Understanding Hydrometeorological Processes Concerning Indian Precipitation: Insights from Oxygen and Hydrogen Stable Isotopes in Conjunction with Meteorological Parameters

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Understanding Hydrometeorological Processes Concerning Indian Precipitation: Insights from Oxygen and Hydrogen Stable Isotopes in Conjunction with Meteorological Parameters

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by

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supervised by

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भौतिक अनुसंधान प्रयोगशाला

Physical Research Laboratory

Dedicated to
My Guru and My Mentor

DECLARATION

I declare that this written submission represents my ideas in my own words and where others' idea or words have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be cause for disciplinary action by the Institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed.

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Thesis Approval

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Doctor of Philosophy

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Supervisor	Chairman

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Abstract

Hyderometeorological processes govern the availability and distribution of water in space and time. In the current scenario of global climate change, various trends in amount, intensity and spatial distribution of rainfall, are well recognized with reference to rising temperatures. However, the underlying subtle hydrometeorological processes governing rainfall pattern and distribution are still not quite clearly understood. Until climate driven major changes in hydrological cycle and its socio-economic consequences are identified, understanding contemporary hydrometeorological processes is very much important because it serves as an early warning system. In an agrarian country like India, with its unique geographical and climatic conditions, slightest vagaries in weather systems can disrupt the socio-economy of country. Indian weather systems are predominantly known to be governed by seasonal reversal of winds and the rainfall (monsoon) associated with it. Even though the broad patterns of monsoon and its linkages with other synoptic scale pressure-temperature systems are well known, there are still considerable knowledge gaps in understanding of various hydrometeorological processes operating at different spatial and temporal scales. Insights into these processes, derived from large scale circulation models, have limitations due to constraint on the spatial resolution, and yet pending ground validation through independent means. Therefore, an alternate approach to understand hydrometeorological processes is desirable. Stable isotopes of oxygen and hydrogen in rainwater can be used as tracers to understand the origin, movement and mixing of water molecules, in conjunction with meteorological parameters. Thus, it can be used to identify and understand various hydrometeorological processes governing distribution and availability of precipitation. With this backdrop, under the aegis of a National Programme on Isotope Fingerprinting of Waters of India (IWIN), precipitation samples were collected from 41 Indian stations spread across the country for their oxygen and hydrogen isotopic analysis, and interpretation of isotope data in light of various meteorological parameters. Study was done to discern various hydrometeorological processes operating at three spatial scale viz., mega-scale (~1000 km), mesoscale (~100 km) and microscale (~1 to 5 km), which concern precipitation in India. Some of the important inferences drawn from the interpretation of isotope data in the present study are: (i) despite being surrounded by marine water bodies in three directions (east, west and south) and bounded by Himalayan mountains in the north, which restricts the moisture laden winds from travelling further north, evaporation from the falling raindrops is one of the dominant processes across the country; (ii) during pre-monsoon

and post monsoon the contribution of continently derived moisture is significant; (iii) Orographic barrier posed by the Western Ghats to the southwest monsoonal winds causes nominal isotopic depletion in precipitation in leeward side compare to windward side, which indicate enormity of moisture drawn from Arabian Sea (AS) during southwest monsoon season; (iv) continentally recycled moisture predominantly contributes the northern Indian precipitation; (v) in northeast India maximum moisture for rainfall is derived from continental recycling from wetlands, and variation in the availability and isotopic makeup of local surface waters govern the isotopic composition of precipitation (vi) systematic pattern of depletion in precipitation isotope during late southwest monsoon (Aug-Sep), observed from long-term (2005 – 2016) isotopic study, is attributed to multitude of processes such as increased continentally recycled moisture in precipitation, increased rainout fraction due to decreased wind velocity, lowering of cloud base temperature and increased proportion of convective rain; (vii) during the post-monsoon season, contrary to expectation in southern Indian peninsula, isotopic signatures show significant continentally derived precipitation, instead of precipitation derived from the Bay of Bengal (BOB) vapour.(viii) The estimated evaporative loss from falling raindrops for the four representative stations is Jammu: Maximum 52% and Minimum 8%; Jorhat: Max 15% and Min 4%; Ahmedabad Min 8% and Hyderabad Max 29% and Min 15%. (ix) Based on the backward wind trajectory analysis done for four stations, maximum estimated contribution of continentally derived moisture in annual precipitation was found to be ~87% at Jammu and minimum contribution of continentally derived moisture in annual precipitation was found to be ~19% at Ahmedabad.

List of Abbreviations

AMIP	Atmospheric Model Inter-comparison Project
ARL	Air Resource Laboratory
AS	Arabian Sea
BOB	Bay of Bengal
CF	Continuous Flow
CLWC	Cloud Liquid Water Content
DOE	Department of Energy
DP	Daily Precipitation
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Niño-Southern Oscillation
ERA	ECMWF Re- Analysis
ERSST	Extended Reconstructed Sea Surface Temperature dataset
FP	Fortnightly precipitation
GC	Gas Chromatography
GCM	Global Circulation Model
GDP	Gross Domestic Product
GISP	Greenland Ice Sheet Precipitation
GMWL	Global Meteoric Water Line
GVA	Gross Value Added
HDPE	High Density Poly Ethylene
HYSPLIT	Hybrid Single Particle Lagrangian Integrated Trajectory Model
IAEA	International Atomic Energy Agency
IMD	India Meteorology Department
IMWL	Indian Meteoric Water Line
IOD	Indian Ocean Dipole
IRMS	Isotope Ratio Mass Spectrometer
ITCZ	Intertropical Convergence Zone
IWIN	Isotope Fingerprinting of Waters of India
LMDZ	Laboratoire de Météorologie Dynamique atmospheric general circulation model with Zooming
NCAR	National Center for Atmospheric Research

NCEP	National Centers for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
OLR	Outgoing Long-wave Radiation
PET	Potential evapotranspiration
RF	Rainfall
RH	Relative Humidity
SCIAMACHY	SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY
SLAP	Standard Light Antarctic Precipitation
SPEI	Standardized Precipitation Evapotranspiration Index
SQL	Structured Query Language
SS	Stainless Steel
SST	Sea Surface Temperature
SWING	Stable Water Isotope Intercomparison Group
TMI	TRMM Microwave Imager
TRMM	Tropical Rainfall Measuring Mission
VSMOW	Vienna Standard Mean Ocean Water
WD	Western Disturbances

Chapter 1

Introduction

The contemporary global hydrological cycle is experiencing a great deal of fluctuations and uncertainties in terms of amount and timings of rainfall caused by the rise in global temperature and other anthropogenic factors. For instance, Trenberth (2011) and Nageswararao et al. (2016) have reported 7% increase of atmospheric water vapour for 1^{o}C increase in global temperature; around 5–10% increase in annual precipitation over mid and high latitudes; and 3% decrease in subtropical precipitation have been reported (Houghton et al., 2001; Vinnikov et al., 1990). Rainfall variability in terms of extreme amounts and shift in timings is one of the significant factors adversely affecting the socio-economy (Lanzafame, 2014; Olayide and Alabi, 2018; Richardson, 2007). Nations with higher population density and insufficient infrastructure are more vulnerable to the adverse effects of climate change.

India, due to its unique geo-climatic and socio-economic conditions, with higher average population density (382 persons per km^2) and the agrarian economy is severely threatened by the change in climate as observed in recent decades. India is home to 17.7% of the global population of which, 58% of the population depends primarily on agriculture for their livelihood (Gadgil and Gadgil, 2006). However, only 4% of global freshwater is available to India. India receives about 1090 mm of average annual precipitation (Parthasarathy et al., 1994), the spatial distribution of which is highly uneven. According to Koppen climatic classification, India can be divided into six different climatic zones (Montane, Humid subtropical, Tropical wet and dry, tropical wet, Semiarid and Arid) based on seasonal precipitation and temperature patterns (Kottek et al., 2006). Within these large homogenous meteorological regions, several highly localized meteorological phenomena have been reported in the recent past (Guhathakurta et al., 2011; Kashid and Maity, 2012).

Slightest vagaries in weather system can disrupt the socio-economy of the country. In the recent past, numerous extreme weather events have been recorded (De et al., 2005). Three major metro cities of India namely, Mumbai (Jul), Chennai (Oct and Dec) and Bangalore (Oct) experienced the consecutive flash floods in the same year (2005) causing substantial damages to economy and loss of life (Guhathakurta et al., 2011). Based on the daily rainfall dataset, Goswami et al., (2006) have shown significant rising trends in the frequency and the magnitude of extreme rain events over central India during the Southwest Monsoon from 1951 to 2000. Statistically significant increasing trends in rainfall extremes are identified over many parts of India, consistent with the indications from climate change models and the hypothesis that the hydrological cycle will intensify as the planet warms (Krishnamurthy et al., 2009). Although the non-parametric test, as well as the linear trend analysis, identified decreasing trends in the frequency of wet days in most parts of the country, the great desert areas of the country have experienced an increased number of wet days (Guhathakurta et al., 2011). Using Standardized Precipitation Evapotranspiration Index (SPEI) calculated from long term (1901–2010), high resolution, monthly gridded temperature and rainfall datasets it is observed that the frequency of multi-year (24 months) monsoon droughts over India has increased in a statistically significant manner which is attributed to the increase in surface air temperatures and drying of the atmosphere (Niranjan Kumar et al., 2013). Examination of 132 years of rainfall data has revealed that the severe droughts in India have always been associated with El Nino events (Krishna Kumar et al., 2006). Based on 122 years (1877-1998) of cyclone frequency data over the North Indian Ocean, it is observed that there is a trend in the enhanced cyclogenesis during November and May (Singh et al., 2001). Thus, trends in various weather indices in numerous studies confirm that the weather systems in the Indian subcontinent are changing.

Until major climate change and its socio-economic consequences are clearly identified, it is important to understand the contemporary hydrometeorological processes in various timescales, which determine the spatio-temporal distribution of water in the atmosphere, surface and sub-surface domains in different climatic zones (Hartmann et al., 2013). It can also serve as an early warning system for ongoing changes as well as for the interpretation of the paleoclimate proxies in land and ocean records (Masson-Delmotte et al., 2013).

The mechanics of hydrological and meteorological processes and their broad linkages with other synoptic processes and factors such as El-Nino Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), North Atlantic sea surface temperature and European ice cover, governing the inter-annual variability of Indian precipitation are well-known. There are subtle variations in the hydrometeorological processes operating in different spatio-temporal scales, which are not understood clearly (Stocker et al., 2013). Therefore, it is crucial to understand and discern the hydrometeorological processes and factors concerning rainfall, such as (i) moisture source variation; (ii) continental recycling of vapour; (iii) advective and convective mixing of vapour masses; and (iv) evaporation from the falling raindrops, operating at different spatial scales viz., mega-scale (~1000 km), mesoscale (~100 km) and microscale (~ 1 to 5 km). Insights into these processes, derived from large scale circulation models, have limitations due to constraint on the spatial resolution, and ground validation through independent means is sought for. Therefore, an alternate approach to understand hydrometeorological processes is desirable.

Stable isotopes of oxygen and hydrogen in rainwater can be used as tracers, in conjunction with meteorological parameters (reanalysis products, satellite-derived and ground-based), to understand the above-mentioned hydrometeorological processes. Specific aspects which can be addressed using stable isotopes are moisture source identification, rainout history, recycling of vapour, evaporation from falling raindrops and cloud microphysical processes. (Breitenbach et al., 2010; Deshpande et al., 2013a; Deshpande and Gupta, 2012; Jeelani et al., 2017; Lekshmy et al., 2015; Midhun et al., 2018; Oza et al., 2020; Rahul et al., 2018; Saranya et al., 2018; Unnikrishnan Warrier and Praveen Babu, 2012).

The oxygen and hydrogen isotopic composition of precipitation samples, collected from 41 stations across the country under a National Programme on "Isotope Fingerprinting of Waters of India (IWIN)" (Deshpande and Gupta, 2008; Deshpande and Gupta, 2012) has been examined and interpreted in this study to discern the hydrometeorological processes from three different spatial perspectives viz. mega-scale, mesoscale and microscale.

1.1 Motivation

- Hydro-meteorology governs the distribution of water in space (atmosphere, surface and sub-surface) and time, which in turn governs the socio-economy, particularly in an agrarian country such as India.
- Global circulation models cannot capture the regional or local features because of limited resolution

- About 60% of the global inland precipitation is derived from continentally recycled moisture (Van Der Ent and Tuinenburg, 2017).
- Understanding contemporary hydro-meteorology can serve as an early warning system for imminent changes.
- Contemporary hydro-meteorology can also serve as a tool to understand paleoclimate signatures recorded in various continental archives.

1.2 Scientific Aims and Objectives

- To understand mega-scale (~1000 km), mesoscale (~100 km) and microscale (~1 – 5 km) hydrometeorological processes concerning the spatio-temporal distribution of precipitation.
- To examine the validity and limitations of classical isotope effects in the Indian sub-continent.
- To identify various moisture sources and quantify its contributions in the regional precipitation.
- To understand the role of evapotranspiration in local recycling and quantify it.
- To estimate evaporation from the falling raindrops.

The general hydrological background, the motivation and the scientific objectives enumerated above form the overarching purpose of this study.

Chapter 2

Isotope Rationale

Isotopes are nuclides of an element with the same atomic number - Z (i.e. the number of protons) but, different mass number – A (i.e. total number of neutrons and protons). Isotopes are of two types: i) radioactive (decays to product nuclide over time) and ii) stable (does not decay). Stable isotopes of oxygen (^{16}O, ^{17}O, ^{18}O) and hydrogen (^{1}H and ^{2}H or D) are the most important tracers used in hydrology, as they are an integral part of the water molecule itself. The different combinations of these isotopes form isotopic water molecules with different masses, known as water isotopologues. Table 2.1 enlists all the water isotopologues along with their relative abundances [source: Clark and Fritz (1997b)].

During the phase (solid-liquid-vapour) change, in the course of the hydrological cycle, the heavier water isotopologues get preferentially partitioned and concentrated in the phase having a comparatively smaller degree of freedom for molecular movement due to difference in their molecular masses, and consequently their physical properties (e.g. bond strength, rotational, vibrational and translational frequencies, density, collision frequency and vapour pressure). Therefore, by monitoring the relative abundances of isotopologues, various hydrological processes can be traced and understood.

2.1 Expressing Isotopic composition

The isotopic composition is expressed as the relative deviation of abundance ratios (*R*) of less abundant to more abundant isotopes in the sample from that of the international standard reference material such as VSMOW [Vienna Standard Mean Oceanic Water; Gonfiantini (1978)]. Isotopic composition is reported in δ notation as per mil (‰) deviation from the international standard as given below:

$$\delta = \left(\frac{R_{sample}}{R_{standard}} - 1\right) \times 10^{3}\ ‰$$

Where, $R = {}^{18}O/{}^{16}O$ for oxygen *and* $R = D/{}^{1}H$ for hydrogen isotopic composition, referred to as $\delta^{18}O$ or δD respectively.

Table 2. 1: Relative abundances of oxygen and hydrogen isotopes along with relative abundances of water isotopologues

Isotopes	Abundance (%)	Water Isotoplogue	Abundance (%)
^{1}H	99.98	$H_2{}^{16}O$	99.73
D	0.015	$HD^{16}O$	0.015
^{16}O	99.76	$D_2{}^{16}O$	2.24×10^{-6}
^{17}O	0.035	$H_2{}^{17}O$	0.035
^{18}O	0.205	$HD^{17}O$	5.25×10^{-6}
		$D_2{}^{17}O$	7.88×10^{-10}
		$H_2{}^{18}O$	0.20
		$HD^{18}O$	3.07×10^{-5}
		$D_2{}^{18}O$	4.6×10^{-6}

2.2 Isotope Fractionation

The differential partitioning of isotopologues between two interacting phases during a phase change reaction is known as isotopic fractionation. The isotope fractionation occurs because of the difference in molecular masses and consequent physical properties of isotopologues. The isotopic fractionation is quantitatively expressed in terms of fractionation factor (α) as the ratio of isotopic ratios of two co-existing phases:

$$\alpha_{Liquid}^{Vapour} = \frac{R_{Vapour}}{R_{Liquid}}$$

In per mil (‰) notation α is represented as:

$$\varepsilon = (\alpha - 1) \times 10^3$$

ε is known as fractionation or enrichment factor. Depending on the physical conditions during a phase change reaction, water isotopologues may undergo equilibrium and kinetic fractionation as described below.

- **Equilibrium Fractionation**

Equilibrium fractionation occurs when there is thermodynamic equilibrium between two interacting phases (e.g. water and vapour in a cloud) in a closed system. Several laboratory experiments have been undertaken to empirically determine the value of the equilibrium fractionation factor for different temperature ranges (Clark and Fritz, 1997). Majoube (1971)gave an empirical formula for the computation of equilibrium fractionation (α_{eq}) as follow

$$\ln(\alpha_{eq}) = \frac{C_1}{T^2} + \frac{C_2}{T} + C_3$$

Where, C_1, C_2 and C_3 are constants (table 2.2) and T is the temperature (in Kelvin) above 273.15 K. Horita and Wesolowski (1994) have integrated available empirical values and have given a formula which is valid from 0 ºC to 374 ºC temperature range. Equilibrium fractionation

Table 2. 2: Values of constants in the empirical equation for the computation of equilibrium fractionation (Majoube, 1971) for ^{18}O and D

	C_1	C_2	C_3
^{18}O	1.137×10^3	-0.4156	-2.066×10^{-3}
D	-24.884×10^3	-76.248	-52.612×10^{-3}

is a temperature-dependent phenomenon and the magnitude of fractionation is inversely related to the temperature.

- **Kinetic Fractionation**

The isotopic fractionation occurring in the absence of thermodynamic equilibrium is in general known as kinetic fractionation or non-equilibrium fractionation (α_{kin}). It is associated with the unidirectional reaction in an open system such as evaporation or vapour deposition. Non-equilibrium conditions and resultant unidirectional reaction can arise due to several factors such as a sudden change in the temperature or sudden addition/removal of the mass of reactant/product. However, the most common cause of kinetic fractionation in the hydrological cycle is the diffusion of vapour mass from higher to lower concentration gradient in undersaturated air column. Lighter isotopic molecules have higher diffusive velocities compared to the heavier isotopic molecules. Therefore, isotopes get differentially partitioned between two reservoirs, between which mass flux occurs.

The relative humidity (h) of air column, through which isotopic molecules diffuse with different velocities, is the single most important parameter governing the magnitude of diffusive kinetic fractionation, though temperature, air turbulence, wind velocity can also play some role.

Gonfiantini (1986) gave approximate empirical formulations for computation of kinetic enrichment ($\Delta\varepsilon$), as follows:

$$\Delta\varepsilon^{18}O = 14.2 \times (1-h); \Delta\varepsilon^{2}H = 12.5 \times (1-h)$$

2.3 Rayleigh Model of Rainout

Assuming equilibrium condition between vapour and liquid phases and homogeneity in a vapour parcel, the Rayleigh model predicts the isotopic composition of diminishing vapour parcel from which continuously condensate is raining out. It is assumed that during condensation, fractionation happens under isotopic equilibrium between condensate and remaining vapour, and that condensate is immediately removed after formation from the vapour. The diminishing vapour parcel becomes progressively depleted in heavy isotopes at the successive stage of condensation. The resultant rain at each successive stage of rainout is also isotopically depleted.

Some of the specific assumptions in the Rayleigh rainout model are: i) the abundance of heavy isotopologues is much less compared to lighter ones; ii) the isotopic fractionation occurs with instantaneous isotopic equilibration; iii) the process is isothermal and; iv) the reservoir is homogeneous (i.e., no isotopic gradient across the reservoir).

According to the Rayleigh model based on above assumptions, the isotopic ratio (R) of the diminishing vapour parcel is a function of its initial isotopic ratio (R_0) and the residual fraction (f) of the diminishing vapour parcel and the temperature-dependent equilibrium fractionation factor (α), as given below.

$$R = R_0 \times f^{(\alpha-1)}$$

In δ notation, the same equation can be approximated as

$$\delta_f \cong \delta_0 + \varepsilon.\ln(f)$$

Where, δ_0 is the initial isotopic composition of diminishing vapour parcel and δ_f is the isotopic composition of vapour parcel when residual vapour fraction is *f*.

The isotopic composition of instantaneous rain (δ_{li}) can be computed as

$$\delta_{li} = \delta_f + \varepsilon$$

The isotopic computation of accumulated rain can be obtained through simple mass balance, as given below.

$$\delta_l = \frac{\delta_0 - \delta_f.f}{(1-f)}$$

Fig 2.1 shows the $\delta^{18}O$ and δD evolution of diminishing vapour and instantaneous rain.

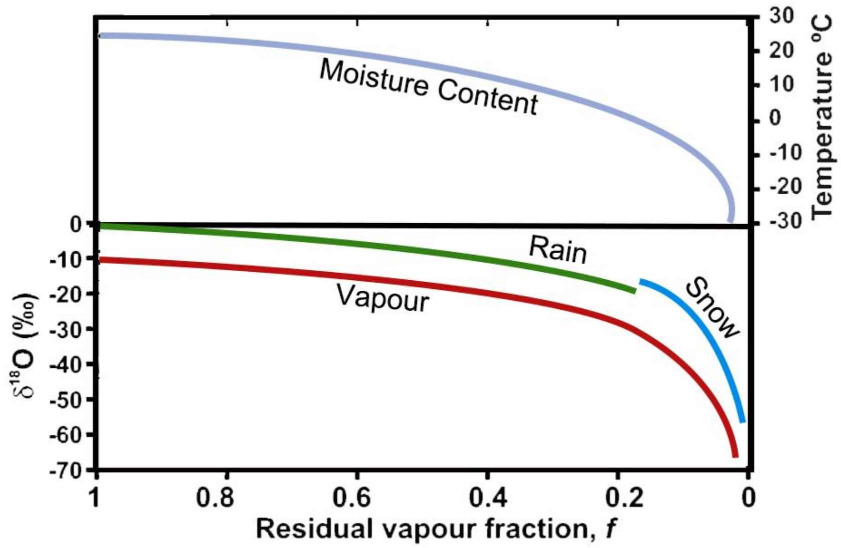

Figure 2. 1: Isotopic evolution of diminishing vapour mass and corresponding rain generated from it.

2.4 Global Meteoric Water Line

The Global Meteoric Water Line (GMWL) is the observed relationship between $\delta^{18}O$ and δD of global precipitation. Originally this relationship was given by Craig, 1961 based on the isotopic composition of surface water samples ($\delta D = 8 \times \delta^{18}O + 10$). However, Rozanski et al. (1993) redefined GMWL based on the isotopic composition of precipitation samples collected from 219 GNIP (Global Network of Isotopes in Precipitation) stations as,

$$\delta D = (8.17 \pm 0.07)\delta^{18}O + (11.27 \pm 0.65)$$

The above-defined relation suggests that in spite of huge spatial variability in climatic and geographical features of the globe, $\delta^{18}O$ and δD correlate and behave in a fairly predictable manner.

The slope of GMWL is the manifestation of the ratio of equilibrium fraction for ^{18}O and D (εD / $\varepsilon^{18}O$), which ranges between ~8.2 ‰ to 9.5 ‰, for temperatures ranging from 0ºC to30ºC. The intercept of ~10 ‰ in GMWL indicates the presence of additional deuterium in the natural hydrological cycle and suggests the involvement of kinetic fractionation during the evaporation process. If the entire rain forming mechanism was under equilibrium condition, then the $\delta^{18}O$ and δD relationship would have been $\delta D \cong 8(\delta^{18}O) + 0$. However, the non-zero intercept indicates kinetic fractionation mainly due to atmospheric humidity gradient in the source region during evaporation.

The GMWL is an average of many Local Meteoric Water Lines (LMWLs), which may differ from GMWL due to variation in the local geographical and hydro-meteorological conditions. However, GMWL provides a frame of reference for the interpretation of the hydrological process at a given location, which caused the difference between GMWL and LMWL.

2.5 The deuterium excess (d – excess)

Whenever there is kinetic fractionation involved the net ratio of fractionation of D to ^{18}O is different from 8 because unlike equilibrium fractionation, the magnitude of kinetic fractionation for ^{18}O is more compared to that for D. Therefore, during the evaporation process liquid gets relatively more enriched in ^{18}O compared to D. Correspondingly, the resultant vapour gets relatively more enriched in D compared to ^{18}O. Therefore, the rain generated from such a vapour also contains the excess of D over what can be accounted for by equilibrium fractionation between water and vapour. Considering this fact, Dansgaard (1964) defined a new parameter, called d-excess (also referred to as d) to quantitatively express the kinetic effect in fractionation as:

$$d - excess = \delta D - (8 \times \delta^{18}O)$$

The benefit of the d-excess parameter is that it can be computed and interpreted for an individual rain event, unlike the intercept of $\delta^{18}O$ – δD regression line, which is useful only for the bulk of data.

2.6 Isotope Effects

The two major controlling factors affecting the oxygen and hydrogen isotopic compositions of rain are i) the magnitude of fractionation during phase change, which in turn is dependent on temperature and humidity, and; ii) the extent of phase change reaction (e.g. the extent of rainout from condensing vapour mass, the extent of evaporative loss from a falling raindrop). In the hydrological cycle, these two governing factors determine the characteristic isotope signatures of rain which change geographically in a systematic manner. Such characteristic isotope signatures are known as isotope effects. Various isotope effects, along with their causal mechanisms, are described below.

- **Temperature Effect**

Observation: Strong positive correlation between mean annual surface temperature and isotopic composition of precipitation (Dansgaard, 1964; Jouzel et al., 1997; Rozanski et al., 1993)

Mechanism: The major source of moisture for global precipitation is the tropical oceans. As the winds driven by pressure gradients travel from high pressure to low-pressure regions, they transport moisture poleward, in the direction of decreasing temperature. In the course of its transportation, heavier isotopes in vapour parcel get rainout preferentially leading to progressive depletion in heavier isotopologues with decreasing temperature.

- **Amount Effect**

Observation: Negative correlation between the amount of monthly average rainfall and isotopic composition of precipitation (Dansgaard, 1964; Gat, 1996; Lee and Fung, 2008; Lekshmy et al., 2015; Lekshmy et al., 2019; Lekshmy et al., 2014; Risi et al., 2010a; Rozanski et al., 1993)

Mechanism: The negative correlation between the amount of rainfall and its isotopic composition can be ascribed to three factors (Dansgaard, 1964), namely, (i) considering a given mass of condensing vapour, the total amount of condensate and its mean isotopic composition decrease as cooling progresses; (ii) isotopic exchange between falling drops and environmental vapour is most pronounced for lighter rain resulting in its isotopic enrichment; (iii) evaporation from raindrops while falling through low humidity air at lower altitudes.

- **Altitude Effect**

Observation: Negative correlation between altitude and precipitation isotopic composition (Bortolami et al., 1979; Moser and Stichler, 1970; Siegenthaler and Matter, 1983; Yonge et al., 1989).

Mechanism: Orographic precipitation occurs as the winds carrying vapour mass rises while moving over a mountain and cools adiabatically. Due to continuous rainout from vapour mass rising till the top of a mountain, the vapour gets progressively depleted in heavier isotopologues and so does the successive rain.

- **Latitude Effect**

Observation: Negative correlation between latitudes and isotopic composition of precipitation (Rozanski et al., 1993)

Mechanism: It is based on the same mechanism as the temperature effect. As most of the moisture is generated near tropics and it travels meridionally poleward, due to successive rainout, the isotopic composition of condensing moisture gets progressively depleted. In turn, rain at a successive stage of rainout also becomes progressively depleted.

- **Continental Effect**

Observation: Negative correlation between inland distance from the coast and precipitation isotopic composition (Rozanski et al., 1993) .

Mechanism: As vapour mass traverse from its source region (generally oceanic) to inland, continuous rainout leads to the removal of heavier isotopologues from the original vapour mass and therefore gradual isotopic depletion in precipitation occurs as the vapour parcel moves inland continental region, away from the marine source area.

Departures from these isotope effects may occur due to variation in moisture source, hydro-meteorological processes, orography and local weather. Apart from these five well-known isotope effects, recently few more such correlations are discovered, some of them are listed below.

- **Convection and rain isotope**

Aggrawal et al. (2016) reported that during deep convection due to strong updraft, near boundary layer moisture ($\delta^{18}O$ ~-12‰ to -10‰) raises rapidly and gets condensed and falls rapidly with downdraft resulting in isotopically enriched rain. In contrast, stratiform rain where tropospheric moisture ($\delta^{18}O$ ~-40‰ to -50‰) condenses and gets equilibrated with lower altitude moisture results in depleted rain.

In contrast, Lekshmy et al. (2014) have associated deep organized convection to isotopically depleted rain based on the following reasoning: i) usually convective rains are associated with heavy rainfall, and according to Rayleigh model, with increased condensation, the vapour becomes progressively depleted and so does the consecutive rains; ii) because of heavy rainfall and high intensity the ambient air gets saturated, retarding the extent of evaporation from falling raindrops and thus retarding isotopic enrichment and; iii) unsaturated downdraft vapour and recycled vapour (both relatively depleted in ^{18}O) feeds the sub-cloud through strong updraft, resulting in isotopically depleted rain.

- **Moisture Residence Time and Rain Isotopes**

A positive correlation was found between the atmospheric residence time of moisture (vapour) and ^{18}O in rainwater at monthly to inter-annual time scales (Aggarwal et al., 2012). The lower moisture residence time suggests strong atmospheric circulation, high moisture conversion in the atmospheric boundary layer and increased convection. Thus due to convection and strong updraft, the boundary layer recycled moisture mixes with depleted (in ^{18}O) tropospheric vapour. Also, the condensation of this moisture is likely to occur as ice, resulting in isotopically depleted rain.

- **Raindrop Size and Rain Isotopes**

Managave et al. (2016) have reported both positive and negative correlation between raindrop size and d-excess of rainwater. During undersaturated sub-cloud conditions, the smaller raindrops with lower terminal velocities experience greater evaporation during fall. As evaporation leads to lower values of d-excess in the liquid (and higher d-excess values in evaporated vapour), the positive correlation between raindrop size and d-excess is observed.

In contrast, during saturated sub-cloud conditions, smaller raindrops with lower terminal velocities readily equilibrate with ambient water vapour (usually with high values of d-excess), leading to the negative correlation between raindrop size and d-excess.

Chapter 3

Methodology

For analysis and interpretation, many ground-based, remotely sensed, reanalysis and modeled datasets are used. Methods, materials and data of overall importance to this thesis are described in this chapter. However, detailed information about specific datasets, its synthesis and application in addressing a particular question are discussed in the "Data Used" section of respective chapters.

3.1 About IWIN National Programme

Realising the applicability of stable isotopes of oxygen and hydrogen in understanding the hydrological processes, many researchers across the country have studied different components of the hydrological cycle using water isotopes in conjunction with various ground-based, remotely sensed and modelled datasets (Gupta and Deshpande, 2005). These studies in India were undertaken in relatively smaller geographical areas of river basins or catchments and were not enough to quantify the continental scale hydrological processes in terms of various land-ocean-atmosphere interactions and exchanges.

To overcome this limitation, a multi-institutional collaborative National Programme for Isotope fingerprinting of Waters of India (IWIN) (Deshpande and Gupta, 2008; Deshpande and Gupta, 2012) was formulated by the Physical Research Laboratory (PRL), Ahmedabad, envisaging a national water isotope network, which was launched in 2008. This research programme was jointly funded by the Department of Science and Technology (DST), Government of India and PRL. Under the umbrella of IWIN national programme, a collaboration of ten research institutes and four central agencies was made with an aim to isotopically characterise the entire hydrological system of India (i.e. marine waters of the Arabian Sea and the Bay of Bengal, precipitation, water vapour, surface waters, rivers and groundwater) to discern various hydrological processes operating on different spatiotemporal scales and to quantify the mass exchange in them.

The present study is based on the isotopic analysis of 3310 rainwater samples collected under the aegis of IWIN National programme from 41 stations spread across the country (Fig. 3.1) and interpretation of isotope data in conjunction with various ground-based and remotely sensed observations and modelled meteorological parameters. Out of 41 rainwater collection network stations (Table 4.1), 29 stations collected fortnightly accumulated rain samples and at seven stations daily accumulated rain samples were collected, and five stations collected both, fortnightly as well as daily accumulated rain samples, either simultaneously or alternately. The duration of rainwater sampling ranged from a minimum of one year to a maximum of 12 years.

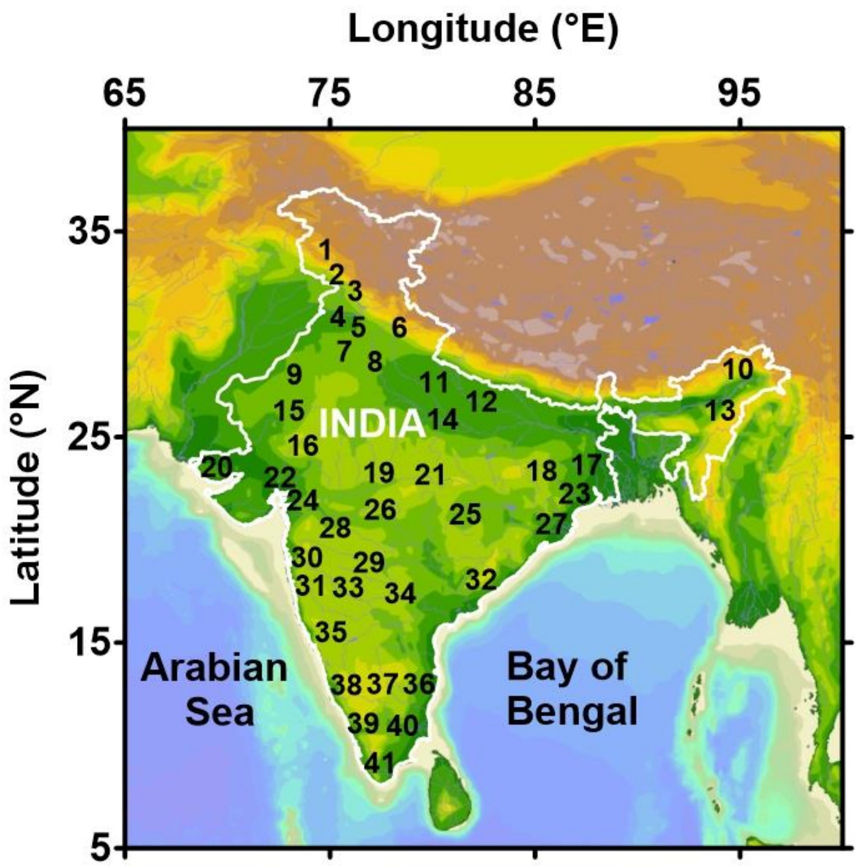

Figure 3. 1: Station locations on the elevation map

3.2 Sampling

The rainwater samplers suitable for Indian conditions were indigenously designed (Deshpande et al., 2010) based on the IAEA/GNIP guidelines and the standardised procedure was prescribed for sample collection. More than 50 identical rainwater samplers were fabricated in PRL workshop, and these were used for sampling at each of the Network stations using a standardised procedure. This ensured uniformity of the sampling procedure and the quality of samples.

The rainwater sampler used in this study is shown in Fig. 3.2 and the description of each component is listed below.

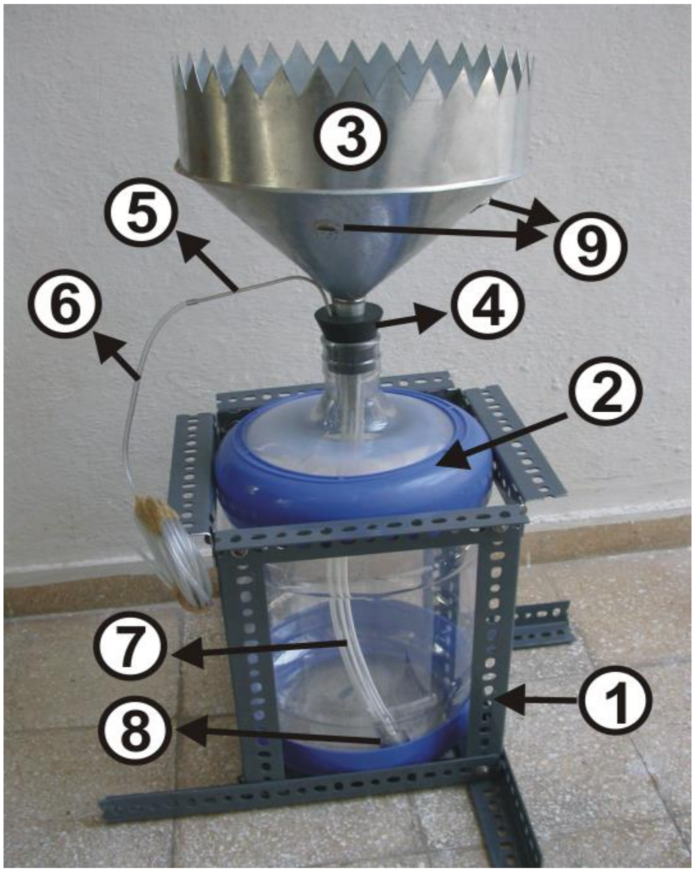

Figure 3. 2: Rainwater sampling Device. Please read the text for description of the numbered items.

1. Slotted-angle metallic stand for housing the sampling device and to prevent it from toppling due to heavy winds.
2. 20-Litre poly bi-carbonate Carboy for collection of the rainwater. It could accommodate up to 28.3 cm of rainfall collected through a metallic funnel of 30 cm diameter.
3. Wide diameter (30 cm) funnel ensured collection of even small amount of rainfall of low intensity. The large volume of the carboy (20 Litre) ensured that a large amount of rainfall of high intensity could also be accommodated.
4. Rubber Cork holding the funnel and tightly fixed into the carboy.
5. SS tube pierced through the rubber cork (Fig. 3.3 c) into the carboy, the purpose of this is to provide the pathway for air-outlet from the carboy, which becomes airtight due to rubber cork fixed tightly to the carboy.
6. Thin, 10 ft. long PVC tube is connected to the other end of SS tube (Fig. 3.3 c) to reduce the interaction between the air within and outside the carboy
7. Thick PVC tube connected to the funnel (Fig. 3.3 c) is to dispense the rainwater from the funnel into the carboy
8. SS weight connected to the thick PVC tube is to keep it straight and just above the base of the carboy.

9. Hooks for tying the funnel with the metallic stand by cotton string (Fig 3.3. a) to ensure that the funnel does not blow away with the wind.

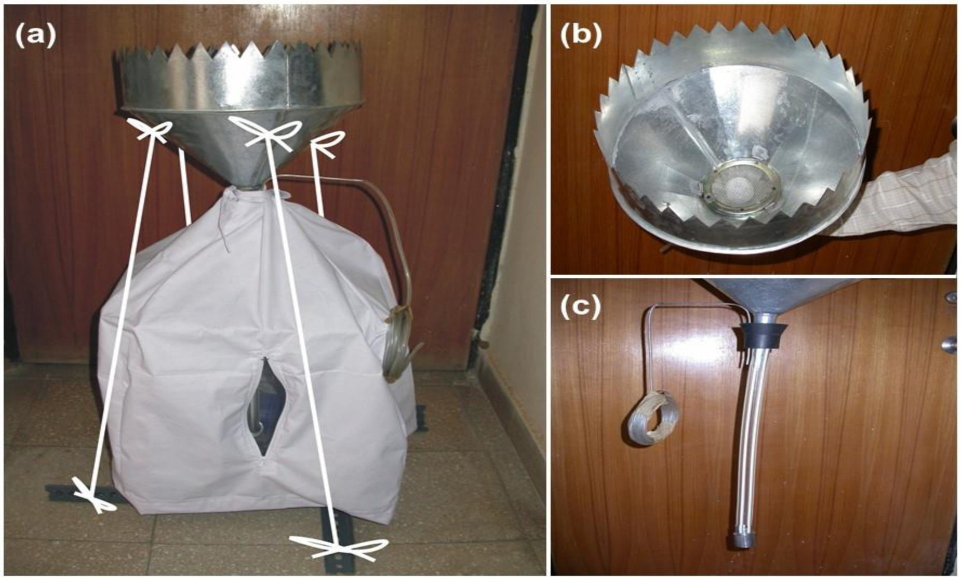

Figure 3. 3: (a) Cotton Jacket covering the sampler; (b) wired mesh and plastic ball fitted in funnel; and (c) Connections of PVC tube and SS pipe

Apart from these nine major components, there is a wired mesh disk, a small plastic ball and a white cotton jacket. The wired mesh and the ball are fixed in the funnel, as shown in Fig 3.3. (b) with the help of three stoppers provided in the funnel. Purpose of the ball is to close the opening of the funnel as far as possible and thus reduce the evaporation when there is no rainfall. As soon as there is rainwater in the funnel, the ball is lifted due to buoyancy and rainwater flows into the carboy. The wired mesh is to prevent any coarser undesirable objects from getting into the carboy, and also it prevents the ball from popping out of the funnel. White cotton jacket is to protect the carboy from direct sunlight and thus, minimise the evaporation of accumulated rain.

(i) Sample Collection Protocols

The following protocols were followed at all the rain sample collection stations:

- The fortnightly accumulated rainwater samples were collected on every 1st and 16th day of every month. In case of a holiday on these dates, the sample was collected a day prior to or after the scheduled date.

- The daily accumulated rainwater samples were collected every day in the morning around 10 am to avoid the evaporation of accumulated rainwater sample during the remaining hot sunny hours of the day.

- At some of the stations where both fortnightly and daily rainwater samples were collected, two separate sets of rainwater sampling devices were set up.

- For the collection of the sample, rubber cork was pulled out first with all its attachments, and the cotton jacket was removed

- The carboy was taken out of the stand and shaken well for mixing and homogenisation of the collected rainwater and the droplets on the wall of the carboy.

- The total volume of the accumulated rainwater was measured using a 1000 ml graduated cylinder provided with the sampling device. The volume of accumulated rainwater was recorded along with the temperature and RH at the time of sampling.

- A 250 ml HDPE (High-Density Polyethylene) sampling bottle was thoroughly rinsed and cleaned with a rainwater sample from the measuring cylinder after the volume was measured. It was then filled till the brim and sealed with inner stub and pilferage proof cape (Fig. 3. 4).

Figure 3. 4. 250 ml HDPE sampling bottle with inner stub and pilferage proof cape

- No chemical or preservative was added to the rainwater sample.

- A standardised IWIN sample code was then written on the sampling bottle using a waterproof marker pen.

- A sample submission data sheet was designed, and all the information requested, like sampling date, sampling time, temperature, RH, amount of rainfall, etc., was filled in.

- The daily and fortnightly samples collected following above protocol were then transported to PRL, Ahmedabad.

