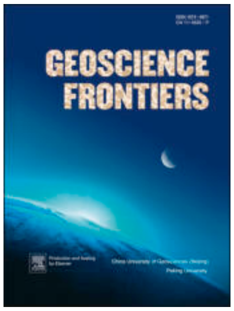

Climatic periodicities recorded in lake sediment magnetic susceptibility data: further evidence for solar forcing on the Indian summer monsoon

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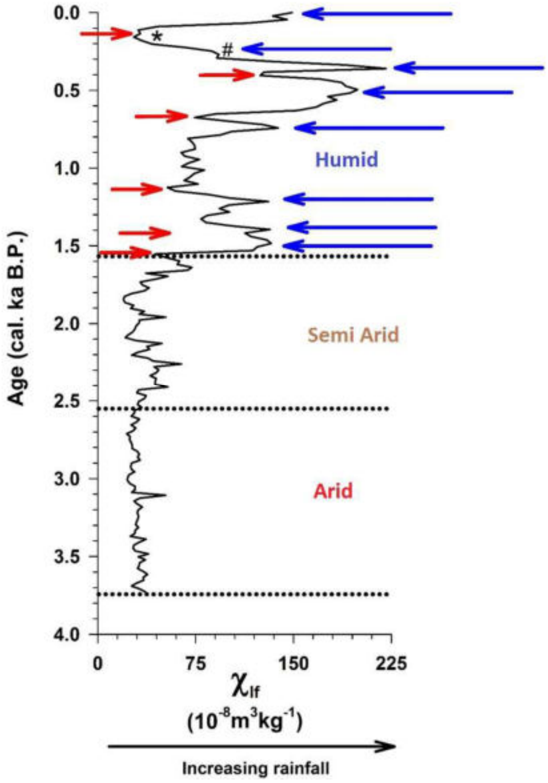
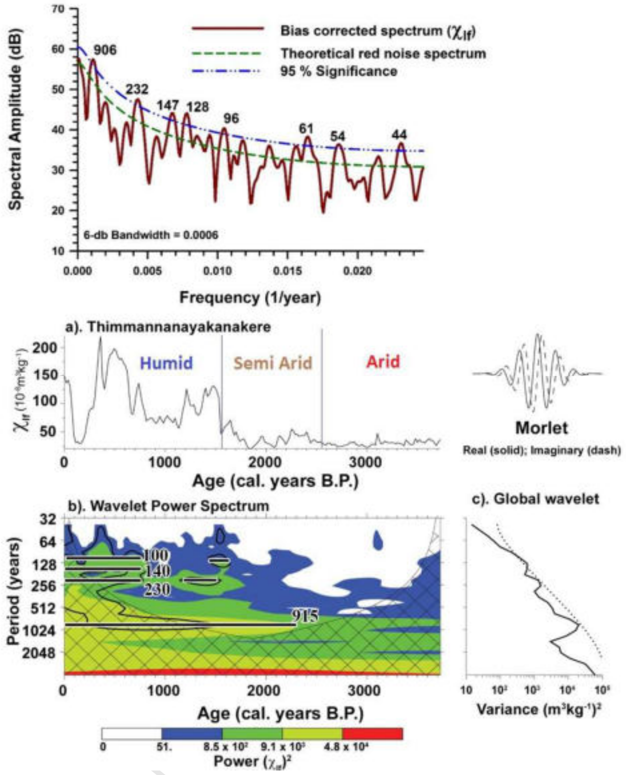
PII: S1674-9871(17)30022-1
DOI: 10.1016/j.gsf.2017.01.004
Reference: GSF 529

To appear in: *Geoscience Frontiers*

Received Date: 14 October 2016
Revised Date: 9 January 2017
Accepted Date: 19 January 2017

Please cite this article as: Warrier, A.K., Sandeep, K., Shankar, R., Climatic periodicities recorded in lake sediment magnetic susceptibility data: further evidence for solar forcing on the Indian summer monsoon, *Geoscience Frontiers* (2017), doi: 10.1016/j.gsf.2017.01.004.


Age (cal. ka B.P.)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
*
#
Humid
Semi Arid
Arid
0
75
150
225
χlf
(10⁻⁸m³kg⁻¹)
Increasing rainfall


Spectral Amplitude (dB)
Bias corrected spectrum (χlf)
Theoretical red noise spectrum
95 % Significance
906
232
147
128
96
61
54
44
6-db Bandwidth = 0.0006
Frequency (1/year)
a). Thimmannanayakanakere
χlf (10⁻⁸m³kg⁻¹)
Humid
Semi Arid
Arid
Age (cal. years B.P.)
Morlet
Real (solid); Imaginary (dash)
b). Wavelet Power Spectrum
Period (years)
100
140
230
915
c). Global wavelet
Variance (m³kg⁻¹)²
Age (cal. years B.P.)
0
51.
8.5 x 10²
9.1 x 10³
4.8 x 10⁴
Power (χlf)²

Climatic periodicities recorded in lake sediment magnetic susceptibility data: further evidence for solar forcing on the Indian summer monsoon

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ABSTRACT:

The Indian summer monsoon exhibits considerable spatio-temporal variability. It is therefore important to understand its dynamics and the inherent periodicities. In this study, we have performed spectral and wavelet analyses of magnetic susceptibility data for sediments from Thimmannanayakanakere (TK)–a small lake in southern India. The main objective of this investigation is to identify and explain the possible origin of the prominent periodicities present in the magnetic susceptibility data. Significant periodicities in the TK χ_{lf} data are centered at 906, 232, 147, 128, 96, 61, 54 and 44 years, which might have a solar origin. The wavelet power spectrum of the raw and detrended χ_{lf} data confirms the findings of spectral analysis and also provides temporal variations of the significant cyclicities during the past 3700 cal. years B.P. Positive correlation is documented between sunspot activity and TK χ_{lf} data; cross-spectral analysis of the reconstructed sunspot data and TK χ_{lf} data suggest that there is a strong coherence between the two datasets as significant periodicities are documented in both. There is a good match between the TK χ_{lf} and the reconstructed total solar irradiance data for the past 1200 years. However, an out-of-phase relationship is documented at certain time-intervals, which may be attributed to uncertainties in the age-depth model. The results obtained from this study show that solar variations are the main controlling factor of the southwest monsoon and, like other archives from different regions in India, the TK lake sediments have also recorded these solar signatures.

