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Contrasting pattern of hydrological changes during the past two millennia from central and northern India: Regional climate difference or anthropogenic impact?

Praveen K. Mishra[a,b], Sushma Prasad[a,c,*], Norbert Marwan[d], A. Anoop[e], R. Krishnan[f], Birgit Gaye[g], N. Basavaiah[h], Martina Stebich[i], Philip Menzel[g], Nils Riedel[i]

[a] Wadia Institute of Himalayan Geology, 33 GMS Road, Dehradun 248001, India
[b] Institute for Earth and Environmental Science, University of Potsdam, Karl-Liebknecht-Straße 24-25, 14476 Potsdam, Germany
[c] ERA Scientific Editing, Grosse Fischerstrasse 10, 14467 Potsdam, Germany
[d] Potsdam Institute for Climate Impact Research, Telegrafenberg A 51, 14412 Potsdam, Germany
[e] Department of Earth and Environmental Sciences, Indian Institute of Science Education and Research (IISER) Mohali, Sector 81, SAS Nagar, Manauli, 140306, Punjab, India.
[f] Indian Institute of Tropical Meteorology, Pune, India
[g] Universität Hamburg, Institute of Geology, Hamburg, Germany
[h] Indian Institute of Geomagnetism, New Panvel, Navi Mumbai, India
[i] Senckenberg Research Institute, Research Station of Quaternary Palaeontology, Am Jakobskirchhof 4, D-99423 Weimar, Germany

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ABSTRACT

High resolution reconstructions of the India Summer Monsoon (ISM) are essential to identify regionally different patterns of climate change and refine predictive models. We find opposing trends of hydrological proxies between northern (Sahiya cave stalagmite) and central India (Lonar Lake) between 100 and 1300 CE with the strongest anti-correlation between 810 and 1300 CE. The apparently contradictory data raise the question if these are related to widely different regional precipitation patterns or reflect human influence in/around the Lonar Lake. By comparing multiproxy data with historical records, we demonstrate that only the organic proxies in the Lonar Lake show evidence of anthropogenic impact. However, evaporite data (mineralogy and $\delta^{18}O$) are indicative of precipitation/evaporation (P/E) into the Lonar Lake. Back-trajectories of air-mass circulation over northern and central India show that the relative contribution of the Bay of Bengal (BoB) branch of the ISM is crucial for determining the $\delta^{18}O$ of carbonate proxies only in north India, whereas central India is affected significantly by the Arabian Sea (AS) branch of the ISM. We conclude that the $\delta^{18}O$ of evaporative carbonates in the Lonar Lake reflects P/E and, in the interval under consideration, is not influenced by source water changes. The opposing trend between central and northern India can be explained by (i) persistent multidecadal droughts over central India between 810 and 1300 CE that provided an effective mechanism for strengthening sub-tropical westerly winds resulting in enhancement of wintertime (non-monsoonal) rainfall over northern parts of the Indian subcontinent, and/or (ii) increased moisture influx to northern India from the depleted BoB source waters.

1. Introduction

The severe economic and social impacts of extreme events in monsoonal Asia highlight the necessity of identifying long term trends in hydrological stresses that could help to refine predictive models. As instrumental data for the Indian summer monsoon (ISM) region are limited to ca. 130 years, palaeoclimatology has become a valuable tool as it offers a wide range of proxies that can help in reconstructing past climates. However, palaeodata present contrasting scenarios for the past two millennia. On the one hand, oxygen isotope data from northern India (Sahiya cave) (Sinha et al., 2015) indicates that the current drying trend is within the range of ISM variability over longer time scales. On the other hand, evaporite mineralogy and isotopic data from the central Indian Lonar Lake (Anoop et al., 2013; Prasad et al., 2014) indicate intervals of strongly weakened ISM over the past millennium. Further to the east, proxies from Lake Pa Kho (Thailand)

* Corresponding author at: Institute for Earth and Environmental Science, University of Potsdam, Karl-Liebknecht-Straße 24-25, 14476 Potsdam, Germany.
E-mail address: sprasad@erascientificediting.com (S. Prasad).

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indicate additional periods of weaker Asian monsoon, only some of which can be correlated with the records from India (Chawchai et al., 2015). However, a variety of factors determine the (inferred) regional climate: the complexity of forcing mechanisms, moisture sources and pathways as well as the intricacies associated with proxy interpretation. To address these challenges, we have chosen to focus on two well dated sites from India that show divergent signals. Since the precipitation over the Lonar Lake and the Sahiya cave is representative of the regional ISM (Prasad et al., 2014; Sinha et al., 2015), the apparently contradictory trends raise the question if this variability is related to widely different regional precipitation patterns or an artefact of human impact on the Lonar Lake. Lonar is uniquely suitable for decoupling the anthropogenic-climate signal as it is a small lake fed largely by ISM runoff and, to a limited extent by three ISM recharged groundwater fed perennial streams.

The human impact on the Lonar Lake is largely from cattle grazing, banana plantations which use groundwater, influx of organic waste, deforestation, and introduction of new plant species during afforestation efforts over past nearly four decades. The steepness of the crater slopes and the alkaline lake waters ensure that there is no direct human activity on the lake e.g. boating or diversion of lake water. In this study our objectives are to (i) use a new approach to decouple the anthropogenic and climate influence on limnology during the past 2 cal ka using multiproxy data (Prasad et al., 2014) from the Lonar core; (ii) compare the evaporative mineral and isotopic data from Lonar Lake with the $\delta^{18}O$ from north Indian stalagmites (Sahiya cave) to document regional differences; (iii) calculate an ensemble of backward monthly air trajectories to identify moisture sources for both sites; (iv) undertake a land sea comparison to identify causal mechanisms of regional differences.

2. Study area and modern climate

Lonar Lake is a near circular, meteor impact crater lake situated (Fig. 1a) in the semi-arid, core monsoon zone of India (Anoop et al., 2013) and receives its annual rainfall (average 760 ± 50 mm) almost exclusively during the summer monsoon period between June and September (Basavaiah et al., 2014). While the climatological mean rainfall is low over this region during the winter and early spring months, it is important to note there can be occasional heavy rains (> 8 mm/day) during the non-ISM season.

The Lonar Lake is closed, and fed by three perennial streams, surface runoff and ephemeral streams during the monsoon season (Anoop et al., 2013). The modern lake is hyposaline, alkaline (pH = 10), eutrophic and exhibits sub- to anoxic bottom water (Basavaiah et al., 2014). The evaporative nature of the Lonar Lake is also indicated by high $\delta^{18}O$ and δD values relative to rainfall and groundwater (Anoop et al., 2013).

The lake has a maximum depth of ca. 7 m (Anoop et al., 2013). The water level in the Lonar Lake fluctuates in response to ISM precipitation with higher lake level observed during intense monsoon rainfall (Komatsu et al., 2014). Interseasonal lake level changes up to 3 m have been reported by Jha (2003). During the dry season, the lake continuously receives minor groundwater input which is exceeded by evaporation resulting in the significant drop in lake level (Komatsu et al., 2014). Following a succession of intense dry years (e.g. 1982 CE), a thick trona crust has formed on the lake bed (Anoop et al., 2013).

