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Controls on spatiotemporal variations of stable isotopes in precipitation across Bangladesh

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ABSTRACT

Indian summer monsoon (ISM) driven moisture from the Indian Ocean is important for moisture transport to the Asian Water Towers and causing floods and droughts in Bangladesh. Stable isotopic compositions of precipitation ($\delta^{18}O$ and δD) are crucial tracers of ISM moisture transport processes. Here we presented spatiotemporal variations of stable isotopes in precipitation at three stations over Bangladesh in 2017–2018 to evaluate the influence of ISM on intra-seasonal variations of stable isotopes in precipitation in the south of Himalaya, combined with local meteorological data, ERA5 reanalysis and HYSPLIT model. We found that precipitation $\delta^{18}O$ displayed the highest values in May following gradual decrease till the lowest in October. The spatial decrease of $\delta^{18}O$ and δD from southwest to northeast appeared in pre-monsoon and monsoon seasons together with increasing of d-excess eastwards. The weak temperature effect and amount effect were detected at Satkhira only at the daily scale in specific seasons, and the significantly negative correlations between relative humidity and $\delta^{18}O$ were almost detected at three stations in both monsoon and non-monsoon seasons. We suggested that convections over Bay of Bengal (BOB) and tropical Indian Ocean and variable contributions of moisture sources are important factors controlling distinct variations of precipitation $\delta^{18}O$ from west to east Bangladesh. Our results provided a better understanding of the ISM influence on precipitation stable isotopes and variations of the ISM moisture sources, which is crucial to address hydroclimatic interpretations relevant with ISM.

1. Introduction

The Indian summer monsoon (ISM) is directly associated with water resources and hydroclimate-related natural disasters in the Asian Water Towers (AWTs), influencing the lives and livelihoods of more than 2 billion people (Immerzeel et al., 2020). Understanding the contribution of moisture transported by the ISM is crucial for the projection of the regional water cycle and evaluation of the water supply from AWTs to surrounding regions (Breitenbach et al., 2010; Cai et al., 2018; Mukherjee et al., 2007). Instrumental records of traditional meteorological parameters have already provided plenty of information to understand the dynamics of the ISM (Ahmed and Karmakar, 1993; Ananthakrishnan and Soman, 1988; Day et al., 2015; Rafiuddin et al., 2010). However, this information is still not enough to illuminate regional moisture transport processes and quantify the moisture contribution from the Bay of Bengal (BOB) to the AWTs. Water stable isotopes, water molecules consisting of stable isotopes of hydrogen and oxygen, were frequently used to quantify atmospheric water budget, predict moisture source region, and track isotopic fractionation occurred at different reservoirs of the global hydrologic cycle. Due to their efficiency as a tracers of water transfer, water stable isotopes can improve our understanding on the variation of ISM throughout the Earth's evolutionary history (Cai and Tian, 2016; Chakraborty et al., 2016; Rahul et al., 2016; Yang et al., 2016). ISM-driven moisture from the BoB is transported to the AWTs through Bangladesh (extending from 20°34′N to 26°38′N latitude and 88°01′E to 92°41′E longitude, Fig. 1). Therefore, the event-based observations of stable isotopes in precipitation provide a unique tool to evaluate the contribution of different

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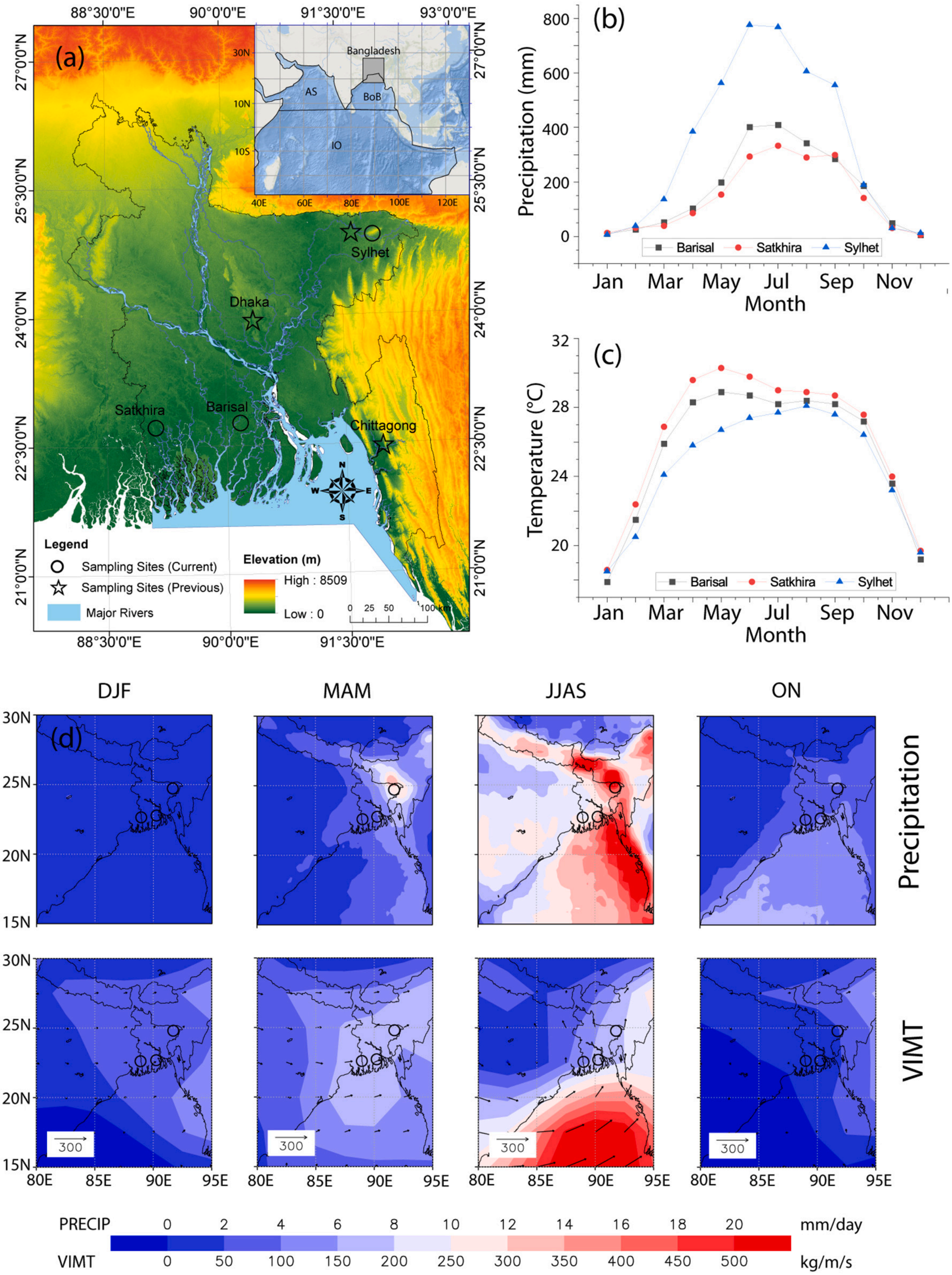

Fig. 1. Location of precipitation sample collection sites and moisture sources separation (a) 1981–2010 average monthly temperature and precipitation amount in the study region (b-c). 1998–2018 averaged seasonal precipitation and 2015–2019 vertically integrated moisture transport (d). Circles and stars indicate station locations for present study and that of Tanoue et al. (2018).

moisture sources and transport to Bangladesh before reaching to AWTs.

Stable isotopes of oxygen (^{16}O, ^{17}O, and ^{18}O) and hydrogen (^{1}H and ^{2}H or D) can be found in natural environment. Isotopic ratios of ^{18}O and D can be expressed using δ notation as $\delta^{18}O$ and δD. Based on isotopic measurements of meteoric water samples from different parts of the world, Craig (1961) established a linear relationship between δD and $\delta^{18}O$:

$$\delta D = 8 * \delta^{18}O + 10$$

The local meteoric water line (LMWL), defined as the linear regression between δD and $\delta^{18}O$ from local precipitation samples, is used to express local hydrological processes (e.g. evaporation and condensation) compared with the global meteoric water line (GMWL, Putman et al., 2019).

