

## A 780-year annually resolved record of Indian Ocean monsoon precipitation from a speleothem from south Oman

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[1] Meteorological records of monsoon rainfall in the Indian Ocean are generally less than 100 years long. The relative brevity of these records makes it difficult to investigate monsoon variation on decadal and centennial timescales, to determine what factors influence the intensity of rainfall on these timescales, or to place possible changes in the twentieth century into a broader historical context. Development of a geologic proxy for rainfall that records annual variation in the monsoon over much longer time periods than are covered by instrumental records would be a significant step forward. We have developed an annually resolved record of monsoon rainfall variation for the past 780 years based on annual layer thickness and stable isotope analyses of a laminated stalagmite from southern Arabia. Our results show that monsoon variation over the past century is not outside of the range of the past 800 years. Decreasing monsoon rainfall over the past century is related to increasing sea surface temperature in the Indian Ocean. Spectral analyses of the record are dominated by cycles that are similar to those observed in records of solar activity on centennial timescales. Decadal to interannual cycles in the record appear to originate in the tropical Pacific Ocean. *INDEX TERMS:* 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 3354 Meteorology and Atmospheric Dynamics: Precipitation (1854); 1620 Global Change: Climate dynamics (3309); 1699 Global Change: General or miscellaneous; *KEYWORDS:* Monsoon, paleoclimate, rainfall, Indian Ocean, speleothem, oxygen isotopes

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### 1. Introduction

[2] The climate of the regions surrounding the Indian Ocean in the Northern Hemisphere is dominated by the seasonally reversing monsoon winds. Studies of recent summer monsoon variation suggest relationships to snow cover in the Himalayas, tropical sea surface temperatures, and teleconnection to El Niño-Southern Oscillation (ENSO) [Webster *et al.*, 1998]. Yet, instrumental records of rainfall in the areas surrounding the Indian Ocean are limited to about 100 years [Sontakke *et al.*, 1993], too short to accurately detect oscillations in rainfall of greater than a few decades. In contrast, most longer records of monsoon variation, derived from marine sediments in the Indian Ocean, lack the resolution to detect changes on timescales of less than several hundred years. Consequently, comparing variations in the monsoon with variation in possible forcing mechanisms is difficult, and how the monsoon

varies cyclically on decadal to centennial timescales remains largely unknown. Because success in predicting the future course of Indian Ocean monsoon rainfall is to a large degree dependent on understanding how the monsoon has responded to possible forcing mechanisms in the past, development of a geologic proxy for rainfall in this region would be of great significance.

[3] One possible recorder of changes in monsoon intensity is speleothems. Speleothems, such as stalagmites, stalactites and flowstones, are formed when calcium carbonate precipitates from degassing solutions seeping into limestone caves. That speleothems contain a paleoclimate signal has been recognized for almost 30 years [Hendy and Wilson, 1968]. Paleoclimate information can be gained from such deposits in several ways, including oxygen and carbon isotope ratios of speleothem carbonate [e.g., Bar-Matthews *et al.*, 1997; Dorale *et al.*, 1998]. Also, in near surface caves in areas with a strong annual climate cycle, variations in the thickness of growth layers can be related to climate [Baker *et al.*, 1993].

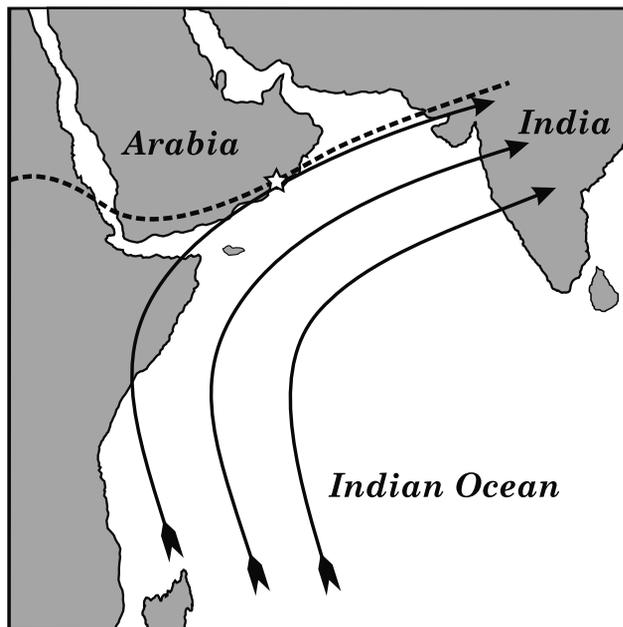
[4] Previous work in southern Arabia, demonstrates that stalagmite  $\delta^{18}\text{O}$  values are inversely related to the amount of rainfall, primarily via an 'amount effect' [Burns *et al.*, 1998, 2001; Neff *et al.*, 2001]. Correlations between oxygen isotope ratios of rainfall and the amount of precipitation typify the strongly convection rainfall systems in tropical

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**Figure 1.** Map of the northwest Indian Ocean region. Arrows show the surface wind pattern during the summer monsoon period, and the dashed line is the location of the ITCZ. Star marks the study site.

regions (e.g. Rozanski). The principle behind the correlation may be thought of as a vertical, temperature-driven, Rayleigh fractionation process: the more intense vertical convection is the greater the fraction of water vapour lost to precipitation and the lower the  $\delta^{18}\text{O}$  values of precipitation. Using this principle, we present a 780 year record of monsoon intensity from an annually-laminated stalagmite from the Salalah area of southern Oman. In addition to oxygen isotopes, the record is based on variations in annual growth layer thickness and carbon stable isotope ratios of stalagmite calcite, which are related to the amount of precipitation.

## 2. Material and Methods

[5] Stalagmite S3 was collected from a small, near-surface cave in the Salalah region of southern Oman (Figure 1). The cave consists of two small chambers connected by a <1 m high passageway. The interior chamber, from which the sample was taken, is approximately 10 m  $\times$  10 m with about a 3 m high ceiling. The cave is poorly ventilated, and measured relative humidity was near 100% on each of the several occasions the cave was visited [Fleitmann, 2001]. Approximately 20 m of limestone bedrock with a thin soil cover overlies the cave, so that the flowpath of water from the ground surface to the cave is quite short. The flora on the hillside above the cave is a mixture of trees and shrubs that use the C3 photosynthetic pathway.