The vicinity of Lonar crater is characterised by semi-arid vegetation but presently most of the area is under agricultural land use. Within the crater the vegetation is more diverse. The rim is overgrown with shrub-savanna, with *Acacia nilotica* and *Rhamnaceae* as dominant arboreals. The inner crater flanks features tree-savannah with *Tectona grandis*, *Wrightia tincoria*, *Butea monosperma*, and *Aegle marmelos* in varying densities. The crater floor mainly hosts *Azadirachta indica* and the salt tolerant *Prosopis juliflora* along the lake shore. The Dhara fan in the northeast is mostly under land use with crop plantations (millets, maize, bananas, and fruit trees) and meadows for grazing cattle. In addition, the Lonar Lake is also characterised by swamp vegetation in and around the Dhara fan (Riedel et al., 2015). Most trees growing in the Lonar crater were planted during 1986 to 1991 by the Forest Department (Babar, 2010) as part of an afforestation initiative. Beside of native trees, non-indigenous species were planted, for example *Eucalyptus* sp., *Delonix regia*, and *Prosopis juliflora* (ECONET, 1999).

3. Materials and methods

Surface sediments, soil, and terrestrial plant samples were collected in January 2007, May 2008, and February 2011 from Lonar Lake, and 10 m long sediment cores were retrieved in May 2008 from lake bed using a UWITEC piston corer. The sediment cores were opened and subsampled in the laboratory. All samples were freeze-dried prior to analyses. A detailed core description and chronology of cores is published in Prasad et al. (2014). Although the published chronological model used the IntCal04 in the then available version of OxCal, there is no significant change (≤ 2 years) in the investigated time interval when IntCal13 is applied in OxCal.

The laboratory procedures have previously been described in detail (Anoop et al., 2013; Prasad et al., 2014) and are briefly summarised here. Continuous down-core X-ray fluorescence (XRF) scanning of the sediment core at 5 mm resolution was performed using the Avaatech XRF Core Scanner III using tube voltage operated at 10 kV. For total carbon and nitrogen determination, around 25 mg of sample material were loaded in tin capsules and burned in the elemental analyzer. Total carbon and nitrogen content were calibrated against Acetanilide, whereas for the nitrogen isotopic composition two ammonium sulphate standards (e.g. IAEA N-1 and N-2) were used. Inorganic carbon (IC) was defined as the difference between TC and TOC. An empirical factor of 1.8 was used to convert TOC into total organic matter (Müller et al., 1986). $\delta^{13}C_{org}$ of the bulk samples were performed using in-situ decalcified samples measured with elemental analyzer (NC2500 Carlo Erba) coupled via a ConFlowIII interface on a DELTA^{plus}XL mass spectrometer (ThermoFischer Scientific). Around 3 mg of sample material were weighted into Ag-capsules, dropped with 20% HCl, heated for 3 h at 75 °C, and finally wrapped into the Ag-capsules and measured as described above. The calibration was performed using elemental (Urea) and certified isotope standards (USGS24, IAEA_CH-7) and proven with an internal soil reference sample (Boden3). The isotopic composition is given in delta notation relative to a standard: δ (‰) = $[(R_{sample} - R_{standard}) / R_{standard})] \times 1000$. The ratio (R) and standard for carbon are $^{13}C/^{12}C$ and VPDB (Vienna PeeDee Belemnite) respectively.

Back trajectories (168 h) were obtained to reconstruct the path of moisture sources in central and northern India. The isentropic backward trajectories (168 h) were acquired using the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model provided by National Oceanographic and Atmospheric Administration (NOAA) and Air Resources Laboratory (ARL). Trajectories for the time period of 168 h (sampled four times daily at 00, 06, 12 and 18 h) were computed at lower troposphere (1500 msl) for the selected anomalous wet and dry multiple years from the ISM season (i.e. JJAS months) (Table S1). For the analysis 'wet' and 'dry' years are selected based on the average rainfall departure (in JJAS) from the 20th century mean from Buldana in central India (ca. 50 km from the Lonar Lake) and Uttarkashi in north India (ca. 50 km from the Sahiya cave) (Table S1). The use of multiyear trajectories reduces the computational errors which are inherited in the HYSPLIT model during the reanalysis process (Sinha et al., 2015).

A correlation analysis was performed using a Gaussian kernel based variant of the Pearson correlation allowing for direct comparison of proxy records with irregular and different sampling points (Rehfeld et al., 2011). Before the correlation test, the proxy time series have been high-pass filtered by a Gaussian kernel based smoothing using a kernel bandwidth of 100 years in order to remove longer time scales that are

