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Stable Isotopic Characterization of Nor'westers of Southern Assam, NE India

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Abstract: Stable oxygen and hydrogen isotopic compositions ($\delta^{18}O$ and δD) of rainwater collected between 2009 and 2011 CE from Hailakandi, southern Assam, north-eastern India have been measured to characterize the extreme rainfall phenomena, delineate moisture sources, determine amount effect and assess the prospect of local proxies for paleoclimate studies. The $\delta^{18}O$ values range from +0.7 to –13.8‰ while δD varies between +12 and –98‰. During the pre-monsoon months (March to May), heavy rains and thunderstorms, called nor'westers (*Kal Baisakhi* in local parlance), occur in some years giving rainfall as much as the monsoons. Strong evaporation and localised convection due to elevated air and sea surface temperature in the region and over the adjacent Bay of Bengal seem to cause nor'wester activity. No amount effect is observed in rain. The *d*-excess values for nor'wester rains is very different from those of monsoon rain; very low *d*-excess values (up to –26‰) were observed in 2010 CE and attributed to vapour originated from re-evaporation of freshwater, contributed by the lowland water bodies and rivers. The meteoric water line for the nor'wester rains, unlike that for the monsoon season, is significantly different from the Global Meteoric Water Line (GMWL). During the monsoon, the rain becomes progressively more depleted in the heavier isotopes (D and ^{18}O), with the lowest δ values occurring in Sep-Oct. Oxygen isotope-based paleoclimatic study in this region appears to be confounded by a strong dependence of the rainwater isotopic composition on the source of moisture, uneven distribution of rains during the monsoon and the pre-monsoon seasons and the absence of amount effect.

Keywords: Nor'westers; Monsoon; Stable isotopes; Meteoric water line; NE India.

Introduction

The South Asian Summer Monsoon (SASM) is a planetary scale weather system that affects a large portion of densely populated regions of east Africa and Indian subcontinent (Wang et al*.,* 2005). In north-east (NE) India, West Bengal and Bangladesh, it is characterised by strong seasonal rainfall with occasional floods. Therefore, SASM variability, its failure and excess have direct impacts on the society, regional agriculture, economy and food security (Mooley and Parthasarathy, 1982; Mukherjee et al., 2007; Parthasarathy et al., 1988; Shah et al., 2006). Often, during the pre-monsoon months (March to May), dusty squalls followed by spells of thunderstorms and heavy rains lash a large part of NE India, West Bengal and Bangladesh (Peterson and Mehta, 1981; Yamane and Hayashi, 2006). These thunderstorms are examples of intensive atmospheric

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vortices and are convective in nature; they are called nor'westers, *Kal Baisakhi* in local parlance. They grow when the atmosphere becomes sufficiently unstable because of localised surface heating. These storms that approach from the NW burst suddenly with great fury usually in the late afternoon. Their paths vary in width from a few hundred metres to more than a km, and the distance covered does not exceed 50 km, but they can cause huge devastation of property and crops. On many occasions, they cause considerable amount of precipitation and in some years (e.g. 2010 CE), the pre-monsoon thunderstorms are so severe and the amount of rainfall is so high that it becomes difficult to distinguish between the pre-monsoon and the monsoon rains. The reconstruction of past variability of nor'westers and the study of causative processes are important because of its societal relevance and for regional climate modelling. It is estimated that the tropical cyclones are going to be intensified with the climate change (e.g., Knutson et al., 2010). Therefore, more systematic study including their past variations is important to understand tropical cyclones. Unfortunately, the studies available on the causative mechanisms of nor'westers are very limited (Roy and Chatterjee, 1929; Sen, 1931) and isotope-based studies are almost nonexistent. An early study of nor'westers by Roy and Chatterjee (1929) showed that they originate when the warm moist southerly or south-westerly wind rides over a westerly or north-westerly cold air mass with a high lapse rate. They observed that the conditions under which nor'westers occur in the region were similar to those giving rise to tornadoes in the Mississippi valley of the United States of America. Sen (1931) suggested that nor'westers are due to katabatic flow of cold air-wedges, i.e., the downslope wind from the high altitude of the eastern Himalaya advancing along the valleys and undercutting the moist southerly winds over the plains of Bengal. In the afternoon, the conditions become favourable for the formation of squalls near the noses of the valley air-wedges at specific locations. The strength of the squalls depends on the temperature difference between the air masses and the depth of the valleys.

Stable water isotopes of nor'wester rains along with other climatic parameters can be useful for delineating their sources and cause. In paleoclimatology, the modern relation of $\delta^{18}O$ (and δD) with climatic parameters such as temperature and the amount of precipitation is extrapolated to reconstruct past climatic conditions using natural archives such as tree rings, ice cores and speleothems (e.g., Ramesh et al., 2010; Sano et al., 2010; Sano et al., 2011). Therefore, the use of $\delta^{18}O$ and δD of rainwater as proxy for past climate change requires a clear and quantitative regional interpretation. This includes the relation between a climatic parameter and $\delta^{18}O$ of rainwater, variation in the rain isotopic composition with season and moisture source. $\delta^{18}O$ and δD of precipitation show a distinct empirical relationship, described by the Global Meteoric Water Line (GMWL, $\delta D = 8 \times \delta^{18}O + 10$) (Craig, 1961; Rozanski et al., 1993). Local Meteoric Water Line (LMWL) may significantly deviate from the GMWL due to moisture recycling and evaporation below cloud base (Srivastava et al.et al., 2015) which helps to understand the precipitation pathways in a region (e.g., Pande et al., 2000).

