

# An Overview on Isotopes in Precipitation of Bangladesh



Abdul Hadi Al Nafi Khan, Md. Abdul Quaiyum Bhuyian, Md. Ariful Ahsan, Farhana Islam, Md. Masud Karim, and Md. Moniruzzaman

## 1 Introduction

Precipitation is an important part of the hydrological cycle, and spatiotemporal variations of precipitation isotopes may lead to conceptualize the processes involved in hydrometeorological and ecological events (Craig 1961; Dansgaard 1964; Liu et al. 2014). The precipitation stable isotopes ( $^{18}\text{O}$  and  $^2\text{H}$ ) have been established as an important tool in Isotope Hydrology which is frequently applied in studying not only the source and dynamics, but also in atmospheric circulation and reconstruction of palaeoclimatic events (Araguas-Araguas et al. 1998). Variation of  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  with respect to space can reveal the source of vapour/moisture and the recycling events that have occurred during the transportation (Bowen and Revenaugh 2003).

Temperature, rainfall amount, altitude, humidity, vapour pressure, latitude, continentality etc. are globally known as environmental and geographic controls over isotopic variations in precipitation (Rozanski et al. 1993; Vuille et al. 2005; Chen et al. 2017). However, in local scale the environmental controls may act differently as moisture recycling, transient eddies and changing moisture sources play roles in relatively smaller domains (Dublyansky et al. 2018).

Global Network of Isotopes in Precipitation (GNIP) programme was started in 1958 with the collaboration of World Meteorological Organization (WMO) to generate better understanding on spatiotemporal climate variation, atmospheric circulation and studying interaction of water between atmosphere and biosphere. From 1961, more than 1000 locations spread across approximately 125 countries

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A. H. A. N. Khan (✉) ·

M. A. Q. Bhuyian · M. A. Ahsan · F. Islam · M. M. Karim · M. Moniruzzaman

Institute of Nuclear Science and Technology, Bangladesh Atomic Energy Commission, Dhaka, Bangladesh

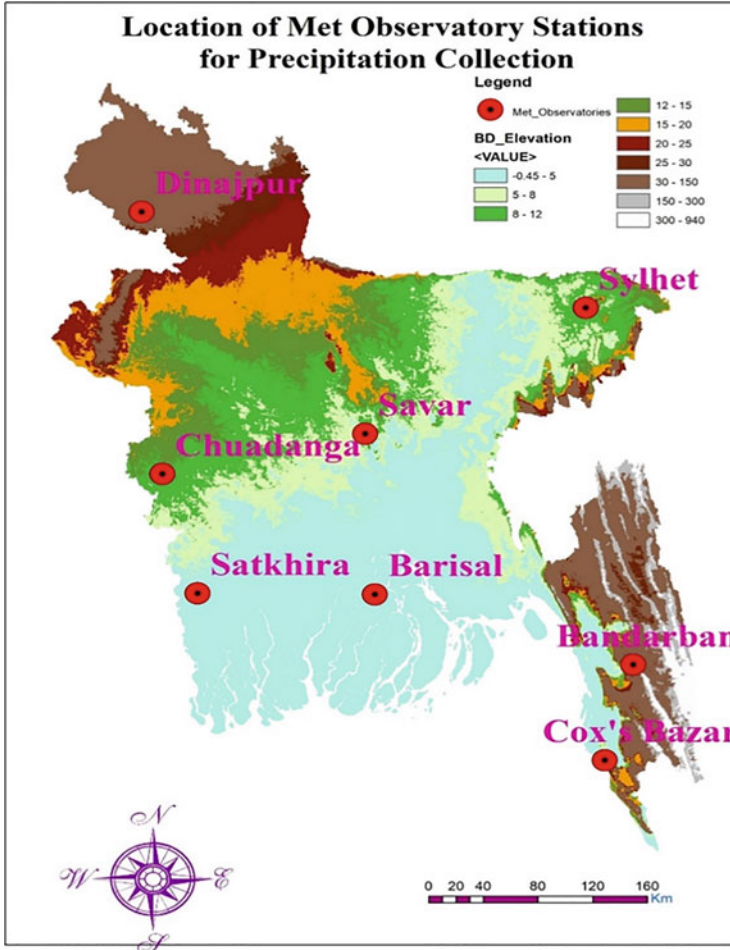
have produced monthly precipitation samples in connection with GNIP programme (IAEA 2019). While somewhat late, GNIP programme was started in Bangladesh since 2009 initially with two stations (Savar at central Bangladesh and Sylhet at northeast of Bangladesh) and currently there are a total of eight GNIP stations in different parts of the country to collect monthly samples.

