The statistical significance of the wavelet power spectrum is tested  
322 by a Monte Carlo method (Torrence and Compo, 1998). The WH spectra depicting statistically  
323 significant powers above the 95% significance level at around 5 years, 11 years and 33 years  
324 suggests possible imprint of sunspot-geomagnetic and ENSO phenomena on the tree ring data.  
325 On shorter time scales, the wavelet power spectrum of the geomagnetic record (Fig. 4d) also  
326 reveals statistically significant power at around 2, 4-8, 11 years period.

#### 327 **(Figure 4)**

328 In order to have better visualization of similar periods in two time series and for the  
329 interpretation of the results, cross wavelet spectrum has been applied. Figure 5 shows the cross  
330 wavelet spectrum of the a) SSN-WH temperature data b) WH data-SOI and c) SSN-SOI data. The  
331 contours (dark black lines) are the enclosing regions where wavelet cross power is significantly  
332 higher, at 95% confidence levels. The wavelet cross-spectra of WH-SSN (Fig.5a) show

333 statistically significant high power over a period of 1895-1985 in 8-16 years band. It is seen that  
334 the WH-SOI cross-spectra (Fig. 5b), the high power is observed at 2–4 year band and 8–16 years  
335 as well. The SSN-SOI spectra (Fig. 5c) shows a strong correlation at 11 years solar cycle, which is  
336 stronger during 1910-1950 and 1960-2000 (Rigozo et. al., 2002, Rigozo et. al., 2003) suggesting  
337 the strongest El Nino and La Nina events indicating solar modulation on ENSO (Kodera, 2005;  
338 Kryjov and Park, 2007). These results show a good correspondence in response of growth of the  
339 tree ring time series during the intense solar activity. Hence the results strongly support the  
340 possible origin of these periodicities from Solar and ENSO events. The interesting conclusion  
341 from Fig. 5 is that WH–sunspot connections are strong at 11 years, ENSO–sunspot also exhibit  
342 strong power around 11 years; the WH–ENSO connections are spread over three bands, the 2–4  
343 y; 4–8 and 8–16 y, covering the solar cycle and its harmonics; the WH-geomagnetic exhibits  
344 strong connections around 2-4, 4-6, 11 years and 35-40 years indicating the influence of solar-  
345 geomagnetic activity on Indian temperature.

#### 346 (Figure 5)

347  
348 The Singular spectral analysis (SSA) is performed for all the four data sets with window length of  
349 40. The SSA spectra with 40 singular values and its corresponding reconstructed series (varying  
350 from RC1-15 in some cases) are plotted are shown in Figure 6 &7. The important insights from  
351 SSA spectra are the identification of gaps in the eigen value spectra. As a rule, the pure noise  
352 series produces a slowly decreasing sequence of singular values. The explicit plateau in the  
353 spectra represents the ordinal numbers of paired eigen triples. The eigen triples 2-3 for the  
354 sunspot data corresponds to 11 years period; eigen triples for 1-2,3-5,6-10,11-14 for the WH  
355 temperature data are related to harmonic with specific periods (periods 33-35y, 11y, 5y, 2y);  
356 eigen triples for 2-5,6-9,10-13 for the geomagnetic data are related to periods 11, 5,2 years.  
357 The eigen triples for the SOI data represents to ~ 5-7, 2 years periods. In order to assess  
358 periodicities, the periodogram and the wavelet power spectra are plotted using the SSA  
359 reconstructed data (SSA-RC) (Figure 8). From the figure 8, the periodogram of SSA-RC of SSN  
360 and Geomagnetic data shows strong power at ~120, 10-11 years; the SOI data shows strong  
361 peaks at 6-9, 3, years & WH data shows strong power at ~32, ~10-11, 3-5 years. The wavelet

362 spectra for all the SSA-RC data confirms the results excepts for the periods at ~120 years, which  
363 is beyond the maximum scaling period chosen for the present wavelet. The coherency plot of  
364 the SSA-RC data sets (Figure 9) indicates a significant power at 33 years, 11 years, 2-7 years in  
365 the WH temperature record suggesting the possible influences of Sunspot-geomagnetic activity  
366 and ENSO through tele-connection and hence significant role of these remote internal  
367 oscillations of the atmosphere-ocean system on the Indian climate system. Researchers have  
368 attributed these phenomena to internal ocean dynamics and involve ocean atmospheric  
369 coupling as well as variability in the strength of thermohaline circulations (Knight et. al., 2005;  
370 Delworth and Mann, 2000).

371 **(Figures 6, 7, 8 & 9)**

372 In general our result agrees well with earlier findings in the sense that statistically  
373 significant global cycles of coupled effects of Sunspot/geomagnetic and ENSO are present in the  
374 land based temperature variability record. However, there are certain striking features in the  
375 spectra that need to be emphasized regarding the western Himalayas temperature variability: i)  
376 Inter-annual cycles in period range of 3-8 years corresponding to ENSO in the wavelet spectra  
377 exhibit intermittent oscillatory characteristics throughout the large portion of the record (Fig 4);  
378 ii) The 11 years solar cycle in the cross wavelet spectrum of SSN and SOI (Figure 5) indicate the  
379 solar modulation in the ENSO phenomena (Kodera, 2005; Kryjov and Park, 2007). iii) The high  
380 amplitude at 11 years in the time intervals 1900-1995 with a strong intensity from 1900-1995  
381 shows a good correspondence with the high temperature variability for the interval of high  
382 solar-geomagnetic activity. The Multi-decadal (30-40 years) periodicity identified here in  
383 Western Himalayan tree ring temperature record matches with North Atlantic sea surface  
384 temperature variability implying that the temperature variability in the western Himalayan is  
385 not a regional phenomenon, but a globally tele-connected climate phenomena associated with  
386 the global ocean-atmospheric dynamics system (Tiwari & srilakshmi, 2009; Delworth et. al.,  
387 1993; Stocker, 1994). The coupled ocean-atmosphere system appears to transport energy from  
388 the hot equatorial regions towards Himalayan territory in a cyclic manner. These results may  
389 provide constraints for modeling of climatic variability over the Indian region and ENSO  
390 phenomena associated with the redistribution of temperature variability. The solar-