In tropics, $\delta^{18}O$ of rain is generally correlated to the amount of monthly rainfall (~1.5‰ depletion for a 100 mm increase in rain (Dansgaard, 1964; Yurtsever and Gat, 1981). This amount effect is useful in paleoclimate interpretation of $\delta^{18}O$ of carbonate/cellulose in natural paleoarchives such as speleothems/tree rings. The pre-instrumental climate of regions influenced by the SASM is reconstructed using terrestrial proxies linked to monsoons (Fleitmann et al., 2003, 2007; Yadava and Ramesh, 2005; Sinha et al., 2007; Yancheva et al., 2007; Zhang et al., 2008; Ramesh et al., 2010; Laskar et al., 2010, 2011, 2013a, 2013b; Narayana et al., 2015). In NE India, isotope data in rainwater is scarce (e.g., Breitenbach et al., 2010). Geomorphic settings and strong monsoonal activities have led to the development of limestone caves that house speleothems in the region (Disney, 2009; Joshi et al., 2009; Baskar et al., 2009). These cave deposits and tree rings have the potential for paleoclimate reconstruction. However, initial studies by Breitenbach et al. (2010) revealed that there is no amount effect in the rainfall in this region, rendering speleothem data uninterpretable in terms of monsoon variability. Nor'westers that cause heavy rainfall during pre-monsoon months (March-May) with a distinct isotopic signature, can significantly contribute in the growth of speleothem and tree rings in the region. The distinct isotopic signature of the nor'wester rains can probably be used to study their past variation in frequency and intensity using paleoclimatic archives such as tree rings and speleothems. This needs a good understanding of the regional rainfall pattern and factors governing its stable isotope variations over time.

A decreasing trend in $\delta^{18}O$ and δD of rainfall, with the lowest values during the late monsoon period, has been reported for Meghalaya, North India and Nepal (Bhattacharya et al., 2003; Gajurel et al., 2006; Sengupta and Sarkar, 2006; Mukherjee et al., 2007; Breitenbach et al., 2010). The GNIP (Global Network for Isotopes in Precipitation) data from Guwahati shows precipitation was enriched in ^{18}O during pre-monsoon months of March-April (–0.2 to +2‰) and was depleted (up to –9‰) during late monsoon month of September (IAEA, 2006). Kumar et al. (2010) also reported similar values from Guwahati. Several previous researchers proposed that the $\delta^{18}O$ and δD in the SASM precipitation regimes are controlled by a number of mechanisms such as amount effect, vapour source dynamics, monsoon seasonality and air circulation (Aggarwal et al., 2004; Araguaś-Araguaś et al., 1998; Breitenbach et al., 2010; Mukherjee et al., 2007; Ramesh et al., 2012; Sengupta and Sarkar, 2006; Yang et al., 2011; Laskar et al., 2014). The region receives its moisture mainly from the Bay of Bengal (BoB), the latter is affected by river runoff, specifically during the monsoon season due to presence of a number of world's largest rivers in the region. This has a profound effect on its mixed layer salinity and isotopic composition (Delaygue et al., 2001; Singh et al., 2010). The mixed layer in the BoB is shallow, restricted to <20 m (Vinayachandran et al., 2002; Sengupta et al., 2008) and the values of $\delta^{18}O$ and δD of surface sea water may decrease significantly due to river runoff during the monsoon season.

Here we present results of isotopic measurements during June 2009 CE to July 2011 CE. The objectives of the study are: to check for amount effect in the rainwater $\delta^{18}O$ and δD, to define a local meteoric water line and identify the factors governing the $\delta^{18}O$ and δD in rainwater, possible driving mechanisms of nor'westers and to explore the potential of natural archives such as speleothems and tree rings in the region for paleomonsoon reconstruction.

Study Area and Geographical Settings

The samples were collected from a village Nobinsunapur (24°41′ N, 92°34′ E, 21 m above sea level), Hailakandi, Assam, NE India (Figure 1). The long-term (1951-1980 CE) mean annual precipitation and temperature are ~3200 mm/yr and ~22° C respectively, obtained from the nearest meteorological station, Silchar (India Meteorological Department, 1999), about 40 km north-east from the sampling site. Meteorological data shows that the region receives most of the rainfall during the SASM season (June to September); however, a significant portion, even up to ~50% of rains, may occur in some years during the pre-monsoon months

