Significant longer-term periodicities in the proxy record of the Indian monsoon rainfall

M.G. Yadava *, R. Ramesh

Planetary and Geosciences Division, Physical Research Laboratory, Navrangpura, Ahmedabad 380 009, Gujarat State, India

Received 23 December 2006; received in revised form 4 March 2007; accepted 2 April 2007

Communicated by W. Soon

Abstract

Fast Fourier transform (FFT) and the maximum likelihood analyses (MLA) of stable carbon and oxygen isotope records ($\delta^{18}O$ and $\delta^{13}C$ time series, proxies for monsoon rainfall) of the last 331 years from an annually laminated speleothem reveal significant power in several periods that have a likely solar origin, e.g. 132, 21, 18, and 2.4 years. These cycles are non-stationary in nature. Using wavelet analysis we find that the ~21-year period is strong during 1850–1920 A.D. Between 1780 and 1920 A.D., low rainfall intervals are concurrent with low solar activity. However, this behaviour breaks down for the older periods. In the $\delta^{13}C$ periodogram, additional significant periods appear viz. ~59, ~8, ~6.5 and ~3 years: these could have originated from solar variations and/or changes in the biological degradation of soil carbon. Surprisingly, while the low power solar cycles (viz. ~22 year and ~2.4 year) are seen in the $\delta^{18}O$ and $\delta^{13}C$ spectra with the ~21 year cycle dominating, the stronger ~11 year cycle is only weakly represented in the proxy record, confirming earlier findings based on a more limited data set.

© 2007 Elsevier B.V. All rights reserved.

Keywords: Proxy monsoon record; Oxygen and carbon isotopes; Solar cycles; Speleothems; Cave deposits

1. Introduction

Causative processes for the spatial and temporal variations in the Indian monsoon rainfall (south west monsoon, abbreviated as SWM), affecting a large population and economy, are yet to be fully deciphered. Some possible controlling factors that may bring out significant variations in SWM at seasonal, decadal or century scales have been proposed (Clemens et al., 1991; Gadgil, 2003; Kripalani and Kulakarni, 1997; Wang et al., 2001; Tiwari and Ramesh, 2007). One example is the changes in the radiation budget induced by the insolation changes and changes in the ocean circulation system (Clemens et al., 1991). Whether solar activity is a dominant controlling factor for these variations is a debatable issue (Cadet, 1979). Taking the weighted average of the instrumental rainfall data, available from several rain gauge stations from the last century and as back as 1871 from some limited number of stations, a rainfall time series has been put together, that serves an index of the monsoon rainfall over the Indian region (Parthasarathy et al., 1995). A spectral analysis of this time series has recently shown significant power in the periods 2.7 year, 16 year and 22 year (Hiremath and Mandi, 2004). Another such study highlights the connection between the Indian rainfall and solar variability (Bhattacharyya and Narasimha, 2005). As instrumental data is limited only to the last ~130 years, longer-term periodicities and their persistence cannot be ascertained. Suitable rainfall proxies are required to reconstruct rainfall time series for older times.

Tree-rings have a very good potential to provide past climate data with annual resolution. In India, ring-width index of trees from Northern India have been used by several workers to provide reconstruction of either past temperature or precipitation (Boragaonkar et al., 1994;
18O/16O and 13C/12C are represented respectively as (Singh and Yadav, 2005). Therefore, they can not be used to reconstruct spring precipitation for March–April–May example, tree rings in the western Himalaya are useful to or precipitation of only certain months in a year. For
are found to be sensitive either to ambient temperature (Bhattacharyya and Yadav, 1999). But ring-width indices can be used as proxies of the past environmental changes (McDermott, 2004). Sometimes annual laminations (similar to the annual rings in trees) can be seen in the cross sectional view of these deposits, if seepage water has a strong seasonality in the influx of the organic compounds, trace elements or detrital content (Frisia et al., 2003). It has been demonstrated that stable oxygen isotope ratio (18O/16O) of annual carbonate (CaCO3) layers can be used as a rainfall proxy, and was used to reconstruct the monsoon rainfall of the past 331 years (ending at 1996 AD). In the same deposit, variations in the stable carbon isotope ratio (13C/12C) had a good resemblance with the variations in the stable oxygen ratio (18O/16O) possibly due to the dominating control of rainfall. Therefore, extension of the annual rainfall data for an additional ~200 years back, from the beginning of the instrumental observations is available (Yadava et al., 2004). In the present work we have carried out spectral analysis of these data.

