# High resolution Holocene monsoon records from different proxies: An assessment of their consistency

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**Available high resolution quantitative monsoon reconstructions for the Holocene period in the Indian region are compared to assess for consistency among the proxy records. There is a good concordance among three different monsoon proxies from western India: (a) Pollen-based reconstruction of annual rainfall in Rajasthan from a sediment core in lake Lunkaransar, (b) stable carbon isotope variations in organic carbon from another core from the same lake, and (c) stable oxygen isotopic variations in surface-dwelling foraminifera from a sediment core in the coastal eastern Arabian Sea. While this is reassuring, the degree of concordance diminishes when records from widely separated sites in the Indian region are compared. Possible causes for this inconsistency are discussed, perhaps the most important among them being the large spatial variations in monsoon rainfall over the Indian region, apparent in modern instrumental records. There is a need to assess the temporal variance of this geographical variability before multi-proxy quantitative monsoon rainfall reconstructions can be integrated as a single time series (somewhat akin to the modern All India Summer Monsoon Rainfall time series compiled by the India Meteorological Department). Such an effort can serve to test and improve palaeoclimate/palaeomonsoon models.**

CENTRAL to the problem of prediction of monsoon rainfall over India is an understanding of the vagaries of the monsoon on different time scales in the past[1]. As instrumental weather records are both geographically and temporally limited, natural archives such as tree rings, corals, varved lake/ocean sediments, speleothems (cave calcites such as stalactites, stalagmites and flow stones), which serve as potential high resolution (annual to decadal) proxies for the monsoon rainfall in the past[2–6], can be used to extend the available database on monsoons farther back in time, with increasing geographical coverage. Earlier, coarse resolution (> 500 years) studies on ocean/lake sediments, and peat deposits have provided qualitative (qualitative because of the difficulty in calibration, in the absence of instrumental records for longer periods of time) information on palaeomonsoon[7–18]. Here discussion is limited to available quantitative results alone. Over the last decade, the development of high sensitivity Accelerator Mass Spectrometric (AMS) method of radiocarbon dating (wherein increasingly smaller amounts of sample are required for $^{14}C$ measurements[19] to yield precise calendar ages at least during the Holocene, i.e. last ~ 10,000 years), has greatly aided high-resolution palaeomonsoon reconstruction from such natural repositories. It is therefore now possible to check for consistency among these proxy monsoon records; a high degree of coherence among the records, if present, may help in integrating them to a single monsoon rainfall time series that can be useful to test and improve mathematical models aimed at monsoon prediction. (This time series can be thought of as the palaeo-equivalent of the All India Summer Monsoon Rainfall record compiled by the India Meteorological Department, and annually predication of this quantity is made by different models, though the meaningfulness of such a single quantity for India as a whole might be questionable[20].) In this paper I compare three such records (see Figure 1 for sample locations): (a) stable carbon isotope rations ($\delta^{13}C$) in a sediment core from lake Lunkaransar, Rajasthan[4]; (b) stable oxygen isotope ratios ($\delta^{18}O$) in a sediment core from the eastern Arabian Sea[6]; (c) and stable carbon and oxygen isotope ratios in a stalactite that grew in the Gupteswar cave, Orissa[5] and (d) the earlier pollen-based reconstruction of monsoon rainfall from a sediment core from Lunkaransar, Rajasthan[21] (other higher resolution records such as tree-ring widths, etc. are limited to about 800 years and are not considered here). The first two cores were dated using the AMS $^{14}C$ technique, whereas the stalactite was dated using the conventional radiocarbon method. The motivation for the selection of the above sites is as follows: sites (a) and (d) in Rajasthan were chosen because they receive very little monsoon rain compared to the rest of the country and therefore might be sensitive to monsoon fluctuations in the past. Site (b) receives freshwater runoff from the Western Ghats during the monsoon; there is a significant north–south gradient in the surface salinity in

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the coastal eastern Arabian Sea during the monsoon season, with higher salinity (lower run-off) in the north (off Saurashtra) and lower salinity (higher run-off) in the south[6] (off Cochin). Past fluctuations in the monsoon rainfall are likely to change this salinity gradient and thus expected to be recorded in the $\delta^{18}O$ of planktonic foraminiferal shells that grew there. Site (c) was selected on the sole criterion that it is in a limestone terrain suitable for the formation of stalactites. In addition, it is near the coast and therefore will sample the first rain on land as air masses enter India from the east, thus preventing complicating factors such as re-evaporation of rain water and mixing with the cloud vapour.