Table 3. 1: Comparison of previously analyzed and reanalyzed values of random samples

	$\delta^{18}O$ (‰)		δD (‰)	
IWIN UMC Code	**Previous Analysis**	**Reanalysis**	**Previous Analysis**	**Reanalysis**
UMC-10956	1.8 ± 0.1	1.8 ± 0.1	10 ± 1	10 ± 1
UMC-21199	3.4 ± 0.1	3.6 ± 0.1	21 ± 1	22 ± 1
UMC-21207	0.6 ± 0.1	0.4 ± 0.1	7 ± 1	7 ± 1
UMC-21220	0.4 ± 0.1	0.3 ± 0.1	8 ± 1	9 ± 1
UMC-21237	0.9 ± 0.1	0.6 ± 0.1	17 ± 1	17 ± 1
UMC-22157	3.7 ± 0.1	3.5 ± 0.1	24 ± 1	24 ± 1
UMC-22162	0.3 ± 0.1	0.4 ± 0.1	10 ± 1	9 ± 1
UMC-25253	0.2 ± 0.1	0.1 ± 0.1	8 ± 1	9 ± 1
UMC-25275	0.5 ± 0.1	0.5 ± 0.1	9 ± 1	9 ± 1
UMC-25410	0.1 ± 0.1	0.2 ± 0.1	7 ± 1	7 ± 1

Once the samples are received at PRL, a unique IWIN UMC Number (IWIN Unique Master Code) was given to each and every sample, and all the relevant information provided along with the samples from each station was recorded in a SQL based internal server, and then after ensuring the integrity of each sample bottle in terms of its air-tightness, they were stored at 25 ºC temperature in the IWIN repository (if not, those samples were rejected). To ensure proper preservation of samples at random previously analysed samples were reanalysed, and the results were found to be fairly consistent (Table 3.1).

3.3 Isotope Analysis

The oxygen and hydrogen isotopic analysis of rainfall samples was carried out using Isotope Ratio Mass Spectrometer (IRMS) in continuous flow mode. Mass Spectrometry is a technique to separate the ions based on their mass to charge ratios. In this study Thermo Scientific Delta-V-plus IRMS in continuous flow mode along with Gas bench II was used (Fig. 3.5) The IRMS consists of three major components, namely, i) source for ionising the gaseous samples; ii) magnetic analyser for separating the sample ion beams; and iii) detector comprising multiple ion collectors and detector electronics.

Figure 3. 5: Thermo Fisher Delta V+ IRMS at IWIN laboratory, PRL Ahmedabad

Only gaseous samples can be injected into the ion source of IRMS. Therefore well-established gas equilibration method (Epstein and Mayeda, 1953) was used in which water samples were equilibrated with CO_2 (H_2) gas for $\delta^{18}O$ (for δD). The equilibrated gas captures the isotopic imprints of water, and the equilibrated gas is then introduced in the mass spectrometer.

For measurement of $\delta^{18}O$ (δD) using Isotope Ratio Mass Spectrometer:

1. For $\delta^{18}O$ measurements, 12 ml exetainer (quartz vials) fitted with air tight-caps were flushed with 99.7 % He + 0.3% CO_2 mixture for 8 min using a specialised flushing needle with two openings, one of the opening forces mixture gas into the vial, and the air within is flushed out through the other hole.
2. For δD measurements, 12 ml exetainer fitted with air tight-caps is flushed with 98 % He + 2 % H_2 mixture for ~6 min using the similar needle.
3. As part of the established standardised laboratory procedure for oxygen and hydrogen isotope analyses using IRMS in Continuous Flow mode using Gas Bench in IWIN IRMS laboratory (Maurya et al., 2009), 300 μl of the sample was injected in the pre-flushed exetainer vials using the disposable syringe.
4. Then for $\delta^{18}O$ (δD) measurement, the vials were left for 16:00 hrs (01:30 hrs) without any catalyst (with platinum catalytic rods) for equilibrium with CO_2 (H_2) at 25 ºC in thermostated sample tray of Gas bench II. The laboratory temperature was also maintained at 25 ºC using air conditioners.
5. Equilibrated gas is then introduced to IRMS through GC column of Gas bench II for isotope measurement.

6. In order to ensure the quality, every batch of 80 samples included 21 secondary lab standards. The reproducibility of measurement was found to be better than 0.1‰ for $\delta^{18}O$ and 1‰ for δD.

(i) IRMS Calibration

As part of the IRMS calibration exercise under the IWIN National Programme, four secondary laboratory standards were prepared. Two of the secondary laboratory standards, (IWIN-1 and IWIN-3) were synthesised at IWIN-IRMS-PRL laboratory, to have comparatively depleted and enriched isotopic composition. This was achieved respectively by distillation and evaporation. The other two secondary standards (IWIN-2 and IWIN-4) were natural water samples of groundwater and river water, respectively. A set of these four secondary laboratory standards were sent to isotope hydrology laboratory of IAEA, Vienna for providing certified isotopic values which can be used to calibrate the IRMS under IWIN National Programme. The $\delta^{18}O$ and δD analyses were performed at IAEA using both gas source IRMS and Laser Analysers (both LGR and Picarro), and average values were provided to IWIN which were taken as the authentic certified value to be used as calibrated benchmark values with respect to which results of secondary laboratory standards are compared.

The IWIN IRMS laboratory at PRL was also independently calibrated with international standard reference materials (VSMOW2, GISP and SLAP2) obtained from IAEA. The secondary laboratory standards were analysed as samples in multiple aliquots in IWIN-IRMS-PRL laboratory using VSMOW2, GISP and SLAP2 as the laboratory reference.

The $\delta^{18}O$ and δD values of secondary laboratory standards obtained from IAEA and that of IWIN-IRMS at PRL are given in Table 3.2. The $\delta^{18}O$ and δD values of secondary laboratory standards obtained from IWIN-IRMS at PRL using the above protocols of isotope analyses are in very good agreement with IAEA certified values, within a narrow range of ± 0.06‰ for $\delta^{18}O$ and ± 0.52‰ for δD.

Table 3. 2: Details of IWIN IRMS calibration and secondary lab standards

IWIN Secondary Laboratory Standard	IAEA, Vienna			PRL, Ahmedabad		
		$\delta^{18}O$ (‰)	**δD (‰)**		**$\delta^{18}O$ (‰)**	**δD (‰)**
IWIN-1	**IWIN-1**	**-6.57**	**-40.5**	**IWIN-1**	**-6.54**	**-39.75**
Standard Deviation (± ‰)		0.07	0.71		0.07	0.91
No. of aliquots					10	7
IWIN-2	**IWIN-2**	**-11.09**	**-73.8**	**IWIN-2**	**-11.01**	**-73.96**
Standard Deviation (± ‰)		0.07	0.75		0.09	1.05
No. of aliquots					10	5
IWIN-3	**IWIN-3**	**15.1**	**36**	**IWIN-3**	**15.07**	**36.8**
Standard Deviation (± ‰)		0.09	0.64		0.1	1.49
No. of aliquots					10	7
IWIN-4	**IWIN-4**	**-2.29**	**-17.6**	**IWIN-4**	**-2.21**	**-17.25**
Standard Deviation (± ‰)		0.1	0.75		0.1	0.84
No. of aliquots					20	17
Sample Volume (μl)					300	300
Equil. Temp. (°C)					32	32
Equil. Duration (hh:min)					00:16	01:30
Name and isotopic composition of Secondary Lab. Standard(s) used as reference material for isotopic analyses				**Lab Std. for $\delta^{18}O$ and dD**	**$\delta^{18}O$ (‰)**	**δD (‰)**
				VSMOW	0.00 ± 0.03	0.01 ± 0.8
				SLAP	–55.37 ± 0.09	–425.46 ± 064
				GISP	–24.74± 0.08	–188.91 ± 0.78

3.4 Additional Data Used

In order to discern hydrometeorological processes governing precipitation using its isotopic composition, various meteorological data from ground-based, satellite-based observational, modeled, and reanalysis were used in this study.

(i) Model data

- **Air Trajectory Model**

To understand and track the history of air parcel reaching the concerned sampling station, 120 hrs back wind trajectories were generated using Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model downloaded from http://ready.arl.noaa.gov/HYSPLIT.php (Draxler and Rolph, 2003; Stein et al., 2015).

The Hybrid Single-Particle Lagrangian Integrated Trajectory Model (HYSPLIT) is a complete system for computing simple air parcel trajectories, as well as complex transport, dispersion, chemical transformation, and deposition simulations. This model is by far the most extensively used atmospheric transport and dispersion models by atmospheric scientists and hydrometeorologists. One of the most important applications of HYSPLIT is the back trajectory analysis to determine the origin of air masses, its progressive movement from the source region to receptor region and change in the most important constituents of air parcel – water vapour, and hence it is very important to understand vapour source dynamics. HYSPLIT has also been used in a variety of simulations describing the atmospheric transport, dispersion, and deposition of pollutants and hazardous materials. The HYSPLIT model has been used extensively in this study, especially to relate observed isotopic composition with vapour source variation and mixing.

Percentage contribution of various moisture sources in precipitation is computed using specific humidity provided by HYSPLIT. Variation in specific humidity (q) provided by HYSPLIT along the trajectory en-route is used as an indicator of moisture uplift through convective evaporation or moisture drop through precipitation (Sodemann et al., 2008b). The underlying assumption here is that the change in moisture over the course of time ($\Delta q/\Delta t$) is the result of net evaporation (E) or precipitation (P) only. Following steps were followed for the computation of moisture source's contribution:

1. Masks for ocean and land filters were created using polygon function in MATLAB software.
2. An algorithm checked if the trajectory is picking up moisture from the ocean or land by tracing specific humidity (q).
3. All addition or removal of moisture from the vapour parcel travelling along trajectory was computed at an interval of 1 hr. Change in q is attributed to moisture pickup or rainfall.
4. While causing rainfall, q from land or ocean are reduced in proportion of their content in the vapour parcel.
5. Step number 4 is repeated until the 0^{th} hour, and final fraction represents oceanic and land derived moisture contribution.

- **Vapour Isotope Model**

For estimation of evaporation from falling raindrops, the modeled $\delta^{18}O$ of vapour at various pressure levels was required. The Stable Water Isotope Intercomparison Group (SWING) phase II archives various isotope enabled General Circulation Models (GCM), we have used LMDZ4 model which is free and nudged by ECMWF [https://data.giss.nasa.gov/swing2/swing2_mirror/LMDZ4/nudged_vl77/; Risi et al. (2010b)]. Nudging is basically averaging of modelled output and reanalysis data at each time step during model integration, and it is used as input for the model in the next step. This technique helps in minimising the errors and derives the output closer to the observed values.

Details of various other satellite-based and reanalysis data used in different chapters are discussed in “Data Used” section of respective chapters.

Chapter 4

Mega-Scale Hydrometeorological Processes concerning India

Mechanisms of various precipitation forming Mega-Scale systems such as Southwest monsoon, Northeast monsoon, Nor'westers and western disturbances (WD), and their broad linkages with other synoptic processes and factors such as El-Nino Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), North Atlantic sea surface temperature and European ice cover, governing the inter-annual variability of Indian precipitation are well-known. However, it is still difficult to assign every particular observed spatio-temporal variation in rainfall over India to one of the various mega-scale (~1000 km) hydrometeorological processes. For example, it may not be easy to ascribe an observed rain event in northwestern Himalaya during late monsoon season to Indian monsoon or Western disturbances (WD). Similarly, it may be difficult to ascribe an observed rain event in Northeast India during the month of May to Nor'westers or Bay of Bengal (BOB) of southwest monsoon. It is, therefore, important to understand how imprints of these mega-scale hydrometeorological processes are manifested in the isotopic signatures in the precipitation across the large geographical expanse of India, and how these mega-scale signatures are superposed by mesoscale and micro-scale processes. With this overarching theme in mind, a total of 2,939 precipitation samples along with relevant meteorological data were collected from 41 stations spread across India. Based on oxygen and hydrogen isotopic analysis and interpretation of these precipitation samples and various meteorological parameters obtained from ground-based or reanalysis products following important inferences are drawn: (i) evaporation from the falling raindrops is one of the most dominant hydrometeorological processes in India; indicated by the lower slope of composite Indian meteoric water line (IMWL) compared to that of the Global Meteoric Water Line (GMWL); (ii) during the pre-monsoon season, majority of country's precipitation is derived from continentally recycled moisture. Signatures of Nor'westers in northeast India and WD in northern India are also observed during pre-monsoon in the isotopic composition of precipitation; (iii) during monsoon season, the isotopic effect of the continental gradient is observed in precipitation across India, wherein there is a progressive isotopic depletion while going away from the two marine vapour source regions, due to progressive rainout from marine vapour parcel during its inland journey; (iv) During the post-monsoon season, contrary to the expectation, isotopic signatures in precipitation of southern Indian peninsula, show a significant contribution of continentally recycled vapour, instead of the BOB vapour. Similarly, in most parts of India, the isotopic composition of precipitation indicates the varying degree of rainout from continentally derived moisture; (v) Significant amount effect is found only along the narrow belt in the Indo-Gangetic plains, whereas, temperature effect was not observed at majority of the stations, implying the complexity of hydrometeorological processes governing Indian precipitation; and (vi) With a view to quantitatively express and compare the relative importance of several meteorological parameters in governing the isotopic composition of precipitation in the Indian subcontinent, a novel correlation index (iH-index) has been defined based on the correlation between 16 important meteorological parameters and the amount weighted monthly precipitation isotopic composition. The $\delta^{18}O$ shows a significant correlation with seven of the sixteen selected parameters, while d-excess does not show any significant correlation. It indicates that mesoscale (~100km) and microscale (1 to 5 km) hydrometeorological processes play a dominant role superposed on the mega-scale processes, in governing regional precipitation.

4.1. Introduction

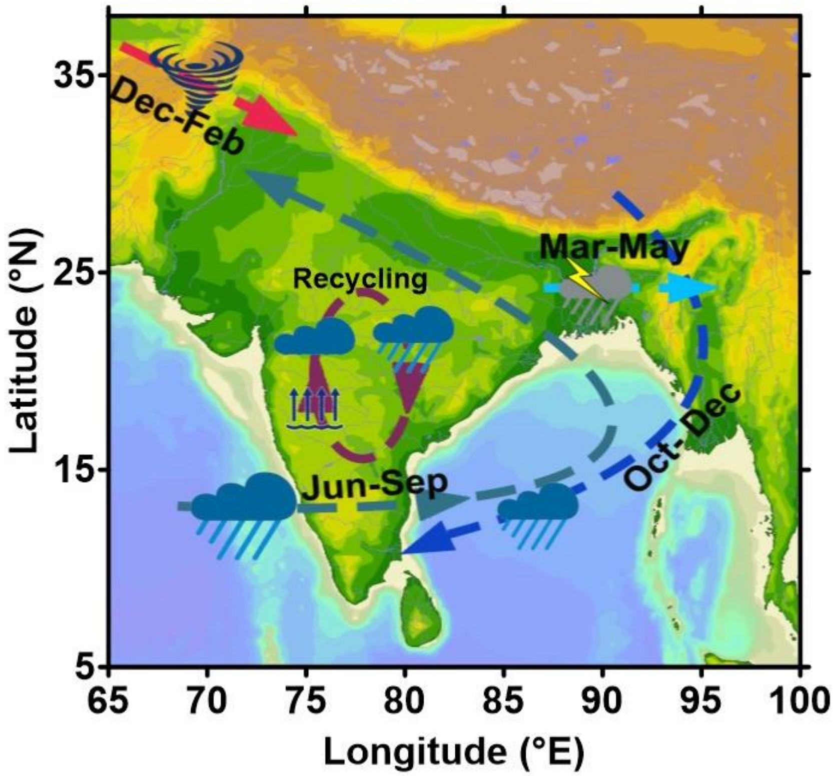

Figure 4.1: Illustration showing various precipitation forming systems in India and their respective time-frames

India in South Asia is a vast landmass (3,060,500 km^2), surrounded by marine water bodies from three sides [Arabian Sea (AS) in the west, Indian Ocean in the South, Bay of Bengal (BOB) in the east] and the lofty Himalayan mountains in the north, confining the moisture-laden monsoonal winds within India. About 21% (~642,700 km^2) of the total land area is under forest cover, and 60% (~1,830,000 km^2) of its total land area is cultivable area. It has 12 major and 46 medium river basins (Central Water Commission; http://www.cwc.gov.in). Agriculture is the primary source of income for 58% of the Indian population, and it contributes 16.1% of country's total GVA (http://www.Indiabudget.gov.in). Rainfall variability has a large impact on agricultural production and economy (Gadgil and Gadgil, 2006). India receives about 1090 mm of average annual precipitation (Parthasarathy and Yang, 1995). However, the spatial distribution of this water is highly uneven for instance, northeast India gets ~2000 mm of annual precipitation, whereas northwestern India receives only ~740 mm (Kumar et al., 1992).

Four major mega-scale systems responsible for delivering precipitation (Fig. 4.1) in different parts of the country during different times of year are: (i) southwest monsoonal winds during Jun-Sep bring rain almost to the entire country; (ii) northeast winds during retreating monsoon (Oct-Dec) bring rain to southern India; (iii) Western Disturbances (WD) bring rains to northern India during Dec-Feb; (iv) Nor'westers are the thunderstorms which bring significant rain in northeastern India during Mar-May. The above-mentioned mega-scale systems can be broadly distributed in three time-frames viz., pre-monsoon (Jan-May), southwest summer monsoon (Jun-Sep), post-monsoon/northeast monsoon/ (Oct-Dec). The known dynamics of all the precipitation fetching systems in these three time-frame are discussed briefly in the following:

(i) Pre-monsoon

During pre-monsoon (Jan-May), India receives about 120 mm precipitation, which accounts for ~11% of annual Indian precipitation.

In the northeast region, there is occurrence of heavy precipitation along with thunderstorms during Mar-Apr. It receives 25% (~500 mm) of its annual precipitation during pre-monsoon, especially in Mar-Apr. These heavy precipitations are associated with Nor'westers, also locally known as Kalbaisakhi. Nor'westers are atmospheric instabilities caused when warm and moist southerlies, flowing from BOB, are overrun by the upper-level cool and dry westerlies (Roy and Chatterji, 1929). It may cause deep convection leading strong moisture updraft from the local water bodies and heavy rains.

In the northwestern region, WD bring ~22% (~288 mm) of its annual precipitation during Dec-Feb. The WD are extratropical storms originating from the Mediterranean Sea or the western Atlantic Ocean, which are carried by the subtropical westerly jets and transported eastward towards India with an average velocity of 8º - 10º longitude per day (Dimri et al., 2015; Rao and Srinivasan, 1969a).

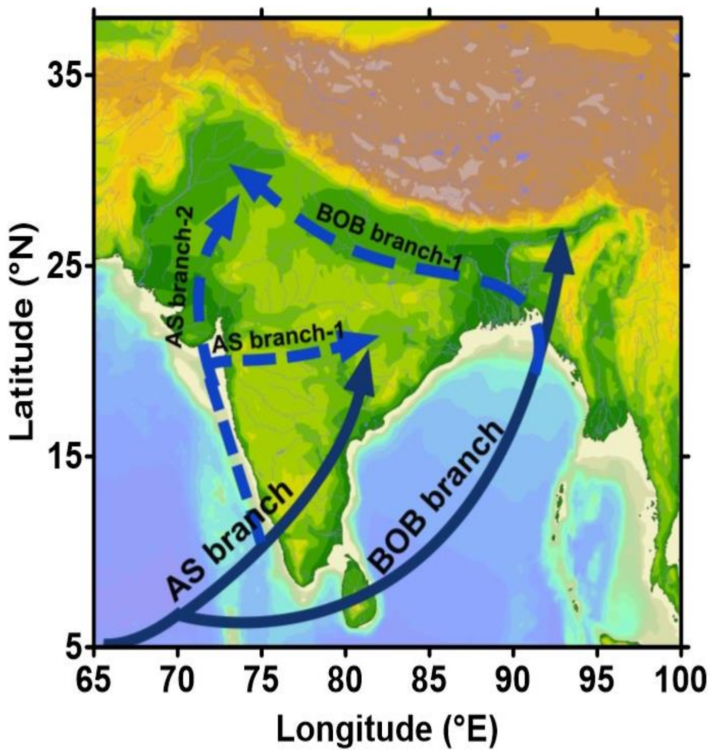

Figure 4. 2: Illustration showing bifurcation of monsoonal winds into the Arabian Sea and Bay of Bengal branches

(ii) Southwest Monsoon

The word monsoon, is originally derived from Arabic word *mausim* means season, and traditionally signifies the seasonal reversal of winds and the rainfall associated with it. There are several monsoon systems in the world with complete or partial reversal of winds. The Indian monsoon is one of the major monsoon systems of Asia, predominantly driven by the seasonal northward (Jun-Sep) and southward (Oct-Dec) migration of the inter-tropical convergence zone (ITCZ) (Gadgil, 2018; Privé and Plumb, 2007). The southwest monsoon contributes ~78% (~850.2 mm) of the annual average precipitation (Parthasarathy and Yang, 1995). During Summer the ITCZ migrates northward, and the moisture-laden northwest winds from the south of the equator cross the equator and enter the Northern hemisphere. According to Ferrel's law, these winds get deflected rightward in the northern hemisphere and flow over the Indian landmass from the southwest to northeast direction. During its journey, these winds bring moisture from the northern Indian Ocean and the AS. Due to the triangular shape of the Indian peninsula, the southwest winds bifurcate into AS and BOB branch as illustrated in Fig. 4.2. The AS branch further splits into three major branches, one crosses the Western Ghats and progresses northeastwards; the second one (AS branch-1) enters mainland India through Narmada, and Tapi basin and; the third branch (AS branch-2) enters through Gujarat coastline and travels parallel to the Aravali mountain range. The BOB branch travels northeastwards, and upon reaching the Himalayan foothills, it gets deflected to northwestward and travels rapidly through a quasi-stationary lower pressure trough, roughly over the Indo-Gangetic plains, towards the northwestern regions of India. The AS branch-2 and BOB branch-1 meet near Delhi in north India (Das, 2005).

(iii) Northeast monsoon / Post-monsoon

During winter months (Oct-Dec), the ITCZ migrates to the south of the equator and causes the gradual reversal of winds in the Indian subcontinent from southwest to northeast direction. This withdrawal of winds from the southwest and setting up of winds from the northeast is also referred to as retreating monsoon or post-monsoon in some literature (Das, 2005). The southern Indian peninsula receives ~30-60% and rest of the country receives ~11% (120 mm) of its annual precipitation through the retreating monsoon during October to December (Rajeevan et al., 2012b).

Apart from above-mentioned mechanisms, continental recycling also plays an important role in governing the spatio-temporal distribution of precipitation. Pathak et al. (2014) have reported high continental recycling during post-monsoon due to increased availability of soil moisture and vegetation. They found the highest (25%) contribution of continentally recycled moisture in precipitation in the northeast region. However, it is much less than the estimated global average recycled precipitation of ~60% (Van Der Ent and Tuinenburg, 2017).

Despite the recognition of various broad precipitation forming systems with other synoptic processes such as El-Nino Southern Oscillation (ENSO) (Kumar et al., 2007), Indian Ocean Dipole (IOD) (Ashok et al., 2001), North Atlantic sea surface temperature and European ice cover (Clemens et al., 1991), governing the inter-annual variability of Indian precipitation are well-known. However, there is still a considerable knowledge gap in the understanding of mega-scale (~1000 km) hydrometeorological processes, which decide the water availability in space and time. It is therefore important to understand ongoing hydrometeorological processes in more details using other non-conventional means such as the isotopic character of precipitation. Improved understanding about the relationship between the isotopic composition of rain and contemporary hydrometeorological processes is also important for interpreting various isotopic proxies of paleoclimate.

Stable isotopes of oxygen and hydrogen in rainwater can be used as tracers to understand the origin, movement and mixing of water molecules, in conjunction with meteorological parameters (reanalysis products and ground-based) to discern the above-mentioned hydrometeorological processes. Specific aspects which can be addressed using stable isotopes are moisture source identification, rainout history, recycling of vapour, evaporation from falling raindrops and cloud microphysical processes. (Breitenbach et al., 2010; Deshpande et al., 2013a; Deshpande and Gupta, 2012; Jeelani et al., 2017; Lekshmy et al., 2015; Midhun et al., 2018; Oza et al., 2020; Rahul et al., 2018; Saranya et al., 2018; Unnikrishnan Warrier and Praveen Babu, 2012).

The oxygen and hydrogen isotopic composition of 2,939 precipitation samples, collected from over 41 stations across the country under a National Programme on Isotope Fingerprinting of Waters of India (IWIN) (Deshpande and Gupta, 2008; Deshpande and Gupta, 2012) has been examined and interpreted in this study to discern the mega-scale hydrometeorological processes.

4.2. Climate

According to Koppen climatic classification, India can be divided into six different climatic zones (Montane, Humid subtropical, Tropical wet and dry, tropical wet, Semi-arid and Arid) based on seasonal precipitation and temperature patterns (Kottek et al., 2006). India Meteorological Department (IMD) has classified four seasons viz., pre-monsoon (March-May), Monsoon (June-September), post-monsoon (October-December) and winter (January-February) (Attri and Tyagi, 2010). The climate over India is largely influenced by monsoon variability (Wang, 2006). Country's annual average precipitation is about 1090 mm (Parthasarathy and Yang, 1995). The long-term (1901-2012) average annual temperature of the country is ~24ºC with a maximum average temperature of ~27ºC during Jun-Sep and minimum average temperatures of ~19ºC during Jan-Feb. For details of the climate record, reference is made to the India Meteorological Department website (https://mausam.imd.gov.in).

4.3. Data Used

In order to understand the mega-scale hydrometeorological processes concerning the spatio-temporal distribution of precipitation in India, a total of 3,310 daily accumulated (DP) or fortnightly accumulated (FP) precipitation samples were collected from 41 stations under the aegis of IWIN (Deshpande and Gupta, 2008; Deshpande and Gupta, 2012) national programme. For details of sample collection protocols and isotopic analysis, reference is made to Chapter 3.

Out of 3,310 samples, 371 (~11%) samples are not considered in this chapter because these atypical samples had extremely high or low d-excess, which are not related to synoptic rain forming system but instead, are caused by localised weather perturbations which may be accentuated by a variety of local anthropogenic or natural geographic factors (Oza et al., 2020). The aim of the present chapter is to understand the mega-scale hydrometeorological processes, and such extraordinary samples with imprints of localised perturbations may bias the overall results and general trend. However, in other chapters, where location-specific processes are being studied, these samples have been appropriately considered.

The summary of the isotope data used in this chapter is presented in table 4.1, and the details of the meteorological parameters used are listed in table 4.2.

4.4. Results and Discussions

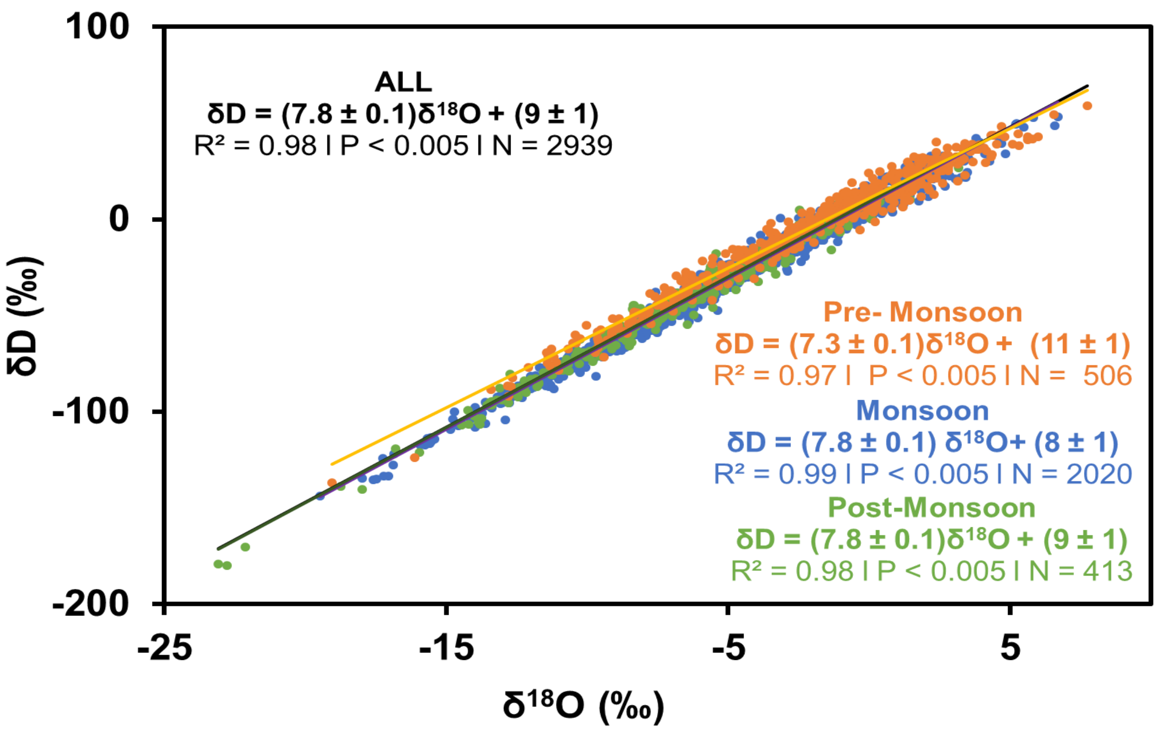

Figure 4. 3 Composite Indian meteoric water line (IMWL) along with seasonal meteoric lines

The composite δ^{18}O- δD regression line for all the 2939 precipitation samples collected from 41 stations spread across the country is shown in Fig. 4.3. From this point onwards this composite line will be referred to as Indian Meteoric Water Line (IMWL). It is noteworthy that this is the most comprehensive meteoric waterline for India, based on rainwater samples collected from 41 stations spread across different hydrometeorological or climatic zones. The earlier IMWL (Kumar et al., 2010) was defined without samples from warm and semi-arid western India where maximum evaporation from falling raindrops is expected, and also it was based on a fewer number of samples. The slope and intercept of IMWL, [$\delta D = (7.8\pm0.1)\ \delta^{18}O + (9\pm1)$; $R^2 = 0.98$; $P < 0.005$; $N = 2939$], is lower than that of the Global Meteoric Water Line (GMWL) [$\delta D = (8.17\pm0.07)\ \delta^{18}O + (11.27\pm0)$; Rozanski et al. (1993)], and also lower than that reported earlier by Kumar et al. (2010) [$\delta D = (7.93\pm0.06)\ \delta^{18}O + (9.94\pm0.51)$; $R^2 = 0.98$; $N = 272$]. The slope less than that of GMWL suggests the signature of secondary evaporation from the falling raindrops (Dansgaard, 1964; Stewart, 1975) as one of the important processes governing the isotopic composition of precipitation in India.

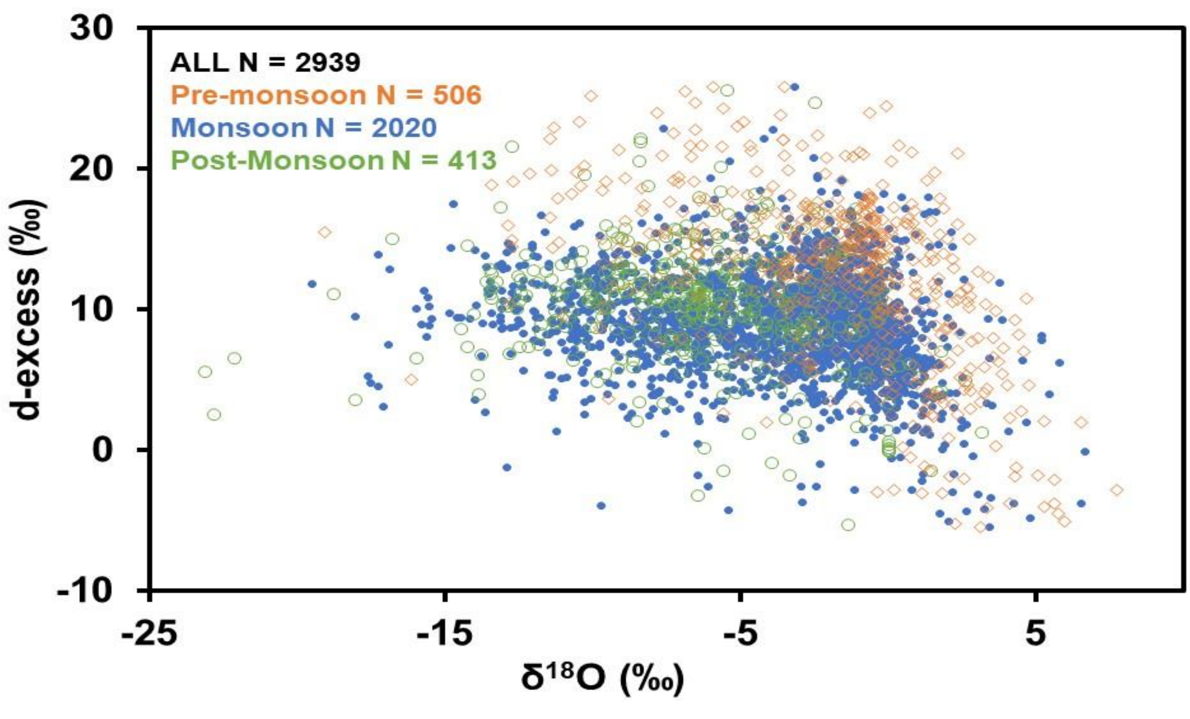

Figure 4. 4 $\delta^{18}O$ – d-excess scatter plot for all Indian precipitation samples, with seasonal identifiers

Table 4. 1. Summary of precipitation isotope data of the individual stations

			Amount weighted average			Minimum			Maximum			$\delta^{18}O$-δD regression line			
Station ID	**Station**	**N**	**$\delta^{18}O$**	**δD**	**d**	**$\delta^{18}O$**	**δD**	**d**	**$\delta^{18}O$**	**δD**	**d**	**Slope**	**Inter cept**	**R^2**	**P value**
1	Srinagar	233	-6.7	-40	14	-19.1	-140	-4	6.6	53	26	7.8±0.1	13±1	0.97	<0.005
2	Jammu	79	-3.9	-20	11	-12.9	-90	-5	7.8	59	26	7.4±0.1	8±1	0.98	<0.005
3	Kangra	50	-7.2	-48	9	-14.6	-108	-1	4.1	40	26	8.1±0.2	11±1	0.98	<0.005
4	Ludhiana	23	-6.1	-39	10	-12.6	-92	1	2.5	28	20	8.0±0.2	11±1	0.99	<0.005
5	Patiala	50	-7.3	-48	10	-14.5	-106	-4	6.6	54	24	7.9±0.1	9±1	0.98	<0.005
6	Ranichauri	51	-10.2	-69	12	-19.5	-144	4	2.7	33	17	7.9±0.1	11±1	0.99	<0.005
7	Hisar	40	-6.8	-46	8	-14.8	-106	-5	5.6	41	23	7.5±0.2	4±1	0.98	<0.005
8	Delhi	52	-6.2	-41	8	-15.7	-114	-3	4.5	39	16	7.6±0.1	5±1	0.98	<0.005
9	Bikaner	15	-5.7	-39	6	-9.5	-72	0	0.7	14	13	8.3±0.3	7±2	0.98	<0.005
10	Dibrugarh	56	-7.6	-49	12	-22.1	-170	5	3.1	37	18	8.4±0.1	14±1	0.99	<0.005
11	Lukhnow	38	-7.6	-52	9	-12.2	-90	-5	6.0	43	19	7.7±0.1	7±1	0.99	<0.005
12	Faizabad	21	-6.9	-45	9	-12.5	-88	6	0.2	11	12	8.1±0.1	10±1	0.99	<0.005
13	Jorhat	268	-6.7	-43	11	-23.1	-180	2	4.6	44	18	8.3±0.1	13±1	0.99	<0.005
14	Kanpur	13	-9.4	-66	10	-13.4	-95	7	-2.9	-11	13	7.7±0.2	7±2	0.99	<0.005
15	Jodhpur	32	-5.5	-37	7	-11.4	-79	-4	4.3	33	15	7.4±0.2	3±1	0.99	<0.005
16	Udaipur	36	-6.0	-40	8	-13.4	-95	-3	5.6	43	16	7.4±0.2	5±1	0.98	<0.005
17	Nadia	18	-2.9	-15	8	-11.3	-80	2	3.3	32	16	7.6±0.2	8±1	0.99	<0.005
18	Ranchi	31	-8.2	-55	11	-14.7	-101	2	3.4	34	17	7.8±0.1	8±1	0.99	<0.005
19	Bhopal	41	-6.4	-41	10	-14.2	-99	-5	5.8	42	21	7.4±0.2	7±1	0.98	<0.005
20	Bhuj	39	-5.2	-31	10	-10.7	-79	0	2.1	17	18	7.2±0.2	5±1	0.97	<0.005
21	Jabalpur	85	-6.8	-44	11	-13.5	-97	-2	1.3	17	19	8.0±0.1	10±1	0.99	<0.005
22	Ahmedabad	341	-4.1	-24	9	-13.2	-92	-6	3.7	33	23	7.7±0.1	8±0.3	0.98	<0.005
23	Kolkata	35	-6.2	-40	9	-13.0	-94	4	2.5	28	15	8.0±0.1	9±1	0.99	<0.005
24	Anand	64	-4.3	-26	8	-15.4	-114	4	0.5	11	16	8.0±0.1	9±1	0.99	<0.005
25	Raipur	39	-7.2	-48	10	-15.9	-121	3	3.3	30	18	7.7±0.1	8±1	0.99	<0.005
26	Akola	7	-4.4	-26	9	-7.2	-50	4	2.6	25	14	7.7±0.5	8±2	0.98	<0.005
27	Bhubaneswar	40	-5.6	-36	9	-11.0	-79	3	3.2	29	13	7.9±0.1	8±1	0.99	<0.005
28	Aurangabad	43	-3.9	-22	10	-14.5	-107	3	3.5	33	16	7.7±0.1	8±1	0.99	<0.005
29	Parbhani	35	-4.5	-28	9	-12.4	-88	4	4.1	39	17	7.6±0.1	7±1	0.99	<0.005
30	Mumbai	35	-2.5	-11	9	-9.8	-74	2	1.2	12	15	7.9±0.1	9±1	0.98	<0.005
31	Dapoli	276	-2.7	-11	10	-9.8	-66	3	1.5	18	17	7.8±0.1	10±1	0.97	<0.005
32	Visakhapatnam	48	-5.3	-32	10	-9.5	-67	3	1.8	20	17	7.4±0.2	7±1	0.98	<0.005
33	Solapur	50	-3.5	-19	9	-9.7	-71	3	2.8	28	13	7.5±0.1	7±1	0.99	<0.005
34	Hyderabad	173	-4.7	-28	10	-13.4	-98	3	2.5	25	18	7.8±0.1	9±1	0.99	<0.005
35	Goa	222	-1.7	-6	8	-13.8	-107	2	1.9	18	18	7.7±0.1	8±1	0.96	<0.005
36	Chennai	23	-6.2	-38	12	-8.8	-59	6	-1.9	-2	16	7.7±0.3	10±2	0.97	<0.005
37	Bangalore	58	-3.7	-18	12	-14.0	-103	4	3.4	33	16	7.8±0.1	10±1	0.99	<0.005
38	Mangalore	51	-2.6	-9	12	-11.9	-83	8	2.8	33	18	7.8±0.1	12±1	0.99	<0.005
39	Thrissur	40	-2.6	-14	7	-7.6	-50	2	0.2	4	14	6.8±0.2	4±1	0.98	<0.005
40	Kovilpatti	19	-8.2	-54	11	-13.6	-97	3	0.6	13	16	7.6±0.2	8±1	0.99	<0.005
41	Thiruvananthapuram	69	-3.7	-17	12	-13.5	-97	6	0.3	13	18	8.0±0.1	13±1	0.99	<0.005

Table 4. 2. List of meteorological parameters used and their descriptions

Parameter	Abbreviation	Unit	Description
Seasonality	SN	months	For the present study, a seasons means either pre-monsoon (Jan-May), monsoon (Jun-Sep) and post-monsoon (Oct-Dec)
Surface T	ST	ºC	It was recorded at stations during the collection of precipitation sample
Surface RH	Sh	%	It was recorded at stations during the collection of precipitation sample
Rainfall	Rf	cm	It was recorded at stations during the collection of precipitation sample
*Cloud Liquid Water Content	CLWC	kg kg^{-1}	It is mass of cloud liquid water droplet per kg of moist air, the altitude of maximum CLWC at the individual station can be considered as the altitude of condensation
*Pressure	CP	hPa	Pressure height at which the CLWC is maximum
*Temperature	CT	ºC	The temperature at the altitude of CLWC maximum
*Column Specific humidity	q	kg kg^{-1}	It is mass of water vapour per kg of moist air, the average of q between the altitude of CLWC maximum and ground was used
*Wind Speed	CWS	m s^{-1}	It is computed from U and V wind components at the height of maximum CLWC
*Vertical Wind Velocity	CVV	Pa s^{-1}	It is the upward or downward speed of air parcel; It is obtained at 500 hPa, where -ve speed indicates convection
*Cloud Base height	CH	m	It is the height of the lowest base of cloud from the ground
*Convective Rain Rate	CRR	kg m^{-2} s^{-1}	It is the rate of precipitation generated from the convective type of clouds
*Evaporation	EV	m	It is the accumulated amount of evaporated water
*Surface net Solar Radiation	SSR	J m^{-2}	It is the amount of solar radiation received at ground
*Top net Thermal Radiation	TTR	J m^{-2}	It is thermal radiation emitted out from the top of the atmosphere; It is negative of OLR; Thus, indicative of convection
*Total Cloud Cover	TCC	(0 - 1)	It is the proportion of grid covered by clouds; It can range between 0 and 1

* Meteorological parameters obtained from ERA5 reanalysis data at the spatial resolution of 0.25º latitude x 0.25º longitude over the box 1º latitude x 1º longitude with the station at the centre.

Along with the IMWL, Seasonal $\delta^{18}O$ - δD regression lines for samples collected from all the stations are also plotted in Fig. 4.3. The slope and intercept for monsoon [$\delta D = (7.8\pm0.1)\ \delta^{18}O + (8\pm1)$; $R^2 = 0.99$; $P < 0.005$; N = 2020] and post-monsoon [$\delta D = (7.8\pm0.1)\ \delta^{18}O + (9\pm1)$; $R^2 = 0.98$; $P < 0.005$; N = 413] are similar to that of IMWL, whereas the slope of pre-monsoon [$\delta D = (7.3\pm0.1)\ \delta^{18}O + (11\pm1)$; $R^2 = 0.97$; $P < 0.005$; N = 506] is significantly lower compared to that of GMWL as well as IMWL, which indicates maximum secondary evaporation from the falling raindrops, compared to the other two seasons. This is due to the fact that during the pre-monsoon period, most parts of the country experience high temperature and lower humidity, and also the precipitation amount is less compared to the other two seasons. All these weather conditions facilitate evaporation from falling raindrops (Liu et al., 2008; Meng and Liu, 2010; Peng et al., 2007).

