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Establishing the Effect of Aridity on the Stable Isotopes ($\delta^{18}O$ and δD) of Precipitation in Cold Desert, Ladakh

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Abstract: Ladakh or the land of high passes is a cold desert in India that lies in the Greater Himalayas on the eastern side of Jammau and Kashmir State. It is a favourite tourist destination due to its scenic beauty, barren, rugged terrain and majestic mountains. In order to understand the influence of aridity on the isotopic composition ($\delta^{18}O$ and δD) of precipitation in the region we collected precipitation samples across the arid region. Precipitation was found to be highly depleted in heavier isotopes inJanuary and at higher altitudes and enriched in July and lower altitudes. The significant finding of this research was that the precipitation samples were depleted in heavier isotopes with lower d-excess than the neghbouting temperate regions. The slope of local meteoric waterline was found to be lower than the GMWL, western Himalayan and Kashmir HimalayanLMWL.The study suggested that the aridity has a strong influence in controlling the stable isotopic composition of precipitation [1].

Key words: Precipitation · Stable Isotopes · Ladakh · Aridity

INTRODUCTION

The stable isotope composition ($\delta^{18}O$ and δD) in natural water is extensively used to investigate the Earth's hydrologic cycle and climatic change [2, 3]. Precipitation is a vital component in the natural water cycle, spatial dependence and temporal variations in precipitation isotopes are convenient in understanding hydrological, meteorological and ecological processes [4, 5]. Researchers are increasingly using isotopic observations to study atmospheric water vapour sources and influencing factors [6, 7]. The interaction between the falling drops and the surrounding atmosphere during a rain event may change the original isotope content [7, 8]. The main crest of Himalayas forms the climatic boundary between the region dominated by the influence of Indian summer monsoons to the south and relatively cold dry and continental climate, which characterizes much of the western Himalayas, to the north. Western Himalayas, the part of youngest mountain chain on the surface of earth, gives rise to world's one of the major river-system viz. the Indus.

In spite of the hydrological importance of the region, little work has been carried out on the meteorology of the Ladakh, upper Indus basin [9, 10] and very few studies have been carried out on stable isotopic (δ^2H and $\delta^{18}O$) characteristics of glaciers and precipitation [11] and surface water [12, 13]. For the first time, we have usedstable water isotopes of precipitation, NCEP/NCAR reanalysis and Hysplit back trajectory modeling to study the mechanism controlling and modifying the isotopic composition ($\delta^{18}O$ and δD) of precipitation in the arid conditions inLadakh, upper Indus basin.

Study Area: The Indus basin stretches from the Himalayan Mountains in the north to the dry alluvial plains of Sindh province in Pakistan in the south and finally flows out into the Arabian Sea.In India, the basin spreads over states of Jammu & Kashmir, Himachal Pradesh, Punjab, Rajasthan, Haryana and Union Territory of Chandigarh covering an area of 3, 21, 289 Sq.km, which is nearly 9.8% of the total geographical area of Indus. The geographical extent of the basin in Jammu and Kashmir (Ladakh) is between (32°30' to 35°00' N and longitude 75°50' to 79°10' E) covering an area of 59, 146 Km^2. Ladakh, upper Indus basin also referred as Trans-Himalayas is bounded by the higher Himalayan range on the east and by the Karakoram Range on the north with an elevation ranging from 2700 to > 7000 (m, asl). (Fig. 1).