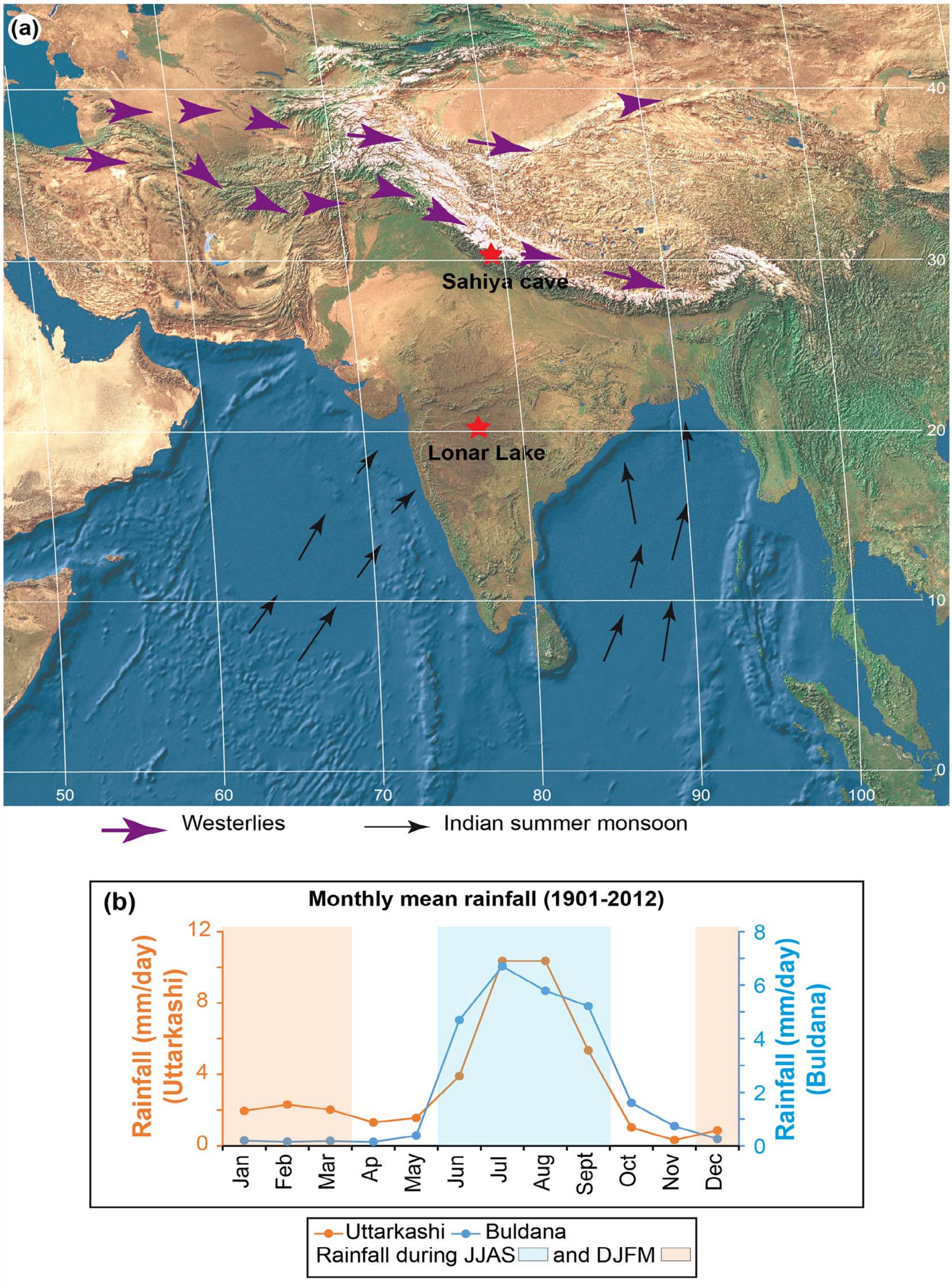

Fig. 1. (a) Location of study areas discussed in the text; (b) monthly mean rainfall (1901 to 2012) from the study areas.

not of interest in our study (probably caused by changes in the solar irradiance that would act as a common driver in both records). The correlation was then calculated within overlapping periods of 500 years (overlap 450 years). In order to estimate the significance of the results, a confidence interval was calculated. For each of the moving periods of 500 years, we created 500 phase randomization based surrogate time series (Prichard and Theiler, 1994). The correlation values between the surrogates of the both proxies provide empirical test distributions of the correlation coefficient and the 5% and 95% quantiles represent the 90% confidence interval regarding the null-hypothesis that the time series in the considered time period are uncorrelated.

4. Results

Variations in stable isotopes of organic matter, TOC and TN contents, as well as C/N for the past two millennia in the Lonar Lake are shown in Fig. 2. Detailed investigations on Lonar core sediments encompassing the past 2000 years indicate the presence of evaporative calcite and gaylussite in specific intervals (Anoop et al., 2013). In the interval under consideration, the first appearance of gaylussite is dated to − 40 CE with a prominent gaylussite zone between ~550–1350 CE (Fig. 2) (Anoop et al., 2013; Prasad et al., 2014). There is strong enrichment of $\delta^{18}O$ values (arrow in Fig. 2d) of bulk carbonate (by ca.

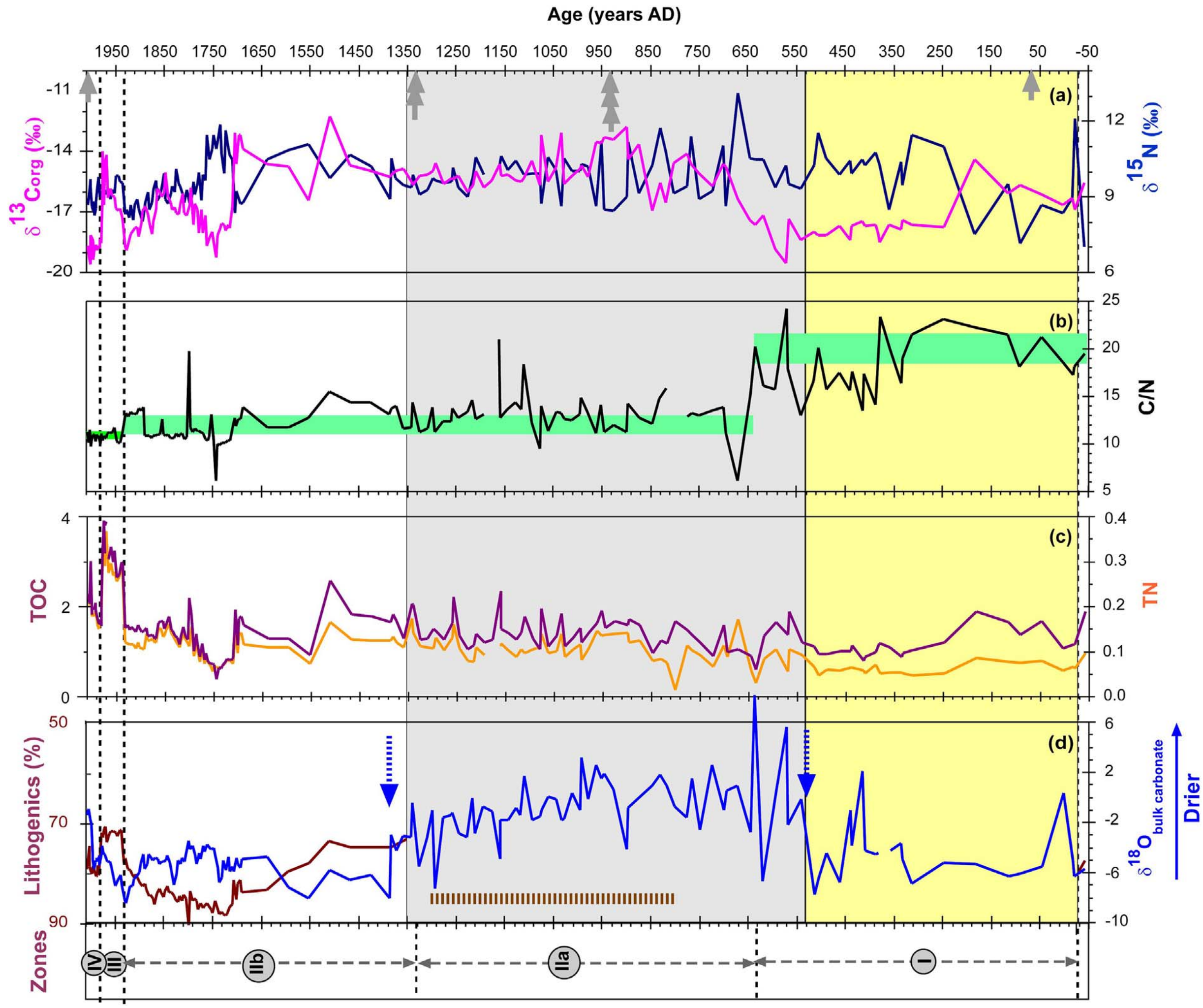

Fig. 2. Variations in organic proxies (a) carbon and nitrogen isotopic composition of bulk organic matter; (b) C/N. The mean values of C/N (with 1 standard deviation) are marked by horizontal green bars; (c) TN and TOC; (d) oxygen isotopic composition of bulk evaporite carbonate (excluding gaylussite) and lithogenics. Grey arrowheads on the upper age axis indicate the number of radiocarbon dates. Dashed vertical black lines are used to separate productivity zones in the lake (see text for details). Blue dotted arrows in (d) indicate prominent shifts in the oxygen isotope curve. The yellow bar indicates appearance of gaylussite and the grey bar indicates persistence of gaylussite. The horizontal dark brown dashed bar in (d) indicates section with highest $\delta^{18}O$ enrichment in gaylussite crystals. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

6‰) at around 540 CE (1460 cal year) followed by stable $\delta^{18}O$ values until 1380 CE (arrow in Fig. 2d). The boundaries of these shifts are largely coincident with the prominent gaylussite zone. Highest $\delta^{18}O$ enrichment (brown dashed line in Fig. 2d) is shown by gaylussite crystals between ca. 800–1300 CE indicating this to be the interval with lowest P/E (Anoop et al., 2013).