The $\delta^{18}O$ - d-excess relation for all the 2939 samples is plotted in Fig 4.4. with seasonal identifiers. During pre-monsoon $\delta^{18}O$ and d-excess ranges between -19.1‰ to 7.8‰, and 5‰ to 26‰, respectively. A slight trend of decreasing d-excess with increasing $\delta^{18}O$ in pre-monsoon $\delta^{18}O$ – d-excess is observed. The high values of d-excess (> 12‰) are associated with depleted $\delta^{18}O$ (< 2‰), indicating the significant contribution of continentally recycled moisture in precipitation (Froehlich et al., 2002). On the other hand, the lower values of d-excess (< 12‰) are associated with enriched $\delta^{18}O$ (> 2‰), indicating significant secondary evaporation from the falling raindrops (Dansgaard, 1964). During monsoon and post-monsoon $\delta^{18}O$ – d-excess plot is a scatter without any significant trend. The $\delta^{18}O$ and d-excess ranges between -19.1‰ to 6.7‰, and -6‰ to 26‰, respectively during monsoon, whereas during post-monsoon, the $\delta^{18}O$ and d-excess ranges between -23.1‰ to 3.2‰, and -5‰ to 26‰, respectively.

In Fig. 4.5 (a) the bars represent the slopes and intercepts of the $\delta^{18}O$- δD regression lines, which will be referred to as Local Meteoric Water Line (LMWL) from this point onwards, for all 41 individual stations. The regression line slopes of the majority (31) of LMWLs is lower than that of the GMWL, indicating evaporation from the falling raindrops is one of the dominant processes across the country. Whereas the slopes LMWLs of remaining ten stations is similar to (~8.1) or slightly higher than that of GMWL. At all these ten stations, except Bikaner (Station ID: 9) the RH during rainy days remains high (>70%), either due to availability of abundant surface water, proximity to a marine water body, or a large number of consecutive rainy days, which retards the secondary evaporation from the falling raindrops. Therefore, the slope of LMWLs remains largely unaltered (Dansgaard, 1964; Stewart, 1975). The higher slope may be attributed to equilibrium condensation happening at relatively lower temperatures (Majoube, 1971). The higher intercept values (>11) at Jorhat, Dibrugarh and Thiruvananthapuram (Station ID: 10, 13 and 41) indicate the substantial contribution of continentally derived moisture in precipitation (Froehlich et al., 2002). Bikaner is located in the arid region of Rajasthan, where significant evaporation from the falling raindrops is anticipated but, contrary to the expectation, the LMWL slope value for Bikaner is 8.3. Since this slope value is incompatible with the ground facts of weather condition at Bikaner, and also it is based on a limited number of samples (N=15), no inference has been drawn from the slope value.

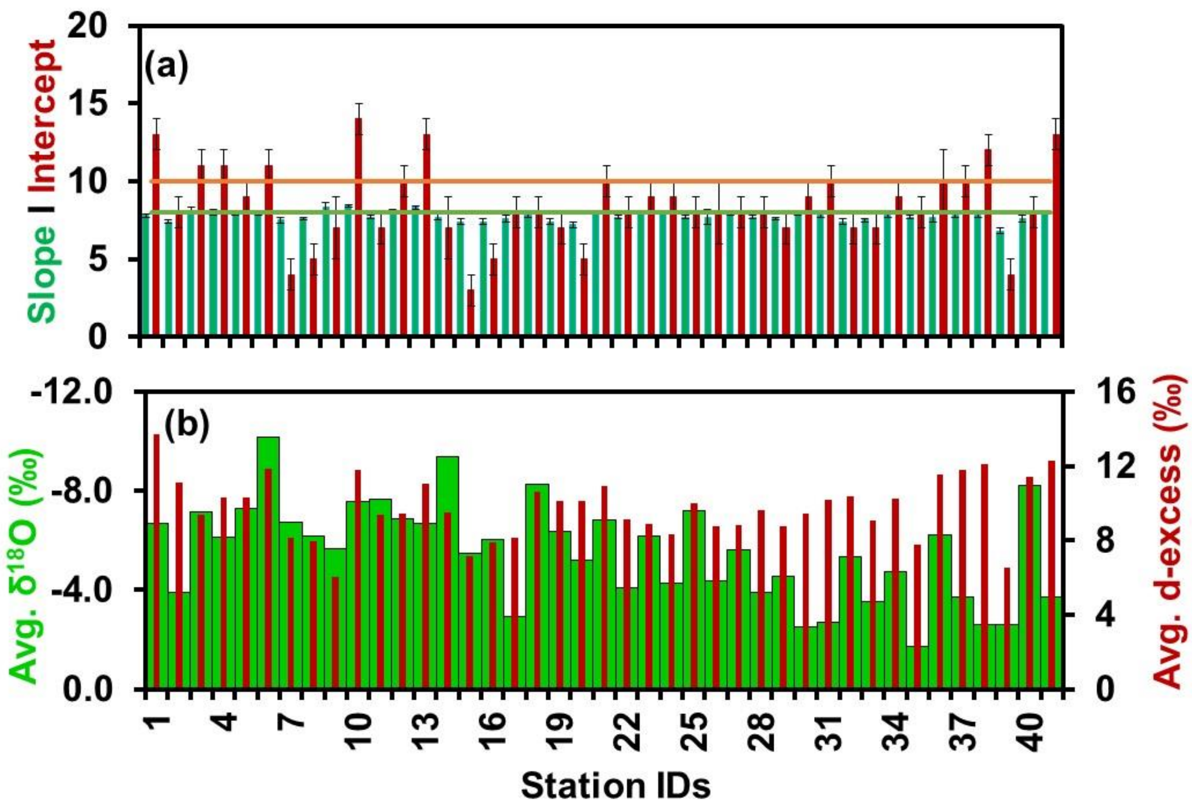

Figure 4. 5 (a) Bar chart showing slope and intercept values for local meteoric water lines of (LMWL) of individual stations. The green and orange horizontal lines indicate the slope and intercept value of the global meteoric water line (GMWL); (b) bar chart showing amount weighted average $\delta^{18}O$ and d-excess values of individual stations. On the x-axis station IDs are in sequence from left to right.

The amount weighted average $\delta^{18}O$ and d-excess for all the 2939 samples were found to be -5.1‰ and 10‰, respectively. The amount weighted average $\delta^{18}O$ and d-excess for individual stations are plotted in Fig 4.5 (b).

The amount weighted average values of $\delta^{18}O$ and d-excess for individual stations provides an important handle for isotopically characterising the rainfall and observing its geographical variation. However, the underlying hydrometeorological processes are governed by a multitude of meteorological parameters and geographical factors which need to be examined for inferring the processes. Nevertheless, for preliminary understanding, following four inferences can be drawn based on the four different scenarios of the combination of $\delta^{18}O$ and d-excess values, as reported in the literature. These four scenarios are: (i) high values of average d-excess (>10‰) associated with low values of average $\delta^{18}O$ (<-5.1‰) can be attributed to precipitation generated from continentally derived moisture (Froehlich et al., 2002) or that formed under lower ambient RH (Gat et al., 2011), which has undergone significant rainout (Gonfiantini et al., 2001); (ii) high values of average d-excess (>10‰) associated with relatively enriched average $\delta^{18}O$ (>-5.1‰) values can suggest precipitation from continentally generated moisture, which has not undergone significant rainout (Froehlich et al., 2002; Gonfiantini et al., 2001); (iii) low values of average d-excess (<10‰) associated with relatively enriched average $\delta^{18}O$ (>-5.1‰) d values indicate significant evaporation from falling raindrops (Dansgaard, 1964; Stewart, 1975); (iv) low values of average d-excess (<10‰) associated with relatively depleted average $\delta^{18}O$ (<-5.1‰) values may suggest precipitation from marine moisture source with significant rainout (Gonfiantini et al., 2001).

Spatial distributions of amount weighted $\delta^{18}O$ and d-excess in precipitation across the country during pre-monsoon, monsoon and post-monsoon seasons are shown in Fig. 4.6, and Fig. 4.7, respectively. Major observations and the inferences drawn from these spatial distributions are discussed below. It should, however, be noted that some of the inferences drawn for mega-scale processes in the following may only be indicative in nature, and not necessarily confirmatory and should be treated accordingly. More conclusive inferences are drawn for mesoscale and micro-scale processes, not just based on spatial distribution but based on more quantitative methods, in the subsequent Chapters.

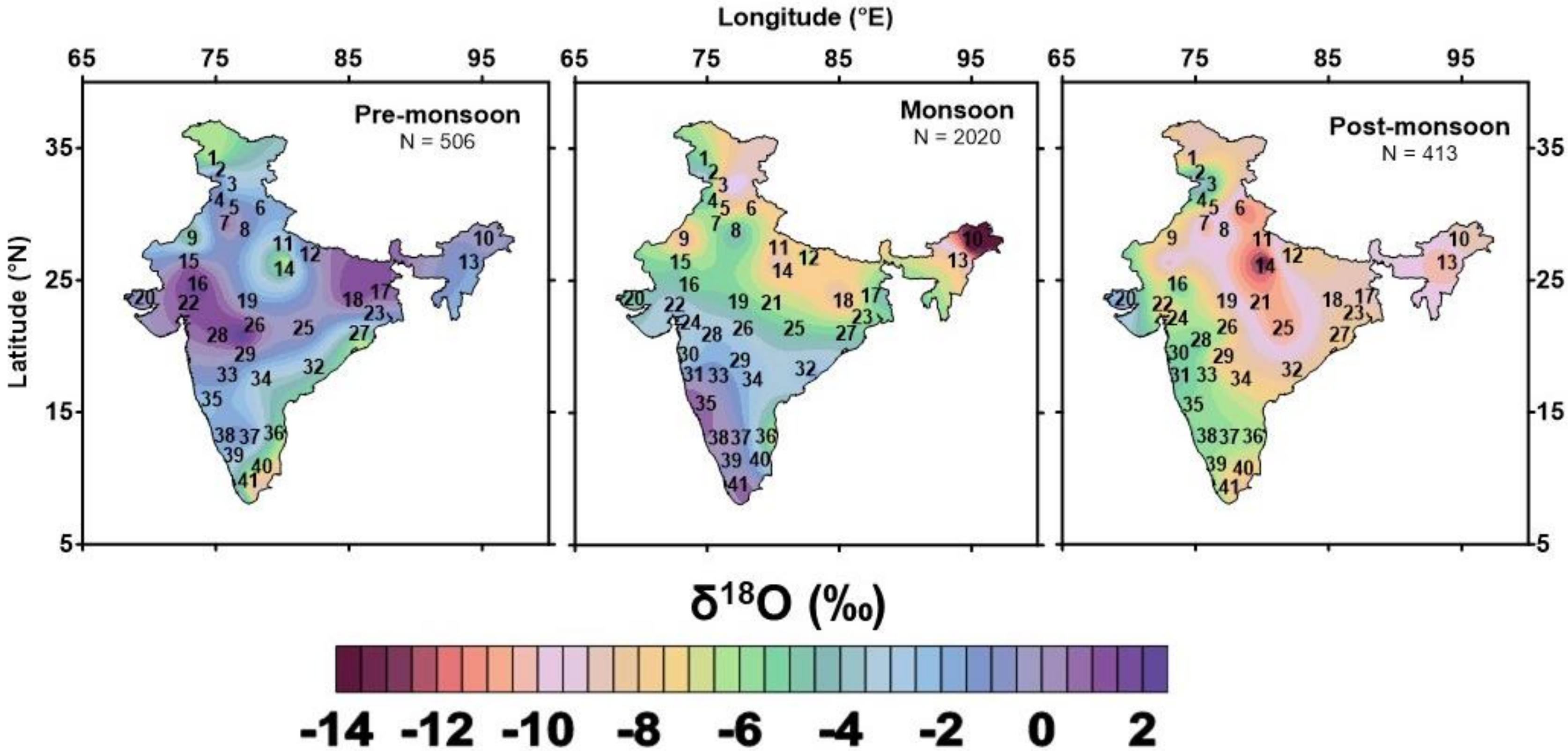

Figure 4. 6 Seasonal contour maps showing the spatial variation of amount weighted precipitation δ^{18}O across the country. The labels represent station IDs

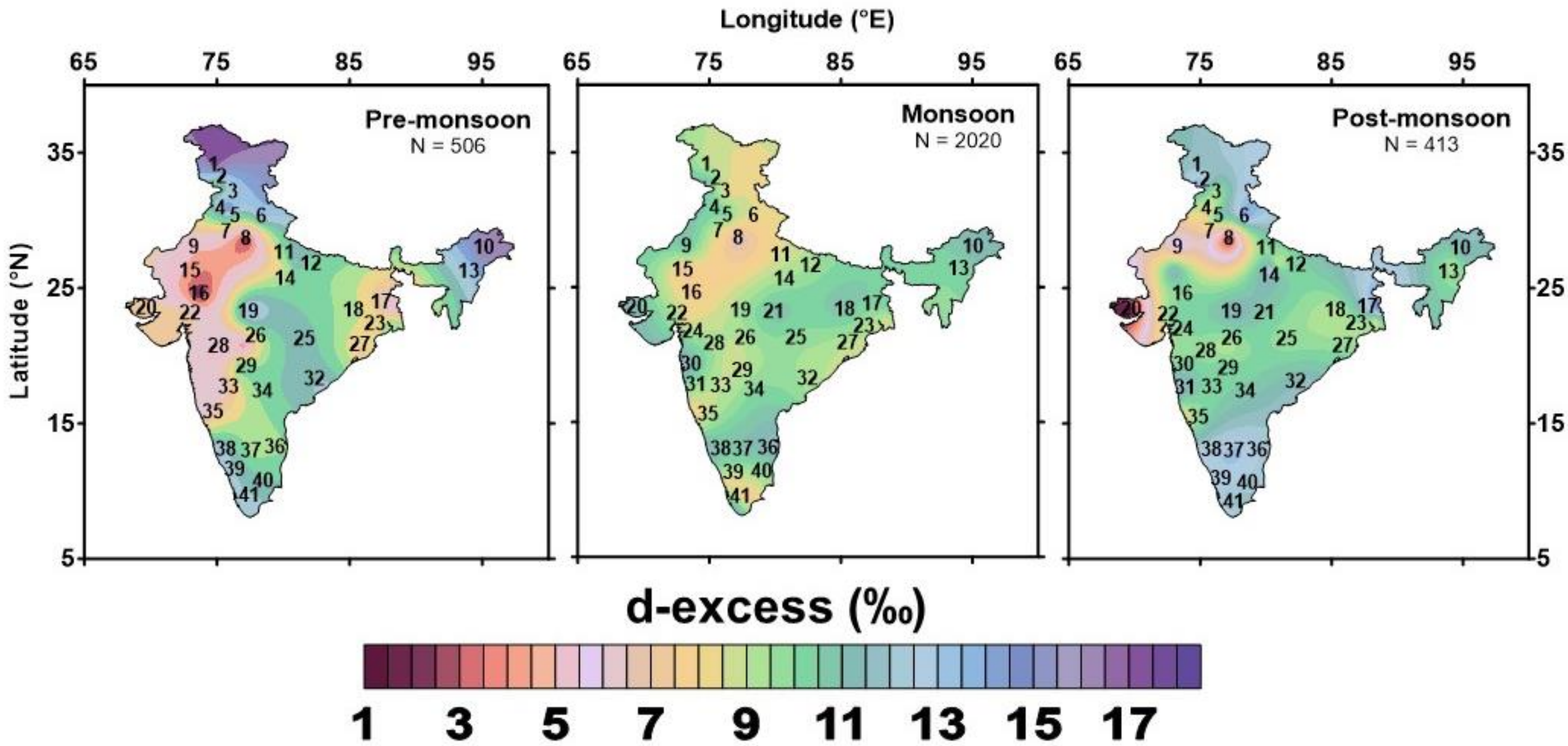

Figure 4. 7 Seasonal contour maps showing the spatial variation of amount weighted precipitation d-excess across the country. The labels represent station IDs

Major observations and inferences derived from Fig 4.6 and Fig. 4.7 are:

(i) Pre-monsoon (Jan-May)

- It can be observed from the pre-monsoon spatial distribution maps that the majority of locations receives isotopically enriched (δ^{18}O >-2‰) precipitation with d-excess in the range of 9‰ to 11‰, indicating the contribution of continentally derived moisture, from evaporatively enriched (in δ^{18}O) surface waters and soil moisture, in the precipitation (Froehlich et al., 2002).

- In some parts of western India, δ^{18}O values in precipitation are exceptionally enriched (>0‰), with very low d-excess values (<5‰) indicating significant evaporation from the falling raindrops (Stewart, 1975). This can be ascribed to arid to the semi-arid type of climate in western India, and very scanty precipitation during pre-monsoon season.

- Unlike western India, in northeast India, enriched δ^{18}O values (> -2‰) in precipitation are associated with high d-excess values (~11‰ to 14‰), indicating the contribution of continentally recycled moisture in precipitation, this may be attributed to the high availability of surface waters in this region and Nor'westers, which causes deep convection, thunderstorms and heavy precipitation during pre-monsoon season.

- In northwest India (Jammu-Kashmir) depleted δ^{18}O (< -4‰) in precipitation is associated with very high d-excess (>13‰). It may be attributed to WD, which brings Mediterranean moisture, formed under low RH conditions, to the regions of northern India (Jeelani and Deshpande, 2017).

- Depleted δ^{18}O (< -4‰) in precipitation during pre-monsoon is also found along the southeastern coastal region but, with d-excess in the range of 10‰ to 12‰. It may be attributed to continentally derived precipitation from the surface waters and soil moisture replenished by the retreating monsoon (Oct-Dec).

- The pre-monsoon precipitation isotopic composition of Bikaner and Kanpur (station IDs: 9 and 14), is significantly distinct compared to their surrounding region. At Bikaner, the amount weighted average pre-monsoon $\delta^{18}O$, and d-excess in precipitation are ~-6‰ and ~5‰, respectively. In comparison, at Kanpur, $\delta^{18}O$, and d-excess in precipitation are ~-7‰ and ~9‰ respectively. It may indicate precipitation from the vapour parcel with varying degree of rainout history at both the stations but, no conclusive inference can be drawn because only two rain events at Bikaner and three rain events at Kanpur were observed during pre-monsoon.

(i) Monsoon (Jun-Sep)

- The continental effect in isotopes in precipitation is observed as the winds from the AS branch of southwest monsoon enter peninsular India after crossing the Western Ghats, and traverse from southwest to northeast across India causing a trend of gradual isotopic depletion (from 1‰ to -6‰). The d-excess, however, exhibits no such pattern from southwest to northeast direction, and it ranges between 9‰ to 11‰. It indicates that as the southwest winds carrying moisture from the AS rains out progressively while traversing in the northeast direction, according to the Rayleigh model the isotopic composition of residual vapour and the resultant precipitation gradually depletes (Gonfiantini et al., 2001). However, the absence of the corresponding trend in d excess also suggests that there could be a variable admixture of recycled moisture.
- At Goa, Thrissur and Kovilpatti (station ID: 35, 39 and 40), the average $\delta^{18}O$ values during monsoon season are found to be -1.2‰, -2.7‰ and -1.4‰, respectively with d-excess of ~8‰ at all the three stations. The enriched $\delta^{18}O$ and low d-excess indicate evaporation from the falling raindrops (Stewart, 1975). Kovilpatti lies in the rain shadow zone and receives less precipitation during the monsoon period, thus due to scanty rainfall evaporation from the falling raindrops is possible. However, it cannot be inferred conclusively due to less number of samples (N = 3). On the other hand, Goa and Thrissur are coastal regions lying on the windward side of Western Ghats and receives significant precipitation during monsoon; both Goa and Thrissur lie in front of Chorla Ghat and Palghat mountain gaps, respectively.

Ramachandran (1972) have reported increased wind speeds in the mountain gaps, thus probably the increased wind speeds facilitate the evaporation from the falling raindrops (Stewart, 1975). In spite of copious rains in the Western Ghats, no significant isotopic depletion is observed at Kovilpatti on the leeward side of Western Ghats, compared to Goa and Thrissur on the windward side. This indicates that despite huge rainfall in the Western Ghats, the proportion of moisture it drains from the original marine vapour parcel is not significant enough to cause isotopic depletion on the leeward side.

- The moisture-laden BOB branch travels northeastwards and crosses the orographic barrier of Garo-Khasi-Jaintia hills and causes heavy precipitation in the windward side. Thus, Meghalaya (on the windward side) receives copious precipitation (~12,000 mm) and significantly rained out vapour parcel enters the Assam valley. The depleted $\delta^{18}O$ (<-8‰) may indicate the precipitation from significantly rained out vapour parcel. However, the corresponding decrease in d-excess values are not observed; on the contrary, the d-excess values are quite high (~11‰). Thus, depleted $\delta^{18}O$ and high d-excess indicate precipitation from isotopically depleted continental moisture, which may be attributed to the availability of surface waters replenished by floods in Brahmaputra River (Chowdhury and Sato, 1996; Dhar and Nandargi, 2000).

- The BOB branch deflected by the Himalayas and drawn towards the quasi-stationary low-pressure monsoon trough, travels toward northwest India and provides precipitation in the Indo-Gangetic plains of north India. The depleted $\delta^{18}O$ (<-7‰) in precipitation with d-excess of ~9‰ towards northwest indicate isotopic depletion due to progressive rainout (Gonfiantini et al., 2001).

- A trend of isotopic depletion in precipitation is observed along the path of AS Branch from Gujarat till Delhi (station ID: 8). The $\delta^{18}O$ values vary along the path from ~-2‰ to ~-6‰, and d-excess values range from 11‰ to 7‰. It indicates Rayleigh type isotopic depletion due to progressive rainout (Gonfiantini et al., 2001). This trend can be attributed to the AS branch which enters through Gujarat coast and travels towards northwestern India and rains out progressively along its path. It passes over the arid and dry region. Thus, the possibility of picking any continental moisture is unlikely. This branch further meets with the BOB branch near Delhi, and together with BOB branch, it travels further north toward Punjab, Haryana, Jammu and Kashmir.

- The $\delta^{18}O$ and d-excess of precipitation in the north of Delhi range between ~-6‰ to ~-10‰, and ~8‰ to ~10‰, respectively, indicating isotopic depletion related to progressive rainout (Gonfiantini et al., 2001). However, comparatively enriched $\delta^{18}O$ (-4.3‰) and high d-excess (11‰) in the precipitation of Jammu (station ID: 2) suggest the significant contribution of continentally derived moisture in precipitation (Froehlich et al., 2002).

(ii) Post-monsoon (Oct-Dec)

- The depleted $\delta^{18}O$ (<-7‰) in precipitation at the majority of locations is observed. However, this depleted $\delta^{18}O$ in precipitation is associated with both low (<10‰) and high (>10‰) values of d-excess. Low values of d-excess along with depleted ^{18}O in precipitation can be attributed to the precipitation from significantly rained out vapour parcel (Deshpande et al., 2010). Whereas, the high values of d-excess along with depleted $\delta^{18}O$ can be attributed to precipitation from isotopically depleted continentally recycled moisture (Froehlich et al., 2002). During monsoon, the surface waters and soil moisture get replenished by the monsoonal precipitation ($\delta^{18}O$: ~-4‰ to ~-8‰). The significant contribution from the evapotranspired vapour generated from these surface waters and soil moisture can cause the observed depleted value of $\delta^{18}O$ and high values of d-excess. Also depending on the initial quantity of vapour mass varying amount of rainout can cause varying degree of decrease in d-excess values of precipitation, according to the Rayleigh model of rainout (Gonfiantini et al., 2001). Thus, the observed isotopic composition of rain during post-monsoon is caused by the contribution of continentally derived moisture in the precipitation.
- In the southern portion of the Indian peninsula, the significantly high values of d-excess (~13‰) and depleted $\delta^{18}O$ ranging from -6‰ to -8‰ indicate the

significant contribution of continentally recycled moisture in precipitation during post-monsoon. This observation and inference are in agreement with that of Warrier et al. (2010).

- The exceptionally low values of d-excess (<5‰) in the rains of western parts of Gujarat and Rajasthan may be attributed to the significant evaporation from the falling raindrops, as these regions are dry and arid, and also precipitation in these regions during post-monsoon is very scanty.

- At the northern stations of Srinagar, Jammu and Kangra (Station ID: 1, 2 and 3) the amount weighted $\delta^{18}O$ for post-monsoon precipitation are -8.8‰, -3.1‰ and -4.2‰, and the corresponding amount weighted d-excess values are 12‰, 14‰ and 9‰. The depleted $\delta^{18}O$ with the high value of d-excess in Srinagar's rain can be attributed to the WD (Jeelani and Deshpande, 2017), which usually starts from December. In contrast, high d-excess and enriched $\delta^{18}O$ in post-monsoon rain at Jammu indicate the significant contribution from continentally recycled moisture (Froehlich et al., 2002). The low d-excess associated with enriched $\delta^{18}O$ in the precipitation of Kangra may be attributed to the evaporation from the falling raindrops. The climatological (1990-2001) RH at Kangra during post-monsoon was found to be ~65% (http://www.indiawaterportal.org). Thus, low RH may facilitate evaporation from the falling raindrops.

Amount effect in isotopes is a negative correlation observed between the amount of monthly averaged rainfall and isotopic composition of precipitation. It was first described by Dansgaard (1964); it has a great significance in the paleoclimatic studies. The oxygen isotopes in various paleoclimatic archives such as tree rings, speleothems and ice core are used as a proxy for reconstructing the past rainfall. Various researchers in India have used amount effect to reconstruct past rainfall based on oxygen isotopes in different paleoclimatic archives (Ramesh et al., 1986; Ramesh and Yadava, 2005; Sukhija et al., 1998; Yadav et al., 2004).

However, from the contemporary precipitation data obtained from 41 stations spread across the country, it can be observed from Fig. 4.8 that in the majority of the stations amount effect is not very significant. It may be attributed to complex interplay of various hydrometeorological processes, such as source variation, cloud dynamics and mixing of vapour masses which can vary over a short space-time scales under favourable conditions (Aggarwal et al., 2012; Aggarwal et al., 2016; Lee et al., 2012; Lekshmy et al., 2015; Lekshmy et al., 2014).

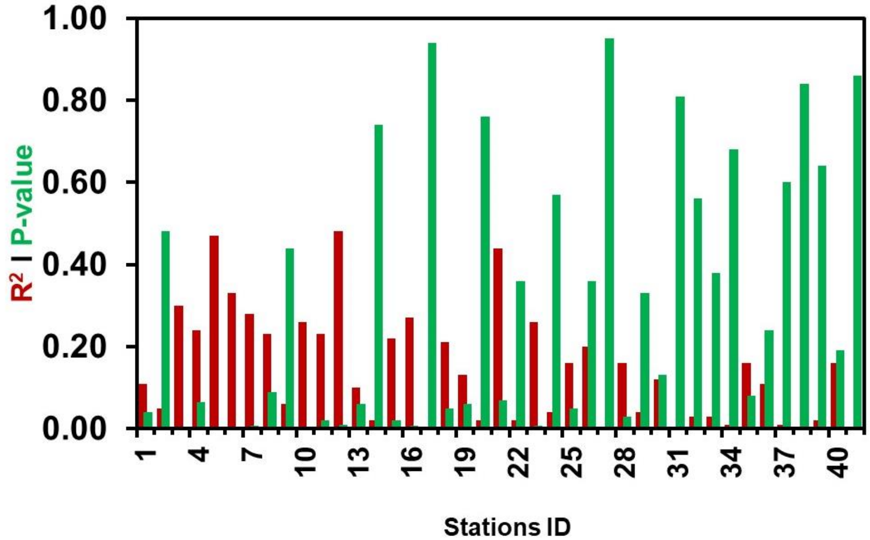

Figure 4. 8 Bar chart showing the statistical significance of rainfall amount and $\delta^{18}O$ at individual stations. On the x-axis station IDs are in sequence from left to right.

Out of 41 stations, only eight stations exhibit statistically significant ($R^2 > 0.25$; P-value < 0.05) trend between rainfall and $\delta^{18}O$ (Fig. 4.8). It is noteworthy that out of these eight stations, six stations viz., Kolkata, Faizabad, Ranichauri, Hissar, Patiala and Kangra (station ID: 23, 12, 6, 7, 5 and 3) lie along a narrow belt in the Indo-Gangetic plains. During monsoon majority of precipitation along this belt is brought by the BOB branch; thus, moisture source more or less remains the same. Therefore, the amount effect at these stations may be attributed to Rayleigh related rainout process (Gonfiantini et al., 2001).

At Dibrugarh (station ID: 10) also the major precipitation moisture source is continentally recycled vapour from abundant surface waters in the Assam valley, as evident from high d-excess values in precipitation, round the year. Thus, at Dibrugarh also amount effect may be attributed to Rayleigh rainout (Gonfiantini et al., 2001).

Udaipur (station ID: 16) is another station where significant amount effect is observed but, unlike Dibrugarh, the amount effect here may be attributed to significant evaporation from the falling raindrops because the amount of precipitation is very less (annual precipitation: ~65cm) and it is located in the dry and arid region of Rajasthan.

The temperature effect in isotopes is the observed positive correlation between mean monthly surface temperature and the isotopic composition of precipitation. Like the amount effect, the temperature effect is also important in the paleoclimatic reconstruction. The oxygen isotopes in various paleoclimatic archives such as tree rings, speleothems, corals, foraminifera and ice core, are used as a proxy to past temperatures, based on the relationship between temperature and water isotopologues in precipitation. Several authors have reconstructed past temperature and monsoon strength based on temperature effect (Achyuthan et al., 2007; Andrews et al., 1998; SARASWATI et al., 1993)

Fig. 4.9 is a bar chart representing statistical significance (R^2 and P-values) of mean monthly surface temperature and amount weighted monthly $\delta^{18}O$ of precipitation at individual stations (N = 41) spread across India. It can be observed from Fig. 4.9 that no statistically significant relation between surface temperature and $\delta^{18}O$ of precipitation exists at the majority of the stations (37 out of 41), due to complex interplay of various other hydrometeorological processes, differently governing the precipitation at various locations, as discussed earlier. The four stations at which statistically significant ($R^2 > 0.25$; P-value < 0.05) correlation between

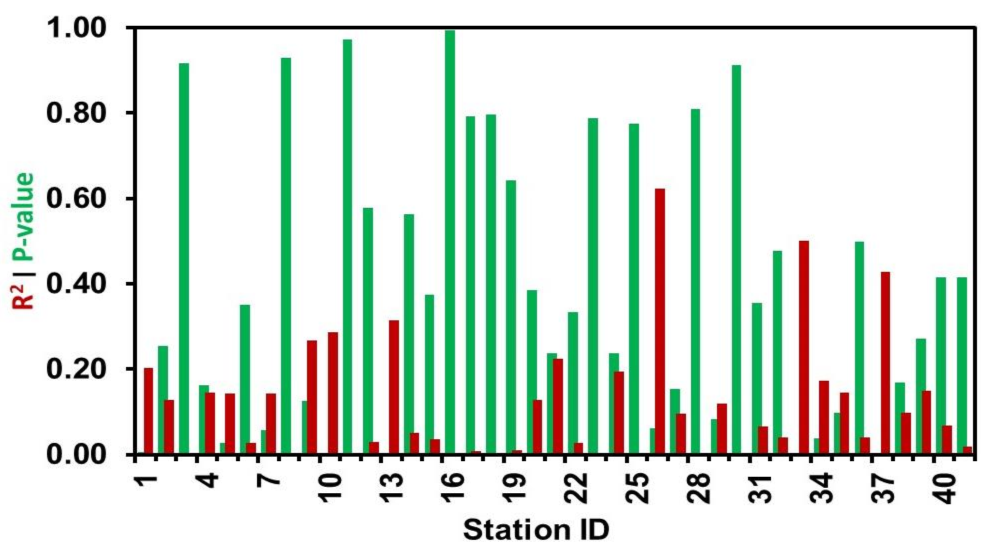

Figure 4. 8 Bar chart showing the statistical significance of surface temperature and $\delta^{18}O$ at individual stations. On the x-axis station IDs are in sequence from left to right

temperature and $\delta^{18}O$ of precipitation is observed are Jorhat, Dibrugarh, Solapur and Bangalore (station ID: 13, 10, 33 and 37).

Jorhat and Dibrugarh, in the Assam Valley, mostly derive precipitation from continentally recycled moisture, almost throughout the year. The isotopic composition of these surface waters itself changes throughout the year. During summers due to progressive evaporation the surface water gets isotopically enriched and during monsoon and late monsoon the floods in Brahmaputra River (Chowdhury and Sato, 1996; Dhar and Nandargi, 2000) replenishes the surface water with isotopically depleted waters. Therefore, the observed temperature effect in precipitation at Jorhat and Dibrugarh is actually the manifestation of variation of source isotopic composition.

Solapur and Bangalore in southern India receive precipitation mainly through southwest monsoonal winds (Jun-Sep) and northeast winds during post-monsoon (Oct-Dec). During monsoon, the southwest winds bring isotopically enriched precipitation (as seen in Fig. 4.6) whereas, during post-monsoon northeast winds bring rains generated from continentally recycled depleted moisture (Fig. 4.6). Thus, at Solapur and Bangalore, the temperature effect is the manifestation of moisture source variation.

It can be argued from the above discussions that complex hydrometeorological processes such as vapour source variation, cloud dynamics and mixing of vapour masses, govern the isotopic composition of precipitation in India. Thus, paleoclimatic studies based on classical isotope effects such as amount effect and temperature effect can lead to erroneous inferences about past climate if regional processes are not accounted for. A newer approach for interpreting isotopic variation in paleo archives is required, instead of straight forward temperature and rainfall reconstruction, precipitation isotopes may be used to understand complex processes such as convection, continental recycling of moisture and evaporation, etc.

With the above arguments in mind, a first of its kind Isotope-Hydrometeorology (iH) index (table 4.3) is proposed and is presented in this study, which holistically integrates the dependence of rain's isotopic composition on various meteorological parameters. The iH index is thus, a novel approach to quantitatively express the spatially integrated correlation between isotopic composition and meteorological parameter. In the present study, the iH index integrates the correlation between isotopic composition and meteorological parameters for the entire Indian landmass across which the sampling stations are spread. The iH-index provides for a convenient tool which can be used as an area-integrated and correlation-normalized number representing the extent to which a particular meteorological parameter can influence the isotopic composition of rain. The value of iH-index quantitatively conveys the effective control that a meteorological parameter exerts on the isotopic composition of rain. Sixteen different meteorological parameters (listed in table 4.2) were identified, in consideration of the fact that these can possibly control the isotopic composition of precipitation, due to their possible indirect effect on fractionation. The present iH-index is developed based on the preliminary correlation analysis of these 16 meteorological parameters with monthly amount weighted precipitation isotopes of individual stations (N=41). The overall weighted positive correlation coefficient (r_+) and weighted negative correlation coefficient (r_-) for each meteorological parameter with isotopic composition were computed using equation 4.1 and 4.2, respectively.

$$r_+ = \frac{\sum(r_{+i})(S_{+i})}{\sum S_+} \tag{4.1}$$

$$r_- = \frac{\sum(r_{-i})(S_{-i})}{\sum S_-} \tag{4.2}$$

Where, S_+ and S_- are the number of stations having a positive and negative correlation with a given meteorological parameter, respectively, and i is the value of correlation coefficient ranging between -1 and +1. For the purpose of computation the correlation coefficient (r_+ or r_-) has been rounded of to 0.1.

The iH correlation index (r) was computed using equation 4.3.

$$iH - index = \frac{\sum(r_+)(S_+) + \sum(r_-)(S_-)}{\sum S_+ + \sum S_-} \tag{4.3}$$

The iH-index ranges between -1 to +1; it represents the strength of the correlation, whereas, the positive and negative sign indicates a positive or negative relationship between a meteorological parameter and precipitation isotopes in entire India. Fig. 4.10 (a) and (b) are bar plots showing iH correlation index respectively for $\delta^{18}O$ and d-excess with meteorological parameters.

It is observed from Fig. 4.10 (a) that seasonality, surface RH, amount of rainfall and condensation temperature have a significant negative correlation with monthly amount weighted precipitation $\delta^{18}O$, and cloud base height, wind speed at condensation height and total solar radiation have a significant positive correlation with monthly amount weighted precipitation $\delta^{18}O$. All other meteorological parameters examined for iH index are found to have a weak correlation with precipitation $\delta^{18}O$.

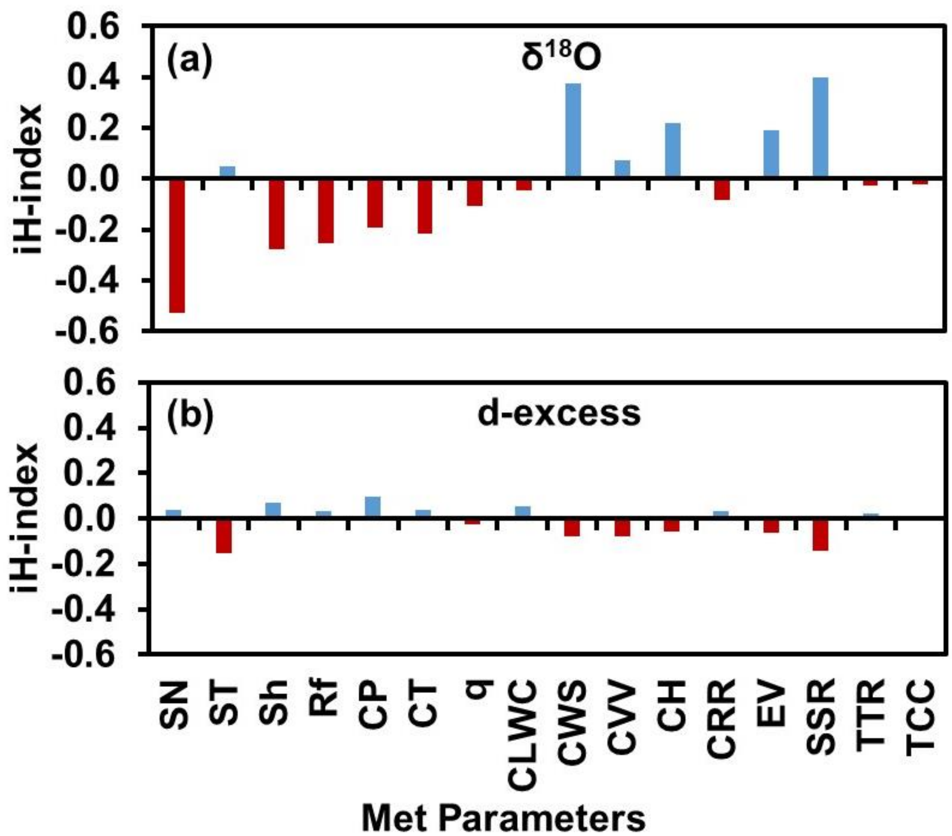

Figure 4. 9: Bar chart showing iH-index correlation between (a) $\delta^{18}O$ and meteorological parameters, and (b) d-excess and mteorological parameters

- The significant negative correlation between seasonality and precipitation $\delta^{18}O$ indicates a trend of isotopic depletion in precipitation from pre-monsoon to southwest monsoon to northeast monsoon/ post-monsoon. It may be attributed to the combined effect of evaporation from falling raindrops, variation in temperature and seasonal variation in moisture source.

- The significant negative correlation between surface RH and precipitation $\delta^{18}O$ may be attributed to the isotopic composition of evaporated vapour as the surface RH has an inverse relationship with kinetic fractionation whose magnitude increases with decreasing RH (Gonfiantini, 1986). Thus, with the lower surface RH, the evaporated vapour generated will have enriched $\delta^{18}O$ and vice versa. It may be noted that the magnitude of kinetic fractionation is more for ^{18}O than for ^{2}H, and consequently, d-excess can also be expected to have such a dependence on RH. Thus, during the events of continental recycling surface RH governs the isotopic composition of evaporated vapour and the precipitation caused by the same.

- The negative correlation between the amount of rainfall and precipitation $\delta^{18}O$ may be attributed to two possible mechanisms: i) Heavier isotopologues get preferentially condensed. Thus higher rainfall amount leads to isotopic depletion of the condensing vapour mass, and therefore the successive precipitation is also isotopically depleted and; ii) During low-intensity rainfall the ambient air is not saturated enough leading to secondary evaporation from falling raindrops, which in turn enriches the rain.

- Condensation temperature is inversely correlated with the equilibrium fractionation factor (Majoube, 1971). Thus, at lower condensation temperature, isotopically enriched precipitation is generated and vice versa. It explains the observed negative correlation between condensation temperature and precipitation $\delta^{18}O$.

- The positive correlation between cloud base height and precipitation $\delta^{18}O$ can also be attributed to condensation temperatures because the temperature and altitude are inversely related. Thus, as the cloud base height increases the temperature decreases and therefore, condensation occurs at lower temperature resulting in isotopically enriched precipitation.

- The positive correlation between wind velocity at condensation height and precipitation $\delta^{18}O$ can be explained as the higher wind velocity at condensation height disrupts the equilibrium condensation with lighter isotopologues being preferentially carried away by the wind, and heavier isotopologues can preferentially condense and vice versa.

- Matuszko (2012) have shown that the lowest values of total solar radiation are associated with the densely cloudy sky while the highest values of total solar radiation are associated with a partly cloudy and partly clear sky. Cloudiness may also be related to the precipitation. Thus, lower solar radiation indicates higher precipitation which leads to isotopic depletion and vice versa. The positive correlation between total solar radiation and precipitation $\delta^{18}O$ may be attributed to the amount of precipitation. This observation for the first time points at the probable relationship between cloudiness and the isotopic composition of rain.

Table 4. 3 iH-index $\delta^{18}O$ and d-excess correlation with meteorological parameters

	$\delta^{18}O$					d-excess				
Met Parameter	S_-	S_+	**weighted r_-**	**weighted r_+**	**iH-Index**	S_-	S_+	**weighted r_-**	**weighted r_+**	**iH-Index**
SN	36	0	-0.53	0.00	-0.53	15	17	-0.31	0.34	0.04
ST	17	17	-0.29	0.39	0.05	22	13	-0.39	0.24	-0.15
Sh	28	9	-0.45	0.26	-0.28	14	19	-0.29	0.33	0.07
Rf	28	8	-0.41	0.30	-0.26	15	17	-0.20	0.24	0.03
CP	28	9	-0.37	0.36	-0.19	13	20	-0.25	0.32	0.09
CT	28	9	-0.39	0.32	-0.22	16	19	-0.26	0.28	0.04
q	23	14	-0.38	0.34	-0.11	23	13	-0.24	0.35	-0.03
CLWC	22	17	-0.30	0.28	-0.05	17	17	-0.20	0.31	0.05
CWS	5	34	-0.16	0.45	0.37	19	14	-0.31	0.24	-0.08
CVV	13	21	-0.35	0.33	0.07	17	14	-0.32	0.21	-0.08
CH	11	24	-0.38	0.49	0.22	16	16	-0.33	0.22	-0.06
CRR	24	13	-0.30	0.32	-0.08	12	15	-0.27	0.27	0.03
EV	9	27	-0.24	0.34	0.19	19	13	-0.33	0.33	-0.06
SSR	3	33	-0.10	0.44	0.40	25	12	-0.36	0.30	-0.14
TTR	22	16	-0.28	0.31	-0.03	21	16	-0.19	0.31	0.02
TCC	23	15	-0.27	0.36	-0.02	16	14	-0.24	0.28	0.00

In spite of the fact that an apparent relationship between $\delta^{18}O$ and some of the meteorological parameters is observed, as reported in the foregoing, there is no significant correlation observed between any meteorological parameter and d-excess in precipitation. This could be attributed to the fact that d-excess values depend on simultaneous variation in $\delta^{18}O$ and δD values, which are governed by the regional phenomenon and factors such as evaporation from falling raindrops, convection and atmospheric column RH and temperature, which are known to have a slightly different magnitude of fractionation for ^{18}O and ^{2}H, though its direction is same.