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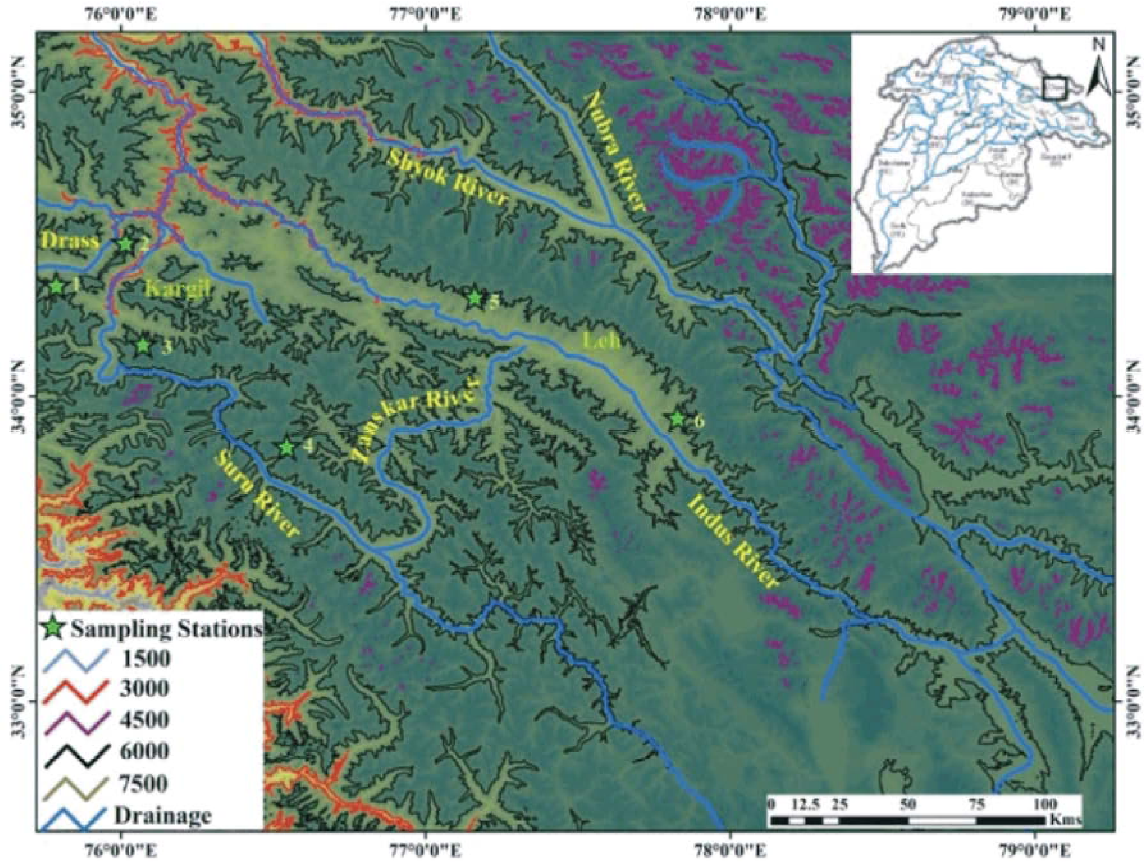

Fig. 1: Location map showing sampling sites inLadakh, Upper Indus Basin

The area experiences four distinctive seasons: winter (December to February), spring (March to May), summer (June to August) and autumn (September to November) and has cold-arid climate. Theclimate of Himalayas is dominantly controlled by the westerly circulation and southwest monsoons throughout the year [7, 14]. The average annual precipitation received at Leh weather station is 115 mm. Precipitation is dominantly observed from the month of January to May, accounting for 85.74% of the annual precipitation. The maximum precipitation is received in the month of January (120mm) and minimum in the month of September (22mm). The average annual temperature observed at Leh weather station (34°08'09"N and 77°32'47"E) is 5.2°C. The maximum temperature observed in the month of July(14°C) and minimum temperature is observed in the month of January (-8°C).

MATERIALS AND METHODS

Monthly precipitation samples were collected at a few stations across the upper Indus basin, Ladakh (Fig. 1). Composite monthly sampleswere collected using a standard rain gauge with a long narrow tube attached to the 5-litre plastic container, fitted with a funnel, to minimize the evaporative loss of stored rainwater [3, 7]. The samples were immediately transfered in 10 ml polyethylene plastic bottles with inner and outer caps to avoid isotope exchange with air moisture. Fresh snow samples in winter were collected in one-litre wide-mouthed bottles, capped and allowed to melt at room temperature. The melt water was immediately transferred to the 10 ml high-density polyethylene (HDPE) bottles. The samples were sent to Geosciences Division, Physical Research Laboratory (PRL), Ahmedabad (India), for analysis of stable isotopes. The stable isotope ratios of oxygen and hydrogen were measured using an isotope ratio mass spectrometer (Delta V plus, Thermo Scientific) in continuous flow mode and following the standard gas equilibration method. For $\delta^{18}O$ (or $\delta^{2}H$) measurements, 300 µl of water was equilibrated with CO_2 (or H_2) for 16 h (or 1 h) and the equilibrated gas was analysed for isotopic ratio $^{18}O/^{16}O$ (or $^{2}H/^{1}H$).