2. Data and analysis

We process the raw data of δ18O and δ13C (ratio 18O/16O and 13C/12C are represented respectively as δ18O = [(18O/16O)sample/(18O/16O)standard] − 1] × 1000‰ and δ13C = [(13C/12C)sample/(13C/12C)standard] − 1] × 1000‰) time series (Fig. 1) derived from a speleothem that grew at the Akalagavi cave (Uttar Kannada District, Karnataka, India, 15°10’N, 74°30’E) for spectral analysis. The δ18O of speleothem is controlled by δ18O of local precipitation, which in tropical regions is inversely proportional to the amount of rainfall, as revealed by numerous measurements made by the International Atomic Energy Agency (Yurtsever and Gat, 1981). The validity of this has been tested for the Indian monsoon rainfall by the actual collection and measurement of δ18O of rainfall and its amount (see Yadava and Ramesh, 2005). About 100 mm of increase in rainfall causes 1.5‰ in the δ18O of rainfall and therefore in that of the speleothem. The experimental uncertainty of isotopic measurements (0.1‰) translates into an uncertainty of ~2 mm in the reconstructed rainfall. The time series of speleothem δ18O is thus taken as the primary proxy record of the past rainfall. The response of this proxy is assumed to be linear during the ~3 centuries of the record (e.g., Fleitmann et al., 2003).

High values (i.e., more positive) of δ18O reflect low rainfall years and low (i.e. more negative) values, high rainfall. For details of the calibration and the comparison of the reconstructed rainfall with the All India Summer Monsoon Rainfall (Parthasarathy et al., 1995), reference is made to Yadava et al. (2004) and Yadava and Ramesh (2005); both are well correlated in the overlapping time span of ~100 years, within dating errors and sampling resolution. Correlation with local rainfall could not be attempted as the India Meteorological Record data has significant data gaps for the nearest station (Karwar). Thus, we believe the proxy record represents major changes in the all-India monsoon, apart from the regional components.

δ13C is a potential, secondary rainfall proxy as δ13C has a significantly high correlation with δ18O (r = 0.62, n = 301); therefore, we use the same approach here i.e. high δ13C values reflect low rainfall years. However unlike δ18O, δ13C is yet to be calibrated quantitatively against rainfall. The experimental uncertainty is 0.1‰.

The raw data of δ18O and δ13C have 301 measurements spread unequally spaced in time over the 331 years. The average sampling interval is 1.1 ± 0.4 year. We use SAVGOLFIT3.6 code (Schulz and Mudelsee, 2002) that provides spectral power of the data against the red-noise for unequally spaced time series. We also use SPECTRUM code (Schulz and Stattegger, 1997) that determines spectral coherency between unequally spaced data sets. To resolve the low power, high frequency components we use Savgol

Please cite this article in press as: Yadava, M.G., Ramesh, R., Significant longer-term periodicities in the proxy record ...New Astron. (2007), doi:10.1016/j.newast.2007.04.001