Data from the organic proxies for the past two millennia in the Lonar Lake are shown in Fig. 2 (a–c). There is a shift from dominantly terrestrial organic matter with large scatter in Zone I (− 40 to 640 CE) towards mixed organic matter sources between 640 and 1930 CE in Zone II (a, b) (lower C/N with reduced scatter, see also Figs. 2b and 3a). There is a final shift to dominant aquatic productivity (Fig. 2b) after 1930 CE that is also accompanied by a short interval of increased TOC and TN into the lake (Figs. 2c, 3b) and $\delta^{15}N$ enrichment between 1930 and 1980 CE in Zone III (Figs. 2a, 3c) with a return to previous values in Zone IV (1980–2008 CE).

Based on the interrelationships between the abundance of gaylussite mineral, lithogenics, and the organic proxies from the past two millennia the climate record from the Lonar Lake can be divided into four zones (Fig. 2):

(i) Zone I (− 40 to 640 CE): showing first appearance of gaylussite mineral (Anoop et al., 2013). The C/N value ranges between 13 and 24 suggesting mixed organic matter sources (i.e. terrestrial and aquatic).

(ii) Zone II (640 to 1930 CE): characterised by increased gaylussite, reduced C/N and lithogenic input the lake. This zone is further divided into two sub-zones based on the major changes in $\delta^{18}O_{carb}$ values (− 0.95‰ in Zone IIa to − 3.04‰ in Zone IIb).

(iii) Zone III (1930 to 1980 CE): marked by dominance of aquatic productivity (low C/N), accompanied by a short interval of increased TOC and TN into the lake (Figs. 2c, 3b) and enrichment of $\delta^{15}N$ between 1930 and 1980 CE (Figs. 2a, 3c).

(iv) Zone IV (1980 to 2008 CE): short period is characterised by sharp decrease in $\delta^{13}C_{org}$ and increase in TOC and TN values.

5. Discussion

In the following section we will evaluate the Lonar data to address specific questions: (i) Is it possible to identify anthropogenic signals in the sediment proxies (organic and evaporitic isotopes) and link them with activities in the catchment? If yes, then which processes were responsible for transferring this signal to the sediment? (ii) Is there an identifiable climate signal in the Lonar sediments? Does it lie within the

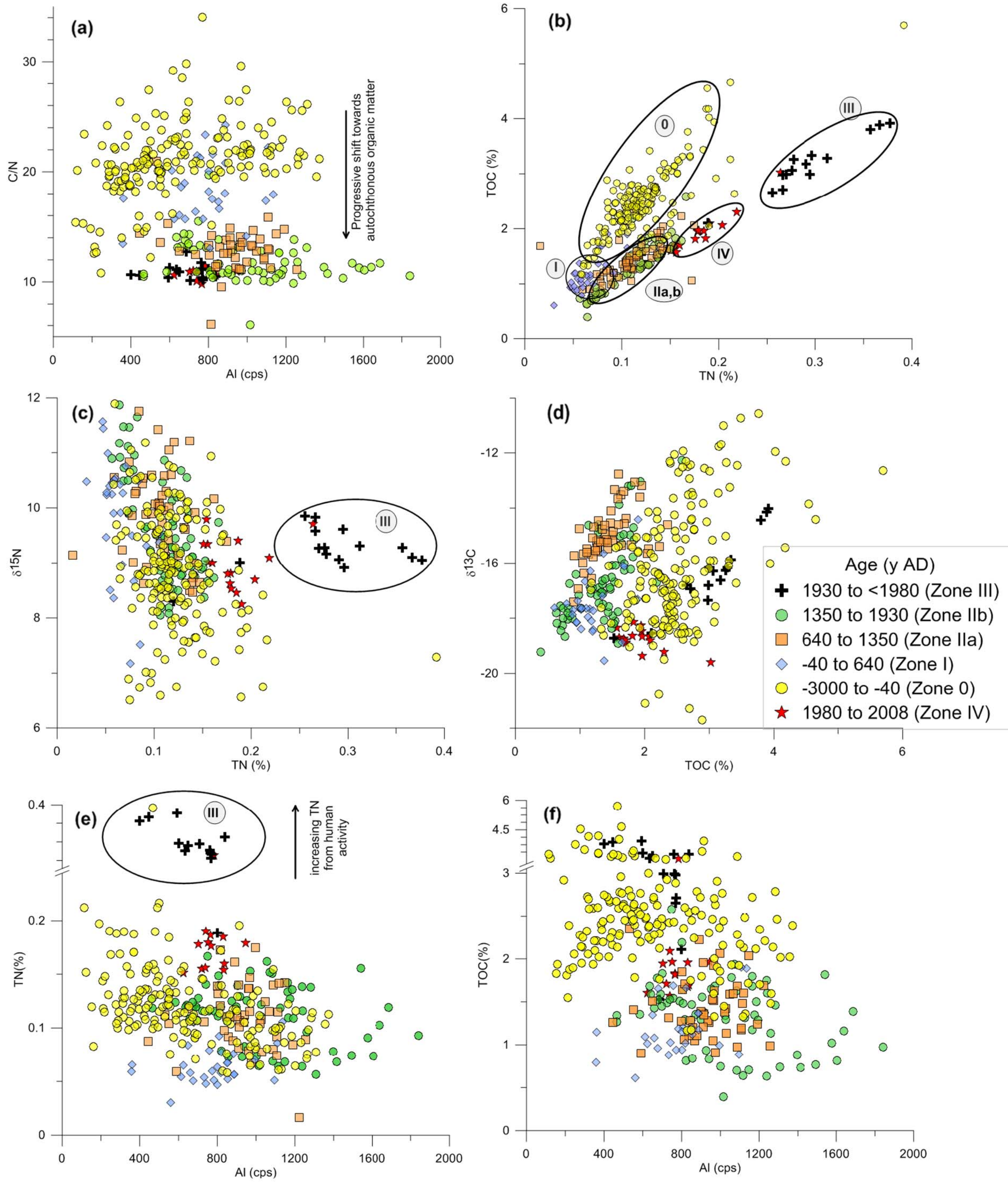

FIG 3

Fig. 3. Cross plots of proxy data from zones identified in Fig. 2. Zone 0 is pre-anthropogenic (− 3000 cal year to − 40 CE, used as baseline to indicate natural variability), Zone I (− 40 to 640 CE), Zone II (a: 640–1350 CE with persistent gaylussite; and b: 1350–1930 CE without gaylussite), Zone III (1930–1980 CE), and Zone IV (1980–2008 CE). The same legend is applicable to all plots in this figure. The final shift to stronger eutrophication ca. 1930 CE is linked to human activity that led to increased TOC and TN deposition in the lake.

range of modern ISM variability? (iii) How does the climate signal in Lonar compare with the north Indian stalagmite record? (iv) Can we identify mechanisms underlying climate change?

To answer these questions, we first undertake an intercomparison of the organic and evaporitic proxies in the Lonar Lake.

