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Isotope fingerprinting of precipitation associated with western disturbances and Indian summer monsoons across the Himalayas

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Precipitation samples were collected across the Himalayas from Kashmir (western Himalaya) to Assam (eastern Himalaya) to understand the variation of the stable isotopic content ($\delta^{18}O$ and δD) in precipitation associated with two dominant weather systems of the region: western disturbances (WDs) and Indian summer monsoon (ISM). Large spatial and temporal variations in isotopic values were noted with $\delta^{18}O$ and δD values ranging from -30.3 to $+9.3‰$ and -228 to $+59‰$, respectively. The d-excess values also exhibit a large range of variation from -30 to $+40‰$. In general, heavier isotopic values are observed in most of the samples in Jammu, whereas lighter values are observed in majority of the samples in Uttarakhand. Precipitation at Jammu seems to have undergone intense evaporation while that from Uttarakhand suggest normal Rayleigh fractionation/distillation of the air mass as it moves from the source region to the precipitation site and/or orographic lifting. The d-excess of rainfall in Kashmir has a distinctly higher median value of 18‰ compared to other precipitation sites with a median of 9–12‰. Using distinct isotopic signatures, the regions receiving precipitation from two different weather systems have been identified.

Keywords. Isotopes; precipitation; western disturbances; Indian summer monsoons; Himalayas.

1. Introduction

The stable isotopes of oxygen and hydrogen have become an important tool not only in isotope hydrology, but also in studies related to atmospheric circulation and paleoclimatic investigations (Araguás-Araguás *et al.* 2000). The isotopic signature of precipitation provides valuable information about vapour source and atmospheric circulation pattern. In the modern environment, the isotopic composition of precipitation provides a conservative tracer for the origin, phase transitions, and transport paths of water (Dansgaard 1964; Rozanski *et al.* 1993; Gat 1996). $\delta^{18}O$ and δD of precipitation are dominantly controlled by atmospheric parameters such as temperature, relative humidity, and evaporation (Dansgaard 1964; Yurtsever and Gat 1981; Rozanski *et al.* 1993), and by geographic factors such as altitude, latitude, moisture source, and transport process (e.g., Craig 1961; Siegenthaler and Oeschger 1980; Gat 1996; Kendall and Coplen 2001). The deuterium excess, $d = \delta D - 8 \times \delta^{18}O$ (Dansgaard 1964), a measure of deviation of data points from a line with slope 8 through VSMOW (Araguás-Araguás *et al.* 2000), is considered as an additional tool to identify the moisture source, near surface relative humidity and the wind speed over the source (Marlivat and Jouzel 1979; Jouzel and Merlivat 1984; Johnsen *et al.* 1989). Recycling of moisture to the atmosphere increases the d-excess of the atmospheric vapour and consequently of the precipitation formed by condensation of this vapour. High d values (∼20‰) are found in vapour generated under low relative humidity conditions, e.g., vapour generated at the Mediterranean Sea (Gat and Carmi 1970). The western disturbances (WDs) and the Indian summer monsoon (ISM) are the two dominant weather systems of the Himalayas. These airflows are responsible for the bulk of the Himalayan precipitation. The flow of the Himalayan rivers is primarily dependent upon the strength, behaviour and duration of WDs and ISM. The WDs are synoptic weather systems that propagate eastward from the Mediterranean region towards south Asia (Madhura *et al.* 2015). These are embedded in the sub-tropical Westerlies, which often extend down to lower atmospheric levels over the north Indian latitudes and produce significant rainfall over western Himalayas and northern India during DJFMA (Pisharoty and Desai 1956). WDs are active across western Himalaya during the summer months as well, when their frequency reduces significantly (Dhar *et al.* 1984; Dimri *et al.* 2004). The ISM develops in response to the movement of the Inter Tropical Convergence Zone (ITCZ) that separates wind circulation of the northern and southern hemispheres (Gadgil 2003). Arabian Sea and the Bay of Bengal are the two principal sources of oceanic vapour to the Indian subcontinent during ISM (Das 2005). ISM remains active from June/July to September (Rao 1976). Post - ISM the precipitation in eastern Himalayas may be caused due to the atmospheric disturbances over the Bay of Bengal. It is important to understand the observed spatial and temporal isotopic variation in precipitation across the Himalayas in terms of the geographical extent of influence and the contributing moisture source. The main objective of this study is to assess the variability in $\delta^{18}O$ and δD of precipitation associated with WDs and ISM (figure 1).

2. Methodology

Precipitation samples were collected across the Himalayas (table 1, figure 1) from Kashmir in the western Himalaya to Assam in the eastern Himalaya for the analysis of $\delta^{18}O$ and δD. Most of the precipitation samples for this study were collected under the aegis of the National Program (IWIN) for Isotope Fingerprinting of Waters of India (Deshpande and Gupta 2012). Monthly composite samples were collected in Kashmir (from 5 sites), Himachal Pradesh (2 sites), Uttarakhand (4 sites) and Assam (3 sites) in 2009 and 2010. All these samples were analyzed using IWIN-IRMS facility at Physical Research Laboratory (PRL), Ahmedabad, following standard equilibration method in which water samples were equilibrated with CO_2 (or H_2) and the equilibrated CO_2 (or H_2) gas was analyzed in Delta V Plus (IRMS) in continuous flow mode using Gasbench II (Maurya *et al.* 2011). Some of the published data was also used to understand the synoptic view and behaviour of isotopes in precipitation across the Himalayas; 15 precipitation sites from Kashmir (Jeelani *et al.* 2010, 2013), 10 sites from Uttarakhand (Kumar *et al.* 2010; Rai *et al.* 2014), 01 site from Nepal (Gajurel *et al.* 2006) and 01 site from Meghalaya (Breitenbach *et al.* 2010). IMD, New Delhi from its sub-offices, provided the meteorological data.