Geographically, Bangladesh is a small delta which shares its south border with the Bay of Bengal, which contributes significantly to the incidence of summer monsoon in South Asia. This monsoon climate affects the lives of the huge number of population inhabiting this area. Vapour source and moisture transportation patterns are very important factors for understanding and simulating the seasonal climatic condition and variability of monsoons (Aggarwal et al. 2004). Thus, as a tracer (Liu et al. 2014), stable isotopes in precipitation in a local scale can bear significant information on moisture source and its transportation and it can also be important input for regional and global climate models (Bowen and Revenaugh 2003; Hughes and Crawford 2012). Moreover, detailed knowledge on stable isotopes in precipitation can facilitate better understanding of groundwater recharge (Gonfiantini et al. 1998). The current study aims to investigate the following areas: (1) Basic characteristics of stable isotopes ( $^{18}\text{O}$  and  $^2\text{H}$ ) and their spatiotemporal variation across Bangladesh; (2) Source of moisture and its transportation throughout the year.

## 2 Study Area and Methodology

Bangladesh is located within a subtropical monsoon climate region and experiences extensive seasonal variations in terms of temperature, humidity and rainfall amount. Four noticeable seasons are observed in Bangladesh: northeast monsoon or winter (December–February), pre-monsoon or summer (March–May), southwest monsoon (June–September) and post-monsoon or autumn (October–November) (Ahasan et al. 2010; Shahid 2010; Khatun et al. 2016; Mullick et al. 2019). The hottest months are April and May during the summer season, when monthly normal temperature occurs in the range of 21.1–36 °C throughout the country. The coldest month is January with a monthly normal temperature range of 10.4–27.4 °C across different parts (Mullick et al. 2019). Heavy rainfall is observed in most regions with some exceptions in the dry, western part of the country covering the Rajshahi division. About 75% of the total rainfall amount in a year is recorded during the monsoon period (Shahid 2010). Relatively lower amount of rainfall is experienced by the west-central, central and east-central parts of Bangladesh. Annual rainfall varied in the range of 1200–1400 mm in those regions for the period of 1961–2010. For the same period, the range was 2400–2600 mm in the northeastern region and 3200–3400 mm for southern and southeastern parts (Ahasan et al. 2010).

Bangladesh maintains a total of eight GNIP stations for precipitation sample collection aiming isotopic analysis. The stations are located in different climatic and geographic zones of the country namely, Dhaka (SR), Chuadanga (CN), Dinajpur (DN), Barishal (BS), Satkhira (KH), Sylhet (HT), Bandarban (BN) and Cox's Bazar (XB). Dhaka (SR) is in the central part of Bangladesh; BS, KH and XB are three



**Fig. 1** Location Map of GNIP stations in Bangladesh

coastal stations; DN is in the northwestern part of the country; CN is located in the south central part of Bangladesh. Location of the current GNIP stations in Bangladesh is portrayed in Fig. 1.

For the sample collection process, mainly two types of rainfall collectors are used in Bangladesh. The old setup is comprised of a High Density Polyethylene (HDPE) bottle and a funnel while a Ping-Pong ball is placed at the funnel mouth to prevent evaporation during rainfall. Recently three of the stations (XB, HT, SR) are using PALMAX (Croatia) rainfall collector. Whichever the type, the rain collector is placed in an open space to collect the rain. Collected rainwater is immediately transferred after each rainfall event to a bottle which is kept sealed and stored inside a room. At the end of the month, monthly composite sample is prepared from the collected event based samples (IAEA 2014). Analysis was done by Liquid Water Isotopic Analyzer (LWIA) in Isotope Hydrology Laboratory of IAEA.

The isotopic results are expressed as  $\delta$ -values and in ‰ (per mil.) unit, which are relative to VSMOW (Vienna Standard Mean Ocean Water) on a normalized scale.

$$\delta (\text{‰}) = (R_{\text{sample}} - R_{\text{standard}}) / R_{\text{standard}} \times 1000,$$

where R refers to the  $^{18}\text{O}/^{16}\text{O}$  or  $^2\text{H}/^1\text{H}$  ratio.