RESULTS AND DISCUSSIONS

Variation of Stable Isotopes in Precipitation: During the observation period the stable isotopic composition ($\delta^{18}O$ and δD) of precipitation varied from-17.1to -7.3‰ and -150 to -45‰ with a mean of -12‰ and –88‰, respectively. The lower isotopic values in precipitation is observed in Leh (-12.85‰) whereas less depleted heavier isotopes in precipitation is found in Drass (-11.48‰) and Kargil (-11.84‰). It was observed that the precipitation at higher altitudes is depleted in heavy isotopes than at lower elevations, which is consistent with the well-known altitude effect. A significant correlation ($R^2 = 0.97$; $p = 0.0001$) existed between the average monthly $\delta^{18}O$ (and δD) of precipitation and the altitude of precipitation sites (Fig. 2). It is important to note that the altitude of Leh is higher (3450m, asl) than the altitude of Kargil (3144m, asl) and Drass (2860m, asl) precipitation sites.

The estimated altitude gradient of upper Indus basin is -0.25‰ per 100 m increase in elevation for $\delta^{18}O$ and -2.39‰ per 100 m increase in elevation for δD. The observed altitudinal gradients are similar to those reported in other parts of the Himalayas [7, 14].

In January the precipitation was found to be highly depleted in heavier isotopes and in July the precipitation is enriched in heavier isotopes (Fig. 3) and there is a progressive increase in isotopic values of precipitation from January to July and progressive decrease in isotopic value from September to December (Fig. 3). This is in consistent with the increase in temperature fromJanuary to July and decrease in temperature from September to December. August is an exception, when the isotopic value of precipitation abruptly drops, without much change in the temperature. This seems to be due to amount effect as the precipitation amount in August in Drass and Kargil is higher, but in Leh there is not significant increase in precipitation amount. Therefore, amount affect does not hold good.

Looking at the d-excess of the precipitation (Fig. 3) the decrease in d-excess from January to June with increase in temperature indicates the effect of temperature in modifying the isotopic composition of rainfall. Similarly, the increase in d-excess from September to December with decrease in temperature suggested the decreasing influence of temperature with its drop. The lower isotopic value associated with lower d-excess and high temperature in August strongly suggests the change in moisture source of precipitation. We know that during June/July to September the precipitation is dominated by the southwest monsoons across the Himalayas [15, 16, 7]. The similar conclusions are also reported in other parts of western Himalayas including Tibet [6, 16], Kashmir valley [7, 17]. The enriched heavy isotopes and lower d-excess of precipitation in July and September indicates the significant influence of temperature in modifying the isotopic composition of precipitation. A significant positive correlation was found between the monthly $\delta^{18}O$ (and δD) of the precipitation and ambient temperature and a weak correlation was found with precipitation amount (Fig.4). This type of weak correlation is reported in other parts of the Himalayas [7] and in south Asia [18, 19].

Variation of D-Excess in Precipitation: The d-excess value is considered as most vital parameter indicating regional water vapor sources. The calculated D-excess values of the precipitation ranged from 21 to -2 ‰ with an average of 11‰ respectively. The higher d-excess values were observed from October to April and lower from May to September (except August), (Fig. 3). The higher d-excess values of precipitation samples are ascribed to the moisture brought by western disturbances [7]. Higher d-excess in precipitation reveals that moisture is evaporated from dry climatic conditions [22]. The lower d-excess in June–September (Fig. 3) indicates the moisture brought by the Indian summer monsoon in western Himalayas [20, 21]. Because the moisture is from the direct evaporation over humid ocean surface [22].