ARTICLE IN PRESS


545

Fig. 1. The raw δ18O (a) and δ13C (b) time series from Yadava et al. (2004).
filters (Press et al., 1992) of different widths. The original data is subtracted from the filtered data to detect high frequencies. We have used Savgol filters of width 15, and order 3 (filter 1), width 10 and order 4 (filter 2), and width 3 and order 4 (filter 3). We also use the maximum likelihood method (Muller and MacDonald, 2002) to extract the low power cycles in the time series. We first take the data and subtract high frequencies using filter 1, and then a band of certain cycles are removed from it to check if low power cycles have attained a significant power level. We also present in the subsequent sections wavelet analysis of the data to test if periods identified in the periodogram are stationary or otherwise. As the data is unequally spaced and the code used for the wavelet analysis (Torrence and Compo, 1998) accepts only equally spaced data, we have interpolated the 301 data values at each year and created an equally spaced (n = 331) data set. Morlet function has been used as a wavelet in each analysis presented here. Finally we use the group sunspot numbers (source: http://www.ngdc.noaa.gov/STP/SOLAR/data) and use the SPECTRUM code to estimate its coherence with the $\delta^{18}$O and $\delta^{13}$C time series.

3. Significant periods in the proxy record

Initially, we do not remove trends to estimate the actual unbiased power spectrum. Spectral analysis of the raw $\delta^{18}$O data shows three significant periods viz. 132, 21 and 2.6 year (Fig. 2a). Several other cycles are insignificant, probably due to power leakages in the side lobes of the dominant low frequency components suppressing the other low power, high frequency components in the periodogram. Removing low frequency components using Savgol filters results in an increase in the power level at 21 year and several additional significant periods viz. 5.4, ~4, ~3.6 and 2.4 year (Fig. 2c, e and g). A similar analysis for $\delta^{13}$C data (Fig. 2b, d, f and h) shows significant power at 330, 21, 13.5, and short periods of 6.4, 5.6, 4.8, 3.1, 2.8, 2.7, 2.6, 2.5 and 2.3 year. All these cycles are resolvable as the resolution at 6-db bandwidth is 0.012 in the frequency scale.

To further check the significance of the power around ~21 year, we remove all slow cycles successively and observe the new power spectra. As seen in Fig. 3a, c, e and g two more periods become significant in $\delta^{18}$O power spectrum viz. 19.6–16.4 with a peak at 17.9 and 13.2–11.1 with a peak at 12.2 at 95% level. The other peaks at 3.9, 3.6 and 2.3 are similar to those seen in the previous analysis (Fig. 2e and g). For $\delta^{13}$C a similar approach results in significant power in periods at 21 year and a band of cycles starting from 14.3 to 11.9 year with a peak at 13 year (Fig. 3d and f). Two new cycles appear with significant power, 59 year (Fig. 3b) and ~8 year (Fig. 3f and h). Other cycles viz. 6.7, 5.5, 3.3, 2.8 and 2.6, considering the resolution (0.012) are same as of the previous analysis (Fig. 2d, f and h).

The highest power obtained at 132 year period in the $\delta^{18}$O power spectrum (Fig. 1a) may coincide with the 130 year cycle in the $\Delta^{14}$C decadal time series (Damon and Peristykh, 2000), aurora observations and aridity proxy record of a lake in the northern Great Plains (Yu and Ito, 1999). The 132-year period is also reported from a stalagmite $\delta^{18}$O time series from Southern Oman that receives rain during southwest monsoon (Fleitmann et al., 2003). All periods above 80 years appear to have significant powers in the $\delta^{18}$O time series (Fig. 2a). They can be correlated to the periodicities of the atmospheric $^{14}$C reconstruction based on tree rings, which are bands with peaks at 353, 288, 149, 130, 104 and 88 years (72–83-year-Gleissberg cycle; Damon and Peristykh, 2000). High power for periods 125 and above with a peak at 330 year in $\delta^{13}$C record (Fig. 2b) can be associated with the 353, 288, 149, 130 year periods in the $\Delta^{14}$C record. It seems that higher periods in the $\Delta^{14}$C variations could also be present in our record, however, possibly due to leakage of their power in the side lobes and power due to second harmonics of the other higher periods, they are not resolvable. Lower frequency cycles can be resolved only when longer time series becomes available.

