Decadal variability in the Indo-Gangetic monsoon rainfall during the last ~2800 years: Speleothem ^{18}O evidence from the Sota cave, **Uttar** Pradesh

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Abstract

A speleothem (cave deposit) collected from the Sota cave in the Chitrakoot district of Uttar Pradesh has been analyzed for stable isotopes of oxygen and dated by the radiocarbon method. Within the time span covered by the sample (2800 yr BP) the amplitude of ^{8}O changes is vety large (> 2‰) and therefore cannot be explained merely by past variations in air temperature. We discuss several isotopic processes and show that changes in the past rainfall should have been the prime factor responsible for large variations in the speleothem ^{8}O Rainfall in the cave locality has been reconstructed for the last 2800 yr .The average value of the rainfall has an increasing trend with a periodicity of about ~ lkyr. We have compared the past rainfall of the Sota cave with similar reconstructions available from Gupteswar and Dandak caves and find that there are similarities and the extremely low rainfall events around 2000 and 1700 yr BP are also seen in the new record although they may be slightly shifted in time considering the age uncertainties. Low rainfall years in the reconstruction are associated with similar events observed in the instrumental and historical records.

Keywords

Speleothems Southwest monsoon Rainfall Stable isotopes Radiocarbon Uttar Pradesh.

Introduction

Mineral deposits of various shapes and colors occurring in limestone caves are collectively known as speleothems their composition being mostly calcium carbonate and rarely gypsum and halite. They are formed when rainwater percolates through soil zones above a cave seeps through cracks in the underlying bedrock and drips around fissures in the cave interior (Gascoyne 1992; Lauritzen 1995). This happens due to higher pCO_2 in the soil pores due to root respiration and bacterial decomposition of the organic matter within the soil zone that raises the partial pressure of CO_2 to several times the atmospheric value. Rainwater dissolves CO_2 forming carbonic acid, which dissolves acid-soluble fractions while seeping. The seepage water is loaded with several ions and soluble components in trace quantities, and when it encounters low pCO_2 in the cave gallery (due to air circulation between the cave chamber and the atmosphere) a super-saturation of dissolved ions leads to CO_2 degassing and carbonate precipitation. Ceaseless dripping forms successive growth layers of $CaCO_3$ at the dripping spot in the form of tubes or 'soda-straw'. Blockage of the tube or flow outside thickens it near the ceiling and leads to a conical shape, called stalactite (growing downward). When the dripping rate is high so that the solution does not reach equilibrium on the roof of the cavern, additional carbonate precipitates on the floor forming stalagmite (growing upward) and flowstones (thin carbonate layers on the floors or on the cave walls). Ultimately stalactites and stalagmites may join to form pillars or curtains of carbonates (Faure, 1991; Ivanovich and Harmon, 1995; Lowe and Walker, 1998). Major speleothem formations occur during the wet season when the seepage is more. The seepage water acts as a transferring medium; carbonate in the bedrock strata is re-deposited as speleothem in the cave gallery. Generally the crystal structure is calcite and less often aragonite or a mixture of both.

Investigations of Indian speleothems for palaeoclimate reconstruction have started recently. A few studies carried out so far (e.g. Yadava and Ramesh, 1999 a & b; 2001; 2004; Yadava, 2002; Yadava et al. 2004) have shown that the oxygen isotopic composition in speleothems is primarily governed by the amount of monsoon rainfall in the cave locality, suggesting that it can be used as a potential proxy for the same. During growth, certain elements are derived from soil or bedrock and are incorporated in speleothems at trace levels. Their geochemistry is also controlled by the rainfall throughput (Yadava and Ramesh, 2001). Present day rainfall in India has large regional variations (Ramesh, 2001). Patterns of the past rainfall can be ascertained from ^{18}O profiles of speleothems from different geographical locations. In the present paper, isotopic investigation of a stalactite from a north Indian cave, 'Sota', is presented.