Thus, the correlation varies regionally and therefore, upon the integration of all the regional correlation, it gets cancelled out. Similarly, many meteorological parameters correlated differently to $\delta^{18}O$ of precipitation in different regions; thus, the regionally integrated values do not show significant correlation. However, this study emphasises the fact that the mesoscale (~100 km) and microscale (~1 to 5 km) hydrometeorological processes have a more significant impact on precipitation isotope and thus on precipitation itself. Therefore, understanding of the hydrometeorological process at mesoscale and microscale is important.

It should also be noted that the iH-index discussed above is based on the preliminary correlation analysis of various meteorological parameters with precipitation isotopes. There are some limitations associated with this study such as: (i) the correlation study is done on a monthly time scale; (ii) the isotope data is point source whereas the meteorological parameters are obtained at 1^{o} longitude x 1^{o} latitude (iii) monthly averaged meteorological parameters were used regardless of the number of rainy days in that particular month and; (iv) significance analysis (P-value) was not performed because of variation in resolution of meteorological and isotopic data. Despite above limitations, this study highlights and opens up a new possibility that in future with the availability of more daily precipitation samples and improved resolution of meteorological parameters, there is a scope for more precise and refined study, which can give an in-depth understanding of relationships between various meteorological parameters and precipitation isotopes.

4.5. Conclusion

In order to understand the mega-scale (~1000 km) hydrometeorological processes, rigorous analysis of isotopic and meteorological parameters associated with Indian precipitation is done based on 2,939 precipitation samples collected from 41 stations spread across the country. Some of the important findings drawn from the study are listed below:

- A composite and most comprehensive Indian meteoric water line (IMWL) has been defined [$\delta D = (7.8\pm0.1)\ \delta^{18}O + (9\pm1)$; $R^2 = 0.98$; $P < 0.005$; $N = 2939$]. The slope and intercept of IMWL are lower than that of the GMWL, which signifies the role of evaporation from falling raindrops in India, surrounded by large marine water body and bordered by lofty Himalayan mountains in the north obstructing the monsoonal winds.

- The significance of evaporation from falling raindrop is further confirmed by the local meteoric water line (LMWL) slopes of 31 stations out of 41, which are less than that of the GMWL.
- From the spatial distribution of $\delta^{18}O$ and d-excess across the country during three time-frames of pre-monsoon, southwest monsoon and northeast monsoon / post-monsoon, following inferences can be drawn:

(1) Pre-monsoon

i. At the majority of locations isotopically enriched ($\delta^{18}O$ >-2‰) precipitation with d-excess in the range of 9‰ to 11‰, indicates the contribution of evaporatively enriched surface waters and soil moisture in the precipitation.

ii. In arid and semi-arid western India, isotopic signatures of significant evaporation from the falling raindrops are found.

iii. High continentally recycled moisture in precipitation associated with Nor'westers in northeast India is indicated by enriched $\delta^{18}O$ (>-2‰) high d-excess values (~11‰ to 14‰).

iv. In northern India depleted $\delta^{18}O$ (< -4‰) in precipitation with high d-excess (>13‰) may be attributed to WD.

v. Depleted $\delta^{18}O$ (< -4‰) in precipitation with high d-excess (10‰ to 12‰) along the southeastern coast may be attributed to continentally derived precipitation from the surface waters and soil moisture replenished during previous post-monsoon (Oct-Dec).

(2) Southwest Monsoon

i. The continental isotopic effect in precipitation is observed from southwest to northeast in the Indian peninsula

ii. In northeast India, the depleted $\delta^{18}O$ and high d-excess indicate rainfall from isotopically depleted continental moisture, which can be attributed to the availability of surface waters replenished by floods in Brahmaputra River

iii. The BOB branch of the southwest monsoon, deflected by the Himalayas into a low-pressure trough, travelling northwestward in Indo-Gangetic plains, progressively rains out; as indicated by depleted $\delta^{18}O$ (<-7‰) in precipitation with d-excess ~9‰

iv. As one of the AS branches travels along arid regions from Gujarat to Delhi, it rains out progressively as suggested by the trend of $\delta^{18}O$ (-2‰ to -6‰) and d-excess (11‰ to 7‰)

v. The trend in $\delta^{18}O$ (-6‰ to -10‰) and d-excess (8‰ to 10‰) of precipitation in the north of Delhi indicates progressive rainout. However, comparatively enriched $\delta^{18}O$ (-4.3‰) and high d-excess (11‰) in the precipitation of Jammu suggest the contribution of continentally derived moisture in precipitation.

(3) Post-monsoon

i. The depleted $\delta^{18}O$ (<-7‰) in precipitation at the majority of locations is observed with both low (<10‰) and high (>10‰) values of d-excess which is attributed to the varying degree of rainout from continentally derived moisture.

ii. In the southern portion of the Indian peninsula, the isotopic signature of BOB vapour is not observed, instead, significantly high values of d-excess (~13‰) and depleted $\delta^{18}O$ (<-6‰) indicate the significant contribution of continentally recycled moisture.

iii. In dry and arid parts of Gujarat and Rajasthan, exceptionally low d-excess (<5‰) in the precipitation is attributed to significant evaporation from the falling raindrops

iv. In northern India, within a small spatial area, varied isotopic signatures in the precipitation indicate multiple hydrometeorological processes such as the effect of WD, continental recycling and evaporation from falling raindrops.

- Significant amount effect is found only along the narrow belt in the Indo-Gangetic plains. Also, at majority of the stations (37), no significant temperature effect was observed. It implies the complexity of hydrometeorological process and interplay of other meteorological parameters governing Indian precipitation.

- Based on the correlation between 16 meteorological parameters and the amount weighted monthly precipitation isotopic composition, a novel correlation index (iH-index) for the Indian subcontinent has been defined. Out of 16 meteorological parameters, $\delta^{18}O$ values show a significant correlation with seven parameters, while d-excess values do not show any significant correlation. This again indicates that mesoscale (~100 km) and microscale (1 to 5 km) hydrometeorological processes play a dominant role in governing regional precipitation.

Chapter 5

Mesoscale Hydrometeorological Processes: Northern India

The summer monsoon (Jun-Sep), Western Disturbances (Dec-Feb) and continentally derived moisture are the principal moisture regimes concerning precipitation in the northern India. However, the varied Himalayan topography, diverse land cover, multiple moisture regimes give rise to a variety of complex, mesoscale (~100 km) and microscale (~ 1 - 5 km), weather conditions in northern India. In order to understand the mesoscale hydrometeorological processes concerning regional precipitation, daily accumulated precipitation samples were collected from Jammu (32.73°N, 74.87°E; 327 m asl) during 2009-11. Some of the key insights drawn from the oxygen and hydrogen isotopic analysis of precipitation samples, in conjunction with various meteorological parameters are as follows: (i) evaporation from the falling raindrops is one of the dominant processes controlling the isotopic signatures of precipitation throughout the year; (ii) Moisture from Mediterranean Sea region doesn't seem to contribute to rain during the period of Western Disturbances (WD); (iii) The high d-excess and depleted $\delta^{18}O$ during WD period is ascribed to one or more of the factors, namely, continental recycling, kinetic effect during condensation, and vapour deposition under supersaturated conditions; (iv) depletion in $\delta^{18}O$ in the beginning of monsoon is associated with increased moisture contribution from the Arabian Sea (AS) and longer rainout history of vapour parcel; (v) isotopically most depleted ($\delta^{18}O < -10$ ‰) precipitation during mid-monsoon is ascribed to continentally derived recycled moisture arising from precipitation in the Indo-Gangetic plains; (vi) enrichment in $\delta^{18}O$ during late monsoon is ascribed to relatively shorter rainout history of vapour due to weakening of monsoonal winds, continental recycling from progressively enriching inland waters and evaporation from falling raindrops.

5.1. Introduction

The Himalayas in the North play an important role governing the Indian rain bearing systems, such as Indian summer monsoon, Northeast winter monsoon and Western disturbances (WD). The lofty Himalayas provide a barrier between warm and moist, moisture-bearing air mass of the Indian subcontinent in the south and cold and dry extratropical air in the north (Boos and Kuang, 2010). The orography of the Himalayas also plays a dominant role in governing the amount of precipitation (Sinha et al., 2013). The vast Himalayan region is known for wide-ranging topographical features, land use – land cover and arrays of regional climate (Dimri et al., 2013). Viste and Sorteberg (2013) have shown that in the mountainous terrain the precipitation is primarily controlled by the interaction between advected moisture, land cover and topography of the region.

The northernmost part of India consisting the union territories of Jammu and Kashmir, and Ladakh is a vast land area (101,387 km^2) which houses the western Himalayas. The varied topography (high mountain ranges, mountain passes, valleys, plains and foothills), diverse land cover (lakes, rivers, agricultural fields and forests), multiple moisture regimes such as WD, Southwest monsoon and continental recycling, give rise to a variety of complex, mesoscale and microscale, weather conditions in the region (Dimri and Mohanty, 2009). The WD are extratropical storms originating from the Mediterranean Sea or the west Atlantic Ocean and travelling eastwards with an average velocity of 8^{o} - 10^{o} longitude per day (Dimri et al., 2015; Rao and Srinivasan, 1969b). The western Himalayas pose an orographic barrier to the WD leading to post-monsoon and pre-monsoon (Dec-Feb) precipitation in this part of the country. About 22% of the region's annual precipitation is derived through WD, which is essential for sustaining winter crops. The majority (80%) of the population residing here is dependent on agriculture for their livelihood. The agricultural area occupies ~35% of total land area, 40% of this area is irrigated by rainwater (WD and monsoon) whereas, remaining 60% is irrigated through rivers, tributaries and canals of Indus river system (farmech.dec.gov.in). About 20% of the total area is forested (jkforest.gov.in). Thus, in the absence of any marine body in the vicinity and abundant surface waters, agricultural and forested land, continental moisture is expected to contribute in regional precipitation dominantly.

The city of Jammu (32.73°N, 74.87°E; 327 m asl) lies on the uneven terrain of Shivalik hills in the North and plains in the south. The Tawi River flows through Jammu and supports the irrigation of agricultural fields in the region. The valley of Kashmir and Jammu are separated by the Pir Panjal range. The earlier views on the role of Pir Panjal in blocking the monsoonal winds from entering into the Kashmir valley has been recently revised (Jeelani et al., 2017). Jammu lies on the windward side of the Pir Panjal and hence it experiences both, the Indian monsoon as well as the WD. Jammu lies at the end of the AS and BOB branches of monsoon (Das, 2005). The unique geographical setting of Jammu is perfect for studying the mesoscale hydrometeorological processes concerning the regional precipitation. Apart from the purely academic interest in understanding the hydrometeorology of the region to have a better insight into the past and future climate change processes, it is essential to study these processes because they govern the availability and distribution of water in the region, and its socio-economy.

Oxygen and hydrogen stable isotopes are important tracers to understand and trace the hydrometeorological processes such as vapour source variation, continental recycling of moisture, rainout history, cloud microphysics and evaporation from falling raindrops (Breitenbach et al., 2010; Deshpande et al., 2013a; Jeelani et al., 2017; Lekshmy et al., 2015; Midhun et al., 2018; Oza et al., 2020; Rahul et al., 2018; Saranya et al., 2018; Unnikrishnan Warrier and Praveen Babu, 2012). Thus, with the aim to identify the moisture sources during different seasons, estimate the continental recycling and understand the role of monsoon and WD in northern India, 97 daily accumulated precipitation samples were collected from Jammu during 2009-11 for the isotopic analysis, and interpretation of isotope data in light of other meteorological parameters.

5.2. Climate

Jammu (32.73°N, 74.87°E; 327 m asl), located in the foothills of the northwestern Himalayas, experiences humid subtropical climate. During summer the maximum average temperature goes up to ~39 ^{o}C during June, and the lowest average temperature of ~8 ^{o}C is recorded in January, during winter. The average annual potential evapotranspiration (PET) in the region is ~ 6.3 mm/day (www.indiawaterportal.org). The long term average annual temperature and precipitation of Jammu are 23.7 ^{o}C and 1,332 mm, respectively. It receives precipitation both during the WD (~ 288 mm; ~22%) and monsoon (~ 970 mm; ~73%). For details of the climate record, reference is made to the India Meteorology Department website (https://mausam.imd.gov.in).

5.3. Data Used

Under the aegis of IWIN National Programme (Deshpande and Gupta, 2008; Deshpande and Gupta, 2012), 97 daily accumulated rainfall samples were collected from Jammu during 2009-2011. The details of sample collection and isotopic analysis is presented in Chapter 3.

The details of other meteorological parameters derived from satellite, modelled and reanalysis open platforms, which are used for interpreting isotope data of Jammu are listed below:

- Ensembles of four 120 hr back wind trajectories, each starting at six hourly intervals and at the height of 1500 m from Jammu is obtained from Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model [http://ready.arl.noaa.gov/HYSPLIT.php (Stein et al., 2015)]. Percentage moisture contribution from each source (Arabian Sea, Bay of Bengal and continentally recycled moisture) and average distance travelled by the wind trajectories are computed using the specific humidity and geographical coordinates, (Sodemann et al., 2008a; Sodemann et al., 2008b)

- For estimation of the convective and stratiform fraction of rain, the hourly convective percentage and rain rate are obtained from Tropical Rainfall Measuring Mission (TRMM) TMI (TRMM Microwave Imager) 3G68 at the spatial resolution of 0.5º latitude x 0.5º longitude (Kummerow et al., 2001) over the box of 31.72° N; 73.85° E and 33.72° N; 75.85° E.

- The climatological (1981 – 2010) monthly Outgoing Longwave Radiation (OLR) data, over the box of 20° N, 65° E and 40° N, 95° E, was obtained from NOAA interpolated OLR data (http://www.cdc.noaa.gov/cdc/data.interp_OLR.html) with a spatial resolution of 2.5° latitude × 2.5° longitude (Liebmann and Smith, 1996).

- The NCEP/NCAR Reanalysis-1 monthly climatological (1981 – 2010) vertical wind velocity (ω) at 500 hPa at the spatial resolution of 2.5º latitude x 2.5º longitude (Kalnay et al., 1996) over the box of 20º N, 65º E and 40 ºN, 95º E. was obtained from http://www.esrl.noaa.gov.

5.4. Results and Discussion

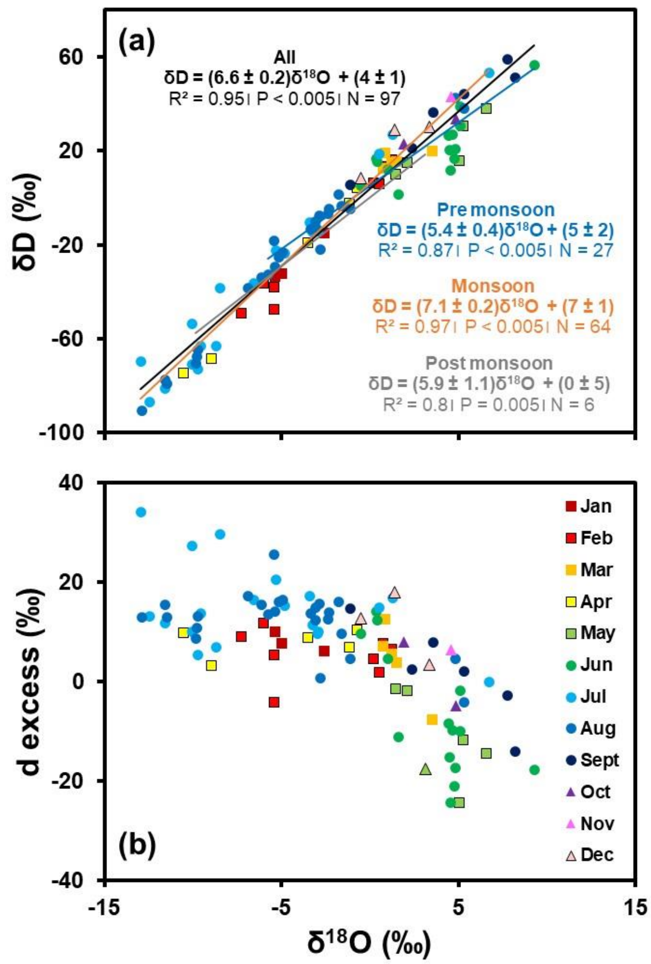

Figure 5. 1: (a) $\delta^{18}O$ - δD regression line and; (b) δ18O – d-excess plot of daily rainfall samples with month-wise identifiers

Based on 97 daily accumulated precipitation samples, the overall and seasonal (pre-monsoon, monsoon and post-monsoon) $\delta^{18}O$ – δD regression lines are shown in fig: 5.1 (a) with month-wise and seasonal identifications of the daily samples. The slope (6.6 ± 0.2) and intercept (4 ± 1) of regression line plotted with all the samples is lower than that of the Global Meteoric Water Line (GMWL) [slope: 8.17±0.07; intercept: 11.27±0.65; Rozanski et al. (1993)]. The lower slope is an indication of significant evaporation from the falling raindrops (Friedman et al., 1962) throughout the year. It is further justified by the relatively high (~6.3 mm/day) rates of annual average (climatological) potential evapotranspiration (PET) in the region. The pre-monsoon (Jan-May) and the post-monsoon (Oct-Dec) regression lines' slopes (5.4 ± 0.4 and 5.9 ± 1.1, respectively) are further lower. However, during monsoon, the slope of $\delta^{18}O$ – δD line is relatively higher but still lower (7.1 ± 0.2) than the GMWL. Thus the evaporation from falling raindrops is a predominant process, especially during the non-monsoon period compared to monsoon. It can be attributed to the significantly lower average (climatological) rainfall during the non-monsoon period (~34 cm) compared to the monsoon period (~100 cm). During low rainfall, the ambient atmosphere remains relatively undersaturated which facilitates the diffusive/ evaporative loss from the falling raindrops. The $\delta^{18}O$ – d-excess scatter is plotted in fig. 5.1 (b). Majority of the enriched

$\delta^{18}O$ (> 1 ‰) samples associated with low d-excess (< 10 ‰) are from Mar-June, again suggesting significant evaporation from the falling raindrops during pre-monsoon months.

No systematic pattern is seen from the $\delta^{18}O$ and d-excess time-series plots (fig. 5.2 a and b). Also, no pattern analogues to that observed in isotopic composition of rain was found in convective and stratiform rain fraction (fig. 5.7). However, some peculiar observations can be

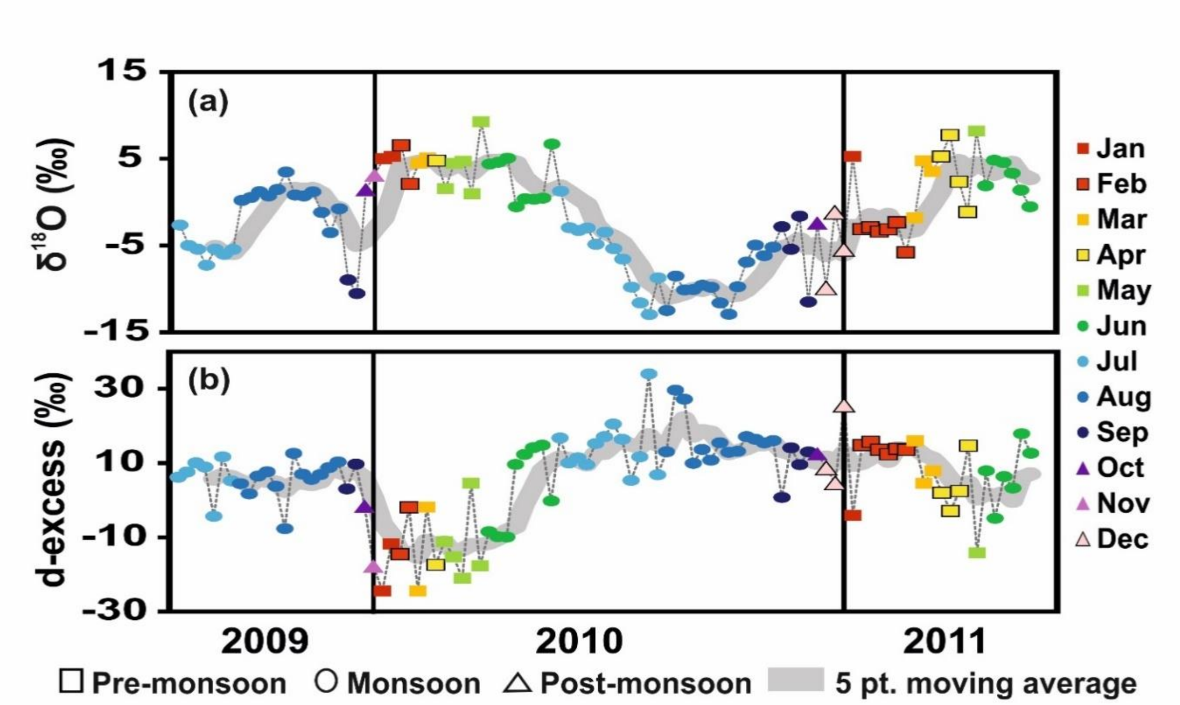

Figure 5. 2: The daily time-series of $\delta^{18}O$ (a) and d-excess (b) with month wise identifiers. The width of each year represents the number of rainy days in that year.

drawn from inter and intra-seasonal variation in isotopic compositions. Some of these observations are: (i) enriched $\delta^{18}O$ and high d-excess during Dec-Feb 2009-10, reverses during Dec-Feb 2010-11; (ii) gradual trend of $\delta^{18}O$ depletion during mid-Jun to mid-Jul; (iii) isotopically most depleted values during mid-Jul to Aug and; (iv) gradual trend of $\delta^{18}O$ enrichment during Sep-Oct. In the following, the inferences drawn from the observations mentioned above are discussed in detail.

(i) Enriched $\delta^{18}O$ and low d-excess during 2009-10 Dec-Feb, reverses during 2010-11 Dec-Feb

During 2009-10 Dec-Feb the $\delta^{18}O$ is enriched (> 1 ‰) whereas the d-excess is low (< 10 ‰). On the other hand, during 2010-11 Dec –Feb the $\delta^{18}O$ is depleted (< -1 ‰) whereas the d-excess is high (> 10 ‰) but during Mar-May enriched $\delta^{18}O$ and low d-excess is common to both the years, as seen from fig. 5.2 (a) and (b). Generally, from December to February, the isotopic signature of WD in precipitation is associated with high d-excess and depleted $\delta^{18}O$ values (Jeelani and Deshpande, 2017). The low d-excess and enriched $\delta^{18}O$ are ascribable to evaporation from raindrops (Gat et al., 1994). The low (~64%) RH and rainfall (~2 cm) during 2009-10 Dec-May and 2010-11 Mar-May (~8 cm), compared to that (~81% and ~14 cm) during 2010-11 Dec-Feb, facilitates the evaporation from the falling raindrops. Thus, it is hypothesized that during 2009-10 Dec-May and 2010-11 Mar-May, the evaporation from the falling raindrops is the dominant process. On the other hand, during 2010-11 Dec-Feb, the effect of WD might be recorded in the isotopic composition of precipitation, though the number of WD in 2011 was less (17) compared to that (23) in 2010 (Midhuna et al., 2020). While it may seem that faint signatures of WD are preserved in rainfall during 2010-11 Dec-Feb, the overall effect of WD in Jammu is not prominent because examination of 120 hrs. back trajectories indicate that in both the years the maximum estimated moisture contribution (~97%) was from the continental recycling. To further confirm this estimation, 240 hrs back trajectories were also examined for the months of Dec-Feb, and it was concluded that the actual moisture reaching northern India from the Mediterranean Sea or the west Atlantic Ocean in negligible (< 1%). Based on the velocity of WD (8º - 10º longitude per day; Dimri et al., 2015) and the distance (~57º longitude) between the Mediterranean Sea and Jammu, the time taken by the WD to reach Jammu is estimated to be 6 – 7 days. Whereas the median of global atmospheric moisture residence time is about 5 days and during winters it reduces by several days (Van Der Ent and Tuinenburg, 2017). Thus, the possibility of significant moisture from the Mediterranean region reaching Jammu/northern India is not supported by evidence, at least for these two years. Consequently, the argument of moisture from the Mediterranean Sea or West Atlantic Ocean, resulting in high d-excess and depleted $\delta^{18}O$ in pre monsoon 2011 at Jammu is ruled out. However, the depression does travel to northern India through WD as seen from negative vertical wind velocities at 500 hPa (fig. 5.3), which causes strong convection promoting continental recycling. The $\delta^{18}O$ and d-excess of Indus River system are reported in the range of -

16.9 ‰ to -12.5 ‰ and 7 ‰ to 15 ‰ (Sharma et al., 2017). The water of the Indus River system through various rivers, tributaries and canals is used for irrigation of vast agricultural fields. The evapotranspiration from these irrigated waters introduces moisture with depleted $\delta^{18}O$ and high d-excess into the atmosphere through convection, and its adiabatic cooling leads to precipitation.

The high d-excess and depleted $\delta^{18}O$ can also be the manifestation of kinetic effect during condensation or vapour deposition under supersaturated conditions (Deshpande et al., 2013a; Souchez et al., 2000). Thus, continental recycling and kinetic condensation/deposition under supersaturation can result in the observed isotopic signature of depleted $\delta^{18}O$ and high d-excess. However, significant evaporation from the falling raindrops can reverse this isotopic signature.

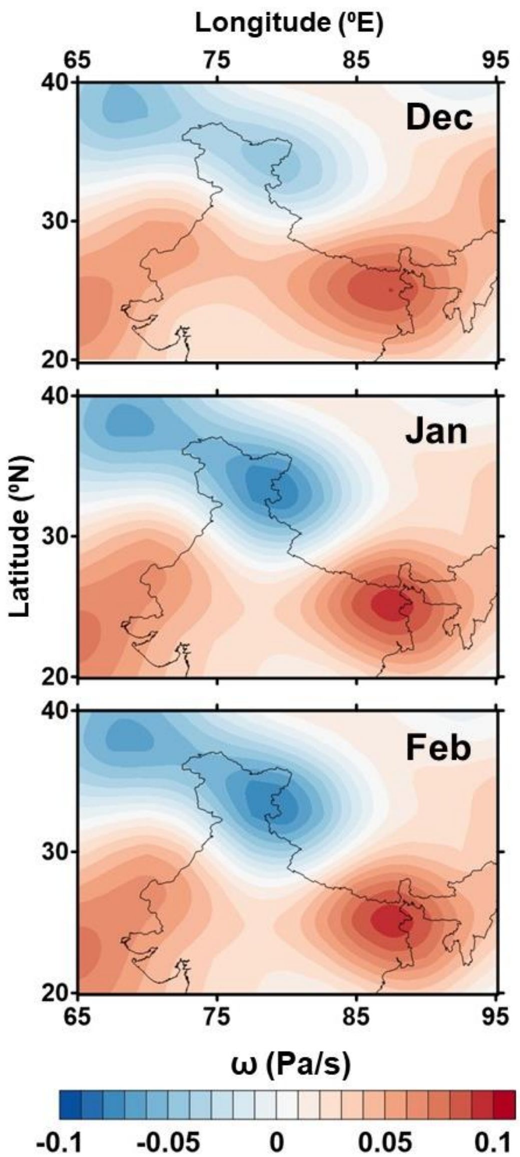

Figure 5. 3: Map showing monthly climatological (1981-2010) variation of vertical wind (ω) velocity during the period of WD (Dec-Jan) over northern India. The negative and the positive values of ω refere to the upward and downward wind velocities, respectively

(ii) The gradual trend of $\delta^{18}O$ depletion during mid-Jun to mid-Jul

The AS branch starts reaching Jammu from mid-June onwards as evident from the 120 hrs back wind trajectories (fig. 5.4). The gradual $\delta^{18}O$ depletion trend from June to July can be explained through following: (a) relative increase (Jun: 10% to Jul: 28%) in the Arabian Sea (AS) moisture contribution (fig. 5.5) and; (b) increased rainout due to increased (Jun: 2800 km to Jul: 3400 km) average distance travelled by trajectories (fig. 5.5).

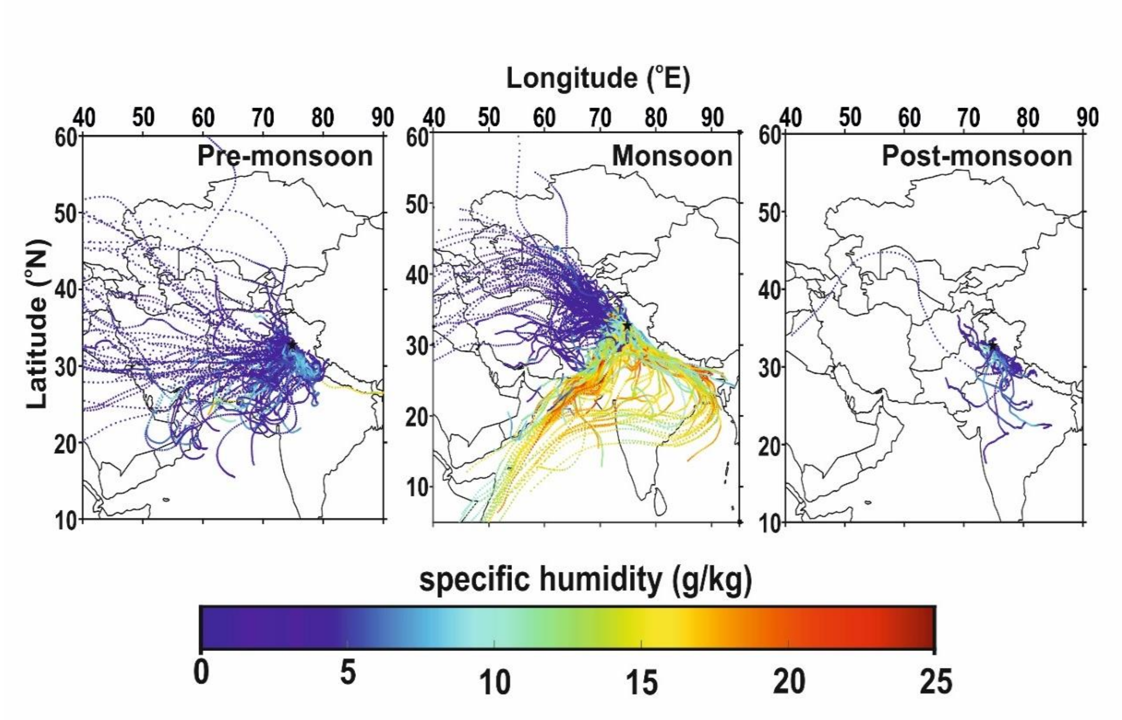

Figure 5. 5: Map showing seasonal ensembles of four 120 hrs. backward trajectories starting from Jammu. The colour code indicates specific humidity in g kg^{-1}

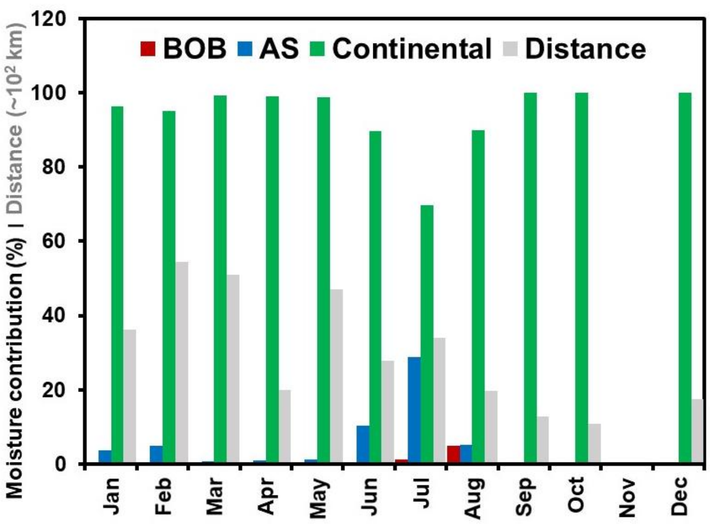

Figure 5. 4: Bar chart showing monthly variation in moisture contribution from various sources and average monthly distance traversed by 120 hrs. backward trajectories

(iii) Isotopically most depleted values from mid-Jul to August

Isotopically most depleted $\delta^{18}O$ (< -10 ‰) in precipitation samples are observed during mid-July and August, which suggests the shift in wind regime as the BOB branch progresses northwestwards (fig. 5.4). Although the contribution of the BOB moisture is negligible in the Jul-Aug rainfall of Jammu (fig. 5.5), the maximum contribution is of continentally recycled moisture from Indo-Gangetic plains. Furthermore, the low (< 240 W/m^2) OLR values progressively shifting northwestwards during Jul-

Aug (fig. 5.6), also indicates the increased convection along the Indo-Gangetic plains. The Indo-Gangetic plains receive the monsoonal rains through the BOB branch from as early as 10th June (Krishan et al., 2013). Various authors have reported depleted $\delta^{18}O$ in Indo-Gangetic precipitation, ranging between -5 ‰ to -10 ‰ [Palampur and Ranichauri: -8.7 ‰ and -10.5 ‰, (Jeelani et al., 2017); Delhi and Allahabad: -5.7 ‰ and -7.4 (Araguás-Araguás et al., 1998; Gupta and Deshpande, 2003); Kolkata: -5.4 ‰, (Sengupta and Sarkar, 2006); Gangetic West Bengal: -9.3 ‰ (Mukherjee et al., 2007)] during monsoon. Thus, due to abundant availability of depleted surface water and soil moisture by mid-July and August (from the rains of Jun-Jul), through evapotranspiration this continentally derived moisture is added to atmosphere and transported to Jammu, which leads to isotopically depleted rain during mid-July and August.

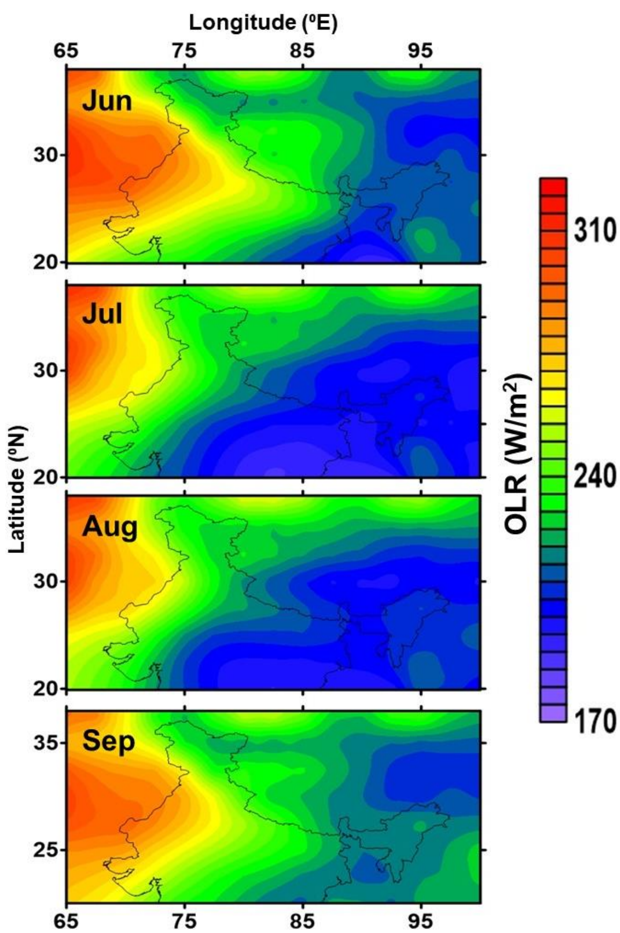

Figure 5. 6: Map showing monthly climatological (1981-2010) variation of Out Going Long Wave Radiations (OLR) during the period of monsoon (Jun-Sep) over northern India

(iv) The gradual trend of $\delta^{18}O$ enrichment during Sep-Oct

The gradual $\delta^{18}O$ enriching trend during Sep-Oct can be explained through the combination of the various hydrometeorological process such as: (a) due to weakening of monsoonal winds the continentally derived moisture from nearby area (within a few hundreds of kilometers), suffers less rainout (before reaching Jammu) as evident from the decreased (Aug: 2000 km, Sep: 1300 km and Oct: 1100 km) average distance travelled by the 120 hrs backward wind trajectories (fig. 5.5); (b) progressive $\delta^{18}O$ enrichment of surface waters and soil moisture due to continuous evaporation, leads to enriched vapour and thus enriched precipitation and;

(c) less rainfall amount (Sep: ~7 cm, Oct: ~4 cm), compared to that of August (~91 cm), causing evaporative $\delta^{18}O$ enrichment of raindrops.

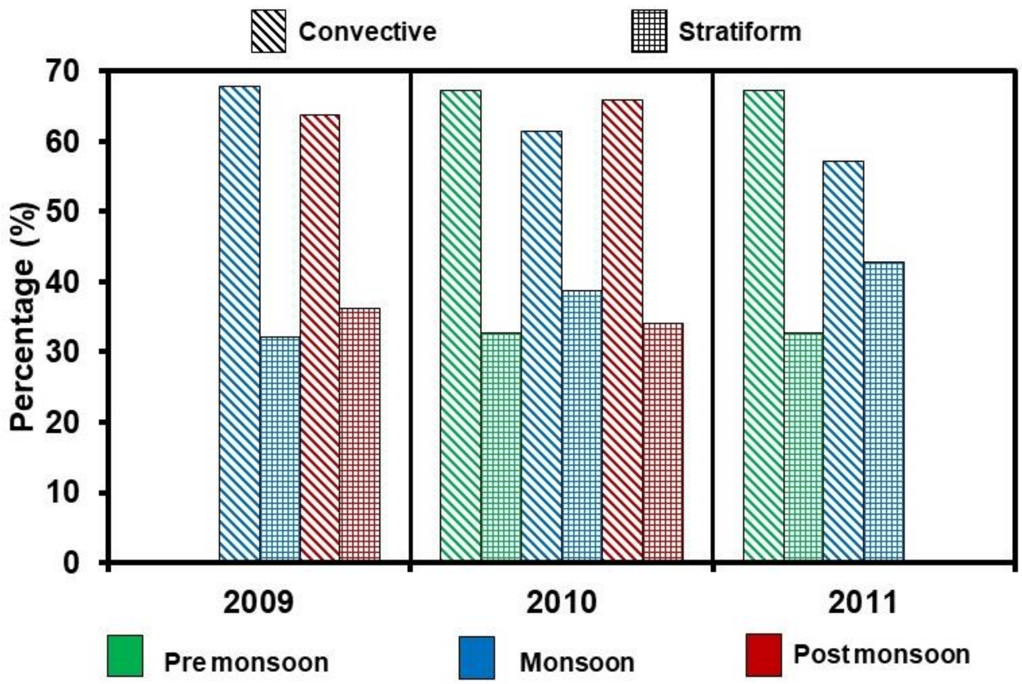

Figure 5. 7: Seasonal proportion of rain derived from convective and stratiform clouds during 2009-11

Throughout the monsoon period, the relatively high d-excess (> 10 ‰) is because Jammu is significantly distant from both the marine water bodies (AS and BOB) therefore, the maximum (~83%) moisture for precipitation, during monsoon (Jun-Sep), is contributed by the continental recycled moisture, generated in under-saturated ambient atmospheric conditions, even during the monsoon period.

5.5. Conclusion

Based on the characteristic isotopic signature and other meteorological parameters associated with 97 daily accumulated rainfall samples collected from Jammu, following important mesoscale hydrometeorological processes concerning precipitation in northern India are identified:

- Evaporation from the falling raindrops is one of the dominant process controlling the isotopic signatures of precipitation throughout the year; as evident from the lower slope (6.6 ± 0.2) of local meteoric water line.
- Contrary to expectation, insignificant moisture from the Mediterranean Sea is derived during the period (Dec-Feb) of WD. The high d-excess and depleted $\delta^{18}O$ during 2010-11 Dec-Feb is due to continental recycling from irrigation waters derived from Indus River System ($\delta^{18}O$: -16.9 ‰ to -12.5 ‰; d-excess: 7 ‰ to 15 ‰) and/or kinetic effect during condensation or vapour deposition, under supersaturated conditions.
- Significant evaporation from the falling raindrops can alter the isotopic signature during pre-monsoon 2010.
- Gradual depletion in $\delta^{18}O$ in the beginning (Jun-Jul) is associated with increased moisture contribution from the AS and higher rainout from vapour parcel before reaching Jammu.
- Isotopically most depleted ($\delta^{18}O < -10$ ‰) precipitation during mid-monsoon (Jul-Aug) is ascribed to continentally derived recycled moisture from precipitation in Indo-Gangetic plains.
- Gradual enrichment in $\delta^{18}O$ during late monsoon (Sep-Oct) is associated with smaller rainout from vapour parcel before reaching Jammu, due to weakening of monsoonal winds, progressively enriching inland waters contributing to rainfall through continental recycling and evaporative enrichment of raindrops due to low rainfall amount.

Chapter 6

Mesoscale Hydrometeorological Processes: Northeast India

The unique geographical setting of northeast India, such as proximity to the Bay of Bengal (BOB), mountains surrounding it from three directions, and the availability of abundant surface water leads to complex interplay of several mesoscale (~100 km) hydrometeorological processes and factors such as: (i) effect of orographic barrier; (ii) role of advected moisture from the BOB; (iii) contribution of continentally recycled moisture in rainfall; (iv) effect of floods in the Brahmaputra; (v) effect of Nor'westers and deep convection; and (vi) evaporation from falling raindrops. One or more of this process and factor govern the spatio-temporal distribution of rainfall in the region, and hence it is important to understand them. With this in mind, 257 daily accumulated rainfall samples were collected from Jorhat city (26.75° N, 94.20° E; 116m asl) in the State of Assam in Northeast India, for its isotopic analysis and interpretation in light of various meteorological parameters to discern the underlying processes and factors. Some of the important insights drawn from the study are: (i) maximum moisture for rainfall at Jorhat is derived from continental recycling; (ii) evaporation from falling raindrops is minimal at Jorhat; (iii) enriched $\delta^{18}O$ and high d-excess with the slight trend of $\delta^{18}O$ depletion are ascribed to continentally recycled moisture generated from progressively enriched surface waters, and increased condensation temperature during pre-monsoon; (iv) exceptionally high d-excess indicates deep convection associated with Nor'Westers during April-May; (v) $\delta^{18}O$ baseline shift and trend of $\delta^{18}O$ depletion during monsoon is ascribed to isotopic depletion of the surface waters, due to floods in the Brahmaputra River and orographic rainout of advected moisture from the BOB; and (vi) evasion of the orographic barrier due to variation in wind direction and progressive isotopic enrichment of surface waters due to evaporation causes the trend of isotopic enrichment in post-monsoon rain.