The major outcome of this work is that 22-year double sunspot cycle or Hale cycle is dominant in both the $\delta^{18}$O and $\delta^{13}$C time series. However, the 10–11-year (the Schwabe) cycle has a very low power. Peaks appear at 11.4 year (Fig. 3e) in $\delta^{18}$O and at 13 year in $\delta^{13}$C (Fig. 3f). In fact bands that have significant power are little higher than 11 year, at 13.7–11.1 in $\delta^{18}$O and 14.3–11.9 in the $\delta^{13}$C (Fig. 3e and f). The currently accepted accepted decadal sunspot cycle period is between 10 and 11 years (Olvera, 2005), with the length of the solar cycle varying from 9 to 13 years. Over the last 825 years North Atlantic Ocean has been shown to exhibit 12.5–13 year periodicity in climatic variability due to coupled tropical ocean atmosphere dynamics (Black et al., 1999). Therefore, period 12–13 year here may originate partly due to similar ocean atmosphere coupling in the region (Gupta et al., 2005). Analysis of causal processes have shown that the 11-year cycle, sometimes seen in the climatic reconstructions are most likely due to climatic system and unlikely due to solar sunspot cycle (Moore et al., 2006). Another period of ~18 year is significant in the $\delta^{18}$O record but not in $\delta^{13}$C (Fig. 3c and d). FFT analysis of Indian monsoon rainfall (Hiremath and Mandi, 2004) shows that there are periodicities of 22 and 16 years. The 18 year peak also appears in the spectral analysis of decadal data $\Delta^{14}$C time series (Damon and Peristykh, 2000).

Several shorter periods appear both in the $\delta^{18}$O and $\delta^{13}$C viz. 8, 8.1, 6.4, 6.7, 5.6–5.4, 4.8–3.6, 3.3, 3.1 and 2.8–2.3 years. The period 8 and 8.1 years also appears with low amplitudes in the $\Delta^{14}$C spectral analysis (Damon and Peristykh, 2000). Other cycles may be partly due to the harmonics of higher (bands of) periods: such as 5.4 may be due to 4th harmonic of 21 year (5.4 × 4 = 21.6) and 2.3 may be due to 9th harmonic of the 21 year (2.3 × 9 = 20.7). However, part of the power could also be due to actual periodicities of 2-3 years in the solar activity (Bazilevskaya et al.,...
Fig. 2. Power spectrum using REDFIT3.6 for $\delta^{18}$O (left panels) and $\delta^{13}$C (right panels). (a and b): for the data shown in Fig. 1. The dark line shows the power spectrum, the dashed line shows the 95% significance level and the dotted line, the theoretical red noise spectrum. Basic data is subtracted from Savgol filtered data to obtain the high frequency power spectrum. We have used Savgol filters of width 15, and order 3 (filter 1), width 10 and order 4 (filter 2) and width 3 and order 4 (filter 3). (c and d): power spectrum for data treated with filter 1. (e and f): for data treated with filter 2. (g and h): for data treated with filter 3. Numbers shown near peaks are the periodicities in years.
Fig. 3. Power spectrum using REDFIT3.6 for $\delta^{18}O$ (left panels) and $\delta^{13}C$ (right panels). Raw data is first treated with filter 1 to remove slow components. Subsequent to this frequencies up to certain cut off values are again removed using the best-fit method. The dark line shows the power spectrum, the dashed line the 95% significance level and the dotted line, the theoretical red noise spectrum. (a and b): power spectrum with periods up to 94.3 year removed. (c and d): up to 25.4 year removed (e and f): up to 14.7 year removed. (g and h) up to 10.6 year removed. Numbers shown near peaks are the periodicities in years.
or due to tropical QBO (Quasi-biennial oscillations) in the earth’s atmosphere. The QBO is a quasi-periodic oscillation of the equatorial zonal wind between easterlies and westerlies in the tropical stratosphere with a mean period of 2.3 to 2.4 years and is believed to be functioning as conduit to transfer solar effects to lower altitudes (http://web.cecs.pdx.edu/~ssp/Reports/). Satellite based solar observations since 1978 (Wilson, 1997) show that solar magnetic activity modulates the energy received at the top of the atmosphere that may be origin of the cycles in the weather and climate of the Earth.