Cave location

In the foothills of the Vindhyan ranges, in the Chitrakoot district (25°10'N 80°53'E) of Uttar Pradesh, there are two caves within half a km distance from each other viz. 'Guptgodavari' and 'Sota'. As tourists frequent the former, most of the speleothems have been destroyed and the remaining are worshipped as deities. The latter (Sota) is very shallow, the roof thickness being less than 3m and length ~10m, and as the entrance is very narrow, is rarely visited (Figure 1). Therefore, speleothems were seen to be in a pristine condition. The cave is above the ground level ensuring that the drip water originates from monsoon precipitation and not ground water. A stalactite growing in a narrow chamber close to the end of the cave was collected on 10, Oct 1997 October marks the end of the summer monsoon in this region (Climatological Tables, 1960) However, occasional rain spells are experienced in this month .There were no rain spells in the region within the preceding week of sampling. During sample collection, the inside of the cave and the stalactite's outer surface were found dry, implying that the stalactite collected had either stopped growing or all the rain water received during the previous rain spells had fully percolated within a short period (probably less than a month) and the cave surfaces dried up Relative humidity and the ambient temperature were 64% and 27°C respectively.

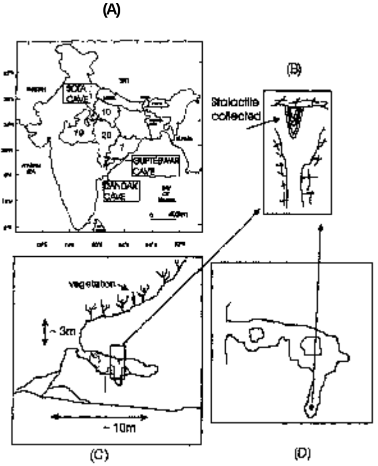
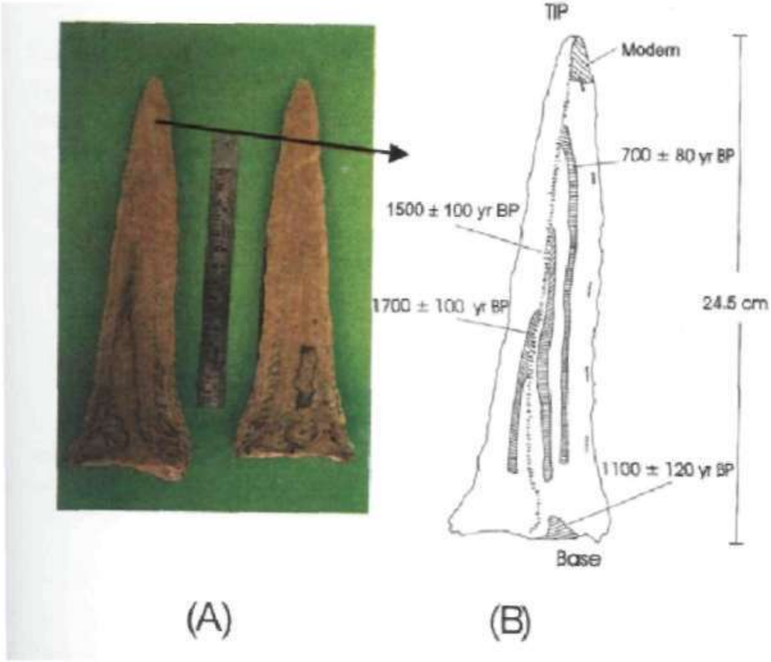


Fig. 1. *Sketch showing Sota cave and the stalactite (A) India Map showing locations of Sota Dandak and Gupteswar caves Numbers show the meteorological subdivisions in which these caves are located (B) Vertical cross sectional view of the cave (C) Horizontal cross sectional view of the cave (D) Location of the stalactite inside the cave*

Preparation of sub-samples for Stable isotope analysis and Radiocarbon dating

The stalactite was cut into two pieces along its length using a motorized diamond cutter. A photograph of the sectional view of the stalactite is shown in Figure 2. For stable isotope analysis subsamples of about 5 mg were recovered from each visible layer, using a hand operated and slow speed portable electric drill fitted with stainless steel bits (diameters between 0.4 to 1.0mm). The growth layers and sub sampling points are shown in Figure 2. The ratio of stable isotopes of oxygen ($^{18}0/^{16}0$) was analyzed by reacting sub samples with ~100% orthophosphonc acid in an evacuated glass set up. The resulting CO_2 was introduced into mass spectrometer. Further details of the procedure are discussed in Yadava and Ramesh (1999b). Size of each stable isotope sub-sample was ~lmm and the sampling interval was also ~lmm. Isotopic ratios are presented as $\delta^{18}0$ relative to the PDB standard (where, $\delta^{18}0=[(R_{sam}/R_{std})-1]*1000$, $R={}^{18}0/{}^{16}0$: subscnpts 'sam' and 'std' represent sample and standard, respectively). The overall precision in $\delta^{18}0$ was ± 0.12‰.