391 geomagnetic effects play a major role in abnormal heating of the land surface thereby indirectly  
392 affects the atmospheric temperature gradient between the land-ocean coupled systems. In the  
393 present work, the connections between solar/geomagnetic activity and ENSO on the WH time  
394 series are found to be statistically significant, especially when they are studied over contrasting  
395 epochs of respectively high and low solar activity. The correlation plots for the SSA-RC data sets  
396 of WH-sunspot, WH-aa index, WH-SOI and Sunspot-aa index are plotted in figure 10. It is  
397 noticed that there is a correlation plots for the Geomagnetic-sunspot activity has a maximum  
398 correlation value at 1 year lag suggesting the strong influence of sunspot & geomagnetic forcing  
399 on one another. The cross-correlation plot for the WH data and the SOI represents a maximum  
400 value at zero lag. The correlations plot for WH-sunspot & WH-geomagnetic index exhibits  
401 almost the identical results suggesting the possible impact of solar activities on the Indian  
402 temperature variability.

### 403 (Figures 10)

404 The net effect of solar activity on temperature record therefore appears to be the result  
405 of cooperating or counteracting influences of earth's magnetic activity on the shorter and  
406 longer periods, depending on the indices used; scale-interactions, therefore, appear to be  
407 important. Nevertheless, the link between Indian climate and solar/geomagnetic activity  
408 emerges as having the strong evidence; next is the ENSO-solar activity connection.

409

### 410 **5. Conclusions:**

411 In the present paper, we have studied and identified the periodic patterns from the published  
412 Indian temperature variability records using the modern spectral methods of Singular spectral  
413 analysis (SSA)-Wavelet methods. The application of wavelet analysis for the SSA reconstructed  
414 time series, along with the removal of noise in the data identifies the existence of a high-  
415 amplitude, recurrent, multi-decadal scale patterns that are present in Indian temperature  
416 records. The power spectra of WH temperature data shows strong high power at ~62 years, 32-  
417 35 years, 11 years, 5 years and 2-3 years suggesting a strong influence of solar-geomagnetic-  
418 ENSO effects on the Indian climate system. The presence of dominant amplitude at 33-year  
419 cycle periodicity corresponds to Atlantic Multidecadal Oscillation (AMO) cycles. It also suggests

420 the Sun-temperature variability probably involving the induced changes in the basic state of the  
421 atmosphere. The 30-40 yrs periodicity in Western Himalayan tree ring temperature record  
422 matches with the global signal of the coupled ocean-atmospheric oscillation (Delworth et. al.,  
423 1993; Stocker, 1994) implying that the temperature variability in Himalayan is not a regional  
424 phenomenon, but seems to be tele-connected phenomena with the global ocean-atmospheric  
425 climate system. The coherency plots of the SSA reconstructed WH-Sunspot; WH-geomagnetic  
426 and WH-SOI data sets show strong spectral signatures in the whole record confirming the  
427 possible influences of Sunspot-geomagnetic activities and ENSO through teleconnection and  
428 hence the significant role of these remote internal oscillations of the atmosphere-ocean system  
429 on the Indian temperatures. We conclude that the signature of solar-geomagnetic activity  
430 affects the surface air temperatures of Indian subcontinent. However, long data sets from the  
431 different sites on the Indian continent are necessary to identify the influences of the 120 years  
432 solar-geomagnetic cycles.