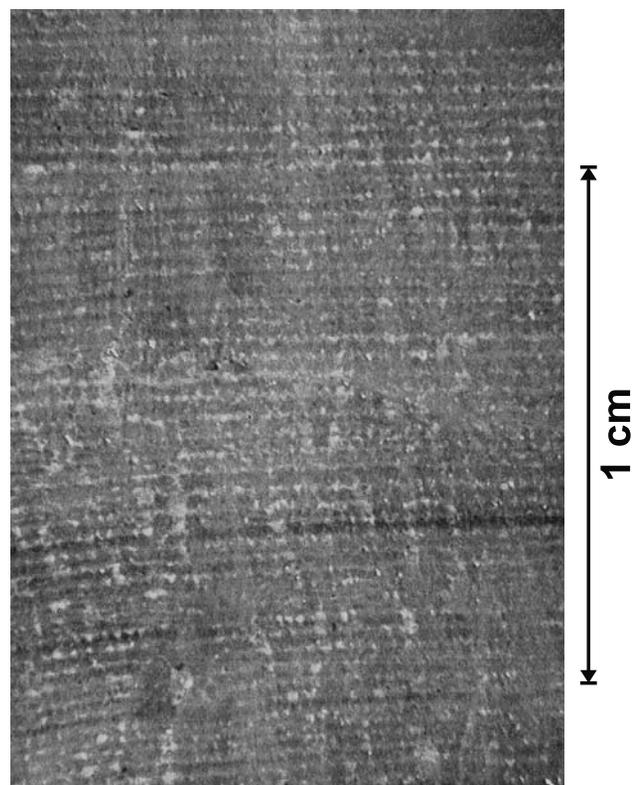
[6] The modern climate of the area is subject to highly seasonal variation in rainfall, controlled by the changing monsoon wind pattern of the Indian Ocean. Annual rainfall averages from 150 mm at lower altitude to 500 mm higher in the Dhofar Mountains. In most years, more than 75% of total annual precipitation falls during the summer

monsoon months of June, July and August (Ministry of Water Resources, Sultanate of Oman, unpublished data, 1978–1994). Precipitation occurs not as the heavy rains normally associated with the monsoon, but as fine mist and rain and occult precipitation sourced by fog. S3 was actively growing at the time of sampling, in November 1996.

[7] The sample was cut into halves and polished. The stalagmite consists of white, crystalline calcite throughout. No evidence of a growth hiatus, such as clay bands, etched irregular surfaces, or truncated laminations is present. The slabbed section revealed very regular, sub-millimeter, growth laminations (Figure 2). Over the total length of the 27 cm, 780 layers were counted using digitized photomicrographs. Multiple counts indicate an error of  $\pm 5$  laminae at the bottom of the sample. At the same time, the thickness of each lamination was measured. The average thickness is 0.34 mm.

[8] For oxygen and carbon stable isotope ratio determinations, a total of 603 samples were taken using a hand-held dental drill with an 0.4 mm drill bit. Samples were taken at approximately 0.4 mm interval. About 0.5–1 mg of powder was drilled for each sample and analyzed with an on-line, automated, carbonate preparation system linked to a VG Prism II ratio mass spectrometer. Results are shown as the per mil difference between sample and the VPDB standard in delta notation, where  $\delta = (R_{\text{sample}}/R_{\text{standard}} - 1) \times 1000$ , and R is the ratio of the minor to major isotope. Reproducibility of standard materials is 0.08‰ for  $\delta^{18}\text{O}$  and better than 0.04‰ for  $\delta^{13}\text{C}$ .

[9] The depositional ages of two samples were determined by measuring the U/Th ratios of the samples by thermal ionization mass spectrometry (Table 1). The samples were



**Figure 2.** Plain light photomicrograph of a thin section of stalagmite S3 showing very regular laminations.

**Table 1.** Stalagmite S3 Uranium and Thorium Isotope Concentrations and Calculated Ages

Depth, nm	[Th-232]		[Th-232]		[U-234]		[U-238]		dU-234		Age		Age (Corrected)	
	pg/g	+/-	ng/g	+/-	ng/g	+/-	mg/g	+/-	per mil	+/-	a	+/-	a	+/-
149	0.020	0.003	0.414	0.005	0.016	0.0001	0.279	0.0007	44.1	3.9	460	60	420	55
245	0.029	0.001	0.318	0.003	0.014	0.0001	0.243	0.0006	40.9	4.7	780	25	740	24

weighed and dissolved in 7N HNO<sub>3</sub>. After dissolution, a <sup>229</sup>Th spike and <sup>233</sup>U/<sup>236</sup>U double spike was added for determination of concentration. Isotopic measurements were performed on a Finnigan MAT 262 thermal mass spectrometer equipped with a retarding potential quadrupole system (RPQ). Uranium was determined with a single electron multiplier (<sup>233</sup>U, <sup>234</sup>U, <sup>235</sup>U and <sup>236</sup>U) and one Faraday cup (<sup>238</sup>U). The natural ratio of <sup>235</sup>U/<sup>238</sup>U was used to calibrate the yield of the multiplier. The peak flatness is less than 0.2% (over 150 ppm in mass). The concentration of the <sup>233</sup>U/<sup>236</sup>U double spike was calibrated against the NIST CRM 960 uranium standard material. The <sup>234</sup>U of this standard was measured at  $-31.8 \pm 4.1\%$  in good agreement with other workers. The reproducibility of the isotope ratio of <sup>234</sup>U/<sup>238</sup>U during the period of the measurement was at 0.3%. The peak flatness of the RPQ used for determination of <sup>230</sup>Th was less than 0.2% (over 150 ppm in mass). We used a <sup>229</sup>Th spike calibrated against an internal <sup>230</sup>Th/<sup>232</sup>Th standard (HDAKT-1). The reproducibility of the concentration of <sup>232</sup>Th was 0.8%. <sup>238</sup>U and <sup>232</sup>Th blanks were routinely measured and taken into account.

### 3. Results and Discussion

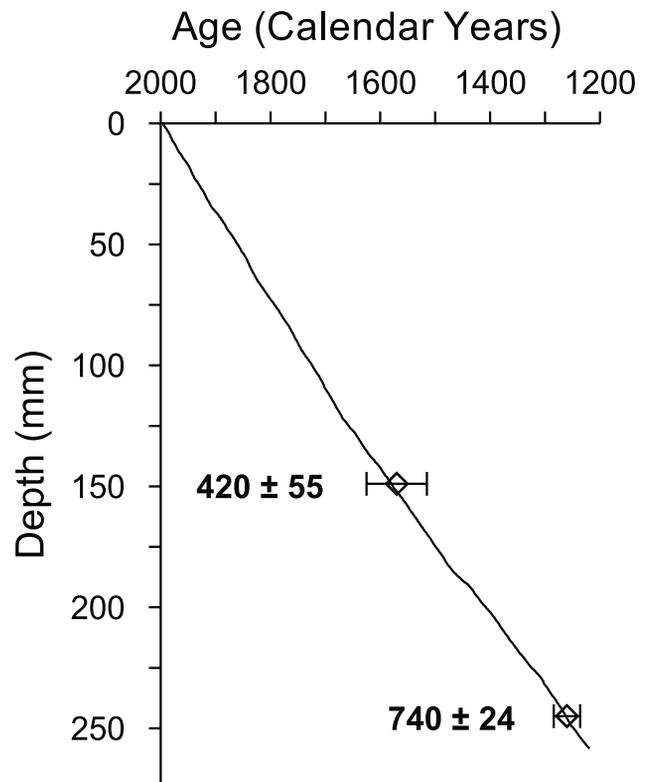
#### 3.1. Paleoclimatology of Stalagmite S3

[10] The very regular laminations revealed in the polished slab of S3 (Figure 2) together with the seasonally varying precipitation pattern, strongly suggest that the laminae are annual. The chronology constructed using the growth layer thickness measurements was verified using the two Th/U age determinations. Measurements at 150 mm and 245 mm, yield ages of  $420 \pm 55$  and  $740 \pm 24$  years, respectively. These values fall almost precisely on the age versus depth graph (Figure 3) determined by layer counting. The age versus depth graph shows that stalagmite S3 grew at a quite constant rate beginning at  $1215 \pm 5$  A.D. An age for each stable isotope samples was assigned using the age-depth plot derived from the annual growth layer thicknesses. The average sampling interval for the stable isotope analyses is 1.3 years (Figure 4).