6.1. Introduction

Northeast region in the foothills of Arunachal Himalaya is a vast landmass (262,179 km^2) comprising the Indian states of Assam, Arunachal Pradesh, Meghalaya, Sikkim, Manipur, Mizoram, Nagaland, and Tripura. About 64% of the total land area of northeast India is under forest cover (Forest Survey of India), and ~16% is cultivated area (Dikshit and Dikshit, 2014). The mighty Brahmaputra River with the mean discharge of ~21,000 m^3 s^{-1} (Lambs et al., 2005), flows through this region. Northeast India has abundant surface waters in the form of rivers, tributaries, flood plains, ponds, lakes, wetlands and paddy fields.

Northeast India is one of the most important regions to study the hydrometeorological processes because of its unique geographical setting and resultant micro-climate. Arunachal Himalayas surround it in the North, Purvanchal Range in the east and southeast and Garo-Khasi-Jaintia in the south, opening only from the west. Goswami et al. (1999) have reported the negative correlation between rainfall of northeast India and rainfall of the rest of the country during monsoon because northeast India has different climate and different annual cycle of rainfall. The average annual rainfall of the region is ~2000 mm, and ~25% of it rains during the pre-monsoon period, especially in March-May (Mahanta et al., 2013). The pre-monsoon heavy rainfalls are associated with Nor'westers. Nor'westers are the atmospheric instabilities caused when warm and moist southwest winds are overrun by the cold and dry westerlies (Roy and Chatterji, 1929). It initiates deep convection and severe thunderstorms in the Northeast region. Northeast India receives ~1,500 mm of rainfall during monsoon, which is much higher than the country's average rainfall [856 mm; Parthasarathy and Yang (1995)]. This hefty rainfall together with glacial melting during summers causes severe floods in Brahmaputra River (Dhar and Nandargi, 2000), disrupting the normal life and socio-economy of the region. These floods refill the water in low lying flood plains and widespread wetlands of the region, which then gets progressively evaporated and isotopically enriched throughout rest of the year. Wetlands occupy ~25% of the total geographical area of northeast India (National Wetland Atlas). Thus large-scale evapotranspiration and continental recycling of moisture can be expected in northeast India. Based on dynamic recycling model forced by NCEP reanalysis data for the period of 1980-2010, Pathak et al. (2014) have reported highest moisture recycling (~25%) in the northeast India, which is much less than the estimated global average recycled precipitation of ~60% (Van Der Ent and Tuinenburg, 2017).

Stable isotopes of oxygen and hydrogen in rainwater can be used as important tracers to identify various hydrometeorological processes concerning precipitation such as moisture source variation, rainout history, vapour recycling, post-precipitation modifications and cloud microphysical processes (Breitenbach et al., 2010; Deshpande et al., 2013a; Deshpande and Gupta, 2012; Jeelani et al., 2017; Lekshmy et al., 2015; Midhun et al., 2018; Oza et al., 2020; Rahul et al., 2018; Saranya et al., 2018; Unnikrishnan Warrier and Praveen Babu, 2012).

Jorhat city in the state of Assam is located on the bank of the Brahmaputra River in the Assam valley, just ~550 km in the north from the Bay of Bengal. It experiences severe floods during July and relatively minor floods in September, like the rest of northeast India (Chowdhury and Sato, 1996). About 588 wetlands are occupying ~46,000 ha of area in and around Jorhat (National Wetland Atlas). The spatio-temporal distribution of rainfall in this region is governed by interplay of various mesoscale (~100 km) hydrometeorological processes and factors, namely, (i) effect of orography; (ii) role of advected moisture from the Bay of Bengal; (iii) contribution of continentally recycled moisture in rainfall; (iv) effect of floods in the Brahmaputra; (v) effect of Nor'westers and deep convection and; (vi) evaporation from falling raindrops. With a view to understand how these processes relate to the rainfall in the region, 257 daily precipitation samples were collected from Jorhat (26.75° N, 94.20° E; 116m asl) during 2010-11 for isotopic analysis and intrepreatation of isotope data in conjunction with other meteorological parameters.

6.2. Climate

Jorhat located in the eastern extreme of Indian Himalaya experiences a humid subtropical climate with long term annual average temperature of about ~24^{o}C and ~2324 mm of rainfall. Most of the rainfall (~1403 mm) is received during ISM, followed by Nor'wester (~657 mm) and post-monsoon (~197 mm). For details of the climate record, reference is made to the India Meteorology Department website (http://mausam.imd.gov.in).

6.3. Data Used

For the isotopic analysis, 257 daily accumulated rainwater samples were collected from Jorhat during 2010-11, under the aegis of IWIN National Programme (Deshpande and Gupta, 2008; Deshpande and Gupta, 2012). For the details of sample collection and isotopic analysis, reference is made to Chapter 3.

Various satellite-based, modelled, and reanalysis meteorological data obtained from open platforms are used in the study. The details of the meteorological data used are enlisted below:

- Ensembles of four 120 hr backward wind trajectories, starting at every six hourly intervals and at the height of 1500 m from Jorhat is obtained from Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model [http://ready.arl.noaa.gov/HYSPLIT.php (Stein et al., 2015)]. The percentage moisture contribution from each source (Arabian Sea (AS), Bay of Bengal (BOB) and Continentally recycled moisture) and average distance travelled by the wind trajectories are computed using the specific humidity and geographical coordinates (Sodemann et al., 2008a; Sodemann et al., 2008b).

- For estimation of the convective and stratiform fraction of rain, the hourly convective percentage and rain rate are obtained from Tropical Rainfall Measuring Mission (TRMM) TMI (TRMM Microwave Imager) 3G68 at the spatial resolution of 0.5º latitude x 0.5º longitude (Kummerow, C. Y. et al., 2001) over the box of 25.75° N, 93.20° E and 27.75° N, 95.20° E.

- The ERA5 Reanalysis monthly vertical wind (ω) obtained at 21 pressure levels ranging from 250 hPa to 1000 hPa at the spatial resolution of 0.25º latitude x 0.25º longitude over the box of 26.25° N - 93.70° E and 27.25° N - 94.70° E was downloaded from http://www.cdc.climate.copernicus.eu/.

- The ERA5 Reanalysis monthly cloud liquid water content (kg kg^{-1}) obtained at 21 pressure levels ranging from 250 hPa to 1000 hPa at the spatial resolution of 0.25º latitude x 0.25º longitude over the box of 26.25° N - 93.70° E and 27.25° N - 94.70° E was downloaded from http://www.cdc.climate.copernicus.eu/.

- The NCEP/NCAR Reanalysis-1 monthly climatological (1981 – 2010) temperature at 700 hPa at the spatial resolution of 2.5º latitude x 2.5º longitude (Kalnay et al., 1996) over the box of 20º N, 80º E and 30ºN, 100º E was obtained from http://www.esrl.noaa.gov/.

6.4. Results and Discussion

The annual and seasonal $\delta^{18}O$ and δD regression lines for 257 daily accumulated rainfall samples at Jorhat are plotted in Fig. 6.1 (a). Isotopically the most enriched samples ($\delta^{18}O$ > -4‰) are from Jan-Jun. On the other hand, isotopically the most depleted samples ($\delta^{18}O$ < -15‰) are from the Sep-Oct. The slope (8.3±0.1) of the annual regression line is slightly greater than that (8.17±0.07) of the Global Meteoric Water Line [GMWL; Rozanski et al. (1993)] which suggests condensation at lower temperatures, minimal evaporation from falling raindrops (Clark and Fritz, 1997b). Whereas, the higher value of intercept (13±1), compared to that (11.27±0.65) of GMWL, indicates significant contribution of continentally recycled moisture (generated under relatively lower atmospheric RH, compared to that of Oceanic RH) to the rainfall (Clark and Fritz, 1997b). The monsoon [$\delta D = (8.1 \pm 0.1)\ \delta^{18}O + (11 \pm 1)$] and post-monsoon [$\delta D = (8.2 \pm 0.2)\ \delta^{18}O + (11 \pm 2)$] $\delta^{18}O$-δD regression lines are similar to GMWL, indicating negligible evaporation from falling raindrops. However, the slope (7.6±0.2) of pre-monsoon $\delta^{18}O$-δD regression line is slightly lower than the slope of GMWL, suggesting evaporation from the falling raindrops (Friedman et al., 1962). Fig. 6.1 (b) shows $\delta^{18}O$-d excess scatter plot. One of the major observation from Fig. 6.1 (b) is that the Jan-Jun samples form a distinct cluster with relatively enriched $\delta^{18}O$ (> -4‰) and high d-excess (> 10‰) compared to that of Jul-Dec with June's sample spotted in both the clusters. This distinct characteristic of high d-excess and enriched $\delta^{18}O$ may be attributed to precipitation derived

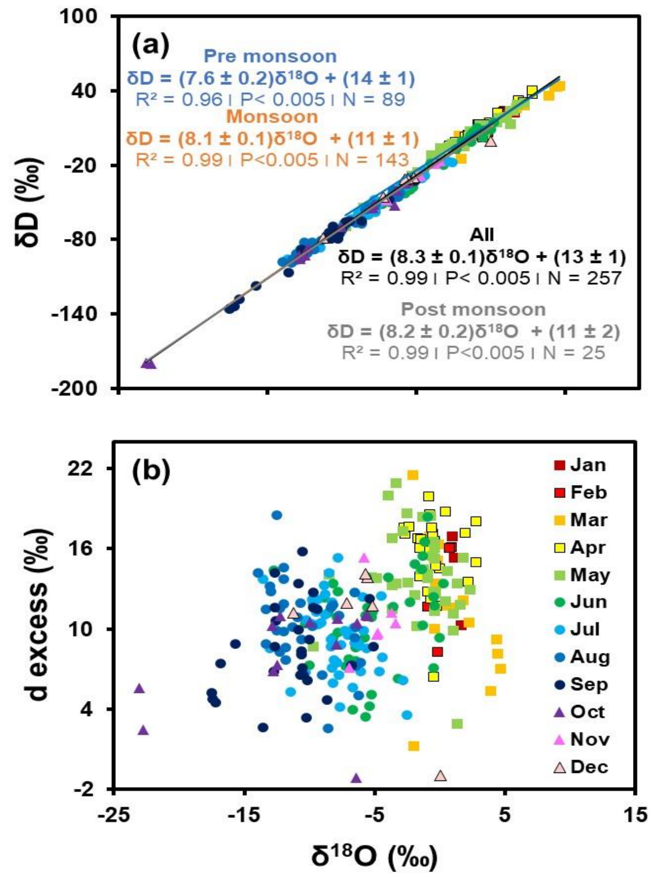

Figure 6. 1 (a) $\delta^{18}O$ - δD regression lines and; (b) $\delta^{18}O$ – d excess plot of daily rainfall samples with month-wise identifiers

from continentally recycled moisture (Froehlich et al., 2002) with minimal rainout history (Dansgaard, 1964).

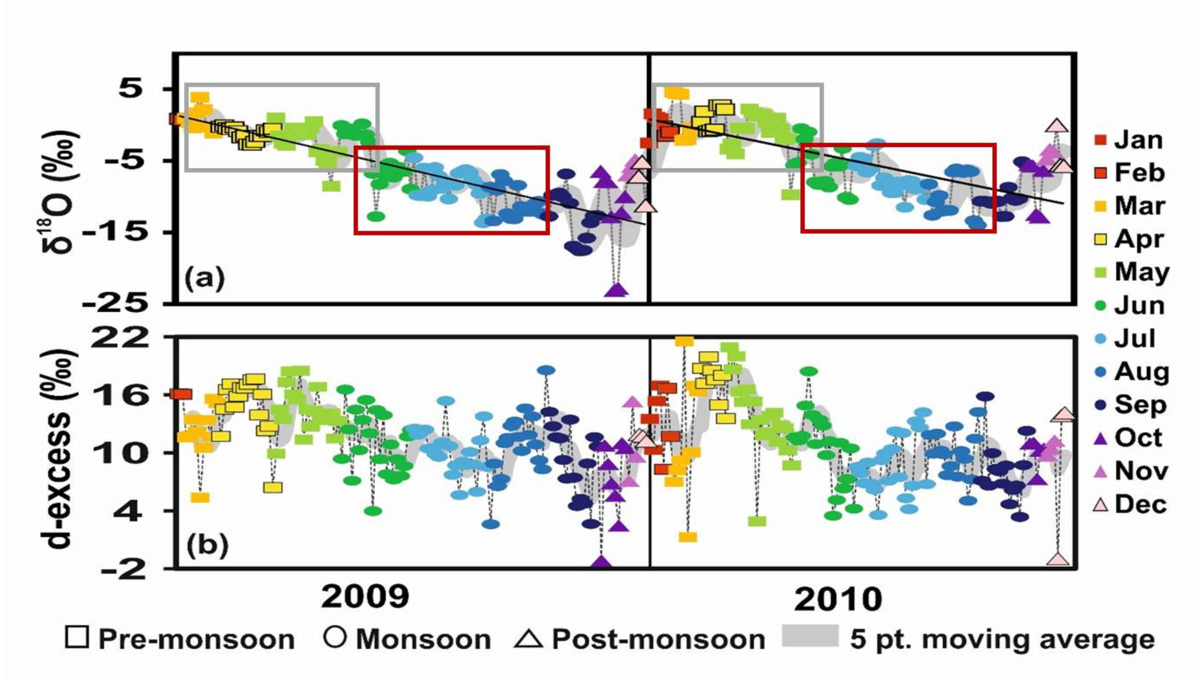

Figure 6. 2: The daily time-series of $\delta^{18}O$ (a) and d-excess (b). The width of each year represents the number of rainy days in that year. The red box highlights the baseline shift in $\delta^{18}O$ from mid-June onwards compared to grey box

The time series plots of $\delta^{18}O$ and d-excess are plotted in Fig. 6.2 (a) and (b) for the daily accumulated rainfall samples collected from Jorhat. The $\delta^{18}O$ time series shows an overall annual trend of isotopic depletion. Superposed over this trend are seasonal and daily variations. There are three peculiar trends in $\delta^{18}O$: (i) enriched $\delta^{18}O$ in pre-monsoon with slight depleting trend; (ii) sudden shift in the baseline from mid-June and trend of $\delta^{18}O$ depletion during monsoon; and (iii) trend of progressive enrichment in $\delta^{18}O$ during post-monsoon. In order to understand the underlying hydrometeorological processes governing the observed isotopic trends in rainwater, the trends as mentioned above in $\delta^{18}O$ are discussed in the following along with the corresponding variation in d-excess and other meteorological parameters.

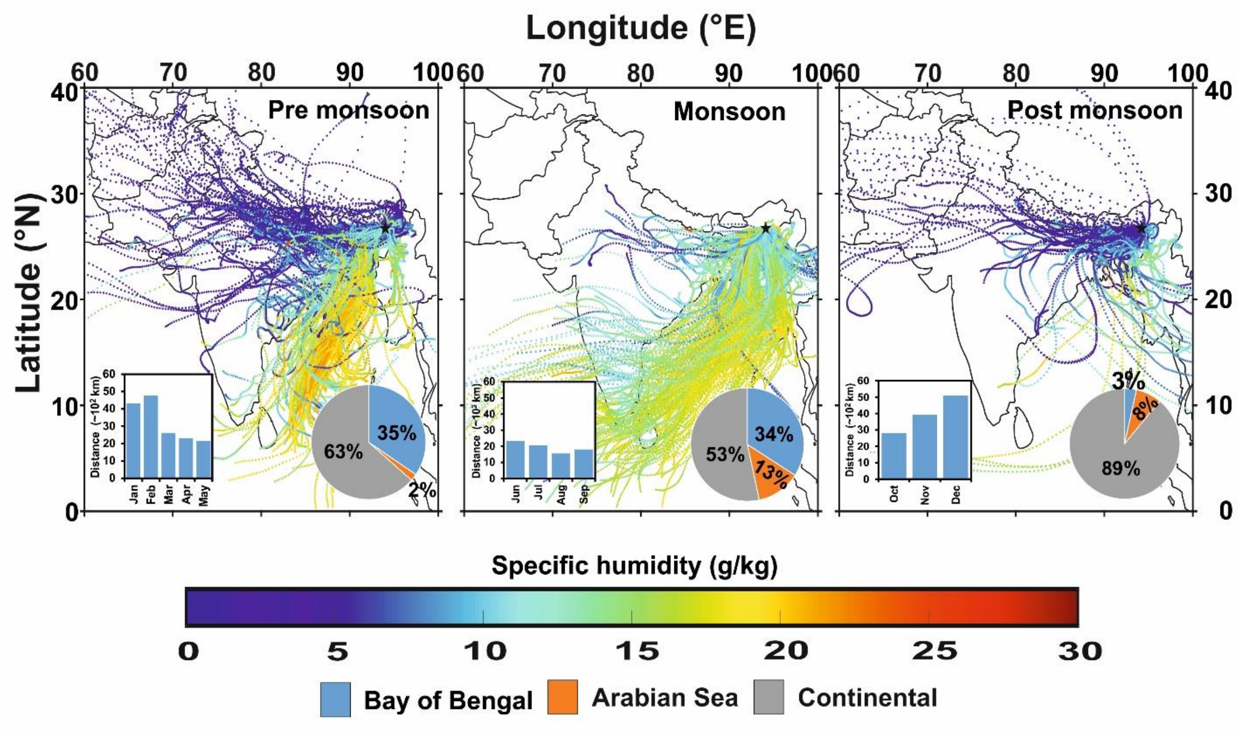

Figure 6. 3 Map showing seasonal ensembles of four 120 hrs. backward trajectories, starting from Jorhat. The colour code indicates specific humidity in g kg^{-1}. The inset pie charts represent the percentage source moisture contribution, represented by legends at the bottom. Whereas the inset bar charts show the monthly average distance travelled by the wind trajectories

(i) Enriched δ^{18}O in pre-monsoon with slight depleting trend

The overall δ^{18}O of rain samples during pre-monsoon (Jan-May) is enriched (> -5‰). Also, within pre-monsoon rainfall, there exists a slight depletion trend in δ^{18}O (~1‰ to ~-5‰) from January to May. The corresponding d-excess is also high (> 10‰), with exceptionally high d-excess values going up to ~18‰ during April and May. The overall high d-excess and enriched δ^{18}O during pre-monsoon indicates rainfall from continentally recycled moisture derived from the evaporated and hence isotopically enriched surface waters (wetlands and soil moisture) in and around Jorhat. It is further confirmed by the high contribution (63%) of continentally recycled moisture during pre-monsoon, estimated using 120 hrs backward wind trajectories (inset pie chart of Fig. 6.3).

The coefficient of diffusive fractionation for $\delta^{18}O$ is greater than that for δD for a given value of RH. Therefore, the d-excess is strongly dependent on the atmospheric humidity (Gonfiantini, 1986). Due to lower RH over continental areas compared to oceans, the continental moisture recycling tends to increase the d-excess in convecting vapour mass and the rainfall resulting from it (Froehlich et al., 2002). The two exceptionally high d-excess bumps (Fig. 6.2. b) during April and May can be attributed to deep convections associated with Nor'Westers. During deep convections and strong updraft, the moisture-laden air is uplifted to high altitudes, the atmospheric moisture (RH) tends to reduce with the rise in altitudes. Thus, passage of vapour mass through low relative humidity air column for a longer distance causes strong kinetic fractionation and consequently results in high d-excess in the uplifted vapour and the associated rainfall. It is further justified by the negative vertical wind velocities, indicating updraft, going as high as 300 hPa during April and May (Fig. 6.4).

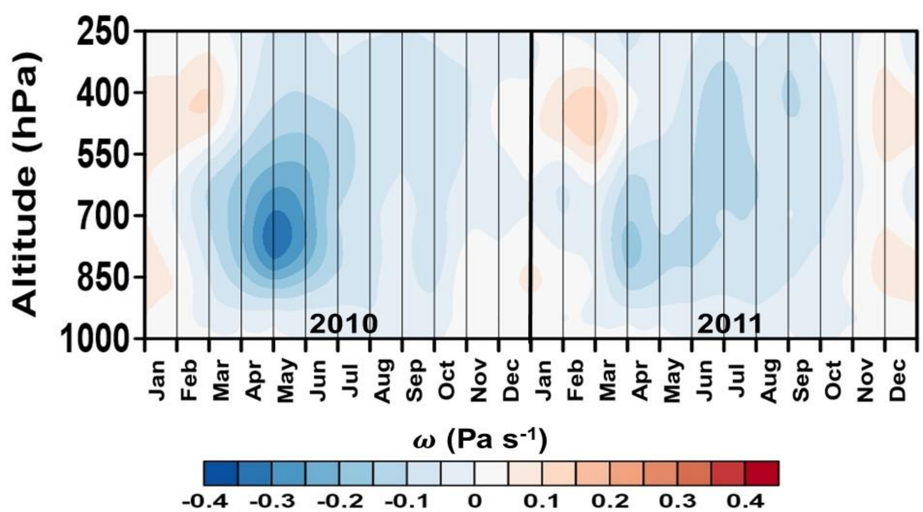

Figure 6. 4: Monthly variation in the vertical profile of vertical velocity (ω) during 2010 and 2011

The depleting trend in $\delta^{18}O$ during pre-monsoon can be ascribed to the ambient temperature change during pre-monsoon months. The average climatological air temperatures at 700 hPa (closest available temperature data to the height of maximum cloud liquid water content height; 750 hPa) show a steady rise during Jan-May (Jan: 19.1ºC; Feb: 21.1ºC; Mar: 25.0ºC; Apr: 28.4ºC and; May: 30.7ºC). The equilibrium fractionation factor is inversely proportional to the condensation temperatures; thus, with the increasing air temperature at condensation height, the magnitude of fractionation will decrease, resulting in the isotopic depletion in the rain as manifested in the observed trend of isotopic depletion during pre-monsoon.

(ii) A sudden shift in the baseline from mid-June and trend of δ^{18}O depletion during monsoon

The shift in the δ^{18}O baseline of ~4‰ in mid-Jun or July, and a trend of consistent isotopic depletion thereafter from July (δ^{18}O: ~-5‰) to September (δ^{18}O: ~-15‰) can be observed from Fig. 6.2. (a). This sudden shift in δ^{18}O can be attributed to the influx of marine vapour from the BOB due to the onset of monsoon. The trend of isotopic depletion can be attributed to the depletion in surface waters of BOB due to high riverine discharge [up to 12000 m^3 s^{-1}; Achyuthan et al. (2013)] and rainfall during Jun-Sep. However, the depletion in the BOB surface water is up to ~-2‰ during monsoon, which alone cannot explain the isotopic depletion of ~10‰ in rainfall at Jorhat. In spite of the fact that Jorhat is located close (~550 km) to the BOB, the maximum relative contribution (53%) of moisture to rainfall is by continental recycling (inset pie chart of Fig. 6.3), even during the monsoon, as estimated from 120 hrs backward trajectories. It is because of the Purvanchal Range and Garo-Khasi-Jaintia in southeast and south, which pose the orographic barrier to the moisture-laden winds from the BOB during monsoon. Thus, most of the moisture from the BOB rains out in the windward side of these mountains, and continental moisture from the valley contributes significantly. Therefore, the isotopic composition of surface water available for evapotranspiration and convection plays an important role in deciding the isotopic composition of recycled moisture, and the rainfall derived from it.

Due to glacial melting and heavy rains, northeast India experiences severe floods during July and relatively minor floods during September in the Brahmaputra River (Chowdhury and Sato, 1996). Based on decade long (1987-1998) flood dataset obtained from various discharge sites on the Brahmaputra and its tributaries, Dhar and Nandargi (2000) have reported the highest frequency of floods in the Brahmaputra and its tributaries during July. The low lying areas, flood plains and wetlands get fed by the floods during Jun-July. Lambs et al. (2005) have reported very depleted (δ^{18}O: -11.97‰ and δD: -85.35‰) isotopic values of the Brahmaputra River during August. Thus, the flood plains, wetlands and surface waters get replenished by the isotopically depleted waters. Therefore, the admixture of convection of evapo-transpired vapour from isotopically depleted continental waters and advected vapour from the BOB causes the sudden baseline shift (during mid-Jun or July) and depleting $\delta^{18}O$ trend throughout the monsoon.

(iii) The trend of progressive enrichment in $\delta^{18}O$ during post-monsoon

The distance travelled by the 120 hrs backward wind trajectories increases from October (~2800 km) to December (~5100 km) as seen from the inset bar chart in Fig. 6.3 post-monsoon. However, corresponding isotopic depletion due to rainout (Gonfiantini, 1986) is not observed in the rainfall samples. Instead, highly depleted values of $\delta^{18}O$ (-23.1‰ in 2010 and; -12.8‰ in 2011) in rainfall at Jorhat are found in October, which follow the trend of enrichment towards December.

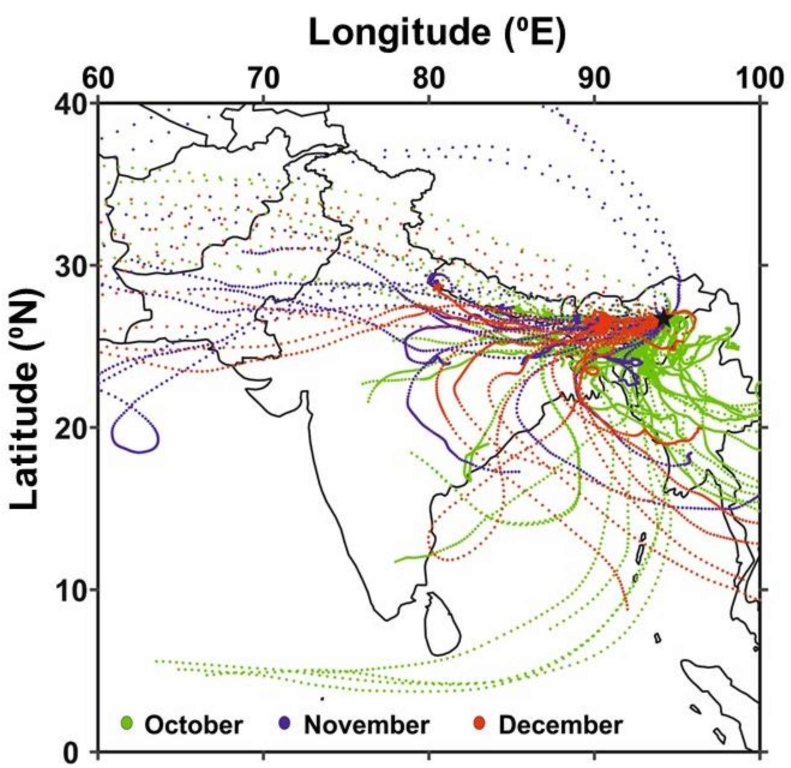

Figure 6. 5: Map showing directions of four 120 hrs. backward trajectories, starting from Jorhat during Oct-Dec.

As estimated from backward wind trajectories, 89% of the moisture in rainfall is contributed from continental recycling during post monsoon (inset pie chart of Fig. 6.3). Pathways traversed by the 120 hrs backward wind trajectories in each post-monsoon month (Oct-Dec) is shown in Fig. 6.5. During October, due to weakening of southwest winds and southward propagation of Inter-Tropical Convergence Zone (ITCZ), the southeasterly winds bring the continental moisture from Myanmar region to Jorhat. The southeasterly winds, in course of their travel from Myanmar (Fig. 6.5) to Jorhat, encounters the Purvanchal range, which causes orographic rainout and isotopic depletion in residual vapour (Gonfiantini, 1986). Also, the September floods cause the further isotopic depletion of surface waters in and around Jorhat. Thus, the admixture of continentally derived vapour from Myanmar and the local recycling causes the observed isotopic depletion ($\delta^{18}O$ < -12‰) in the rain during October. During November and December, probably due to Western Disturbances (WD), westerlies drawing moisture from the Indo-Gangetic plains and northeast regions enter Assam valley from the west (Fig. 6.5). West is the only open direction; thus, unlike northeasterly winds, the westerlies do not undergo orographic rainout and resultant isotopic depletion. Also, the surface waters of Indo-Gangetic plains (irrigated fields, soil moisture) and the northeastern region (wetlands and flood plains) which got replenished during monsoon, get isotopically enriched due to progressive evaporation. Thus, even though the distance traversed by 120 hrs backward trajectories increases from Oct toDec (inset bar charts of Fig. 6.3), because of the absence of orographic barrier in the west of Jorhat and progressive evaporative enrichment of surface waters cause the observed trend of isotopic enrichment in post-monsoon.

Lekshmy et al. (2014) at Kerala and Oza et al. (2020) at Ahemedabad have related annual trend of isotopic depletion to the increased fraction of convective rainfall during late/post-monsoon period. However, at Jorhat, no trend in convective rainfall analogous to annual isotopic depletion was observed (Fig. 6.6). It could be possibly because of the complex interplay of various hydrometeorological processes mentioned in the foregoing and not due to any single process.

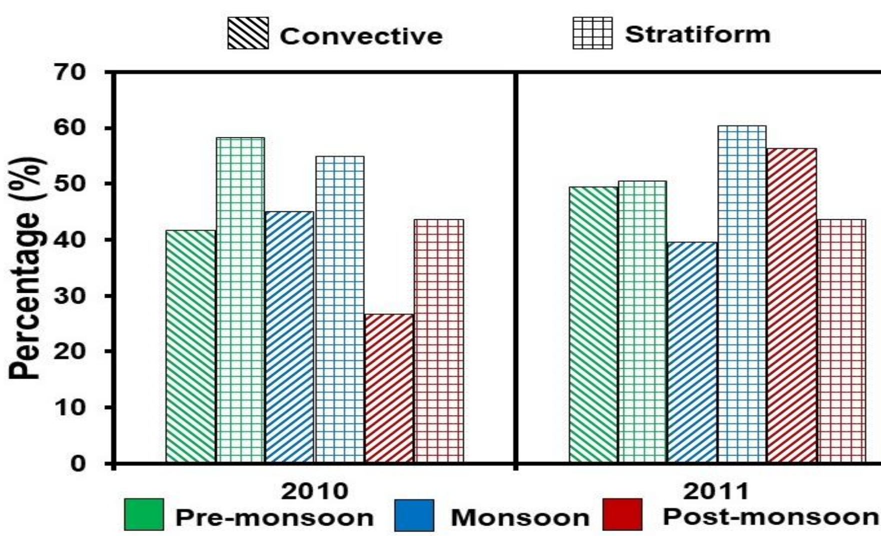

Figure 6. 6: Seasonal proportion of rain derived from convective and stratiform clouds during 2010-11

6.5. Conclusion

Important hydrometeorological processes concerning the rainfall of the northeast region are identified and studied based on the rigorous isotopic analysis of 257 daily accumulated rainfall samples, collected from Jorhat, in conjunction with various meteorological parameters. Some of the major inferences drawn from the study are as follows:

- Evaporation from falling raindrops is minimal at Jorhat, as indicated from the slope (8.3±0.1) of annual δ^{18}O- δD regression line slightly higher than that of GMWL.
- The contribution of continentally recycled moisture is maximum in the rainfall at Jorhat throughout the year, as indicated by the intercept (13±1) higher than that of GMWL and also estimated from 120 hr backward wind trajectories.
- The enriched δ^{18}O and high values of d-excess along with the slight trend of δ^{18}O depletion in the pre-monsoon are ascribed to continentally recycled moisture generated from progressively enriched surface waters and increased condensation temperature, respectively.
- The exceptionally high d-excess indicates deep convection associated with Nor'westers during April-May.
- The isotopic depletion of the surface waters, due to floods in Brahmaputra River together with depleted vapour advected from the BOB due to orographic rainout, causes the δ^{18}O baseline shift and a trend of δ^{18}O depletion during monsoon.
- The trend of isotopic enrichment in post-monsoon rainfall is ascribed to the evasion of the orographic barrier due to variation in wind direction (from southeast to west) and progressive isotopic enrichment of surface waters due to evaporation.

Chapter 7

Mesoscale Hydrometeorological Processes: Western India

Long term (2005-2016) daily precipitation isotope data ($\delta^{18}O$, δD and d-excess) from Ahmedabad in semi-arid Western India are examined in light of various meteorological parameters and air parcel trajectories to identify prominent patterns in the isotopic character and discern the underlying hydrometeorological processes. One of the most prominent and systematic annual patterns is the isotopic depletion (average $\delta^{18}O$: -2.5‰ in Jun-Jul; -5.2‰ in Aug-Sept) in the second half of the southwest monsoon, which is observed in the 10 out of the 12 years of this study. Four geographically feasible causal factors have been examined if they contribute to observed late monsoon isotopic depletion. These factors are: (1) increased contribution of terrestrially recycled vapour; (2) intra-seasonal change in sea-surface, surface-air and cloud base temperatures ; (3) increased rain-out fraction from marine vapour parcel; and (4) increase in relative proportion of convective rain. It is inferred from the present study that isotopic depletion in the second half of southwest monsoon is associated with: (i) increased contribution (45% from 36%) of terrestrially recycled moisture; (ii) 1.9° C lower cloud base temperature; (iii) increased rainout fraction due to decreased wind velocity (6.9 m/s from 8.8 m/s); and (iv) an increase of 22.3% in the proportion of convective rain. Daily rain events with atypical isotopic composition (20‰ < d-excess <0‰) are ascribed mainly to local weather perturbations causing sudden updraft of moist air facilitating terrestrial recycling of water vapour.

7.1 Introduction

Western India comprise of Indian states of Gujarat, Rajasthan, Maharashtra and Goa. It occupies an area of 508,032 km^2 of total land area. It receives ~985 mm of annual rainfall. Southwest monsoon (Jun-Sep) contributes 91% (~897 mm) of region's annual rainfall. Western India has varied climatic zones, according to Koppen climatic classification, Gujarat and Rajasthan experience semi-arid to arid climate whereas, Maharashtra and Goa experiences Tropical wet and dry climate. The annual rainfall in arid and semi-arid regions of western India is ~732 mm. The low rainfall in this region is attributed to (i) the geographical alignment of Aravalli Range, which lies parallel to the Arabian Sea (AS) branch carrying southwest monsoonal winds. Thus, orographic precipitation is not possible and; (ii) the uplifting of warm and dry air, due to heating of Thar desert and Rann of Kutchh, inhibits condensation (Das, 2005). However, ~54% of total geographical area is under agriculture and the livelihood of majority of people of this region is directly or indirectly dependent on agriculthure. Therefore, understanding hydrometeorology of the region is important because it controlls the distribution and availability of water.

Ahmedabad city (23.03°N; 72.55°E) in the hot semi-arid western India is an important geographic location to investigate the hydrometeorological processes because it has been experiencing erratic weather extremes such as heatwaves, cloud bursts, floods and droughts superposed on the climate normals.

To understand the hydrometeorological processes, stable isotopes of oxygen and hydrogen in precipitation are very important tracers, which can provide information about the source of vapour, rainout history, vapour recycling, post-precipitation modifications and cloud microphysical processes. Several isotope studies have provided useful insights about hydrometeorological processes relevant in different parts of the country (Breitenbach et al., 2010; Deshpande and Gupta, 2012; Deshpande et al., 2013b; Jeelani et al., 2018; Jeelani et al., 2017; Lekshmy et al., 2015; Midhun et al., 2018; Rahul and Ghosh, 2018; Saranya et al., 2018; Warrier and Babu, 2011).

With the long term perspectives, stable isotopes of oxygen and hydrogen have been monitored in daily precipitation at Ahmedabad for 12 years (2005-2016) under the aegis of a National Program on Isotope Fingerprinting of Waters of India (IWIN) (Deshpande and Gupta, 2008; Deshpande and Gupta, 2012). A rigorous analysis of this important isotope dataset in conjunction with other ground-based and remotely sensed meteorological parameters is presented here with a view to understand the hydrometeorological processes revealed by observed isotopic trends in precipitation of this region.

7.2 Climate

The summer (Mar-Apr-May), monsoon (Jun-Jul-Aug-Sept), and winter (Nov-Dec-Jan-Feb) are the three main seasons witnessed by Ahmedabad city in the hot semi-arid western India, with transition from warm - wet climate to cold - dry climate in Oct. Except during monsoon months, weather is mostly dry with average annual RH being 55%. During summers the average maximum temperature is 43^{o}C whereas, during winters the average minimum temperature is 13^{o}C. The long term (1981-2010) average annual rainfall at Ahmedabad is ~80 cm of which ~93% occurs in 30-35 rainy days during four monsoon months (Deshpande et al., 2015). Southwest monsoon is the major driving mechanism which brings rain to this region during Jun-September (Das, 2005). The Indian summer monsoon is driven by the seasonal reversal of wind pattern controlled by the temperature and pressure gradients and associated with the annual northward and southward motion of the intertropical convergence zone (ITCZ). For detailed meteorological information about Ahmedabad, reference is made to the Government of India website of India Meteorological Department (IMD), Meteorological Centre, Ahmedabad (http://www.imdahm.gov.in/).

7.3 Data Used

Under the aegis of a National Programme on Isotope Fingerprinting of Waters of India (IWIN), a total of 368 daily rain events have been sampled in this study over a period of 12 years from 2005 to 2016 for their oxygen and hydrogen isotopic investigations to discern the underlying hydrometeorological processes. The details of sample collection and isotopic analysis is presented in Chapter 3.

The details of other meteorological parameters derived from satellite, modelled and reanalysis open platforms, which are used for interpreting isotope data of Ahmedabad are listed below:

- Ensembles of five 120 hr back wind trajectories, each starting at six hourly intervals and at the height of 1500 m from Ahmedabad is obtained from Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model [http://ready.arl.noaa.gov/HYSPLIT.php (Stein et al., 2015)]. Percentage moisture contribution from each source (AS, BOB and Continentally recycled moisture) and average distance travelled by the wind trajectories are computed using the specific humidity and geographical coordinates, (Sodemann et al., 2008a; Sodemann et al., 2008b).

- Sea surface temperature in the box of 10.3-23.5° N; 55.0-73° E, for the study period (2005-2016), obtained from NOAA's Extended Reconstructed Sea Surface Temperature (ERSST) data downloaded from http://apdrc.soest.hawaii.edu (Huang et al., 2017).
- Monthly climatological (1981-2010) average tropospheric air temperature data was obtained from NCEP/NCAR Reanalysis (Kalnay et al., 1996) at 850 hPa (cloud base height) over the area between 10.3° N-23.5° N and, 55.0° E-73.0° E (downloaded from www.apdrc.soest.hawaii.edu) for the months of Jun-Sep.
- Monthly climatological (1981-2010) mean wind speed data at 850 hPa (cloud base height) was obtained from NCEP/NCAR Reanalysis (Kalnay et al., 1996) over the area of 15-25° N and 60-70° E (downloaded from www.apdrc.soest.hawaii.edu).
- Monthly averaged outgoing long wave radiation (OLR) data from KALPNA1 – VHRR was downloaded from www.mosdac.gov.in for the period of 2005-12.

7.4 Results and Discussion

The amount weighted average $\delta^{18}O$ of all (N = 368) daily precipitation samples is -4.0±3.3‰, which also includes 39 rain events with typical $\delta^{18}O$ values but atypical d-excess values of >20‰ or <0‰. If such rain events are ignored, the amount weighted average $\delta^{18}O$ (i.e. d-excess within 10±10‰; N = 329) is -4.1± 3.3 ‰. Majority of these atypical events were observed during monsoon however, six of such events have also occurred during the non-monsoon period. The $\delta^{18}O$ and δD of the 39 daily rain samples with atypical d-excess were reanalyzed to confirm that the observed isotopic composition is indeed a genuine imprint of peculiar hydrometeorological process.

A long term (12 years: 2005-2016) daily time-series of $\delta^{18}O$, d-excess, temperature, Relative Humidity (RH) and amount of daily rainfall for typical rain events (d-excess: 10±10‰) is plotted in Fig. 7.1, along with annual rainfall and number of rainy days for each year. Width of the time-series for each year represents the number of rainy days in that year. One of the most prominent and systematic annual patterns emerging from Fig. 7.1 is that of isotopic depletion (lower $\delta^{18}O$) in the second half of the southwest monsoon, observed in the 10 out of the 12 years of this study (except 2007 and 2013). The average $\delta^{18}O$ values for the months of Aug-Sept (-5.2 ‰) during 2005 to 2016 is 2.7 ‰ lower than that for Jun-Jul (-2.5 ‰). No significant correlation between $\delta^{18}O$ or d-excess and temperature or RH were observed, suggesting that the observed (Fig. 7.1) decreasing trend in $\delta^{18}O$ in the second half of the southwest monsoon is not related to

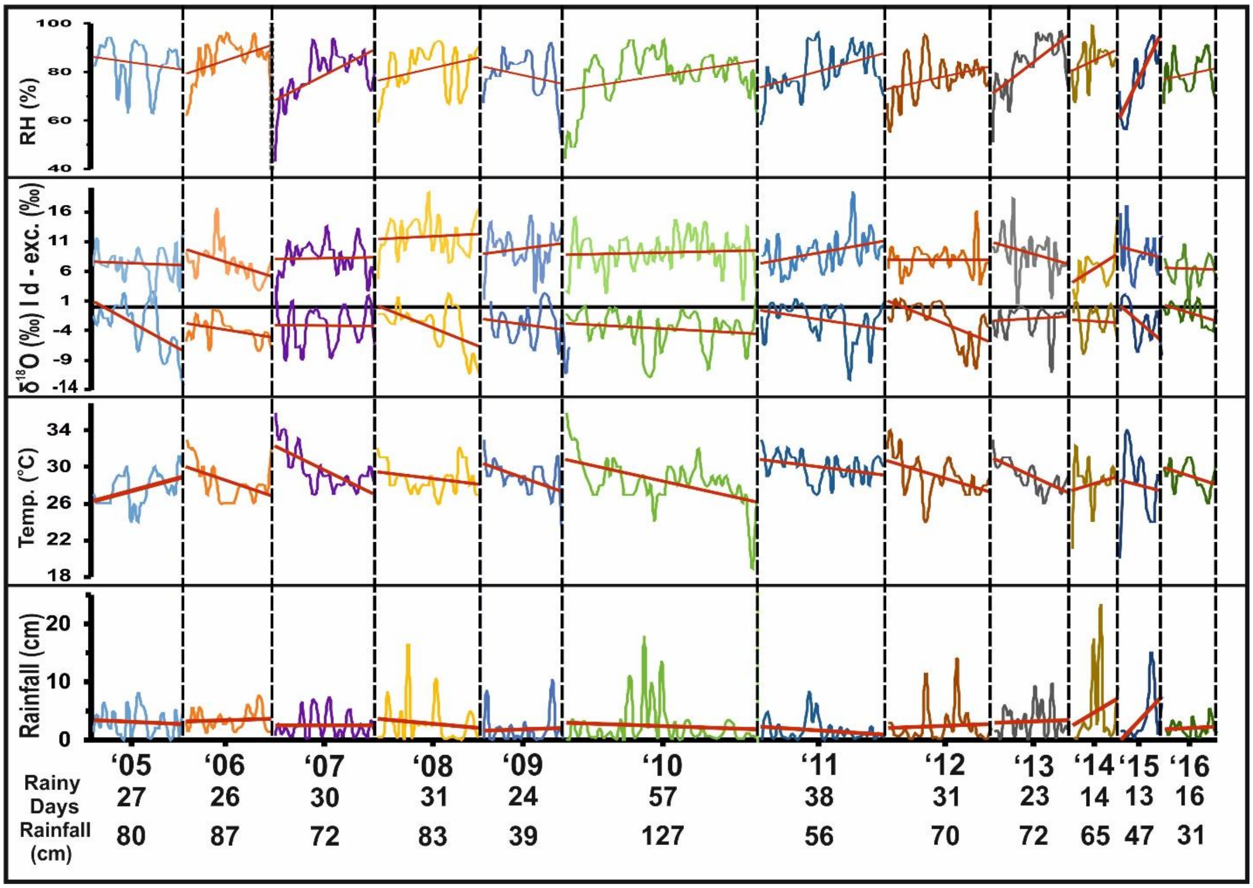

Figure 7. 1: A long term (12 years: 2005-2016) daily time-series of $\delta^{18}O$, d-excess, temperature, RH and amount of daily rainfall for typical rain events (d-excess: 10±10‰) is shown, along with annual rainfall and number rainy days for each year. Width of the time-series for each year represents the number of rainy days in that year.

temperature, amount of rainfall and RH during the corresponding period.