433

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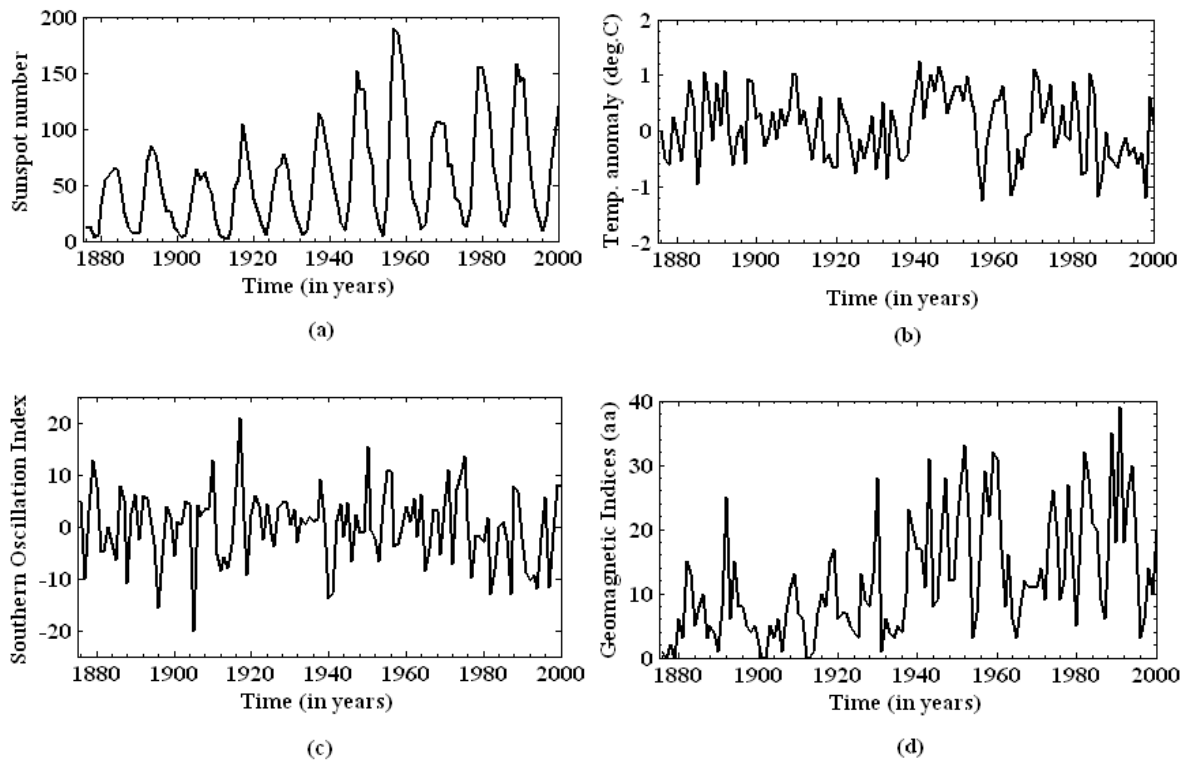
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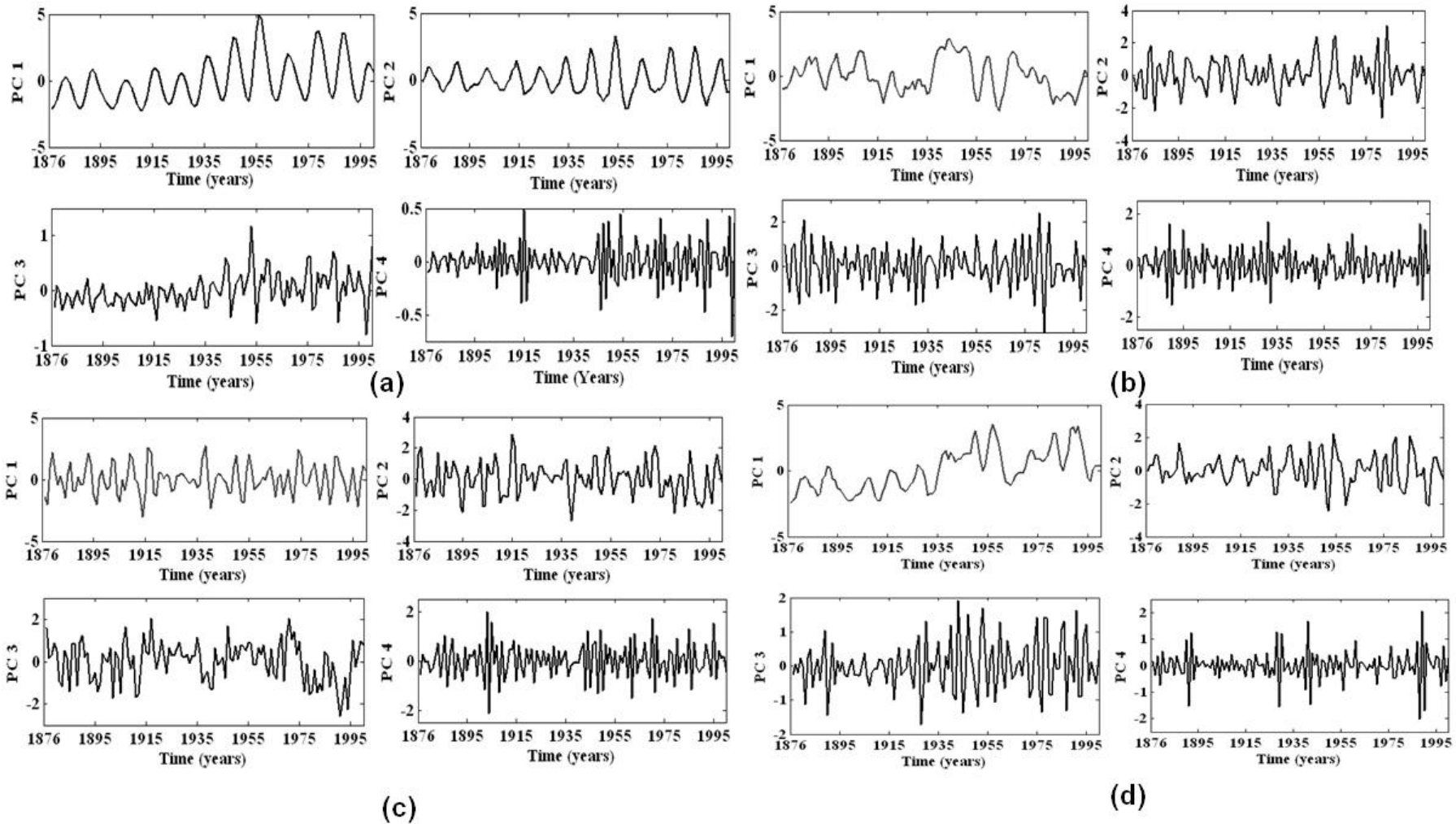
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635 **Figure 1. Time series data of (a) Sunspot Index (b) the mean pre-monsoon temperature**  
 636 **anomalies of the Western Himalayas (Yadav et. al., 2004) (c) Southern Oscillation Index**  
 637 **(SOI) and (d) Geomagnetic Indices (aa indices) for common period 1876-2000.**

