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Seasonal variation in isotopic composition and the origin of precipitation over Bangladesh

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Abstract

Water isotopic composition ($\delta^{18}O$ and δD) in terrestrial proxies of past precipitation enable us to better understand and interpret variation in the Indian Summer Monsoon (ISM). Previous studies have suggested that the origin of precipitation is an important factor controlling the isotopic composition of precipitation around the Indian subcontinent; however, it is difficult to quantify using the Lagrangian approach because the approach does not satisfy the assumption of an adiabatic process over a convective area. We investigated the isotopic composition of precipitation at three sites over Bangladesh in 2010 and estimated the origins of precipitation by the Eulerian approach using an isotope-incorporating Atmospheric General Circulation Model. Our observations showed similar seasonal and intraseasonal variations in the $\delta^{18}O$ values of precipitation among the sites, whereas the temporal characteristics of the precipitation amount differed among the sites. The isotopic composition was linked to the migration of organized convective activity around the region. The model showed that the pre-monsoon season (from mid-March to early June) was characterized by high $\delta^{18}O$ values of precipitation originating from the Bay of Bengal and the Arabian Sea. In the ISM season (from mid-June to early October), the contribution of these sources to precipitation gradually decreased, while the contribution from the Indian Ocean increased, resulting in decreasing $\delta^{18}O$ values of precipitation due to the enhanced rainout process during the transportation. These moisture contributed less to precipitation over Bangladesh in the post-monsoon season (from mid-October to November), whereas moisture originating from the Pacific Ocean and land surface (i.e., recycling of water) contributed to precipitation in the season. Because the recycling of water originated from past precipitation with low $\delta^{18}O$ values in the ISM season, its contribution to precipitation reduced the $\delta^{18}O$ values of precipitation in the ISM and post-monsoon seasons. These results suggest that the origins of precipitation and the migration of organized convective activity are the dominant factors controlling the isotopic composition of precipitation in the region. These characteristics can be used to identify monsoon onset and withdrawal based on water isotopic composition.

Keywords: Isotopic composition of precipitation, Bangladesh, Origins of precipitation, Isotope-incorporating atmospheric general circulation model, Indian summer monsoon

Introduction

The Indian Summer Monsoon (ISM), which is characterized by strong seasonality of rainfall and floods, affects regional society and agriculture around the Indian subcontinent. An understanding of the ISM is needed to forecast its onset, withdrawal, duration, intensity, and variation. To further understand and forecast the ISM, many studies have attempted to reconstruct paleo-ISM variation from oxygen isotope ($\delta^{18}O$) variations in terrestrial proxies of past precipitation (e.g., stalagmites, tree rings, and sediment) in the region (e.g., Fleitmann et al. 2003; Wang et al. 2005; Yancheva et al. 2007; Wang et al. 2008; Zhang et al. 2008).

The interpretation of paleo-ISM variation from $\delta^{18}O$ values of terrestrial proxies is mainly based on the "amount effect," i.e., the negative relation between the amount and isotopic composition of precipitation, which has been observed in tropical regions at monthly or daily

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time scales (e.g., Dansgaard 1964; Araguás-Araguás et al. 1998; Risi et al. 2008; Kurita et al. 2009). The amount effect is due to the increase in the removal of heavier water isotopes ($H_2{}^{18}O$ and $HD^{16}O$) from cloud vapor, as heavier water isotopes are preferentially removed from cloud vapor (e.g., Dansgaard 1964). However, it has not been observed at stations around the Indian subcontinent (e.g., Datta et al. 1991; Araguás-Araguás et al. 1998; Bhattacharya et al. 2003; Breitenbach et al. 2010; Midhun and Ramesh 2016), except in the southeastern part of peninsular India and Sri Lanka (Lekshmy et al. 2015).

Because the amount effect cannot be applied to reconstruct $\delta^{18}O$ variation in terrestrial proxies around the Indian subcontinent, many studies have explored the factors controlling the isotopic composition of precipitation in the region (e.g., Datta et al. 1991; Bhattacharya et al. 2003; Sengupta and Sarkar 2006; Breitenbach et al. 2010; Lekshmy et al. 2014, 2015; Chakraborty et al. 2016; Midhun and Ramesh 2016). For example, Bhattacharya et al. (2003) investigated the isotopic composition of precipitation in Bombay and New Delhi and concluded that it reflected oceanic moisture, with low $\delta^{18}O$ values, during the ISM season and continental moisture, with high $\delta^{18}O$ values, during the winter monsoon season. In addition, Breitenbach et al. (2010) assessed the isotopic composition of precipitation for every rainfall event in the northeastern part of India and estimated the travel distance of air parcels during their transport from the vapor source regions to the observation site using the Lagrangian approach (i.e., backward trajectory analysis). They found that low $\delta^{18}O$ values of precipitation were associated with long-distance transport. Similarly, Lekshmy et al. (2014) and Chakraborty et al. (2016) found low $\delta^{18}O$ values of precipitation when air parcels passed over a convective area over the Indian Ocean. This finding was supported by a study based on multiple simulations of isotope-incorporating Atmospheric General Circulation Models (AGCMs) (Midhun and Ramesh 2016), which showed that the inter-annual variability in $\delta^{18}O$ values of precipitation around the Indian subcontinent was controlled by rainout in the upstream area of the moisture flux. This suggests that the origins of moisture and rainout in the upstream area are the dominant controlling factors of the isotopic composition of precipitation in the region.