Fg2(A) *Two half sections of the stalactite from Sota cave (B) Sketch showing sampling spots for the sub samples for the stable isotope studies (by dots) and for the radwcaibon dating (by patches)*

For radiocarbon dating carbonate powder was recovered from the tip and the base of one of the slices using a drill machine and carborundum files .The age details are listed in the Table. 1. Residual specific ^{4}C activity of the carbonate was measured by preparing benzene from sub samples followed by liquid scintillation spectrometry (Yadava and Ramesh 1999b).

Table .1. Details of the sub samples from Chitrakoot stalactite and their ^{4}C ages

Sample code	Depth from tip (mm)	Sample weight (g)	Apparent age / ^{4}C activity yr BP
PRL -2113	0-2.1	35	Modern 117.69 ± 1.46 pM A ^{4}C = 176. 9 ± 14.6 %o
PRL- 2203	42. 8- 53. 0	23	700 ± 80
PRL- 2201	91.4- 109. 8	49	1500 ± 100
PRL- 2202	133.8- 166.0	17	1700 + 100
PRL -2112	235. 8- 244.6	40	1100 ± 120

The routine procedures of the radiocarbon dating method are standardized to the preparation and counting of lml of benzene. About 9 g of calcium carbonate is required to prepare lml of benzene with a high chemical yield. If the sub sample amount is small then age uncertainty increases. However if the amount of the sample is increased by taking more stalactite layers the age resolution becomes poor Sota stalactite is small in size (~24.5 cm) and therefore optimum amounts of sub samples for dating were recovered from the spots as shown in Figure 2.

Results and Discussion

Radiocarbon dating

The permil deviation of the sample ^{14}C activity (A) from the absolute activity of the international standard (A_{abs}) is given as (Stuiver and Polach 1977).

$$^{4}C = [A/A_{abs} - 1].\ 10^{3}\ \%_{0}$$

and percent modern is defined as

$$pM = (A/A_{abs}).\ 100\ \%$$

All the quoted errors in the Table 1 are based on the number of accumulated counts of the sample reference and background plus additional errors caused by the dilution (Stuiver and Polach, 1977) .The ages reported are rounded to the nearest multiple of ten as per the convention of reporting radiocarbon ages (Stuiver and Polach, 1977).

The ^{14}C age of the speleothem is greater than that of organisms deriving carbon from the atmosphere. This is due to contribution of ^{14}C free carbon (called dead carbon) from the leached carbonate bedrock (reservoir effect). The extent of dilution of ^{14}C by dead carbon depends upon various local factors of the cave system such as open system or closed system dissolution (Clark and Fritz, 1997). The Sota stalactite was collected during October 1997 (fall season) and the cave was found to be totally dry. There is bomb ^{14}C in the tip (Table 1), which proves that the stalactite has been actively growing; the growth is mainly during wet periods (monsoon months). Thickness of the soil plus bedrock above the cave is ~3-5 m, therefore the cave is very shallow. During the dissolution of the bedrock it is highly likely that the seepage water is well mixed with the soil CO_2 phase. In such a situation open system dissolution (Clark and Fritz, 1997) takes place and we can assume that the dead carbon contribution is negligible. The tip is assigned 0 yr BP as the conventional ^{14}C age (precisely, it is associated with the year 1997, the year of collection). The total length being 24.46 cm, as shown in the Table 1, all the ages follow stratigraphic order (i.e. they increase from the tip towards the base) except at the base (PRL-2112: ~1100 yr BP). During scooping from the base, it was noticed that there are possible contributions from some of the other younger layers near the flank. Therefore, we omit this age for the chronology purpose. For the age fixation of stable isotope sub samples, the following approach was applied a) the tip (0mm) was assigned 0 yr BP, layer at 48mm (centre of PRL-2203) was assigned 700 yr BP, ages of all the other layers in between were estimated by a simple linear interpolation assuming a constant deposition rate- ~0.07mm/yr; b) the layer at 12.9cm (center of the PRL-2201 and PRL-2202) was assigned 1600 yr BP (mean of 1500 and 1700 yr BP), for other layers, ages were assigned by assuming a constant deposition rate- ~0.09mm/yr, by linear interpolation for layers between 4.8 and 12.9cm, and by extrapolation for layers beyond 12.9cm. Each stable isotope sample (lmm size) covered a ~12 yr time span. These tentative age assignments should be verified by using the U-Th method of dating (Schwarz, 1986).