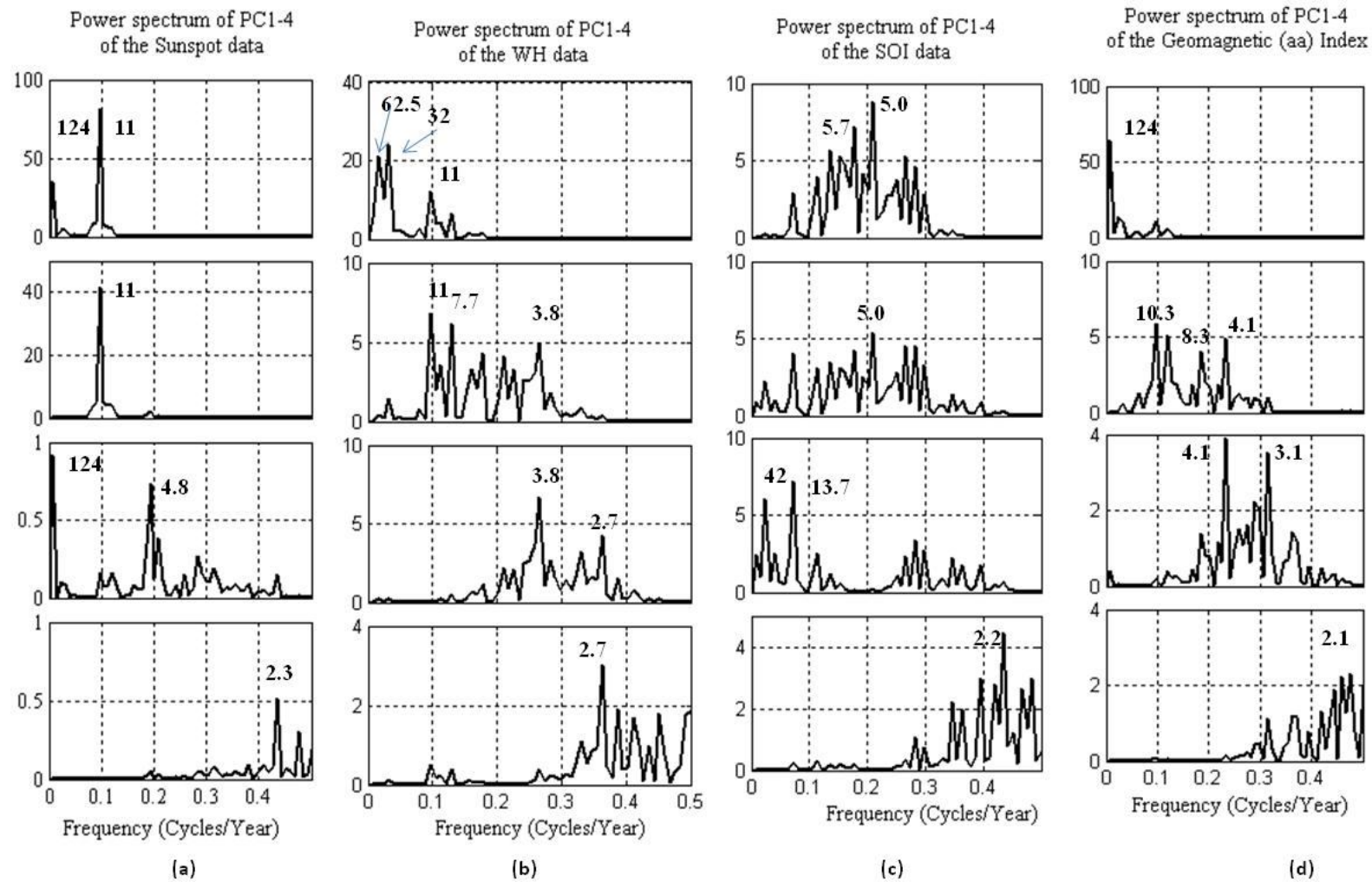
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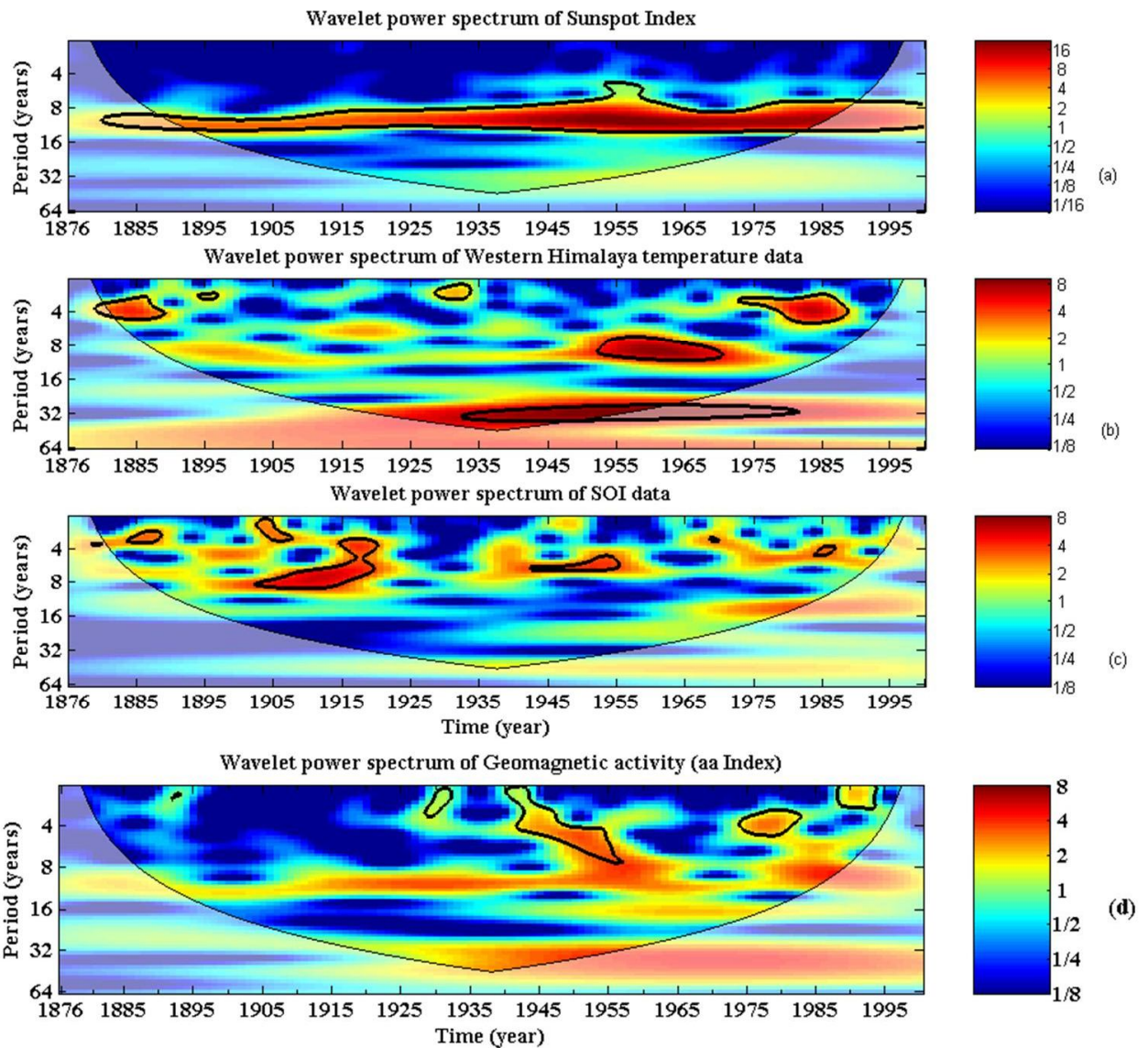