Results of the isotopic analysis and meteorological data were collected from WISER database of IAEA. Total 297 monthly samples have been used in this study from those stations having the collection period of 2009–2017. Most of the stations were operational since 2014 while observation of HT and SR stations were started from 2009.

Observation of meteorological variables, including the precipitation amount (P, mm), temperature (T, °C), relative humidity (RH, %) and vapour pressure (Vp, hPa) were available at each GNIP stations except in BN. BN shares the meteorological data from its nearest meteorological observatory station in Rangamati. All isotopic and most of the meteorological data are taken from IAEA-WISER database (WISER 2018). A portion of meteorological data was used from Reliable Prognosis (RP5 2018). A summary of two major meteorological controls, temperature and rainfall for the GNIP stations has been provided in Table 1.

### 3 Results

#### 3.1 Variation in $\delta^2\text{H}$ and $\delta^{18}\text{O}$

The overall isotopic composition in precipitation (maximum, minimum and average) has been summarized in Table 2. The patterns of stable isotopic composition has been found to be different in different seasons in Bangladesh. The usual isotopic trend for June–September is: XB > CN > DN > SR > BN > KH > HT > BS. The major portion of rain occurs for a year during this period in Bangladesh. For the rest of the year the trend changes into: DN > KH > SR > BS > CN > BN > HT > XB. No distinct difference is found among the coastal and other stations in both the seasons. The mean monthly isotopic variation occurs within a very small range ( $\delta^{18}\text{O} = -6.998\text{‰}$  to  $-5.58\text{‰}$ , arithmetic average) during June–September. However, Cox's Bazar shows the most enriched signature during the monsoon season while the most depleted during the non-monsoon months. This reflects the effect of seasonality and change of moisture source in this station. Satkhira and Barisal are the other two coastal stations, but showing relatively depleted  $\delta^{18}\text{O}$  values, especially during monsoon months. The weighted  $\delta_p$  values show a somewhat surprising order: HT > XB > SR > CN > DN > KH > BN > BS. The reason for Sylhet station to be in the first position may be attributed to high rainfall during the months of April and May, which is relatively enriched. The reason of KH and BS stations to be depleted in isotopes may be a result of mixing with recycled vapour.

**Table 1** Summary data of rainfall and temperature of the eight rainfall stations of Bangladesh (Climate data 2019)

Rainfall station name	Yearly avg. temp. (°C)	Yearly rainfall avg. (mm)	Lowest rainfall avg. (mm)	Lowest rainfall avg. month	Highest rainfall avg. (mm)	Highest rainfall avg. month	Lowest temp. avg. (°C)	Highest temp. avg. (°C)	Temp. variation over the year (°C)
Dhaka	25.8	1990	6	December	372	July	18.8	28.9	10.1
Sylhet	24.8	3876	8	December	780	June	18.5	28.1	9.6
Chuadanga	26.2	1422	3	December	287	July	18.7	30.4	11.7
Sathira	26.2	1655	6	December	347	July	19.1	30.2	11.1
Dinajpur	25.0	1728	1	December	402	July	17.4	28.8	11.4
Barisal	25.9	2184	10	January	444	July	19.2	30.3	11.1
Cox's Bazar	25.6	3770	7	January	1060	July	20.5	28.5	8.0
Bandarban	25.9	2528	6	January	570	July	20.5	28.8	8.3

**Table 2** Summary of stable isotopic data in precipitation of different stations of Bangladesh

Station ID	$\delta^{18}\text{O}$ (‰)			$\delta^2\text{H}$ (‰)		
	MIN	MAX	AVG	MIN	MAX	AVG
BN	-10.72	-0.33	-5.34	-75.70	6.50	-32.42
BS	-13.28	0.19	-5.54	-97.80	10.50	-33.25
CN	-12.07	0.83	-4.43	-87.60	14.60	-25.50
DN	-11.35	1.13	-4.67	-80.66	25.60	-25.44
HT	-12.66	1.23	-4.76	-92.60	25.30	-27.34
KH	-10.93	1.24	-4.32	-76.99	12.32	-23.94
SR	-14.35	1.97	-4.68	-107.36	20.90	-28.13
XB	-10.00	-0.18	-5.35	-67.40	8.60	-32.52

### 3.2 Seasonal Variation

Figure 2 describes the monthly  $\delta^{18}\text{O}$  variation for different years in the observed stations. The first 5 months of the year, the samples are found to be more enriched than the monsoon rain samples. DN, SR and BN stations show a linear decreasing trend from the start to end of the year in these stations. In the other five stations, not much variation occurs within the months of January to May, while a marked depletion occurs just after May. From June to September in these five stations, the  $\delta^{18}\text{O}$  values are rather stable showing no distinct trends and mostly varying between  $-10\text{‰}$  and  $-6\text{‰}$  except Cox's Bazar. Cox's Bazar gives relatively enriched value ( $-8\text{‰}$  to  $-2.76\text{‰}$  usually) in that time period.