Oxygen isotopes

In the deeper parts of a cave, where air circulation is poor and high humidity prevails, carbonate precipitates slowly, maintaining isotopic equilibrium between different ionic species. In such a case isotope ratios of oxygen ($^{18}O/^{16}O$) of the ions in the dripping water, which are influenced by the ambient environment of the cave, are preserved in the growing speleothem lamina and can be used to reconstruct the past environment (e.g. Gascoyne, 1992; Lauritzen, 1995, McDermott, 2004).

$^{18}O_c$ (oxygen isotopic composition of speleothem) is related to temperature, due to temperature dependent fractionation ($^{18}O_c/dT$ -0.2l%o/ °C at 25°C, O'Neil et al., 1969) and dependence of $^{18}O_w$ (oxygen isotope composition of precipitation) on the condensation temperature which is 0.5 to 0.9%o/°C between 40°N to 60°N (Rozanski et al. 1993). For mid-latitude and semiarid climatic zones $^{18}O_w$ decreases with increasing rain amount (Dansgaard, 1964; Bar-Matthews et al. 1996; Bar-Matthews and Ayalon, 1997; Fricke and O'Neil, 1999) and the temperature dependence is very weak. In tropical locations any obvious temperature correlation is not observed for the modern rainfall (Dansgaard, 1964, Yurtsever and Gat, 1981; Bar-Matthews and Ayalon, 1997; Fricke and O'Neil, 1999). The $^{18}O_w$ is rather dependent on the amount of rainfall (Yurtesever and Gat, 1981): more rainfall is associated with less of ^{18}O content in the precipitation; this is termed as the "amount effect" (Dansgaard, 1964). Hence, in tropical caves the ^{18}O of freshly deposited calcite layers on a growing speleothem is depleted with increasing temperature (due to temperature dependent fractionation during carbonate precipitation) and precipitation and usually, the ambient temperature of a cave is the mean annual surface air temperature and hence ^{18}O of the speleothem layers are a good proxy for the past variations in ^{18}O of meteoric water.

Amount dependence of ^{18}O of rainfall

Tropical regions are characterized by converging air masses that are forced to move vertically rather than horizontally. They are cooled due to adiabatic expansion, while surface temperature gradient remains negligible. Amount effect is believed to be (Dansgaard, 1964; Rozanski et al. 1993; Fricke and O'Neil, 1999) due to 1) gradual saturation of air mass below the cloud base, an effect that diminishes evaporation during precipitation and hence shift towards lower ^{18}O, 2) preferential loss of ^{18}O from the cloud as rainout continues.

For island stations in the equatorial belt annual temperature fluctuation remains within a narrow range; therefore, the amount of precipitation is largely dependent on the air circulation patterns. For such stations a linear relationship (Yurtsever and Gat, 1981) between the mean monthly $^{18}O_m$ of precipitation and the mean monthly rainfall is observed:

$$^{18}O_m = (-0.015 \pm 0.002)*P_m - (0.47 \pm 0.42)$$

P_m is the mean monthly rainfall, with correlation coefficient r = 0.87 for 14 island stations (each has at least 40 monthly observations). Average rate of depletion is found to be -1.5 ± 0.2‰ for a 100mm increase in the monthly rainfall. This depletion rate should be applicable to those locations where annual temperature fluctuations remain within a narrow range. During the monsoon season in 1999, precipitation samples collected at Jharsuguda (22°N, 84°E), which receives majority of the annual rainfall during southwest monsoon, monthly depletion rate for 100mm increase in the monsoon rainfall was found to be -2.2 ± 0.8‰ (Yadava and Ramesh, 2004: based on daily samples collected during three successive months: July, August and September). This agrees well with the depletion rate observed at the island stations. It suggests that during the monsoon months when the vast continental land area cools down and attains a moderate temperature till the monsoon is active, the amount effect at the inland sites is the same as what is observed at the island stations. We have converted ^{18}O of speleothem into rainfall, assuming that changes in the speleothem ^{18}O had been solely due to variations in the ^{18}O of the annual rain, and that the depletion rate experienced at the island stations is also applicable at the cave site.