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 641 **Figure 2. First four principal components (PCs:1-4) for time series (a) Sunspot numbers (b) the mean pre-monsoon temperature anomalies**  
 642 **of the Western Himalayas (c) SOI index and (d) Geomagnetic Indices (aa indices) for the period 1876-2000.**



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644 Figure 3. Power spectra of the first four principal component (PCs) (PC1-4 shown in Fig. 2) for all the data sets with their significant  
 645 periodicities at 124, 11, 4 and 2.8 years are indicated in bold letters.

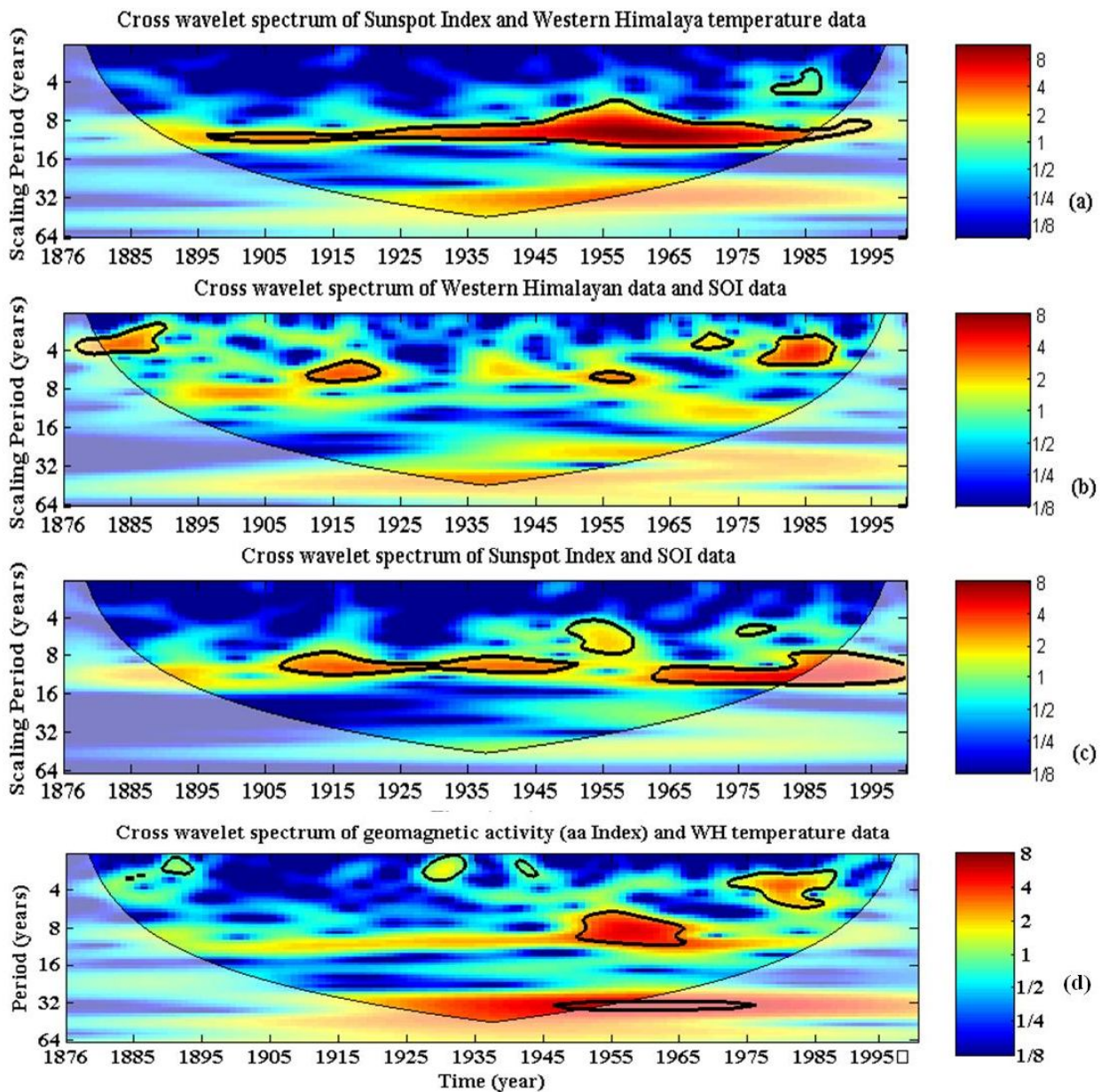


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647 **Figure 4. Wavelet power spectrum of (a) Sunspot Number (b) Western Himalaya temperature**  
 648 **data (c) Southern Oscillation Index (SOI) and (d) Geomagnetic activity (aa Indices) with cone**  
 649 **of influence (lighter shade smooth curve) and black lines indicate significant power on 95%**  
 650 **level compared to red noise based on first order auto-regressive (AR(1)) coefficient. The**  
 651 **legend on right indicates the cross-wavelet power.**