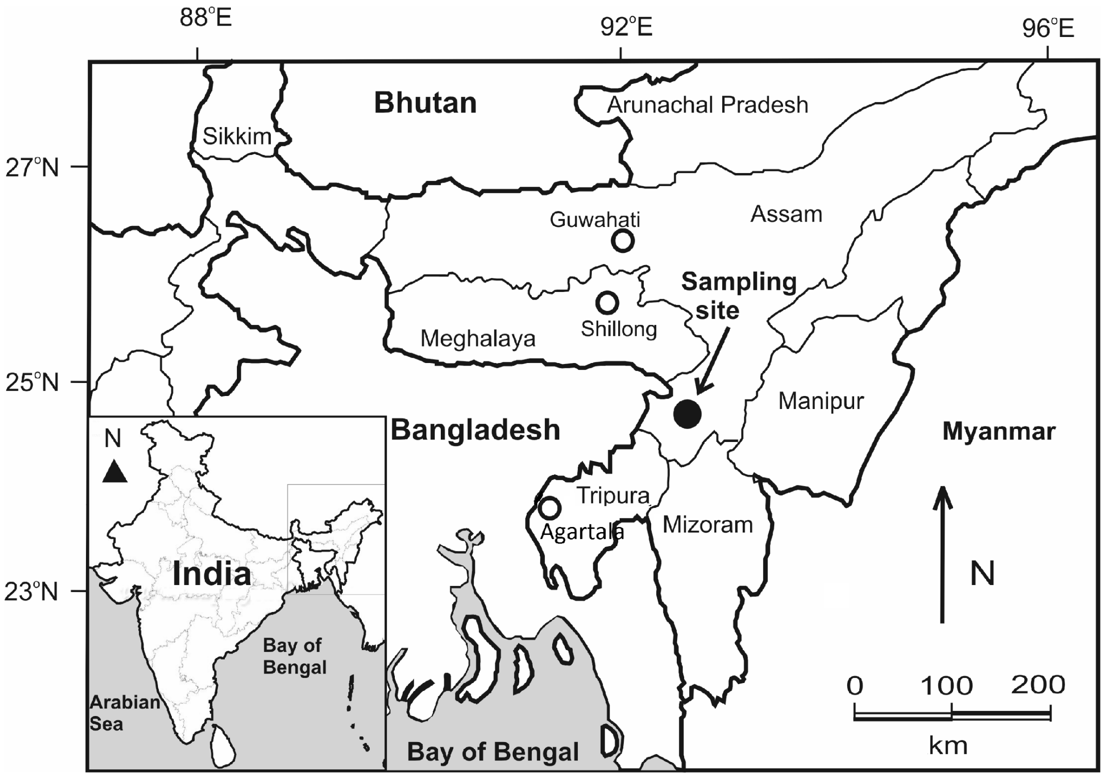

Figure 1: Map of NE India with the location of the study site (solid circle). Inset shows the map of India.

(March to May). During the monsoon months, the source of rainfall is the BoB and the Indian Ocean. In the post-monsoon season (October to December) drier conditions prevail with occasional rainfall associated with atmospheric disturbances over the BoB. The contribution of the winter monsoon to the annual rainfall is not very significant (<5 %) (Indian Institute of Tropical Meteorology sub-divisional homogeneous monthly rainfall data: ftp://www.tropmet.res.in/pub/data/rain/iitm-subdivrf.txt).

Materials and Methods

We collected 250 rain water samples between 2009 and 2011 CE. Continuous sampling was carried out from June 2009 to July 2011 except during July-December, 2010 CE because of logistic problems. The sampling was done on an event basis, or twice in a day in case of incessant rain. The samples were collected in a 10 L carboy and stored in airtight polypropylene bottles. Precautions were taken to avoid re-evaporation from the carboy during collection. The $\delta^{18}O$ and δD of the rain was measured at the Physical Research Laboratory using a dual-inlet stable isotope ratio mass spectrometer (Europa Scientific GEO 20-20) equipped with a water equilibration system. The isotopic composition of waters is reported relative to VSMOW (Vienna Standard Mean Ocean Water) with an external precision of 0.1‰ and 1‰ for $\delta^{18}O$ and δD, respectively. A secondary laboratory standard collected from the Narmada River was used after every ten samples to check the reproducibility. Also, three randomly selected samples were repeated in each batch of 59 samples for precision check. The accuracy of the measurements was checked occasionally by running three international standards viz., VSMOW, GISP and SLAP. These were also used to correct the stretching factor of the mass spectrometer. Stretching factor is specifically important for δD measurements as its variation is approximately an order of magnitude larger than the variations in $\delta^{18}O$. Also there is an important correction factor associated with δD measurement caused by the formation of H_3^+ ions in the source of mass spectrometers and it varies from instrument to instrument. In order to resolve the issue, an isotopically light standard such as SLAP is measured along with VSMOW against the same working reference and the difference obtained is multiplied by a factor called "stretching factor" so that $\delta D_{(SLAP\text{-}VSMOW)}$ = -–428 ‰ (Coplen, 1988).

Results

Rainfall Variation in the Region

Mean monthly relative humidity and temperature in the region are shown in Figure 2A. A comparison of the observed monthly rainfall for the years 2009, 2010 and 2011 CE with that of the long-term average are shown in Figure 2B. Compared to the long-term average in the region, ~100% higher rainfall is observed in the April-May months of 2010 CE (Figure 2B) due to nor'westers and is almost absent during the same season in 2011 CE, a year without any pre-monsoon nor'wester activity. However, the rainfall during the monsoon season of 2009 CE is not very different from the long-term average.

Stable Isotope Variations in Precipitation

Rainfall $\delta^{18}O$ and δD values range from +1‰ to –13.7‰ and +32‰ to –98‰, respectively (Figure 3). The most enriched values are observed during April–May. The values gradually deplete during the course of the monsoon, and reach the lowest during September–October. No such trend is observed either in the temperature or the amount of rainfall. Co-variation of the amount of rainfall and $\delta^{18}O$ is shown in Figure 4. There is no significant amount effect. Amount effect is also absent in the monsoon rainfall, even after excluding events in which rain is too high (>10 cm per day) or too low (<0.2 cm per day).

Deuterium Excess

The deuterium excess or *d*-excess is defined by $d = \delta D - 8 \times \delta^{18}O$ (Dansgaard, 1964). The *d*-excess mainly reflects the condition of the source of moisture and secondary evaporation below the cloud base. The *d*-excess values are shown in Figure 3. Although the *d*-excess does not show any definite trend, it is strikingly different for the pre-monsoon season of the year 2010 CE (shown by the encircled region). During March to 20th May 2010 CE, the *d*-excess values were very low (-9 to -27‰). During the monsoon, *d*-excess varies between 8 and 15‰, barring a few days.

Local Meteoric Water Line

Rainwater $\delta^{18}O$ and δD follows a linear relationship termed as the Meteoric Water Line (MWL). The relationship for the region is shown in Figure 5. The Local Meteoric Water Line (LMWL) during monsoon season is described by $\delta D = (7.88 \pm 0.09)\, \delta^{18}O + (10.7 \pm 0.5)$. This is not significantly different from the Global Meteoric Water Line (GMWL). During the pre-monsoon