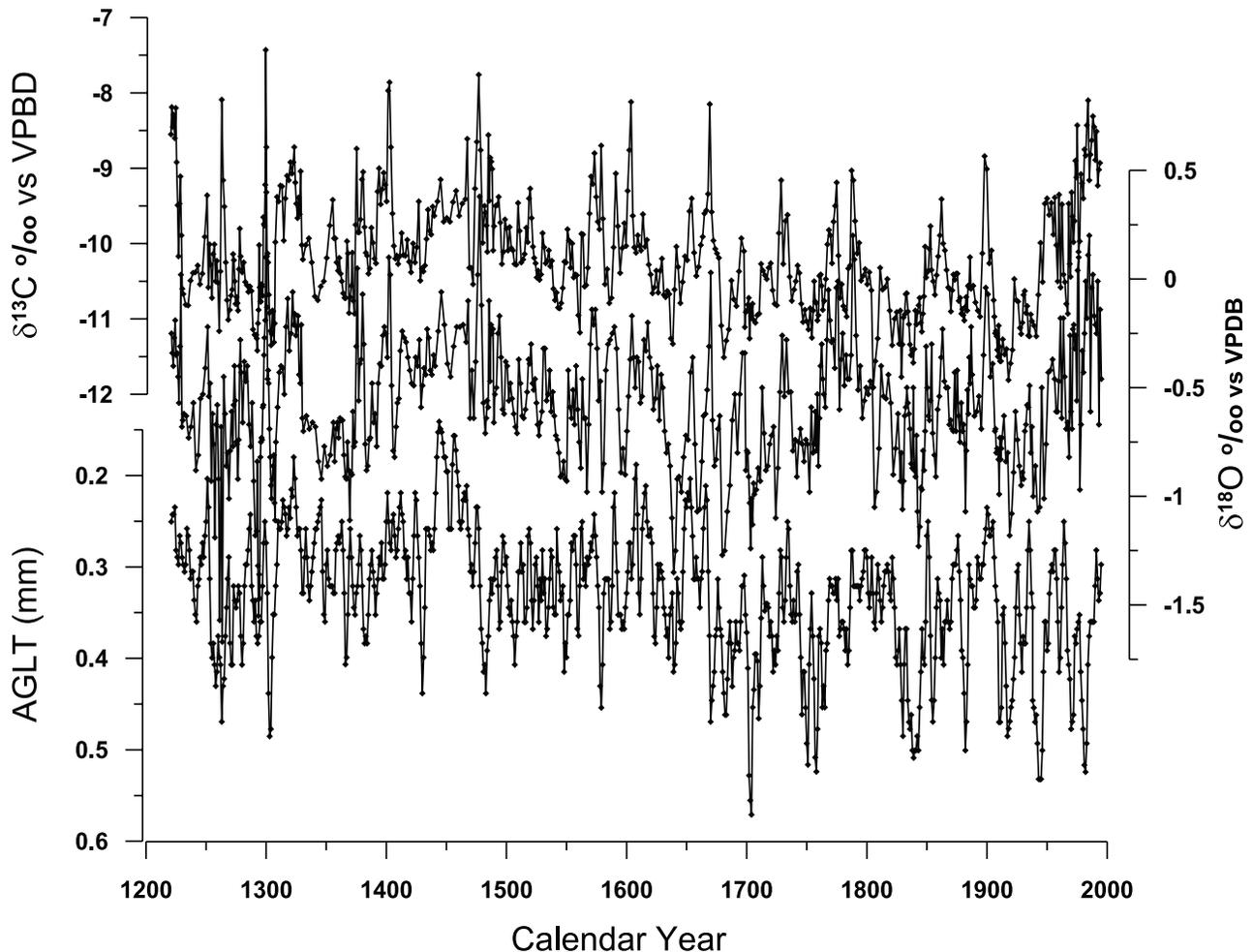
[11] We derive paleoclimate information from S3 using three essentially independent parameters: annual layer thickness and oxygen and carbon stable isotope ratios of speleothem carbonate. The annual laminations vary from 0.1 to 0.8 mm in thickness, with an average of 0.35 mm (Figure 3). The  $\delta^{18}\text{O}$  values of stalagmite S3 mostly fall in the range of 0‰ to  $-1\%$  (VPDB). These values are about 0.5 per mil enriched in <sup>18</sup>O with respect to values expected for isotopic equilibrium with cave drip waters (+1 to  $-1\%$  versus MOW) and cave temperatures (26°C). The  $\delta^{13}\text{C}$  values of carbonate from S3 range from  $-8$  to  $-11\%$ . Measurements of the isotopic composition of monsoon rainfall in the region of the cave show that drip waters and rainwaters are isotopically indistinguishable [Fleitmann, 2001].

[12] Time series of all three parameters are plotted in Figure 3. Our interpretation is that all three of these factors vary primarily in response to changes in the amount of precipitation, although controlled by different mechanisms. Variations in laminae thickness reflect changes in annual delivery of dissolved calcium and carbonate to the stalagmite and should be positively correlated to the amount of drip water [Baker *et al.*, 1998]. Cave Defore is very near surface cave, with only about 20 m of limestone bedrock above the cave. That annual laminations are present is evidence that drip water flow very quickly responds to seasonal changes in rainfall. On annual timescales, increases in monsoon precipitation amount result in a thicker annual layer being deposited.

[13] Changes in the oxygen isotope ratios of the stalagmite calcite primarily reflect changes in the  $\delta^{18}\text{O}$  value of drip water which varies over time mainly as a result of changes in  $\delta^{18}\text{O}$  of precipitation. The direct effects of temperature on the isotopic records, through the temperature dependence of the water-calcite oxygen isotope fractionation factor, are likely to have been minimal. The range of



**Figure 3.** Age versus depth plot for speleothem S3 as determined by layer counting. Also shown are two U/Th age determinations with error bars. The two timescales agree within the error of the U/Th ages.