The high relative humidity over the Arabian Sea and Bay of Bengal during summer season gives rise to lower d-excess values in precipitation. However, in winter the lower relative humidity above the warm sea surface of the Mediterranean Sea leads to a higher d-excess values in precipitation [3, 7]. Lower d-excess in the months of June, July and September is associated with higher $\delta^{18}O$ values and lower precipitation amount demonstrates the effect of evaporation on the falling rain droplets due to lower rainfall and lesser RH, which increase evaporation and decrease d-excess of precipitation. Thus, the lower d values in the monsoon period are further decreased mainly in JJS. Although definitive seasonal trend in $\delta^{18}O$ is not apparent in June, July and September (JJS), there is a decrease in monthly average d-excess from 17 to 10 ‰ in JJS (Fig. 3). The depletion of $\delta^{18}O$ in precipitation with decrease in d-excess in the month of August indicates the humid condition which prevent evaporation of falling raindrops. This type of isotopic signature is representative of south west monsoons in other parts of Himalayas [3, 6, 7].

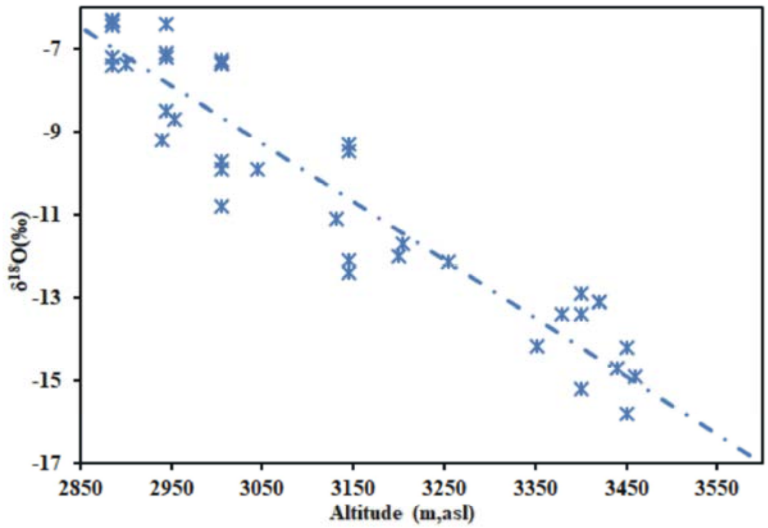

Fig. 2: Scatter plot showing the relationship of $\delta^{18}O$ with altitude of precipitation samples in Ladakh, upper Indus basin

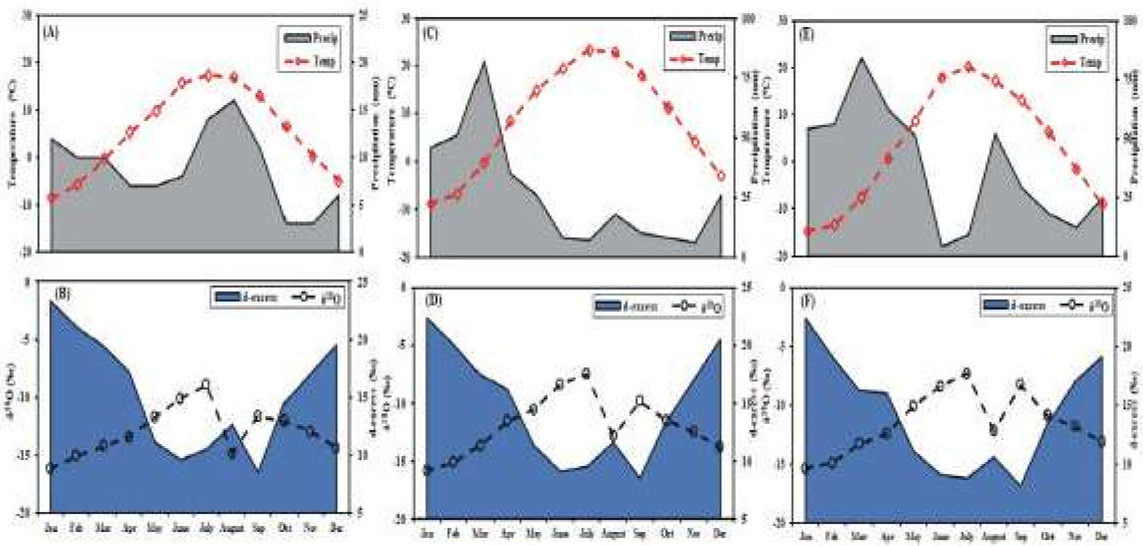

Fig. 3: Monthly variation of $\delta^{18}O$ in precipitation at all sampling sites along with the monthly precipitation and temperature across the upper Indus basin Ladakh.