### 3.3 Construction of Local Meteoric Water Lines

Craig (1961) constructed a linear  $\delta^2\text{H}$ - $\delta^{18}\text{O}$  relationship on the basis of 400 water samples collected from rivers, lakes, and precipitation which is popularly known as Global Meteoric Water Line, GMWL ( $\delta^2\text{H} = 8 \times \delta^{18}\text{O} + 10$ ) (Craig 1961). Collected precipitation samples in connection to this study were plotted against Craig's GMWL as shown in Figs. 3 and 4. In both marine and non-marine stations, the monsoon samples were very close to the GMWL (Fig. 3), while some divergence is observed in the non-monsoon season (Fig. 4). Local Meteoric Water Lines (LMWLs) were constructed for each stations. LMWL for each station has been presented in Table 3. The local meteoric lines are much similar to GMWL with the slope very close to 8, while DN and XB show some deviations in slope and intercept respectively. The positioning of the samples against GMWL and LMWLs clearly demonstrates the equilibrium condensation of vapour in cloud (Dansgaard 1964; Gat 1996; Managave et al. 2015).

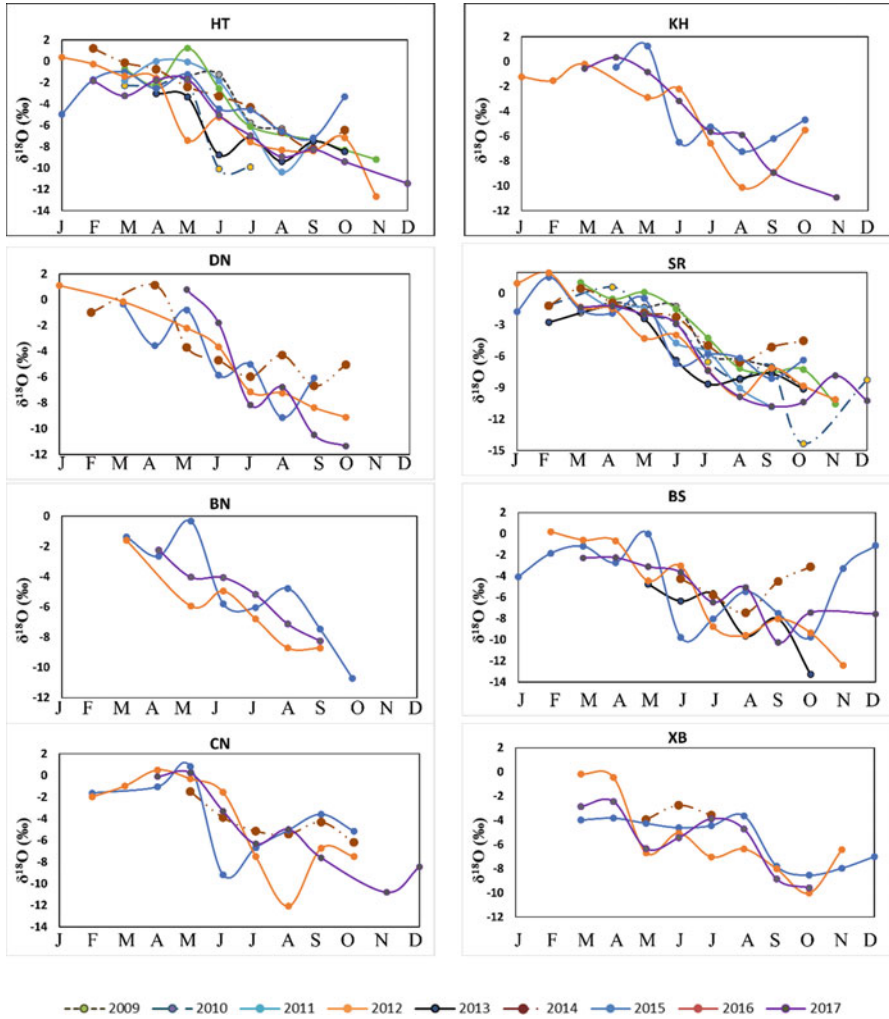


Fig. 2 Monthly Stable Isotopic trend in GNIP stations of Bangladesh

### 3.4 Deuterium Excess

The deuterium excess (or d-excess), defined by  $d\text{-excess} (\text{‰}) = \delta^2\text{H} - 8 \cdot \delta^{18}\text{O}$  (Dansgaard 1964) is an important parameter which is specifically sensitive to the conditions in determining moisture source conditions and the effect of evaporation on particular water types (Pfahl and Sodemann 2014). The distribution of d-excess (Fig. 5) over different months of a year show wide dispersion from January to April and smaller variation during the monsoon months. Some samples are falling below the line maintaining  $d\text{-excess} = 10\text{‰}$ , mostly during the first half of the year, while

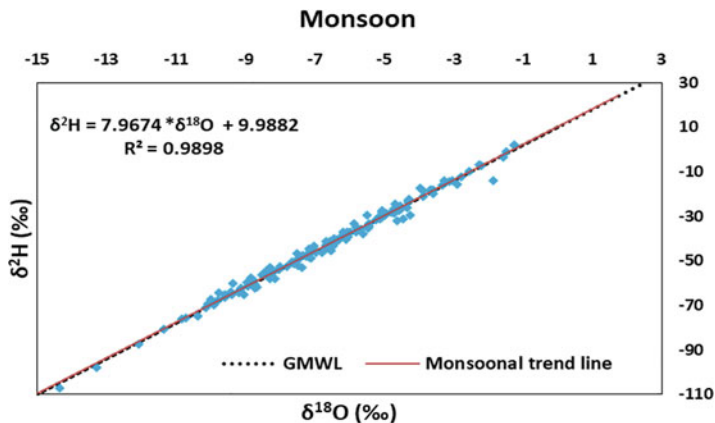


Fig. 3 Monsoon samples against GMWL

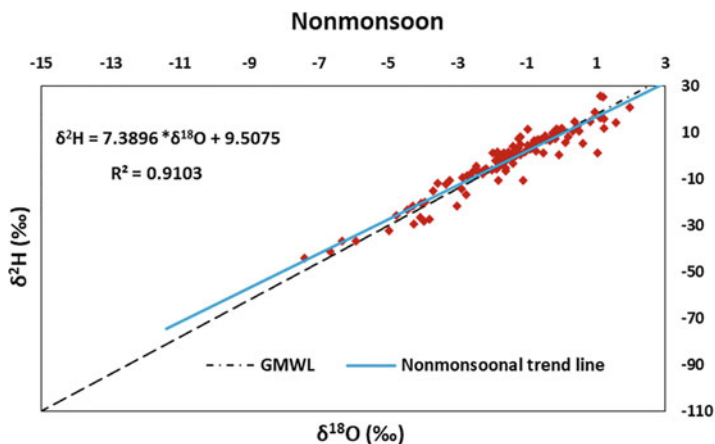
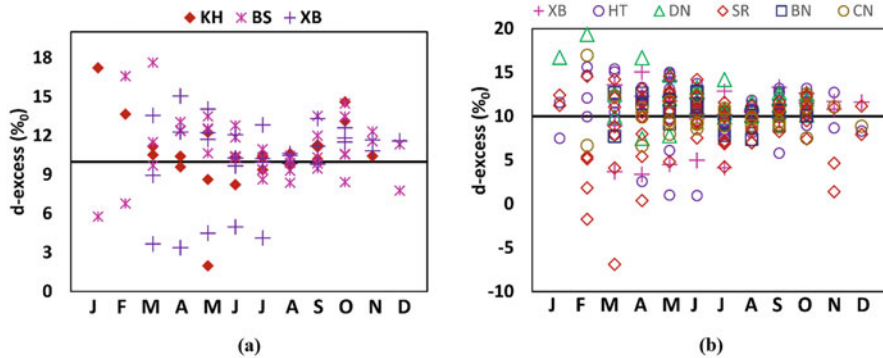