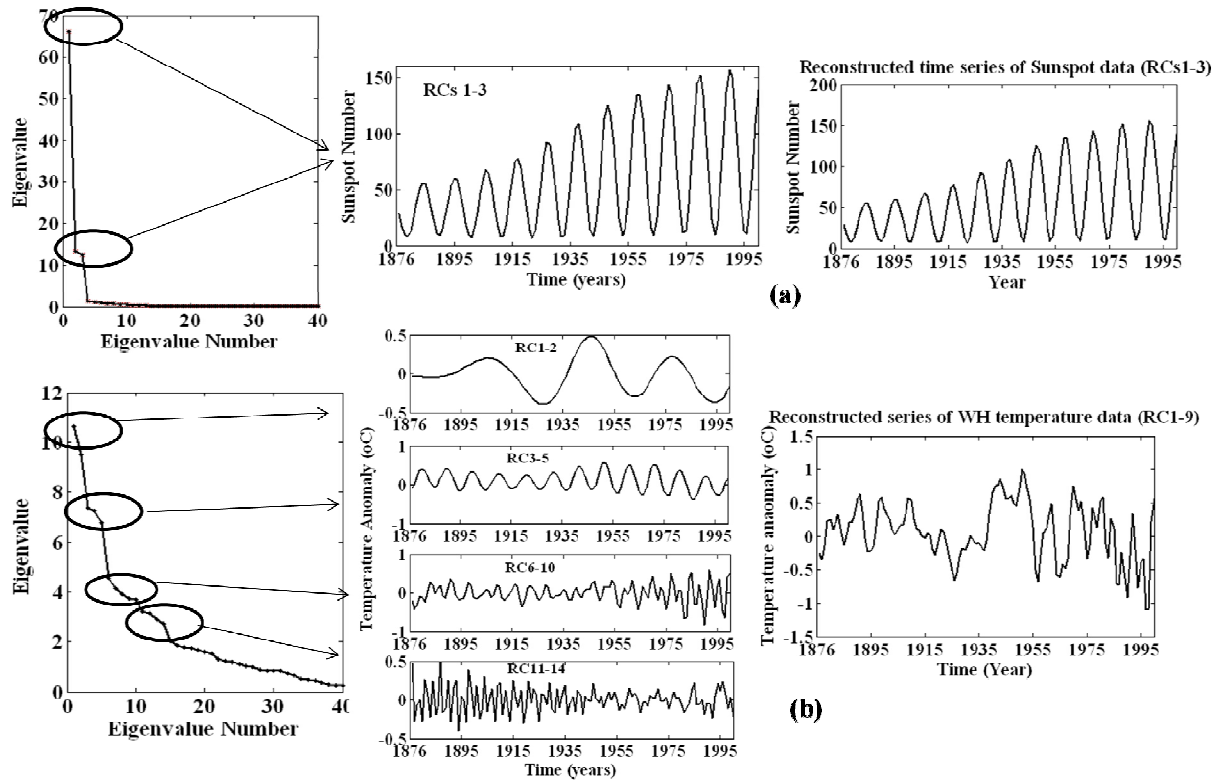
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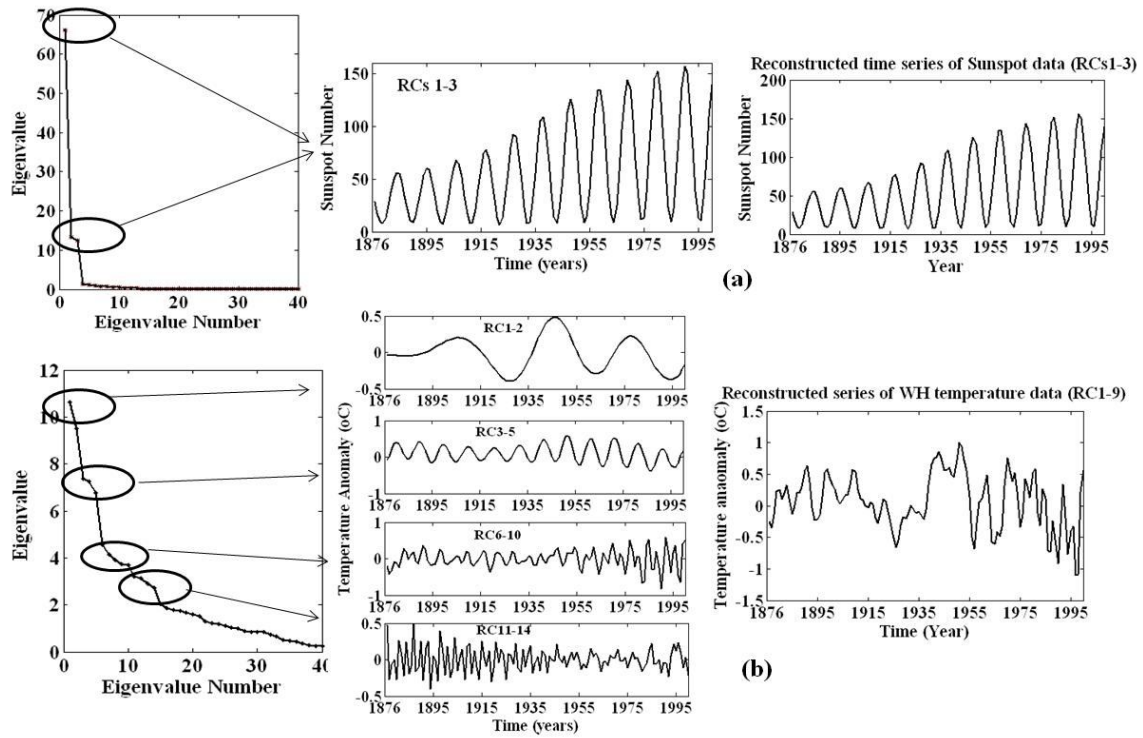
655 **Figure 5. Cross Wavelet spectrum between (a) Sunspot number-Western Himalayan data**  
 656 **(b) Western Himalayan-Southern Oscillation Index (c) Sunspot number- Southern**  
 657 **Oscillation Index and (d) Geomagnetic: aa indices-Western Himalayan data with cone of**  
 658 **influence (lighter shade smooth curve) and black lines indicate significant power on 95%**  
 659 **level compared to red noise based on AR(1) coefficient. The legend on right indicates the**  
 660 **cross-wavelet power.**