Although some studies have indicated that the recycling of water is an important factor for precipitation variability around the Indian subcontinent based on land–atmosphere coupling simulations (e.g., Guimberteau et al. 2012; Yamashima et al. 2014) and satellite observations (e.g., Ono and Takahashi 2016), the recycling of water has not been discussed as a possible factor controlling the isotopic composition of precipitation around the region, as it is difficult in the Lagrangian approach to quantify the contribution of the recycling of water to precipitation (Breitenbach et al. 2010). In the Lagrangian approach, an individual air parcel trajectory can be observed; however, the uncertainties of the method can be large when an air parcel passes over a convective area due to an unsatisfied assumption of the adiabatic process. On the other hand, the Eulerian approach focuses on specific locations through which the fluid flows as time passes. In addition, the Eulerian approach is easily combined with an isotope-incorporating AGCM. This approach can be used to estimate the origins of moisture and precipitation in many regions (e.g., Yoshimura et al. 2004; Ichiyanagi et al. 2005; Shinoda et al. 2005; Sato et al. 2007; Hiraoka et al. 2011; Suwarman et al. 2013; Kudo et al. 2014; Belgaman et al. 2016) and to evaluate the atmospheric hydrological cycle in the model by comparing the simulated and observed isotopic composition of precipitation. In this study, we estimated the origins of precipitation using an isotope-incorporating AGCM over Bangladesh. The dominant factors controlling seasonal variation in the isotopic composition of precipitation in the region were further investigated. Origins of moisture estimated by the Eulerian and Lagrangian approaches were compared to understand the uncertainty of both approaches in the region. The results of the study will enhance our understanding of the atmospheric hydrological cycle associated with the ISM over Bangladesh and provide a way to identify the timing of monsoon onset and withdrawal using water isotopic composition.

Methods/Experimental

The isotopic composition of precipitation was observed at three sites over Bangladesh. We used an isotope-incorporating Global Spectral Model (IsoGSM, Yoshimura et al. 2008) to simulate seasonal variation in the isotopic composition of precipitation and then estimated the origins of precipitation using the Eulerian approach based. The estimated origins of moisture were compared to the estimation based on the Lagrangian approach.

Study area

We observed the amount and isotopic composition of precipitation at three sites over Bangladesh: Sylhet (91.88° E, 24.91°N), Dhaka (90.38°E, 23.78°N), and Chittagong (91.81°E, 22.35°N) (Fig. 1). In Bangladesh, the precipitation is high during summer, and it is low during winter. In this study, we defined the dry winter (pentad 1–13, January to early March), pre-monsoon (pentad 14–31, mid-March to early June), ISM (pentad 32–56, mid-June to early October), and post-monsoon (pentad 57–67, mid-October to November) seasons based on the analysis by Hoque et al. (2011) and the observed seasonal variation in the isotopic

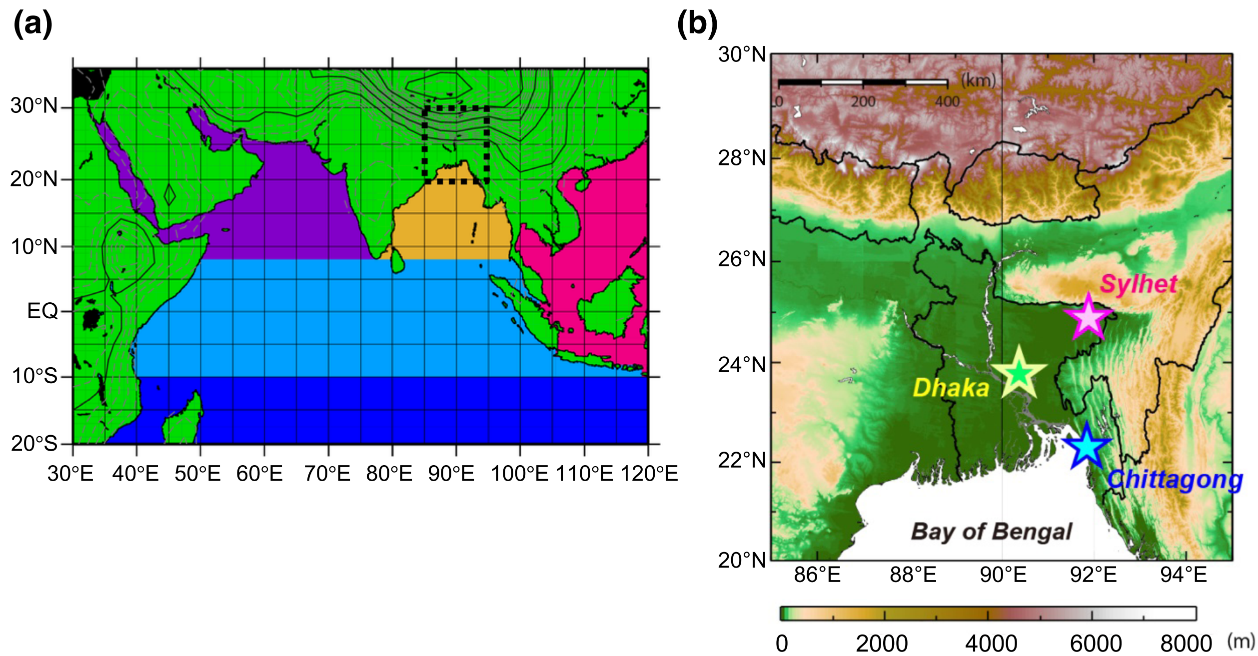

Fig. 1 a Surface geo-potential height (contour) in this study. The solid and dashed contour intervals are 1000 and 200 gpm, respectively. Vapor source regions were divided into seven regions: the Pacific Ocean (red), the Bay of Bengal (Yellow), the Arabian Sea (purple), northern part of the Indian Ocean (light blue), southern part of the Indian Ocean (dark blue), land surface (green), and others (black). The dotted line indicates the area of (**b**). **b** Locations of the observation sites over Bangladesh. The topographic data (GTOPO30) were downloaded from the United States Geological Survey (USGS)

composition of precipitation. The pre-monsoon season was characterized by dominant westerly winds and unorganized deep convection (Matsumoto 1997; Islam and Uyeda 2008). In the ISM season, a southwesterly moisture flux is dominant over Bangladesh, and precipitation is caused by deep convection and cyclone activity over the Indian Ocean and the Bay of Bengal (Islam and Uyeda 2008; Hatsuzuka et al. 2014). In this season, a huge amount of water vapor is transported from the Bay of Bengal to Bangladesh (Hoque et al. 2011), and it precipitates on the southern slope of the Meghalaya Plateau due to orographic upward currents (e.g., Fujinami et al. 2017). Precipitation in the northeastern part of Bangladesh (e.g., Sylhet) is relatively high in the country. In the post-monsoon season, dry northwesterly and southwesterly winds are dominant in the region (Hoque et al. 2011), and precipitation is frequently caused by atmospheric disturbances over the Bay of Bengal (Breitenbach et al. 2010).