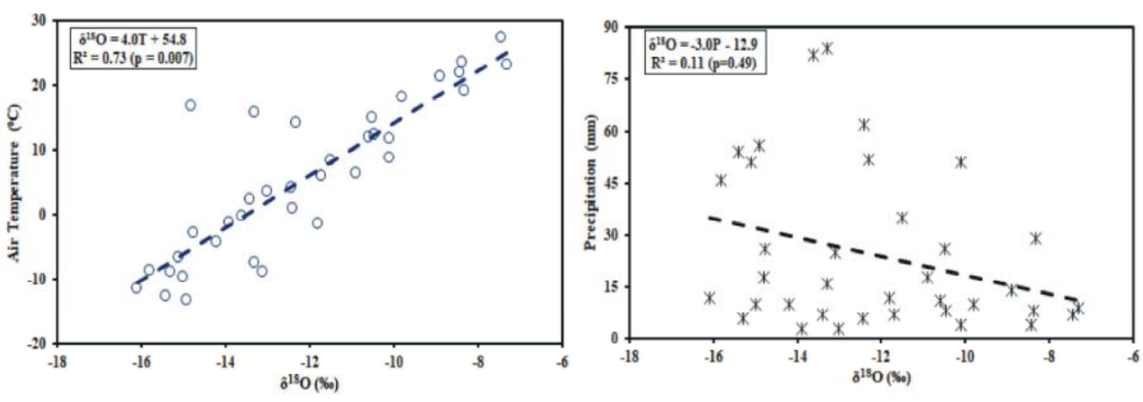

Fig. 4: The relation of $\delta^{18}O$ with average air temperature and average precipitation amount.

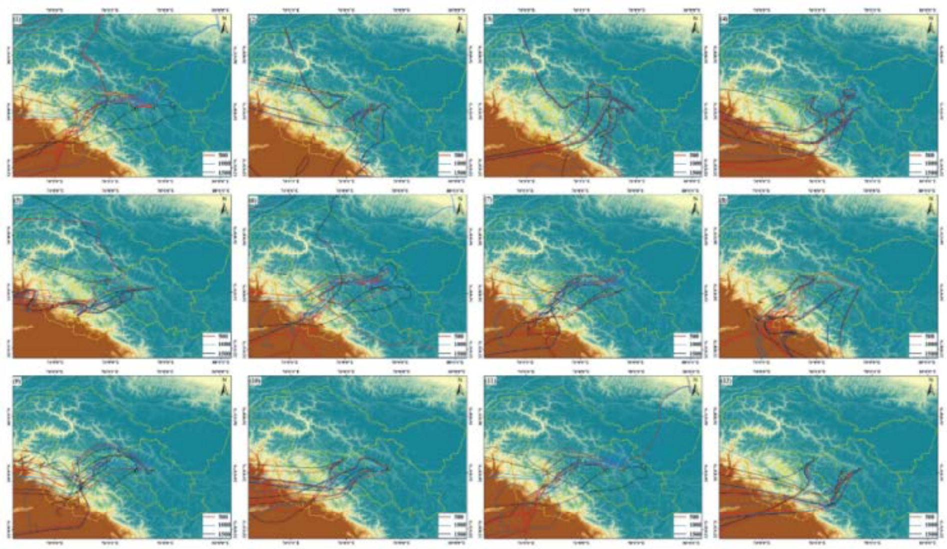

Fig. 5: HYSPLIT reverse-calculated 96-hr trajectories ended at upper Indus basin. For each trajectory model, the red, blue and blacklines in map view represent the path of air parcels terminating at (A) 500, (B) 1000, (C) and 1500 m AGL for the 96-hr period prior to the specified date for the month of 2016. The sampling stations in the observation network are marked as yellow stars. The yellow curve denotes the national boundary of Jammu and Kashmir. The satellite-derived land cover is acquired from Earth Explorer (https://earthexplorer.usgs.gov/)