An example of amount effect in the summer monsoon rainfall of New Delhi is presented in Figure 3, where both ^{18}O and the monthly rainfall data are taken from the IAEA/WHO GNIP database (2001) for the period 1960 to 1995 A.D. The data obey the relationship:

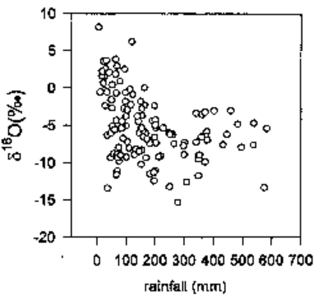


Fig. 3. *Data of ^{18}O (relative to SMOW) and amount of summer monsoon rainfall in New Delhi (1960 to 1995 A D.) showing amount effect. Source IAEA/WHO GNIP database.*

$$^{18}O_m = (-0.013 + 0.003)*P_m - (2.82 \pm 0.60)$$

with a correlation coefficient of 0.4, significant at 0.001 level (n=125, Student's t value 4.75). The correlation improves if we disregard the unusually high rainfall (>350mm) events during this period:

$$^{18}O_m = (-0.027 + 0.004)*P_m - (1.24 \pm 0.71)$$

with a correlation coefficient of 0.5, significant at 0.001 level (n=107, t=6.08).

The noise in the data (unexplained variance of 75-80%) is possibly due to the two different sources of moisture for the rainfall at New Delhi, the Arabian Sea and the Bay of Bengal). Present day annual rainfall in India shows large geographical variations (Ramesh, 2001) and therefore, ideally one should have a calibration of amount of the annual rainfall and its ^{18}O for each cave site, for a more accurate rainfall reconstruction.

Rainfall reconstruction

At Chitrakoot there is no rain-gauge station and hence for the monthly rainfall data we selected nearby stations, Allahabad (at ~100km from Sota), Satna (~72km) and Banda (~65km). An important observation is that there are large regional variations in the rainfall withinlOOkm distance. The average annual rainfall for these stations, based on instrumental observations from 1931 to 1960 (Climatological Tables 1970) is listed in the Table 2. Most rainfall is received in the area during June to September (summer rain). There are rain spells in other months, which contribute 12-14%.

Table 2: Climate data of the three stations near Sota cave (Climatological Tables 1970).

Stations/distance from the Sota cave (km)	Banda ~65	Allahabad ~100	Satna ~72	Average of three stations
Annual rain (mm)	1003.6	1026. 8	1137.1	1056..0
Summer rain (mm) June-Sept, (percent of annual rain)	872.9 (87%)	904.7 (88%)	978. 1 (86%)	918.6 229.6*
Annual av. Temp (°C)	26.1	25.4	26. 4	26. 0

• average monthly rain during wet season (June-Sept.)

The average annual rainfall of the three stations (Banda, Allahabad and Satna) is 1056.0 mm (Table 2). During the summer monsoon (June to Sept.) average monthly value is 229.6 mm. And hence the annual rain is 4.6 (=1056.0/ 229.6) times the mean monthly rain during the summer season. Assuming that all the variations in the stalactite ^{18}O are due to the past variations in the amount of rainfall (i e. because of the amount effect), the rainfall equation for the Sota cave is:

$$P_a = (100/1.5)* 4.6*(^{18}O_{tip} - ^{18}O_i) + 1056.0$$

$$\text{or } P_a = 306.7*(^{18}O_{tip} - ^{18}O_i) + 1056.0$$

Where, $^{18}O_i$ and $^{18}O_{tip}$ are the oxygen isotopic composition of the calcite at any depth and at the tip respectively. Using the above equation the speleothem oxygen isotopic composition was converted into rainfall (Figure 4).

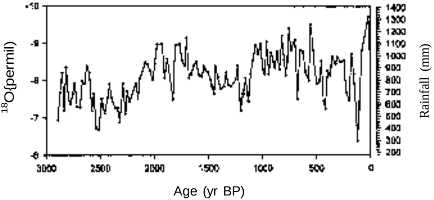


Fig. 4. *Age versus* ^{18}O *(relative to PDB) for the Sota stalactite, rainfall scale is shown on the right*

Variations in the past rainfall

The following inferences can be drawn from the rainfall reconstruction covering last ~2800 yrs:

a) Average level of the past rainfall has an increasing trend, and exhibits a slow oscillation of ~1000 yr.

b) Low rainfall durations are observed during, 2.5 kyr, 1.7 kyr, 1.2 kyr, 600 yr, 450 yr and ~100 yr ago.