Many previous studies documented the effects of local meteorological variations and atmosphere circulations as well as convective activities on precipitation stable isotopes worldwide. Dansgaard (1964) established the 'temperature effect' (the positive correlation between δ-values and temperature) and 'amount effect' (the negative correlation between δ-values and precipitation amount) as two of the crucial factors controlling variations of stable isotopes in precipitation. The classic theory suggested that the amount effect was primarily noticeable in low-latitude regions influenced by monsoons, while the temperature effect was much significant in mid and high latitudinal regions (Dansgaard, 1964; Zhang et al., 2019). However, the performance of the amount effect was observed weakly and even nonexistent over the Indian subcontinent to some extant (Araguas-Araguas et al., 1998; Bhattacharya et al., 2003; Breitenbach et al., 2010; Datta et al., 1991; Midhun et al., 2013; Tang et al., 2015).

Convective activities and moisture transport processes were focused to probe the impact on variations of stable isotopes in precipitation in the past 20 years. Bhattacharya et al. (2003) revealed that precipitation stable isotopes at Bombay and New Delhi bear a greater influence of the moisture source and the lower (higher) $\delta^{18}O$ values were associated with oceanic (continentally recycled) moisture sources. Breitenbach et al. (2010) found that lower (higher) $\delta^{18}O$ values at Southern Meghalaya, NE India were associated with long (short) transport distances. Lekshmy et al. (2015) and Chakraborty et al. (2016) found that lower $\delta^{18}O$ values occur when air parcels come across a convective system over the Indian Ocean. Midhun et al. (2018) found that $\delta^{18}O$-depleted (enriched) precipitation events were associated with a higher number of air parcel trajectories originating from the Bay of Bengal (Arabian Sea) branch of moisture transport at six stations across northern and central India. Sinha and Chakraborty (2020) suggested that event-based $\delta^{18}O$ in precipitation displayed significant correlation with ambient vapor over a wide range of rainfall amount and correlation considerably weakened for rainfall exceeding ~36 mm/day over Port Blair, BoB. Their case study suggested that vapor-rainwater isotopic exchange contributes to $\delta^{18}O$ enrichment in subsequent precipitation events. Tanoue et al. (2018) suggested that moisture from the BoB and Arabian Sea (AS) primarily contributed to pre-monsoon precipitation in Bangladesh and the influence from the BoB and AS decreased significantly in ISM season when moisture predominantly originated from the Indian Ocean (IO) during January to December 2010 based on IsoGSM simulations. In post-monsoon season, moisture from Pacific Ocean (PO), BoB and continentally recycled moisture primarily contributed to precipitation in Bangladesh. However, the understanding of local and regional meteorological influence is still limited in Bangladesh and the isotopic variations in the southern Bangladesh where ISM moisture landing firstly is poorly probed.

To better understand the characteristics of precipitation stable isotopes when Indian monsoon moisture just lands before advecting into AWTs and probe the possible controls on their variations, our study presented the daily precipitation stable isotopes and corresponding meteorological data from three stations in Bangladesh during February 2017–September 2018. In section 2, we introduced the study area and data used in this study. In section 3, we probed the local meteorological influence by correlation analysis between daily precipitation $\delta^{18}O$ and meteorological observations (air temperature, precipitation amount and relative humidity) and regional moisture influence by combined analyses with back trajectory, outgoing longwave radiation (OLR) and regional meteorological elements. Conclusions and perspectives are provided in the last section.

2. Materials and methods

2.1. Study area

Bangladesh is located in the south of Himalayas and is southwardly open to the BoB (extending from 20°34′N to 26°38′N latitude and 88°01′E to 92°41′E longitude, Fig. 1) where ISM-driven moisture first interact with land on its way to AWTs. The manifest seasonal and spatial variations of temperature and rainfall are related to influence of ISM (Fig. 1, Pour et al., 2018).

In the pre-monsoon season (MAM), 19% of the total annual rainfall occurs with the total moisture flux (sum of zonal and meridional flux) of ~100 kg/m/s transported by the westerlies and higher (~10 mm/day) rainfall occurred in the northeastern Bangladesh than others. The averaged air temperature ranges between 23.50 °C and 30.30 °C, while the highest evapotranspiration rate and temperature with the occurrence of occasional line squalls and tropical cyclones are observed in coastal areas (Mukul et al., 2019; Shahid, 2010). In the monsoon season (JJAS), more than 70% of the total annual rainfall occurs and reaches to ~20 mm/day for seasonal average (Das, 2017; Mullick et al., 2019), associated with the maximum precipitation (~3000 mm) in the northeastern Bangladesh, and the temperature ranges between 27.40 °C and 29.80 °C. From southwest to northeast, precipitation amount increases in both pre-monsoon and monsoon seasons although it shows the similar seasonal patterns at three stations. The southwest winds take total about 500 kg/m/s moisture flux towards Bangladesh which is centered in AS and BoB (extended region in Fig. 1d that did not shown here). In the post-monsoon season (ON), 8% of the total annual rainfall occurs and the temperature ranges between 22.20 °C and 27.90 °C. Only 2% of the total annual rainfall occurs in winter (DJF), and temperature ranges are between 16.30 °C and 23.30 °C. The westerlies dominant again with less than 100 kg/m/s averaged moisture flux in the Bangladesh in the post-monsoon season and winter. Here we primarily focused on MAM, JJAS and ON, and exclude DJF because of the very small number of precipitation events in that season.

Here we focused on Satkhira, Barisal and Sylhet stations due to the precipitation samples collection, along a southwest-northeast transect over the Bangladesh (Fig. 1). During our sampling period, the air temperature remained within the 12.8–34 °C range with an average of ~25 °C. Approximately 70% of the total annual rainfall occurred in JJAS for each station. The highest precipitation amount is observed at Sylhet with the highest elevation of 20 m a.s.l. from pre-monsoon to post-monsoon seasons (1100 mm, 2786 mm and 254 mm, respectively), and the lowest is observed at Satkhira (276 mm, 1249 mm and 151 mm, respectively), while Barisal in between (422 mm, 1446 mm and 211 mm, respectively). We consider our study period a representative sample for a typical monsoon year representing an identical stable isotopic composition in precipitation.

2.2. Sampling and laboratory analysis

From February 2017 to September 2018, a total of 502 daily precipitation samples were collected at the Barisal, Satkhira and Sylhet stations with assistance from the Bangladesh Atomic Energy Commission (BAEC). All these stations are manned to ensure continuous operations, and precipitation yielded only one sample once a day, which was filled as much as possible after the precipitation event. The humid environment, immediate collection and cold storage facilities ensured minimal post-sampling evaporation. Samples were later transported to the Key Laboratory of Tibetan Plateau Climate Change and Land Surface Processes, Chinese Academy of Sciences for laboratory analysis. Measurements were performed with a Picarro L-2130i analyzer using a cavity ring-down system at an analysis rate of 18–21 samples per batch, not including standard samples. Analytical uncertainties for $\delta^{18}O$ and δD were ± 0.1‰ and ± 0.4‰, respectively. One primary (USGS50) and one secondary standard of identical isotopic compositions with respect to sample values were used during measurements, with the secondary standard being the main standard. All the precipitation and standard samples were continuously injected six times. To avoid the memory effect of the analyzer during isotopic measurements, the first three injections were discarded, and the average of the last three injections was used in the analyses. All the standard samples were tested against Vienna Standard Mean Ocean Water 2 (VSMOW2).

2.3. Meteorological data

The daily air temperature, relative humidity and precipitation amount data collected from the Bangladesh Meteorological Department (BMD) are used in this study to detect the local meteorological influence. The daily air temperature and relative humidity data at the 1000 hPa level from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 reanalysis as well as precipitation data from the Tropical Rainfall Measurement Mission (TRMM) are used for regional analysis. Multisatellite estimates from the TRMM daily precipitation product (3B42 V7.0) come with gauge calibration and were selected because of their higher spatial resolution (0.25° x 0.25°) and extensive usage in previous studies (Chakraborty et al., 2016; Rahul and Ghosh, 2019; Rohrmann et al., 2014; Vimeux et al., 2005). To evaluate the influence of convective activities on precipitation $\delta^{18}O$, we used OLR data from NOAA's National Centers for Environmental Information (NCEI) website available at https://www.ncei.noaa.gov/data/outgoing-longwave-radiation-daily/access/.