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662 **Figure 6. Singular spectra with its SSA decomposed components & its reconstructed time**  
 663 **series for (a) Sunspot Number and (b) Western Himalaya temperature data.**

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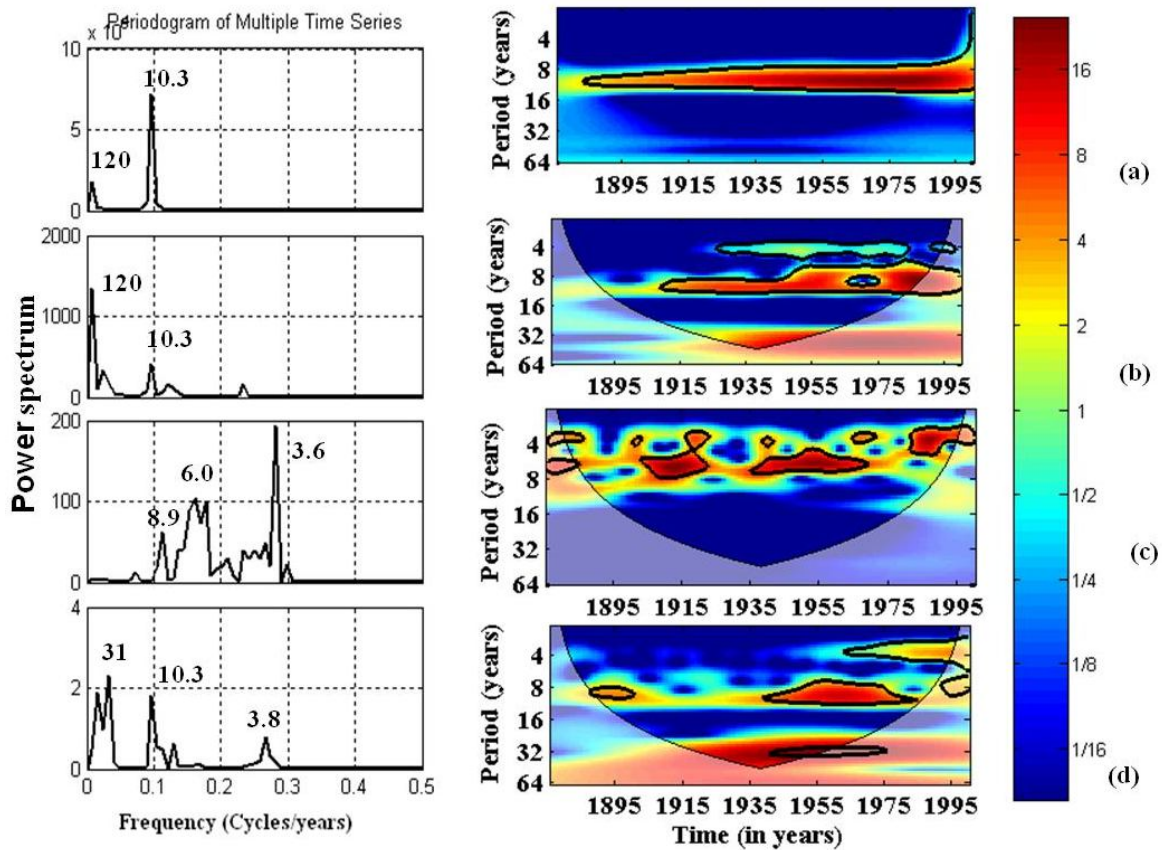


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**Figure 7. Singular spectra with its SSA decomposed components & its reconstructed time series for (c) SOI and (d) Geomagnetic activity (aa Indices).**



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669 **Figure 8. Power spectrum and Wavelet power spectrum of SSA reconstructed (a) Sunspot**  
 670 **data (b) Geomagnetic Indices (aa index) (c) SOI index and (d) the Western Himalayas**  
 671 **temperature data with cone of influence (lighter shade smooth curve) and black lines indicate**  
 672 **significant power on 95% level compared to red noise based on AR(1) coefficient. The legend**  
 673 **on right indicates the cross-wavelet power.**