3. Results and discussion

3.1 *Variation of stable isotopes and d-excess in precipitation*

Large variations in isotopic values were noted spatially and temporally across the Himalayas (figures 2–4) with $\delta^{18}O$ and δD values ranging from –30.3 to +9.3‰ and −228 to +59‰, respectively. The d-excess values also exhibit a large range of variation from −30 to +40‰. The lowest $\delta^{18}O$ and δD values are mostly found in Uttarakhand and the highest values in Jammu. There is no systematic and contiguous geographical trend in the variability of isotopic composition across the length of Himalayas (figure 2). However, there are subtle aspects of the isotopic variation at different stations, together with oscillating behaviour from west to east, which can be ascribed to interplay of complex hydro-meteorological processes operating in the Himalayan region. The variation of stable isotopes in precipitation across the Himalayas is discussed under the following heads:

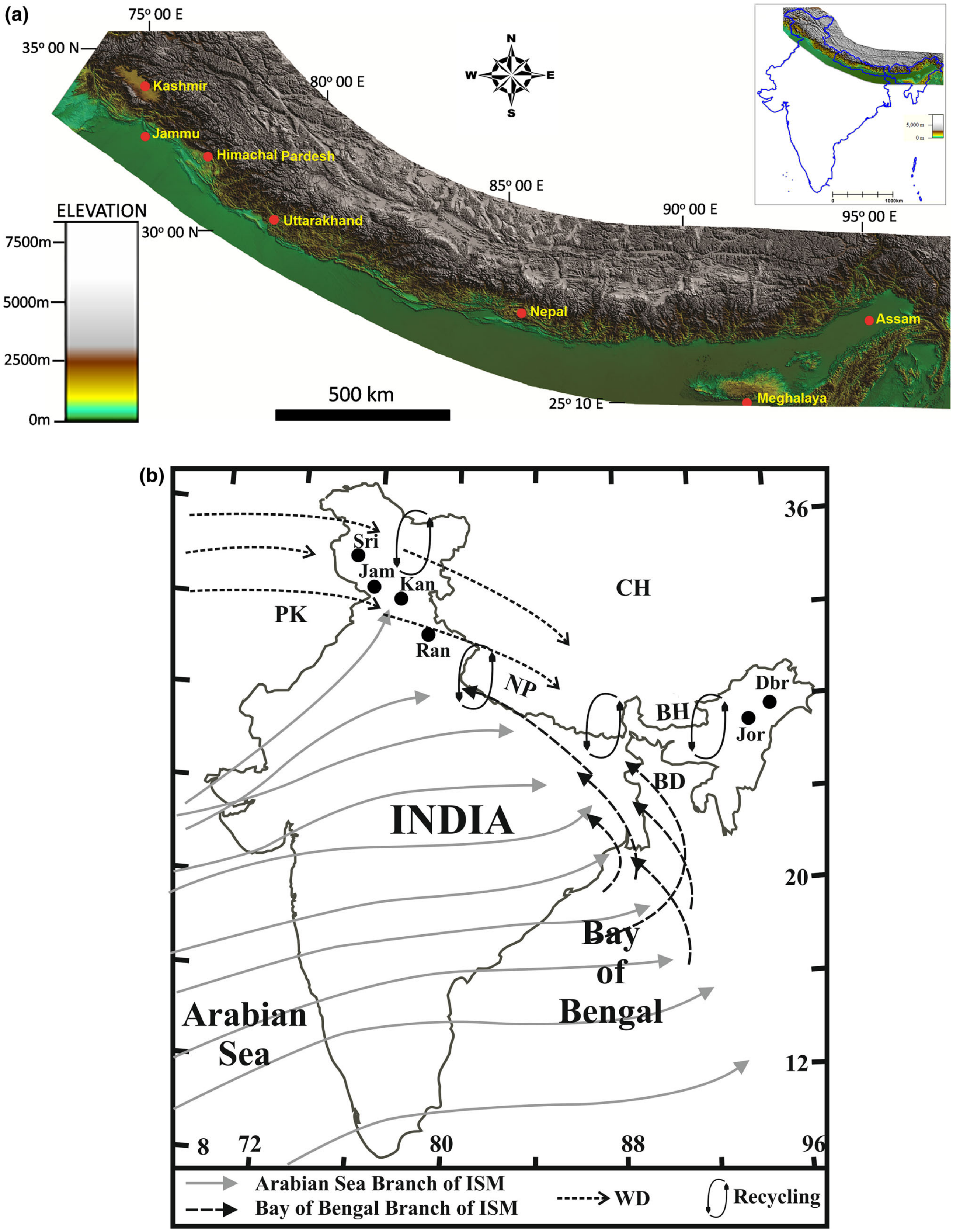

Figure 1. (**a**) Locations of the sampling regions across the Himalayas. (**b**) Map of India showing schematic circulation pattern of Arabian Sea branch of the ISM, Bay of Bengal branch of ISM, Western Disturbances and the local recycling.

Table 1. *Statistical summary of isotopic composition of precipitation of various stations across the Himalayas.*

Region code	Region name	No. of stations	Average precipitation (mm)			δ^{18}O (‰)				D-excess (‰)			
						WDs		ISM		WDs		ISM	
			Annual	WDs	ISM	Range	Mean	Range	Mean	Range	Mean	Range	Mean
KMR	Kashmir	15	756	386	258	1.5 to 5.3	−6.6	−9.3 to −1.2	−3.9	18 to 24	18	−9 to 7	4
JMU	Jammu	02	1304	192	1058	−5.5 to 5.3	1.8	−9.7 to 0.4	−3.7	−15 to 16	−1	5 to 13	9
HML	Himachal	02	1932	290	1561	−9.8 to −2.1	−1.8	−13.4 to −1.1	−5.9	7 to 17	14	4 to 13	10
UTK	Uttarakhand	10	2322	212	2034	−12.6 to −1.5	−5	−17.5 to −1.9	−8.8	14 to 22	15	8 to 14	9
ASM	Assam	03	1786	94	1166	−7.8 to 0.3	−2.7	−12.8 to −7.7	−8.6	9 to 24	14	8 to 13	10
NPL	Nepal	01	1560	170	1209	−13 to −1	−1.2	−17 to −12	−8.1	16 to 41	13	5 to 10	8
MGL	Meghalaya	01	6514	315	4797	−14.7 to −5.9	−4.2	−12.4 to −5.1	−6.7	11 to 14	13	9 to 13	11