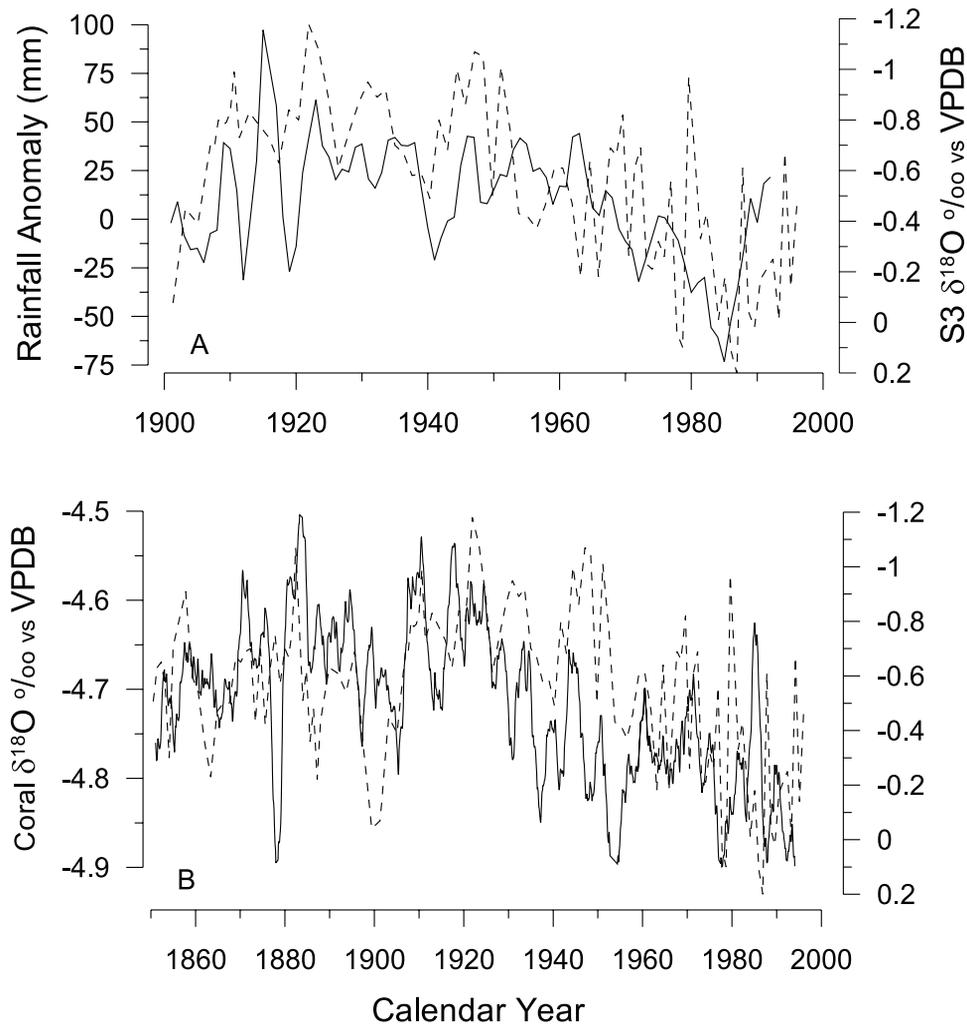
**Figure 4.** (bottom) Layer thickness, (middle)  $\delta^{18}\text{O}$ , and (top)  $\delta^{13}\text{C}$  of speleothem S3 versus calendar year. See color version of this figure at back of this issue.

observed  $\delta^{18}\text{O}$  values (1.2‰) would require more than  $5^\circ\text{C}$  of variation in average annual temperature, too large to be reasonable. Nor is the isotopic composition of rainfall related to temperature in low-latitudes [Rozanski *et al.*, 1993]. More likely is that the stalagmite  $\delta^{18}\text{O}$  values are inversely related to the amount of rainfall, primarily via an amount effect [Rozanski *et al.*, 1993]. A number of additional processes might also contribute to variation in the  $\delta^{18}\text{O}$  signal, for example changes in evaporation in the soil zone, humidity within the cave itself, groundwater infiltration rate or kinetic fractionation [Hendy, 1971] associated with changes in the drip rate. However, all of these processes affect the oxygen isotopic ratios of speleothem calcite in the same “direction” as an amount effect: wetter conditions result in more negative isotopic ratios. Thus, while we cannot with certainty establish the exact degree to which individual factors influence the  $\delta^{18}\text{O}$  values of S3 carbonate, for all processes wetter conditions produce more negative  $\delta^{18}\text{O}$  values.

[14] The carbon isotope ratios of speleothem carbonate are also often sensitive indicators of climate [e.g., Frumkin *et al.*, 2000]. In the case of stalagmite S3, the overall  $\delta^{13}\text{C}$  values are determined by the photosynthetic pathway of the plant community in the recharge area and the degree of rock

water interaction. The quite negative  $\delta^{13}\text{C}$  values, from  $-8\text{‰}$  to  $-11\text{‰}$ , reflect the regional C3 plant community and short groundwater flowpath between the soil zone and the cave. As is the case for  $\delta^{18}\text{O}$ , a number of different factors related to rainfall amount play a role in causing the observed variation in  $\delta^{13}\text{C}$ . These include: changes in the amount of  $^{12}\text{C}$  depleted, plant-respired  $\text{CO}_2$  input to the groundwater in the soil zone as a response to rainfall induced changes in plant activity; more/less interaction with bedrock limestone as the result of less/more rapid flow; or varying kinetic isotope effects related to changing drip rates. As is the case for  $\delta^{18}\text{O}$  values, all of these processes affect  $\delta^{13}\text{C}$  in the same “direction” with regard to increasing rainfall: more rainfall results in lower carbonate  $\delta^{13}\text{C}$  values.

[15] Figure 3 shows that all three measured parameters vary in concert and in a consistent manner with regard to changing precipitation. Thicker growth layers are associated with more negative  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values. The linear correlation coefficient ( $r^2$ ) between growth layer thickness and  $\delta^{18}\text{O}$  is 0.57, and that between the two isotopes is 0.62. That all three measured parameters vary together in the sense expected suggests that stalagmite S3 is an accurate recorder of changes in the amount of precipitation. As a further test of the relationships between rainfall amount and



**Figure 5.** Comparison of S3  $\delta^{18}\text{O}$  (orange line) with (a) 3-point running average of historical rainfall data from East Africa and southern Arabia [Vose *et al.*, 1992] for the period from 1900–1990, and (b) 25-point running average of coral  $\delta^{18}\text{O}$  values from the Seychelles Islands [Charles *et al.*, 1997]. See color version of this figure at back of this issue.