Keywords: Spectral analysis; Periodicity; Paleorainfall; Lake sediments; Magnetic susceptibility; Southern India.

1. Introduction

There have been considerable fluctuations in the Earth's climate since its origin ~ 4.5 Ga ago. Several external and internal forcings are responsible for these fluctuations. Solar activity, volcanic eruptions, tectonic activity etc. are a few important ones that play an important role in changing the Earth's climate. Over the past few years, considerable work has been carried out to determine the influence of the various forcing mechanisms on the Earth's climate, especially the monsoon. Remarkable interest was evinced to determine the behavior of the climate system at different periodicities (Berger et al., 2002), which occurred on different time-scales. Millennial scale periodicities were deciphered from marine sediments (Bond et al., 1997), although decadal- to century-scale periodicities were detected through detailed investigations of various archives like lacustrine sediments (Liu et al., 2009; Chen et al., 2015; Ojala et al., 2015; Saarni et al., 2016) and speleothems (Yadava and Ramesh, 2007; Muňoz et al., 2015). To identify the millennial-, centennial- and/or decadal-scale periodicities, spectral analysis is carried out on proxy records obtained from paleoclimate archives.

The Indian monsoon is of prime importance to the Indian subcontinent as its agriculture and economy are inextricably linked to the SW monsoonal rainfall. The large spatio-temporal variability of the Indian monsoon (Hartmann and Michelsen, 1989) warrants a documentation of its dynamics and the inherent periodicities. A clearer understanding of these aspects would enable better prediction of the future rainfall scenario for the subcontinent. Prominent periodicities in the Indian monsoon have been identified based on the analysis of instrumental rainfall data (Hiremath and Mandi, 2004; Sarita Azad et al., 2010). However, to ascertain the stationarity or the temporal extent of the periodicities, longer records of past rainfall are required. An important archive for paleoclimatic studies are lake sediments that have the advantage of recording the regional and local climate with a good temporal resolution. Despite this advantage, only limited studies have been carried out on lake sediments of southern India to decipher paleoclimate and the periodicities therein (Sandeep et al., 2015). Using environmental magnetism as a tool, Shankar et al. (2006) reconstructed the paleoprecipitation variability for the past 3,700 cal. years B.P. based on sedimentary magnetic susceptibility variations in a small lake known as Thimmannanayakanakere (TK; 14°12’13.96”N; 76°23’50.43”E) in Chitradurga District, Karnataka, southern India. The chronology was built with the help of two radiocarbon dates that were obtained by ^{14}C dating of bulk organic matter present in the sediments. They also proposed the use of magnetic susceptibility (χ_{lf}) as a proxy for rainfall in the tropics. This proposition was based on the good correlation documented between the proxy and instrumental rainfall data and good correspondence with historical records (of a drought in 1876 AD and a high-rainfall event in 1741 AD) and other proxy records from different archives coming from diverse geographical regions. Based on the χ_{lf} data (Fig. 1), Shankar et al. (2006) suggested that the TK region witnessed arid (~3700–2550 cal. year B.P.), sub-arid (2550–1575 cal. year B.P.) and humid (1575 cal. year B.P. to the present) climates. Later, Warrier and Shankar (2009) and Warrier et al. (2014) respectively provided geochemical and sedimentological lines of evidence to support the proposition. In this investigation, we identify and explain the possible causes of the significant periodicities present in the magnetic susceptibility data.

Spectral analysis of paleoclimatic data can provide vital information on climatic variability present in proxy climate data (Ghil et al., 2002). There are several methods to carry out spectral analysis of paleoclimate data; for example, Fourier techniques using the Blackman-Tukey method (Blackman and Tukey, 1958), maximum entropy technique (Thomson, 1982), singular spectrum techniques (Broomhead and King, 1986) and wavelet analysis (Torrence and

Compo, 1998). Spectral analysis using REDFIT program (Schulz and Mudelsee, 2002) was successfully used to determine significant periodicities in unevenly spaced paleoclimatic time series. Similarly, wavelet transform was used for numerous studies that dealt with El Niño–Southern Oscillation (ENSO; Gu and Philander, 1995), and dispersion of ocean waves (Meyers et al., 1993). In this study, we carried out spectral and wavelet analyses of the TK χ_{lf} time series and reconstructed sunspot data (Solanki et al., 2004).

2. Methods

2.1 Spectral analysis

Spectral analysis of the TK magnetic susceptibility data (Shankar et al., 2006) and reconstructed sunspot number data (Solanki et al., 2004) was carried out using the freeware program REDFIT (v.3.8; Schulz and Mudelsee, 2002). To detect the presence of low-frequency components, the raw data were treated with a Savgol filter (Press et al., 1992) of width 10 and order 4. The filtered data were subtracted from the original, and the resultant data run on REDFIT. Table 1 gives the configuration of the analytical parameters of the program that were used for analyzing the time series.

2.2 Wavelet analysis

As wavelet analysis requires evenly spaced data, linear interpolation of the TK magnetic susceptibility data was carried out using ORIGIN v.8. Wavelet transform analysis was carried out using the interactive software available at http://paos.colorado.edu/research/wavelets (Friddell et al., 2003). The configuration details of the program are given in Table 2.