2.4. Lagrangian back trajectory analysis and moisture fluxes

Using the Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT version 4.2.0) developed at the Air Resources Laboratory of National Oceanic and Atmospheric Administration (NOAA), we performed back trajectory analysis to identify moisture sources and transport pathways (Stein et al., 2015). Meteorological data from the Global Data Assimilation System (GDAS) were used for the computation of daily trajectory endpoints because of their higher spatial resolution (1.0° x 1.0°) compared with those of the National Centers for Environmental Prediction (NCEP) data (2.5° x 2.5°) (Zhang et al., 2019).We used 500 m AGL as the starting height because our analysis for the 1979–2018 average lifting condensation level (LCL) suggests that air parcels typically become saturated with moisture at this height over Bangladesh throughout the year (Figures did not shown). We computed trajectories in reverse mode for 120 h, and at each point, particles were released every 6 h (at 0000, 0600, 1200, and 1800 UTC). Statistical clustering of similar trajectories was performed through HYSPLIT's internal clustering module. Changes in specific humidity along the clustered trajectories were also computed to obtain a clear visualization of the moisture variation in the region.

3. Results and discussion

3.1. Temporal variation in precipitation $\delta^{18}O$

We first investigated the temporal variations of daily stable isotopes in precipitation ($\delta^{18}O$ and deuterium excess) and local meteorological parameters (air temperature, relative humidity, precipitation amount and OLR) at three stations (Fig. 2). Satkhira station had the largest $\delta^{18}O$ and d-excess range, while the range for Barisal was the lowest. $\delta^{18}O$ displayed the highest values (1.49‰, −1.69‰ and − 1.98‰ for Satkhira, Barisal and Sylhet stations, respectively) in May at three stations, while the lowest (−13.78‰, −10.34‰ and − 8.89‰ for Satkhira, Barisal and Sylhet stations, respectively) in October (Table 1). The spatial decrease of $\delta^{18}O$ and δD from west to east appeared in MAM and JJAS, while d-excess was found increasing eastwards. In MAM, averaged $\delta^{18}O$ values for Satkhira, Barisal and Sylhet stations were 0.88‰, −1.78‰ and − 1.97‰, respectively, showing significant isotopic enrichment at Satkhira and δD showed similar pattern with an average of 10.20‰, −12.16‰ and − 2.51‰, respectively. Averaged d-excess had the smallest values at Satkhira (3.17‰), and was increasing eastwards through Barisal (11.58‰) to Sylhet (13.25‰). In JJAS, averaged $\delta^{18}O$ (δD) values varied from −4.22‰ (−26.71‰) at Satkhira to −6.73‰ (−43.09‰) at Sylhet, consistent with decreasing eastwards, and d-excess values were increasing from Satkhira (7.05‰) to Sylhet (10.76‰). In ON, averaged $\delta^{18}O$ and δD values show opposite variations from Satkhira (−10.82‰ for $\delta^{18}O$, −76.16‰ for δD) to Sylhet (−8.89‰ for $\delta^{18}O$, −59.08‰ for δD) as the most depleted values in the year, while d-excess values for all three stations were above 10.0‰ with maximum at Sylhet (12.06‰) and minimum at Satkhira (10.37‰) from east to west. In DJF, Satkhira did not have any precipitation samples. Averaged $\delta^{18}O$ and δD values increased eastwards from Barisal (−7.79‰ for $\delta^{18}O$, −50.11‰ for δD) to Sylhet (−5.81‰ for $\delta^{18}O$, −33.87‰ for δD), and d-excess values decreased eastwards.

Our observations were consistent with Tanoue et al. (2018), who reported $\delta^{18}O$ variation in precipitation over Bangladesh within the −15.0‰ to 1.0‰ range. The spatial variations of $\delta^{18}O$ and δD clearly presented the typical latitude effect in pre-monsoon and monsoon seasons. However, such spatial pattern disappeared in post-monsoon and winter due to the fade-away influence of Indian monsoon. We found Barisal and Sylhet have more close ranges of d-excess during our observations, which may be related with the similar moisture fluxes patter (Fig. 1d) although Satkhira and Barisal almost located at the same latitude very near the BoB and the monthly precipitation at Sylhet (< 30 mm/day) almost twice higher than that at other stations.

At the monthly scale, the seasonal distribution of $\delta^{18}O$ is characterized by peak $\delta^{18}O$ values in May and minimum in October (Fig. 2). The monthly average $\delta^{18}O$ ranged between −12.0‰ and 3.0‰ throughout the study period, with March–May $\delta^{18}O$ values within the −5.0‰ to 3.0‰ range, while the range for July–November was −12.0‰ to −6.0‰. Tanoue et al. (2018) reported March–May $\delta^{18}O$ values for the eastern Bangladesh within the −3.45‰ to −1.82‰ range, while within the −15.94‰ to −7.28‰ range during the July–November period, similar with our observations. D-excess, however, did not show the consistent seasonal patterns among the three stations. Almost opposite shifts of d-excess with $\delta^{18}O$ at Satkhira and similar shifts at Sylhet together with Barisal in between. OLR show the minimum in monsoon season and maximum in winter at three stations, gradual decreasing after April from ~300 W/m^2 to ~200 W/m^2, and show the similar seasonal pattern with $\delta^{18}O$ at Sylhet only. Temperature correspondingly increase from winter (~20 °C) to summer (~30 °C) and have an approximately inverse variation with corresponding $\delta^{18}O$. The seasonal patterns of relative humidity and $\delta^{18}O$ are inverse seemingly, and out-phase variation between precipitation amount and $\delta^{18}O$ occurred in monsoon season occasionally. Majority of heavy rainfall (> 50 mm) events occurred in monsoon season only, associated with significant isotopic depletion. At Sylhet station, > 70 mm daily rainfall was recorded for six consecutive days during March 30 and April 4, 2017, which were associated with little change in $\delta^{18}O$ values correspondingly. However, heavy rainfall events in ON resulted in significant $\delta^{18}O$ depletions at all three stations. The similar conditions were found at other stations. This resulted from the contribution of different moisture sources. We provided detailed discussions in section 3.4.

3.2. Local meteoric water line

Fig. 3 illustrates the distribution of δD-$\delta^{18}O$ at the three stations throughout the study period. The local meteoric water lines at these three stations are established. Among the stations, the highest LMWL slopes were found at Sylhet (8.26), which indicates the significant evaporation occurred at Sylhet (Craig, 1961; Rozanski et al., 1992), while the lowest exist at Satkhira (7.49) in monsoon season, which indicates a weak condensation at Satkhira, and the slope at Barisal is equal to 8 for the global meteoric water line (GMWL), suggesting a limited impact of non-equilibrium processes on precipitation. The LMWL intercepts were increasing from west to east with the lowest values at Satkhira (4.07) and the highest at Sylhet (12.93). Intercepts at