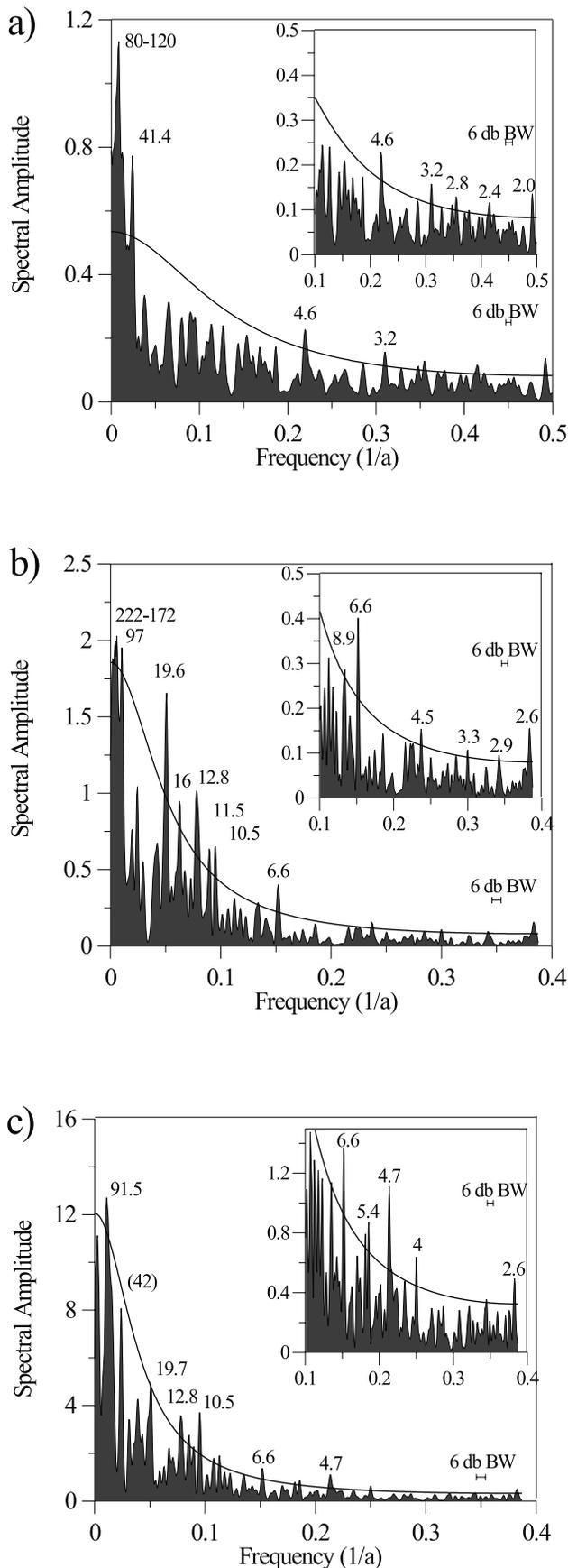
stable isotopes, we sought to calibrate measured rainfall amount and isotopic values of speleothem carbonate. For southern Oman, such a calibration is greatly hindered by the lack of any long, continuous meteorologic record of rainfall. Therefore, we compared the S3 speleothem isotopic record with a time series of gridded annual precipitation anomalies from the Global Historical Climatology Network [Vose *et al.*, 1992] over a broader area from  $10^\circ$  to  $20^\circ$  N and  $30^\circ$  to  $55^\circ$  E, essentially the eastern Sahel region of Africa, Yemen and western Oman (Figure 4a). Similar overall patterns for rainfall anomalies and  $\delta^{18}\text{O}$  are observed. Individual anomalies in the two records are not always correlated, yet the trend of increasing  $\delta^{18}\text{O}$  and decreasing rainfall from the period 1920–1930 through about 1980 can be observed in both records. Other compilations of meteorological records from the Sahel region of Africa also show a trend of decreasing rainfall over this period [Folland *et al.*, 1986].

[16] We also compared our speleothem  $\delta^{18}\text{O}$  record to a smoothed (to remove the large annual variation) coral  $\delta^{18}\text{O}$  record from near the Seychelles Islands in the central Indian Ocean [Charles *et al.*, 1997]. The coral record is primarily a

function of sea surface temperature (SST) variation related to changes in the intensity of monsoon wind-driven upwelling [Charles *et al.*, 1997]. Despite possible differences in age models of several 1–3 years, the coral and speleothem  $\delta^{18}\text{O}$  curves are remarkably similar (Figure 4b). They also show the expected interrelationship, with more negative coral values (warmer SST and weaker monsoon wind) associated with less negative speleothem values (less precipitation). Based on the comparisons between the speleothem and regional rainfall and coral records, we conclude that speleothem S3 is an accurate recorder of monsoon-related changes in precipitation over a broad region.

### 3.2. Long-Term Trends in S3 Data Set

[17] The 780 yearlong time series (Figure 3) show no significant long-term trend in any of the three rainfall proxies. Nor are values from the post-industrial period or 20th century anomalous compared to those from the pre-industrial period. In contrast, high-resolution data covering approximately the same time period from Himalayan ice cores show a marked increase in  $\delta^{18}\text{O}$  values in the late 20th