3. Results and discussion

3.1 Significant periodicities in the TK magnetic susceptibility data

Figure 2a shows the results of spectral analysis carried out on the raw χ_{lf} time-series. Significant periodicities (at 95% confidence level) documented are 906, 232, 147, 128, 96, 61, 54 and 44 years (Table 3). Many of them are linked to solar activity (von Rad et al., 1999; Agnihotri et al., 2002; Thamban et al., 2007). The 906-year periodicity is similar to the 950-year cyclicity documented in the magnetic susceptibility data for an eastern Arabian Sea sediment core (Thamban et al., 2007), stalagmites from Oman (Neff et al., 2001), Alaskan lake sediments (Hu et al., 2003) and reconstructed ^{14}C data from northern hemisphere tree-rings (Lean, 2002). Variations in the activities of cosmogenic isotopes like ^{14}C and ^{10}Be as recorded in continental archives possess information on the cyclicity of solar activity in the past (Raspopov et al., 2008). The presence of this periodicity in the ^{14}C data indicates that it is related to variations in the solar activity. The 232-year periodicity is related to the ~210-year Suess cycle (the de Vries cycle; Usoskin and Mursula, 2003). This cycle is generally believed to be one of the most intense solar cycles during the Holocene. According to Wagner et al. (2001), the periodicity was prominent 50,000 and 25,000 years ago. They made this observation by studying the ^{10}Be activity in Greenland ice as a proxy for past variations in solar activity. This periodicity was also reported in the variations of radiocarbon concentrations in tree-rings (Muscheler et al., 2003). Agnihotri et al. (2002) reported a ~210-year periodicity, which is related to the Suess cycle, in the organic carbon, nitrogen and Al variations in a sediment core from the northeastern Arabian Sea. This periodicity is also documented in the varve sediments off the Karachi coast (von Rad et al., 1999). Tiwari and Ramesh (2007) reported ~ 215 and ~230-year periodicities in the abundances of foraminiferal species *G. menardii* and *G. ruber* respectively in an Arabian Sea sediment core.

Other proxy records which documented these periodicities are the δ^{18}O and δ^{13}C in peat cellulose, NE China (Hong et al., 2001), δ^{18}O of stalagmite, Oman (Neff et al., 2001), and iron oxide content in a Tibetan lacustrine sediment core (Ji et al., 2005). The presence of these cyclicities in the TK χ_{lf} record suggests that the southwest monsoon has a dominant quasi-periodicity of ~200 years, which corresponds to the Suess cycle of ~210 years. The power recorded at the 128-year periodicity in the χ_{lf} spectral data (Fig. 2a) may coincide with the 130-year cycle documented in the spectral record of the reconstructed atmospheric ^{14}C decadal time series (Damon and Peristykh, 2000), aurora observations and aridity proxy record of a lake in the northern Great Plains, North America (Yu and Ito, 1999). A 132-year periodicity was also reported from the δ^{18}O time series of speleothems from Southern Oman (Fleitmann et al., 2003) and Akalagavi, northern Karnataka, India (Yadava and Ramesh, 2007). It is noteworthy that locations of both the speleothems receive rainfall during the southwest monsoon.

The 96-year periodicity in the TK χ_{lf} data may be related to the 88-year cycle, which is known as the Gleissberg cycle of solar origin (Wolf, 1862; Gleissberg, 1939). The signals of the Gleissberg cycle were also documented in solar irradiance (Reid, 1997) and auroral records (Feynman and Fougere, 1984). Several workers reported the presence of this 88-year periodicity in proxy records from the Arabian Sea sediment cores (Thamban et al., 2007; Agnihotri et al., 2002) and varved sediments off the Pakistan coast (von Rad et al., 1999). The 54 and the 44-year periodicities apparent in the TK χ_{lf} spectral record were also considered to be of solar origin by Berger and von Rad (2002).

The raw χ_{lf} data were treated with a Savgol filter (Press et al., 1992) to remove the low-frequency components present in the data. The aim of this step was to check the presence of high-frequency components as they are usually suppressed by low-frequency components

(Yadava and Ramesh, 2007). The periodogram obtained from the spectral analysis of the detrended time-series is shown in Fig. 2b. The additional periodicities obtained from this analysis are 106, 84, 73 and 64 years. Tiwari and Rao (2004) also reported the presence of a spectral power near the 65 to 70-year periodicity in coral deposits from the Arabian Sea. A periodicity of 50 to 70 years was also documented in the global mean temperature record (Minobe, 1997). Kerr (2000) reported this 65 to 70-year oscillation in instrumental records, proxy climate data and climate models. The presence of these periodicities in the TK χ_{lf} data lends support to the possible link between the southwest monsoon and solar activity. Several shorter periodicities like the Schwabe cycle (11 years), the Hale cycle (22 years) and the ENSO cycle are not documented probably due to the coarse temporal resolution of the TK data (sampling resolution is ~22 years).

The results of wavelet analysis of the raw and the detrended data (SAVGOL filtered minus the raw χ_{lf} data) are shown in Figs. 3 and 4. Black lines indicate the temporal variations of the significant periodicities. The results show significant peaks at 906, 232, 147, 128, 96, 61, 54 and 44 years (95% confidence level). The 915-year cycle is continuous throughout the past 3000 cal. years B.P., reaching its maximum power between 2200 years B.P. and the Present. The 230-year Suess cycle is apparent mostly around 1800 cal. years B.P. and is absent prior to 2000 cal. years B.P. Shorter cycles like the 140 and 100-year ones manifest themselves for a short period between 1700 and 1500 cal. years B.P. and then again from 1000 cal. years B.P. onwards. These cycles too, like the 235-year Suess cycle, are absent prior to 2000 cal. years B.P.

Fig. 4 shows the wavelet power spectral map for the detrended χ_{lf} data (SAVGOL filtered minus the raw χ_{lf} data). It confirms the periodicities revealed by spectral analysis (Fig. 2b). The 106, 84, 73 and 64-year periodicities seem to exist during the past 3700 cal. years B.P. However, they have a strong power at 3100 cal. years B.P., during 1700–1000 cal. years B.P. and from 800 cal. years B.P. to the Present. During all the above-mentioned periods, rainfall was generally high (as suggested by high χ_{lf} values) in the TK region. This indicates that the solar cycles were strong during high rainfall periods as seen in the wavelet power spectrum map. Hence, TK magnetic susceptibility data have recorded the solar cycles, and there appears to be a solar control of the Indian monsoon.