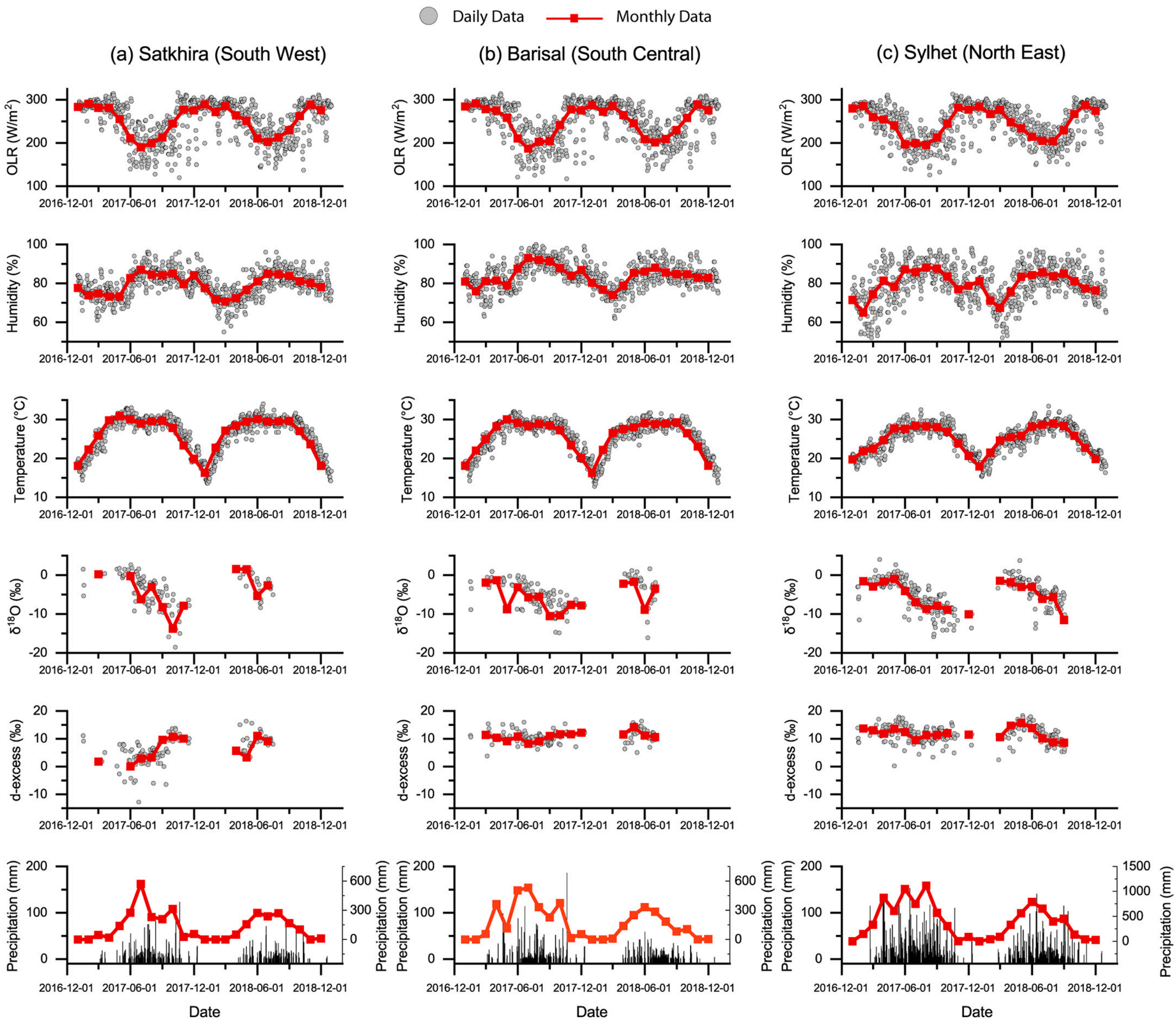

Fig. 2. Temporal variations of precipitation stable isotopes ($\delta^{18}O$ and d-excess) and local meteorological parameters (OLR, relative humidity, air temperature and precipitation) from February 2017 to September 2018. Although we did not include δD in the figure, the variations in δD were identical to $\delta^{18}O$ because they are mathematically related to each other.

Table 1

Summary statistics for annual and seasonal amount weighted average $\delta^{18}O$, δD and deuterium excess at Barisal, Satkhira and Sylhet Station during 2017–2018 period. Also included seasonal maximum and minimum $\delta^{18}O$, δD and deuterium excess values for Barisal, Satkhira and Sylhet.

Time	Statistic	Satkhira (in ‰)			Barisal (in ‰)			Sylhet (in ‰)		
		$\delta^{18}O$	δD	d-excess	$\delta^{18}O$	δD	d-excess	$\delta^{18}O$	δD	d-excess
Annual	Average	−4.01	−25.9	6.16	−5.4	−34.15	10.94	−5.07	−28.62	11.93
DJF	Minimum	N/A	N/A	N/A	−7.8	−50.26	11.81	−13.62	−101.3	2.41
	Maximum	N/A	N/A	N/A	−7.68	−48.83	12.7	−1.17	1.76	13.71
	Average	N/A	N/A	N/A	−7.79	−50.11	12.19	−5.81	−33.87	9.61
MAM	Minimum	−2.88	−6.67	−5.52	−8.75	−60.88	3.78	−10.77	−80.51	0.2
	Maximum	1.73	18.66	16.33	1.12	17.53	16.35	4.01	43.39	20.48
	Average	0.88	10.2	3.17	−1.78	−12.16	11.58	−1.97	−2.51	13.25
JJAS	Minimum	−15.91	−114.78	−12.79	−16.12	−117.44	6.2	−15.88	−113.11	3.36
	Maximum	2.64	20.48	13.63	1.61	19.82	15.96	−0.01	12.48	16.65
	Average	−4.22	−26.71	7.05	−6.2	−39.28	10.35	−6.73	−43.09	10.76
ON	Minimum	−18.58	−134.8	8.42	−11.9	−83.72	7.13	−14.21	−102.95	4.89
	Maximum	−4.97	−27.33	13.81	−4.36	−24.3	15.37	−7.28	−48.12	15.73
	Average	−10.82	−76.16	10.37	−8.99	−60.31	11.65	−8.89	−59.08	12.06

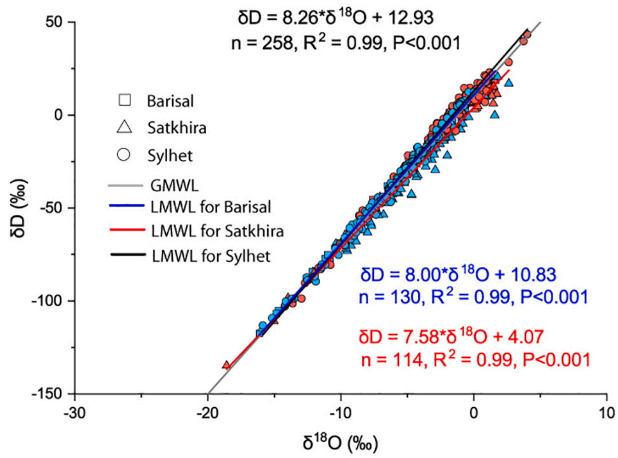

Fig. 3. LMWL showing the $\delta^{18}O$-δD relationship and their deviation from the GMWL proposed by Craig (1961).

the Barisal station (10.83) were close to the GMWL intercepts. The lowest values at Satkhira in both the monsoon and non-monsoon seasons reflected much high humidity at moisture sources (Table 2).

Jeelani et al. (2018) studied stable isotopic variation at Jorhat station located near Sylhet, showing the similar LMWL slopes (8.38 at Jorhat) for the monsoon season. However, a large discrepancy of slope was found in the non-monsoon season between these two stations (8.11 at Sylhet and 7.70 at Jorhat). This may result from different years' sampling.

3.3. Main factors influencing the variation of $\delta^{18}O$ in Precipitation

3.3.1. Temperature and precipitation amount

Dansgaard (1964) established the 'temperature effect' (decrease in δ-values with temperature decrease) and 'amount effect' (higher δ-values in sparse rain) as two of the important controls that influence variations in the isotopic compositions of precipitation. The temperature effect is significant in the temperate and polar regions while amount effect is primarily noticeable in low-latitude regions (Zhang et al., 2019). The majority of recent studies over the Indian subcontinent at different temporal resolutions ranging from event to interannual scales suggested that the amount effect is weak and even nonexistent in this region (Araguas-Araguas et al., 1998; Bhattacharya et al., 2003; Breitenbach et al., 2010; Datta et al., 1991; Midhun et al., 2013; Tang et al., 2015).

We investigated the possible effects of temperature and precipitation amount firstly (Fig. 4). Among three stations, a weakly positive correlation between air temperature and $\delta^{18}O$ at Satkhira was found in monsoon season ($p < 0.01$, n = 79, $r = 0.46$) and observed duration ($p < 0.01$, n = 114, $r = 0.30$) at daily scale (Fig. 4). Such correlation gradually weakens from the west to east turning to a negative correlation at Sylhet ($p < 0.01$, n = 158, $r = -0.28$, in monsoon season; $p < 0.01$, n = 258, $r = -0.43$, during observed duration). None of significant correlations was found in non-monsoon season at these three stations. A weak precipitation effect was only observed at Satkhira in non-monsoon season and observed duration at daily scale. Our results are similar with those from Tanoue et al. (2018) and Rahul and Ghosh (2019). In addition, the significantly negative correlations between relative humidity and $\delta^{18}O$ are almost detected at three stations in both monsoon and non-monsoon seasons, and the correlation coefficients were decreasing from southwest to northeast although the precipitation amount was increasing from southwest to northeast. The strongly negative relationship between $\delta^{18}O$ and relative humidity over Bangladesh is consistent with the findings of Chen et al. (2015) on Northwest China and Yu et al. (2015) on the Tibetan Plateau. It reflected that high relative humidity was associated with low $\delta^{18}O$ and the influence of humidity and precipitation amount was generally decreasing with the increasing distance from the BOB, especially in monsoon season. It may related with the different contributions from ocean and land surface. Satkhira near the coast is dominated by moisture from BOB directly as the onefold moisture source. Along the Indian monsoon transport, precipitation occurred which resulted in more depleted $\delta^{18}O$ values to inland, and air mass exchanged and mixed with land-surface moisture which is characterized by high d-excess values. Sylhet is located farthest from BOB among three stations. More complexed influences relevant to multi-sources mixing overwhelmed the influence of local meteorological conditions. At regional scale, the measured $\delta^{18}O$ values at three stations did not show any significant correlations with regional meteorological variables ($\delta^{18}O$-relative humidity, $\delta^{18}O$-temperature and $\delta^{18}O$-precipitation) at surrounding grids at all seasons. Therefore, we suggested that temperature and precipitation amount in the region did not dominate variations of precipitation $\delta^{18}O$ in Bangladesh.