5.1. Comparison of evaporite and organic proxies in the Lonar Lake (climate versus human impact)

In contrast to calcite and aragonite that form in surface waters (Leng and Marshall, 2004; Reddy and Hoch, 2011), the primary gaylussite mineral is precipitated by evaporative concentration of brine (Eugster and Hardie, 1978; Mees et al., 1991) at the sediment–water interface (Bischoff et al., 1991). Gaylussite usually succeeds the precipitation of calcite and is the first sodium carbonate mineral to be precipitated during progressive evaporation of saline, alkaline waters (Rankama and Sahama, 1964; Renaut et al., 1986).

The organic matter preserved in lake sediments is often a mixture of allochthonous (in particular soil and terrestrial plant organic matter) and autochthonous sources. The isotopic composition of the organic sediments depend on their photosynthetic pathways as the C_4 plants ($\delta^{13}C$ in the range of ca. −12‰) favour conditions of low soil moisture and aridity, while C_3 plants ($\delta^{13}C$ in the range of ca. −27.1‰) plants dominate areas of higher soil moisture and precipitation (Talbot and Johannessen, 1992; Prasad et al., 1997; Xu et al., 2006: Prasad et al., 2016). Land plants can have a wide range of $\delta^{15}N$ values averaging at around 4‰ (Maksymowska et al., 2000).

The $\delta^{13}C$ record of the phytoplankton (autochthonous) component of lake sediments is governed by changes in organic productivity, salinity, and pH of the lake water (Stuiver, 1975). Photosynthetic organic productivity preferentially uses ^{12}C and ^{14}N, leaving the DIC and DIN pools enriched in ^{13}C and ^{15}N, respectively (Swart, 1983; Talbot and Lærdal, 2000). Under CO_2 deficient conditions (< 0.01 mol/l), which prevail in highly alkaline water (Schelske and Hodell, 1991; Xu et al., 2006), phytoplankton is forced to change from CO_2 to HCO_3^- based metabolism, which produces relatively ^{13}C enriched organic matter (Talbot, 1990; Leng and Marshall, 2004). The nitrogen isotopic composition of organic matter in lake sediments can reveal the sources of organic matter, the nutrient source and the trophic state (e.g. Meyers, 2003; Ogrinc et al., 2005). Certain cyanobacteria, can fix atmospheric N_2 during photosynthesis which produces organic matter with $\delta^{15}N$ close to 0‰, the value of nitrogen in air. As in the case of carbon, elevated pH (Menzel et al., 2013), as well as oxygen deficiency, enhance the $\delta^{15}N$ of nutrients in lake water via ammonium volatilization or, respectively, reduction of reactive nitrogen (Heaton, 1986; Leng et al., 2006). Investigations of modern sediments in Lonar Lake (Menzel et al., 2013) have also shown that high $\delta^{15}N$ and low C/N values are found in shallow waters with aquatic organic matter dominated by microbially reworked cyanobacterial mats – aerobic degradation can cause $\delta^{15}N$ enrichment of up to 5–9‰ (Macko and Estep, 1984).

In the Lonar sediments, the shift from dominantly terrestrial organic matter towards mixed organic matter sources (terrestrial and aquatic) at ca. 640 CE (Fig. 2, Zone 1 to Zone IIa) also coincides with reduced inflow of lithogenics suggesting declining surface runoff and the dominance of evaporitive processes into the lake basin (Fig. 2d). Interestingly, there appears to be an apparent discrepancy between the hydrological and biological proxies (Fig. 2b and d). The appearance of evaporitic gaylussite indicates the onset of lower P/E at −40 CE and its intensification at 540 CE (Fig. 2d), thus preceding the onset of eutrophication (at ca. 640 CE, as inferred from the shift to lower C/N in Fig. 2b) by ~680 years. The productivity and isotopic shifts identified in the organic proxies are not reflected in the $\delta^{18}O$ of evaporitic carbonates suggesting an additional human impact on organic proxies.

A comparison of archaeological/historical record with the proxies, as well as an understanding of the processes influencing the proxies can be used to decouple the climate versus anthropogenic impact. Human influence on organic proxies can be seen in the increased influx of nutrients into the lake triggered by increased erosion (caused by changing land use and vegetation cover) and/or use of animal dung or fertilizers in the banana plantation within the crater. Our investigations of the modern catchment and lake surface sediments show that Aluminium (Al) is contributed by catchment erosion and its distribution parallels the lithogenic content in surface sediments and is an indicator of detrital input into the lake (Basavaiah et al., 2014).

Plots (Figs. 2b and 3a) show that the C/N ratios, as indicators of aquatic productivity are lower after 640 CE. This change is most likely due to human influence as the date of the productivity shift coincides with the building of the oldest temple in the crater (Osae et al., 2005). A marked increase in herb pollen values further points to intensified anthropogenic impact on the vegetation beginning at ca. 1.2 cal ka (750 CE) (Prasad et al., 2014). The period prior to the interval under discussion (−40 to 2008 CE), considered to be the background, is named as Zone 0 (−3000 to −40 CE). Zone I (−40 to 640 CE) shows higher C/N values with a large scatter due to varying amounts of terrestrial vegetation brought by inflow (Fig. 3a). The shift towards decreased C/N ratios (640–1930 CE) in Zones II (a,b) is caused by increased autochthonous contribution, though no significant difference is seen between the gaylussite (IIa) and non-gaylussite (IIb) zones. Fig. 2c shows that during 1930–1980 CE (Zone III), TN and TOC are strongly elevated in comparison to Zone 0 (see also Fig. 3b) though their isotopic composition lies within the previous range. Based on our field studies and available literature (Babar, 2010; Yannawar and Bhosle, 2013; Dabhade, 2013) we attribute the high TOC and TN during Zone III to the influx of sewage, and nitrogen based fertilizers into the lake by increased surface inflow (Fig. 2c). Extensive afforestation was initiated in Lonar Crater between 1986 and 1991 CE by the Maharashtra State Forest department resulting in reduced erosion. This is reflected in the lowered TOC and TN values in the sediment between 1980 and 2008 in Zone IV (Fig. 2c, Fig. 3e and f).

5.2. Is there an identifiable climate signal in the proxies? Does this lie within the range of modern ISM variability?

As discussed above, the human influence is seen in geochemical, pollen, and organic matter derived signals preserved in the sediments.

The changes in evaporitic carbonate isotopic composition and mineralogy (beginning −40 CE and more prominently at ca. 540 CE, Anoop et al., 2013) precede the human impact on organic proxies by ca. 680 years. The groundwater input into the lake in modern times is very small and most of the inflow is from the surface runoff into the crater, unimpeded by human activity. Hydrochemical and isotope data from inflowing streams and lake waters indicate that evaporitic processes play a dominant role in the precipitation of carbonates within this lake (Basavaiah et al., 2014). Due to these reasons, we consider the evaporite minerals to be reliable indicators of P/E balance of the lake. The formation of gaylussite zones during the past two millennia clearly indicates that there have been intervals of prolonged droughts.