3.2 The 60-year cycle

The TK χ_{lf} spectral data show a significant 61-year periodicity. This cycle is believed to be an important feature of the recent variability of the Indian monsoon (Sinha et al., 2005). Modern instrumental rainfall records also reveal the presence of this cycle (Parthasarathy et al., 1993; Sontakke et al., 1993). It is also discernible in several proxy records of the summer monsoon variability. For example, Agnihotri et al. (2002) reported the 60-year periodicity in their spectral data of the sedimentary organic carbon, nitrogen and Al contents of an Arabian Sea sediment core for the past millennium. Sinha et al. (2005) documented this cycle between 11.7 and 15.2 ka B.P. in the δ^{18}O time series of a speleothem from the western Himalaya. Yadava and Ramesh (2007) reported a 59-year cycle in the δ^{13}C record of Akalagavi speleothem, but it is not documented in the δ^{18}O record of the same speleothem because of the presence of shorter periodicities. The Nile River level, which is closely associated with the southwest monsoon variability, also exhibits the 60-year cycle in the 1400-year historical record (Kondrashov et al., 2005). The prevalence of the 60-year periodicity in proxy records and also in instrumental rainfall data suggests that the Indian monsoon is controlled by solar activity on a multi-decadal scale.

3.3 Comparison of the TK χ_{lf} data with Sunspot Activity and Total Solar Irradiance

The annual sunspot data for the past four centuries were taken from ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS/YEARLY and a 22-year moving average of the data was calculated to match the temporal resolution of TK χ_{lf} data (22 years). Fig. 5a shows the relationship between χ_{lf} and sunspot activity during the past three centuries. There is a significant correlation in the data set ($r = 0.66$; significant at 1% level; $n = 12$), which suggests that solar activity has a profound influence on the southwest monsoon. Hiremath and Mandi (2004) obtained the wavelet power spectrum of the sunspot data and the Indian monsoon rainfall time series, which indicated a strong correlation between the two. Spectral analysis of the reconstructed sunspot data (Solanki et al., 2004) was carried out to reveal significant periodicities in solar activity. Fig. 5b shows important periodicities centered at 205, 154, 127, 97, 61, 42 and 34 years. These periodicities are also recorded in the spectral data of TK magnetic susceptibility (Fig. 2), which lends support to the view that the southwest monsoon is primarily controlled by solar activity. Cross-spectral analysis, which is usually performed to estimate the coherency between two datasets (Schulz and Statteger, 1997), was carried out on the reconstructed sunspot data and TK χ_{lf} data for the past 3700 years using the Fortran program, SPECTRUM (Schulz and Statteger, 1997). The results showed a high coherency for several periodicities like 133, 107, 62 and 44 years, indicating a strong association between the two parameters (Fig. 6). Cross-spectral analysis supports the earlier interpretation of the spectral and wavelet data that solar activity has a remarkable influence on the Indian monsoon.

The total solar irradiance (TSI) data (from ftp://ftp.ncdc.noaa.gov/pub/data/paleo/climate_forcing/solar_variability/steinhilber2009tsi.txt) for the past 1200 years (Steinhilber et al., 2012) and the TK χ_{lf} data were compared (Fig. 7) to determine if TSI controls the Indian monsoonal rainfall. The variations in χ_{lf} are in tune with those of TSI during the Dalton Minimum (1790–1860 AD) and the Maunder Minimum (1645–1720 AD). The historically recorded high-rainfall event of 1741 AD, reflected as a high χ_{lf} value, coincides with the TSI maximum between the Dalton and Maunder Minima of the Little Ice Age (LIA). The high-rainfall event at 1640 AD corresponds to the small maximum between the Maunder and Spörer Minima. Around 1260 AD rainfall was high and is comparable to the modern rainfall amount. This corresponds to the Medieval Warm Period (MWP; 1100–1400 AD). However, the rainfall was not consistently high during the entire span of MWP. χ_{lf} also shows a decrease in rainfall during the Wolf Minimum (1282–1342 AD) and the Oort Minimum (980–1120 AD). The influence of total solar irradiance on the Indian monsoon is well documented in several studies (von Rad et al., 1999; Agnihotri et al., 2002; Sandeep et al., 2015): Periods of increased TSI are characterized by high rainfall and *vice versa*. Based on proxies like organic carbon, nitrogen and Al contents in a sediment core from the Arabian Sea, Agnihotri et al. (2002) documented that periods of solar minima were probably associated with a reduced summer monsoon (low surface productivity) and *vice versa*. Similar results (association between TSI and productivity proxy) were also documented by Tiwari et al. (2005) and Tiwari and Ramesh (2007) from their data on foraminiferal species from the eastern Arabian Sea sediment cores. Sandeep et al. (2015) showed that the sedimentary χ_{lf} variations in Pookot Lake (SW coast of India) are similar to those in TSI data. However, there is an out-of-phase relationship between TSI and TK χ_{lf} data during certain time intervals, which may be attributed to uncertainties in the age-depth model (Shankar et al., 2006).

4. Conclusions

The results obtained from the spectral and wavelet analyses of Thimmannanayakanakere (TK) sediment χ_{lf} and reconstructed sunspot data and a comparison of the TK χ_{lf} data with total solar irradiance data are summarized below:

- Significant periodicities in the TK χ_{lf} data are centered at 906, 232, 147, 128, 96, 61, 54 and 44 years, which are possibly of solar origin.
- Low-frequency periodicities obtained after filtering the raw χ_{lf} data are centered at 106, 96, 84, 73, 64, 61 and 43 years. Similar low-frequency periodicities are documented as well in a coral record from the Arabian Sea.
- Wavelet power spectrum of the raw and detrended χ_{lf} data confirms the findings of spectral analysis and also provides temporal variations of the significant cyclicities during the past 3700 cal. years B.P.
- The 60-year cycle documented in the instrumental rainfall record and other proxy data is also discernible from the TK χ_{lf} spectral data.
- The positive correlation between sunspot activity and TK χ_{lf} data, and the cross-spectral analysis of the reconstructed sunspot data and TK χ_{lf} data, suggest that there is a strong coherence between the two datasets as significant periodicities are documented in both.
- There is a good match between the TK χ_{lf} and the reconstructed total solar irradiance data for the past 1200 years. However, during certain time-intervals an out-of-phase relationship is discerned, which may be attributed to uncertainties in the age-depth model.
- The results obtained from this study show that the Sun exerts a profound control on the southwest monsoon and that the TK sediments have truly recorded the solar signatures.