3.3.2. Convective activities

Convective activities impact precipitation events, which leave signals on stable isotopes in precipitation, especially in tropical region (Chakraborty et al., 2016; Rahul et al., 2016; Saranya et al., 2018; Wei et al., 2018). OLR is widely considered to be a proxy presenting convective activities. Low OLR values indicate intensive convective activities, vice versa. To quantitatively account for the convective influence, we followed a simplified two-step procedure. Firstly, we quantified the deviation of OLR from the long-term average, which allows us to formulate a simplified index of convective strength. Secondly, pixel-based correlation coefficients were calculated to determine the regional OLR-$\delta^{18}O$ relationship at the grid-point level, providing the estimation of the convective effects on $\delta^{18}O$. A significant OLR-$\delta^{18}O$ relationship can justify the convective influence on $\delta^{18}O$ depletion/enrichment in the region. We did not have enough observations to perform statistical correlation between $\delta^{18}O$ and OLR in winter, thus, focused on other seasons.

Fig. 5 shows the spatial correlations between the precipitation $\delta^{18}O$ and the regional OLR at Satkhira. Remarkable correlations were detected between daily precipitation $\delta^{18}O$ and the regional OLR with distinctly seasonal variations. The significantly inverse correlation emerged over BOB at different time leads in MAM and it was intensified and moved southwestward to tropical Indian Ocean when precipitation occurred. This indicated the intensive convection over BOB was associated with enriched precipitation $\delta^{18}O$ at Satkhira in pre-monsoon season, vice versa. In JJAS, such inverse correlations weakened over BOB and manifest positive correlations emerged in the tropical Indian

Table 2
Annual and seasonal LMWL for the stations used in this study.

Station	Monsoon + Non- Monsoon	Only Monsoon	Only Non- Monsoon
Barisal	$\delta D = 8.00*\delta^{18}O + 10.83$ $n = 130$, $R^2 = 0.99$	$\delta D = 7.91*\delta^{18}O + 9.65$ $n = 78$, $R^2 = 0.99$	$\delta D = 7.92*\delta^{18}O + 11.48$ $n = 52$, $R^2 = 0.99$
Satkhira	$\delta D = 7.58*\delta^{18}O + 4.07$ $n = 114$, $R^2 = 0.98$	$\delta D = 7.56*\delta^{18}O + 2.99$ $n = 79$, $R^2 = 0.97$	$\delta D = 7.49*\delta^{18}O + 6.05$ $n = 35$, $R^2 = 0.99$
Sylhet	$\delta D = 8.26*\delta^{18}O + 12.93$ $n = 258$, $R^2 = 0.99$	$\delta D = 8.23*\delta^{18}O + 12.26$ $n = 158$, $R^2 = 0.99$	$\delta D = 8.11*\delta^{18}O + 13.20$ $n = 100$, $R^2 = 0.99$

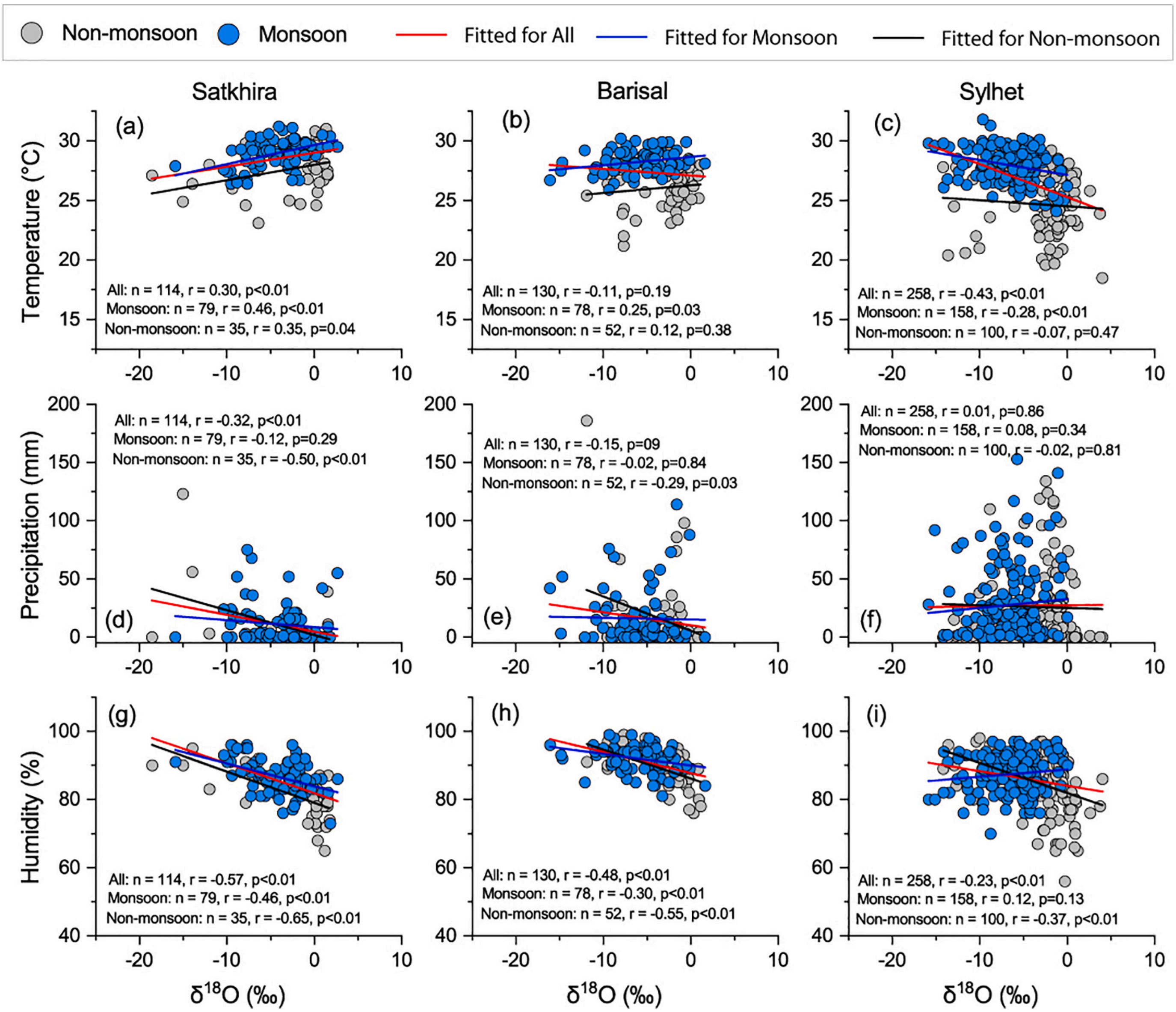

Fig. 4. Correlations between daily precipitation δ^{18}O and local air temperature (a-c), precipitation amount (d-f) and relative humidity (g-i) at three stations.

Ocean and northern India, and the inverse correlation strengthened slightly over BOB when precipitation occurred. This indicated that the convection over the tropic Indian Ocean played more important role on variations of precipitation δ^{18}O at Satkhira than that over the BOB in monsoon season. The intensive convection over the tropic Indian Ocean was associated with low precipitation δ^{18}O at Satkhira. In ON, the spatial correlation was more complicated than that in other months. The inverse correlation emerged in 10 N–20 N BOB and it turned into positive correlations when precipitation occurred, while the opposite changes emerged in Bangladesh. This indicated that the intensive convection over BOB together with weak convection over the Bangladesh resulted in low precipitation δ^{18}O at Satkhira in post-monsoon season. The influence of local convection in Bangladesh was much stronger in post-monsoon season than that in both pre-monsoon and monsoon seasons.

The east convection over BOB was more important to precipitation δ^{18}O at Sylhet in pre-monsoon season (Fig. 6). The weak convection over BOB was associated with enriched precipitation δ^{18}O in monsoon season and influences of convections over tropical Indian Ocean and BOB was strengthening with the development of precipitation event. What's more, the significant positive correlations were found at the northern India. In post-monsoon season, the significant inverse correlation was found over the BOB. The spatial pattern of correlations between precipitation δ^{18}O at Sylhet and regional OLR are almost opposite with that at Satkhira in the three seasons, especially over BOB. This indicated that the intensive convection over BOB was associated with high precipitation δ^{18}O at Satkhira together with low precipitation δ^{18}O at Sylhet. Such precipitation δ^{18}O variations conformed to rainout influence although precipitation effect was not been detected at Sylhet. It presented as a seesaw effect of convections over BOB on precipitation δ^{18}O in Bangladesh.