4. Sixty-year cycle in the proxy record

Several workers have reported presence of 60 year cycle in the Indian summer rainfall time series (Parthasarathy et al., 1993). Agnihotri et al. (2002) have reported presence of 60 ± 10 year cycle in the organic carbon and nitrogen contents of a sediment core from eastern Arabian-sea. Sinha et al. (2005) have observed 60 year cycle in the high-resolution $\delta^{18}O$ time series between 11.7 and 15.2 kyears using a stalagmite from the western Himalaya. We observe a significant 59 year peak in the $\delta^{13}C$ time series (Fig. 3a and b). In order to check further for the presence of 60-year cycle in our raw data, we have removed all slow cycles up to period 94.3 year and fast cycles starting from Nyquist frequency (~2 year) to 50.8 year. This has resulted in significant power for periods from 200 to 50 year with a peak at 50 in $\delta^{18}O$, and 150–44 with a peak at 66 year in $\delta^{13}C$ (Fig. 4a and b). This shows that the 60 ± 10 year cycle is suppressed in our data, because the slow cycles, more than ~60 year appear in the $\delta^{18}O$ and $\delta^{13}C$ time series.

5. Coherency spectrum between sunspot and $\delta^{18}O$ and $\delta^{13}C$

In Fig. 5, we present the cross spectrum analysis between $\delta^{18}O$ and $\delta^{13}C$ and the group sunspot number (gssn). High coherency is found for several frequencies

![Figure 4](image4.png)

![Figure 5](image5.png)

Fig. 4. Power spectrum for $\delta^{18}O$ (a) and $\delta^{13}C$ (b) time series, when all periods except 94.3 to 50.8 year are removed from the basic data to check for the presence of the 60 year cycle. Numbers shown near the peaks indicate the range of periods significant at 95% level, with limits at both ends and the peak value in between.

Fig. 5. Coherency spectrum between group sunspot numbers (1666 to 1995) and $\delta^{18}O$ time series (a); and between sunspot and $\delta^{13}C$ time series (b). SPECTRUM code (Schulz and Stattegger, 1997) used with a Hanning window and over-sampling factor (OFAC) of 4.0, the number of segments (nseg) that overlap each other by 50%. 3. The horizontal bars show the 90% confidence limits for each peak. Numbers shown near peaks are the periodicities in years.

Please cite this article in press as: Yadava, M.G., Ramesh, R., Significant longer-term periodicities in the proxy record ...New Astron. (2007), doi:10.1016/j.newast.2007.04.001
both in $\delta^{18}$O and $\delta^{13}$C at 90% significance level (we choose 90% level so that some low power cycles can be included). Periods where $\delta^{18}$O and gssn have high coherency are 330 (due to trends in the time series), 22, 13.4, 5, 4.2 and 2.4 years. Similarly for $\delta^{13}$C are, 330, 24.4, 13.8, 12.5, 9.4, 5.5, 5, 3.6, 3.5, 3.4 and 2.6 years. Many of these cycles are (resolution = 0.012) same as those shown in the earlier periodogram (Figs. 1 and 2). El Nino events have occurrences at every 4–5 years, but their linkage with the monsoon is believed to be very weak (Wang et al., 2001; Kripalani and Kulakarni, 1997) in the recent past. This means that two-time series $\delta^{18}$O and $\delta^{13}$C are significantly correlated to sunspot occurrence and several cycles observed in them could be sun-induced.

It is puzzling that the 59 year cycle appearing in the $\delta^{13}$C power spectrum does not show significant coherency with gssn.