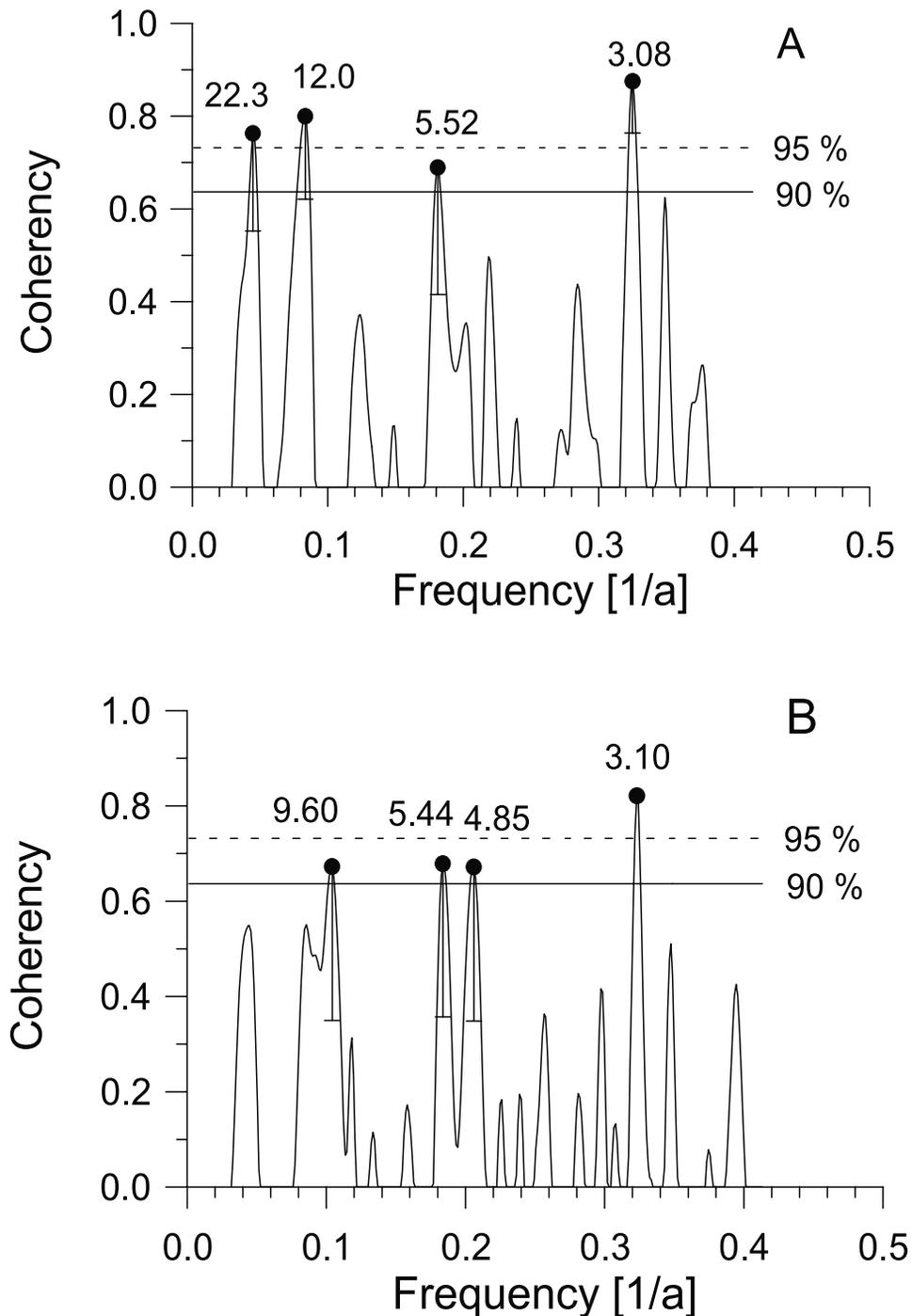
century compared to the previous  $\sim 400$  years [Thompson *et al.*, 2000]. Accumulation rate in the ice cores decreases from the 19th to 20th centuries [Thompson *et al.*, 2000]. Both changes are thought to reflect the global warming trend of the twentieth century [Mann *et al.*, 1998]. It might be expected that monsoon rainfall would increase in response to increased temperatures and decreased snow cover in the Himalayas, which are thought to control the timing of the onset and intensity of monsoon rainfall in the following summer [Dickson, 1984; Meehl, 1994a]. Yet, our record suggests that such an increase did not occur. Over most of the twentieth century monsoon rainfall was decreasing. The explanation may be that monsoon intensity responds to the difference in temperature between the Indian Ocean and the Tibetan Plateau [Meehl, 1994b], rather than solely to conditions within the latter. Warming of the Indian Ocean during the 20th century may have decreased the land-sea thermal gradient and reduced monsoon intensity [Meehl, 1994b]. The correspondence between Indian Ocean mean annual sea surface temperatures (the Seychelles coral  $\delta^{18}\text{O}$  record [Charles *et al.*, 1997]) and precipitation (S3  $\delta^{18}\text{O}$ ) supports this hypothesis.

### 3.3. Spectral Analyses

[18] Spectral analyses of layer thickness,  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  were done using the Spektrum program for unevenly sampled data sets [Schulz and Stettger, 1997]. All three records contain cyclical components (Figure 5). As is the case for speleothem records of monsoon variation during the early Holocene [Neff *et al.*, 2001], most of the identified cycles are close to those observed in various records of solar activity [Sonnett *et al.*, 1992]. The  $\sim 200$  year cycle in  $\delta^{18}\text{O}$ , which is present in the  $\delta^{13}\text{C}$  but does not exceed the 90% confidence limit, is close to the 206 year cycle in solar activity. Similarly, the 80–120 year cycle in layer thickness, 97 year cycle in  $\delta^{18}\text{O}$  and 91 year cycle in  $\delta^{13}\text{C}$  are within error of the 90 year Gleisberg cycle observed in records of sunspot activity. These two cycles are also present in the  $\Delta^{14}\text{C}$  record of tree rings, in which they are attributed to solar forcing [Stuiver and Braziunas, 1993].

[19] Cycles of around 20 year and 12 year in duration are present in both isotopic records. These cycles are similar in length to the 20–23 year Hale cycle in magnetic solar activity and to the 11 year sunspot cycle, respectively. However, the total change in solar irradiance over the 11 year solar cycle is around 0.1%, and perhaps 0.2 to 0.3% on centennial timescales, with somewhat greater variability at

**Figure 6.** (opposite) Spectral analyses of (top) layer thickness, (middle)  $\delta^{18}\text{O}$ , and (bottom)  $\delta^{13}\text{C}$  data sets. Also shown are red noise curves for each data set. Spectral peaks which rise above the red noise line are statistically significant at the 90% confidence level. The layer thickness record has statistically significant (at the 90% confidence level) cycles at  $\sim 101$ , 41, 4.6 year and a cluster of cycles between 3.2 and 2.0 year. The  $\delta^{18}\text{O}$  records has significant cycles at  $\sim 204$ , 97, 19.8, 16.1, 12.8, 6.6 year, and several cycles of 4.5 year to 2.6 year in length. The  $\delta^{13}\text{C}$  record shows a very similar pattern to  $\delta^{18}\text{O}$ , except that the  $\sim 200$  year and 16 year cycles are not present, and the  $\sim 20$  year cycle falls below the 90% confidence level.

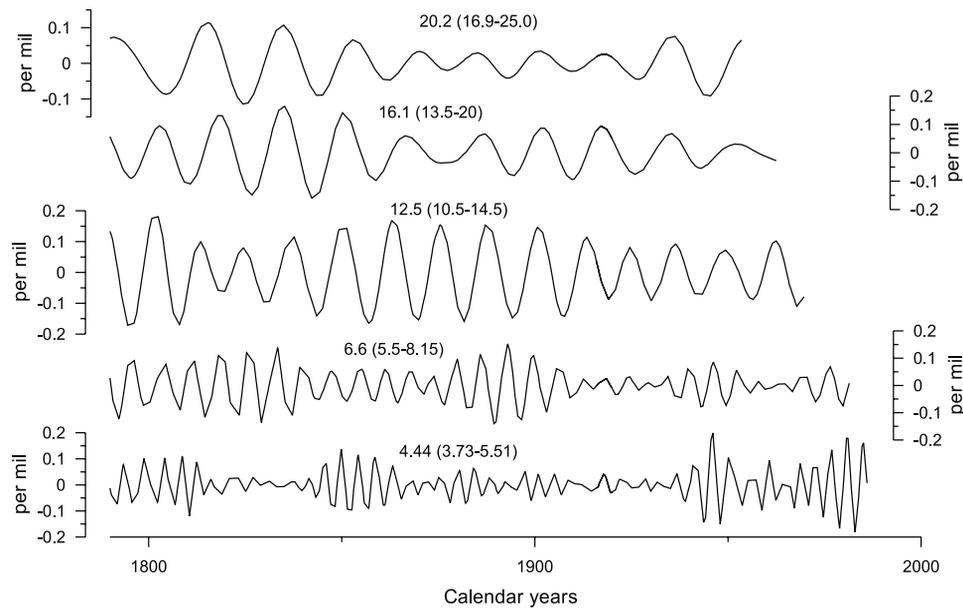


**Figure 7.** Cross-spectral analysis of the S3 and (a) Seychelles coral  $\delta^{18}\text{O}$  [Charles *et al.*, 1997] and (b) the NINO3.4 sea surface temperature records. Strong coherency between S3 and the coral is observed for decadal ( $\sim 20$  and  $\sim 12$  year) and interannual ( $\sim 5$  and  $\sim 3$  year) cycles. Coherency between S3 and the Nino3.4 data is strongest at the  $\sim 3$  year cycle.