Observation of precipitation samples and analysis methods

We observed the amount and isotopic composition of precipitation at Sylhet, Dhaka, and Chittagong at 3 h intervals (00UTC, 03UTC, 06UTC, 09UTC, 12UTC, 15UTC, 18UTC, and 21UTC) from January to December 2010. The Bangladesh Meteorological Department operates a pluviometer with precipitation water and reads the amount of precipitation every 3 h. We arranged for part of the collected precipitation water to be transferred to a 15 ml bottle. We collected a total of 1416 precipitation samples. These samples were stored in dark and cool locations prior to the analysis of isotopic composition.

The precipitation samples were analyzed by a mass spectrometer (DELTA-V, Thermo Fisher Scientific, Waltham, MA, USA) in the Graduate School of Science and Technology, Kumamoto University, Japan. The equilibrium of CO_2 and H_2 gases with precipitation samples was prepared by H_2–H_2O (Horita et al. 1989) and H_2O–CO_2 (Epstein and Mayeda 1953) equilibrium techniques, respectively, with an automatic equilibration setup. The automatic setup was connected to a dual-inlet system on the DELTA-V instrument. We measured the isotopic ratios of the CO_2 and H_2 gases and calculated the relative difference between sample water and Standard Mean Ocean water using two laboratory standards (AMW, $\delta D = 0.59‰$ and $\delta^{18}O = -0.262‰$; CIW, $\delta D = -89.88‰$ and $\delta^{18}O = -12.730‰$). To validate the measurements of the isotopic ratio of precipitation samples, we included one laboratory standard (KTW, $\delta D = -47.32‰$ and $\delta^{18}O = -7.300‰$) and checked the δD and $\delta^{18}O$ values every analysis. The analytical errors for δD and $\delta^{18}O$ were less than $\pm 0.5‰$ and $\pm 0.05‰$, respectively. The measured

3 h isotopic composition of precipitation was averaged to a daily value (from 00UTC to 21UTC) and weighted by the precipitation amount to compare the simulation results.

Description of IsoGSM

IsoGSM is based on the Scripps Experimental Climate Prediction Center's global spectral model with heavy water isotopes ($H_2{}^{18}O$ and HDO) as tracers. The major physical processes included in the model are the relaxed Arakawa–Schubert scheme (Moorthi and Suarez 1992), the Noah land surface model (Ek et al. 2003), the Chou radiation scheme (Chou and Suarez 1994), and a planetary boundary scheme (Hong and Pan 1996). The physical schemes of water isotopes included in the model are the parameterization of equilibrium fractionation among vapor, liquid, and ice (Majoube 1971a, 1971b), kinetic fractionation for surface evaporation from open water (Merlivat and Jouzel 1979), condensation from vapor to ice under super-saturated conditions at temperatures lower than − 20 °C (Jouzel and Merlivat 1984), and evaporation and isotopic exchange between falling raindrops and vapor in surrounding air (Stewart 1975). Midhun and Ramesh (2016) validated the amount and $\delta^{18}O$ value of precipitation derived from multi-GCM simulations, and IsoGSM showed good temporal and spatial variations in the simulations.

Simulation design

We selected the T62 horizontal resolution (approximately 180 km) and 28 vertical layers in this study. Although the IsoGSM simulation was performed for the period of 1979–2010, we used only the model output for the year 2010. The simulation output was generated at daily intervals and interpolated into 17 vertical pressure levels (1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, and 10 hPa).

Daily sea surface temperatures and ice distributions were obtained from the National Oceanic and Atmospheric Administration (NOAA) Optimum Interpolation Sea Surface Temperature V2 (Reynolds et al. 2002) at 1.0° × 1.0° horizontal resolution. The National Centers for Environmental Prediction/Department of Energy Reanalysis 2 (NCEP/DOE R2), with a horizontal resolution of 250 km (Kanamitsu et al. 2002), was used for the initial condition of the IsoGSM simulation.

IsoGSM applied a global downscaling technique, which nudged temperature and wind speed at scales larger than 1000 km toward the NCEP/DOE R2 for every 6 h for all sigma levels (Yoshimura and Kanamitsu 2008). This method did not nudge the fields of isotopic composition and humidity. Several validation studies using this method for a limited number of observations have shown that the nudging technique downscales global climate fields in the model reasonably well at various time scales (e.g., Yoshimura et al. 2008; Uemura et al. 2008; Frankenberg et al. 2009; Berkelhammer et al. 2011; Yoshimura et al. 2011).

The seven vapor source regions considered in this study are shown in Fig. 1a: the Bay of Bengal (brown), the Arabian Sea (purple), the northern part of the Indian Ocean (light blue), the southern parts of the Indian Ocean (blue), the Pacific Ocean (magenta), land surface (green), and others (Black). These divisions were based on the published literature regarding the origins of precipitation around the Indian subcontinent (Numaguti 1999; Yoshimura et al. 2004; Breitenbach et al. 2010). We confirmed that the relative contribution of moisture originating from these regions to precipitation over Bangladesh was above 80%, indicating that the selected vapor source regions were sufficient to represent the dominant sources of precipitation in the region.