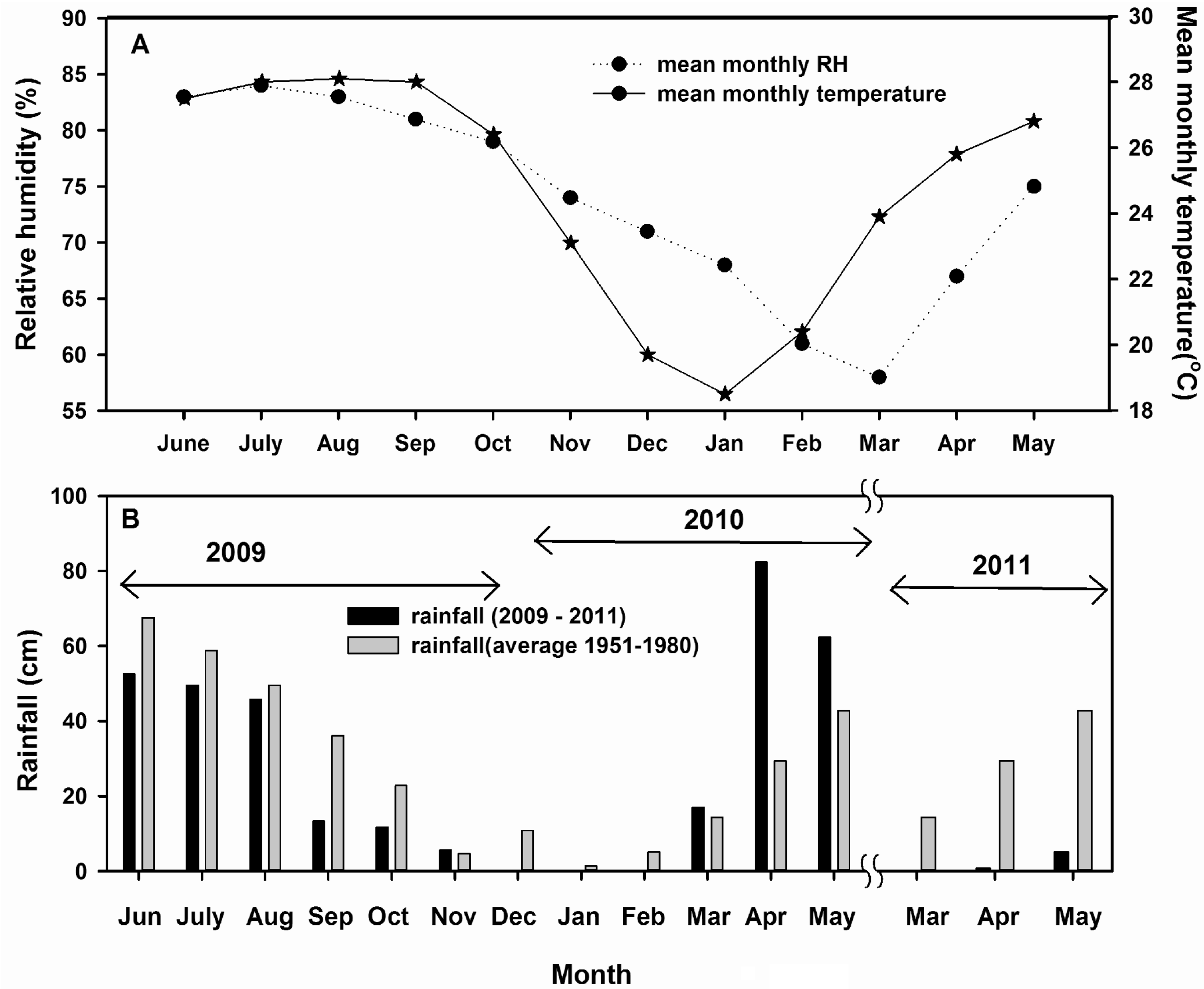

Figure 2: Climate data from India Meteorology Department station Silchar: (A) Mean monthly temperature and humidity (30 years average from 1951 to 1980 CE). (B) Monthly rainfall for the studied period (black bars) and compared with the long-term average (grey bars). Very high rainfall is observed during April-May, 2010 CE, while it is extremely less during the same season of 2011 CE.

of 2010 CE, the LMWL was considerably different: $\delta D = (6.8 \pm 0.3)\ \delta^{18}O + (-2.4 \pm 0.8)$, $R^2 = 0.91$ (n = 54), while for 2011 CE it was $\delta D = (6.7 \pm 0.4)\ \delta^{18}O + (13.4 \pm 1.0)$, $R^2 = 0.97$ (n = 12) (Figure 5). The slopes are the same within the experimental uncertainties for the pre-monsoon rains in 2010 CE and 2011 CE though the intercepts are very different.

Discussion

Rainfall Variation in the Region

Pre-monsoon rain is very significant in the year 2010 CE; nor'wester caused 1440 mm rainfall in March-April of this year which is much higher than the long-term average (720 mm) (Figure 2). Mean monthly SST anomaly in the northern BoB and air temperature during pre-monsoon months of 2010 and 2011 CE are shown in Figures 6 and 7 respectively. SST in 2010 CE was ~1.5°C higher than that in 2011 CE. Similarly, air temperature in 2010 CE was higher compared to that in 2011 CE, by ~4°C in April. The SST oscillations in the BoB are believed to be closely linked to the large scale atmospheric convection (Agarwal et al., 2007; Webster et al., 1998; Yasunari, 1979). Enhanced temperature in 2010 CE probably caused local low pressure zones, increased evaporation, convection and hence thunderstorms with heavy showers.