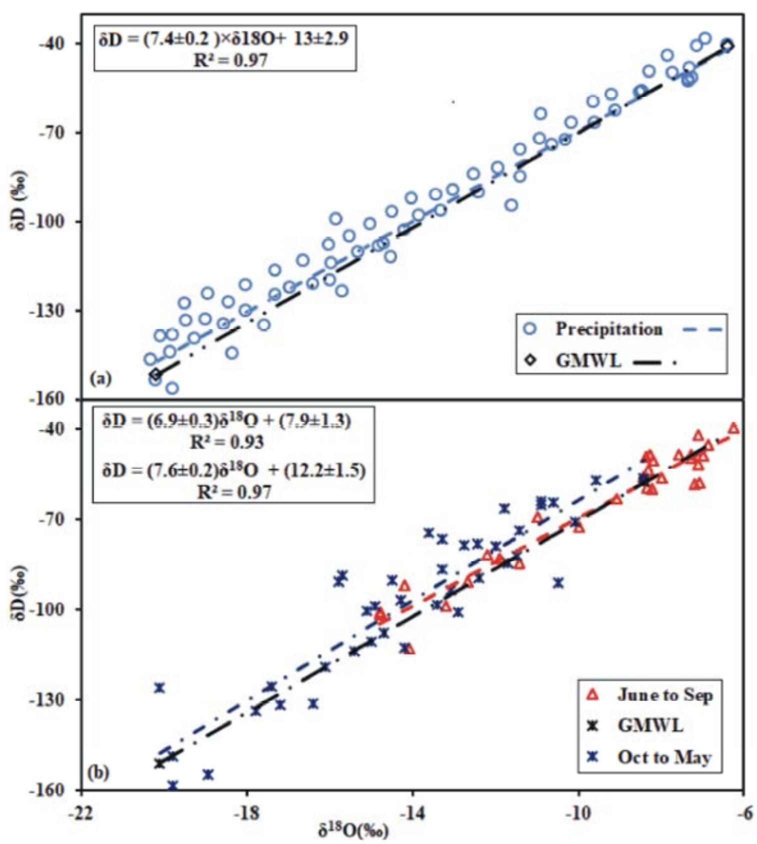

Fig. 6: The local meteroic water line of Ladakh, upper indus basin based on (a) monthly data and (b) seasonal isotopic composition of the precipitation data