6. Temporal variations of periods in the proxy record

Stationary behaviour may or may not exist for the periods appearing in $\delta^{18}$O and $\delta^{13}$C time series. This can be tested using wavelet analysis. As we have interpolated the unequally spaced data to get values at equally spaced interval (1 year), some red bias might have been introduced in the resulting equally spaced time series. Therefore we discuss results from filter1 treated data. Wavelet map of the raw $\delta^{18}$O data treated with filter 1 is shown in Fig. 6. In the map power corresponding to 18–21 year period is mainly clustered around 1850–1912. Clustering also appears for the wavelet power corresponding to periods 8–12 year around 1780 and 1920. Therefore, through the wavelet map it is clear that 21-year cycle seen in FFT analyses (Figs. 2 and 3) also appears here predominantly in the $\delta^{18}$O time series between 1850 and 1920 A.D.

A similar wavelet map for the raw $\delta^{13}$C time series treated with filter1 is shown in Fig. 7. Map shows high wavelet power for the period 18–21 year clustered around 1850–1920, similar to $\delta^{18}$O wavelet map. Power clustering in the wavelet spectrum was also observed in the analyses of homogeneous Indian monsoon rainfall time series during 1850–1920 (Bhattacharyya and Narasimha, 2005). The duration 1850–1920 is characterized by a relatively high mean value of the $\delta^{18}$O and $\delta^{13}$C (low rainfall epoch: Fig. 1). During this period large numbers of drought years were observed in India (Parthasarathy et al., 1995). These evidences reconfirm that speleothem isotopes have faithfully recorded past monsoon changes. Significant wavelet power around 1920 for the periods 8–12 years can be seen in the wavelet map (Fig. 6). Around this period two drought years (viz 1918, 1920) can be seen in the instrumental rainfall record (Parthasarathy et al., 1995).

During 1780–1800, clustering of power associated with periods 12–15 appears in the wavelet map (Figs. 6 and 7). It is interesting to note that wavelet power clustering for the periods from 10 to 20 year is observed mainly during the 19th century (1780–1920). We observe in our proxy reconstruction that low rainfall decadal epoch (1850–1920) are concurrent with the duration of low solar activity (Fig. 8). This observation corroborates the earlier conclusion of Bhattacharyya and Narasimha (2005). For the other durations (leaving 1780–1920) in the last 331 years significant power clustering is not observed in the reconstructed time series indicating that the monsoon system and solar link may not be persistently related. For example,

![Wavelet map of $\delta^{18}$O time series after removing the low frequency components using filter 1. The left side shows Fourier period (in year) and the bottom shows time (year). The line contours are plotted to show the boundaries of the grey levels (shown in the box) that indicate power that is significant at 90% level. Area between thick dark line and the time axis is the “cone of influence”, where edge effects are important. (b) Global wavelet spectrum for the same data. The dashed line shows confidence level at 90% level.](image-url)
during the early part of the Maunder minimum, $\delta^{18}$O record shows the lowest value (or highest rainfall, Fig. 8). But around the Dalton minimum, $\delta^{18}$O values do not show low values (high rainfall). This is also in contrary to the behaviour seen during the 1850–1920 interval.

To look for temporal variations of the shorter cycles in the $\delta^{18}$O record we treat the raw data with filter 2 and generate a wavelet map. The $\delta^{18}$O wavelet power for the shorter periods (Fig. 9) between 2 and 8 years shows that: (1) the 2–3 year period is persistent most of the time. Twice,
around 1680 (during high rainfall) and 1860 (during low rainfall), a strong power is seen. (2) Periods of 3–7 years appear only part of the time in the whole time series, e.g. around 1680, 1715, 1760, 1870–1880 and 1965. (3) Power clusters appearing between 1870 and 1920 and 1960–1980 for the periods 5–8 years are similar to results obtained by Kailash and Narasimha (2000) on the instrumental rain data. From the wavelet map one may notice that rainfall change on a time scale of 7–8 years occurred twice i.e., around 1680 and 1870.