Backward trajectory analysis

We conducted a 10 day backward trajectory analysis to estimate the probable origins of moisture over Bangladesh. We assumed that air parcels transported at a constant pressure level (850 hPa) and had the same horizontal wind speed. The location of air parcel at the next time step ($\lambda+\Delta\lambda$, $\phi+\Delta\phi$) could be predicted by the following equation:

$$\Delta\lambda = \frac{u(\lambda,\phi)\times 60\times 60\times 30}{2\pi(H+R)\cos\phi}$$
$$\Delta\phi = \frac{v(\lambda,\phi)\times 60\times 60\times 30}{2\pi(H+R)},$$

where λ and ϕ indicate the longitude and latitude of air parcels, respectively, u and v indicate the horizontal and meridional wind speed (m/s), respectively, R is the radius of the earth (6.3773×10^6 m), and H is the geopotential height at the constant pressure level. Horizontal and meridional wind speed were taken from 6 h nudged IsoGSM simulations and a Japanese 55 year reanalysis (JRA-55) (Kobayashi et al. 2015; Harada et al. 2016) and interpolated into 0.5° × 0.5° resolution and 30 min intervals using a bilinear method. A backward trajectory analysis was used to estimate the general origin of moisture at the synoptic scale, although it could not reflect local moisture sources (i.e., the recycling of water) (e.g., Breitenbach et al. 2010). In addition, this method assumes an adiabatic process, which is not maintained when an air parcel passes over a convective area. Trajectories were calculated for the sampling days.

Data

We used the NOAA interpolated outgoing longwave radiation (OLR) with a spatial horizontal resolution of

2.5° × 2.5° at a daily time interval in the year 2010 to compare organized convective activity with variations in the isotopic composition of precipitation. A Hovmöller diagram of the averaged OLR was calculated over 85–97.5° E. We identified convective activity using the criterion OLR < 220 W/m^2.

Results

Seasonal variation in the amount and isotopic composition of precipitation

The temporal characteristics of the daily precipitation were different among the three sites (Fig. 2). Heavy precipitation events (> 50 mm/day) occurred frequently at Sylhet from April to October, while they were less frequent at Dhaka and Chittagong. This difference reflects the precipitation system.

The δ^{18}O value of precipitation displayed a clear and similar seasonal variation among the sites. The δ^{18}O values gradually decreased from mid-May and increased from early October, corresponded to the ISM season. In addition, intraseasonal variation (about 2~4 weeks) was found, with depletion occurring in mid-May, mid-June, early and late August, and early October. Fujinami et al. (2011) and Murata et al. (2017) showed that the intraseasonal variation of precipitation was dominant around Cherapunji in the northeastern part of India. These results indicate that the δ^{18}O value of precipitation over Bangladesh can be controlled by seasonal and intraseasonal

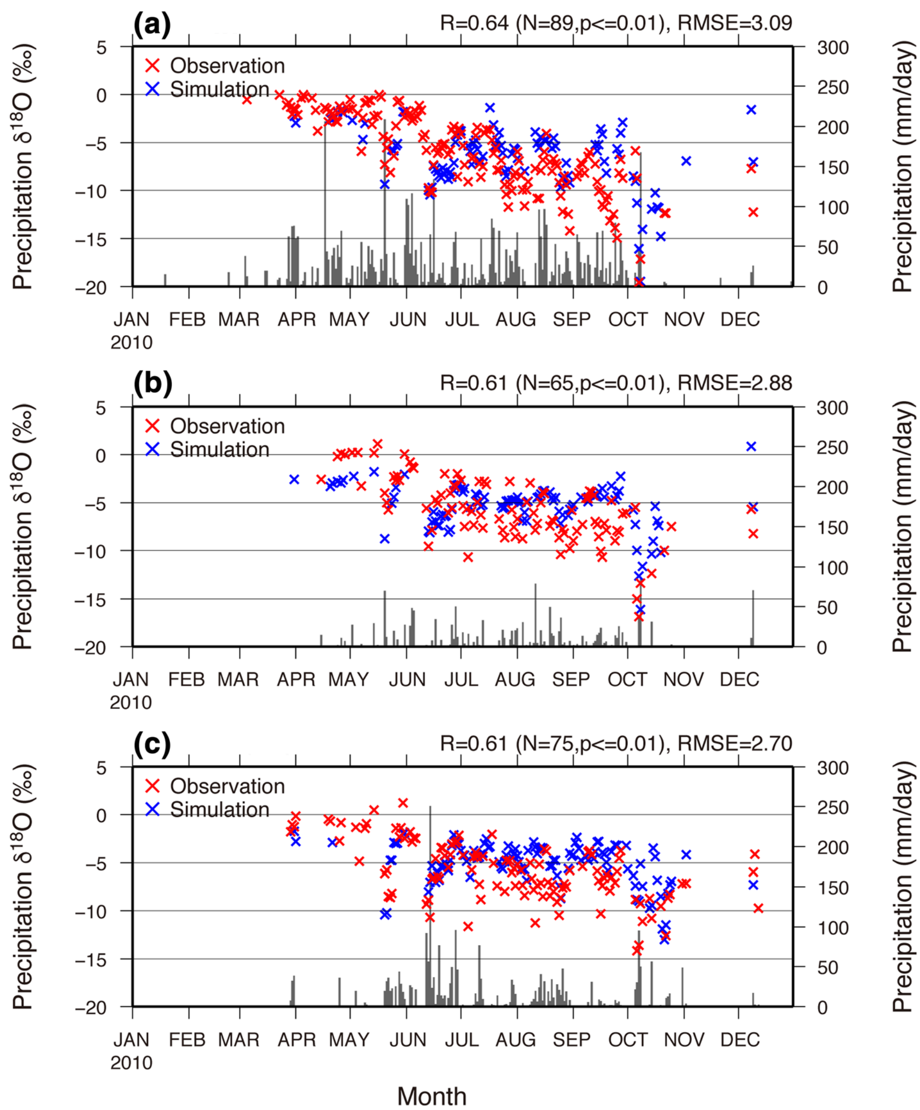

Fig. 2 Daily variations in the amount (bar) and δ^{18}O values (cross) of precipitation in 2010 at Sylhet (**a**), Dhaka (**b**), and Chittagong (**c**). Red and blue crosses indicate observations and IsoGSM simulations, respectively. The correlation coefficient (*R*), number of samples (*N*), probability (*p*), and root mean square error (RMSE) between the observed and simulated δ^{18}O values of precipitation are shown

variations (e.g., the ISM and monsoon low-pressure system).