The distinct spatial patterns of correlations between precipitation δ^{18}O at Barisal and regional OLR were also detected in the three seasons (Fig. 7). In pre-monsoon season, the spatial correlation pattern between precipitation δ^{18}O at Barisal and regional OLR was more consistent with that to Sylhet, showing a positive correlation over BOB. However, it was turned to similar with that to Satkhira in monsoon season, appearing the inverse correlation over BOB and positive correlation over the tropical Indian Ocean. In the post-monsoon season, the spatial correlation pattern was more consistent with that to Satkhira at the

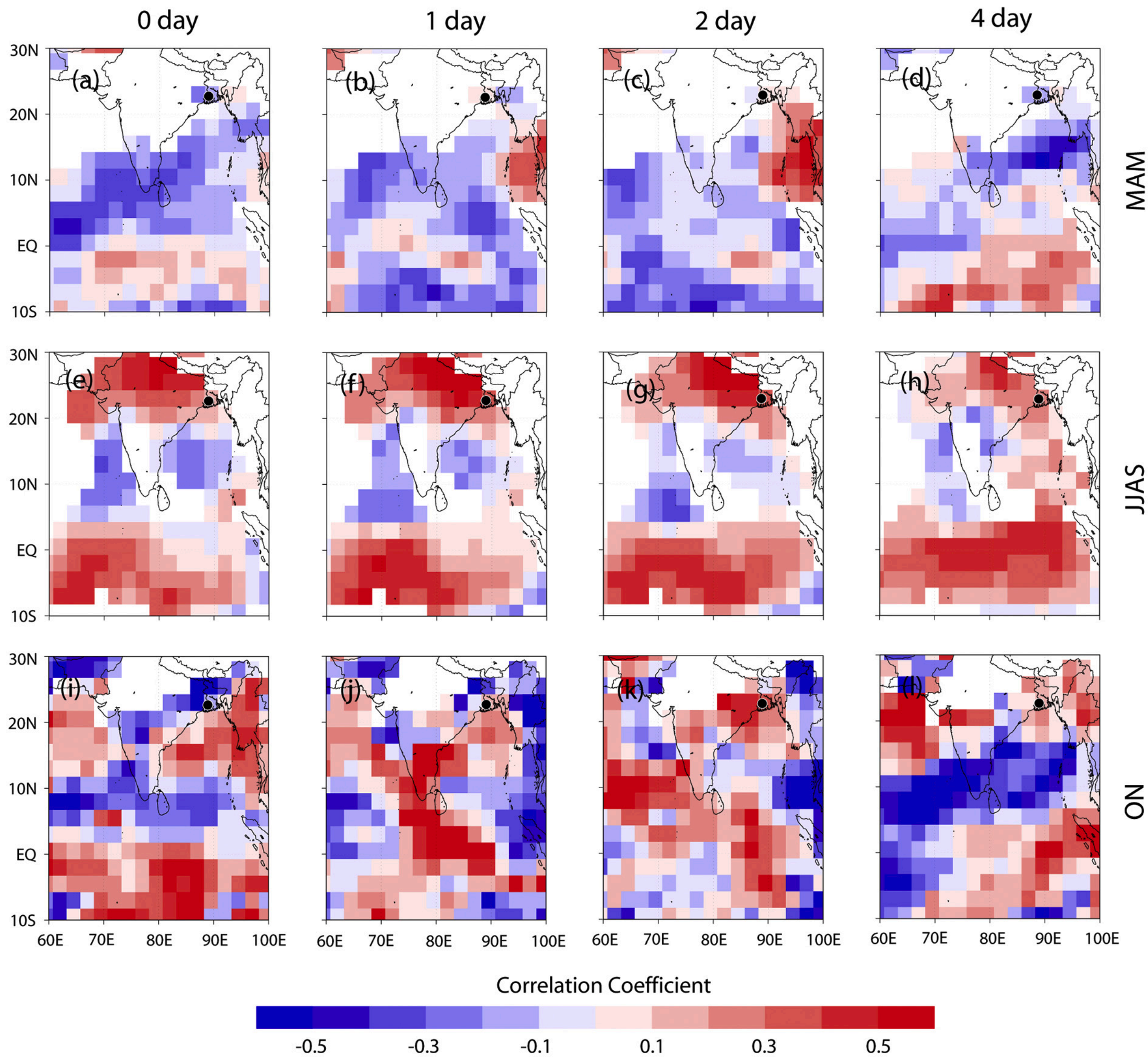

Fig. 5. Daily correlation between precipitation $\delta^{18}O$ at Satkhira and regional OLR in MAM (a-d), JJAS (e-h) and ON (i-l) during the observation duration. (a), (e) and (i) stand for correlations calculated synchronous; (b), (f) and (g) stand for correlations at the time lead of 1 day; (c), (g) and (k) stand for correlations at the time lead of 2 days; (d), (h) and (l) stand for correlations at the time lead of 4 days. Correlation coefficients significant at $p < 0.05$ are displayed in the figure.

time leads of 0 and 1 day.

In summary, convections over BOB and tropical Indian Ocean impact precipitation $\delta^{18}O$ from west to east Bangladesh significantly, resulting in distinct variations of precipitation $\delta^{18}O$ at different locations due to the monsoon moisture transport. For example, the strong convections above BOB in pre-monsoon season associated with depleted $\delta^{18}O$ at Barisal and Sylhet, while enriched $\delta^{18}O$ at Satkhira. In monsoon season, the intensive convections over the tropical Indian Ocean led to depleted $\delta^{18}O$ at all three stations, while BOB performed diversely. At Satkhira and Barisal located in the south, strong convective activities over BoB resulted in enriched $\delta^{18}O$, while Sylhet located in the north experienced $\delta^{18}O$ depletion. In post-monsoon season, strong convections over the tropical Indian Ocean and BOB led to depleted $\delta^{18}O$ at Barisal and Satkhira together with enriched $\delta^{18}O$ at Sylhet.

3.3.3. Back trajectories and moisture sources

Many studies over the Tibetan Plateau have suggested that changes in the moisture sources and moisture transport processes significantly change the stable isotopes in precipitation (Li et al., 2017; Yu et al., 2015; Gao et al., 2013). Here, back trajectory analysis with HYSPLIT for 5 days with precipitation events revealed four main moisture transport pathways for these stations, namely, southwest winds from the BOB, southwest winds from the AS, southwest winds from the tropical Indian Ocean (IO), and continentally recycled moisture (CR). Definitions for BoB, AS, IO and CR used in this study were consistent with the classification system used by Tanoue et al. (2018). Changes in specific humidity along the clustered trajectories were also computed to obtain a clear variation of the moisture along the transport paths.

In pre-monsoon season, moisture predominantly originated from the BoB for the three stations accounted for 75% at Satkhira, 84% at Barisal and 61% at Sylhet, associated with manifest changes of specific humidity along trajectories approximately 9.0 g/kg (Fig. 8). Contribution of moisture from AS was less than 15% for all stations. Changes of specific humidity along the clustered trajectories also indicated that the moisture increased primarily over the BoB near the southern Bangladesh. Tanoue et al. (2018) suggested the similar contributions of BoB and AS to pre-monsoon precipitation in Bangladesh. The significant $\delta^{18}O$ depletion (−1.78‰) observed at Barisal was associated with moisture from BoB through southerly winds (Bhattacharya et al., 2003). Midhun et al. (2018) confirmed that $\delta^{18}O$-depleted precipitation events were associated with a large number of trajectories originating from the BoB. Contributions from CR that brought moisture from India are very