3.1.1 *Spatial variation in isotopic characteristics*

Spatially, the Himalayan precipitation shows large range in isotopic values. Despite large variability in isotopic composition of monthly composite precipitation, about 20% samples showed similar isotopic signature across the Himalayas (δ^{18}O: –5.7 to −4.3‰ and δD: −35 to −21‰). The heavier isotopic values (w.r.t. this common signature) are observed in most of the samples (>60%) in Jammu (most enriched in heavier isotopes), Himachal and Nepal, whereas lighter isotopic values are observed in majority of the samples (>50%) in Uttarakhand (most depleted in heavier isotopes), Kashmir, Assam and Meghalaya. The samples with heavier isotopic values indicate the effect of differential degree of evaporation, with most intensive evaporation at Jammu station. A significant inverse correlation exist between average monthly δ^{18}O and d-excess of precipitation at Jammu station ($R^2 = 0.85$ and $p < 0.05$). The most depleted values observed in samples suggest the normal Rayleigh fractionation/distillation of the air-mass as it moves from the vapour source region to the precipitation site and/or orographic lifting. The observed isotopic depletion in Uttarakhand may be ascribed to lower temperature owing to its high altitude (∼2200 m). Isotopic compositions of precipitation northwest of Uttarakhand are not found to be lighter. This suggests that in the Himalayas, further northwest of Uttarakhand, there is either a different meteorological regime and/or significant admixture of transpired vapour in the region.

The d-excess of about 35% of precipitation samples across the Himalayas show narrow range (10−13‰) except Kashmir, where only ∼10% samples fall in this category. The d-excess of rainfall in Kashmir has a distinctly higher median value of 18‰ compared to other precipitation sites with a median of 9−12‰. This indicates at least two dominant and isotopically distinguishable sources of precipitation, viz., WDs and ISM. It is observed that the d-excess of precipitation NW of Uttarakhand show much larger variability compared to the precipitation towards east of Uttarakhand, except in Assam. A large range of variation in d-excess (figure 2) observed in Assam (eastern Himalayas), Jammu, Kashmir and Himachal Pradesh (western Himalayas) suggest contribution of vapour from secondary sources: local recycling, evaporation of falling raindrops, etc. In Assam, being nearer to

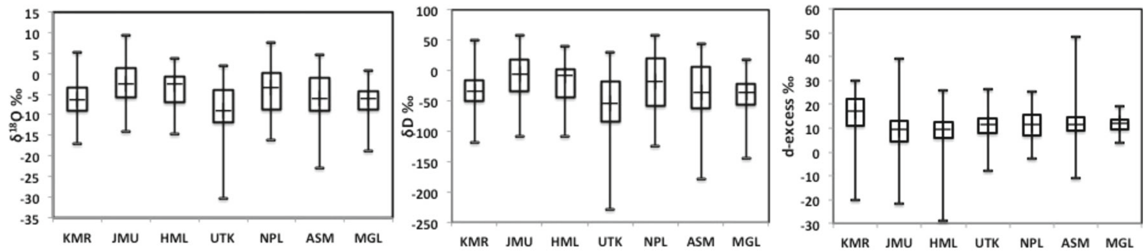

Figure 2. Box and Whisker plots showing minimum, first quartile (Q1), median, 3rd quartile (Q3) and maximum values of δ^{18}O, δD and d-excess in annual precipitation across the Himalayas depicting spatial variation in the isotopic characteristics. The horizontal axis represents different regions: KMR (Kashmir), JMU (Jammu), HML (Himachal Pradesh), UTK (Uttarakhand), NPL (Nepal), ASM (Assam), and MGL (Meghalaya).

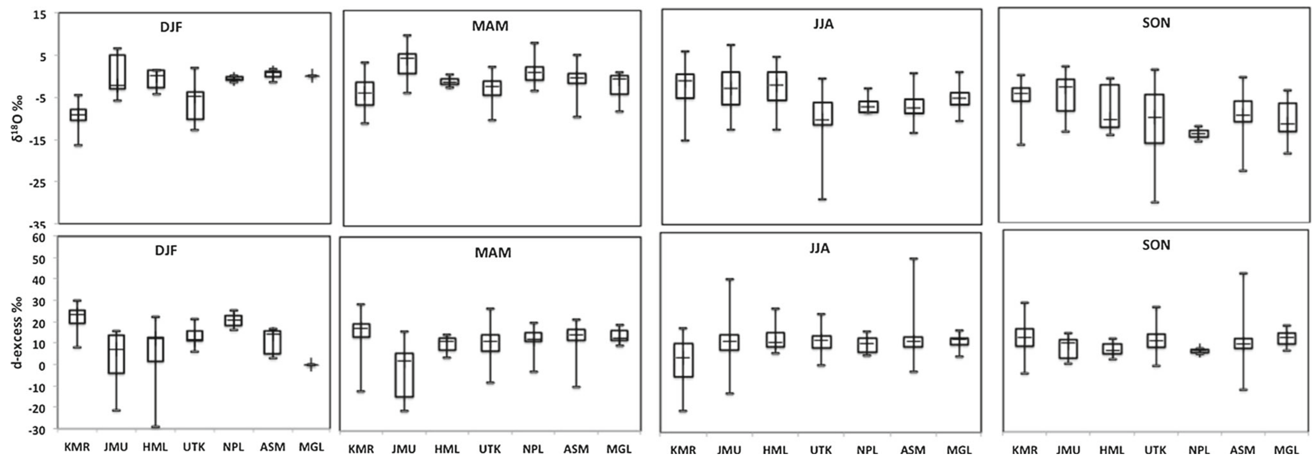

Figure 3. Box and Whisker plots showing minimum, first quartile (Q1), median, 3rd quartile (Q3) and maximum values of δ^{18}O and d-excess in seasonal (DJF: Dec–Jan–Feb; MAM: Mar–Apr–May; JJA: Jun–Jul–Aug; SON: Sep–Oct–Nov) precipitation across the Himalayas. Horizontal axis represents different regions; KMR (Kashmir), JMU (Jammu), HML (Himachal Pradesh), UTK (Uttarakhand), NPL (Nepal), ASM (Assam), and MGL (Meghalaya).