Validation of IsoGSM simulation

The isotopic composition of precipitation reflects the components of the atmospheric hydrological cycle, including the rainout history of water vapor (e.g., Yoshimura et al. 2003; Ichiyanagi et al. 2005; Fudeyasu et al. 2011) and phase changes in water (e.g., Pfahl et al. 2012). A comparison between the simulated and observed isotopic composition of precipitation is used to validate the atmospheric hydrological cycle in the model, as well as to indirectly assess the reliability of the Eulerian approach (Yoshimura et al. 2003, 2004). Overall, the model successfully replicated the observed seasonal and intraseasonal variations in the isotopic composition over Bangladesh (Fig. 2). The correlation coefficients between the observed and simulated $\delta^{18}O$ values of precipitation at Sylhet, Dhaka, and Chittagong were 0.64, 0.61, and 0.61, respectively, with a significance level exceeding 95%. The root mean square errors (RMSEs) between the observed and simulated $\delta^{18}O$ values of precipitation at Sylhet, Dhaka, and Chittagong were 3.09‰, 2.88‰, and 2.70‰, respectively. This large RMSE was due to the overestimation of the simulated $\delta^{18}O$ values in the depletion events, especially in mid-June, early and late August, and early October.

Figure 3 shows the simulated and observed amount effect (i.e., the relation between the amount and $\delta^{18}O$ value of precipitation) at three sites. We did not find amount effect, except in Chittagong, but the simulation shows the amount effect at the three sites. The correlation coefficients between the simulated amount and $\delta^{18}O$ values of precipitation at Sylhet, Dhaka, and Chittagong were − 0.47, − 0.42, and − 0.26, respectively, with a significance level exceeding 95%. This discrepancy is due to the scale difference between the amount and isotopic composition of precipitation (Kurita et al. 2009). Variation in the isotopic composition of precipitation was mainly associated with large-scale disturbances, whereas that in the local precipitation amount was associated not only with large-scale disturbances but also regional circulation (e.g., nocturnal jet). The model cannot fully resolve the regional circulation due to the rough horizontal resolution, resulting in the stronger simulated amount effect.

A Hovmöller diagram of the NOAA interpolated and simulated OLR are shown in Fig. 4. An organized convective area (OLR < 220 W/m^2) was found at a latitude

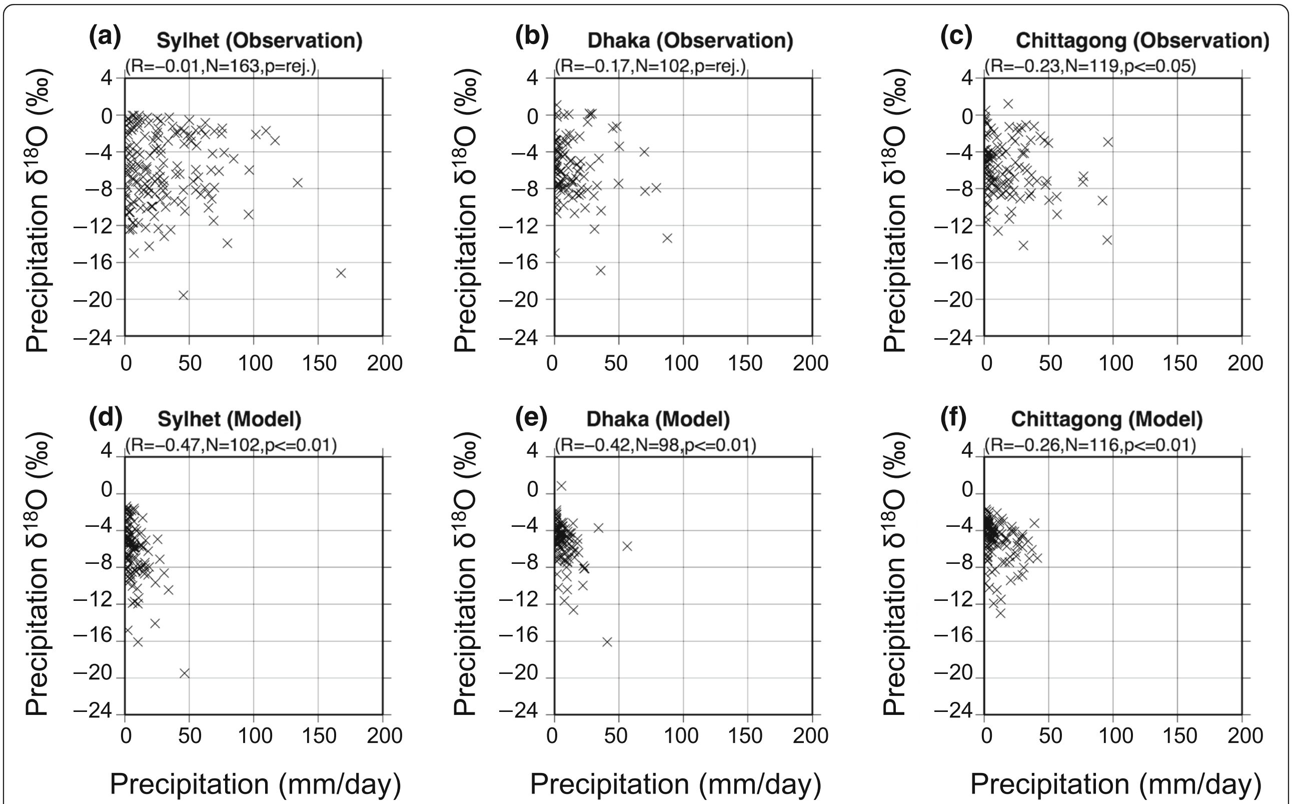

Fig. 3 The relation between the amount of and $\delta^{18}O$ values of precipitation for observations (**a**, **b**, **c**) and IsoGSM simulations (**d**, **e**, **f**) at Sylhet (**a**, **d**), Dhaka (**b**, **e**), and Chittagong (**c**, **f**). Values with a simulated precipitation amount of < 1.0 mm/day were excluded