Fig. 4 Non-monsoon samples against GMWL

**Table 3** Local Meteoric Water Lines of GNIP stations of Bangladesh

Station	LMWL equation
Satkhira (KH)	$\delta^2\text{H} = 7.94 \times \delta^{18}\text{O} + 10.41$
Cox's Bazar (XB)	$\delta^2\text{H} = 7.68 \times \delta^{18}\text{O} + 8.56$
Barishal (BS)	$\delta^2\text{H} = 8.06 \times \delta^{18}\text{O} + 11.33$
Dhaka (SR)	$\delta^2\text{H} = 7.82 \times \delta^{18}\text{O} + 8.19$
Sylhet (HT),	$\delta^2\text{H} = 8.05 \times \delta^{18}\text{O} + 10.95$
Dinajpur (DN),	$\delta^2\text{H} = 8.23 \times \delta^{18}\text{O} + 13.29$
Bandarban (BN)	$\delta^2\text{H} = 8.19 \times \delta^{18}\text{O} + 11.29$
Chuadanga (CN)	$\delta^2\text{H} = 8.01 \times \delta^{18}\text{O} + 10.05$
Combined (all stations)	$\delta^2\text{H} = 7.97 \times \delta^{18}\text{O} + 10.15$



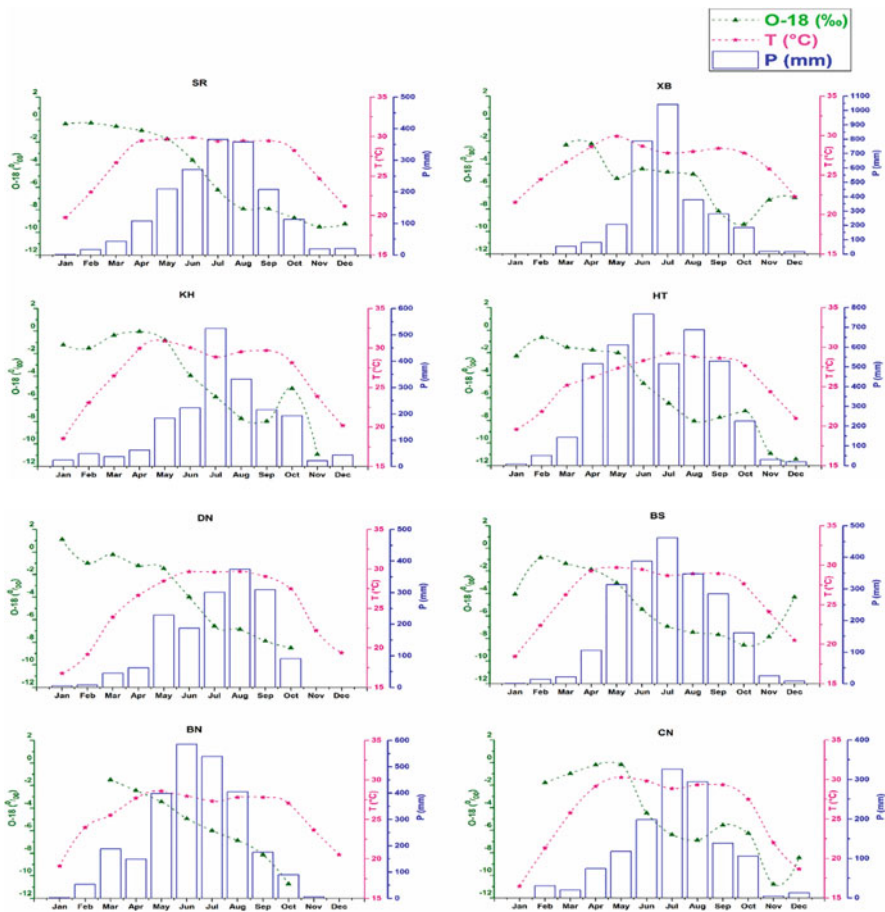


**Fig. 5** Deuterium excess variation over the year (a) d-excess variation in coastal stations (b) d-excess variation in nonmarine stations (XB is included to compare)

the major portion falls above the line. Precipitation with higher d-excess values (>10‰) indicates intense evaporation (Managave et al. 2015; Dublyansky et al. 2018) while smaller d-excess values result from recycling events (Datta et al. 1991). Therefore, in non-monsoonal rain, mixture from evaporation and recycled rain can be projected from deuterium excess values. In the period of July to September, when the maximum share of the monsoonal rain occurs, the d-excess values are quite similar to the XB station or other marine stations, confirming the similar source of vapour without significant recycling events or evaporation.