the Bay of Bengal, the d-excess similar to that of Meghalaya is expected, which is not the case. The eastern Himalayas receive precipitation from the Bay of Bengal branch of the ISM (Das 2005). The increase in d-excess in 25% of the samples in Assam (Q3 to maximum) and its large variation from 15 to 48‰ (highest d-excess) indicates the possibility of local recycling, long distance transport of vapour and/or the source of precipitation from WDs. However, decrease in d-excess associated with increase in δ^{18}O, in 25% of the samples (Q1 to minimum) in Kashmir and its large variation from 11 to −20‰ indicates the possibility of evaporation of falling rain and/or the source of precipitation from ISM. Similarly, 25% of the samples in Himachal Pradesh and Jammu also indicate the effect of evaporation on precipitation. The high d-excess (>12‰) of most (50%) of the samples from Nepal station suggests local recycling, long distance transport of vapour and/or the sources of precipitation from WDs.

3.1.2 *Temporal variation in isotopic characteristics*

The highest d-excess is observed in Kashmir in December–February (DJF); 75% of the samples (figure 3; between Q1 and maximum) have very high d-excess of ≥20‰, while only 3% of the samples have d-excess of <15‰. Higher d-excess (than global average of ∼10‰) is also observed in 75% of the samples (between Q1 and maximum) in Uttarakhand (d-excess >12‰) and Nepal (d-excess > 16‰) though the values are lower compared to Kashmir. Moderately high d-excess (>14‰) is observed in 50% of the samples in Assam. Lowest d-excess is observed in Jammu, Himachal and Meghalaya in DJF. As we know that WDs are dominant during this period (DJF), the results suggest that the moving air mass undergo a lot of modifications from west to east Himalayas. High d-excess in precipitation in Kashmir during the months of DJF suggests contribution of vapour

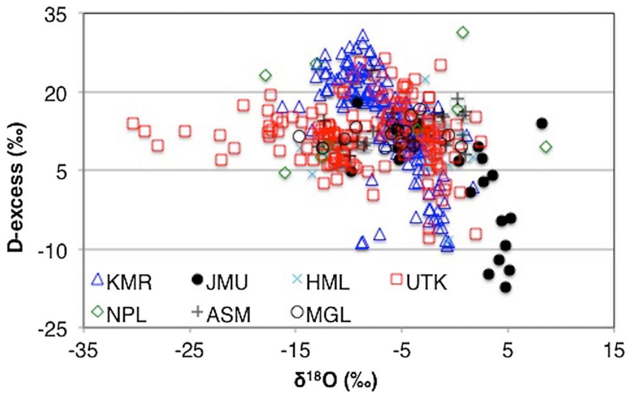

Figure 4. Relationship between δ^{18}O and d-excess of average monthly precipitation across the Himalayas.

generated under relatively lower relative humidity, much less than global average value of 80% for most of the oceans and 75% over most of the land surfaces, excluding dry areas (Dai 2006). During the months of DJF, the WDs are responsible for long distance transport of vapour generated from Mediterranean Sea or Caspian Sea under lower relative humidity. Vapour generated under lower relative humidity condition, such as that in Mediterranean region, is known to have high d-excess of around 20‰ (Gat and Carmi 1970). Due to long distance transport of such an air parcel over the continent, its isotopic composition is expected to change from its initial value due to various processes like picking up of locally recycled vapour, rainout effect, etc. Relatively depleted isotopic composition and high d-excess (around 15‰) is observed in the northeast monsoon rainfall in Kerala, located in southern part of India compared to the ISM rains of this station. This was attributed to the long distance transport of the northeast monsoon currents over continental region (Deshpande *et al.* 2003; Warrier *et al.* 2010). However, contrary to this, in the present study, it was noticed that during the period of WDs the ambient temperatures are low (average monthly regional temperature ranges from 8 to 14°C) and the contribution of local moisture to precipitation may be less. Therefore, there may be a little isotopic modification of residual vapour mass transported from Mediterranean region to the study area.

In Jammu and Himachal Pradesh, the d-excess decreases in DJF, which is also associated with the increase in δ^{18}O (enriched ^{18}O) indicating the evaporation of rain. The observed high d-excess (∼20‰) during DJF in Uttarakhand, Nepal and farther east in Assam suggest the vapour generated under lower relative humidity condition, i.e., the influence of WDs. However, it needs to be ascertained if this high d-excess in precipitation signifies the influence of WDs in the central and eastern Himalayas or significant local recycling of vapour. In Uttarakhand, in DJF, higher d-excess (w.r.t. other stations except Kashmir), associated with low δ^{18}O (depleted ^{18}O) suggests the dominant influence of WDs without the significant effect of evaporation. In Nepal and Assam, the high d-excess (∼20‰) is associated with high δ^{18}O (enriched ^{18}O) possibly suggesting dominant influence of transpiration, which tends to increase δ^{18}O of vapour over the forest floor (Lai and Ehleringer 2010) or the influence of WDs with evaporation.