Acknowledgments

We are grateful to the Department of Space, Government of India, for supporting this work through a research project to RS ("Paleoclimate of the past few centuries from Lake- and Tank-bed sediments of Southern India"; ISRO-GBP/WG-1 letter No. 9/5/2/2004-II) under the Geosphere–Biosphere Program. AKW and KS thank the Department of Space, the Council of Scientific and Industrial Research and the University Grants Commission, Government of India for Junior and Senior Research Fellowships. We thank the Associate Editor and two anonymous reviewers for their valuable comments that helped in improving the manuscript.

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FIGURE CAPTIONS

Figure 1. Paleoclimate / paleomonsoonal rainfall variability reconstructed for the past 3.7 cal. ka B.P. for the TK region on the basis of χ_{lf} (Shankar et al., 2006). High rainfall periods are marked with long blue arrows and low rainfall periods with short red arrows. Historical records of the 1876 AD drought (*) and the 1741 AD high rainfall event (#) are also shown.

Figure 2 (a) Periodogram for the magnetic susceptibility data of TK sediments; (b) Periodogram for the detrended magnetic susceptibility data (SAVGOL filtered minus the raw χ_{lf} data).

Figure 3 (a) Magnetic susceptibility (χ_{lf}) data for the past 3700 cal. years B.P.; (b) Wavelet power spectrum for the TK χ_{lf} data. Note: The contour levels were chosen such that 75%, 50%, 25%, and 5% of the wavelet power is above each level, respectively. The cross-hatched region is the cone of influence, where zero padding has reduced the variance. Black contour is the 10% significance level, using a red-noise (autoregressive lag1) background spectrum; (c) Global wavelet power spectrum (black line). Note: The dashed line is the significance for the global wavelet spectrum, assuming the same significance level and background spectrum as in wavelet power spectrum.

Figure 4 (a) Detrended χ_{lf} data (Savgol filter minus the original data) for TK sediments; (b) Wavelet power spectrum for the detrended data. Note: The contour levels were chosen such that 75%, 50%, 25%, and 5% of the wavelet power is above each level, respectively. The cross-hatched region is the cone of influence, where zero padding has reduced the variance. Black contour is the 10% significance level, using a red-noise (autoregressive lag1) background spectrum. (c) Global wavelet power spectrum (black line). Note: the dashed line is the significance for the global wavelet spectrum, assuming the same significance level and background spectrum as in wavelet power spectrum.

Figure 5 (a) Correlation between sunspot number and TK χ_{lf}; (b) Periodogram for the reconstructed sunspot data (Solanki et al., 2004).

Figure 6 Cross-spectral analysis of the reconstructed sunspot data (Solanki et al., 2004) and χ_{lf} data for TK sediments.

Figure 7 Comparison of the TK χ_{lf} data for the past 1150 years with reconstructed total solar irradiance (TSI) based on cosmogenic radioisotopes (Steinhilber et al., 2012).

TABLE CAPTIONS

Table 1. Configuration details of the REDFIT program used for spectral analysis (refer to Schulz and Mudelsee (2002) for more details).

Table 2. Settings of the interactive wavelet software used for wavelet transform analysis of all evenly spaced time series (refer to Torrence and Compo (1998) for explanation).

Table 3. A summary of the significant periodicities in the Thimmannanayakanakere sediment χ_{lf} time series, their possible origins and other palaeoclimatic records showing similar periodicities.

Table 1. Configuration details of the REDFIT program used for spectral analysis (see Schulz and Mudelsee, 2002 for more details).

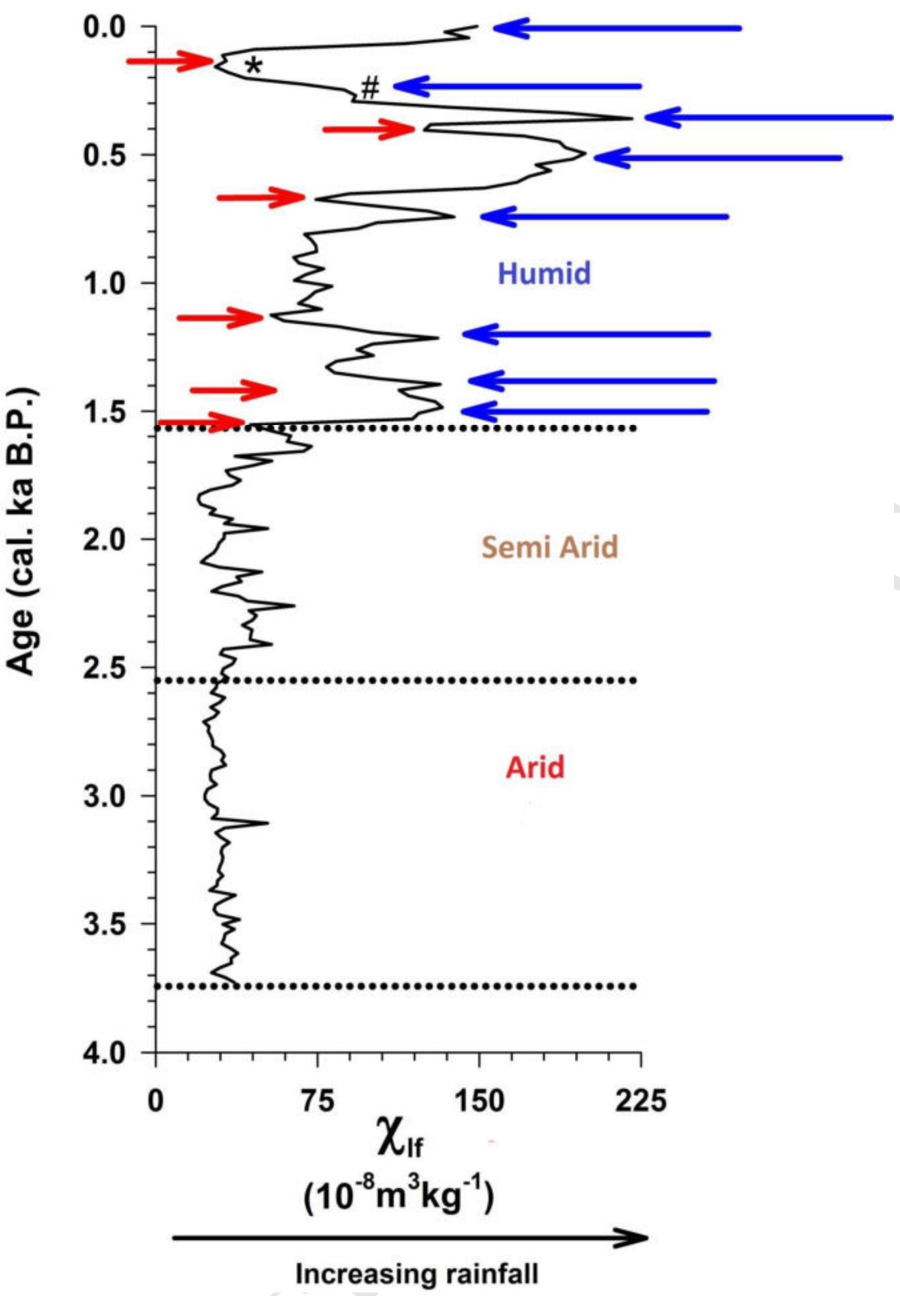
Parameter	**Value**
Number of Monte-Carlo simulations (nsim)	1000
Oversampling factor for Lomb-Scargle Fourier transform (ofac)	4.0
Maximum frequency to analyse (hifac)	Nyquist frequency [1.0]
Number of segments with 50 % overlap (n50)	2
Prescribed value for p (rhopre)	-99.0
Window type to suppress side lobes (iwin)	Welch [1]
Level of significance	95 %