higher wavelengths [Fligge and Solanki, 2000]. Any direct effect of changing solar irradiance on the monsoon, such as through increased or decreased sensible heating of the Tibetan Plateau is very unlikely. Nor do comparisons of solar forcing with the S3 records show any direct link between the two.

[20] Alternatively, the decadal scale cycles in monsoon rainfall recorded by S3 may be related to decadal variability

in other parts of the climate system. The monsoon has been shown to strongly interact with both the El Niño–Southern Oscillation (ENSO) [Webster *et al.*, 1998; Charles *et al.*, 1997; Cole *et al.*, 2000], and decadal-scale variability in the tropical Pacific. In particular, coral records of Indian Ocean SST's are coherent with tropical Pacific climate at interannual to decadal periods [Charles *et al.*, 1997; Cole *et al.*, 2000]. A number of cycles with periods of 2–3 years are



**Figure 8.** Bandpass filtered spectra of the S3  $\delta^{18}\text{O}$  record at frequencies centered on 20, 16.1, 12.5, 6.6, and 4.5 years.

found in both of the speleothem isotopic records, and within the layer thickness record, indicating that ENSO-type variability is present. Cycles of 4.6 year in layer thickness and 6.6 year in both isotopic records, which may be ENSO-related are also present. El Niño events correlate with anomalous warming in the equatorial Indian Ocean [Chambers *et al.*, 1999] and often with reduced monsoon rainfall [Webster *et al.*, 1998].

[21] Using cross-spectral analysis, we made comparisons between the decadal and interannual periods in the speleothem record, the Seychelles coral  $\delta^{18}\text{O}$ , and the Niño 3.4 ENSO index [Kaplan *et al.*, 1998]. The highest coherency occurs between the speleothem record and coral data from the Seychelles (Figure 6a), with cycles at 22 y, 12 y, and 3 year all coherent at the 95% confidence level and at 5.5 year at 90% confidence level. The NINO3.4 index is also coherent with the S3  $\delta^{18}\text{O}$  record in ENSO bandwidths, the 3 year cycles in the records is coherent at 95% confidence level, and 4.8 y, 5.4 year and 9.6 year cycles are coherent at the 90% confidence level (Figure 6b). The strong coherence between monsoon rainfall (S3  $\delta^{18}\text{O}$ ) and Indian Ocean SST (Seychelles coral  $\delta^{18}\text{O}$ ), and the further demonstrated coherence between the latter and Pacific climate records [Charles *et al.*, 1997; Cole *et al.*, 2000] suggests that the decadal components of monsoon rainfall variability also have their origin in the tropical Pacific and are related to decadal ENSO variability.

[22] Because of the strong coherency between the S3  $\delta^{18}\text{O}$  and other tropical climate records, and because the S3 record is longer, by at least 400 years, than any existing coral record we can use the S3 data to address the question of what the dominant frequencies of tropical climate variation have been over the past almost 800 years. We made bandpass filtered records for each of the decadal and shorter frequencies in the S3  $\delta^{18}\text{O}$  record (Figure 6). Based on a 155 year coral record, Urban *et al.* [2000] suggested that a change in ENSO behavior from dominance by decadal-scale

variability before  $\sim 1900$  to shorter periods thereafter. They also noted a shift to a concentration centered at approximately 4 years around 1955. The S3  $\delta^{18}\text{O}$  record shares some of these characteristics, with generally weakening decadal variance over much of the past 150 years, and sharp strengthening of 4 year cyclicality at around 1950 (Figures 7 and 8). Urban *et al.* [2000] also suggested a relationship between background climate and the frequency of ENSO variance, with cooler global climate periods associated with increased decadal variability. While this pattern may be valid for the late nineteenth and twentieth centuries, the longer term perspective provided by the S3 speleothem record shows no coherent relationship between global temperature estimates of the past six centuries [Mann *et al.*, 1998] and the dominant frequency of monsoon rainfall variation. For example, the periods from 1300–1350 and 1650–1750 show strong decadal variance in S3  $\delta^{18}\text{O}$ , but neither period is anomalously cool in reconstructed temperature records [Mann *et al.*, 1998].

#### 4. Conclusions

[23] The oxygen and carbon isotopic ratios and annual growth layer thicknesses of a stalagmite from the Salalah area of southern Oman provide a record of changes in monsoon rainfall over the past 780 years. The  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values of speleothem calcite are inversely related to precipitation, while growth layer thickness is proportional to precipitation. None of the three time series shows a unidirectional trend, nor is the 20th century anomalous in comparison to the previous 700 years. Over most of the twentieth century monsoon rainfall was decreasing in response to warming of the Indian Ocean. Spectral analyses of the three time series demonstrate that on centennial timescales, monsoon variation is primarily related to solar variation. On decadal and shorter timescales, monsoon variation is associated with decadal variation in the tropical

Pacific and ENSO. No general relationship between the strength of ENSO-scale variation and the background state of global temperatures is observed.

[24] **Acknowledgments.** We are very grateful to Ali Al Kathiri for showing us the location of Cave Defore and to Zaher Al Suleimani of the Ministry of Water Resources and Hilal bin Mohammed al Azri of the Ministry of Commerce, Sultanate of Oman, for their support and cooperation.