## Results and discussion

Bryson and Swain[21] provided the first quantitative palaeomonsoon reconstruction for the Indian region based on pollen analyses of sediment cores from the Didwana and Lunkaransar lakes of Rajasthan. The type of pollen that gets buried in the lake sediments depends on the ambient vegetation, which in turn depends on the performance of the summer and winter monsoons in the region. Thus, by identifying pollen grains in the sediment core that belong to different species of plants, it is possible to derive information on wet/arid environments that prevailed in the past. A calibration based on modern pollen counts and the rainfall isohyets provided a transfer function to convert observed down-core pollen counts to actual winter/summer rainfall quantitatively. The top panel in Figure 2 shows this record from the lake Lunkaransar, with an average time resolution of ~ 220 years. It is seen that the variations in the annual rainfall are quite large (a factor of 3, ranging from 300 to 1200 mm).

More recently another box core was raised from the same lake and organic carbon was used for AMS radiocarbon[4] dating. The stable carbon isotope ratios of the organic carbon was also measured (the average time resolution of sampling was ~ 120 years). These are shown in the middle panel of Figure 2. To facilitate comparison between the Bryson and Swain reconstruction and the $\delta^{13}C$ data, uncalibrated $^{14}C$ dates are used (calibration refers to the correction of ages for past variations in the production rate of $^{14}C$ due to solar modulation of cosmic rays[19]; calibrated age = $(1.065 \pm 0.008)$ times the uncali-

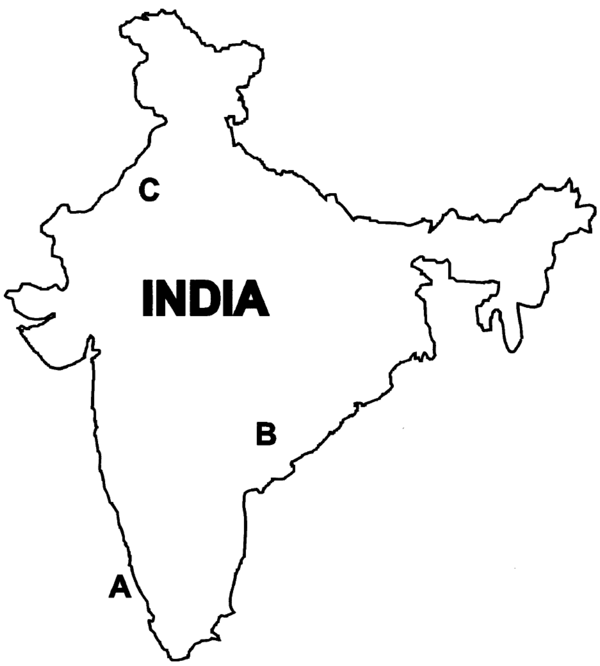


**Figure 1.** Map of India showing the approximate locations of proxy monsoon records: A, Planktonic foraminiferal oxygen isotope record[6] from the eastern Arabian Sea; B, oxygen isotopic record[5] of a stalactite from the Gupteswar cave, Orissa; C, Lake Lunkaransar sediment record (pollen[21] and stable carbon isotopes of organic carbon[4] from two different cores from the same lake).