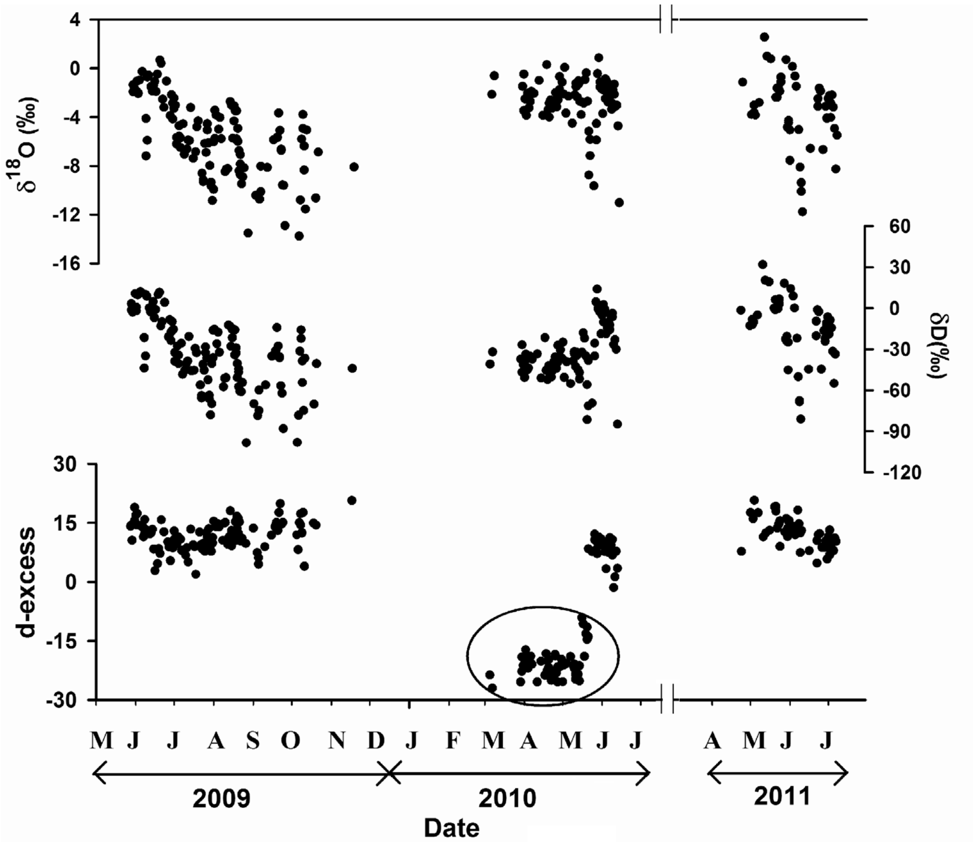

Figure 3: Seasonal variations in δ¹⁸O, δD and *d*-excess in rain. Very low *d*-excess values observed during the pre-monsoon period of 2010 CE is shown by the big ellipse. The effect is not seen in 2011 CE during the same season, when nor'wester activity was very weak.

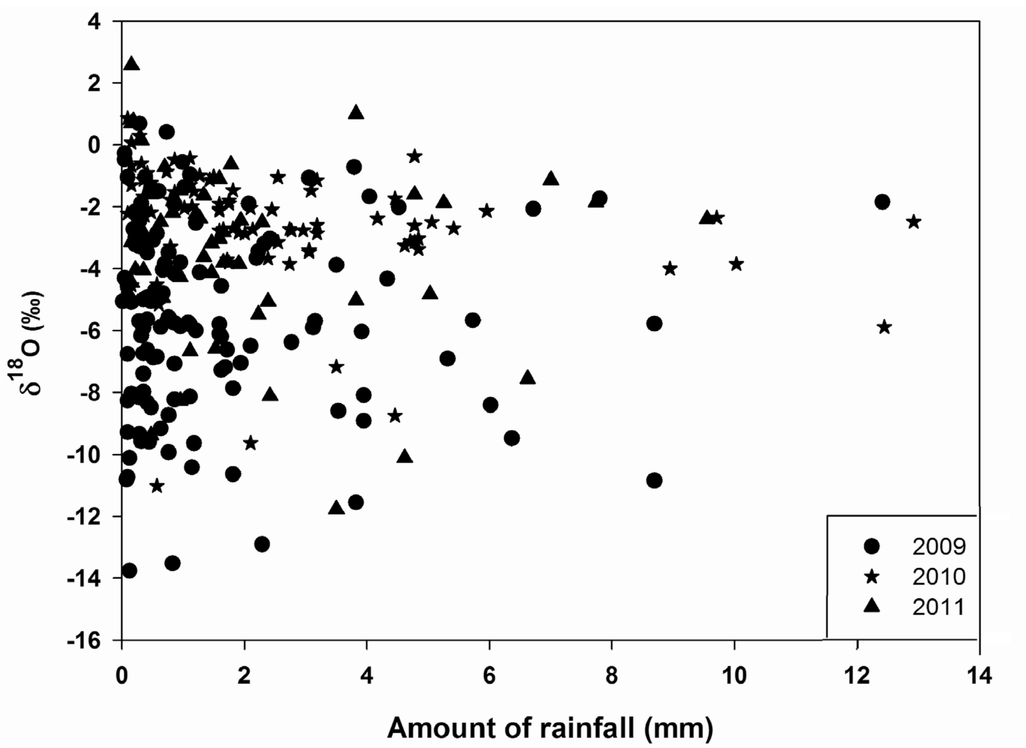

Figure 4: Variation of $\delta^{18}O$ with the amount of event rain. No significant relationship is observed.