From June to August (JJA), when ISM is dominant, the d-excess of ≥8‰ is observed in 75% of the samples (between Q1 and maximum) across the Himalayas (except Kashmir) and >6‰ d-excess is also observed in Nepal (75% samples). The lowest δ^{18}O is observed in Uttarakhand in JJA. The δ^{18}O values are seen to progressively decrease from Meghalaya in the eastern Himalayas up to Uttarakhand in the central Himalayas. Further west of Uttarakhand, the δ^{18}O values increase at Himachal, Jammu and Kashmir. This suggests that up to Uttarakhand in central Himalayas, the moisture regime is dominated by the primary marine source, most likely the Bay of Bengal. Further west of Uttarakhand, there seems to be significant admixture of evapotranspired vapour. However, at these stations west of Uttarakhand, the d-excess is not very high. This suggests that vapour admixture is due to transpiration and not the evaporation, which would have manifested in high d-excess as well. The lowest and distinguishable d-excess in Kashmir during June to September is associated with high δ^{18}O, that is almost similar to that of Jammu and Himachal, which suggests either different source of moisture during this period and/or the admixture of locally derived moisture with that transported through ISM. It is already an established fact that BOB moisture contributes to precipitation in Himalayas. Medina *et al.* (2010) have shown using Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) data that convective systems containing broad stratiform radar echoes occur in the eastern Himalayas in association with BOB depressions, as strong low-level flow transports maritime moisture into the Himalayan region. In the course of its passage over the Bangladesh wetlands, additional moisture is extracted from the diurnally heated surface. Convection is triggered as conditionally unstable flow is lifted upstream of and over the foothills. The convective cells evolve into mesoscale convective systems with convective and stratiform areas. These mesoscale convective systems are advected farther into the Himalayan eastern indentation, where orographic lifting enhances the stratiform precipitation.

In Jammu, the lowest d-excess ($\leq 6‰$) is observed in 75% of the samples (between Q3 and minimum) from March to May, which is the lowest among all the locations across Himalayas and also among all the four seasons. The low d-excess is associated with highest δ^{18}O (enriched ^{18}O) suggesting that falling raindrops in Jammu region experience maximum evaporation during the fall from cloud base to ground level. The effect of evaporation is also discernible here in other seasons as well (figure 3). Monthwise distribution of δ^{18}O and d-excess of monthly composite samples (figure 4) shows that at each station, in different seasons, there are some precipitation samples with extremely high or low values of δ^{18}O and d-excess which lie outside the normal range (mean $\pm$1SD) of variation at that station. This indicates significant role of sporadic hydrometeorological processes in modifying the isotopic composition of such isotopically extreme events which include moisture recycling, sub-cloud evaporation, local/regional convection over land area, etc. Among all the stations, Assam is conspicuous by a large range of variation in d-excess and intermittent rain events with very high d-excess values observed almost throughout the year (figures 3–4), except in MAM. The high d-excess of precipitation with low isotopic value in Assam during DJF can possibly be interpreted as the farther eastward excursion of WDs. Although influence of WDs so much farther in the eastern Himalayas has not been clearly reported earlier, the high d-excess in the Ganga River at Rishikesh in central Himalayas has earlier been ascribed to WDs (Maurya *et al.* 2009). Madhura *et al.* (2015), Agnihotri and Singh (1982) and Dimri *et al.* (2004) also suggested influence of WDs in the western Himalaya and the north of India during winter. Similar high d-excess observed even during June to November months covering southwest and northeast monsoon seasons is unusual. The influence of WDs in Assam cannot be hypothesized during June to November months; therefore, an alternate mechanism for observed high d-excess in rain events at Assam during June to November (JJA and SON) period could be the local recycling. It is to be noted here that in Assam, 9.7% (764,373 ha) of the total area is under wetlands including rivers, streams and riverine wetlands; and the open pan annual evaporation (2.36 mm/day) and annual potential evapotranspiration (3 mm/day) at Jorhat in Assam is lowest in the country (Rao *et al.* 2012). The relative humidity is higher during summer months from June to November. The low values of open pan and potential evapotranspiration and high relative humidity in Assam suggest that atmosphere remains continuously loaded with locally generated moisture during summer months. This recycled moisture seems to mix with vapour advected by monsoonal winds and results in rains with high d-excess during June to November. In contrast, during the winter season (DJF), the low relative humidity increases the chances of evaporation of the light rain events. Lesser rainfall (32 mm), warm temperatures (22°C) and enriched isotopic values than the other seasons (figure 3) in Assam corroborate the evaporation of falling raindrops.

In contrast to low evapotranspiration in Jorhat (Assam) in eastern Himalaya, the estimated evapotranspiration in Jammu in the western Himalayan region is quite high (Nikam *et al.* 2014), with values varying from 6.5 mm/day in May, 6.0 mm/day in June, 4.5 mm/day in July, 3.9 mm/day in August, 4.0 mm/day in September, 3.6 mm/day in October and 2.6 mm/day in November. Due to such a high evaporation demand of atmosphere, the raindrops often undergo significant evaporation during their fall from cloud base to ground. This is manifested in the form of very low d-excess values for several precipitation samples at Jammu almost throughout the year.

3.2 $\delta^{18}O$–δD *regression lines*

The slope of the annual δ^{18}O–δD regression lines (table 2) increases from western Himalayas (Kashmir: 7.1; Jammu: 6.8) to the eastern Himalayas (Assam: 8.2; Meghalaya: 8.1). Except for Jammu and Kashmir, the slopes of regression line for all other stations, i.e., from Himachal Pradesh to Meghalaya, are nearly the same with a very narrow (0.3) range of variation. This suggests the possible existence of two dominant but different hydro-meteorological regimes in Himalayas, namely: (i) from Meghalaya to Himachal Pradesh covering majority of eastern length of Himalayas;

Table 2. *Annual and seasonal slope and intercept of local meteoric water lines (LMWL) in different regions across the Himalayas.*