A plot of amount weighted monthly average $\delta^{18}O$ versus monthly rainfall for typical rain events (Fig. 7.2a) shows statistically insignificant (R^2 = 0.05; p = 0.2) relationship between the two, if all months are considered together. A plot of amount weighted monthly average $\delta^{18}O$ versus average monthly temperature for typical rain events (Fig. 7.2b) also reveals that the monthly average $\delta^{18}O$ is not related ($R^2 = 0.005$; $p = 0.7$) to average monthly temperature. Thus, there is an obvious lack of any amount effect or temperature effect even on monthly timescale.

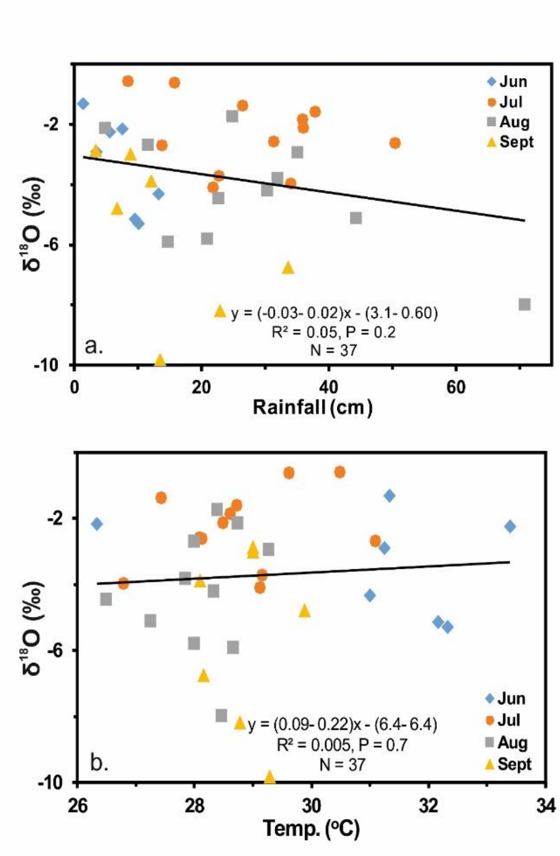

Figure 7. 2: Amount weighted monthly average $\delta^{18}O$ versus monthly rainfall for typical rain events versus their (a) cumulative monthly rainfall and (b) average monthly temperature

The lack of any relationship between the isotopic composition of daily precipitation and weather parameters suggests the role of extraneous hydrometeorological processes/ factors behind the observed systematic isotopic depletion in second half of southwest monsoon, which needs to be explained. It is also to be noted that the observed systematic decrease in $\delta^{18}O$ in the second half of southwest monsoon is not accompanied by any correspondingly systematic pattern in d-excess suggesting the role of processes other than the simple open system of Rayleigh rainout (Gat, 1996).

Several studies have discussed that in view of unclear relationship between oxygen and hydrogen isotopes in precipitation and, temperature and amount of rainfall, conventional framework of Rayleigh distillation may not be adequate to understand the underlying processes. This is due to the fact that the amount and temperature dependencies of isotopic variation may be substantially influenced by vapour source variation, cloud dynamics and mixing of vapour masses which can vary over short space-time scales under favorable conditions (Aggarwal et al., 2012; Aggarwal et al., 2016; Lee et al., 2012; Lekshmy et al., 2015; Lekshmy et al., 2014). The hydrometeorological processes are indeed more complex in Indian subcontinent due to dual monsoon system, proximity to two marine water bodies of the AS and the Bay of Bengal (BOB) with different temperature regimes, the seasonal oscillation of ITCZ and presence of Himalayas as major orographic barrier (Breitenbach et al., 2010;

Deshpande and Gupta, 2012; Deshpande et al., 2013b; Deshpande et al., 2010; Jeelani et al., 2018; Jeelani et al., 2017; Lekshmy et al., 2015; Midhun et al., 2018; Saranya et al., 2018; Warrier and Babu, 2011).

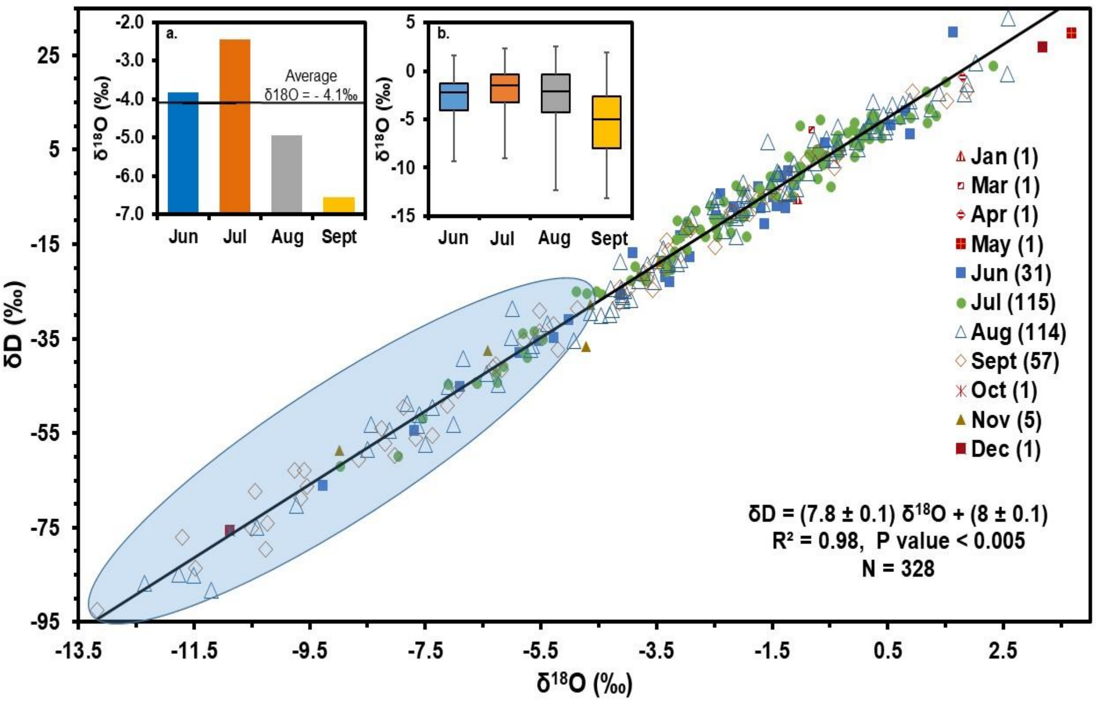

Figure 7. 3: The δ^{18}O-δD regression for typical rain events identified according to their month. Number of daily events in each month is mentioned in the parenthesis. Highlighted within ellipse are rain samples with depleted isotopic composition. Inset a and b shows monthly amount weighted average δ^{18}O and box and whisker plot for the four months of southwest monsoon.

The δ^{18}O-δD regression for typical rain events is plotted in Fig. 7.3, with month-wise identification of each daily rain event. The inset (a) in Fig. 7.3 shows the amount weighted monthly average δ^{18}O values for the four southwest monsoon months and also the 12 years average annual δ^{18}O of daily precipitation (-4.1‰). The δ^{18}O-δD regression line [$\delta D = (7.8 \pm 0.1)\times\delta^{18}O + (8 \pm 0.1)$] for typical rain events at Ahmedabad has a slope comparable to that of the global meteoric water line (GMWL), but the intercept is lower than that for the GMWL [slope: 8.17±0.07; intercept: 11.27±0.65; Rozanski et al. (1993)] indicating secondary evaporation from the falling raindrop. Vertical profiles of precipitation obtained with 16 years of Tropical Rainfall Measuring

Mission's (TRMM) precipitation radar also shows the predominance of evaporation in northwest India (Rao et al., 2016; Saikranthi et al., 2014).

The prominent observation in the inset (a) of Fig. 7.3 is that monthly average $\delta^{18}O$ values in the second half of the southwest monsoon (Aug: -5‰; Sept: -6.5‰) are distinctly lower than the $\delta^{18}O$ values in the first half (Jun: -3.8‰; Jul: -2.5‰), which confirms that isotopic depletion in precipitation in the second half of the southwest monsoon is a systematic phenomenon which is also captured in the daily time series (Fig. 7.1). Several other studies in different parts of India have also reported similar isotopic depletion during post monsoon or late monsoon. For instance, Lekshmy et al. (2015) in Kozhikode, Rahul and Ghosh (2018) in Bangalore have reported depleting trends in $\delta^{18}O$ of post-monsoonal rain and have suggested that the increased contribution from depleted water of BOB is causing isotopic depletion in precipitation at respective stations. Sengupta and Sarkar (2006) have ascribed isotopic depletion in rainfall at Kolkata to the shift in the origin of the monsoon depression from northern to southern BOB, resulting in a longer rainout history of the air parcel. Breitenbach et al. (2010) have inferred that massive fluvial runoff from isotopically depleted Himalayan rivers cause isotopic depletion in surface waters of BOB which results in initially depleted vapour source giving rise to isotopically depleted rainfall in southern Meghalaya in late southwest monsoon. Midhun et al. (2018), however, based on the climatological $\delta^{18}O$-Salinity relationship and estimated $\delta^{18}O$ of surface water have argued that evaporation from freshwater plume in the head BOB region can not contribute to the observed trend in $\delta^{18}O$ of precipitation. Also, Midhun et al. (2018) have observed that ^{18}O depleted rain events at Bhopal and Ahmedabad are associated with trajectories from both the AS and the BOB with only a slight dominance of trajectories from the BOB. Above studies link isotopic depletion in the second half of the monsoon or post-monsoon mainly to the processes concerning the BOB. However, vapour contribution from the BOB is minimal at Ahmedabad (Deshpande et al., 2015), and the above explainations for late monsoon depletion may not be justified for Ahmedabad.

Two important scientific questions emerging from the above observations are: (i) What are the factors/phenomena that cause the observed isotopic depletion at Ahmedabad in the second half of the southwest monsoon? (ii) What causes the atypical isotopic composition of certain daily rain events (n = 39) with d-excess > 20‰ and <0‰?

(1) Late monsoon isotopic depletion

Based on the isotopic and meteorological considerations, the observed isotopic depletion in rain at Ahmedabad in the second half of the southwest monsoon can be ascribed to four possible factors: (a) intra-seasonal change in the sea-surface, surface-air and cloud base temperatures; (b) increased rainout fraction from marine vapour parcel; (c) increased contribution of terrestrially recycled vapour; and (d) Increased proportion of convective rain. These possibilities are examined in the following subsections.

(i) Effect of Intra-seasonal temperature change

Temperatures at three locations, namely, (a) sea surface in the marine source region, (b) at condensation height and (c) in the air column below cloud through which raindrops fall, can affect the isotopic composition of the sampled precipitation.

(a) Sea-surface temperature in marine source region

Average sea surface temperature of the AS shows that the average SST was higher during June (29.1±0.7 ^{o}C) and lower during September (27.2±1 ^{o}C). Since the magnitude of fractionation is inversely related to temperature (Horita and Wesolowski, 1994), the vapour generated from the AS during September (27.2 ^{o}C; 85% RH) would be ~0.2‰ depleted in ^{18}O as compared to that generated during June (29.1 ^{o}C; 85% RH). This factor can contribute to some extent to the observed isotopic depletion in rain during the second half of southwest monsoon.

(b) Cloud base temperature

To estimate the likely effect of seasonal change in cloud base temperature on isotopic compsoition of rain, the average climatological air temperature (at 850 hPa) was used. During June average air temperature was 21.6 ^{o}C whereas, that of September was 19.7 ^{o}C. This 1.9 ^{o}C lower condensation temperature during the second half of southwest monsoon corresponds to a small increase of 0.16‰ in fractionation ($^{18}\varepsilon = (^{18}\alpha - 1) \times 1000$ in ‰) for oxygen (Horita and Wesolowski, 1994) resulting in relatively ^{18}O enriched rain and ^{18}O depleted residual vapour. Therefore, after each successive stage of condensation along the air parcel trajectory, the residual vapour will certainly become progressively more depleted in ^{18}O during September compared to June. This factor can contribute to observed isotopic depletion in the second half of southwest monsoon.

(c) Surface air temperature

The ground level temperature at Ahmedabad is seen to decrease as the southwest monsoon progresses, during all years except two (Fig. 7.1). Temperature comes down after the onset of rainy season because of the increased water availability on surface, in soil and ecological pool due to rainfall and consequent lowering of temperature corresponding to latent heat of vaporization (Camargo et al., 2005; Trenberth and Shea, 2005). Under lower surface air temperature and high relative humidity during second half of southwest monsoon the scope of evaporation from falling raindrops reduces which should result in isotopically lighter rain. This, however, is not the case because isotopic depletion is also observed in those years (2005 and 2014) when corresponding lowering of surface air temperature in the second half of southwest monsoon is not observed. Also in year 2007, the expected lower temperature is observed in the second half of southwest monsoon but corresponding isotopic depletion is not observed.

Among the sea-surface, cloud base and air temperatures, decrease in the cloud base temperature can have a more prominent effect of lowering the isotopic composition of resultant rain because it can play iterative role at each successive stage of condensation during air parcel trajectory.

(ii) Effect of increased rainout fraction

The fluctuation in rainfall along the west coast of India is related to monsoon circulation in the AS (Das, 2005; Narayanan et al., 2004). The observed isotopic depletion in the second half of southwest monsoon can also be caused if there is relatively higher amount of rainout from marine vapour parcel before reaching the study area. This can happen either due to increased intensity of precipitation, or increased distance traversed by air-parcel or longer time spent before reaching Ahmedabad.

Wind speeds (Climatological average) during second half of southwest monsoon (Aug: 8.7 m/s and Sept: 5.1 m/s) is found to be lower by ~2 m/s compared to the first half of the monsoon (Jun: 7.8 m/s and Jul: 9.8 m/s). This reduction in speed has consequence on time spent over the unit area by the air parcel before reaching the study area. Using ensembles of five 120 hour back trajectories, generated by HYSPLIT model, it was found that on an average the number of hours spent in an area (60-70 ^{o}N and 15-25^{o}E) over the AS by the wind trajectories before reaching

Ahmedabad was 7.4 hrs more in the second half (Aug: 35.2 hrs. and Sept: 44.7 hrs.) compared to the first half of the monsoon (Jun: 31.4 hrs. and Jul: 33.7 hrs). Using the approach of change in the specific humidity in the HYSPLIT back trajectories (Sodemann et al., 2008a; Sodemann et al., 2008b), ~44% more rainout is estimated in the month of September compared to June.

A first-order estimate of the extent of higher rainout required to account for the observed isotopic depletion in the second half of southwest monsoon of -2.7‰ (i.e from -2.5‰ in Jun-Jul to -5.2‰ in Aug-Sept) can be made using simple Rayleigh distillation model [$\delta^{18}O_{vapor} = \delta^{18}O_{vapor\text{-}initial} + {}^{18}\varepsilon \times \ln f$ and $\delta^{18}O_{rain} = \delta^{18}O_{vapor} + {}^{18}\varepsilon$] (Clark and Fritz, 1997a; Gupta and Deshpande, 2003). In this formulation, f is the residual vapour fraction taken as the ratio of saturation vapour pressure at variable condensation temperature and that at the ocean surface temperature (25 °C). Considering $\delta^{18}O$ of the AS surface water = 0‰; temperature = 25°C and RH = 85%, the $\delta^{18}O$ of vapour above the boundary layer in the AS is estimated as -11.5‰ [$\delta^{18}O_{vapor\text{-}initial} = \delta^{18}O_{marine\ water} - ({}^{18}\varepsilon + \Delta^{18}\varepsilon)$] (Clark and Fritz, 1997a; Gupta and Deshpande, 2003). In this formulation, $\Delta^{18}\varepsilon$ is the kinetic enrichment for ^{18}O. The value of $\Delta^{18}\varepsilon$ at 85% RH is computed using simplified equation by (Gonfiantini, 1986). The rainout fraction (1-f) computed using simple Rayleigh approach reveals that just 23% increase in rainout can account for 2.7‰ lowering of $\delta^{18}O$ in the second half of southwest monsoon under the assumed conditions.

The longitudes from where vapour is generated during southwest monsoon might also be influenced by low level (below ~800 hPa) temperature inversion in the AS, also known as thermal inversion or monsoon inversion (Das, 2005; Dwivedi et al., 2016). The cross-equatorial low-level Somali jet stream creates upwelling of cold seawater and lower surface air temperature in the western AS. Advection of hot air from Arabian desert over this low temperature air mass creates a thermal inversion. This thermal inversion inhibits convective uplifting of moisture from the AS and prevents the cloud formation. The Moisture Inversion extends upto 65 °E in the AS during beginning of southwest monsoon and prevents cloud building activity west of 65 °E in the AS. The change in monsoon inversion in terms of base altitude inversion, temperature difference [$\Delta T = T\ (950\ hPa) - T\ (850\ hPa)$] and the percentage occurrence of monsoon inversion days during month of July and August reveals that inhibiting effect of thermal inversion recedes farther west-southwestwards in August compared to July (Dwivedi et al., 2016). This means that the moisture pick up region moves farther away into the AS, entailing longer distance to be traversed before reaching Ahmedabad.

It is expected that thermal inversion over such a huge area of several thousand km^2 in the moisture source region of the AS should have some manifestation in intra-seasonal variations of rain isotopic composition. The observed isotope depletion in the second half of southwest monsoon may have linkages with this well-known monsoon inversion but has not been tested so far. In order to test this hypothesis independently, monthly averaged OLR was studied (Fig. 7.4). The high OLR values indicate cloud-free conditions whereas, low OLR values indicate convective cloud building activities (Mahakur et al., 2013). The progressively westward spread of lower OLR (< 240 W/m^2) from June to September (Fig. 7.4) suggests increasing cloud building from farther west of 65 °E in AS. Clouds originating from distant regions in the second half of southwest monsoon can result in isotopically depleted rains at Ahmedabad. However, this possibility is not supported by the back trajectory analyses because the wind trajectories (Fig. 7.5) associated with rain events at Ahmedabad do not overlie the regions with low OLR (Fig. 7.4).

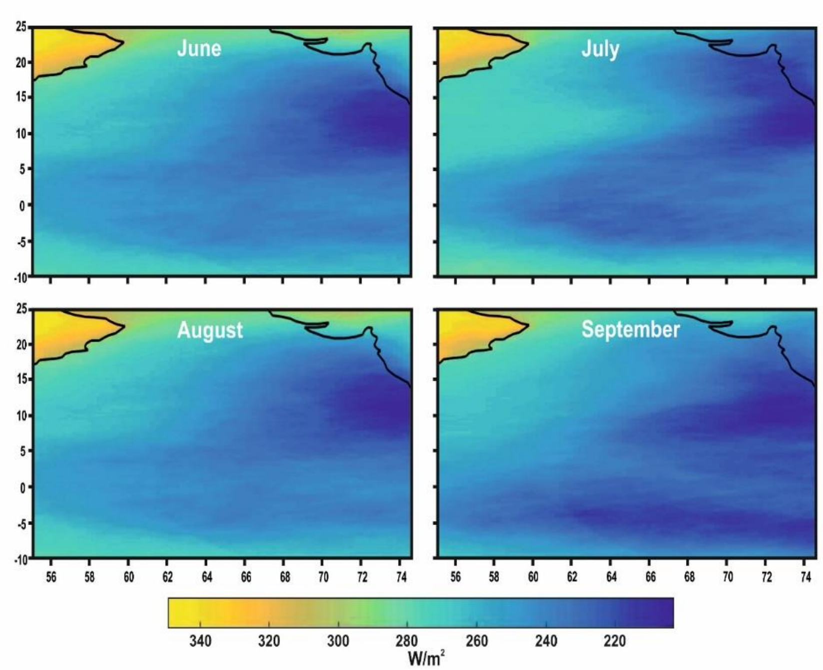

Figure 7. 4: Mean (2005-12) monthly OLR over AS for Jun-Sep. Colour code represents OLR values in W/m^2

(iii) Effect of increased contribution of recycled moisture

Another possible reason for isotopic depletion in second half of southwest monsoon is increased contribution of continentally recycled moisture to the precipitation. Warrier and Babu (2011) have ascribed the depleting trend in isotopic composition of rain in Hyderabad in Southern India during post monsoon to increased contribution of continentally derived moisture. Based on

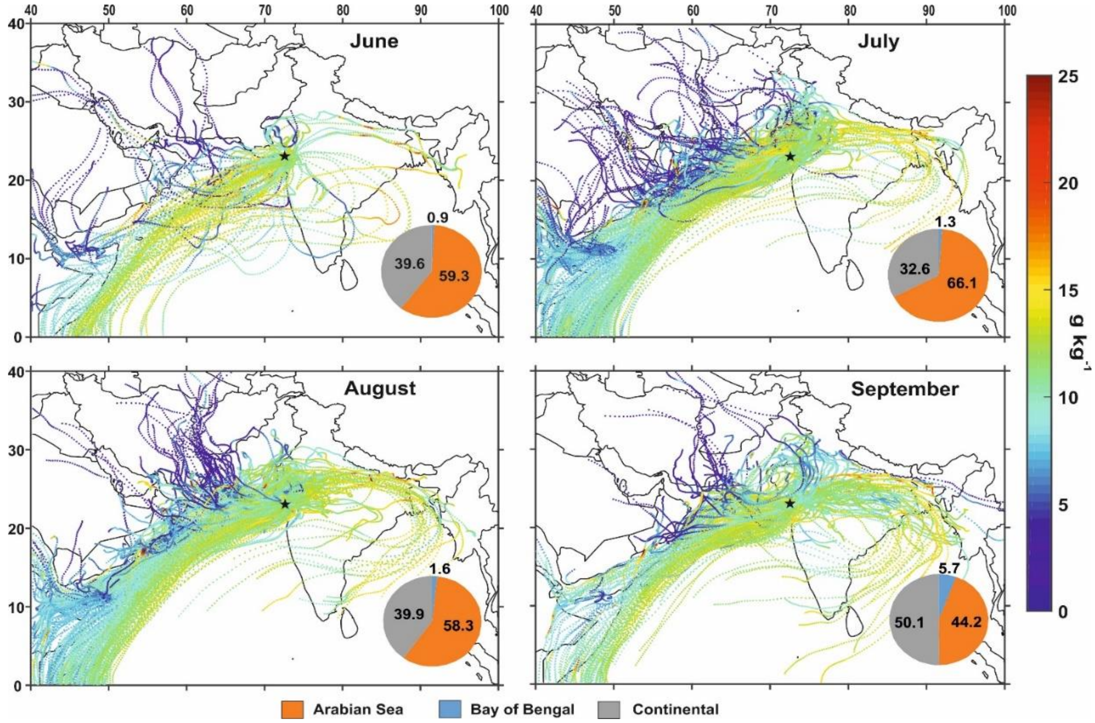

Figure 7. 5: Map showing Ensembles of five 120 hrs. back trajectories initiating at six hourly interval at 1.5 km above ground level (agl), for each daily rain event (including atypical; 20 ‰ < d-excess > 0 ‰) at Ahmedabad, for four southwest monsoon months. The colour code indicates specific humidity in g kg^{-1}. The inset pie charts represent the percentage source moisture contribution, represented by legends at the bottom.

4 years' (2005-2008) daily precipitation data at Ahmedabad, Deshpande et al. (2015) have already shown that about 24% of monsoon rainfall at Ahmedabad is derived from continentally recycled vapors, but in the months of Aug-Sept this proportion increases significantly. In the present study, also wind trajectory analyses have been done. The resultant backward trajectory map (Fig. 7.5) of specific humidity for all the rain events (including atypical rain events) during the southwest monsoon months (Jun-Sept) shows the direction of air-parcel trajectory and variation in the specific humidity of air-parcel in the course of its transportation. The percentage contribution of vapour from the AS, the BOB and the continental recycling during each month of southwest monsoon computed by the method described earlier is shown in the inset pie charts of Fig. 7.5. The average percentage contribution of continentally derived moisture increases significantly from 36.1% in Jun-Jul to 45.0% in Aug-Sep during the second half of southwest monsoon. This observation confirms that increased contribution of continentally derived vapour contributes to the isotopic depletion in the second half of the southwest monsoon. Terrestrial water source in western

India is isotopically lighter [Groundwater: -2.7‰ (Deshpande, 2006); average rainwater: -3.9‰ (Deshpande et al., 2010)] compared to marine water (0±0.5‰) therefore vapour generated from terrestrial water source is expected to be isotopically lighter compared to marine vapour. Increased contribution of continentally derived vapour in second half of southwest monsoon associated with isotopic depletion suggests that the terrestrial water with depleted isotopic composition contributes to depleted values in rainfall. In this part of country, agriculture is extensively dependent on groundwater, which is spread in the agriculture field together with rainwater, which forms major terrestrial vapour source. Thus, increased contribution of terrestrially recycled moisture can substantially contribute to isotopic depletion in the second half of southwest monsoon. It is to be noted that the average contribution of terrestrial moisture in monsoonal rain estimated in the present study (~40.5%) is much more than that (24%) estimated earlier by Deshpande et al. (2015). Also, contrary to observation by Midhun et al. (2018) based on one year's (2013) data, the estimate of moisture contribution from the BOB for rains at Ahmedabad, based on long term isotope data of this study, is found to be negligible (Jun-Jul: 1.1% and Aug-Sept: 3.6%).

Thus, it is inferred that the isotopic depletion in the second half of southwest monsoon at Ahmedabad is related to the contribution of terrestrially recycled moisture and not related to change in the moisture contribution from the BOB.

(iv) Effect of variation in stratiform and convective cloud types

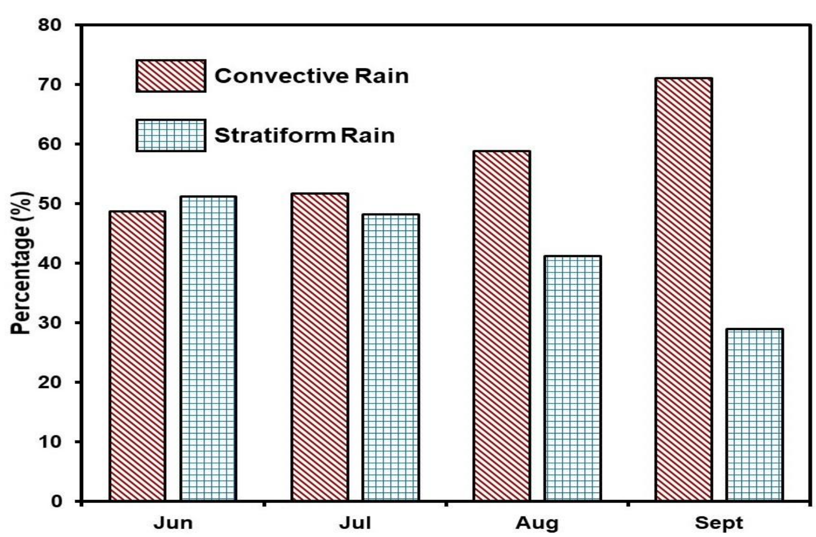

Figure 7. 6: Monthly proportion of rain derived from convective and stratiform clouds at Ahmedabad during the summer monsoon, computed based on TRMM data for 16 years (1998-2013)

There are differences in rain formation processes involved in stratiform and convective clouds, which have been variedly associated with observed isotopic composition of resultant rainfall (Aggarwal et al., 2016; Lekshmy et al., 2014). In order to examine if observed isotopic depletion in the second half of southwest monsoon at Ahmedabad is associated with rain from different cloud types, the proportion of rain from stratiform and convective clouds have been identified based on 16 years (1998-2013) TRMM (2A25) data (Rao et al., 2016; Saikranthi et al., 2014) and plotted in Fig. 7.6. It is seen that percentage of convective rain progressively increases during June (48.7%), July (51.7%), August (58.8%) and September (71%) of southwest monsoon. Thus, proportion of convective rain increases by 22.3% from June to September. Lekshmy et al. (2014) based on rainwater samples at several locations in southern India have shown that isotopically depleted rain events are associated with convective rains. It is therefore, inferred that 22.3% increase in convective rain may contribute to isotopic depletion in the later part of monsoon.

(2) Isotopically erratic rain events

In the preceding section, a broad picture of hydrometeorological processes is generated from a large isotope dataset of precipitation with typical isotopic composition (d-excess within 10±10‰). On the other hand, sporadic daily rain events with atypical d-excess (20‰ < d-excess <0‰) but usual $\delta^{18}O$, are also very important indicators of unusual hydrometeorological processes and weather phenomena, which may not be obvious from their amount of rainfall or temperature. Considering the frequent occurrence of erratic weather events across the world, it is important to detect and study such events identified through their isotopic signatures.

To understand such erratic rain events the $\delta^{18}O$- δD regression lines for all rain events including atypical ones and only typical daily rain events have been plotted in Fig. 7.7, with samples grouped into various classes according to their amount of rainfall and d-excess. When only typical rain events are considered, the $\delta^{18}O$- δD regression line slope (7.8±0.1) is close to global meteoric waterline, however, when all samples including erratic ones are considered the slope (7.0±0.2) is much less. The $\delta^{18}O$-δD regression line for only erratic rain events has slope of 3.5 and intercept of -10.9 with a large scatter, hence the same is not plotted.

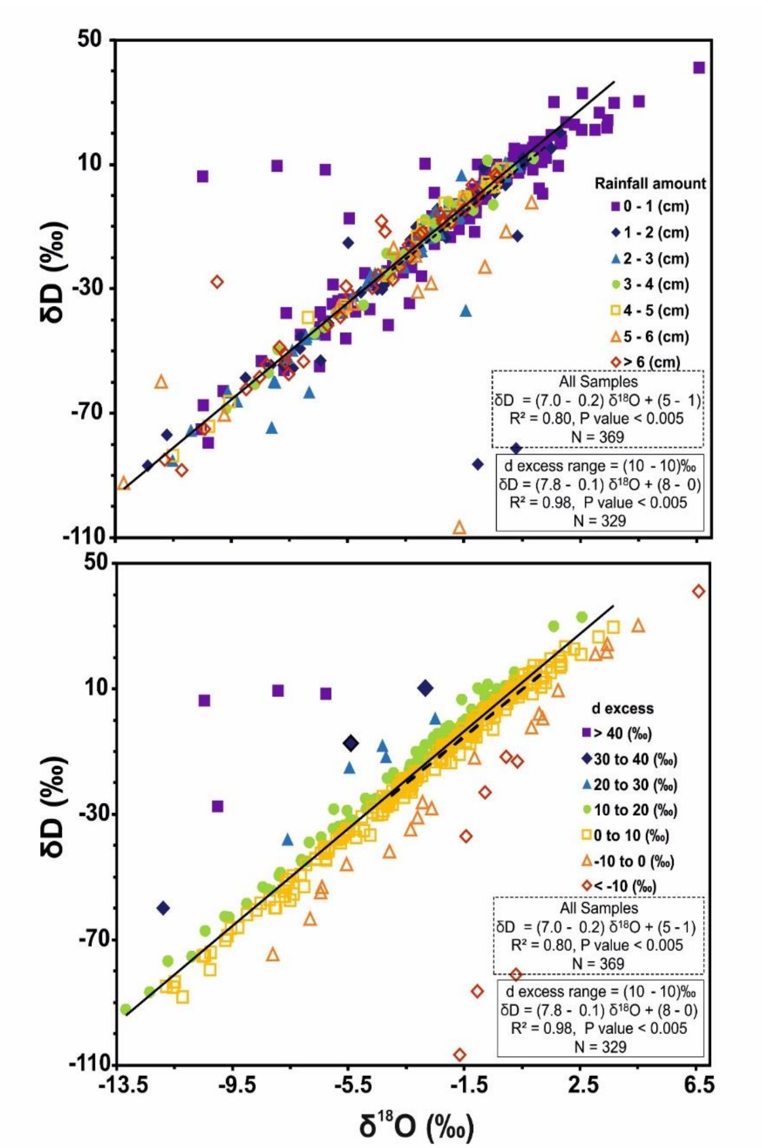

Figure 7. 7: $\delta^{18}O$- δD regression lines for all (atypical and typical) daily rain event represented by broken line as well as rain events with typical d-excess values within range of 10±10‰ represented by solid line. The samples have also been grouped and identified based on range of amount of

Daily rain events with very small (<1 cm/day) and very large (> 6 cm/day) rain amounts are randomly distributed on either side of regression lines (Fig. 7.7a). The same is also true for the daily rain events with very low (<0‰) and very high (>20‰) d-excess (Fig. 7.7b). This confirms that erratic isotopic composition of rain is not primarily governed by the amount of rainfall. This, in turn, suggests that the cloud parcel from which rain is generated on these days is isotopically distinct, either with very high d-excess or very low d-excess.

Comparison of Fig. 7.7a and b reveals that rain events with very high d-excess values (> 20‰) are associated both with very low (< 1 cm/day) and very high (> 6 cm/day) rainfall. The high d-excess indicates continentally derived vapour, and high amount of rainfall from continental source indicates rain events associated with strong convection and rapid upward movement of warm and moist air during thunderstorm. This is also corroborated by low OLR (<240 W/m^2) observed on all such rain events.

On the other hand, rain events with very low d-excess values (<-10‰) are associated with both low (<1 cm/day) and high rainfall (>1 cm/day). Rain events with low d-excess and high amount of rainfall can be ascribed to major rainout from a cloud parcel with significant rainout history. In addition, rain events with low d-excess and low rainfall could also be related to significant evaporation from falling raindrop in a minor rain event which is supported by the fact that on 10 out of 14 such rain events low RH (<60%) was observed.

In view of the above observations it is inferred that isotopically erratic rain events are not related to synoptic rain forming system but instead, are caused by local weather perturbations which may result is sudden updraft of moist air facilitating terrestrial recycling of water vapour and causing rain events of variable magnitudes. Such local weather perturbations may be accentuated by variety of local anthropogenic or natural geographic factors (urban heat island, aerosol emission, orography, wind tunnelling, vegetation cover, water spread for irrigation). In fact, such isotopically erratic rain events provide a unique scope to study effect of anthropogenic factors on rainfall.

7.5. Conclusion

Important hydrometeorological processes are identified from characteristic patterns in the long-term (2005-16) isotope record of daily precipitation at Ahmedabad in semi-arid western India. Important findings from this study are:

- A systematic pattern of isotopic depletion (average $\delta^{18}O$: -2.5‰ in Jun-Jul; -5.2‰ in Aug-Sept) is observed in the second half of southwest monsoon.
- Moisture source contributions computed from 120 hrs backward wind trajectories confirm that there is increased contribution (40.5%) of terrestrially recycled moisture from isotopically depleted sources during the second half of southwest monsoon.
- Due to lower wind speeds in the second half of southwest monsoon the average time spent by the moisture-laden wind trajectories over the AS (60-70 ^{o}N and 15-25^{o}E) increases by ~7.4 hrs leading to higher rainout from the cloud parcel before reaching Ahmedabad.

- Formation of thermal inversion layer in the AS during monsoon months and the westward shift in its longitudinal extent in the second half of monsoon is a major phenomenon of large spatial extent. Its effect on cloud formation is evident in the low OLR. However, its linkage with the observed isotopically depleted rain remained inconclusive, as the backward wind trajectories associated with rainy days did not overlie the low OLR regions.

- The average air temperature at cloud base height of 850 hPa is 1.9°C lower during September compared to June, which corresponds to a small increase of 0.16‰ in ^{18}O fractionation. This lower temperature and higher fractionation at each successive stage of condensation along the air parcel trajectory contributes to isotopically depleted rain in the second half of southwest monsoon.

- Increase in the proportion of convective rain by 22.3% (48.7% in Jun to 71% in Sept) also contributes to isotopically depleted rain in the second half of southwest monsoon.

- Daily rain events with atypical isotopic composition (20‰ < d-excess <0‰) are inferred to be related to a strong convection and rapid upward movement of warm and moist air during thunderstorm; substantial rainout history; or evaporation from falling raindrops.

Chapter 8

Mesoscale Hydrometeorological Processes: Peninsular India

The Indian Peninsula, bounded by the Bay of Bengal (BOB) in the east and the Arabian Sea (AS) in the west, and having abundant surface waters, forests and agricultural fields, is predisposed to dynamic hydrometeorological processes and variable contribution of moisture from two marine sources and terrestrial recycling through evapotranspiration. The oxygen and hydrogen isotopic composition of precipitation over the Indian Peninsula can be used to discern the interplay of hydrometeorological processes and variation in moisture sources. Hyderabad is a representative station located in the middle of the Indian Peninsula. The oxygen and hydrogen isotopic composition of daily accumulated rainfall at Hyderabad has been interpreted in light of various meteorological parameters to discern some of the contemporary hydrometeorological processes. Based on the temporal trend in rain isotopes following major inferences are drawn: (i) a lack of correlation between trends in rain isotopes and various meteorological parameters such as the convective fraction of rain, condensation temperature, rainout history and increased BOB moisture contribution indicates a complex interplay between the multitude of hydrometeorological processes and moisture source variation; (ii) during pre-monsoon (Jan – May) evaporation from falling raindrops is significant; (iii) orographic barrier posed by the Western Ghats causes relative isotopic depletion in the rain during monsoon (Jun-Sep) and; (iv) during post-monsoon (Oct-Dec) continentally recycled moisture is the dominant vapour source, and no effect of northeast winter monsoon is observed.

8.1 Introduction

Precipitation in India is a complex interplay of various ocean-atmosphere-land interaction processes such as spatio-temporal variation in moisture source, moisture transport pathways, types of raining cloud (convective or advective), condensation temperature, continental recycling of moisture, and temperature and RH of the source region. Oxygen and hydrogen stable isotopic composition of rainwater in conjunction with other meteorological parameters can be used as a tracer to understand these processes (Breitenbach et al., 2010; Deshpande et al., 2013a; Deshpande and Gupta, 2012; Jeelani and Deshpande, 2017; Lekshmy et al., 2015; Midhun et al., 2018; Oza et al., 2020; Rahul et al., 2018; Saranya et al., 2018; Unnikrishnan Warrier and Praveen Babu, 2012). Understanding these contemporary hydrometeorological processes in details is necessary to recognize the factors which affect the rainfall and also to assess the change in rainfall pattern and processes, until the long-term effect of climate changes on hydrology is well understood. Also, this knowledge can be employed to have better insights into paleoclimatic studies. Due to its specific geographical setting, the Southern Indian Peninsula is one such region where considerable spatio-temporal variations in the above mentioned hydrometeorological processes can be expected to manifest in the isotopic composition of rainfall.

The southern Indian Peninsula is a vast landmass (~1,600,000 km^2) in the shape of an inverted triangle, bounded by the Arabian Sea (AS) in the west, Bay of Bengal (BOB) in the east and the Indian Ocean in the south. It is flanked by the Western Ghats (average elevation: ~1200 m) and Eastern Ghats (average elevation: ~520 m) running parallel to the western and eastern coastline of Indian Peninsula, respectively. The region also houses about 168,500 km^2 of wetland and forest cover of ~135,800 km^2, which could lead to large scale evapotranspiration. The Peninsula is one of the most densely populated (about 349 persons per km^2) regions of India. About 48% of its residents depend on agriculture for their livelihood, which in turn is dependent largely on monsoonal rains because all the major rivers (Godavari, Krishna, Cauvery and Vaigai) flowing through the region are ephemeral. The southern Indian Peninsula lies between the mean summer and winter positions of Inter-Tropical Conversion Zone (ITCZ) (Sikka and Gadgil, 1980) thus, receives 40 – 70% of annual rainfall during the southwest summer monsoon (Jun – Sept) and rest during the post-monsoon [Oct-Dec; Rajeevan et al. (2012a)] when the ITCZ is retreating southwards. However, the spatial distribution of the amount of rainfall in this region is uneven, mainly because of varied topographical features. The lofty Western Ghats pose a major orographic barrier to the southwest monsoon. Consequently, the coastal strip on the west of Western Ghats receives almost 2000 mm of annual rainfall whereas, the semi-arid rain shadow zone (of Western Ghats) receives ~450 to 700 mm of rainfall annually, while rest of the Peninsula receives about 750 – 1500 mm of annual rainfall. Thus, the precipitation in this region can provide a window to understand the dynamics of the hydrometeorological process and seasonal variation in moisture source contribution from two major marine water bodies (AS and BOB) and continentally recycled moisture through evapotranspiration.

With this backdrop, a total of 172 daily accumulated rain samples were collected from Hyderabad (17.39° N, 78.49° E; alt: 542 m asl) over a period of three years (2009-11) for its isotopic analysis under the aegis of the National Programme on Isotope Fingerprinting of Waters of India (IWIN) (Deshpande and Gupta, 2008; Deshpande and Gupta, 2012). Hyderabad lies almost at the centre of Southern Indian Peninsula, equidistant from the AS as well as the BOB coastline. Also, there are ~169 lakes in and around the city of Hyderabad, occupying ~9055 ha of area [http://hmda.gov.in; Ganesh (2009)]. Therefore, the location of Hyderabad was strategically chosen to study the temporal variation in moisture sources advected from two marine water bodies and convective recycled moisture (from surface waters and vegetation) along with associated meteorological features.

8.2 Climate

Hyderabad experiences the tropical wet and dry climate with an annual mean temperature of 26.8 ^{o}C and rainfall of ~855 mm. The summers are hot here with maximum temperature often exceeding 40 ^{o}C during April and May. Hyderabad receives most (~73%) of its rain from ISM between June-September with maximum rainfall in August (~178 mm). It also receives showers during the post-monsoon period between Oct-Dec, with maximum rainfall of ~97 mm in October. For details of the climate record reference is made to the India Meteorology Department website (http://mausam.imd.gov.in).