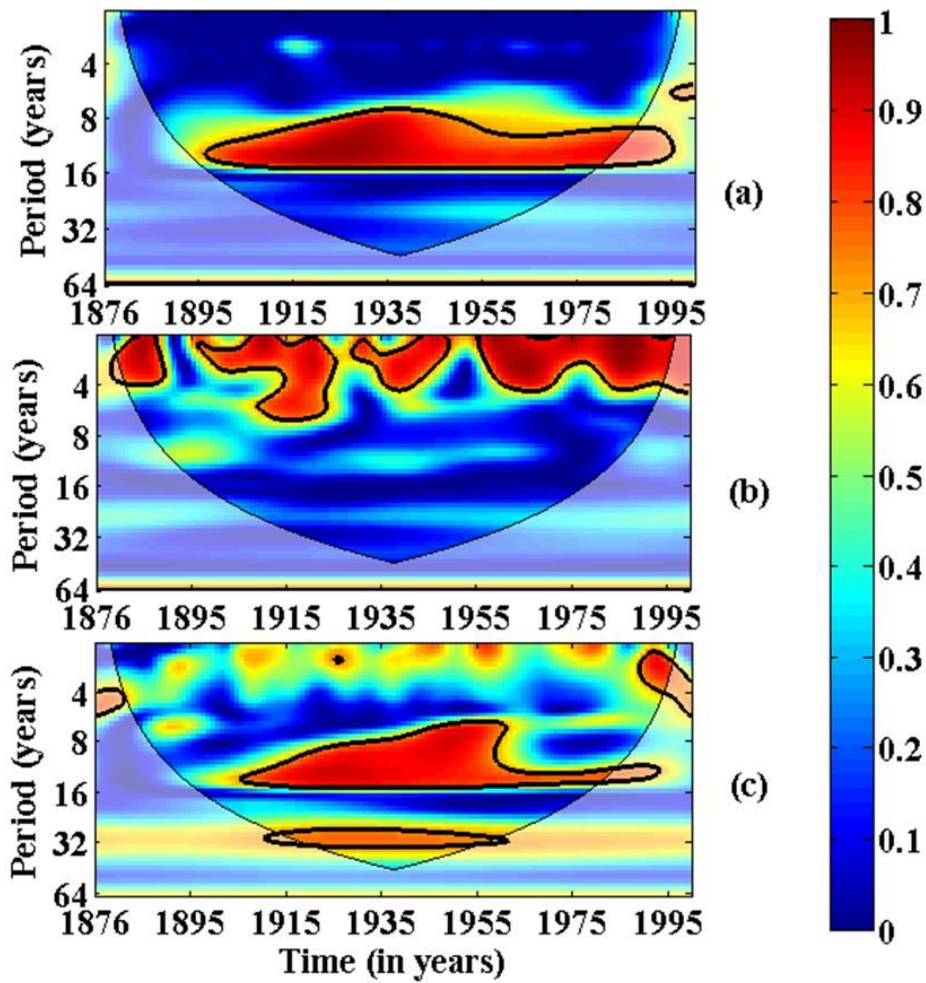
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680 **Figure 9. Squared wavelet coherence plotted for the SSA reconstructed time series between**  
 681 **(a) WH-SSN (b) WH-SOI and (c) WH-aa index with cone of influence (lighter shade smooth**  
 682 **curve) and black lines indicate significant power on 95% level compared to red noise based on**  
 683 **AR(1) coefficient.**

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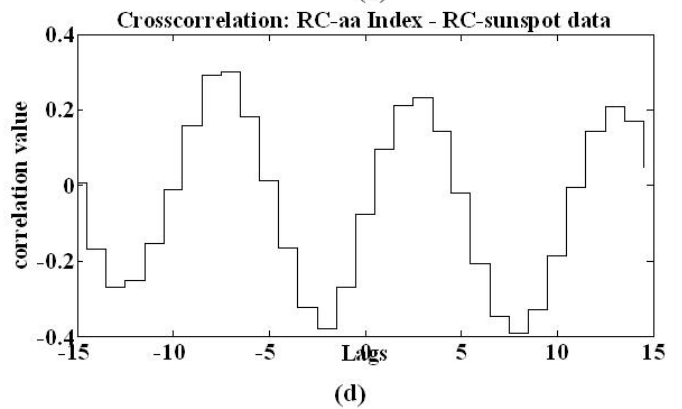
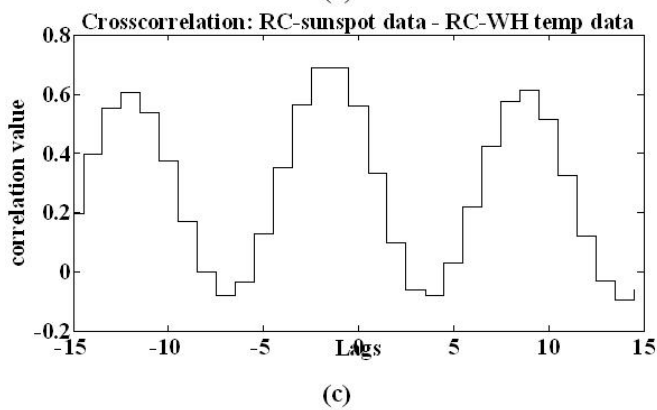
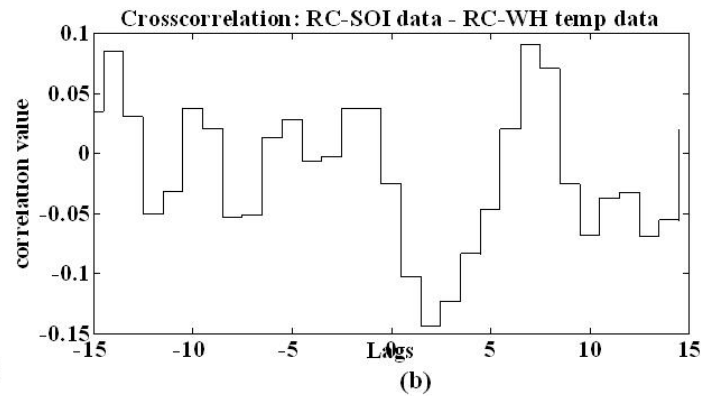
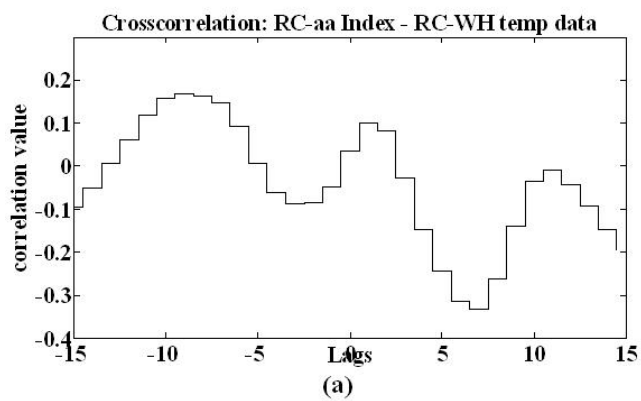
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690 **Figure 10. Cross-correlation of SSA reconstructed time series of (a) aa Index-Western**  
 691 **Himalayan (WH) temperature data; (b) SOI-WH temperature data; (c) sunspot -WH data and**  
 692 **(d) aa Index-sunspot data.**

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