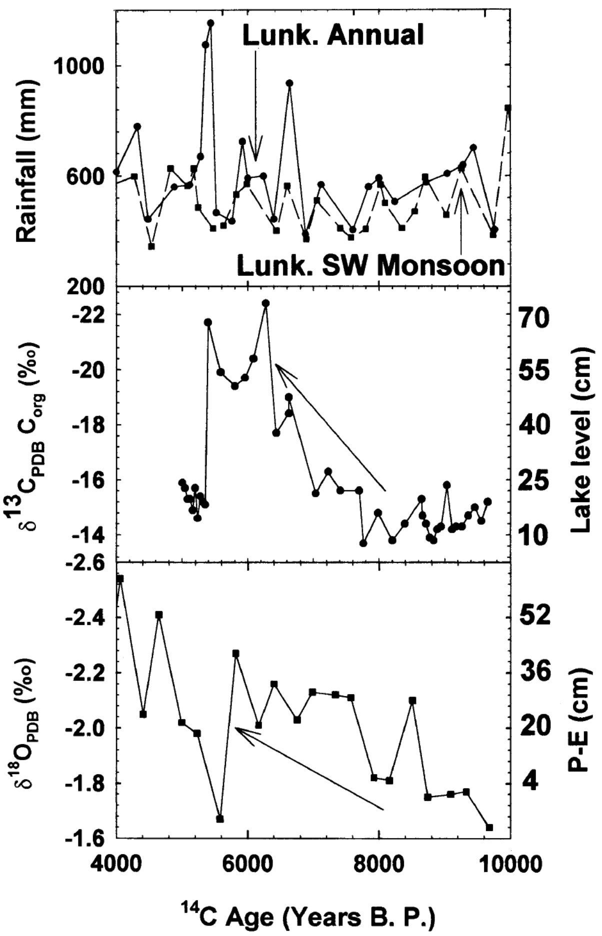


**Figure 2.** Comparison of proxy monsoon records; pollen-based reconstruction from Lunkaransar Lake sediments[21] (top panel), $\delta^{13}C$ of organic carbon[4] from another core from the same lake (middle panel) and $\delta^{18}O$ of surface-dwelling foraminifera (*G. sacculifer*) from a sediment core (3268G5)[6] in the coastal eastern Arabian Sea (bottom panel). All radiocarbon dates are uncalibrated to facilitate comparison with the top panel. Quantitative scales of lake level (cm) and excess of precipitation over evaporation (P–E, cm) are respectively shown on the right side for the middle and bottom panels.

brated age plus $450 \pm 57.65$ in this case). Salt lakes in Rajasthan (such as Lunkaransar) are known to host microbial mat communities that live in the lake bottom. These microbial mats photosynthesize, consuming the dissolved carbon dioxide in the lake water. When the lake level is high (e.g. > 50 cm), the dissolved inorganic carbon in the lake (dissolved carbon dioxide, bicarbonate and carbonate taken together) has a typical $\delta^{13}C$ value of – 21‰, as the microbial mat activity is not able to substantially deplete the dissolved inorganic carbon. When the lake level is low (e.g. < 10 cm), however, the dissolved inorganic carbon is rapidly consumed by the microbial mat community, leading to diffusion of atmospheric carbon dioxide into the lake water. As the latter has a typical $\delta^{13}C$ value of – 6‰, the resulting dissolved inorganic carbon in the lake gets isotopically enriched and organic carbon synthesized in such an environment is enriched in $^{13}C$. This has been verified by laboratory and field experiments[22]. Thus $\delta^{13}C$ of organic carbon in the lake sediment can be used as proxy for palaeolake level, which is directly controlled by the difference between the annual precipitation and evaporation (P–E). Using available experimental data, the organic carbon $\delta^{13}C$ values have been approximately converted to lake level (scale on the right, Figure 2, middle panel). Two extreme events of high annual precipitation at (uncalibrated) $^{14}C$ ages of 5400 and 6300 years BP roughly match the corresponding high precipitation events in the top panel (pollen-based reconstruction). within the dating uncertainties of the latter. The moderately high precipitation between these two extreme wet events also appears in both the records. The sudden onset of aridity at 5200 years BP (uncalibrated age) is also corroborated. The factor of > 3 variation in the Indian monsoon rainfall, as reconstructed by the pollen record has thus been confirmed by independent workers using an entirely different proxy ($\delta^{13}C$).

Sarkar *et al.*[6] reconstructed the P–E values in the coastal eastern Arabian Sea using a sediment core 3268G5 (ca 12°N, 73°E, water depth ~ 600 m), planktonic foraminiferal separates of which were dated using AMS. They observed that the north–south gradient in sea surface salinity (directly controlled by the monsoon run-off from west-bound peninsular rivers, relatively higher in the southern peninsula than the northern part) was reflected both in the surface sea water $\delta^{18}O$ and the $\delta^{18}O$ of modern core top sediments. Using the data of Ramesh Kumar and Prasad[23] of calculated P–E values for this region during the monsoon season (the primary data being temperature, salinity and wind stress), the core-top $\delta^{18}O$ values of planktonic foraminifera (*G. sacculifer*, which lives around ~ 25 m depth in the surface waters, and has a predominant growth during the monsoon season) have been calibrated and a transfer function obtained. Down-core variations of $\delta^{18}O$ of *G. sacculifer* can thus be quantitatively interpreted as P–E variations in the past (these results have since been independently verified based on $\delta^{18}O$ of another planktonic species *G. ruber* from a nearby core[17]). These data are shown in the bottom panel of Figure 2, with the P–E scale on the right, with an average time resolution of ~ 240 years. Again, to facilitate comparison, uncalibrated ages have been used, but a reservoir correction, ~ 500 years, was made (the surface ocean does not have zero age; it appears 'older' due to vertical mixing with deeper waters which have lost some radiocarbon by decay[19]).