8.3 Data Used

A total of 172 daily rainfall samples were collected from Hyderabad for the isotopic analysis, under the aegis of IWIN National Programme (Deshpande and Gupta, 2008; Deshpande and Gupta, 2012). For details of sample collection and isotopic analysis, reference is made to chapter 3.

The details of various other satellite and reanalysis data used in this study are enlisted below:

- Ensembles of four 120 hr backward wind trajectories, each starting at six hourly interval and at the height of 1500 m from Hyderabad was obtained from Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model [http://ready.arl.noaa.gov/HYSPLIT.php (Stein et al., 2015)]. Percentage moisture contribution from each source (AS, BOB and Continentally recycled moisture) and average distance travelled by the wind trajectories are computed using the specific humidity and geographical coordinates (Sodemann et al., 2008a; Sodemann et al., 2008b).

- The hourly convective percentage and rain rate are obtained from Tropical Rainfall Measuring Mission (TRMM) TMI (TRMM Microwave Imager) 3G68 at the spatial resolution of 0.5º latitude x 0.5º longitude (Kummerow et al., 2001) over the box of 16.39° N, 77.49° E and 18.39° N, 79.49° E.

- The NCEP/NCAR Reanalysis-1 monthly climatological temperature at 700 hPa at the spatial resolution of 2.5º latitude x 2.5º longitude (Kalnay et al., 1996) over the box of 5º N, 65º E and 20 ºN, 95º E is obtained from http://www.esrl.noaa.gov/.

8.4 Results and Discussions

$\delta^{18}O$ - δD regression lines and $\delta^{18}O$ - d-excess plot based on 172 daily rain samples are shown in Fig. 8.1 (a) and (b) respectively, with month-wise identification of daily samples. Isotopically most enriched ($\delta^{18}O$ > 2 ‰) values of samples are from March-May, these samples are also associated with low d-excess values (< 0‰), suggesting secondary evaporation from falling raindrops (Dansgaard, 1964). Average temperatures are highest (~30 ºC), and RH is lowest (57%) during March-May, which may facilitate evaporation from the falling raindrops during low-intensity rainfall events. Isotopically most depleted values ($\delta^{18}O$ < -5‰) are from the late monsoon (Aug – Sept) and post-monsoon period, except for two pre-monsoon samples from May. Most of these isotopically depleted ($\delta^{18}O < -6$ ‰) samples are associated with d-excess ranging between 6 ‰ to 14 ‰, this suggests rain from the vapour parcels with significant rainout history and, generated from different moisture sources (AS, BOB or continental) having different RH conditions causing different extent of kinetic fractionation during evaporation (Dansgaard, 1964). It can be ascribed to weakening of southwest monsoonal winds in the wake of southward migration of ITCZ during later part of the southwest monsoon, and initiation of Northeastern winds fetching moisture from the BOB to southern India.

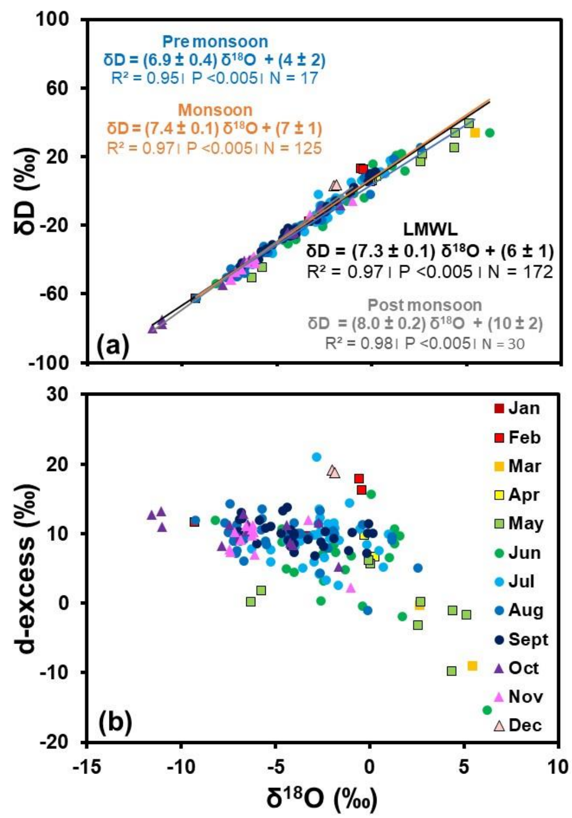

Figure 8.6: (a) $\delta^{18}O$ - δD regression line and; (b) $\delta^{18}O$ – d-excess plot of daily rainfall samples with month-wise identifiers

The $\delta^{18}O$ - δD regression line slope (7.3 ± 0.1) of Hyderabad's Local Meteoric Water Line (LMWL), considering all the 172 rain samples, is lower than that [slope: 8.17±0.07; intercept: 11.27±0.65; Rozanski et al. (1993)] of Global Meteoric Water Line (GMWL). Warrier and Babu (2012) have also reported lower slopes (7.80 ± 0.18; 7.40 ± 0.11; 7.28 ± 0.09) for the monthly accumulated rainfall samples collected from three different locations within Hyderabad. The lower slope indicates significant secondary evaporation of falling raindrops (Clark and Fritz, 1997b; Gat, 1996). The LMWL is an average of seasonal meteoric water lines of Hyderabad. The lower $\delta^{18}O$ - δD regression line slopes of pre-monsoon (6.9 ± 0.4; N = 17) and monsoon (7.4 ± 0.1; N = 125) suggests a significant role of raindrop evaporation even during monsoon period when average RH is relatively higher (72%) compared to pre-monsoon. However, the slope and intercept (slope: 8.0 ± 0.2; intercept: 10 ± 2) of post-monsoon rain samples (N = 30) is similar to that of GMWL; the comparable slope indicates the rainfall generated under equilibrium conditions and intercept of 10 indicates vapour possibly originating from the marine source where the ambient RH is ~85%.

From the time series plot of δ^{18}O and d-excess (Fig. 8.2: a and b), three peculiar observations can be drawn: (i) a systematic seasonal trend of depletion in δ^{18}O from pre-monsoon to post-monsoon in all the three years of study; (ii) during late monsoon (Aug end or Sept) there is a sudden deviation from the overall depleting trend, and slight enrichment in δ^{18}O is observed and; (iii) interannual enriching trend in δ^{18}O of post-monsoon rain.

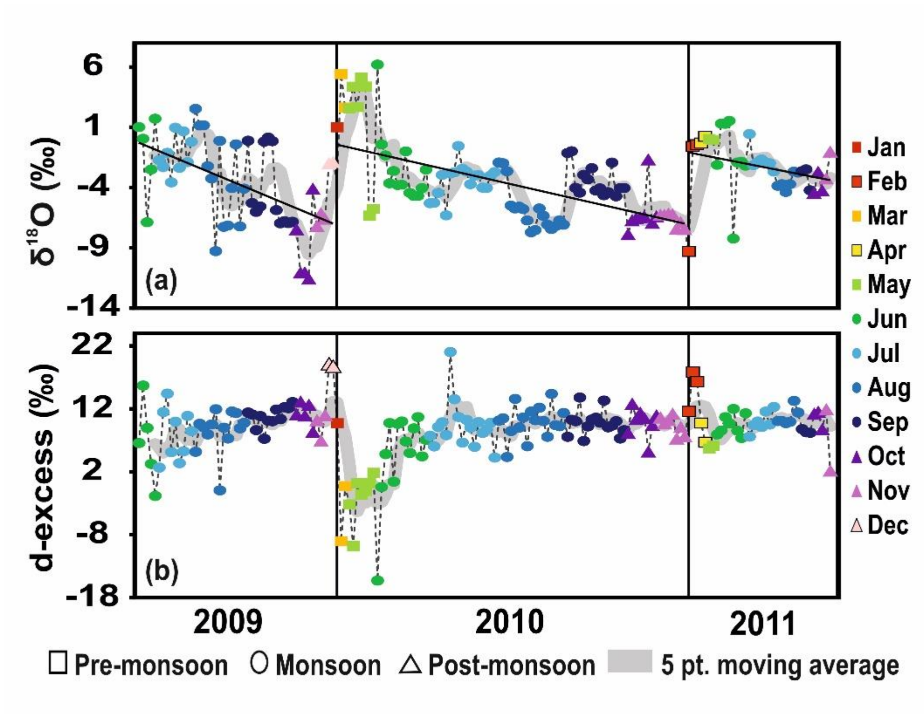

Figure 8.7: The daily time-series of δ^{18}O (a) and d-excess (b). The width of each year represents the number of rainy days in that year

In the following subsections, an attempt is made to understand the underlying meteorological processes governing the above patterns observed in the isotopic composition of daily rainfall.

(i) Seasonal depletion of δ^{18}O in precipitation

In various parts of the subcontinent similar depleting trends in precipitation δ^{18}O have been reported, for instance, Breitenbach et al. (2010) ascribed the post-monsoon isotopic depletion in the rain at southern Meghalaya to the increased discharge of (isotopically depleted) Himalayan Rivers into the BOB, causing isotopic depletion of BOB surface water and the moisture generated from it. However, Midhun et al. (2018), have shown that the evaporation from the admixture of freshwater and saline water in the northern BOB cannot contribute to the observed depletion of $\delta^{18}O$ in precipitation. Lekshmy et al. (2014) and Oza et al. (2020) have suggested increased fraction of convective over stratiform rainfall as one of the reasons for isotopic depletion in precipitation at Kerala and Ahmedabad, respectively. However, any such trend of increasing convective rain fraction during post-monsoon is not observed at Hyderabad (Fig. 8.3). Also, Oza et al. (2020) have ascribed lowered condensation temperature and higher fractionation at successive condensation to the isotopic depletion of rain at Ahmedabad during the late monsoon. The climatological temperature at 700 hPa (average maximum cloud liquid water content) was obtained for a large box (5º-20ºN and 65º-95ºE) encompassing the AS, BOB and the Indian Peninsula. The pre-monsoon, monsoon and post-monsoon temperatures were found to be 9.1 ºC, 9.6 ºC and 8.7 ºC respectively. The temperature at 700 hPa is found to be lower in pre-monsoon, higher in monsoon and, again lower in post-monsoon. Thus, an overall decreasing trend in temperature, analogues to isotopic depletion, is not observed in case of temperature. Sengupta and Sarkar (2006) have associated post-monsoon isotopic depletion in precipitation at Kolkata to long-distance transport of moisture and thus larger rainout history (Gonfiantini, 1986) due to the shifting of monsoon depression from northern BOB to southern BOB. To examine the similar possibility for rains at Hyderabad, the monthly average distance travelled by moisture-bearing air parcels was calculated from the 120 hr backward wind trajectories obtained from HYSPLIT (Fig. 8.4). It is observed that in the case of Hyderabad, moisture-bearing air parcels travel longest distances during monsoon months and not during the post-monsoon months as was observed by Sengupta and Sarkar (2006) for Kolkata. Various authors (Lekshmy et al., 2015; Midhun et al., 2018; Rahul and Ghosh, 2019) have ascribed the post-monsoon $\delta^{18}O$ depletion in precipitation to increased moisture contribution from BOB. Estimation of the percentage contribution of moisture from different sources to precipitation at Hyderabad was done using the change in specific humidity in the HYSPLIT backward trajectories. As seen from the inset pie charts (Fig. 8.4), the moisture contribution from BOB never exceeded that from the AS and continentally recycled moisture. Moreover, the maximum relative contribution of the BOB (33%) is observed during pre-monsoon rather than post-monsoon, when maximum isotopic depletion in precipitation is observed.

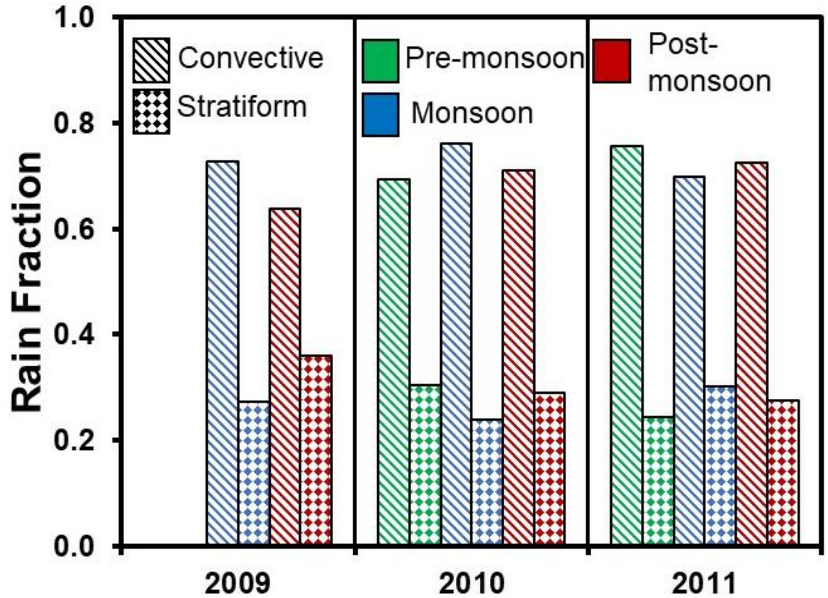

Figure 8.8: Seasonal proportion of rain derived from convective and stratiform clouds during 2009-11.

The aforementioned arguments indicate lack of any single dominant meteorological process governing the isotopic composition of precipitation at Hyderabad, indicating the complex interplay of more than one meteorological process. Therefore, in the following, it is suggested that the change in moisture source with a multitude of the meteorological processes may govern the observed trend of isotopic depletion in the rain at Hyderabad.

During pre-monsoon, as seen from the inset pie chart (Fig. 8.4), the percentage contribution of continentally recycled moisture is high (56 %) in the precipitation at Hyderabad. During pre-monsoon, the major source of evapotranspiration is surface waters and irrigated agricultural fields fed by the surface as well as groundwaters. Lambs et al. (2005) have reported isotopic composition of Krishna ($\delta^{18}O$ = -1.04 ‰; d-excess = -3.90 ‰) and Cauvery ($\delta^{18}O$ = -1.02 ‰; d-excess = -1.52 ‰) rivers. They attributed this characteristically enriched $\delta^{18}O$ and low d-excess to the significant evaporation from the rivers. Sukhija et al. (2006) have reported $\delta^{18}O$ of groundwater in and around Hyderabad in the range of -3.2‰ to 1.7‰. Therefore, in pre-monsoon, the continentally recycled moisture generated from these enriched sources (rivers and groundwater) would result in enriched precipitation. In addition to that, the lowest average amount of rainfall (~11 cm) and the lowest average RH (~ 62%) during pre-monsoon facilitates significant evaporation from falling raindrops resulting in enriched $\delta^{18}O$ and low d-excess of precipitation (Stewart, 1975).

During monsoon, the majority (58%) of rain-bearing moisture comes from the AS. The moisture-laden winds during southwest monsoon get orographically uplifted while crossing the Western Ghats and the vapour parcel gets cooled adiabatically causing the copious rainfall (~ 2000 mm) on the windward side. According to Rayleigh distillation model, the heavy isotopologues get preferentially rained out from the vapour parcel, thus after each successive condensation, the residual vapour parcel becomes isotopically depleted and so does the resultant rain. Thus, vapour parcel with significant orographic rainout over the Western Ghats results in isotopically depleted monsoon precipitation at Hyderabad located on the leeward side.

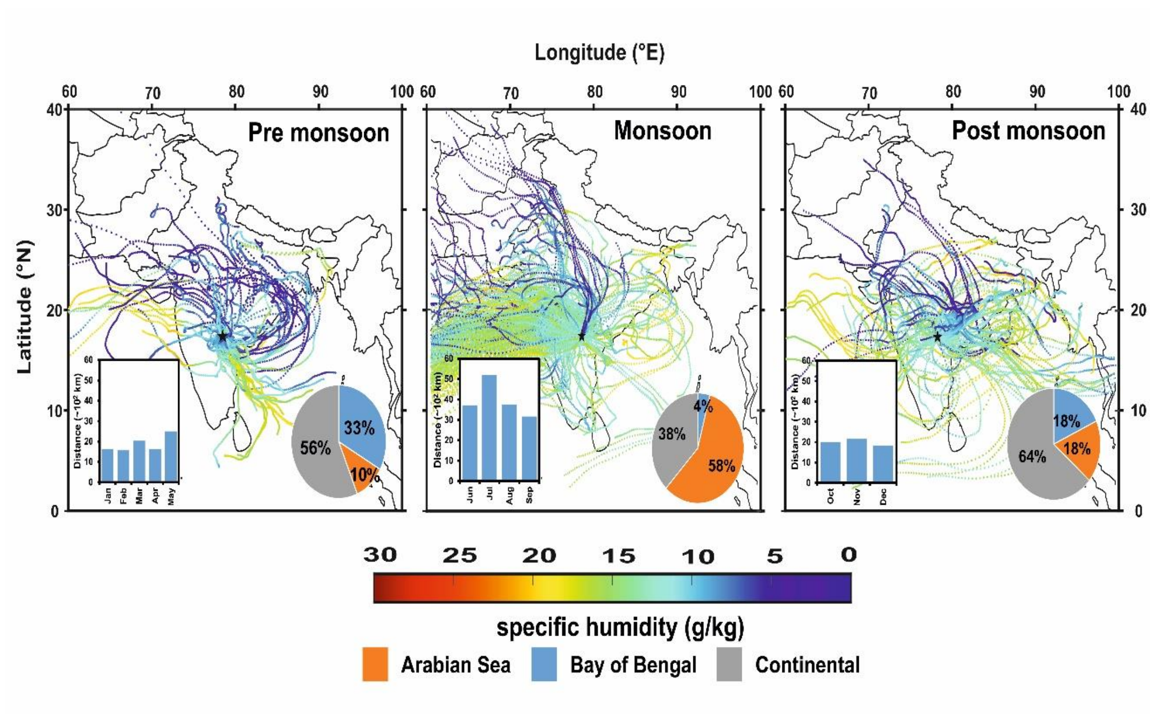

Figure 8. 9 Map showing seasonal ensembles of four 120 hrs. back trajectories starting from Hyderabad. The colour code indicates specific humidity in g kg^{-1}. The inset pie charts represent the percentage source moisture contribution, represented by legends at the bottom. Whereas the inset bar charts show the monthly average distance travelled by the wind trajectories

Contrary to the expectations from geographic setting and seasonal wind regime, the continentally recycled moisture (64%) is the major contributor to rains during post-monsoon at Hyderabad, and not the BOB (18%) moisture. It is possibly due to the fact that Hyderabad is geographically located in farther north latitude (~17 ºN), compared to the coastal Andhra Pradesh and inland region up to ~15.5 ºN where the northeastern winds are known to bring rain (Sreekala et al., 2012) during post-monsoon. The soil moisture and surface waters recharged due to monsoonal rains (during Jun-Sept) contribute to recycled moisture through evapotranspiration. Warrier and Babu (2011) have also ascribed post-monsoon isotopic depletion of precipitation to the increased contribution of recycled moisture. Besides, during post-monsoon, the average condensation temperature (8.7 ºC at 700 hPa) is relatively low. The isotopic fractionation and condensation temperature are inversely related (Horita and Wesolowski, 1994). Thus, lower condensation temperature and higher fractionation at successive condensation steps lead to the isotopic depletion. Also, higher average surface RH (85%) retards secondary evaporation from falling raindrops thus inhibiting evaporative isotopic enrichment of rain. The slope (8 ± 0.2) and intercept (10 ± 2) for post-monsoon $\delta^{18}O$ - δD regression line (Fig. 8.1: a) further justifies the above argument.

Thus complex interplay of vapour source variation, temperature, RH and orography together governs the observed seasonal isotopic variation in precipitation of Hyderabad.

(ii) Sudden enrichment towards the end of the monsoon

Superimposed on the overall depleting trend from pre-monsoon to post-monsoon, there appears a sudden enrichment in $\delta^{18}O$ during September, which is more prominently visible in 2010 and 2011 than in 2009 (Fig 8.2: a). Also, there is no variation in d-excess corresponding with the change in $\delta^{18}O$. This can probably be attributed to the weakening of monsoonal winds (southwest), the average distance travelled by wind trajectories in past 120 hrs is minimum (~3200 km) during September compared to other monsoon months (inset bar charts of Fig 8.4). Thus, with lesser distance travelled the relative rainout fraction will also be smaller in September, consequently lesser isotopic depletion of vapour parcel and resultant rain (Gonfiantini, 1986) can explain the observed trend of isotopic enrichment towards end of the monsoon.

(iii) The inter-annual enriching trend in $\delta^{18}O$ of post-monsoon rain

The $\delta^{18}O$ values of post-monsoon rains show (Fig 8.2 a) a progressive inter-annual enriching trend during the successive years from 2009 to 2011, with a corresponding variation in d-excess (Fig 8.2 b). The same pattern is also observed in the amount weighted seasonal average $\delta^{18}O$ (- 8.2 ‰, - 6.7 ‰ and - 3.9 ‰) of post-monsoon rain during 2009, 2010 and 2011. It is seen that the directions of wind trajectories (Fig 8.5) and the percentage contribution of moisture from different sources (inset of Figure 8.5) are varying in each year for the post-monsoon season. Thus, the seemingly systematic trend in $\delta^{18}O$ is actually a resultant manifestation of non-systematic changes in the various hydrometeorological process. During 2009, after the continentally derived moisture (62%), the second-highest moisture contribution is from the AS (26 %). The trajectories of air parcels bearing moisture from the AS has to cross over the orographic barrier of Western Ghats; where it would shed heavy isotopes through rainout. The resultant depleted vapour parcel mixed with continentally recycled moisture could result in the observed isotopic depletion during 2009 post-monsoon. During 2010 the moisture regime has changed in which the contribution of continentally recycled moisture (61%) remains almost the same as in 2009 but instead of AS, the BOB moisture contribution (25%) is second highest. Unlike moisture-bearing wind trajectories from the AS, the trajectories from the BOB undergo relatively lesser orographic rainout as the Eastern Ghats are relatively shorter compared to the Western Ghats. Thus due to lesser rainout history and admixing of almost the same amount of moisture through continental recycling as 2009

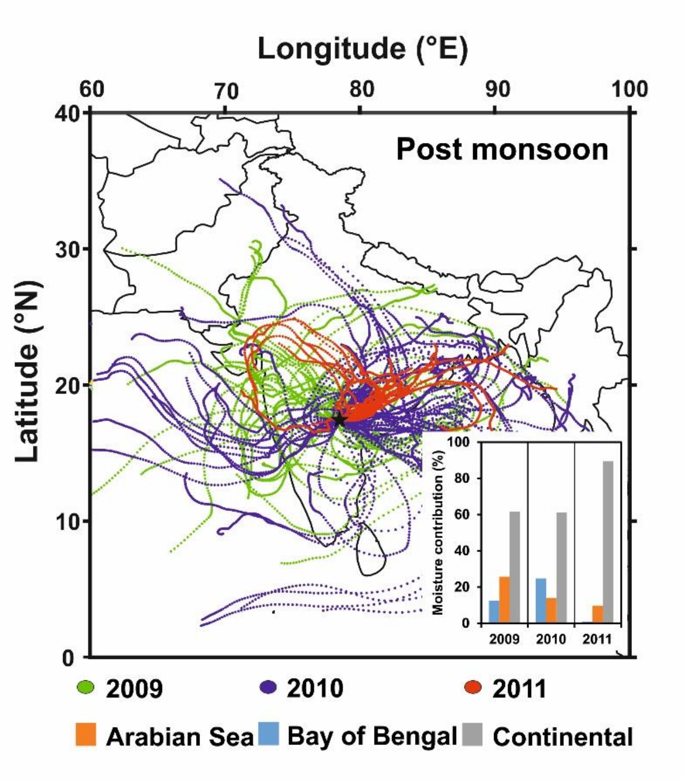

Figure 8. 10: Map showing ensembles of four 120 hrs. back trajectories for the post-monsoon rain of 2009-11. The inset bar chart shows the seasonal percentage source moisture contribution, represented by legends at the bottom

post-monsoon, the resultant 2010 post-monsoonal rain is relatively enriched with respect to that of 2009. In 2011, the moisture regime changed again in which maximum (89%) moisture is continentally derived. The isotopic composition of recycled moisture in post-monsoon depends on the isotopic composition of preceding monsoon, which feeds the surface water and soil moisture. The amount weighted average $\delta^{18}O$ of 2011 monsoon rain is most enriched (- 3.0 ‰) compared to that of 2009 (-3.6 ‰) and 2010 (- 4.3 ‰). Thus, the recycled moisture from isotopically enriched (compared to post-monsoon of 2009 and 2010) continental waters, mixed with little moisture derived from marine (AS or BOB) sources, can lead to the isotopic enrichment in the post-monsoonal rain of 2011.

8.5 Conclusion

Based on Isotopic analysis of 172 daily accumulated rainfall samples in combination with various meteorological parameters at Hyderabad, located in the centre of the Indian Peninsula, important mesoscale hydrometeorological processes concerning regional precipitation are discerned. Some of the key findings are enlisted below:

- The lower slope $\delta^{18}O$ - δD regression line (7.3 ± 0.1) with all 172 samples indicates evaporation from falling raindrops is a significant process governing the isotopic composition of precipitation.
- Absence of any correlation between trends in the isotopic composition of rain and various meteorological parameters (convective fraction of rain, condensation temperature, rainout history and increased BOB moisture contribution) indicate the complex interplay of the combination of hydrometeorological process govern the rainfall of this region.
- The enriched isotopic composition of rain during pre-monsoon is ascribed to higher (56 %) contribution of continentally recycled moisture and greater evaporation from the falling raindrops owing to the lower amount of rainfall (~11 cm) and RH (~62%).
- During monsoon, 58% of moisture in the rain-bearing air parcel is derived from the AS, which undergoes significant rainout due to orographic lifting while crossing

the Western Ghats and thus causing relatively isotopically depleted rain at Hyderabad.

- Effect of Northeast monsoon and thus higher contribution of BOB moisture is not observed at Hyderabad during post-monsoon months (Oct-Dec) because Hyderabad is located farther northward (~17 ^{o}N), compared to the coastal Andhra Pradesh and inland region up to (~15.5 ^{o}N) latitude where northeast monsoon does affects.
- Post-monsoon isotopic depletion is ascribed to the combination of continental recycling, lower condensation temperature (8.7 ^{o}C) and higher surface RH (85%).
- The sudden isotopic enrichment of rain towards the end of monsoon is attributed to lesser distance travelled and consequently lower rainout history of moisture-bearing wind trajectories due to weakening of monsoonal winds.
- A progressive inter-annual enriching trend during the successive years from 2009 to 2011, with a corresponding variation in d-excess, is attributed to the effect of change in the highest relative proportion of vapour derived from the AS in 2009 to BOB in 2010 and continentally recycled moisture in 2011.

Chapter 9

Microscale Hydrometeorolgical Process: Evaporation From Falling Raindrops

Rigorous analyses of measured isotopic composition ($\delta^{18}O$ and δD) of 556 daily rainwater samples collected from four Indian stations viz., Jammu, Jorhat, Hyderabad and Ahmedabad, is done in conjunction with satellite and model-derived meteorological and isotopic parameters to discern prominent hydrometeorological processes and factors in four different climatic zones of the Indian subcontinent. This study has provided new quantitative insights about various hydrometeorological processes across the Indian subcontinent. Some of the important inferences drawn from this study are: (i) the estimated evaporative loss from falling raindrops for the four stations are [Jammu: Maximum 52% and Minimum 8%; Jorhat: Maximum 15% and Minimum 4%; Ahmedabad Minimum 8% and Hyderabad Maximum 29% and Minimum 15%]; (ii) increased availability of surface waters due to flood in Brahmaputra River and high column average RH of 88% results in the lowest evaporative loss from falling raindrops at Jorhat in Northeast; (iii) the high Cloud Liquid Water Content (CLWC) over a longer span of altitude facilitates the interaction of falling raindrop with isotopically depleted ambient vapour and results in isotopically depleted rain; (iv) the observed inverse relationship between the evaporative loss from falling raindrop and the column average RH confirms that the post condensation kinetic processes are realistically accounted in this study and; (v) validation with measured isotope data of rain shows that the LMDZ4-iso modelled rain fails to incorporate evaporative isotopic enrichment and generates negative bias.

9.1 Introduction

The evaporation from falling raindrops is one of the important microscale processes (Gat and Dansgaard, 1972). The major parameters affecting evaporation from falling raindrops are rain rate, air temperature, and relative humidity (RH) (Liu et al., 2008; Meng and Liu, 2010; Peng et al., 2007). Chen et al. (2015) have estimated the extent of evaporation from falling raindrops to be 8.3% during summer (Jun-Sept) and 4.5% during winter (Oct-May) in Northwest China. Worden et al. (2007) have shown that around 20% to 50% of raindrops evaporates near convective clouds, significantly contributing to the humidity in the lower troposphere. Thus, rain re-evaporation can have significant negative feedback and thus alter the local rainfall amount and periodicity.

In a region like Indian subcontinent with varied topographical and meteorological features and agrarian economy, the change in land-use and land-cover can alter the local RH and temperature, which can significantly affect the rain re-evaporation and possibly the amount of rainfall itself. Thus, estimating evaporation from falling raindrops in different climatic zones of Indian subcontinent is very important.

While there are a few studies which estimate evaporation from falling raindrops in different parts of the globe (Chen et al., 2015; Froehlich et al., 2008; Worden et al., 2007), such an estimate for the Indian subcontinent is not known, where it is really important for hydrological budgeting. With a view to bridge this knowledge-gap, daily precipitation samples (N = 556) were collected from four stations viz. Jammu, Jorhat, Ahmedabad and Hyderabad, located in four different climatic zones, under the aegis of a National Programme on Isotope Fingerprinting of Waters of India (IWIN) (Deshpande and Gupta, 2008; Deshpande and Gupta, 2012). Meteorological parameters and isotopic composition of water vapour, necessary for the estimation of evaporation from the falling raindrops, were obtained respectively from various satellite-based observations and modelled data.

9.2 Climate

Comparison of various long-term meteorological parameters and isotopic compositions of rain (2010-11) for all the four stations are presented in table 9.1. For detailed meteorological information about four stations, reference has been made to the India Meteorology Department website (http://mausam.imd.gov.in).

Table 9. 1 Comparison of long term annual averaged meteorological parameters and isotopic characters based on daily rain samples collected during 2010-11 for all the four stations.

Station	Annual Average Temp. (ºC)	Annual Average surface RH (%)	Annual Rainfall (mm)	Rainy Days	Potential Evapo-transpiration (mm/day)	Range in $\delta^{18}O$ (‰)	Range in d-excess (‰)	Slope	Intercept
Jammu	23.7	62.8	1331.6	60.7	6.3	-13 to 9.3	-24.4 to 65.4	6.3±0.2	5±1
Jorhat	24	78.3	2324	154	5.2	-23.1 to 4.6	-1.1 to 21.6	8.3±0.1	13±1
Ahmedabad	27.6	55	751	33.7	6.8	-12.3 to 3.4	-9.2 to 20.8	7.6±0.1	7±1
Hyderabad	26.8	46.2	854.6	49.9	6.6	-9.3 to 6.2	-15.3 to 21.1	7.1±0.1	5±1

9.3 Computation and Data Used

The measured isotopic composition of precipitation (the details of sample collection and isotopic analysis is presented in Chapter 3) was interpreted in conjunction with other associated weather, meteorological and isotopic parameters, obtained from satellite, reanalysis and modelled data products available on various open web platforms. Exhaustive computations were done to estimate: (1) evaporation from falling raindrops, (2) condensation height and temperature, and (3) pristine isotopic composition of vapour generated under convective and advective systems.

One way of estimating the extent of actual evaporation from falling raindrop is to compare the isotopic composition of observed rain with that of modelled rain estimated using isotope enabled GCMs. This approach, however, is not feasible because the modelled rain already includes the possible effect of evaporation under certain assumptions which are known to underestimate the isotopic exchange between the falling raindrops and the surrounding vapour and the partial re-evaporation (Lee and Fung, 2008). For example, the LMDZ-iso can also provide the isotopic composition of condensate in which the intensity of the kinetic processes related to evaporation and interaction with ambient air is accounted for by a tunable parameter set to a value to 0.9, which, however, fails to capture the large variation in atmospheric RH (Bony et al., 2008). It was noticed in this study that the observed $\delta^{18}O$ values of rain matched well with the LMDZ-iso GCM values only in places with high relative humidity and saturated atmosphere. However, for low RH and unsaturated atmosphere, the modelled values were found to be consistently depleted compared to the observed values, with the highest negative bias going up to 7.4‰ in Jammu where RH was 58%. This suggests a gross underestimation of the post condensation kinetic processes (Fig. 9.1).

In view of the above limitations of the modelled isotopic composition of rain, the modelled isotopic composition of vapour is used in this study to generate the pristine isotopic composition of condensate to compute the extent of modification necessary to obtain the observed isotopic values of rain. This approach provides not only the extent of evaporation from falling raindrops but also provides a way to validate the isotope enabled GCMs in terms of the isotopic composition of resultant modelled rain (Fig. 9.1).

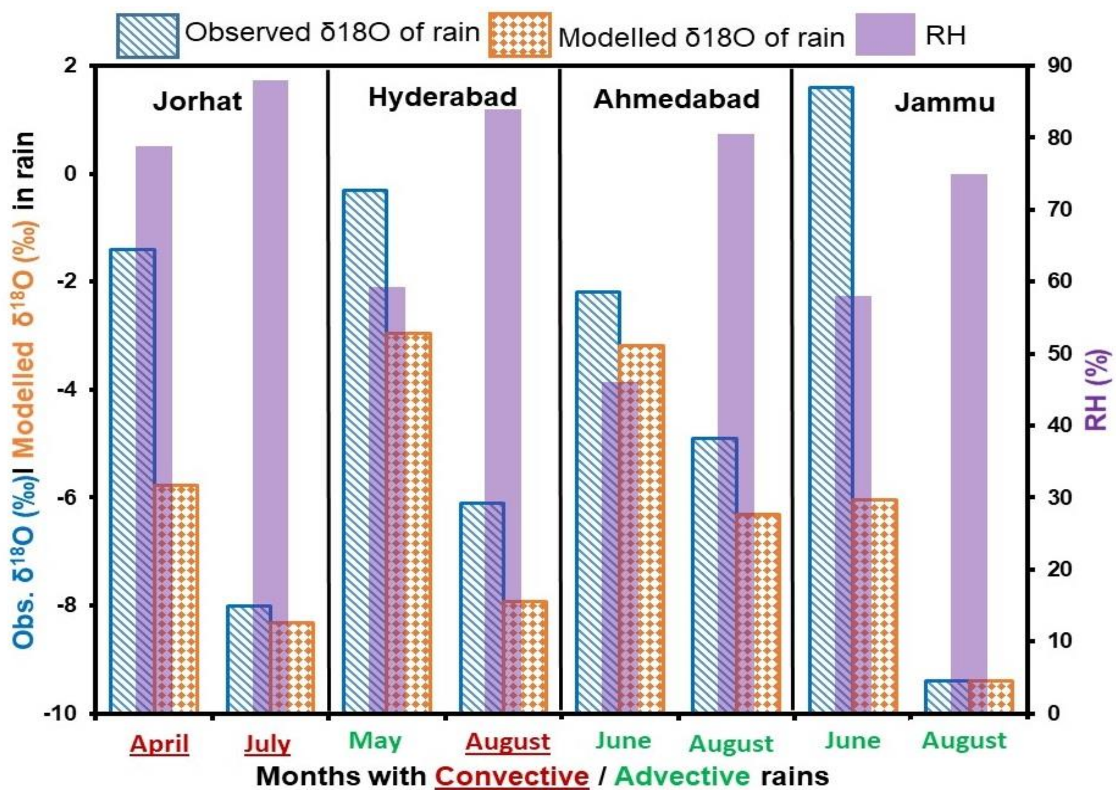

Figure 9. 1: Comparison of the isotopic composition of observed rain with that of the LMDZ4-iso modelled rain with respect to RH for the months with most enriched and most depleted monthly averaged isotopic values of rain for all the four stations

In this study, evaporation from falling raindrops has been estimated for two types of rain-forming processes, namely, advective and convective. In advective systems, it is envisaged that the atmospheric moisture from adjoining regions is advected into the atmosphere over the study area from which rain is generated. On the other hand, in convective systems, it is envisaged that due to surface convergence and resultant updraft, moisture from below the cloud base (and ground level) gets uplifted and mixed with in-cloud moisture from which rain is generated. Vertical wind velocity, ω at the 500 hPa level, was used as an indicator of surface convergence strength (Feng et al., 2009). In this study, under the condition of low values of outgoing Longwave Radiation [OLR < 240 W/m^2; Gadgil (2003)], ω < -0.1 Pa/s is considered to indicate strong updraft due to surface convergence, and -0.025 Pa/s < ω < 0 is considered to indicate weak updraft (Lareau and Horel, 2012; Rose and Lin, 2003). Thus, months which satisfy these conditions are classified as having convection as the dominant process or else advection. The values of ω were obtained from ERA-Interim monthly data at a resolution of 0.75° X 0.75° and at 20 pressure levels ranging from 300 – 1000 hPa (downloaded from http://apps.ecmwf.int/datasets/). The monthly OLR data was obtained from http://www.cdc.noaa.gov/cdc/data.interp_OLR.html at the resolution of 2.5° X 2.5°.

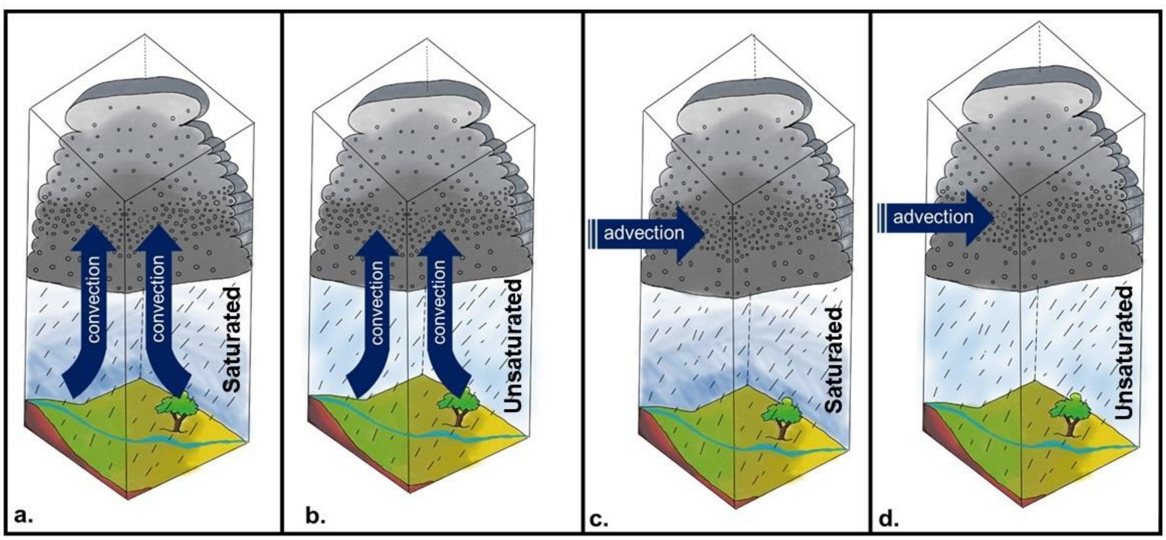

Figure 9. 2: An illustration showing a) convection within saturated air column; b) convection within unsaturated air column; c) advection over saturated air column; and d) advection over unsaturated air column.

It is hypothesized that the degree of saturation of the vertical air column could play a role in both, the convective and the advective rain forming processes, through the interaction of resultant rain with saturated or unsaturated air columns. Hence, four scenarios (Fig. 9.2) are considered, namely: a) convection within saturated air column; b) convection within unsaturated air column; c) advection over saturated air column; and d) advection over unsaturated air column.

Scientific premises and assumptions for the computation of isotopic compositions of vapour under convective and advective systems are given below.

(i) Isotopic composition of vapour in the convective system

In the case of convection, both in the saturated and unsaturated air column, the near-surface level moisture is uplifted to higher altitudes due to updraft. Stronger the updraft, lesser will be the chance for surface moisture to interact and mix with surrounding moisture at different pressure levels, and hence lesser will be the modification in its isotopic composition. Higher the specific humidity of a particular pressure level more will be its contribution of moisture to the updraft. The near-surface level moisture tends to preserve its isotopic signature in the condition of strong updraft and /or unsaturated air column.

In the above framework of possible scenarios of convective systems, the estimated $\delta^{18}O$ of rain-forming vapour is computed using the modelled $\delta^{18}O$ of vapour at different pressure levels, weighed with the ratio of specific humidity to the vertical wind velocity of that particular pressure levels, as follows:

$$\delta_{vo} = \frac{\sum_{i=P1}^{Pn} \delta_i \times \frac{Q_i}{\omega_i}}{\sum_{i=P1}^{Pn} \frac{Q_i}{\omega_i}} \qquad (9.1)$$

Where, δ_{vo} is the estimated value of $\delta^{18}O$ of rain-forming vapour; P1 to Pn represents the pressure levels between which the cloud liquid water content (CLWC) is more than half of its maximum value; δ_i, Q_i and ω_i are respectively the $\delta^{18}O$ of vapour, specific humidity and upward vertical wind velocity at i^{th} pressure levels. The CLWC and Q_i were obtained from ERA-Interim monthly data. The δ_i values were obtained at 19 pressure levels from LMDZ-iso GCM at a resolution of 2.5° x 3.75° nudged by ECMWF (https://data.giss.nasa.gov/swing2/swing2_mirror/LMDZ4/ nudged_vl77/). These pressure levels were chosen to be closest to the ERA INTERIM data from where other weather parameters were obtained.

(ii) Isotopic composition of vapour in the advective system

In the case of advection, both over the saturated and the unsaturated air column, the isotopic composition of vapour at the pressure level where CLWC is maximum, was used as it is, to be the isotopic composition of the rain-forming vapour source (δ_{vo}).

In the foregoing, aspects concerning the isotopic composition of vapour (δ_{vo}) both in the convective and the advective systems are discussed. In the following, the isotopic composition of liquid (δ_{l0}), generated from this rain-forming vapour (δ_{vo}) is computed for a certain value of residual vapour fraction (f_c) when the isotopic composition of vapour changes from $\delta_{vo}$to δ_v.

The residual vapour fractionation f_c, due to condensation from the vapour parcel was computed using a formulation given by (Rahul et al., 2018):

$$f_c = 1 - \frac{Rf}{PWC} \qquad (9.2)$$

Where Rf is rainfall amount and PWC is the total precipitable water content in the atmosphere. Monthly averaged Rf was obtained from TRMM (http://daac.gsfc.nasa.gov/precipitation/TRMM_ README/TRMM_3B43_readme.shtml) and PWC was obtained from NCEP-DOE AMIP-II reanalysis dataset (http://www.cpc.ncep.noaa.gov/products/wesley/reanalysis2/) at 0.25° X 0.25° resolution.