Station	Annual	DJF	MAM	JJA	SON
KMR	$\delta^2H = 7.1 \times \delta^{18}O\,(\pm 0.12) + 10.5\,(\pm 0.89)$ $R^2 = 0.92\,(N = 278)$	$\delta^2H = 8.3 \times \delta^{18}O + 23.4$ $R^2 = 0.94\,(N = 91)$	$\delta^2H = 8.1 \times \delta^{18}O + 18.9$ $R^2 = 0.98\,(N = 81)$	$\delta^2H = 7.9 \times \delta^{18}O + 3.6$ $R^2 = 0.92\,(N = 65)$	$\delta^2H = 7.5 \times \delta^{18}O + 11.9$ $R^2 = 0.95\,(N = 41)$
JMU	$\delta^2H = 6.8 \times \delta^{18}O\,(\pm 0.13) + 4.8\,(\pm 0.78)$ $R^2 = 0.95\,(N = 61)$	$\delta^2H = 6.0 \times \delta^{18}O + 3.8$ $R^2 = 0.94\,(N = 18)$	$\delta^2H = 5.9 \times \delta^{18}O + 4.2$ $R^2 = 0.86\,(N = 20)$	$\delta^2H = 7.1 \times \delta^{18}O + 7.5$ $R^2 = 0.96\,(N = 10)$	$\delta^2H = 8.0 \times \delta^{18}O + 8.2$ $R^2 = 0.98\,(N = 13)$
HML	$\delta^2H = 7.9 \times \delta^{18}O\,(\pm 0.3) + 8.9\,(\pm 1.92)$ $R^2 = 0.96\,(N = 49)$	$\delta^2H = 3.9 \times \delta^{18}O + 0.5$ $R^2 = 0.27\,(N = 5)$	$\delta^2H = 6.4 \times \delta^{18}O + 7.9$ $R^2 = 0.77\,(N = 8)$	$\delta^2H = 8.0 \times \delta^{18}O + 12.5$ $R^2 = 0.98\,(N = 27)$	$\delta^2H = 8.2 \times \delta^{18}O + 8.4$ $R^2 = 0.99\,(N = 9)$
UTK	$\delta^2H = 7.9 \times \delta^{18}O\,(\pm 0.07) + 10.8\,(\pm 0.68)$ $R^2 = 0.99\,(N = 123)$	$\delta^2H = 8.2 \times \delta^{18}O + 14.8$ $R^2 = 0.98\,(N = 23)$	$\delta^2H = 7.0 \times \delta^{18}O + 7.2$ $R^2 = 0.89\,(N = 26)$	$\delta^2H = 8.0 \times \delta^{18}O + 10.9$ $R^2 = 0.99\,(N = 37)$	$\delta^2H = 7.9 \times \delta^{18}O + 9.6$ $R^2 = 0.99\,(N = 37)$
NPL	$\delta^2H = 8.1 \times \delta^{18}O\,(\pm 0.27) + 12.1\,(\pm 1.96)$ $R^2 = 0.98\,(N = 17)$	–	$\delta^2H = 6.3 \times \delta^{18}O + 13.5$ $R^2 = 0.97\,(N = 6)$	$\delta^2H = 7.3 \times \delta^{18}O + 4.4$ $R^2 = 0.94\,(N = 6)$	– –
ASM	$\delta^2H = 8.2 \times \delta^{18}O\,(\pm 0.07) + 13.1\,(\pm 0.49)$ $R^2 = 0.98\,(N = 72)$	$\delta^2H = 6.2 \times \delta^{18}O + 10.9$ $R^2 = 0.91\,(N = 15)$	$\delta^2H = 7.6 \times \delta^{18}O + 13.8$ $R^2 = 0.94\,(N = 17)$	$\delta^2H = 8.2 \times \delta^{18}O + 12.1$ $R^2 = 0.97\,(N = 28)$	$\delta^2H = 8.2 \times \delta^{18}O + 11.6$ $R^2 = 0.96(N = 12)$
MGL	$\delta^2H = 8.1 \times \delta^{18}O\,(\pm 0.07) + 12.3\,(\pm 0.57)$ $R^2 = 0.99\,(N = 48)$	–	$\delta^2H = 7.5 \times \delta^{18}O + 12.6$ $R^2 = 0.99\,(N = 11)$	$\delta^2H = 7.9 \times \delta^{18}O + 10.6$ $R^2 = 0.98\,(N = 19)$	$\delta^2H = 8.2 \times \delta^{18}O + 14.3$ $R^2 = 0.99\,(N = 18)$

and (ii) Jammu and Kashmir in the western part of Himalayas. These two regions have also been identified earlier based on $\delta^{18}O$ and d-excess values. Annually highest intercept (table 2) is observed in Assam and lowest in Jammu. Significantly higher intercept is observed in Kashmir during DJF and MAM, indicating influence of vapour generated under low humidity extra-tropical region and transported under the influence of WDs. In DJF, high intercept is also observed farther southeastward regions of Uttarakhand and Nepal. This suggests the possible influence of extra-tropical vapour in the rainfall at much farther southeastward beyond western Himalayas. During months of DJF, intercept in Assam (10.9) is much lower than that in Uttarakhand (14.8), which suggest the influence of extra-tropical vapour. However, the regression line slope at Assam for DJF is much smaller (6.2) compared to GMWL as well as that at Uttarakhand (8.2), indicating evaporation of raindrops; consequently, the observed intercept may not be the pristine signature and the influence of extra-tropical vapour cannot be completely ruled out. The intercept in Assam and Meghalaya for most of the year (i.e., MAM, JJA, SON) is higher (table 2) compared to GMWL and also compared to the other Himalayan stations in the northwest. This suggests that considerable vapour recycling throughout the year influences eastern extreme of Himalayas. Rainfall in Jammu for most part of the year (except the months SON) has slope (5.9–7.1) and intercept (3.6–23.4) that indicate that rainfall here undergoes significant evaporation before reaching the ground. This possibility is also supported from the fact that relative humidity at Jammu is consistently low (<40%) throughout the year.