Isotopic ($\delta^{18}O$ and $\delta^{13}C$) studies on the evaporative gaylussite crystals and residual bulk carbonates (calcite and aragonite) from the long core show that P/E is the major control on $\delta^{18}O$ enrichment in these minerals (Anoop et al., 2013; Prasad et al., 2014). We consider the $\delta^{18}O_{bulk}$ to be influenced by P/E alone as there is no evidence of changes in precipitation tracks in central India which may supply water with different $\delta^{18}O$ signals during this interval (Sarkar et al., 2015) (see also the hysplit discussion below). The shifts in $\delta^{18}O$ of bulk carbonate (Fig. 2d) are largely coincident with the prominent gaylussite zone providing independent confirmation that the evaporite minerals and their isotopic composition are a reliable indicator of P/E. The average summer rainfall between 2002 and 2011 CE was ca. 20% below the long term mean (Indian Meteorological Department) without any gaylussite formation clearly indicating that a substantially longer interval of reduced ISM is needed for the formation of these evaporites. Based on the mineralogical and carbonate isotopic evidence we conclude that the occurrence of prolonged centennial scale droughts in central India is clearly beyond the range of instrumental ISM variability as no such evaporite zones have been found after 1350 CE.

5.3. How does the climate signal in Lonar Lake compare with the other regional records?

A comparison of the oxygen isotopic signal from Lonar Lake with the Sahiya stalagmite (Sinha et al., 2015) indicates largely opposing signals during 100–1300 CE (Fig. 4a) though the anti-correlation is statistically significant only between 810 and 1300 CE when Lonar Lake was driest (inferred from the maximum enrichment in $\delta^{18}O$ of separated gaylussite crystals, Anoop et al., 2013). We have statistically confirmed

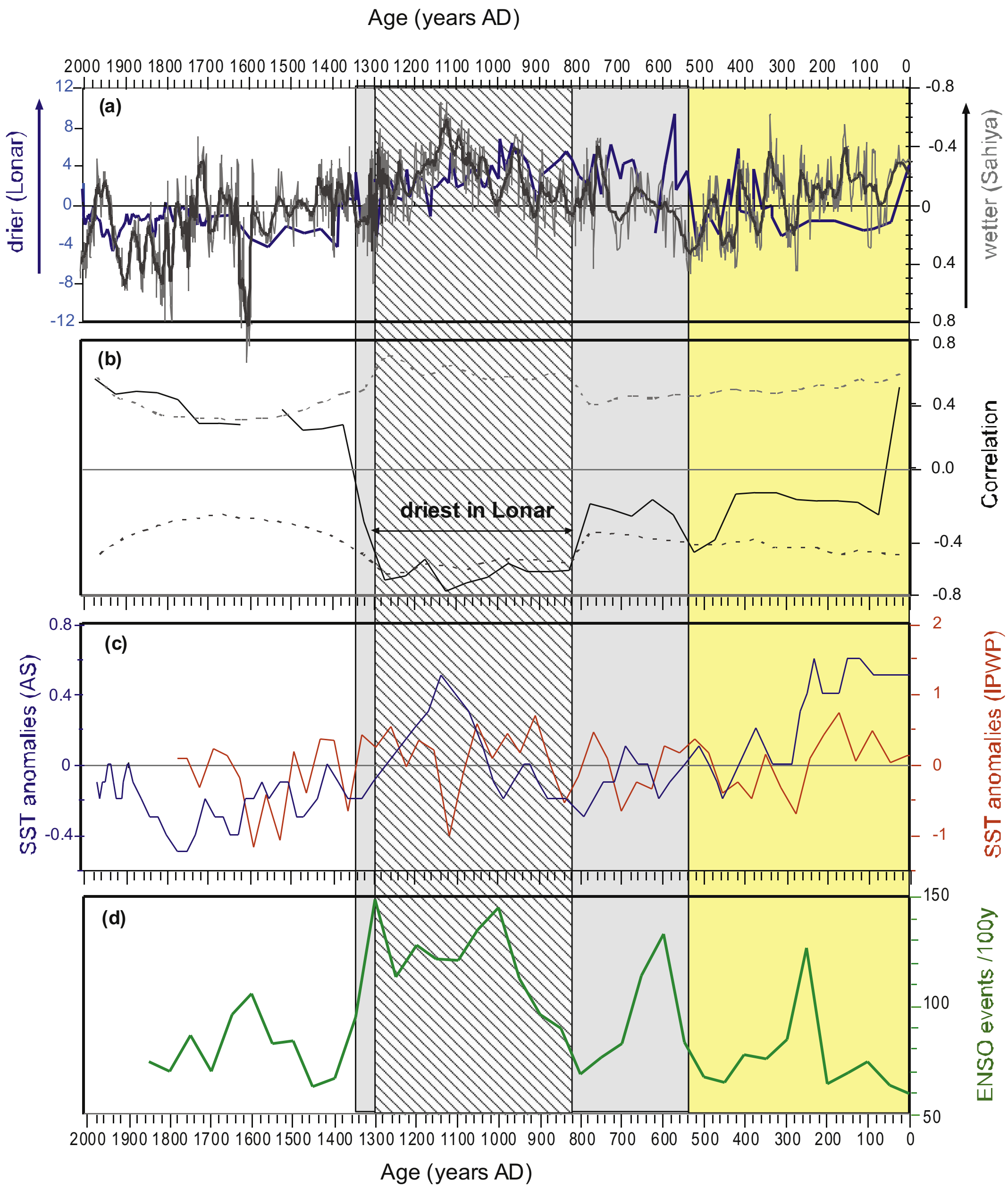

Fig. 4. (a) $\delta^{18}O$ anomalies from Sahiya cave stalagmite (Sinha et al., 2015) and Lonar Lake bulk carbonate (Prasad et al., 2014); (b) sliding window correlation between the Sahiya cave and Lonar Lake $\delta^{18}O$ anomalies indicates significant anti-correlation (90% confidence interval) between the two records during 810 and 1300 CE; (c) SST anomalies in the Indo-Pacific warm pool (IPWP) (Linsley et al., 2010) and the AS (Böll et al., 2015); (d) reconstructed ENSO events (Moy et al., 2002). The yellow bar indicates appearance of gaylussite, whereas the grey bar indicates persistence of gaylussite. The cross hatched zone in the gaylussite zone indicates the driest period in Lonar as inferred from isotopic data from gaylussite crystals (Anoop et al., 2013). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

these results even under consideration of age uncertainties by using a Monte Carlo approach (COPRA framework, Breitenbach et al., 2012) and calculating correlations from the ensembles of the proxy records (consisting of 1000 proxy records due the different realizations of the age models). The correlation values, thus, form empirical test distributions for each time point. Our results show that more than half of the realizations exceed the significance level (Supplementary material). Interestingly, another well dated stalagmite record from Dandak cave (also from the eastern part of the core monsoon zone), where the $\delta^{18}O$ variability has been attributed to the "amount effect" (Sinha et al., 2007, 2011; Berkelhammer et al., 2010) shows depleted values between 810 and 1300 CE but no statistically significant correlation with the Lonar record. The apparent discrepancy could be related to the role of BoB branch of ISM in eastern India where the Dandak cave is located.

During the past six centuries, both north and central India show similar trends. Other low resolution peat and sediment records (Chauhan et al., 2000; Kar et al., 2002; Bhattacharya et al., 2007) from north India also support wetter climate between ca. 800–1300 CE. Since both the archives, stalagmites and lakes, have challenges associated with data interpretation, understanding the causal mechanisms of proxy variability is crucial for identifying the climate signal.