Contour lines showing significant power in the wavelet map for slow components (treated with filter 2) in the $\delta^{13}$C (Fig. 10) show that: for the small period component there are a large number of power clusters of 2–5 year period. However, magnitude of the power is low unlike those seen in the $\delta^{18}$O map (Fig. 9). Power clustering during 1870–1920 is similar to that observed in the $\delta^{18}$O wavelet map. Therefore, power clustering during 1870–1920 should be due to large fluctuations in the past rainfall. Wavelet power clustering at two time intervals around 1835 and 1860 may have been due to low rainfall.

All the periods significant in the $\delta^{18}$O power spectrum also significantly appear in the $\delta^{13}$C power spectrum. However, some additional periods, e.g. 59, 8, 8.1, 6.4, 6.7, 3.1

Fig. 9. (a) Wavelet spectrum of the $\delta^{18}$O time series after removing low frequency components using filter 2. Grey levels indicate wavelet power and black contour lines indicate powers that are significant at 90% level. Thick dotted lines indicate cone of influence, plotted partly as the power at other periods are insignificant. (b) Dark line shows global wavelet spectrum and dashed line indicates 90% significance level.

Fig. 10. (a) Wavelet power spectrum of the $\delta^{13}$C data after removing slow cycles using filter 2. Grey levels indicate wavelet power and black contour lines indicate powers that are significant at 90% level. Thick dotted lines indicate cone of influence, plotted partly as the power at other periods are insignificant. (b) Dark line shows global wavelet spectrum and dashed line indicates 90% significant level.
and 3.3 are seen in the $\delta^{13}$C periodogram (Figs. 2 and 3). $\delta^{18}$O is purely a rain dependent proxy whereas $\delta^{13}$C depends, apart from rainfall, also on the biological degradation process in the soil. The total solar irradiance (defined as energy flux per unit area normally incident at the top of the Earth atmosphere) variation between solar maximum and solar minimum is about 0.14% and also it is non-uniformly distributed across the electromagnetic spectrum (Beer et al., 2000; Bard and Frank, 2006). For example at 140, 200 and 250 nm the solar irradiance has 20%, 8% and 3% variation from solar maximum to solar minimum (Lean et al., 1997). Therefore, processes that are dependent upon the highly variable bands of the spectrum may have significant variations during a solar cycle. A layer of ozone in the upper atmosphere absorbs UV radiation and prevents most of it from reaching the Earth. However, the ozone formation may be strongly influenced by variations in the UV level. New results indicate that decomposition of leaf and litter carried out by fungi and bacterial communities are influenced by the UV variations (Zepp et al., 2003; Searles et al., 2001; Cybulski and Peterjohn, 1999). There are reports of the 11 year cycle in the annual thickness record of the stalagmites (Frisia et al., 2003) for which biologically mediated soil carbon dioxide production or cloud cover variability is offered as a possible link process that may transfer changes in the solar variability to speleothems. These may be the possible reasons why $\delta^{13}$C registered additional fast periods.

The precise relationship between solar irradiance and the sun spot numbers is also not very well known (Beer et al., 2000). It is evident that the group sunspots numbers that have highest spectral power for the 11 year cycle is missing in the $\delta^{18}$O spectrum. The overall insolation variation over the 11 year cycle between the maximum and minimum activity is small and is less than 0.1% (Beer et al., 2000 and Tsiropoula, 2003), that may not be very significant for perturbing the transport of moisture during monsoon period. Rainfall has a variable correlation with the solar variability, positive, negative or no depending upon the time interval and the location (Tsiropoula, 2003). Rainfall in India shows the 11-year cycle only at certain stations (Bhattacharyya and Narasimha, 2005) and not in the All-India rainfall time series (Hiremath and Mandi, 2004). The rhythmic variations in the sun are seen in several features, e.g. sunspots, faculae, flare, radio bursts etc; all these show 11 year cyclic variation.