From the isotopic characteristic ($\delta^{18}O$, δD, d-excess, regression line slope and intercept; figures 2–4 and table 2) of precipitation, it is evident that the Himalayan region from Himachal Pradesh to Meghalaya is influenced primarily by a common marine vapour, originating from the Bay of Bengal and/or the Arabian Sea, being transported through seasonal reversing of winds from winter to summer monsoons. On the other hand, it seems that western extreme of Himalayan region (Kashmir) is primarily influenced by vapour with high d-excess, generated under lower relative humidity, and transported through WDs. Being the area outside the monsoon regime, Kashmir is known to get rainfall from extra-tropical systems like WDs and trough in the Westerlies (Ranade *et al.* 2007). While extra-tropical source of vapour for rainfall in Kashmir is evidently recorded in isotopic composition of precipitation, the same is not possible in case of Jammu because of significant modification of pristine isotope characteristic due to evaporation. The lower slope (6.8) and intercept (4.8) along with lower d-excess at Jammu clearly indicate significant evaporation of falling rain drops (table 2). Since the pristine d-excess value of precipitation at Jammu is modified due to evaporation of raindrops, it is not possible to ascertain whether vapour source for rain at Jammu is principally monsoonal or extra-tropical. This study also highlights the possibility of influence of extra-tropical vapour through WDs, farther southeastward than just Kashmir. Consistently higher d-excess in Assam, almost throughout the year, indicates significant continental recycling of vapour and the influence of WDs in the southeastern end of Himalayas. Monthly composite sample being a mixture of several precipitation events, possibly of different origins, may not be the best option to explain the finer isotopic signatures associated with individual rain events under WDs and ISM. Nonetheless, monthly composite samples can provide broad isotopic signatures to distinguish between the rainfall under WDs and ISM which can be further refined by detailed event based sampling in future. However, monthly composite samples can give us the signature of the dominant precipitation event. In order to better understand the isotopic signatures associated with WDs and ISM, a detailed event-based sampling is required.

3.3 *Controlling factors*

Temperature, amount of precipitation, altitude, latitude, longitude and distance of sampling location from the sea, possible vapour source and typical rainout history of the air parcel are known as various factors influencing the isotopic composition of precipitation at a particular location. Except Jammu and Meghalaya, average $\delta^{18}O$ of the precipitation of all regions showed a good relationship with the average ambient temperature from December/January to May/June (figure 5). As the temperature rise, the $\delta^{18}O$ value of precipitation increases, with the highest correlation recorded in Kashmir ($r^2 = 0.58$). In Jammu, the higher $\delta^{18}O$ values during this period seems to be due the lower rainfall and low relative humidity, which promotes evaporation. However, the precipitation of all the regions showed decrease in $\delta^{18}O$ from

June/July to September/October despite higher ambient temperatures (figure 5). The apparent decrease in δ^{18}O of precipitation, although coincides with higher precipitation amount, may be attributed to the change in the source of precipitation, as the correlation between the precipitation amount and the δ^{18}O of precipitation is statistically insignificant. In order to quantify the possible influence of various controlling factors in the Himalayas, each sample with lower (L), normal (N) or higher (H) values of δ^{18}O, and lower (l), normal (n) or higher (h) values d-excess were categorized in to nine classes (Ll, Ln, Lh, Nl, Nn, Nh, Hl, Hn, Hh) based on the combination of their δ^{18}O and d-excess values (table 3). The range of normal values were taken as (average±1SD) for each location. The values above this range were considered as higher values and values below this range were considered as lower values. The statistical treatment shows that most of the precipitation samples (∼52%) fall in Nn (normal δ^{18}O with normal d-excess) category followed by Ln (16%) and Hn (14%). There are only a few precipitation samples in Ll (1%) and Hh (1%) category. δ^{18}O of Nl category shows better correlation with temperature ($r^2 = 0.47$) followed by Nh ($r^2 = 0.23$), Hh ($r^2 = 0.16$) and Hl ($r^2 = 0.15$). δ^{18}O of Nn category shows very poor correlation with temperature ($r^2 = 0.0$) and precipitation ($r^2 = 0.02$). δ^{18}O of Ll category shows better correlation with precipitation ($r^2 = 0.75$) followed by Hh ($r^2 = 0.16$) and Ln ($r^2 = 0.13$). δ^{18}O of Ll category shows best correlation with relative humidity ($r^2 = 0.85$) followed by Hh ($r^2 = 0.31$) and Nn ($r^2 = 0.22$). This suggests that the temperature and precipitation amount are not dominant factors affecting the δ^{18}O and d-excess of precipitation with normal isotopic composition (Nn) (table 3).

The lowering of temperature with increasing elevation in mountainous regions usually leads to the enhanced condensation and therefore progressive depletion in heavy isotopes of precipitation with altitude widely known as altitude effect. In the present study, the altitude shows a very good correlation ($r^2 = 0.73$) with average δ^{18}O of the precipitation sites located above 1000 m above mean sea level (figure 6) indicating that the isotopic composition of precipitation is significantly influenced by the orographic lifting. The altitude