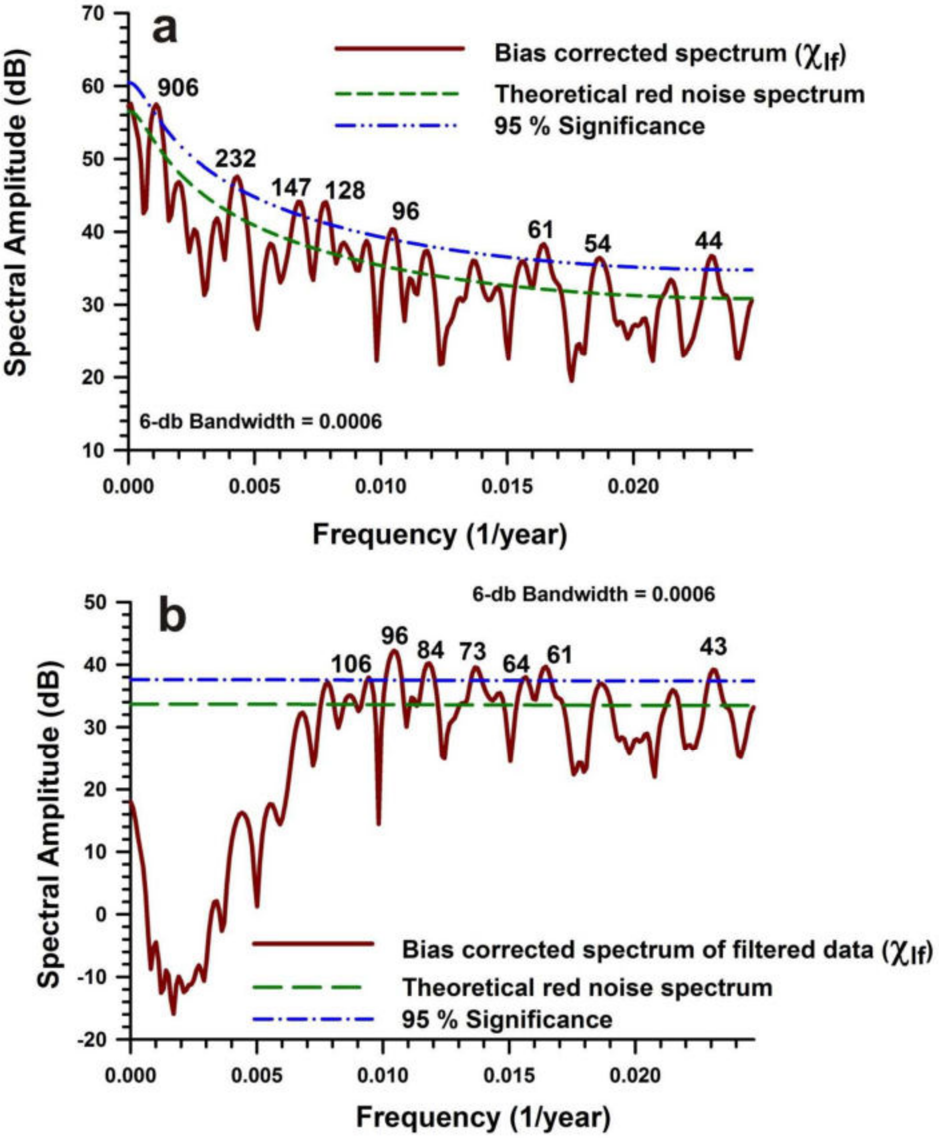
Table 2. Settings of the interactive wavelet software used for wavelet transform analysis of all evenly spaced time series (see Torrence and Compo, 1998 for explanation).