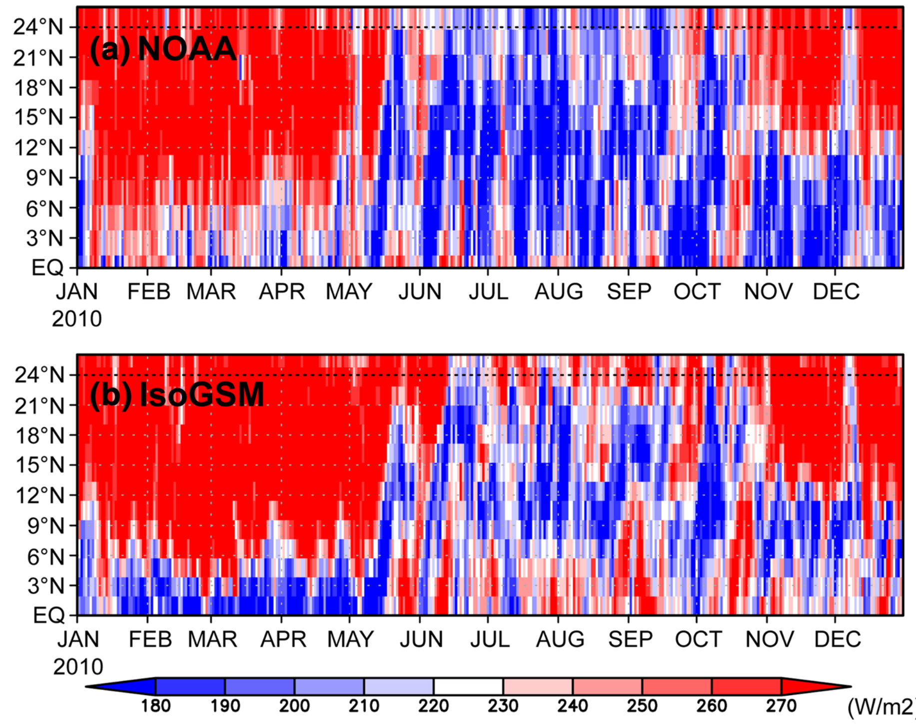

Fig. 4 Hovmöller diagram of the NOAA interpolated (**a**) and simulated (**b**) outgoing longwave radiation (OLR, W/m^2) averaged over 85°E–97.5°E. Black dotted lines represent the latitude of Dhaka

below 10°N until mid-May, after which it moved northward (Fig. 4a). The convective activity frequently appeared around Bangladesh and the Bay of Bengal in late May, mid-June, mid-July, late August, mid-September, and late October. The timing corresponded to depletion events in the δ^{18}O values of precipitation (Fig. 2). The IsoGSM displayed a similar migration of the organized convective area, which appeared around Bangladesh and the Bay of Bengal in mid-June, late August, early September, and late October (Fig. 4b). However, some discrepancies were found; for example, the convective area failed to appear around Bangladesh and the Bay of Bengal in late May and from late June to early September. Moreover, the values derived from the IsoGSM simulation were still underestimated at latitudes below 24°N in the ISM season. The discrepancy and underestimation cause a small convective precipitation amount around Bangladesh, resulting in an overestimation of the simulated δ^{18}O values of precipitation because of a clear positive correlation between the δ^{18}O values of precipitation and the proportional contribution of the convective precipitation amount (Aggarwal et al. 2016).

Origins of moisture and precipitation

Figure 5 shows the spatial patterns of the vertically integrated moisture flux and its divergence averaged for the dry winter, pre-monsoon, ISM, and post-monsoon seasons, as derived from the IsoGSM simulation. The westerly moisture flux was dominant over Bangladesh and the northern part of the Bay of Bengal in the dry winter and pre-monsoon seasons (Fig. 5a, b). A moisture divergence zone appeared in the Bay of Bengal and the Arabian Sea in these seasons, the divergence in the pre-monsoon season was weaker than that in the dry winter monsoon season. The convergence zone was located in the region over the Bay of Bengal, the Indian subcontinent, and the Indochina Peninsula in the ISM season (Fig. 5c). A large moisture flux from the southern part of the Indian Ocean to the Indian subcontinent was dominant. In the post-monsoon season, the convergence zone returned to the southern part of the Bay of Bengal, and a westerly moisture flux gradually became dominant in the northern part of India (Fig. 5d). In the Indonesia peninsula, an easterly moisture flux was dominant in this season.

Figure 6 shows the daily variation in the simulated total precipitable water (TPW) and its origins at Sylhet, Dhaka, and Chittagong. The temporal characteristics of the TPW and its origins were similar among the sites. The TPW increased in mid-March and decreased in mid-October. The oceans close to Bangladesh (the Bay of Bengal and the Arabian Sea) were the dominant source of moisture among the sites in the pre-monsoon