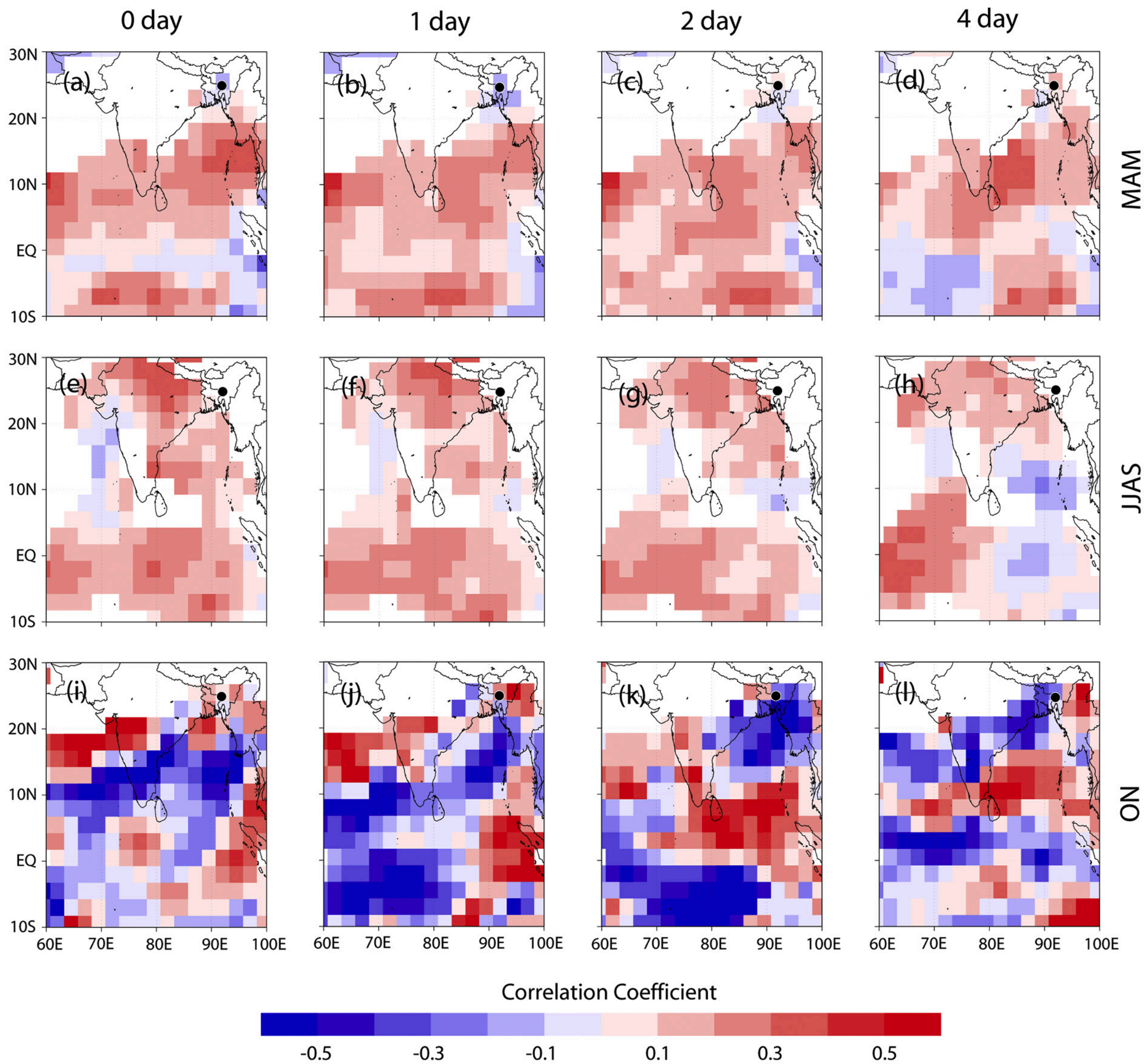

Fig. 6. Same as Fig. 5, but stand for Sylhet. (a), (e) and (i) stand for correlations calculated synchronous; (b), (f) and (g) stand for correlations at the time lead of 1 day; (c), (g) and (k) stand for correlations at the time lead of 2 days; (d), (h) and (l) stand for correlations at the time lead of 4 days. Correlation coefficients significant at $p < 0.05$ are displayed in the figure.

small for Barisal and Satkhira, but 39% for Sylhet. The high $\delta^{18}O$ (0.88‰) at Satkhira with very low d-excess (3.17‰) was associated with BoB moisture that accounted for > 50% of total trajectories.

The $\delta^{18}O$ started to decrease in the beginning of the monsoon season when a large volume of ISM moisture moves inland. In monsoon season, the moisture from IO increased significantly for Barisal, Satkhira and Sylhet stations (Fig. 8), while changes of specific humidity suggested that moisture increased by more than 6 g/kg primarily over the BoB. Continental moisture recycling supplied a very small amount of moisture. The seasonal average $\delta^{18}O$ values were − 6.20‰, and − 6.73‰ at Barisal and Sylhet, respectively, while they were significantly enriched at Satkhira −4.22‰, due to the different moisture contribution between BOB and IO. The more moisture from IO and AS led to more enriched $\delta^{18}O$. Such variations of moisture contributions through transport paths also resulted in gradual increase of d-excess from southwest to northeast (7.05‰ at Satkhira, 11.58‰ at the Barisal and 13.25‰ at Sylhet).

In post-monsoon season, the BoB still supplied majority of the moisture, and changes of specific humidity suggested higher moisture content in the ocean. Contributions from the BoB accounted for 57%, 38% and 80% of total trajectories for Satkhira, Barisal and Sylhet, and CR accounted for 14%, 9% and 3% of total trajectories at Satkhira, Barisal and Sylhet. Sylhet station did not receive any contributions from AS. D-excess values were increasing from Satkhira (10.37‰), Barisal (11.65‰) to Sylhet (12.06‰). Significant $\delta^{18}O$ depletion at Satkhira (−20.0‰) occurred due to heavy rainfall events of October 20–22, 2017.

In winter, BoB accounted for46%, 32% and 23% of total trajectories for Satkhira, Barisal and Sylhet. The contribution of CR increased remarkably, accounted for 50%, 49% and 49% of total trajectories for Satkhira, Barisal and Sylhet, associated with a few samples at three stations. The high d-excess in winter might result from strong influence of westerlies that brought moisture from the far Mediterranean and northwestern India.

In summary, moisture from BoB contributed primarily to pre-monsoon precipitation, and the contribution of moisture originated from IO increased significantly in monsoon season. The post-monsoon precipitation was predominantly controlled by moisture from BOB and AS, and their contributions reduced a lot in winter. The variations of contributions from different moisture origins may result in seasonal