Some climate models have also investigated the effect of solar cycles on climate (e.g., Ruzmaikin, 1999; Shindel et al., 1999; Haigh, 1999; Larkin et al., 2000 and Labitzke et al., 2002; Ruzmaikin et al., 2005). Ruzmaikin (1999) suggested that the 11-year solar activity forcing of climate could be through stochastic resonance with the ENSO. Shindel et al. (1999) suggested that upper stratospheric ozone changes may amplify the observed 11-year solar cycle irradiance changes to affect climate, and several oscillators such as the geopotential height variations could at least in part be driven by solar activity. Haigh’s (1999) review of modelling work on solar cycles and climate showed that the Northern Hemisphere responds to solar changes in a similar way to the injection of volcanic aerosol. He also highlighted some of the limitations of such models, as did Labitzke et al. (2002).

While low power solar cycles (viz. 22 year and ~2.4 year) are seen in the $\delta^{18}$O and $\delta^{13}$C spectra, whereas the stronger 11 year cycle is missing. This confirms earlier...
observations by Mehta and Lau (1997), based on a more limited data set, that the monsoon responds more strongly to the multi-decadal solar irradiance components than to the 11-year component.

Some of the short cycles (4–7 year) seen may have teleconnections with the El Nino/La Nina frequencies. High-resolution data on a modern speleothem from Belize has shown that El Nino Southern Oscillations (ENSO) related changes in the terrestrial carbon cycle can be recorded by stalagmites (Frappier et al., 2002). Based on the statistical analysis of instrumental data from South-east Asia, earlier work had shown that the certain epochs that are above or below of the normal rainfall, were not influenced by El Nino/ La Nina oscillations (Kripalani and Kulakarni, 1997). There was reduction in the strength of the Indian monsoon in the El Nino years and vice versa (Rupa kumar and Pant, 1997). Also, such a link has declined after 1970 (Kumar et al., 1999). A comparison (Fig. 11) of the proxy records with the Southern Oscillation Index (source: ftp://ftp.cru.uea.ac.uk.data) shows that (1) in some years $\delta^{18}O$ and $\delta^{13}C$ have responded to SOL, (2) in some cases $\delta^{18}O$ and $\delta^{13}C$ have responded to SOI with a few years of lag, (3) in the later part of the middle of the 19th century, such a link is rarely seen. Responses of $\delta^{18}O$ and $\delta^{13}C$ differ due to underlying biological processes. It seems that the monsoon system is influenced broadly by two processes, first occurring in the atmosphere (e.g. the Quasi-Biennial Oscillations) second air–sea interaction (e.g. El Nino). There is a complex coupling between them: sometimes-atmospheric processes are dominant and therefore, we see the 21 year period clustered during 1850–1910. In other situations, ocean is more dominant and solar cycles do not appear in the proxy record whereas they are more highlighted by the shorter cycles characterizing ocean related events.

7. Conclusions

We report several periods of possible solar origin in the stable carbon and oxygen isotope records of a speleothem that represent monsoon rainfall variation during the last three centuries. A periodicity of 21 year in $\delta^{18}O$ and $\delta^{13}C$ has significant power, but the ~11 year cycle is weak, confirming the earlier observation that multi-decadal solar components have more influence on the Indian monsoon. Using filtering techniques, several shorter periods ranging between ~7 and 2.3 years are revealed. Most of the shorter periods are likely due to solar origin. However, they may also be due to ocean/atmospheric processes. Most of the periods significant in the $\delta^{18}O$ are also seen in the $\delta^{13}C$ periodogram. However, presence of some additional periods in $\delta^{13}C$ may have been captured due to biological processes. Through wavelet analysis we find that during low rainfall epoch around 1900, 21-year cycle is predominantly seen. Shorter scale (13–2 year) variability may not only be due to sunspot variations but also indirectly due to variability in the climate system.

References


Please cite this article in press as: Yadava, M.G., Ramesh, R., Significant longer-term periodicities in the proxy record ...New Astron. (2007), doi:10.1016/j.newast.2007.04.001