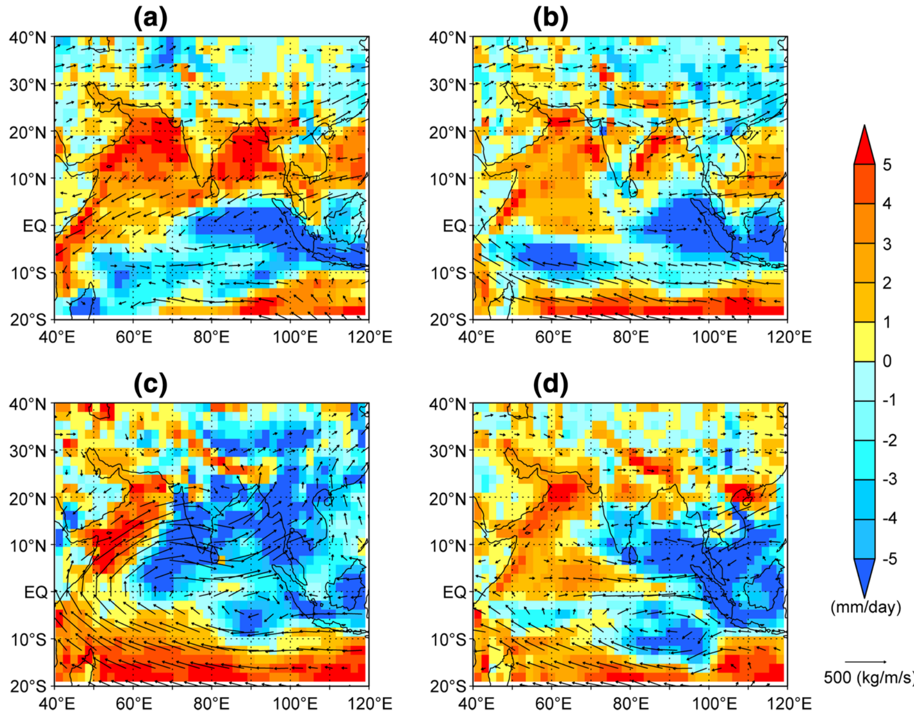

Fig. 5 Spatial distributions of the vertical integrated moisture flux (arrows, kg/m/s) and its divergence (colored, mm/d) in the dry winter (**a**), pre-monsoon (**b**), Indian Summer Monsoon (ISM) (**c**), and post-monsoon (**d**) seasons

season, contributing > 54% of the moisture in the TPW (Table 1). These sources and the Indian Ocean contributed > 61% of the moisture in the TPW in the ISM season. In the post-monsoon season, the contribution of moisture originating from the Bay of Bengal, the Arabian Sea, and the Indian Ocean to the TPW was abruptly reduced (< 12%), whereas moisture originating from the Pacific Ocean and land surface (i.e., the recycling of water) were the main sources of moisture over Bangladesh (> 42%).

The daily variations in the simulated amount and origin of precipitation are shown in Fig. 7. The simulated amount of precipitation was overall underestimated compared with the observed amount (Fig. 2); for example, in the pre-monsoon season at Sylhet, the model could capture heavy precipitation events in late June and early October. Table 2 shows the relative contribution of vapor source regions to precipitation at the sites. The main sources of precipitation in each season were almost identical among the sites. The main sources of precipitation were moisture originating from the oceans close to Bangladesh in the pre-monsoon season (49~60%). The contribution of these moisture sources decreased in the ISM season (36~39%), while the contribution of sources originating from the Indian Ocean increased (26~30%). In the post-monsoon season, the Pacific Ocean and recycling of water were the main sources of precipitation over Bangladesh, contributing approximately half of the precipitation. The recycling of water was the main source of precipitation in the inland region (Sylhet). The contribution of the recycling of water to precipitation seemed to increase from coastal to inland regions due to the high evaporation rate over the Indian subcontinent in the ISM season (4 mm/d; not shown). The contribution of the recycling of water could not be neglected in the inland region, even in the ISM season.

Discussion

We estimated the origins of precipitation using the Eulerian approach combined with IsoGSM. Because the model could capture the observed seasonal and intraseasonal variations in the isotopic composition of precipitation (Fig. 2), the simulated atmospheric hydrological cycle was considered reliable. We summarized the $\delta^{18}O$ values and origins of precipitation in each season. The observed weighted mean of $\delta^{18}O$ value and the total amount of precipitation are summarized in Tables 3. The pre-monsoon season was characterized by high $\delta^{18}O$ values of precipitation (− 3.45 to − 1.82‰) (Fig. 2), with the Arabian Sea and the Bay of Bengal being the main sources of precipitation (Fig. 7). The organized convective activity moved northward and appeared around Bangladesh in the ISM season (Fig. 4). In this season, the $\delta^{18}O$ values of precipitation decreased (− 8.49 to − 7.28‰) (Fig. 2), and the Indian Ocean

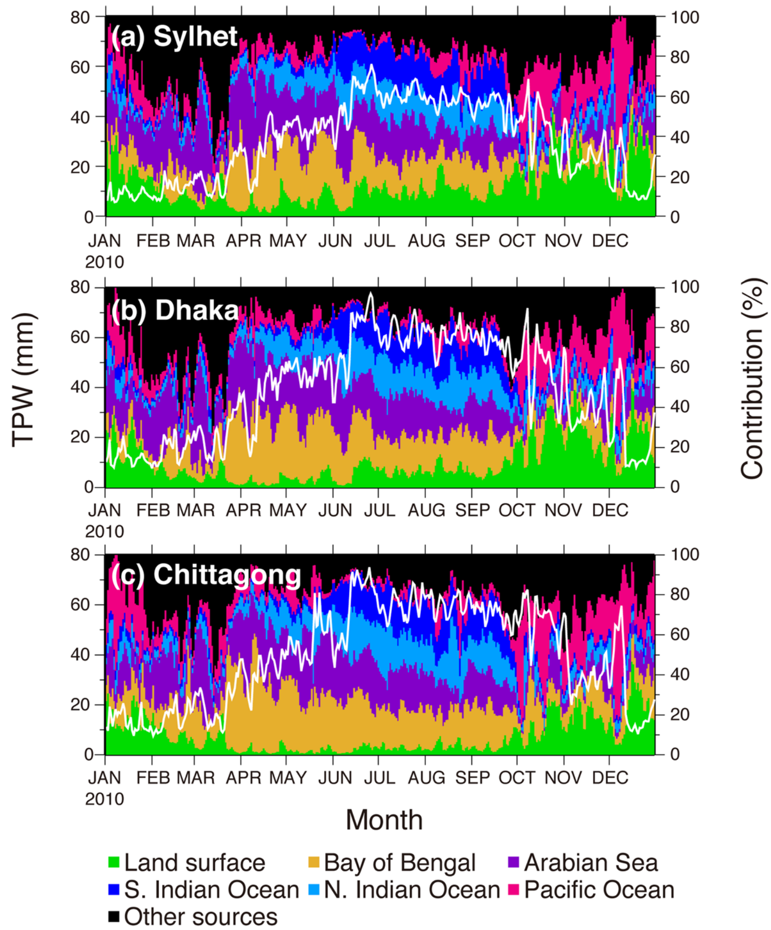

Fig. 6 Daily variation in the total precipitable water (TPW) (white solid line) and its origins at Sylhet (**a**), Dhaka (**b**), and Chittagong (**c**) simulated by IsoGSM. Differences in shading color denote variation in the different vapor source regions shown in Fig. 1a

contributed to precipitation over Bangladesh (Fig. 7). In the post-monsoon season, the convective activity shifted southward (Fig. 4), and the $\delta^{18}O$ values of precipitation were the lowest (− 15.94 to − 9.29‰) (Fig. 2). The Pacific Ocean, the Bay of Bengal, and land surface were the main sources of precipitation in this season (Fig. 7).