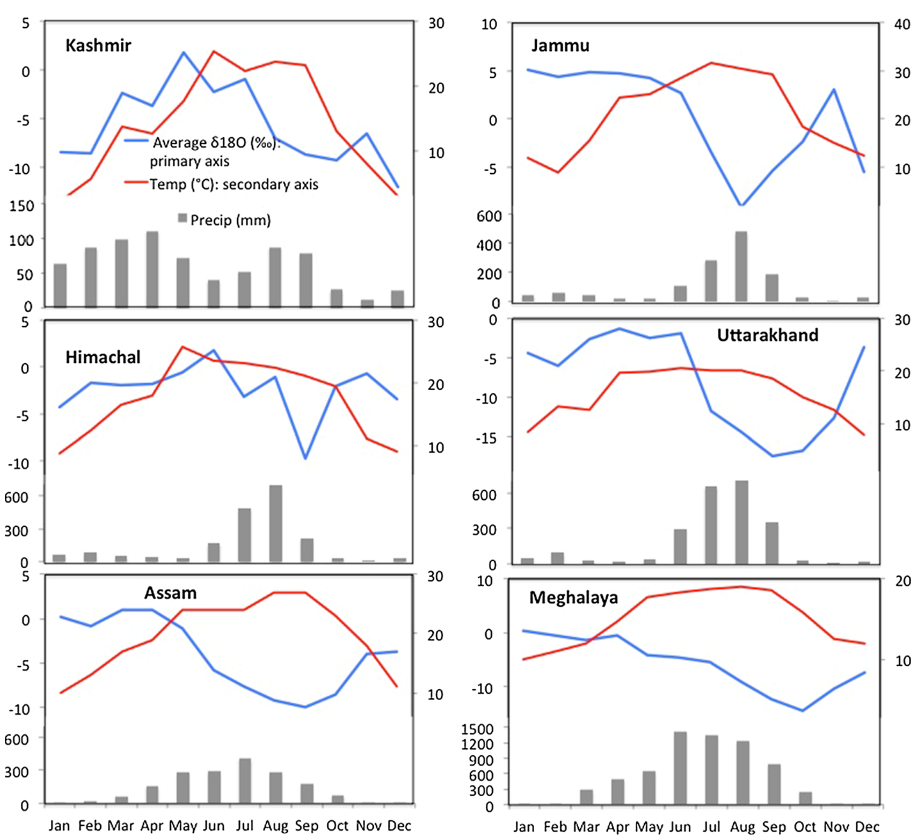

Figure 5. Average monthly δ^{18}O and its relationship with average ambient temperature and precipitation in different regions of the Himalayas.

Table 3. *Categories of precipitation samples based on* $\delta^{18}O$ *and d-excess.*

sl.no.	Category	KMR $\delta^{18}O$ (‰)	KMR D-excess (‰)	JMU $\delta^{18}O$ (‰)	JMU D-excess (‰)	HML $\delta^{18}O$ (‰)	HML D-excess (‰)	UTK $\delta^{18}O$ (‰)	UTK D-excess (‰)	NPL $\delta^{18}O$ (‰)	NPL D-excess (‰)	ASM $\delta^{18}O$ (‰)	ASM D-excess (‰)	MGL $\delta^{18}O$ (‰)	MGL D-excess (‰)
1	Ll	< −9.5	<6	< −4.4	< −7	< −7	<6	< −12	<8	< −9.5	<9	< −9.1	<10	< −12	<9
2	Ln	< −9.5	6 to 21	< −4.4	−7 to 12	< −7	6 to 14	< −12	8 to 19	< −9.5	9 to 14	< −9.1	10 to 16	< −12	9 to 14
3	Lh	< −9.5	>21	< −4.4	>12	< −7	>14	< −12	>19	< −9.5	>14	< −9.1	>16	< −12	>14
4	Nl	−9.5 to −1.8	<6	−4.4 to 4.4	< −7	−7 to 0.2	<6	−12 to −0.6	<8	−9.5 to −5.6	<9	−9.1 to −0.2	<10	−12 to −4.4	<9
5	Nn	−9.5 to −1.8	6 to 21	−4.4 to 4.4	−7 to 12	−7 to 0.2	6 to 14	−12 to −0.6	8 to 19	−9.5 to −5.6	9 to 14	−9.1 to −0.2	10 to 16	−12 to −4.4	9 to 14
6	Nh	−9.5 to −1.8	>21	−4.4 to 4.4	>12	−7 to 0.2	>14	−12 to −0.6	>19	−9.5 to −5.6	>14	−9.1 to −0.2	>16	−12 to −4.4	>14
7	Hl	> −1.8	<6	>4.4	< −7	>0.2	<6	> −0.6	<8	> −5.6	<9	> −0.2	<10	> −4.4	<9
8	Hn	> −1.8	6 to 21	>4.4	−7 to 12	>0.2	6 to 14	> −0.6	8 to 19	> −5.6	9 to 14	> −0.2	10 to 16	> −4.4	9 to 14
9	Hh	> −1.8	>21	>4.4	>12	>0.2	>14	> −0.6	>19	> −5.6	>14	> −0.2	>16	> −4.4	>14

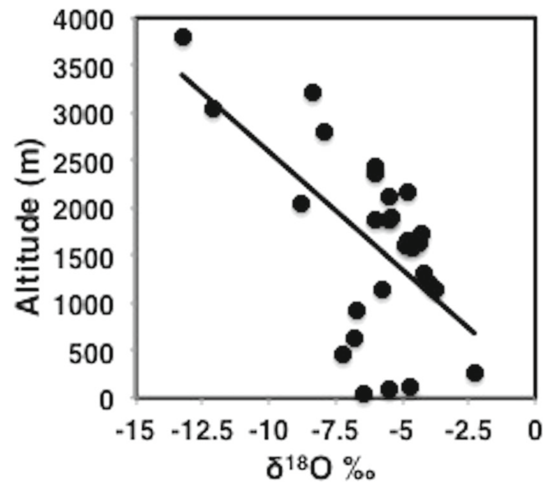

Figure 6. Plot showing average monthly $\delta^{18}O$ *vs.* altitude of the sampling sites.

effect is more pronounced at catchment/watershed scales than the regional/basin scales. The vertical isotopic gradient (altitude effect) of $\delta^{18}O$ measured at Liddar watershed (Kashmir) and Ganga watershed (above 1000 m) is −0.24‰ per km ($r^2 = 0.88$) and −0.35‰ per km ($r^2 = 0.94$), respectively. The observed altitude gradients are within the limits of published values (Clark and Fritz 1997; Poage and Chamberlain 2001; Jeelani *et al.* 2010; Bhat and Jeelani 2015). Latitude and longitude showed poor correlation with the average $\delta^{18}O$ of the precipitation.

4. Conclusions

Monthly composite precipitation samples were collected across the Himalayas to assess the variability in $\delta^{18}O$ and δD of precipitation associated with WDs and ISM, the chief bearers of precipitation in the region. In the present study, it was found that the precipitation associated with WDs have higher d-excess than the ISM reflecting their different vapour origin. The study suggests that the WDs are the dominant bearers of precipitation in western Himalayas, whereas the ISM are the chief bearer of precipitation across the length of Himalayas up to Jammu during JJAS (with local modifications). The study suggested that the local recycling significantly influences the isotopic composition in eastern Himalayas particularly Assam, while as the intense evaporation of falling rain drops affect the isotopic composition of precipitation in Jammu.

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