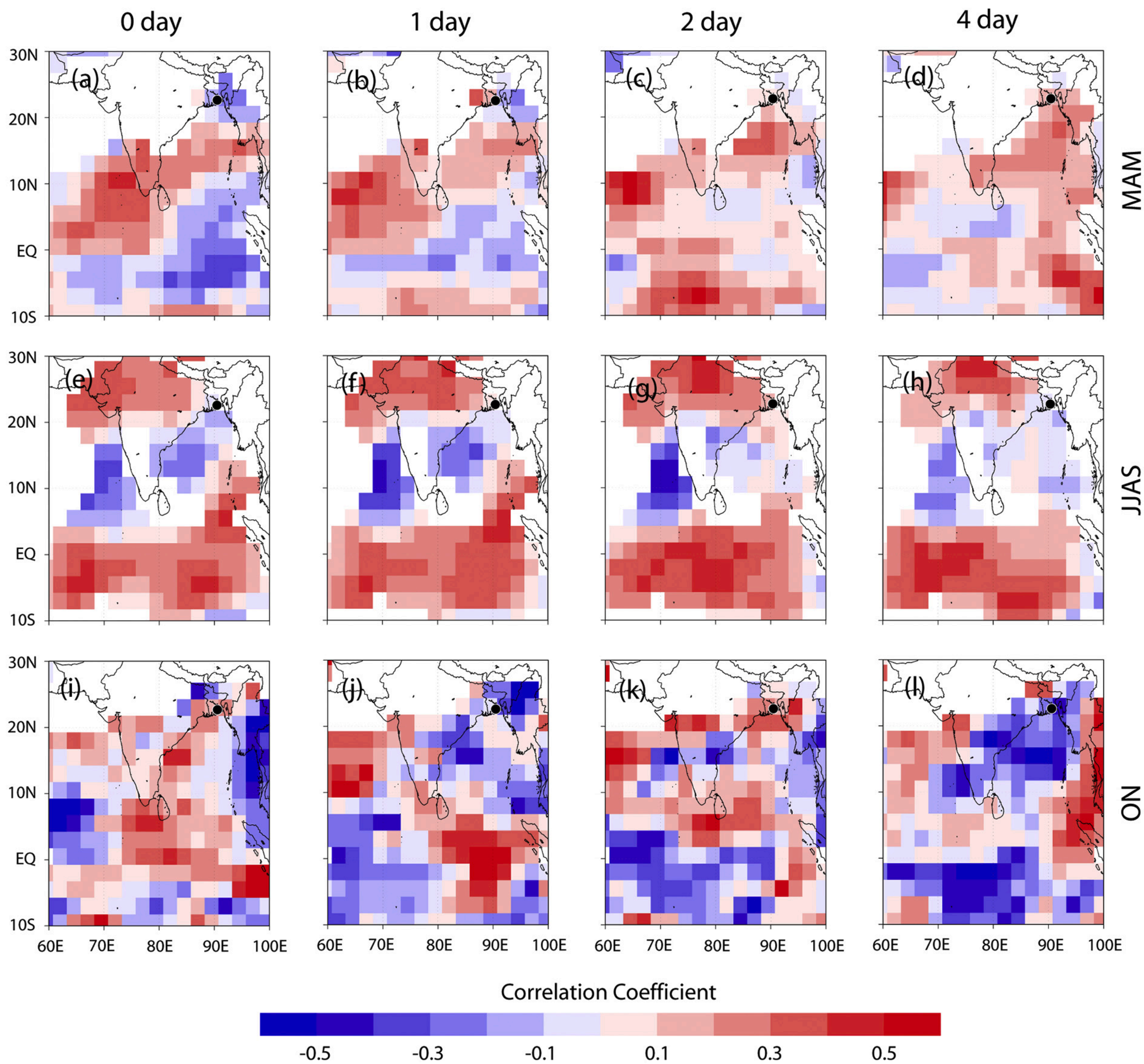

Fig. 7. Same as Fig. 5, but stand for Barisal. (a), (e) and (i) stand for correlations calculated synchronous; (b), (f) and (g) stand for correlations at the time lead of 1 day; (c), (g) and (k) stand for correlations at the time lead of 2 days; (d), (h) and (l) stand for correlations at the time lead of 4 days. Correlation coefficients significant at $p < 0.05$ are displayed in the figure.

variations of precipitation stable isotopes at three stations, consistent with Breitenbach et al. (2010) and Midhun et al. (2018).

4. Conclusions

We have investigated the meteorological drivers of precipitation $\delta^{18}O$ at seasonal and daily scales in Bangladesh, based on daily precipitation sample analysis during the 2017–2018 period. Our results presented the spatial-temporal characteristics of precipitation stable isotopes from southwest to northeast of Bangladesh. Precipitation $\delta^{18}O$ displayed the highest values in March following gradual decrease till the lowest in October. The spatial decrease of $\delta^{18}O$ and δD from southwest to northeast was appeared in pre-monsoon and monsoon seasons, while d-excess was found increasing eastwards. Such spatial pattern disappeared in post-monsoon and winter due to the fade-away influence of Indian monsoon. The slope of LMWL, closed to 8 for GMWL, increased from southwest to northeast, indicating a limited impact of non-equilibrium processes on precipitation. The similar increasing intercepts of LMWL reflected decreasing humidity of moisture sources from southwest to northeast. Our results depict weak temperature effect and amount effect only at Satkhira at the daily scale in specific seasons. The significantly negative correlations between relative humidity and $\delta^{18}O$ are almost detected at three stations in both monsoon and non-monsoon seasons and such relationship was weakening from southwest to northeast opposite to precipitation variations. We found that MAM heavy rainfall events did not lead to significant isotopic depletion, however, that was typically shown in JJAS and ON heavy rainfall events. Convections over BOB and tropical Indian Ocean are important factors that impact distinct variations of precipitation $\delta^{18}O$ from west to east Bangladesh significantly. In addition, we suggested that moisture from BoB was the primary contribution to year-round precipitation in Bangladesh, the contribution of moisture originated from IO increased significantly in monsoon season, and the contribution of land-surface moisture enhanced to about 50% in winter. These variations of moisture sources and convections along the transport paths resulted in the spatial-temporal variations of precipitation stable isotopes in Bangladesh.

Our results call for a better documentation of the role of regional convections along the moisture transport paths and moisture sources when considered variations of the Indian monsoon and westerlies transports at distinct time scales. We also suggested very cautions interpretation of past variations of precipitation $\delta^{18}O$ relevant to

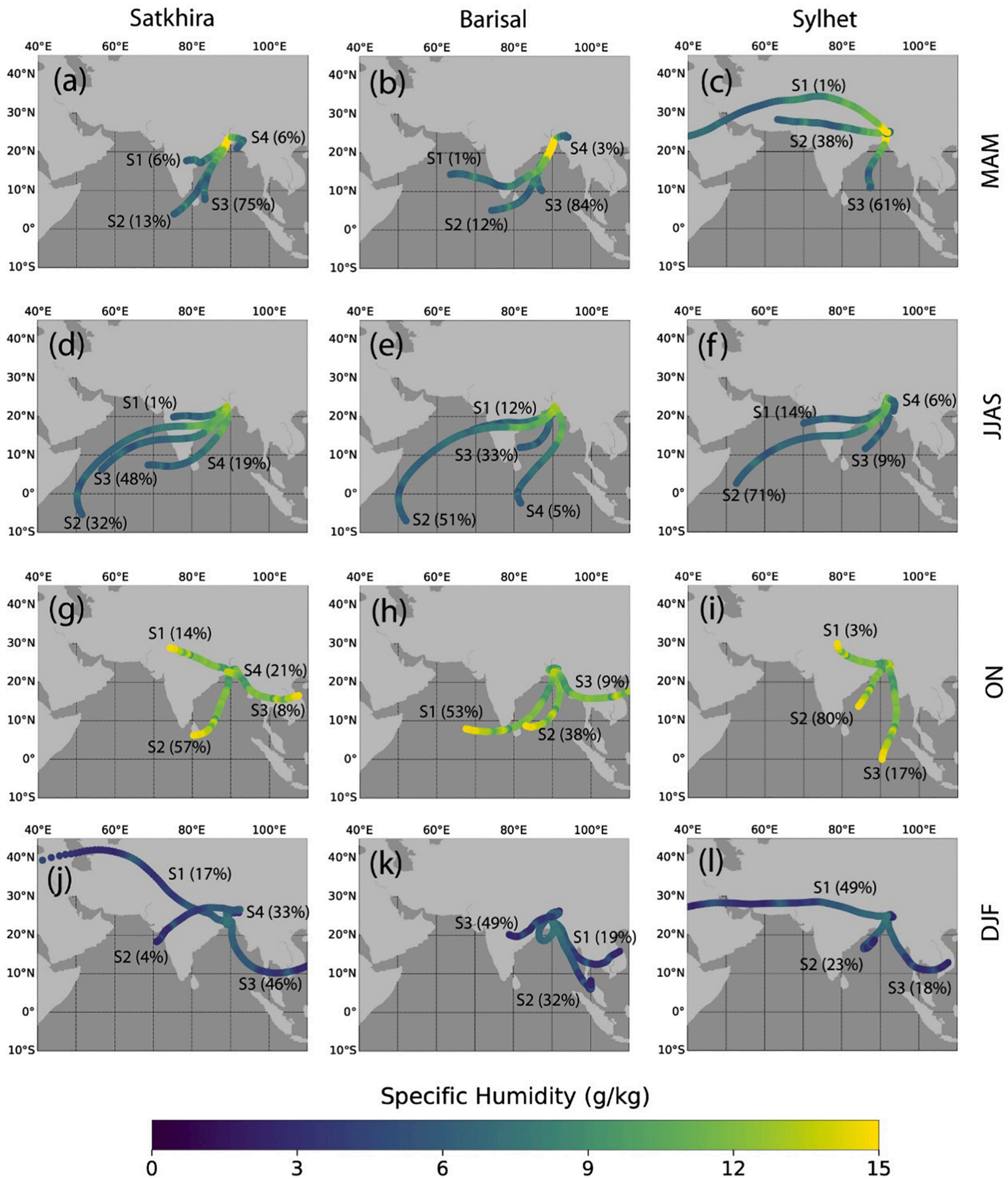

Fig. 8. Specific humidity along the clustered trajectory at three stations. We used categories and boundary conditions of four moisture sources followed Tanoue et al. (2018). Amounts of trajectories originated from one moisture source against the total amounts of trajectories from all sources for each station are calculated to get the percentage of different trajectories.

achievements (e.g. ice cores, lake sediments and tree rings) in the AWTs where the moisture favors the Indian monsoon and westerlies transport across Bangladesh. Investigations of the mechanisms controlling precipitation $\delta^{18}O$ at the inter-annual to decadal scales are required in the future.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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