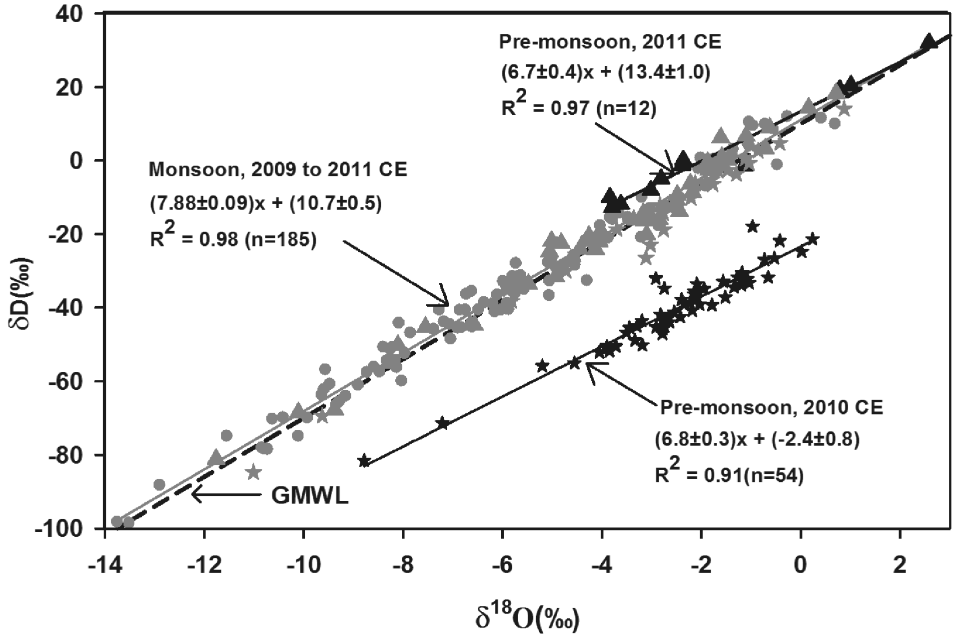

Figure 5: Dual isotope plot for rain water. The solid lines are the best fit lines. The data closely follow the Global Meteoric Water Line (GMWL, dashed line) during the monsoon months (grey symbols). The pre-monsoon (March to 20th May, 2010 and 2011 CE) rainwater isotope data (black stars and triangles) shows significant deviation from the GMWL. The expressions are the fitted values for δD, where *x* denotes δ^{18}O.

As mentioned earlier, nor'westers are confined within spatial spans of less than 1 km × 50 km, the moisture is expected to be derived from local open water bodies unlike the monsoon rains originating from the BoB and beyond. Through NE India and Bangladesh, a number of world's biggest rivers flow into the BoB, which along with the water bodies in the low land areas are the major sources of rainfall during the nor'westers.

Stable Isotopes and the Amount Effect

The pre-monsoon rain, especially during nor'westers, are relatively enriched in ^{18}O and ^{2}H, suggesting an isotopically enriched source, probably from local reservoirs, which are already enriched due to strong evaporation during dry winter in the region, while the monsoon clouds travel longer distances with a gradual depletion in ^{18}O before precipitating at the site. With the progress of the monsoon, more fresh water flows into the BoB, causing a decrease in the δ^{18}O and δD in the surface mixed layer. Vinaychandran and Nanjundiah (2009) showed that the river runoff is mainly confined to the northern part of the Bay of Bengal. The Himalayan rivers carry isotopically depleted waters from the glaciers (Hren et al., 2009), δ^{18}O of which reaches –12‰ in the later months of monsoon (Ramesh and Sarin, 1992). Breitenbach et al. (2010) proposed a decrease in the δ^{18}O of the BoB surface water by 4.5 ‰ during the last months of the monsoon (Sept – Oct). Thus, the BoB surface water reaches the lowest δ^{18}O (and δD) value in the later part of the monsoon and thus evaporated moisture is expected to have the lowest δ^{18}O and δD during this time. GNIP data for New Delhi (India) and Yangon (Myanmar) show that the mean δ^{18}O values are less for monsoonal precipitation than for the non-monsoon precipitation (Araguaś-Araguaś et al., 1998). Also, the shifting of the moisture source during the peak SASM from the BoB to the distant Indian Ocean leads to a further ^{18}O depleted rainwater (Breitenbach et al., 2010).

Data collected by the International Atomic Energy Agency from island stations in the equatorial belt shows the following linear relationship (Yurtsever and Gat, 1981):

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

where P_m is the mean monthly precipitation in mm. The linear correlation coefficient (R) for this amount effect is 0.87 for 14 island stations. The above equation shows that the average rate of depletion in δ^{18}O is 1.5‰ per 100 mm increase in the monthly rainfall. Yadava and Ramesh (2005) reported an amount effect of 2.2 ± 0.8‰ in southwest monsoon rainfall from central India.

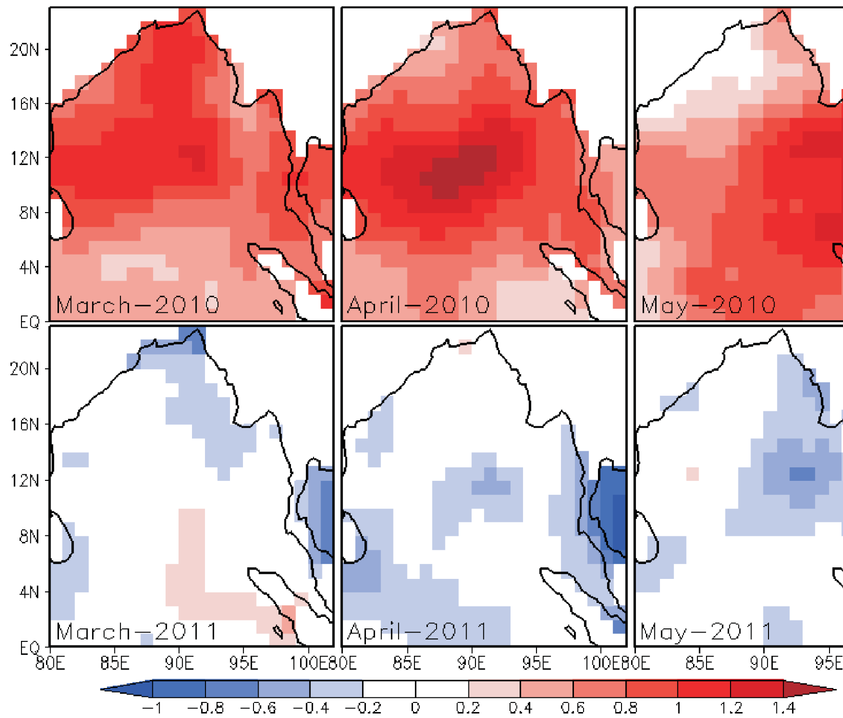

Figure 6: Sea Surface Temperature anomaly (ºK) in the Bay of Bengal for pre-monsoon months of 2010 CE and 2011 CE. The 1º gridded Optimum Interpolation data have been downloaded from http://www.ncdc.noaa.gov/. SST was higher in 2010 CE compared to 2011 CE, especially ~2 ºC in April.