Considering that the time resolution of the oceanic record is poorer than that of the lake record, and that P–E over the ocean is somewhat different from lake level (although both are related to the monsoon rainfall, the oceanic record is conceivably somewhat attenuated), the agreement between the three different monsoon reconstructions shown in Figure 2 is quite reasonable. The increasing trend of monsoon precipitation (i.e. excess over evaporation) between ~ 8000 and 6000 (uncalibrated) years BP is clearly seen in both (middle and bottom panels, arrows in Figure 2). The sudden onset of aridity around 4800 years BP is also discernible. The short arid event around 4400 years BP is observed in the pollen based (top panel) and the oceanic records. Thus the comparison of these records from western India presents a reasonably concordant picture of Holocene monsoon variability.

We now move on to yet another proxy monsoon record, but from the eastern part of India. Yadava and Ramesh[5] reconstructed the monsoon precipitation from $\delta^{18}O$ of a stalactite from the Gupteswar cave, Orissa, using the 'amount effect' in rainfall; i.e. the $\delta^{18}O$ of rainfall in tropical coastal stations is linearly and positively correlated with the amount of rainfall. As the cave calcite $\delta^{18}O$ mainly reflects the former, one can use the 'amount effect' as the transfer function to reconstruct rainfall. Some isotopic modifications due to evaporation during the seepage of monsoon-derived soil water into the cave occurs, but the 'amount effect' is due to the same reason (i.e. evaporation of falling rain drops in the atmosphere); it appears that both these effects act in the same direction to somewhat amplify the amount effect observed in rainfall alone (details to be discussed elsewhere). Selection of sample site is important; the cave site should be located at elevated locations, where ground water contribution is absent (underground caves are best avoided). Also it should be as near the coast as possible to minimize isotopic effects to re-evaporation and mixing of vapour that produces monsoon precipitation. Such care was taken by Yadava and Ramesh[5], who presented a monsoon rainfall reconstruction that goes back to 3400 years BP, with a mean resolution of ~ 17 years. 100-year averages of these data are presented in the top panel of Figure 3, so that it can be compared with the oceanic record during the same ~ 3400-year period, having a resolution of ~ 125 years (in the top part of the core, every cm of the core was analysed and the resolution is relatively higher than the average resolution[6]). We now use calibrated ages (calen-