### 3.5 Meteorological Controls

All eight GNIP stations in Bangladesh are located in the tropical climate region. The maximum monthly average temperature is 26.2 °C in Chuadanga and Satkhira regions, while the yearly highest average rainfall is 3876 mm in Sylhet region. The lowest precipitation is observed in December and January months, with the lowest average of 1 mm in Dinajpur. The month of July sees the highest amount of precipitation with the highest average of 1060 mm recorded in Cox’s Bazar. The maximum monthly average temperature is found in Chuadanga as 30.4 °C during May. In January, the lowest monthly average temperature is recorded as 17.4 °C in Dinajpur. The difference between maximum precipitation (during wettest months) and minimum precipitation (during driest months) are 1053 mm in Cox’s Bazar and 284 mm in Chuadanga respectively. The highest and lowest average temperatures vary by ~11.7 °C (Chuadanga) and ~8.0 °C (Cox’s Bazar) throughout the year. High humidity is the common feature of monsoon period while relatively lower humidity is evidenced in pre or post-monsoon seasons (Khatun et al. 2016; Mullick et al. 2019). RH range during the data collection period at different stations vary from 55% to 90%. Stable isotopic relation with temperature and precipitation is shown in



**Fig. 6** Combined plot of temperature, precipitation and  $\delta^{18}\text{O}$

Fig. 6. Figure 6 indicates that change in isotopic signature does not maintain the same phase all throughout the year. Hence, correlation coefficients were considered differently for January–May and June–October for Table 4, where isotopic correlations with meteorological controls had been determined. Meteorological data was considered only for the isotopic sampling period for this table. Values higher than 0.3 were considered significant and marked bold. Table 4 shows wide variations in the signs and values of correlation coefficients according to stations and seasons. Details on correlation coefficients have been discussed in sections below.

**Table 4** Correlation coefficients between  $\delta^{18}\text{O}$  and meteorological factors

Station ID	January to May				June to October			
	Temp.	Rainfall amount	Relative humidity	Vapor pressure	Temp.	Rainfall amount	Relative humidity	Vapor pressure
KH	0.26	<b>-0.70</b>	0.26	0.23	-0.11	-0.13	<b>-0.30</b>	-0.23
BS	0.17	<b>-0.71</b>	<b>-0.59</b>	-0.07	<b>0.44</b>	<b>-0.40</b>	<b>-0.42</b>	0.18
HT	-0.05	<b>-0.34</b>	<b>-0.34</b>	-0.23	-0.22	0.14	-0.14	<b>-0.31</b>
DN	<b>-0.42</b>	<b>-0.78</b>	-0.19	<b>-0.53</b>	<b>0.31</b>	<b>-0.36</b>	<b>-0.53</b>	-0.21
SR	-0.19	<b>-0.42</b>	<b>-0.48</b>	-0.29	<b>0.36</b>	-0.11	<b>-0.50</b>	-0.12
XB	-0.24	<b>-0.67</b>	-0.28	-0.27	0.07	<b>0.34</b>	-0.03	<b>0.39</b>
BN	<b>-0.31</b>	<b>-0.44</b>	<b>-0.38</b>	<b>-0.37</b>	0.19	<b>0.41</b>	0.18	0.03
CN	<b>0.64</b>	<b>0.30</b>	-0.07	<b>0.68</b>	0.12	<b>-0.53</b>	-0.24	0.06

### 3.5.1 Temperature Effect

Dansgaard (1964) found strong correlation for the plains stations between the annual mean  $\delta^{18}\text{O}$  and temperature on a global scale, with an average change of  $0.7\text{‰}/^{\circ}\text{C}$ . However, the relationship between temperature and isotopic variation depends on the way how the values of temperature are averaged, i.e. weekly mean, monthly mean etc. (Ichiyanagi 2007).

Monthly mean temperature data was used to find the correlation with  $\delta^{18}\text{O}$  in this study. The mean monthly temperature variation occurs in the range of approximately  $16\text{--}30\text{ }^{\circ}\text{C}$  during the sampling periods and inter station variation is rather negligible. Temperature was found to be least significant in most cases. For the period of January to May, maximum temperature dependence (41%) was observed in CN station showing positive correlation. DN station shows negative correlation and around 18% of the isotopic variation is associated with temperature during that period. The other stations have mostly negative correlation and also insignificant temperature dependence. Lower temperature dependence is observed during the monsoon period (June–October). Mean monthly temperature varies between approximately  $27$  and  $31\text{ }^{\circ}\text{C}$  during this time period. Most of the stations show positive correlation during this time period unlike non-monsoon season. Maximum temperature influenced isotopic variation occurs in BS (19%).