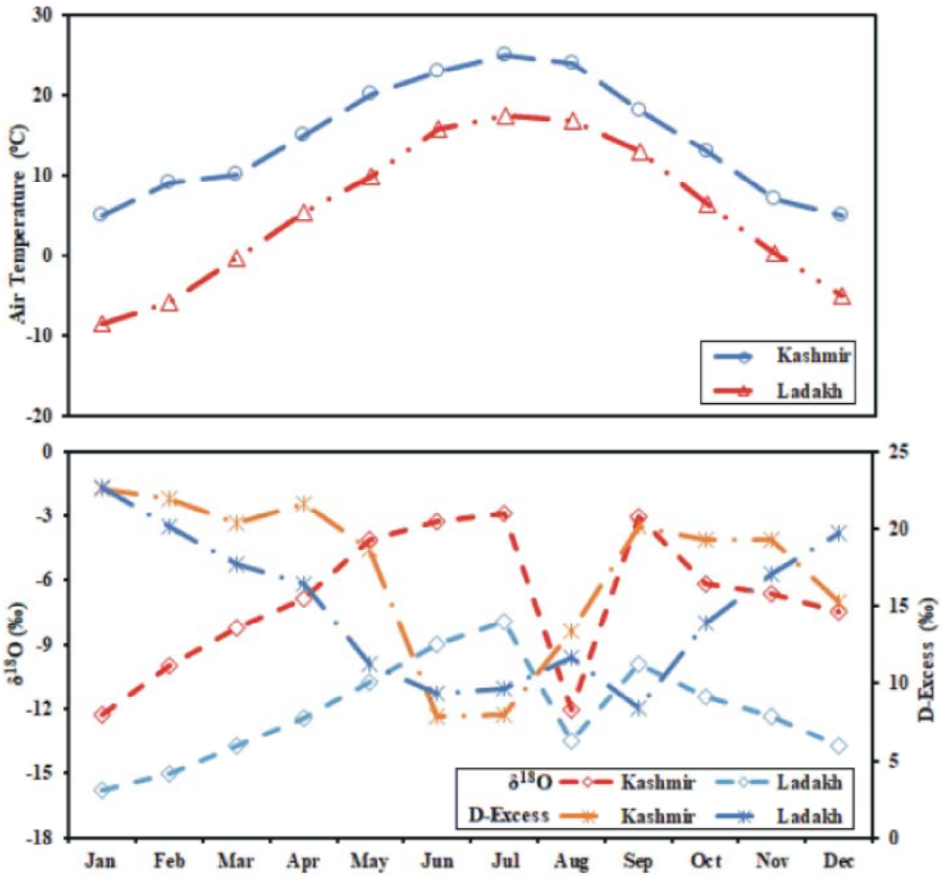

Fig. 7: Temporal variation of $\delta^{18}O$ and d-excess in precipitation in Kashmir valley and Ladakh, upper Indus basin.

The $\delta^{18}O$ and d-excess values were consistent with information for moisture sources of precipitation as examined by HYSPLIT modelling and documented airmass paths (Fig.5).

Local Meteoric Waterline: According to the experimental stable isotope ($\delta^{18}O$ and δD) data, we obtained the local meteoric waterline as: $(7.8\pm0.2) \times \delta^{18}O + (13\pm2.9)$ for upper Indus basin based on weighted monthly data by the least square method (Fig. 6). The slope (7.8) of LMWL was found to be slightly lower than the GMWL and the LMWL of western Himalayas and Kashmir Himalaya. The intercept of the LMWL (13) was higher than that of the GMWL (10.0) and LMWL of western Himalayas (11.51) but lower than Kashmir Himalayas (16.3). The lower slope, exhibits that the precipitation has experienced a certain degree of evaporation of falling raindrops or sub-cloud evaporation.

Effect of Aridity on Stable Water Isotopes: The precipitation in Ladakh region is depleted in ^{18}O and ^{2}H than the precipitation in Kashmir region (-15.6‰ to -0.1‰ for $\delta^{18}O$ and -112‰ to 0.3‰ for δD) [7]. This difference in isotopic values of two regions is ascribed to higher altitude of Ladakh region (2700-7500 m asl) than the Kashmir region (1500-5000 m asl) and climate (Kashmir Valley: Temperate and Ladakh: Cold arid).

It is observed that the ambient temperature and stable water isotopes showed almost similar temporal trend in the two regions. The precipitation samples were depleted in heavier isotopes in January, which become progressively enriched in heavy isotopes up to July consistent with increase in temperature. The stable isotopic values decrease from September to December with the decrease in temperature (Fig. 7). August is an exception, which is discussed above. It is important to note here that the d-excess of precipitation in Ladakh region is unusual due to its lower value (14.8‰) than Kashmir region (17.36‰) and the monthly trend (Fig. 7). Ideally with decrease in temperature (or increase in altitude) the d-excess of precipitation increases with decrease in stable isotopic value (Fig. 7), but in Ladakh region the d-excess of precipitation decreases. Another significant observation is the trend of the d-excess, which is flat during October to May in Kashmir region, progressively decreases from January to May and increases from September to December in Ladakh region. The change in monthly d-excess despite very low ambient temperature in Ladakh region suggests the significant impact of aridity in modifying the isotopic composition of precipitation in the region.

CONCLUSION

A significant positive correlation existed between the average monthly $\delta^{18}O$ (and δD) of precipitation and the altitude of precipitation sites. Precipitation was found to be highly depleted in heavier isotopes in January and enriched in July. A significant positive correlation was found between the monthly $\delta^{18}O$ (and δD) of the precipitation and ambient temperature. The lower slope of LMWL than the GMWL, LMWL of western Himalayas and Kashmir Himalayas and lower d-excess than the neighbouring temperate regions indicate the significant influence of aridity on the stable isotope composition of precipitation.

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