c) Low rainfall events at ~100 yr BP, 450 yr and 600 yr BP can be associated with the famines that are recorded in the history during A. D. 1860-61 and 1837-38, during A. D. 1555-56 and 1326-27, respectively (Srivastava, 1968). Sota cave is part of subdivision-10 (East Uttar Pradesh, Parthsarathy et al, 1995). Very low rainfall observed in the reconstruction around ~100 yr BP may also have been due to deficient rainfall years during A.D. 1877 to 1883 as observed in the instrumental data (Parthsarathy et al, 1995). This other possibility is due to the uncertainty in the dating (±100 yr)

Rainfall reconstruction for the last ~3400 yrs is available based on two speleothems from the Gupteswar cave (GUP) in the Koraput district of Onssa and the Dandak cave (DAN) in the Jagdalpur district of Chhatisgarh (Yadava and Ramesh, 2004) Recently, a high resolution monsoon record has been reconstructed by von Rad et al (1999) using thickness variation in the varved sediments collected from the northeastern Arabian Sea, off Pakistan According to von Rad et al, (1999), precipitation and hence, river run off are assumed to control varve thickness .The ^{18}O profile of the Sota cave (SOT) is compared with those of the Gupteswar cave (GUP), Dandak cave (DAN) and with varve thickness profile and is presented in Figure. 5. In the SOT, DAN and GUP

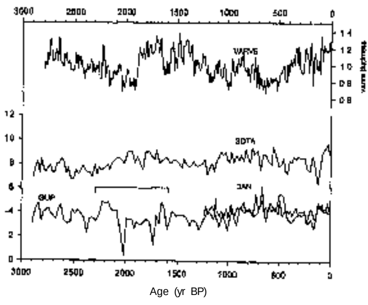


Fig. 5. *A comparison between speleothem ^{18}O (relative to PDB) from Sota cave (SOTA) Gupteswar cave (GUP) and Dandak cave (DAN), and Varve thickness profile (VARVE) from von Rad et al (1999). Speleothem records do not agree for the time interval between the bars*

reconstructions, except during 2300 to 1600 yr BP, rainfall variations have similar trends (Figure 5). During 2300 to 1600 yr BP, while SOTA shows initially an increasing and then a decreasing trend in the rainfall, GUP shows arid periods apart from high and very low rainfall durations. Comparison with the varve profile shows that high rainfall during 1900-1400 yr is commonly observed by both SOTA and varve deposits. During this period the northern part of India and, therefore, possibly SOTA were probably having a comparatively wetter phase than GUP/DAN. This could have been caused by the increased precipitation in the Arabian Sea branch of the monsoon. An alternative possibility is that the extremely low rainfall events seen around 2000 and 1700 yr BP (in GUP) are also seen here, but slightly shifted back in time, considering the age uncertainties (e.g. events at -1800 and 2300 yr BP). During ~1000 to 700 yr BP, rainfall was high and is shown by all the speleothems and the varve data. This could have been due to a large scale strengthening of the southwest monsoon.

The average values of ^{18}O at the tip for the SOTA and GUP/DAN are -8.86%o and -4.45%o respectively. The rainfall at the caves sites is mostly due to a common vapor source that onginates from the Bay of Bengal. Progressive depletion of the ^{18}O of precipitation as the vapor moves inland is called the continental effect (Clark and Fritz, 1997) The distance covered by the cloud mass that precipitates first over GUP/DAN and later at SOTA is ~650 km. Speleothem ^{18}O values at the tip show that the vapor mass should have a continental effect close to -6%o/1000 km. This result is in close agreement with the earlier value for the continental effect observed in northern Indian ground water aquifers (Krishnamurthy and Bhattacharya, 1991).

Conclusions

A stalactite from Sota cave in the Chitrakoot district, U.P., dated using ^{14}C, has been analyzed for the variations in the stable isotopes of oxygen. Large variations in the a^{18}O (more than *2%o)* are used for a high-resolution rainfall reconstruction, representing northern India, for the last ~2800 yr. The most depleted a^{18}O that occurred ~100 yr ago may have been due to deficient rainfall years during A.D. 1877 to 1883. Reconstruction from Sota is similar to what is shown by speleothems from Gupteswar and Dandak except during A.D. 2300 to 1600. Some of the famine years in the historical documents can be associated with the low rainfall periods inferred from the speleothem data.

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