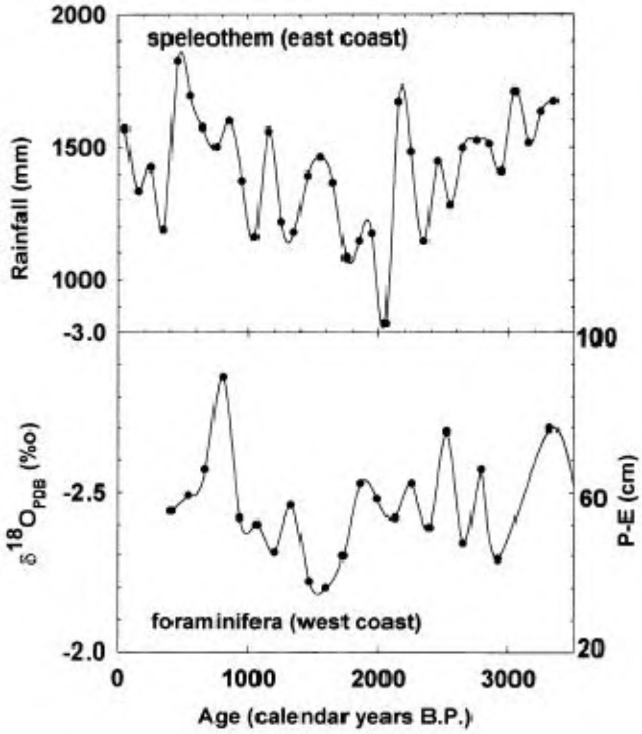


**Figure 3.** Comparison of proxy monsoon records; 100-year averages of monsoon rainfall obtained from $\delta^{18}O$ of a stalactite[5] from the Gupteswar cave, Orissa, for the last ~ 3400 years (top panel) and $\delta^{18}O$ of surface-dwelling foraminifera (*G. sacculifer*) from a sediment core in the coastal eastern Arabian Sea[6] for the same period (bottom panel). Abscissa denotes calendar ages (calibrated). Excess of precipitation over evaporation (P–E, cm) is also shown on the right side for the bottom panel.

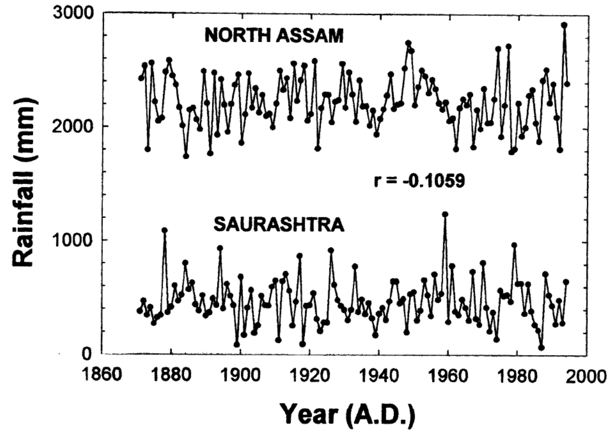


**Figure 4.** Comparison of available instrumental monsoon rainfall records of the eastern (Assam region) and western (Saurashtra) parts of India. $r$ denotes the correlation coefficient between the two time series, without any removal of trend, significant at 0.05 level (Student's $t$ test).

dar ages) for comparison. Obviously the records do not appear to match, in general. It is worth recalling that even in the present day distribution of monsoon rainfall, there is considerable geographical variability; it is common to witness droughts in western India more or less at the same time as floods in the eastern parts (e.g. available records of monsoon rainfall for the eastern (Assam region) and western (Saurashtra) are compared in Figure 4). Therefore, while comparing palaeomonsoon records obtained from widely separated sites, certain amount of geographical variability may occur. However, extreme events are more likely to show up in both the records. For example, the three peaks of excess precipitation at 800, 2500 and 3300 years BP seen in the oceanic record also occur in the cave calcite record, and the timings match within the dating uncertainties. It is also likely that the oceanic record responds preferentially to the high rainfall events (more depleted in $^{18}O$), whereas the cave record is more sensitive to drier events (enrichment of $^{18}O$). This is because in the surface ocean, the isotopic change due to evaporation is limited; there is plenty of water and only a very small fraction can be evaporated. On the other hand, river discharge from a vast area of land channeled through rivers can seasonally deplete the surface waters in $^{18}O$, especially in the near coastal environment. It is notable that the freshwater discharge prevents significant vertical mixing due to density contrast. In the case of caves, the seepage water supply is limited by the available monsoon rainfall; evaporation can significantly alter the $^{18}O$ composition unlike in the case of surface ocean.

## Conclusions

A comparison of various high resolution (100–200 years) quantitative rainfall reconstructions for the Holocene period available todate from the Indian region reveals that significant concordance exists between them, despite the diverse nature of samples and the different proxies used, especially for the western part of India. But this concordance appears to break down when proxy monsoon records from geographically widely separated sites are compared (spectral cross-coherence between the records or simple correlation analysis to determine the degree of similarity was not attempted because the number of data points is too low and the sampling interval of each of these records is different). Among a number of reasons discussed, spatial variations in monsoon rainfall within the Indian subcontinent, as evident in the modern times, appear to be important and likely persisted throughout the Holocene. *Thus, currently it appears possible to check for concordance in such proxy monsoon data only during extreme events, which are geographically more likely to be widespread, by careful selection of samples and isotopic proxies.* Before we are able to integrate the various proxy records of palaeomonsoon into a single time series that can serve to test monsoon models, it is important that we assess the temporal variance of this spatial variability in the monsoon rainfall. For this we need datable fast growing/sedimenting samples from different regions in the subcontinent. Alternatively, one has to await the development of regional models, which can be directly checked using the available palaeodata.


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