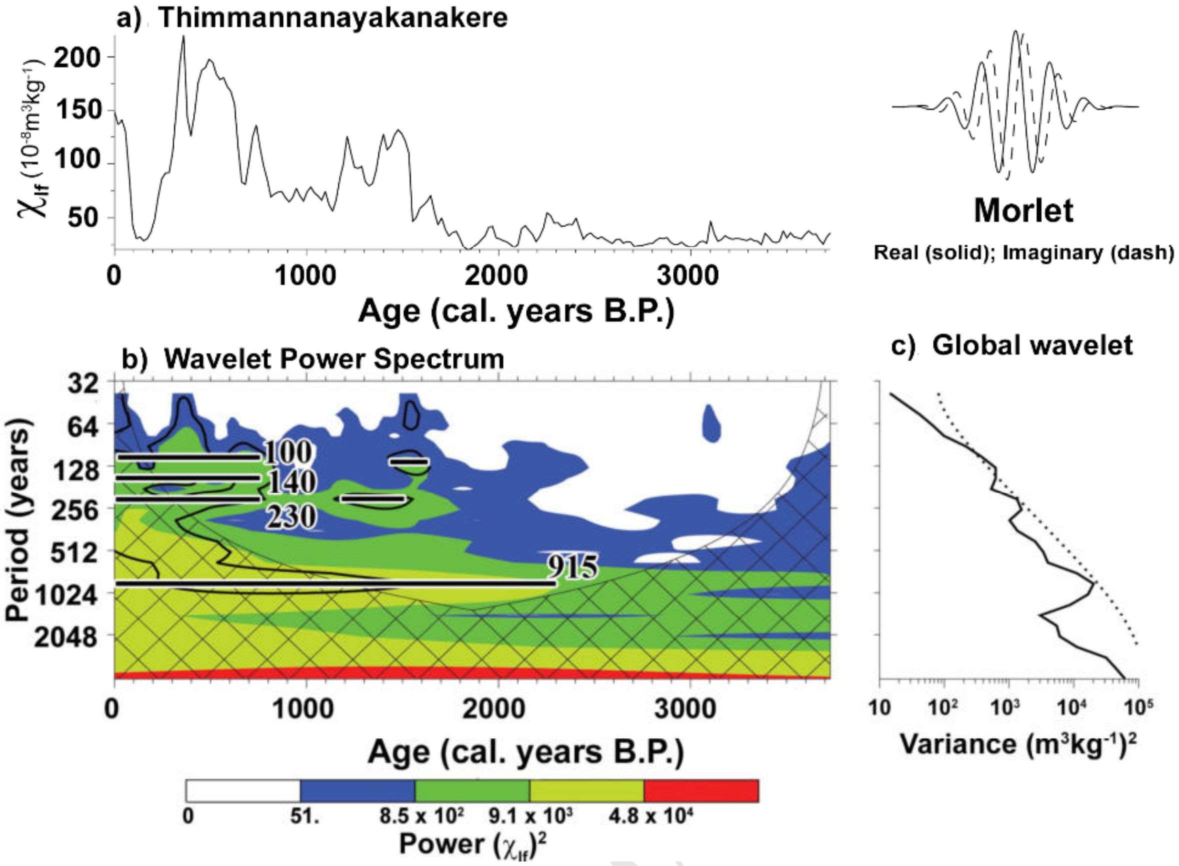
Parameter	**Value**
Mother wavelet (wavelet)	Morlet
ω_o (param)	6
Start scale	2.0
Scale width	0.25
Powers of two	11
Padded with zeros	Yes
Cone of influence	Yes
Level of significance	90 %

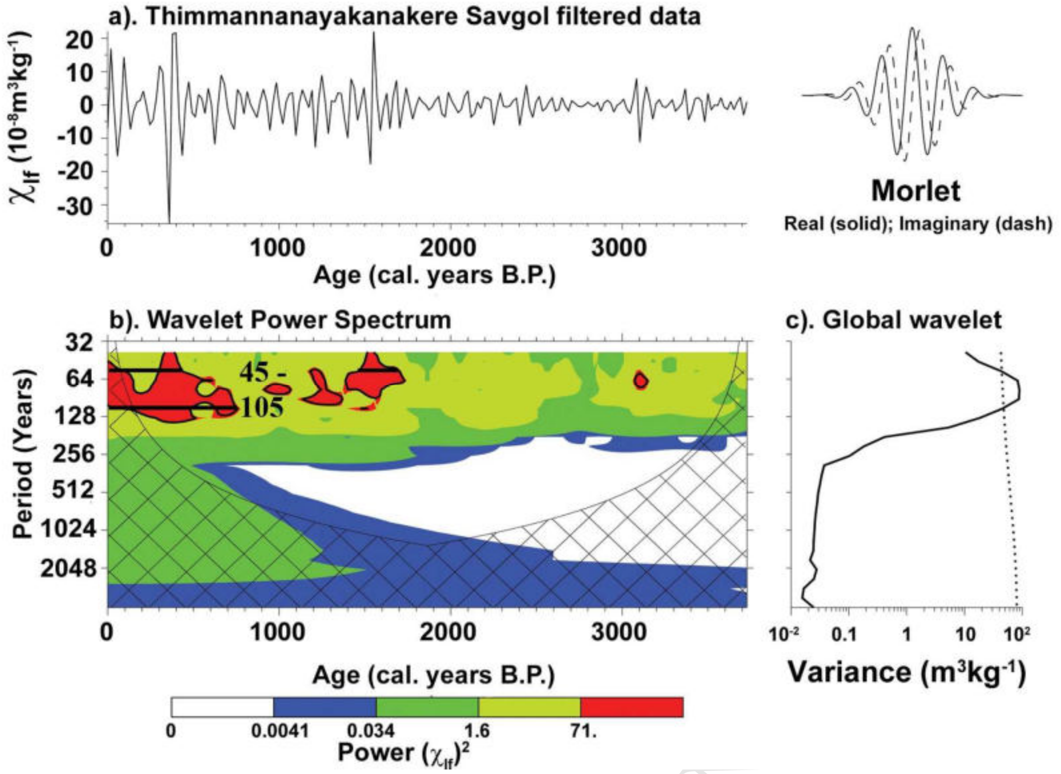
Table 3. A summary of the significant periodicities in the Thimmannanayakanakere sediment χ_{lf} time series, their possible origins and other palaeoclimatic records showing similar periodicities.