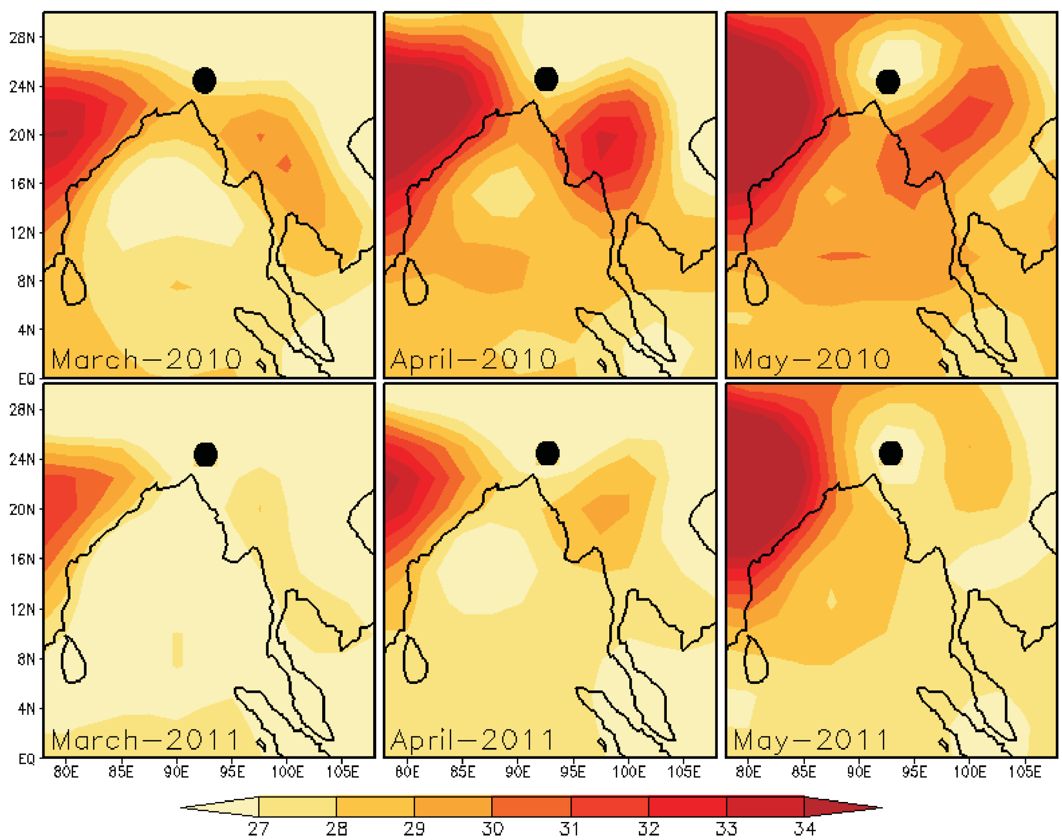

Figure 7: Mean surface air temperature (ºC) at 1000 mb for three months of the pre-monsoon periods of 2010 CE and 2011 CE (http://www.cdc.noaa.gov/). An elevated air temperature by 3-4 ºC at the studied site (black dot) is obvious in the pre-monsoon months of 2010 CE, compared to 2011 CE. Higher air temperature in 2010 CE is probably one of the reasons for low pressure and hence strong local convection and nor'westers in the region.

Amount effect in rainfall $\delta^{18}O$ has also been reported in several south-west monsoon regimes such as New Delhi and Mumbai (Kurita et al., 2009; Rozanski et al., 1993; Zhang et al., 2006; IAEA, 2006). Amount of rainfall and corresponding $\delta^{18}O$ for the present study is shown in Figure 4. Event-wise data do not show any dependence on the amount during the monsoon or non-monsoon rains, even when extreme events were excluded. Breitenbach et al. (2010) also reported absence of amount effect in Meghalaya, a nearby state. Therefore, we conclude that the amount effect is absent in the monsoon precipitation of NE India in general. The probable reasons could be the moisture source variation from pre-monsoon to monsoon to post-monsoon seasons and strong convective activity. These observations prompt us to search for factors other than the amount effect to explain the isotopic composition of rainfall over the study region.

Local Meteoric Water Line and d-excess

LMWL during the southwest monsoon is similar to the GMWL and MWL observed in North and North-Eastern India (Kumar et al., 2010) and Calcutta (Sengupta and Sarkar, 2006). For the pre-monsoon rainfall, however, the slopes are 6.7 and 6.8 for 2010 and 2011 CE, respectively. The lower slopes could possibly be due to the kinetic effect associated with secondary evaporation from raindrops below cloud base and moisture originated from local water bodies. In 2010 CE, very low *d*-excess values are observed in the pre-monsoon months while in 2011 CE, they are not very different from the values for the rest of the year. This could be either due to secondary evaporation below cloud base or because moisture originated from local reservoirs which already suffered severe evaporation, or a combination of both. The observed low *d*-excess values lasted for more than two months in 2010 CE; this cannot be due to secondary evaporation below cloud base, as the vapour from one rain event would mix with the next causing higher *d*-excess in the latter. Thus we conclude that, the lower *d*-excess in the nor'wester rains is mainly due to a substantial component of moisture derived from the local open water bodies rather than the adjacent ocean. These water bodies suffer severe evaporation during the prolonged dry winter in the region leading to lower *d*-excess values. Figure 8 schematically explains the possibility of negative *d*-excess in rain when moisture originates from water bodies that suffered evaporation. Figure 9 shows the vertically integrated moisture fluxes in the region during the pre-monsoon months of 2010 CE. It is clear that a substantial component of moisture is advected from continent. This advected moisture is probably contributed mainly by transpired water and is likely to preserve the source isotopic composition.