5.4. Can we identify mechanisms underlying regional differences?

Either changes in source water composition (Breitenbach et al., 2010) or "amount effect" (Fleitmann et al., 2003) could have caused the observed opposite trend in north and central India. To explore this possibility we have evaluated back trajectories of air mass circulation in

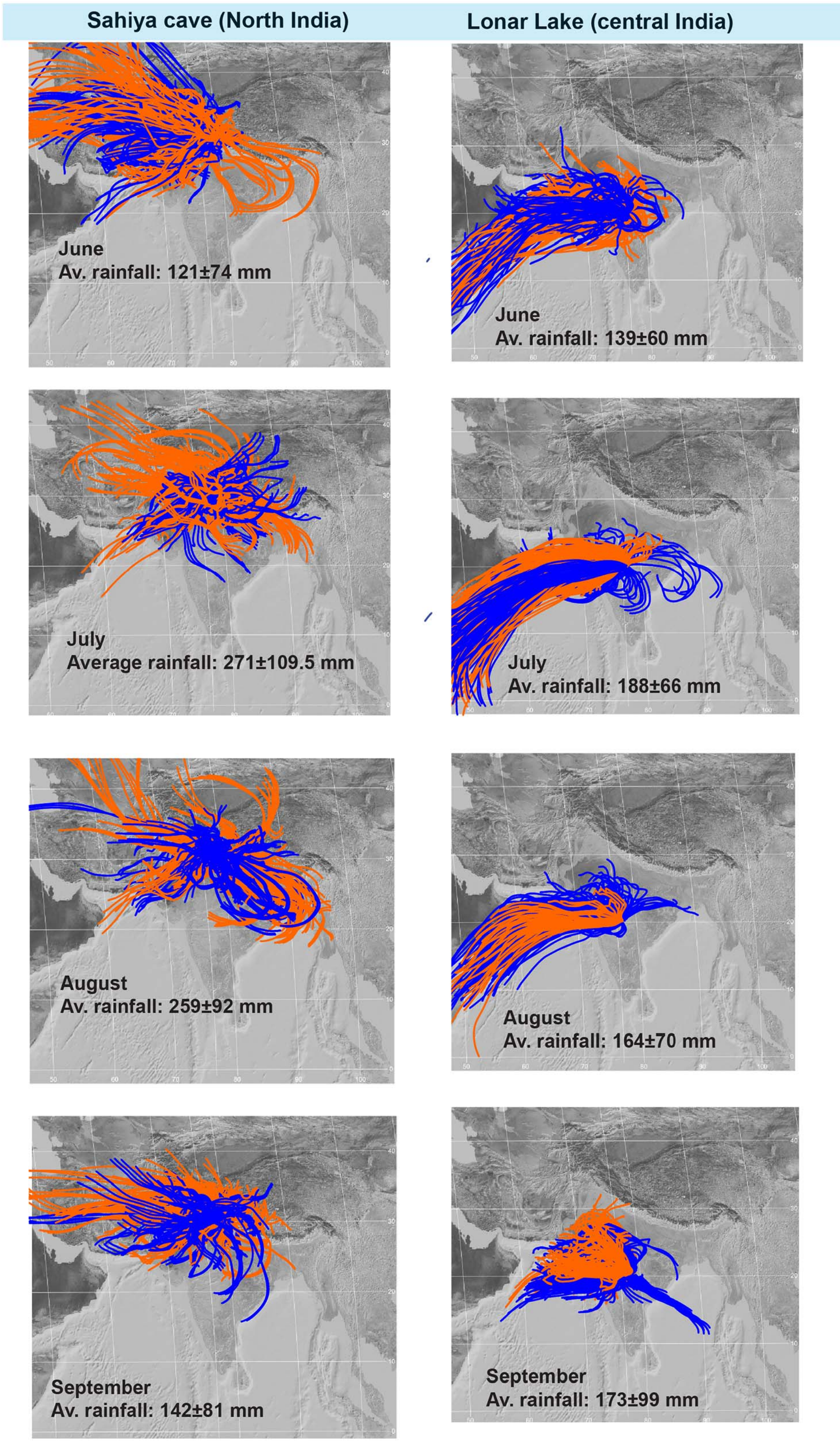

Fig. 5. The HYSPLIT trajectory ensembles depicting air-parcel/moisture transport routes for JJAS for Sahiya cave (north India) and Lonar Lake (central India). The blue and orange lines are associated with periods of anomalously high and low rainfall, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the studied area for several years. For both these sites, data from the nearest (Buldana for Lonar Lake and Uttarkashi for the Sahiya cave) meteorological stations have been used. A variety of precipitation patterns with similar, opposing, and normal seasonal rainfall trends in north and central India (Table S1) have been used.

Fig. 1b shows the annual cycle of climatological mean precipitation (mm/day) averaged around Uttarkashi and Buldana respectively. While the summer monsoon precipitation (June through September) dominates the annual precipitation cycle at both the locations, the mean precipitation over Uttarkashi (~ 2 mm/day) from December through March has a significant contribution to the annual cycle. The non-monsoon winter precipitation over the region of Uttarkashi mostly