In the above formulation, it is assumed that the vapour source region and the isotopic composition of vapour from which rain is generated remain the same for the concerned timeframe of the monthly average. It may be noted that the value of f_c so computed, will be in good agreement with the true value only in case of either a large number of rainy days in a month or consecutive days in case of a fewer number of rainy days.

The isotopic composition of residual vapour (δ_v) is computed using the Rayleigh formulation (Gonfiantini et al., 2001):

$$\delta_v = \delta_{vo} + \varepsilon \ln f_c \qquad (9.3)$$

Where, ε = (α – 1) × 1000, and α is temperature-dependent equilibrium fractionation factor for the liquid to vapour (Horita and Wesolowski, 1994). The temperature at the pressure level where the CLWC is maximum is used as the condensation temperature (T_c) to compute the fractionation factor α. The monthly averaged temperature data was also obtained from ERA-Interim.

The isotopic composition of the liquid condensate δ_{lo} is given by:

$$\delta_{lo} = \frac{\delta_{vo} - f_c\delta_v}{1 - f_c} \qquad (9.4)$$

Both in case of the convective and the advective systems, the condensate is expected to undergo evaporation during its fall through unsaturated air column. The extent of evaporation is determined by the degree of undersaturation given by the RH of the air column. The initial liquid condensate δ_{lo} thus formed would fall through the atmosphere and undergo secondary isotopic modification due to evaporation from falling drops and interaction with the surrounding moisture. Thus, the isotopic composition of the final liquid δ_l that reaches the ground can be computed using formulation given by Stewart (1975), in δ notation:

$$(\delta_l 10^{-3} + 1) = [(\delta_{lo} 10^{-3} + 1) - \gamma(\delta_a 10^{-3} + 1)] f_e^{\beta} + \gamma(\delta_a 10^{-3} + 1) \qquad (9.5)$$

Where, δ_a is the isotopic composition water vapour in the atmosphere (averaged at equal intervals between half maxima of CLWC and ground level); f_e is residual fraction of water remaining in the raindrop after evaporation. The fractional evaporative loss is 1- f_e and the percentage evaporative loss is (1- f_e) × 100. The terms γ and β in equation 9.5 are given by:

$$\gamma = \frac{\alpha_p h}{1-\alpha_p\left(\frac{D}{D'}\right)^n (1-h)} \text{ ; and } \beta = \frac{1-\alpha_p\left(\frac{D}{D'}\right)^n (1-h)}{\alpha_p(\frac{D}{D'})^n \, (1-h)}$$

Where, α_p is the equilibrium fractionation factor between the liquid drop and vapour at its surface computed for the ERA-Interim air temperature (T_a) averaged between the ground level and cloud liquid maxima; h is the ERA-Interim humidity (RH_a) similarly averaged between the ground level and cloud liquid maxima. The D/D' is the ratio of diffusivity constants for H_2O and $H_2{}^{18}O$ molecules in the atmosphere and n is an exponent dependent on the drop size. Values of D/D' and n were taken from Stewart (1975). The value of f_e, was computed for which the modelled value of δ_l matches the observed isotopic composition of rain δ_{obs}. All the weather parameters necessary to compute the extent of evaporation from falling raindrops at each of the four stations in this study were estimated over 4° x 4° boxes with the concerned station lying at the centre, except for the Jorhat where a 4° x 2° box was considered to restrict the latitudinal extent to exclude the orographic highs in the north and south of Jorhat which would bias the computations. Since the LMDZ-iso data were available only till 2010, all the computations were done only for 2010.

As discussed earlier, the CLWC is used for the following three purposes: (1) the pressure levels between which the cloud liquid water content (CLWC) is more than half of its maximum value is used to estimate the isotopic composition of rain-forming vapour in case of the convective system; (2) the pressure level at which the CLWC value is maximum is used to obtain the isotopic composition of rain forming vapour in case of the advective system; (3) the temperature at an altitude at which CLWC is maximum is considered for computing fractionation factor.

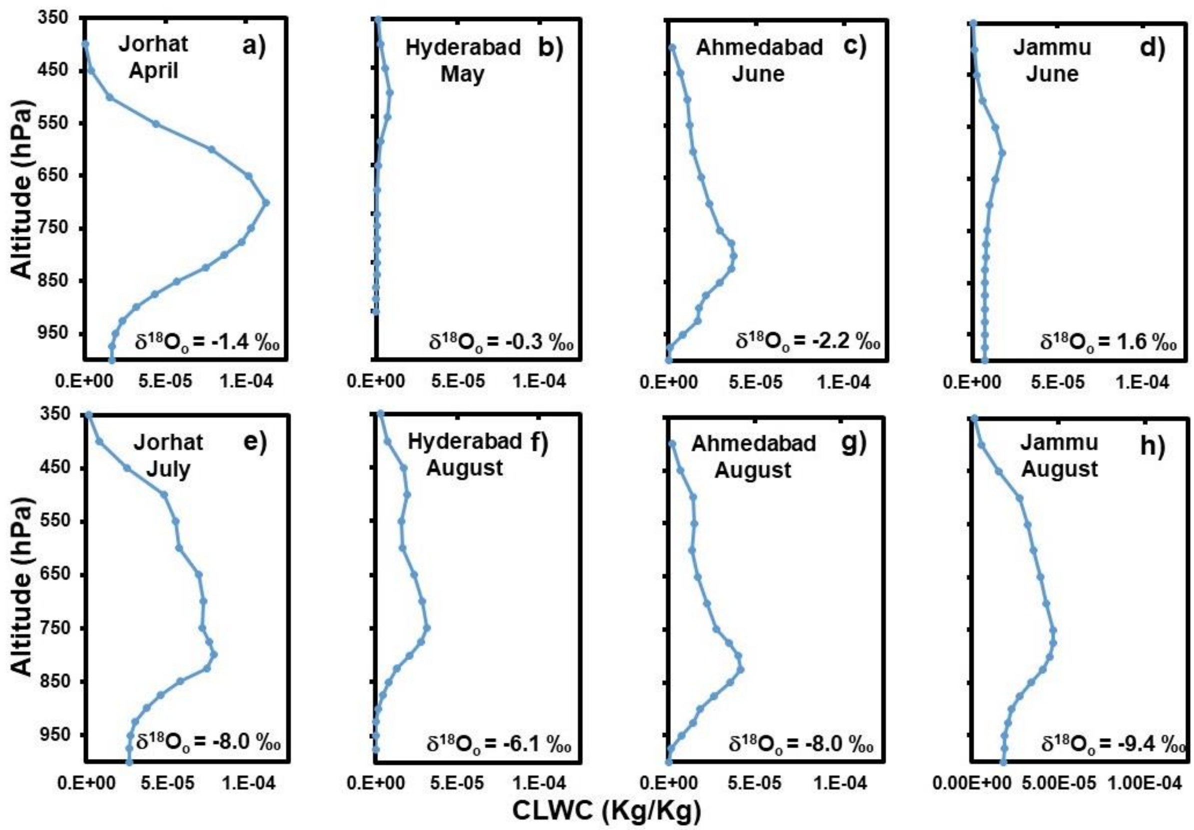

Figure 9. 3: Atmospheric vertical profile of Cloud Liquid Water Content (CLWC) for the months with most enriched and most depleted monthly averaged isotopic values of rain for all the four stations

Fig. 9.3 shows the vertical distribution of CLWC with respect to atmospheric pressure (hPa), for months with the most enriched (Fig. 9.3 a, b, c and d) and the most depleted (Fig. 9.3. e, f, g and h) amount weighted monthly average $\delta^{18}O$ values in the rain. In the case of the months with the most enriched monthly average $\delta^{18}O$ values, a short span of altitude having relatively high values of CLWC is observed. In contrast, in case of months with most depleted monthly average $\delta^{18}O$ values, a comparatively longer span of altitude having high values of CLWC is clearly observed at Jorhat, Hyderabad and Jammu, and less clearly at Ahmedabad. The high CLWC over a longer span of altitude increases the chance of interaction of falling raindrop with isotopically depleted ambient vapour, and the high column-averaged RH further retards the evaporative enrichment from falling raindrops, resulting in isotopically depleted rain.

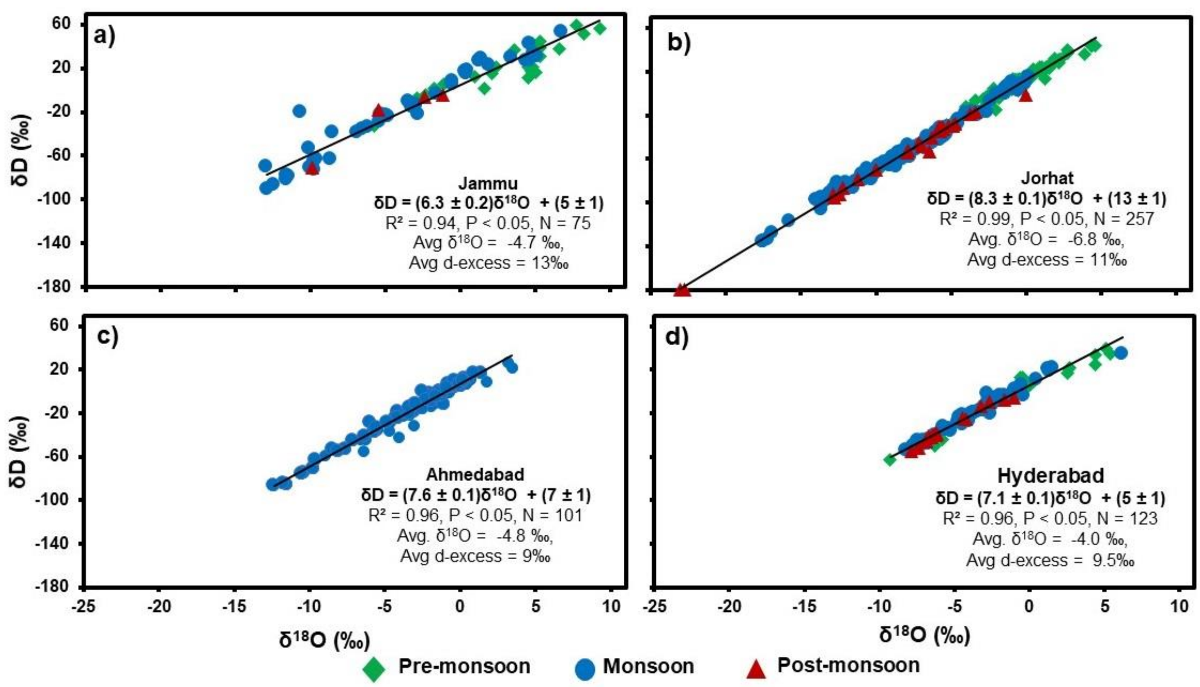

Figure 9. 4: $\delta^{18}O$ - $\delta^{2}H$ regression line based on daily rain samples collected from four stations viz. a) Jammu; b) Jorhat; c) Ahmedabad and d) Hyderabad, with the demarcation of pre-monsoon, monsoon and post-monsoon sample

9.4 Results and Discussion

With a view to identify signatures of major hydrometeorological processes including evaporation from falling raindrops, as imprinted on the isotopic composition of rainwater samples from the Indian subcontinent, the following strategy is adopted.

- The overall interpretations are drawn based on individual regression lines (Fig. 9.4) for each of the four stations.
- The computations for estimating evaporation from falling raindrops is done (as per the methodology described earlier) for the months having the most enriched and the most depleted amount weighted average $\delta^{18}O$ values for the year 2010.

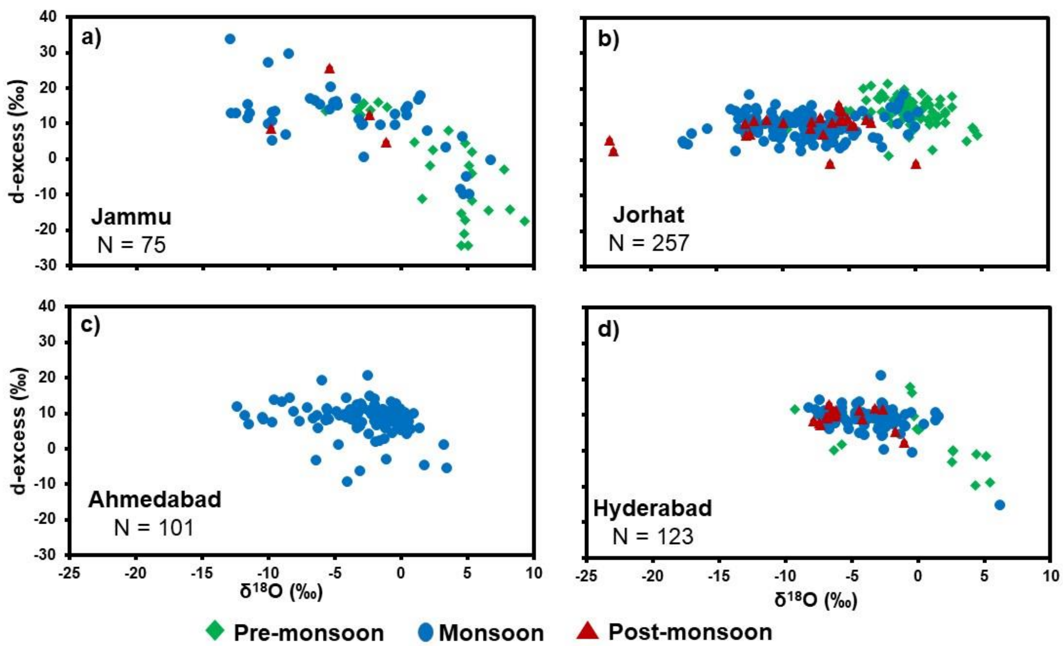

Figure 9. 5: $\delta^{18}O$ – d-excess relationship based on daily rain samples collected from four stations viz. a) Jammu; b) Jorhat; c) Ahmedabad and d) Hyderabad, with demarcation of pre-monsoon, monsoon and post-monsoon sample

(i) Jammu

Local meteoric water line based on 75 daily rain samples collected from Jammu is plotted in Fig. 9.4a. The amount weighted average $\delta^{18}O$ and d-excess were found to be -4.7‰ and 13‰, respectively. The slope (6.3 ± 0.2) and intercept (5 ± 1) of the local meteoric water line at Jammu (Fig. 9.4a) is significantly lower than that of Global Meteoric Water Line (GMWL), suggesting significant evaporation from the falling raindrops. It is seen in Fig. 9.5a that both pre-monsoon and monsoon samples exhibit an inverse relationship between $\delta^{18}O$ and d-excess suggesting dominant role played by evaporation in both the seasons although Jammu is located at the higher latitude and altitude (327 m) compared to other three stations. Contrary to the expectation, the peculiar isotopic signatures of WD [high d-excess and low $\delta^{18}O$; Jeelani and Deshpande (2017)] are not observed in the pre-monsoon months (Jan-May). Both the high and low values of $\delta^{18}O$ are associated with both, high and low d-excess during monsoon, suggesting the varying degree of rainout (low $\delta^{18}O$ with low d-excess or high $\delta^{18}O$ with high d-excess), evaporation from falling raindrops (high $\delta^{18}O$ and low d-excess) and recycled rain (low $\delta^{18}O$ and high d-excess) from depleted surface water bodies fed by glacial melts (Singh, 1990).

The most enriched value of monthly average $\delta^{18}O$ was observed in the month of June (1.6‰). High OLR (255 W/m^2) and negligible upward winds at 500 hPa (-0.03 pa/s) indicate the absence of convection. The cloud top height was 517 hPa, and CLWC maxima were sharply peaking at 600 hPa (Fig. 9.3d) with the condensation temperature of 275.5 K (ε = 11.47‰). The isotopic makeup of the advected vapour undergoing condensation was -19‰. The evaporative loss from the raindrops, necessary to arrive at the observed isotopic composition (1.6‰) of rainfall is estimated to be 52% at a column-averaged RH of 58%. This suggests large scale post condensation modification via kinetic processes which are expected to result in a large variation in d-excess. It is observed that isotopically enriched (depleted) daily rain events were associated with low (high) RH and low (high) d-excess up to -10‰ (15‰). This could be explained by significant variation in daily surface RH ranging from 40% - 60%.

The most depleted average monthly $\delta^{18}O$ value of -9.4‰ was observed in the month of August. High OLR (232 W/m^2) and very low upward vertical wind velocity (-0.05 pa/s) at 500 hPa, suggested no convection. It is known that in the month of August, the southwest monsoon transports moisture from the BOB (Jeelani et al., 2017). The cloud top height in August was 443.8 hPa, and CLWC remained consistently high between 850-500 hPa, with a peak at 775 hPa (Fig. 9.3h). The condensation temperature at 775 hPa was 290.6 K (ε = 10.02‰). The isotopic makeup of advected condensing vapour was found to be -19.8‰. The evaporative loss necessary to arrive at observed isotopic composition of -9.4‰ is estimated to be 8 % under the column-averaged RH of 75%. The d-excess for most (11 out of 13) rainy days of August ranged between 9.98 to 17.16‰.

The relatively high d-excess suggests a small degree of post condensation modification which can be explained by high surface RH values ranging between 73 to 92 %.

(ii) Jorhat

A local meteoric water line based on 257 daily rain samples at Jorhat is shown in Fig. 9.4b. The slope (8.3 ± 0.1) of the meteoric water line is similar to GMWL but, the intercept (13 ± 1) is higher than the GMWL. The amount weighted average $\delta^{18}O$ and d-excess of all the samples were found to be -6.8‰ and 11‰, respectively. Isotopically most enriched rain events were also observed during the pre-monsoon months, whereas most depleted rain events have occurred during monsoon and post-monsoon. The higher values of intercept and the average d-excess suggest a significant contribution of locally derived moisture in the precipitation throughout the year. The widespread wetlands and low-lying flood plains of Jorhat are fed by annual floods in Brahmaputra River (Achyuthan et al., 2013) bringing isotopically depleted [-12‰ (Lambs et al., 2005)] glacial meltwater during the southwest monsoon. It is expected that surface water present in the wetlands and flood plains during monsoon months undergoes evaporative isotopic enrichment until next monsoon.

It is to be noted (Fig. 9.5b) that evaporative enrichment in ^{18}O (Jan-June) is not accompanied by associated lower values of d-excess. This is due to the fact that relative humidity at Jorhat remains high (~ 85%) throughout the year and therefore, although significant evaporation occurs due to availability of water, the kinetic fractionation effects are minimized. It is also to be noted that there are two highly depleted (~ -22‰) rain events in post-monsoon months, possibly due to stray meteorological events such as localized convection.

The most enriched (-1.4‰) monthly amount weighted $\delta^{18}O$ value of rain was also observed in the month of April. Low OLR (228 W/m^2) and high vertical wind velocity at 500 hPa (ω = -0.15 Pa/s) were observed during April, indicative of strong convection. This seems to be associated with strong convection of locally available enriched surface waters, driven by the Nor'westers, also locally known as "Kal Baishakhi" (Laskar et al., 2015). The maximum CLWC was found between 850 to 550 hPa peaking at 700 hPa (Fig. 9.3a). Hence, the condensation temperature of 270.7 K at CLWC peak (700 hPa) was used for the computation of fractionation (ε = 12‰) and isotopic composition of initial liquid condensate. The evaporative loss from the initial liquid condensate, necessary to obtain the observed isotopic value of rain is estimated to be 15% at a column-averaged RH of 78.9%.

The most depleted ($\delta^{18}O$ = -8‰) monthly averaged isotopic value of rain was observed in July, which was associated with relatively weaker convection (OLR = 197 W/m^2 and ω = -0.08 Pa/s) than that in April. Due to significant rainfall and flooding of Brahmaputra river with isotopically depleted [-12‰ (Lambs et al., 2005)] water, the availability of isotopically depleted moisture increases in July compared to April, resulting in higher column average RH (88%). The isotopic dilution of surface waters, due to flooding in the Brahmaputra in the month of July, is also evident in the isotopic composition of modelled surface vapour obtained from LMDZ-iso GCM, which is found to be isotopically depleted (-13.8‰) in July, compared to April (-10.6‰). The CLWC was also found to be high for a wider range within pressure levels of 850 to 550 hPa, with a peak in CLWC at 800 hPa (Fig. 9.3e). The condensation temperature at this peak of CLWC was found to be 273.6 K with ε = 11.67‰. The evaporative loss from the initial liquid condensate, necessary to obtain the observed isotopic value of rain is estimated to be 4%. Such a lower evaporative loss in July, compared to that in April, can be explained as due to the highly saturated vapour column (RH = 88%) in July compared to 78.9% in April.

(iii) Ahmedabad

Based on 101 daily rain samples, a local meteoric water line for Ahmedabad is plotted in Fig. 9.4c. The lower slope (7.6 ± 0.1) and intercept (7 ± 1) compared to that of GMWL suggest significant evaporation from falling raindrops. The amount weighted average $\delta^{18}O$ and d-excess were -4.8‰ and 9‰, respectively.

The most enriched monthly amount weighted average $\delta^{18}O$ of -2.2‰ was observed in the month of June. High OLR (250 W/m^2) and downward winds at 500 hPa (0.0006 pa/s) indicate the absence of convection. It is also known that during June, most of the moisture is advected from the Arabian Sea (AS) owing to southwest monsoon (Oza et al., 2020). Hence, advection has been considered as the primary moisture transport mechanism operating in June at Ahmedabad. Cloud top height of 498 hPa was observed, along with the CLWC peaking sharply at 800 hPa (Fig. 9.3c) with condensation temperature of 292.9 K, at which the value of ε is 9.81‰. The $\delta^{18}O$ of advected moisture at 800 hPa was -13.3‰. The evaporative loss was computed to be 8% at the observed column average RH of 46%. However, the low d-excess (~ -5‰), associated with most enriched δ^{18}O values (~5‰) cannot be explained by such a low estimated value of evaporation from falling raindrop. The probable reason for the underestimation of evaporative loss from the falling raindrops could be due to overestimation of residual vapour fraction (f_c = 92.33%). This overestimation arises due to the fact that there are only a few rainy days during June, discretely spread across the month while the *PWC* and *Rf* values are averaged over the month, as discussed in methodology section.

The most depleted average δ^{18}O (-4.8‰) was found in the month of August. Although based on long term (1998-2013) TRMM data, Oza et al. (2020) have shown that convective rain proportion increases progressively during southwest monsoon, the advected moisture from the AS is the primary source of moisture for rain at Ahmedabad during August. Low OLR (202 W/m^2) along with minimal upward wind velocity (-0.01 Pa/s) at 500 hPa during August 2010 suggests negligible convective activity. Therefore, computations are done considering the advective system for this case. The cloud top height of 344.9 hPa was observed with maximum CLWC ranging between 700-875 hPa and the peak at 825 hPa (Fig. 9.3g) at which the condensation temperature was 291.4 K (ε = 9.95‰). The isotopic makeup of the rain-forming moisture was found to be -16.03‰. The evaporative loss necessary to arrive at the observed isotopic composition of rain (-4.8‰) is estimated to be 8% at column average RH of 80.5%.

(iv) Hyderabad

A local meteoric water line comprising a total of 123 daily rain samples collected from Hyderabad during 2010-11 is plotted in Fig. 9.4 d. The slope (7.1 ± 0.1) lower than that of GMWL, suggests significant evaporation from falling raindrops. Isotopically some of the most depleted as well as most enriched rain samples were found during pre-monsoon. The enriched δ^{18}O samples are associated with low d-excess (Fig. 9.5 d), which again suggests evaporation from falling raindrops. Whereas, the samples with depleted δ^{18}O were associated with high d-excess (Fig. 9.5 d), suggesting recycled moisture (Froehlich et al., 2008; Peng et al., 2010). During monsoonal months, δ^{18}O of rain samples range from -8.2‰ to 1.5‰ with d-excess ranging from 0‰ to 21‰. Samples depleted in δ^{18}O and associated with low d-excess might suggest significant rainout history, whereas samples with low δ^{18}O and high d-excess, suggest the contribution of locally recycled moisture. In addition, there were very few samples with enriched $\delta^{18}O$ and low d-excess during monsoon, indicating evaporation from falling raindrops. Most of the post-monsoon samples were depleted in $\delta^{18}O$ (-7.9‰ to -1‰) and d-excess ranged from 2‰ to 13‰, which suggests varying degree of rainout probably from BOB, due to retreating southwest monsoon. The amount weighted average $\delta^{18}O$ and d-excess of all the samples were -4.0‰ and 10‰, respectively.

Table 9. 2: Shows the required values of isotopic and meteorological parameters necessary for the estimations of evaporative loss from the falling raindrops.

Station	Month	$\delta^{18}O_{obs}$ (‰)	Moisture transport process	$\delta^{18}O_{vo}$ (‰)	T_C (°C)	ε (‰)	f_c (%)	$\delta^{18}O_v$ (‰)	$\delta^{18}O_a$ (‰)	T_a (°C)	RH_a (%)	f_e (%)
Jammu	June	1.6	Advection	-19	2.35	11.5	49.35	-27.1	-18.73	13.85	58	48
Jammu	August	-9.4	Advection	-19.58	17.5	10	60.35	-24.64	-18.74	13.75	75	92
Jorhat	April	-1.4	Convection	-13.02	-2.5	12	34.44	-25.08	-12.62	12.05	78.9	85
Jorhat	July	-8	Convection	-19.07	0.45	11.7	73.65	-22.64	-18.62	14.85	88	96
Ahmedabad	June	-2.2	Advection	-12.94	19.8	9.81	92.33	-13.72	-16.3	19.	46	92
Ahmedabad	August	-4.9	Advection	-16.03	18.3	9.95	82.64	-17.9	-17.98	13.4	80.5	92
Hyderabad	May	-0.3	Advection	-18.78	-0.8	11.8	85.22	-20.66	-12.41	19.45	59.3	71
Hyderabad	August	-6.1	Convection	-18.7	13.8	10.4	72.22	-22.07	-14.82	17.2	84	85

The most enriched monthly amount weighted average $\delta^{18}O$ (-0.3‰) value was found in the month of May. Downward vertical wind velocity (0.022 Pa/s) at 500 hPa and high OLR value (260 W/m^2), indicates the absence of convection. The CLWC was found to peak sharply at 550 hPa (Fig. 9.3b) and therefore, temperature of condensation at 550 hPa (272.4 K) was used to compute ε (11.8‰). Due to absence of convection, the isotopic composition (-18.78‰) of advected vapour at 550 hPa was used to estimate the $\delta^{18}O$ of condensate. For column-averaged RH of 59.3%, the observed isotopic composition of rain (-0.3‰) was achieved from the rain-forming cloud at an estimated the evaporative loss of 29 %, suggesting significant role of evaporation from falling raindrop. This is further supported by low average rain amount of 6 mm/day and low average d-excess of -1.3‰.

The most depleted isotopic values at Hyderabad were found in August, with the average $\delta^{18}O$ of -6.1‰. Low OLR (198 W/m^2) along with small vertical upward velocity (-0.03 Pa/s) at

500 hPa, indicated low to mid convective strength. Cloud top height of 345 hPa was observed with CLWC ranging consistently high between 550–800 hPa, with a peak at 750 hPa (Fig. 9.3f). The condensation temperature at 750 hPa was 286.9 K which was used to compute fractionation (ε = 10.35‰). The column averaged RH was found to be 84%. The $\delta^{18}O$ of rain-forming vapour was computed to be -18.7‰. The estimated evaporative loss necessary to obtain observed isotopic composition of rain (-6.1‰) from the rain-forming vapour is 15%.

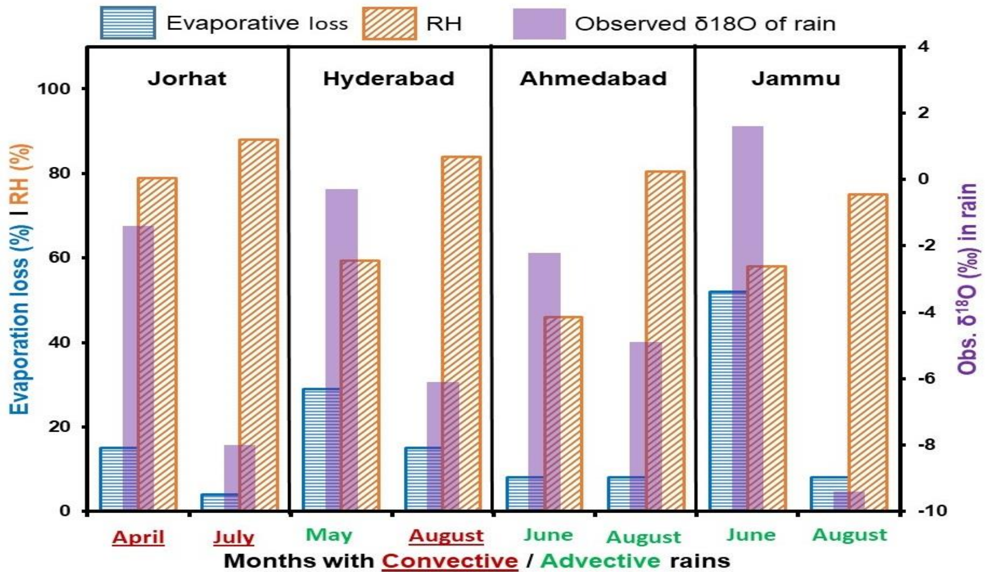

Figure 9. 6: Comparison of percentage evaporative loss (1-f_e×100), column average atmospheric RH and the observed isotopic composition of rain for the months with most enriched and most depleted amount weighted average $\delta^{18}O$ values for all the four stations

Fig. 9.6 compares the evaporative loss, column average atmospheric RH and the observed isotopic composition of rain for the months with most enriched and most depleted amount weighted average $\delta^{18}O$ values for all the four stations. It can be seen that for each station, except for Ahmedabad, the lower column average atmospheric RH values are associated with higher evaporative loss and vice versa. Fig. 9.7 also shows high correlation (R^2 = 75%; $P < 0.05$) between column-averaged RH and evaporative loss from the falling raindrops for the months with most enriched and most depleted rain $\delta^{18}O$ values for all the four stations with an exception in case of June rainfall at Ahmedabad, where evaporative loss is underestimated due to the reasons discussed earlier (section 4.3.). Fig. 9.7 shows that the column-averaged RH is a major controlling factor for

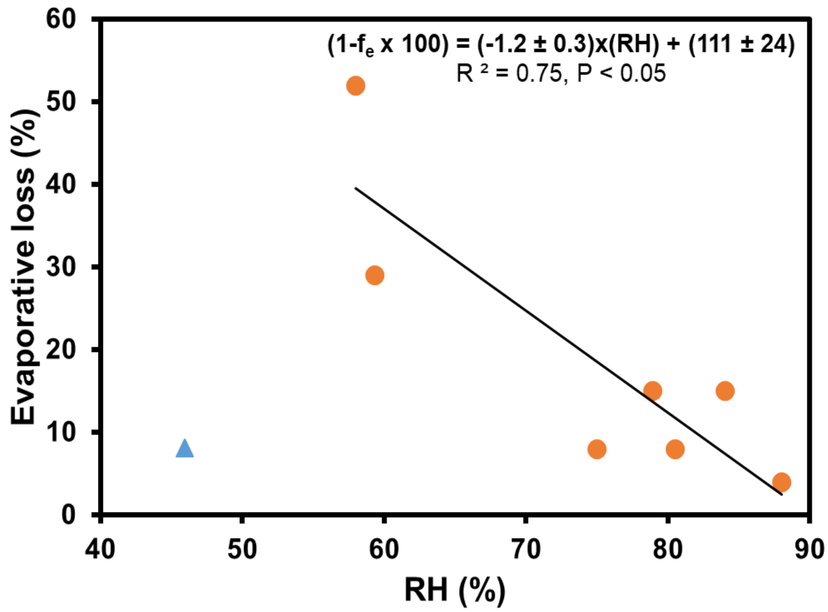

Figure 9. 7: Correlation between column-averaged RH and evaporative loss from the falling raindrops for the months with most enriched and most depleted rain $\delta^{18}O$ values for all the four stations with the exception of June, Ahmedabad (marked with a triangle)

evaporation from falling raindrops estimated in this study which confirms that the method of computation realistically accounts for the kinetic process during evaporation from falling raindrops.

9.5 Conclusion

Exhaustive computations involving combination of isotope data of daily rainwater samples and various other meteorological parameters have been done for the months with most enriched and most depleted amount weighted monthly averaged isotopic composition of rain at all the four stations, as these are indicative of specific hydrometeorological processes and factors such as convection, advection, degree of saturation and cloud liquid content.

Important values of computed and observed parameters are given in Table 2. Some of the important insights derived from this study are given below.

- The estimated values of maximum and minimum evaporative loss from falling raindrops for the four stations are [Jammu: Maximum 52% and Minimum 8%;

Jorhat: Max 15% and Min 4%; Hyderabad Max 29% and Min 15% and Ahmedabad Min 8%]

- Increased availability of surface waters due to flood in Brahmaputra River and high column average RH of 88% results in the lowest evaporative loss from falling raindrops at Jorhat.
- Isotopically depleted rain is associated with high CLWC over a longer span of altitude, which facilitates the interaction of falling raindrop with isotopically depleted ambient vapour. In addition, high column-averaged RH further retards the evaporation of falling raindrops and maintains the isotopic depletion due to long span of CLWC.
- The extent of evaporative loss from falling raindrop is found to be inversely related to column average RH for all stations. [$(1-f_e) \times 100 = (-1.2\pm0.3) \times (RH) + (111\pm24)$; $R^2 = 0.75$; $P < 0.05$]. This also confirms that the scheme of computation in this study accounts for the post condensation kinetic processes realistically.
- The isotopic compositions of LMDZ-iso modelled rain at four locations across the Indian subcontinent are found to be isotopically depleted compared to the observed rain. This negative isotopic bias in the modelled rain arises because it fails to incorporate evaporative isotopic enrichment under low RH condition due to significant spatial variation in the atmospheric RH.

Chapter 10

Conclusions and Way Forward

10.1 Conclusions

The known mega-scale (~1000 km) hydrometeorological systems responsible for delivering precipitation in different parts of India during different times of year are: (i) southwest monsoonal winds during Jun-Sep bring rain almost to the entire country; (ii) northeast monsoonal winds during Oct-Dec bring rain to southern India; (iii) Western Disturbances (WD) bring rains to northern India during Dec-Feb; (iv) Nor'westers are the thunderstorms which bring significant rain in northeastern India during Mar-May. However, subtle variations in the hydrometeorological processes operating in different spatio-temporal scales are still not clearly understood. Therefore, it is crucial to understand and discern the hydrometeorological processes and factors operating at different spatial scales viz., mega-scale (~1000 km), mesoscale (~100 km) and microscale (~ 1 to 5 km). With a view to discern these hydrometeorological processes concerning Indian precipitation, samples were collected from 41 stations spread across the country, for their isotopic analyses and interpretation in conjunction with other associated meteorological paramters and factor. This study was carried out under the aegis of the National Programme on Isotope Fingerprinting of Waters of India (IWIN). All the inferences drawn have been already described in detail in individual chapters but some of the major conclusions of this study are summarized in the following.

(1) Mega-scale hydrometeorological processes

The study provides an integrated synoptic snapshot of various hydrometeorological processes controlling precipitation in different parts of India within three timeframes viz., pre-monsoon (Jan-May), southwest monsoon (Jun-Sep) and northeast monsoon or post-monsoon (Oct-Dec).

- Evaporation from falling raindrops is one of the most dominant hydrometeorological processes in India as evident from the lower slope of composite Indian meteoric water line (IMWL) compared to that of the global meteoric water line (GMWL).

- During pre-monsoon season, majority of country's precipitation is derived from continentally recycled moisture. Signatures of Nor'westers in northeast India and WD in northern India are also observed in the isotopic composition of precipitation.

- During monsoon season, continental isotopic effect in precipitation is found in Indian peninsular region, while in most parts of India, trends of isotopic depletion in precipitation indicates progressive rainout while moving away from marine vapour masses.

- During the post-monsoon season, contrary to expectation in southern Indian peninsula, isotopic signatures show significant continentally derived precipitation, instead of precipitation derived from the Bay of Bengal (BOB) vapour. Similarly, in most parts of India isotopic composition of precipitation indicates varying degree of rainout from continentally derived moisture.

- Significant amount effect in isotopes is found only along the narrow belt in the Indo-Gangetic plains. Also, temperature effect in isotopes was not observed at the majority of stations, implying the complexity of hydrometeorological process governing Indian precipitation.

- Novel correlation index (iH-index) for the Indian subcontinent has been defined based on the correlation between 16 meteorological parameters and the amount weighted monthly precipitation isotopic composition. The $\delta^{18}O$ values show a significant correlation with seven parameters, while d-excess values do not show any significant correlation. It indicates that mesoscale (~100km) and microscale (1 to 5 km) hydrometeorological processes play a dominant role in governing regional precipitation.

(2) Mesoscale hydrometeorological processes

(i) Insights from Northern India

- Evaporation from the falling raindrops is one of the most dominant processes controlling the isotopic signatures of precipitation throughout the year

- Moisture from the Mediterranean Sea region doesn't seem to contribute to rain during the period of WD at Jammu.

- The high d-excess and depleted $\delta^{18}O$ during WD period is ascribed to one or more of the factors, namely, continental recycling, kinetic effect during condensation, and vapour deposition under supersaturated condition.

- Depletion in $\delta^{18}O$ at the beginning of monsoon is associated with increased moisture contribution from the AS and longer rainout history of vapour parcel.

- Isotopically most depleted precipitation during mid-monsoon is ascribed to continentally derive recycled moisture arising from precipitation in the Indo-Gangetic plains.

- Enrichment in $\delta^{18}O$ during late monsoon is ascribed to relatively shorter rainout history of vapour due to weakening of monsoonal winds, continental recycling from progressively enriching inland waters and evaporation from falling raindrops.

(ii) Insights from Northeast India

- Maximum moisture for rainfall is derived from continental recycling.

- Evaporation from falling raindrops is minimal at Jorhat.

- High $\delta^{18}O$ and high d-excess with the slight trend of $\delta^{18}O$ depletion are ascribed to continentally recycled moisture generated from progressively enriched surface waters, and increased condensation temperature during pre-monsoon.

- Exceptionally high d-excess indicates deep convection associated with Nor'westers during April-May.

- $\delta^{18}O$ baseline shift and trend of $\delta^{18}O$ depletion during monsoon are ascribed to isotopic depletion of the surface waters, due to floods in the Brahmaputra River and an orographic rainout of advected moisture from the BOB.

- Evasion of the orographic barrier due to variation in wind direction and progressive isotopic enrichment of surface waters due to evaporation causes the trend of isotopic enrichment in post-monsoon rain.

(iii) Insights from Western India

Long term (2005-2016) daily precipitation isotope data ($\delta^{18}O$, δD and d-excess) from Ahmedabad in semi-arid Western India were examined in light of various meteorological parameters. One of the most prominent and systematic annual patterns is the isotopic depletion (average $\delta^{18}O$: -2.5‰ in Jun-Jul; -5.2‰ in Aug-Sept) in the second half of the Southwest Monsoon, which is observed in the 10 out of the 12 years of this study. It is inferred from the present study that isotopic depletion in the second half Southwest monsoon is associated with:

- Increased contribution (from 36% to 45%) of terrestrially recycled moisture
- 1.9° C lower Cloud base temperature during Aug-Sep
- Increased rainout fraction due to decreased wind velocity (from 8.8 m/s to 6.9 m/s)
- An increase of 22.3% in the proportion of convective rain.

(iv) Insights from the Indian Peninsula

A lack of correlation between trends in rain isotopes and various meteorological parameters such as the convective fraction of rain, condensation temperature, rainout history and increased BOB moisture contribution indicates a complex interplay between the multitude of hydrometeorological processes and meteorological parameters.

- During pre-monsoon (Jan – May), evaporation from falling raindrops is significant.
- Orographic barrier posed by the Western Ghats causes relative isotopic depletion in the rain during monsoon (Jun-Sep), however, nominal difference between isotopic composition of rain on either side of Western Ghats suggests that although total amount of orographic rainfall is large, it is too small a fraction of massive cloud parcels to cause major isotopic difference between windward and leeward sides.

- During post-monsoon (Oct-Dec) continentally recycled moisture is the dominant vapour source, and possible effect of northeast monsoon bringing vapour from BOB is not observed.

(3) Microscale hydrometeorological processes

- The estimated evaporative loss from falling raindrops for the four representative stations is [Jammu: Maximum 52% and Minimum 8%; Jorhat: Max 15% and Min 4%; Ahmedabad Min 8% and Hyderabad Max 29% and Min 15%].
- Increased availability of surface waters due to flood in Brahmaputra River and high column average RH of 88% results in the lowest evaporative loss from falling raindrops at Jorhat.
- The high Cloud Liquid Water Content (CLWC) over a longer span of altitude facilitates the interaction of falling raindrop with isotopically depleted ambient vapour and results in isotopically depleted rain.
- The observed inverse relationship between the evaporative loss from falling raindrop and the column average RH confirms that the post condensation kinetic processes are realistically accounted in this study.
- Validation with measured isotope data of rain shows that the LMDZ4-iso modelled rain fails to incorporate evaporative isotopic enrichment and generates negative bias for Indian precipitation.

10.2 Limitations

The present study provides some new insights into various hydrometeorological processes governing Indian precipitation in different spatial scales. However, there are several limitations associated with the availability and spatio-temporal resolution of isotopic and meteorological data. Some of the limitations are listed below.

- Fewer stations collecting daily precipitation samples
- The isotope data is a point source, whereas the meteorological parameters obtained from satellite or reanalysis datasets are available at wider spatial resolution. Also, because of this significance analysis in chapter 4 was not possible.

- In Chapter 4 monthly averaged meteorological data was used because fortnightly precipitation samples were collected from the majority of stations.
- Observed or measured vapour isotopic data is not available.
- Resolution of LMDZ-iso modelled vapour data (used in chapter 9) was at very poor spatial resolution (3.75º latitude x 2.5º longitude).
- Modelled isotope data available are not validated for the Indian region

10.3 Future Scope

The present study reveals the importance of mesoscale and microscale hydrometeorological processes which governs the distribution and availability of precipitation in a region. It opens up new scope for further research using finer spatially and temporally resolved isotopic and meteorological datasets. Some of the salient points which need to be pursued to advance the understanding are: (1) the event-based isotopic study of precipitation samples can help in understanding cloud micro-physical and rainout related processes; (2) isotopic characterisation of meteorologically extreme events such as cloud burst, cyclones or thunderstorms might help in understanding causal mechanisms; (3) with long term data and more closely located sampling stations, vulnerability of regions with higher continental recycling of moisture to draughts can be assessed; (4) continuous monitoring of isotopic composition of atmospheric vapour can be advantageously used to predict the onset of monsoon; and (5) with a better understanding of mesoscale and microscale hydrometeorological process and their effect on precipitation, isotopes can be used for fine-tuning and validating isotope enabled global circulation models.

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