Possible Paleoclimate Archives to Study Past Nor'wester Activity

Considering the severe societal consequences of nor'westers and possible influence of climate change on their intensity/frequency in a very densely populated region of the globe, it is very important to understand their past variation for climate modelling. The handiest tools to use natural paleoclimate archives such as tree rings and speleothems, the "amount effect" may not work in the region as it is found absent in the monsoon as well as pre-monsoon rains. Also, large amount of pre-monsoon rain in some years complicates further the interpretation of paleoclimatic proxies. However, tree-rings with intra-seasonally resolved δD could possibly be used for identification of nor'wester occurrences (e.g., Managave et al., 2011). δD in the fluid inclusions in the speleothem is another possible candidate for the reconstruction of past nor'wester activity in the region. Fluid inclusions in speleothems are cave drip water originating from the local precipitation and physically trapped in the pores (Yonge et al., 1985; Zhang et al., 2008). $\delta^{18}O$ in such fluids could deviate from its original value due to exchange with the surrounding calcite. On the other hand, no hydrogen isotopic exchange takes place between calcite and inclusion water. Thus δD of the fluid inclusions represents the isotopic composition of the paleo-precipitation. Therefore, δD in tree-rings sampled with seasonal resolution and in fluid inclusions of speleothems can possibly be used to reconstruct past nor'wester occurrences in this region.

Conclusions

Amount effect is not apparent in the oxygen and hydrogen isotope ratios in the NE Indian rain. Nor'wester activity in the pre-monsoon season is probably caused by excess near-surface air temperature in the region and sea surface temperature over the northern BoB resulting in strong convection. The moisture in nor'wester rains mainly originates from the local water bodies such as lowland ponds, lakes and rivers. The $\delta^{18}O$ and δD of rain gradually decreases during the course of the monsoon, reaching the lowest

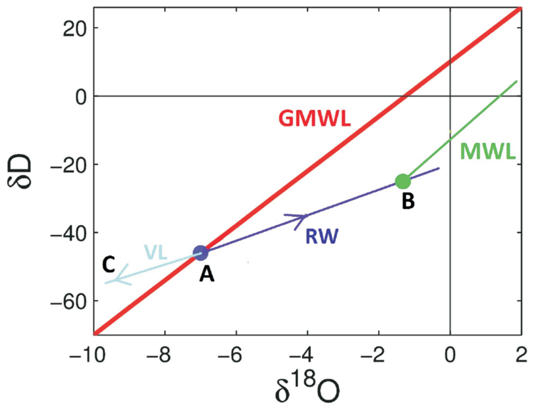

Figure 8: A schematic diagram showing the origin of negative *d*-excess in water originating from sources that suffered evaporation. Suppose a reservoir is fed by meteoric water and starts evaporating at the point A on the GMWL (red). As evaporation proceeds, the isotopic composition of residual water (RW) would shift to point B (green), while that of the vapour from the reservoir would move towards C (VL: vapour line, cyan). Now, if rain forms from vapour from the reservoir after its isotopic composition reaches to B, the meteoric water line (MWL) would have very low *d*-excess as shown by the intercept of green line.

values during September-October; this is attributable to long distance transport of moisture before raining out in the region and the ^{18}O and D depleted surface water in the source (Bay of Bengal) due to a large freshwater input from the Himalayan and peninsular rivers. The Local Meteoric Water Line is indistinguishable from the GMWL during the monsoon season, while it is significantly different during the pre-monsoon months, when it displays a slightly lower slope due to significant evaporation from raindrops below the cloud base. The *d*-excess values during nor'westers are quite low, due to moisture originating from the re-evaporation of freshwater. The paleoclimatic interpretation of proxy climate records in the region is confounded because of nor'wester activity causing significant pre-monsoon rains with a strong dependence of the rainwater isotopes on the source of moisture, and also due to the absence of an amount effect. However, δD in fluid inclusions in speleothems could hold some promise for reconstruction of past nor'wester activity.

Acknowledgements

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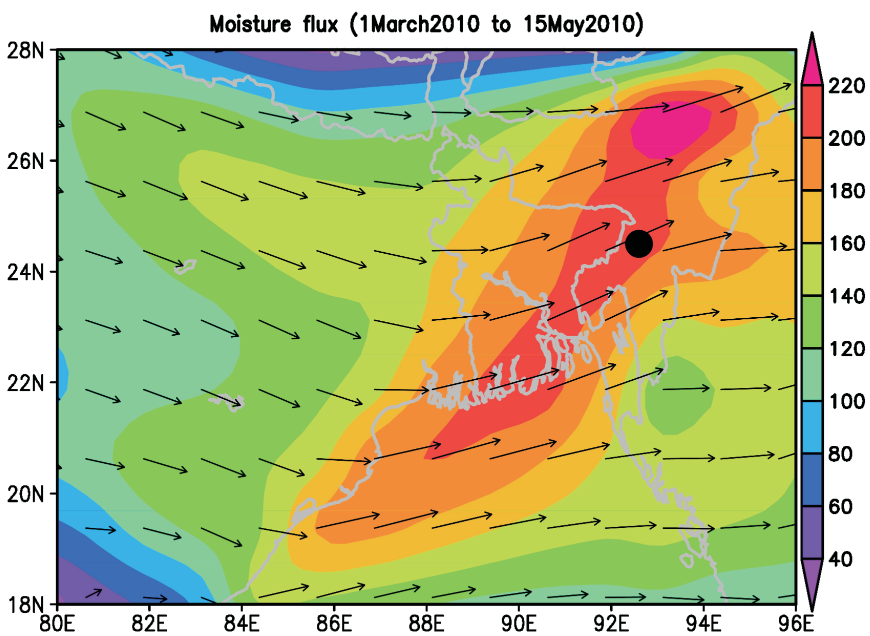

Figure 9: Origin of moisture at the study site (black dot) during the pre-monsoon season (1st March to 15 May) of 2010 CE. Modern-Era Retrospective Analysis for Research and Application (MERRA) dataset was used to obtain the vertically integrated moisture flux in kg/m/s (Riencker et al., 2011).

from the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/.

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