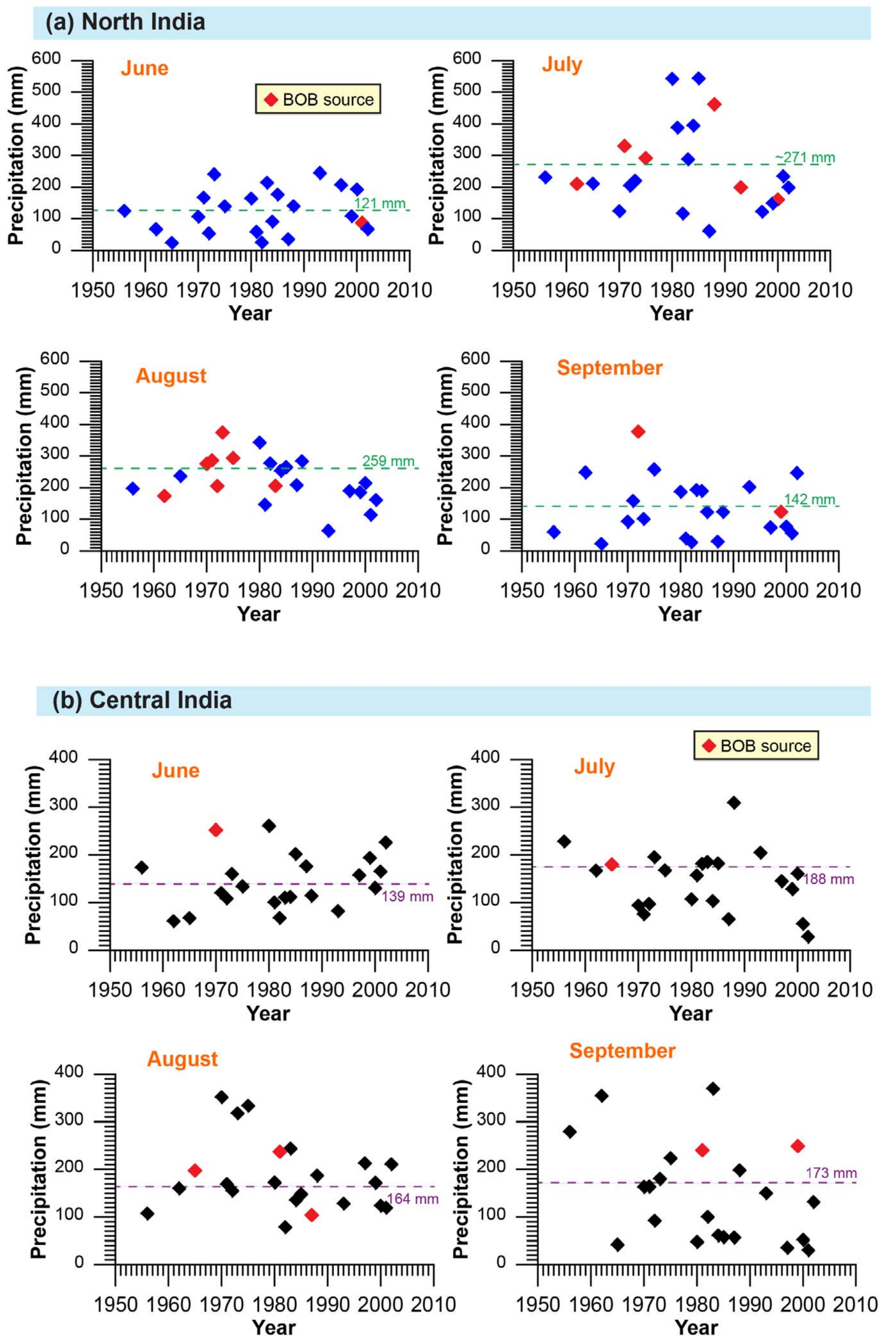

Fig. 6. Annual moisture contribution during the selected years in the central and north India. Dotted lines indicate average seasonal precipitation (in mm) based on the 20th century average.

comes from synoptic weather systems known as "Western Disturbances" (WD), which are embedded in the upper-level sub-tropical westerlies (Madhura et al., 2015; Dimri et al., 2015).

The air mass trajectories for Sahiya cave and Lonar Lake as well as the average seasonal precipitation data from the nearest stations, Buldana (central India) and Uttarkashi (North India) are plotted in Figs. 5 and 6 respectively. The air masses in central India are predominantly derived from the AS. However, independent of the total seasonal rainfall, there is a significant amount of precipitation in north India sourced from the BoB during July and August (Fig. 5). The average sea water isotopic composition of the AS is ~1‰ enriched in $\delta^{18}O$ with respect to the BoB due to large difference in the water river discharge (Delaygue et al., 2001). The BoB shows large seasonal changes in isotopic composition and water salinity of its surface-water (Gupta and Deshpande, 2005). As shown in Fig. 5, even within the ISM realm, intra-annual and seasonal changes in the moisture sources (AS versus BoB) can have significant impact on the regional hydrology and $\delta^{18}O$ values.

The $\delta^{18}O$ variations during 810–1300 CE, between Central and Northern India point to drier (wetter) conditions over Lonar (Sahiya) respectively (Fig. 4a). One possibility could be the increased contribution of the depleted $\delta^{18}O$ moisture from BoB to north India (Sahiya Cave) (Sinha et al., 2015). As noted in Sinha et al. (2015), Sahiya cave is located at the distal end of the BoB branch of the ISM and at the northern periphery of the monsoon trough. Although the monsoon trough is a semi-permanent feature of the summer monsoon system, it is characterised by significant variations on sub-seasonal time-scales. In particular, the spatial structure of the monsoon trough (horizontal and vertical scales) is known to be sensitive to the spatial distribution of latent heating associated with organization of monsoon precipitating systems (Choudhury and Krishnan, 2011). For example, a slight northward shift of the MT during monsoon breaks often tends to enhanced precipitation near the Himalayan foothills (Vellore et al., 2014), including areas near the Sahiya cave.

The second possibility involves the role of stronger subtropical westerly winds (amount effect) under conditions of suppressed monsoon rainfall (ISM droughts), which can give rise to internal feedbacks between mid-latitude circulation and monsoon convection anomalies (e.g., Ding and Wang, 2007; Krishnan et al., 2009). ISM droughts can also be externally forced by persistent ENSO conditions through changes in the Walker circulation that cause anomalous descent over South and Southeast Asia (e.g., Sikka, 1999; Krishna Kumar et al., 2006). Basically the suppression of ISM rainfall/convective activity, either by persistent ENSO conditions or through internal feedbacks, facilitates southward intrusion and subsidence of cold and dry mid-latitude and sub-tropical upper-level westerly winds over the Indian landmass (e.g., Ramaswamy, 1962; Raman and Rao, 1981; Krishnan and Sugi, 2001; Krishnan et al., 2000, 2009; Krishnamurti et al., 2010). In particular, sustenance of monsoon droughts through multiple decades can serve as an effective mechanism for anomalous subtropical westerly winds to pervade over northern parts of the Indian subcontinent all round the year (see Krishnan and Sugi, 2001; Meehl and Hu, 2006). This situation can, however, favour increased wintertime rainfall over the Uttarkashi region of the Western Himalayas, due to enhanced activity of WD (Madhura et al., 2015) and possibly transient heavy events even during the summer monsoon (JJAS) as well (Malik et al., 2016). An extended cave monitoring can clarify the role of westerlies (if any) in the $\delta^{18}O$ variability in the Sahiya stalagmites.

Modelling studies (Polanski et al., 2014) indicate intensified westerlies activity during the Medieval Climate Anomaly (800–1350 CE) which is coincident with the interval of maximum $\delta^{18}O$ contrast between the Lonar Lake and the Sahiya cave. As shown in Fig. 4d, the ENSO variability appears to have been also stronger (Moy et al., 2002) during this period. We conclude that either the strengthening of the upper-level subtropical westerlies and increased wintertime rainfall over the Uttarkashi region, or enhanced contribution from the BoB branch of the ISM to northern India (Figs. 5 and 6) could have resulted in opposing trends in $\delta^{18}O$ observations between central and northern India during the period ca. 810–1300 CE.

6. Conclusion

Using isotopes from bulk organic matter and evaporite minerals, we have decoupled the impact of anthropogenic activities and climate on the Lonar Lake. The elemental values (TOC, TN) and isotopic ratios of organic matter are impacted by anthropogenic activities. The surface inflow governs the lake hydrology and hence the mineralogy and isotopic signal of evaporite minerals. An interproxy comparison shows that the climate induced changes in P/E, as evidenced in evaporitic carbonate isotopic composition and mineralogy, precede the human impact on organic proxies by ca. 680 years.

The comparison of $\delta^{18}O$ data for the past two millennia from two well-dated sites in northern and central India provides evidence of differences in regional precipitation and moisture pathways, as well as human impact on organic proxies in the ISM realm. The Sahiya Cave (north) and Lonar Lake (central) $\delta^{18}O$ anomalies indicate opposite climate trends which are most significant between 810 and 1300 CE (enriched $\delta^{18}O$ in Lonar suggesting drier conditions and depleted $\delta^{18}O$ in Sahiya cave showing apparently wetter conditions (westerlies) or increased contribution from the BoB branch of the ISM). We propose that either of the two mechanisms, an increase in westerly precipitation in northern India or enhanced contribution from the BoB branch (with depleted $\delta^{18}O$) of the ISM to northern India could have resulted in this observed N−S hydrological differences.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloplacha.2017.12.005.

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