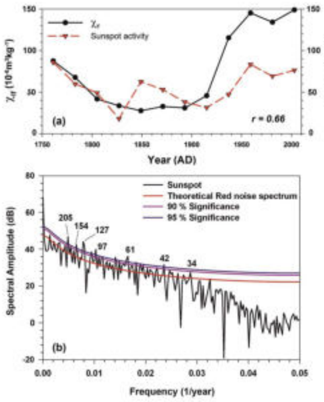
Periodicities in TK Lake sediment χ_{lf} (years)	**Possible origins**	**Similar periodicities in other palaeoclimatic records**
906	Solar	Thamban et al. (2007), Neff et al. (2001), Hu et al. (2003), Lean (2002)
232	210-year Suess (de Vries) cycle of the Sun	Agnihotri et al. (2002), von Rad et al. (1999), Tiwari and Ramesh (2007), Sandeep et al. (2015), Hong et al. (2001), Neff et al. (2001), Ji et al. (2005), Thamban et al. (2007)
128	Solar	Damon and Peristykh (2000), Yu and Ito (1999), Sandeep et al. (2015), Fleitmann et al. (2003), Yadava and Ramesh (2007)
96	88 year Gleissberg cycle of the Sun	Thamban et al. (2007), Agnihotri et al. (2002), von Rad et al. (1999), Damon and Peristykh (2000), Hong et al. (2001), Fleitmann et al. (2003), Sandeep et al. (2015)
61	Solar	Agnihotri et al. (2002), Sinha et al. (2005), Yadava and Ramesh (2007)
54	Solar	Berger and von Rad (2002)
44	Solar	Berger and von Rad (2002)

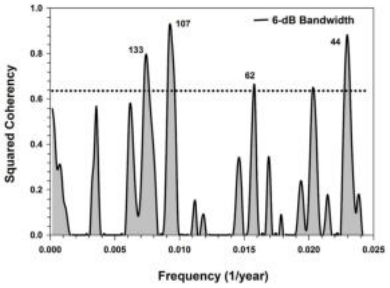

Age (cal. ka B.P.)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
0
75
150
225
χ_{lf}
(10^{-8}m^{3}kg^{-1})
Increasing rainfall
*
#
Humid
Semi Arid
Arid

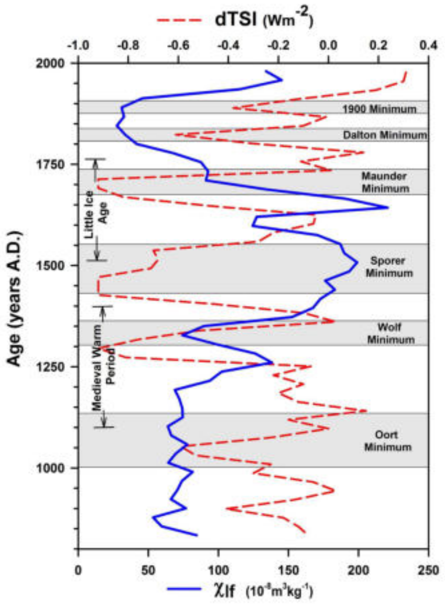

a
Bias corrected spectrum (χ_{lf})
Theoretical red noise spectrum
95 % Significance
906
232
147
128
96
61
54
44
6-db Bandwidth = 0.0006
Spectral Amplitude (dB)
70
60
50
40
30
20
10
0.000
0.005
0.010
0.015
0.020
Frequency (1/year)
b
6-db Bandwidth = 0.0006
106
96
84
73
64
61
43
Bias corrected spectrum of filtered data (χ_{lf})
Theoretical red noise spectrum
95 % Significance
Spectral Amplitude (dB)
50
40
30
20
10
0
-10
-20
0.000
0.005
0.010
0.015
0.020
Frequency (1/year)


a) Thimmannanayakanakere
χ_{lf} ($10^{-8}m^3kg^{-1}$)
200
150
100
50
0
1000
2000
3000
Age (cal. years B.P.)
Morlet
Real (solid); Imaginary (dash)
b) Wavelet Power Spectrum
Period (years)
32
64
128
256
512
1024
2048
100
140
230
915
0
1000
2000
3000
Age (cal. years B.P.)
0
51.
8.5 x 10^2
9.1 x 10^3
4.8 x 10^4
Power (χ_{lf})^2
c) Global wavelet
10
10^2
10^3
10^4
10^5
Variance (m^3kg^{-1})^2


a). Thimmannanayakanakere Savgol filtered data
χ_{lf} ($10^{-8}m^3kg^{-1}$)
20
10
0
-10
-20
-30
0
1000
2000
3000
Age (cal. years B.P.)
Morlet
Real (solid); Imaginary (dash)
b). Wavelet Power Spectrum
Period (Years)
32
64
128
256
512
1024
2048
45 -
105
0
1000
2000
3000
Age (cal. years B.P.)
c). Global wavelet
10^{-2}
0.1
1
10
10^2
Variance (m^3kg^{-1})
0
0.0041
0.034
1.6
71.
Power $(\chi_{lf})^2$


150
100
50
0
χ_{fd} (10^{-8}m^{3}kg^{-1})
χ_{fd}
Sunspot activity
(a)
r = 0.66
Sunspot activity
1750
1800
1850
1900
1950
2000
Year (AD)
80
60
40
20
0
-20
Spectral Amplitude (dB)
Sunspot
Theoretical Red noise spectrum
90 % Significance
95 % Significance
205
154
127
97
61
42
34
(b)
0.00
0.01
0.02
0.03
0.04
0.05
Frequency (1/year)


6-dB Bandwidth
107
133
62
44
Squared Coherency
1.0
0.8
0.6
0.4
0.2
0.0
0.000
0.005
0.010
0.015
0.020
0.025
Frequency (1/year)


dTSI (Wm^{-2})
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
0.2
0.4
Age (years A.D.)
2000
1750
1500
1250
1000
1900 Minimum
Dalton Minimum
Maunder Minimum
Little Ice Age
Sporer Minimum
Wolf Minimum
Medieval Warm Period
Oort Minimum
0
50
100
150
200
250
χlf $(10^{-8}m^3kg^{-1})$

Research Highlights

- Spectral and wavelet analyses performed on lake sediment magnetic susceptibility (χ_{lf}) data.
- Significant periodicities seen in the spectral and wavelet data are possibly of solar origin.
- Strong coherence recorded between sunspot and χ_{lf} data.
- The 60-year cycle documented in the instrumental rainfall record is evident in the χ_{lf} data.