## References

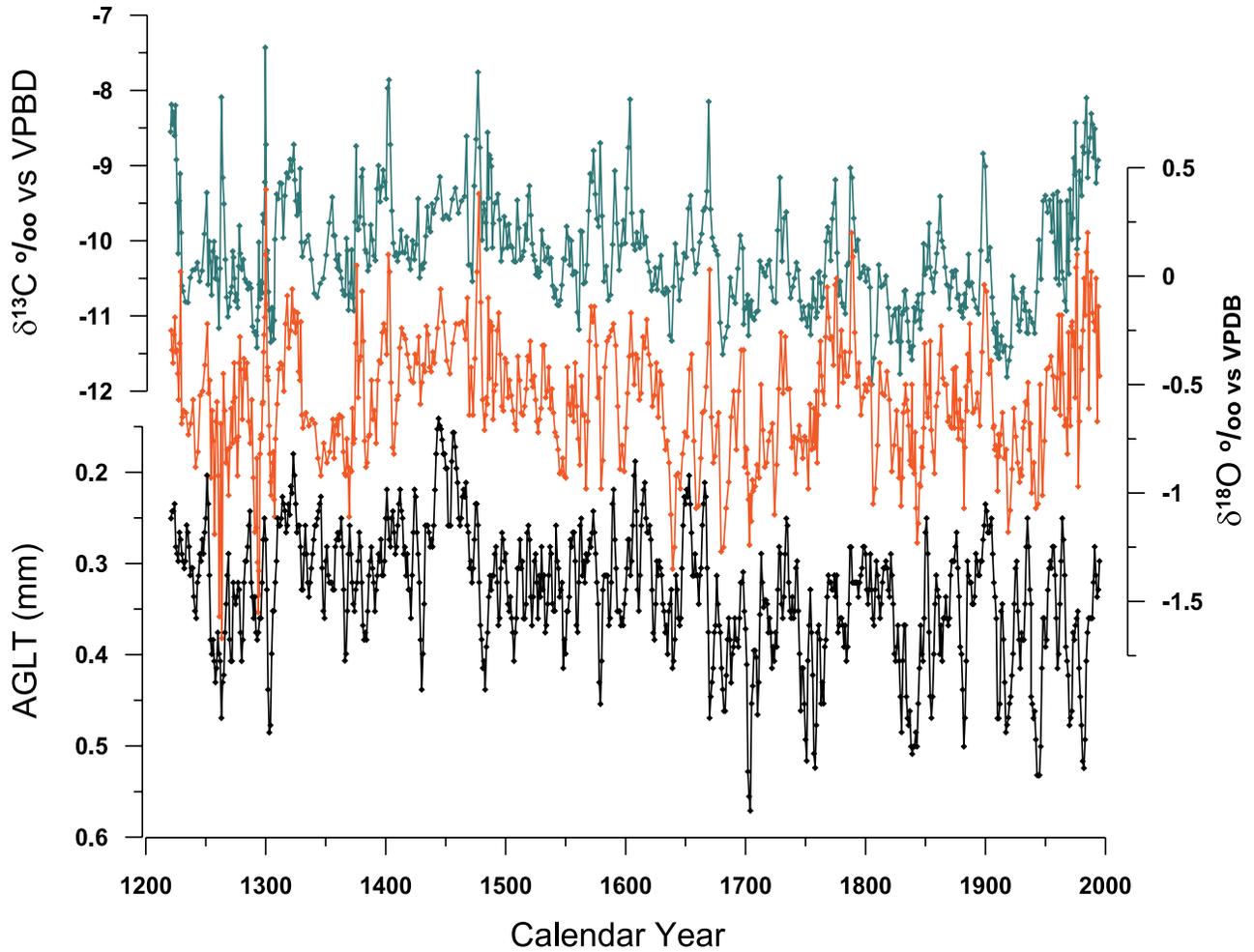
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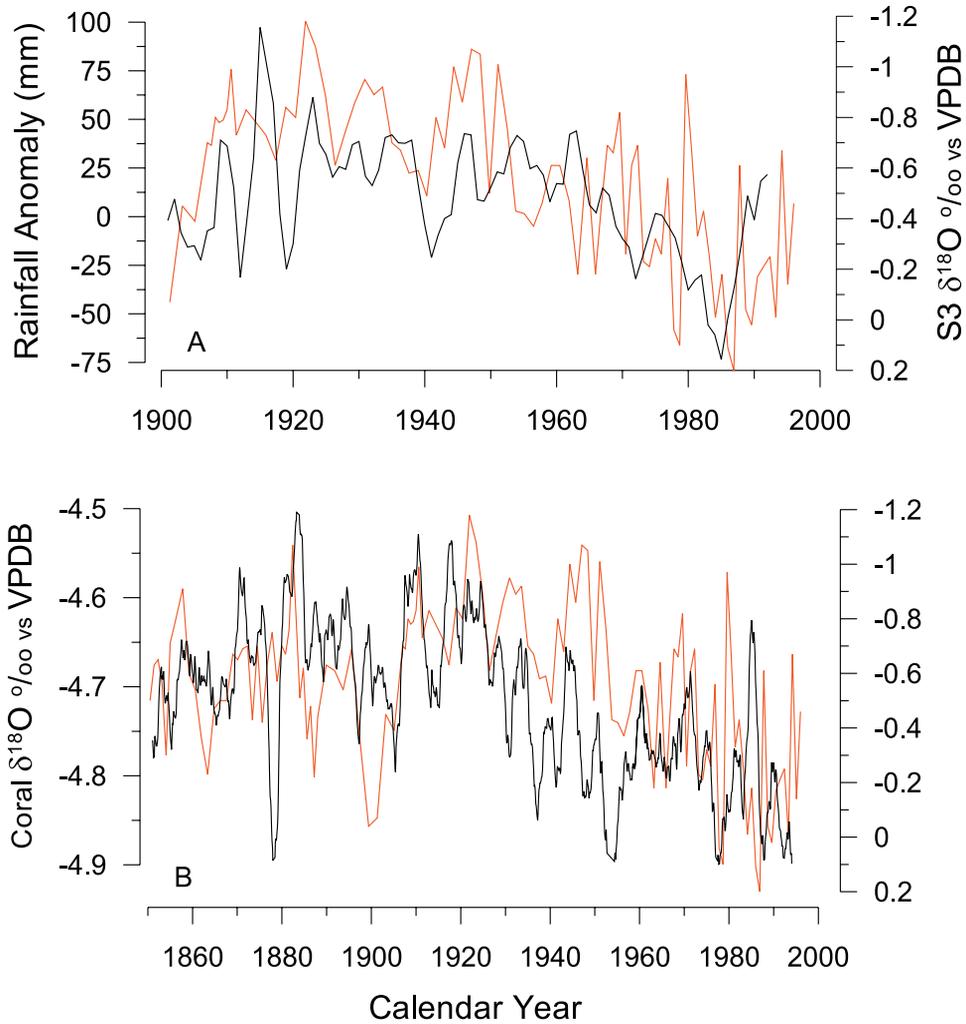
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**Figure 4.** (bottom) Layer thickness, (middle)  $\delta^{18}\text{O}$ , and (top)  $\delta^{13}\text{C}$  of speleothem S3 versus calendar year.



**Figure 5.** Comparison of S3  $\delta^{18}\text{O}$  (orange line) with (a) 3-point running average of historical rainfall data from East Africa and southern Arabia [Vose *et al.*, 1992] for the period from 1900–1990, and (b) 25-point running average of coral  $\delta^{18}\text{O}$  values from the Seychelles Islands [Charles *et al.*, 1997].