### 3.5.2 Amount Effect

The potential influence of monthly rainfall amount to change its isotopic composition is termed as “amount effect” which was first observed by Dansgaard (1964). For the first quarter of the year, average monthly total rainfall ranges from  $0$  to  $55\text{ mm}$  in all stations except in HT where it reaches up to  $\approx 145\text{ mm}$ . The precipitation amount shifts to higher range in later months up to October while the maximum monthly rainfall occurs in XB during July. Amount effect is much stronger during non-monsoon months. All the stations maintain negative correlation with

precipitation amount except CN during January to May. Significant and high amount effect ( $r \approx -0.7$ ) is observed in DN, KH, BS and XB stations, while relatively lower amount effect ( $r \approx -0.5$  to  $-0.3$ ) in the other ones. In June to October the amount effect seems to be less significant. The major isotopic variation ( $r = -0.53$ ) associated to rainfall amount occurs in CN station. However “anti-amount effect” (Tian et al. 2018) is also observed in some stations which includes XB ( $r = 0.34$ ), BN ( $r = 0.41$ ) and HT ( $r = 0.14$ ) stations.

### 3.5.3 Humidity Effect

Relative humidity alongside sea surface temperature, were found to be important factors that influence the isotopic signature of precipitation (Dansgaard 1964; Merlivat and Jouzel 1979; Clark and Fritz 1997; Lachniet 2009; Duy et al. 2018). High d-excess values are likely to occur in lower humid conditions, when rapid evaporation occurs in combination with stronger kinetic isotope effects at that time. On the other hand low d-excess values occur during high humid conditions as a result of slow evaporation (Lachniet 2009; Dublyansky et al. 2018).

Among all the parameters presented here, relative humidity seems to have the largest effect on the spatiotemporal variation of stable isotopic composition of precipitation as seen from Eq. (1). However, monsoonal and non-monsoonal effect due to RH has been presented in Table 4. RH makes mostly negative correlation with  $\delta^{18}\text{O}$  except two instances. BS and SR stations show significant correlation between RH and  $\delta^{18}\text{O}$  in both seasons.

$$\delta^{18}\text{O} = -1.293 * \text{RH} + 73.73 \quad r = -0.5 \quad (1)$$

Almost no correlation ( $r = -0.01$ ) was found between d-excess and RH. This may be possible since, both type of d-excess (high and low) is seen from Fig. 5a, b especially, in non-monsoon period. Therefore, the occurrence and mixture of precipitation from different moisture sources in non-monsoon months can be evidenced from here.

### 3.5.4 Vapour Pressure Effect

Vapour pressure (Vp) is a meteorological parameter which is connected to both RH and air temperature. In most of the cases the nature of influence (positive or negative  $r$  value) is synchronized with temperature. Effect of Vp is more prominent in non-monsoon period rather than the monsoon period. 46% of isotopic variation in CN station was found due to changes in vapour pressure during January to May. DN station also had a remarkable influence from Vp (28%), while unlike CN station, DN has negative correlation. During the monsoon period, most of the stations have positive or negligible correlation.

## 4 Conclusion

A total of 297 monthly data from GNIP stations in Bangladesh have been used in this study to observe the stable isotopic scenario of precipitation. Samples were very close to GMWL, when  $\delta^{18}\text{O}$  values were plotted against  $\delta^2\text{H}$ . The overall LMWL for Bangladesh was found to be:  $\delta^2\text{H} = 7.97 \times \delta^{18}\text{O} + 10.15$ , which shows strong inclination to GMWL and equilibrium evaporation. Furthermore, it can be helpful to detect the recharge period and mechanisms related to groundwater for this region. For most instances, successive depletion of heavy isotopes have been observed from January to December. High humid conditions in monsoon season was found to generate greater amount of rainfall with slow rates of evaporation. Pre or post-monsoon rain results from different vapour sources which also includes fast evaporated moisture in low humid conditions. Amount effect is more prominent during January–May, while it occurs reversely during June–October in some stations. No single parameter could be established as a dominating one throughout the year in any of the stations.

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