Our results suggest that the origins of precipitation and migration of organized convective activity are the main factors controlling the isotopic composition of precipitation over Bangladesh. The observed amount effect was not significant (Fig. 3), indicating that the contribution of the local precipitation amount to the variation in

Table 1 Relative contribution of vapor source regions to moisture in total precipitable water (TPW) for each season

Season	Site	LND	BOB	ARS	NID	SID	PAC
Pre-monsoon	Sylhet		26%	28%	10%		
	Dhaka		29%	28%	11%		
	Chittagong		31%	27%	11%		
Indian Summer Monsoon	Sylhet	14%	16%	16%	14%	15%	
	Dhaka	10%	18%	17%	15%	16%	
	Chittagong		20%	17%	17%	17%	
Post-monsoon	Sylhet	24%					23%
	Dhaka	26%	10%				21%
	Chittagong	17%	12%				25%

Values less than 10% were omitted. *LND* land surface (the recycling of water), *BOB* the Bay of Bengal, *ARS* the Arabian Sea, *NID* the northern part of the Indian Ocean, *SID* the southern part of the Indian Ocean, *PAC* the Pacific Ocean

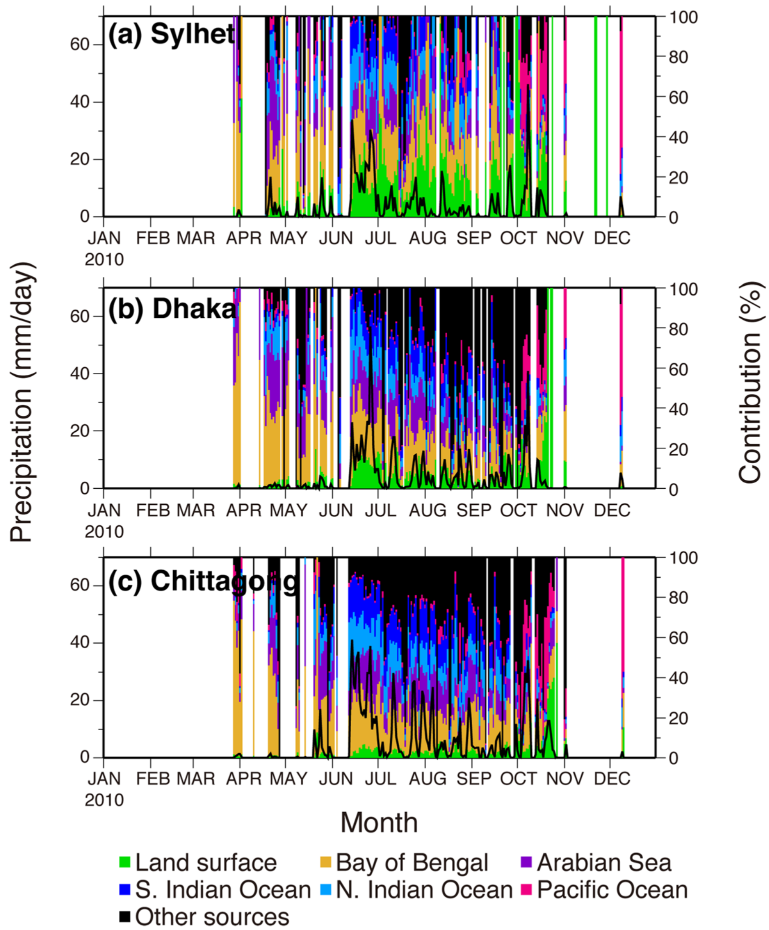

Fig. 7 Daily variation in the simulated amount of precipitation (black line) and its origins at Sylhet (**a**), Dhaka (**b**), and Chittagong (**c**) simulated by IsoGSM. Differences in shading color denote variation in the different vapor source regions shown in Fig. 1a. Values with a simulated precipitation amount of < 1.0 mm/day were excluded

the isotopic composition of precipitation was small. The origin of precipitation was the main factor controlling the isotopic composition of precipitation at the seasonal scale. This indirectly represents the travel distance during transport from the vapor source regions to the sites and the contribution of the recycling of water to precipitation. Long travel distances increase rainout, resulting in decreasing $\delta^{18}O$ values of water vapor and precipitation along the trajectory (e.g., Breitenbach et al. 2010; Midhun et al. 2013). High $\delta^{18}O$ values of precipitation

Table 2 Relative contributions of vapor source regions to precipitation for each season

		LND	BOB	ARS	NID	SID	PAC
Pre-monsoon	Sylhet	10%	34%	26%	11%		
	Dhaka		36%	24%	13%		
	Chittagong		28%	21%	15%		
Indian Summer Monsoon	Sylhet	19%	23%	16%	15%	14%	
	Dhaka	10%	20%	16%	13%	13%	
	Chittagong		22%	16%	15%	15%	
Post-monsoon	Sylhet	24%	12%				37%
	Dhaka	19%	18%				26%
	Chittagong	20%	11%				29%

Values less than 10% were omitted. *LND* land surface (the recycling of water), *BOB* the Bay of Bengal, *ARS* the Arabian Sea, *NID* the northern part of the Indian Ocean, *SID* the southern part of the Indian Ocean, *PAC* the Pacific Ocean

Table 3 Summary of the weighted mean of $\delta^{18}O$ value and the total amount of precipitation at three sites in each monsoon season

Season	Site	$\delta^{18}O$ ‰	Precipitation (mm)
Dry winter	Chittagong	–	0
	Dhaka	–	0
	Sylhet	− 0.08	84
Pre-monsoon	Chittagong	− 3.45	454
	Dhaka	− 1.82	311
	Sylhet	− 2.56	2175
Indian Summer Monsoon	Chittagong	− 7.62	1712
	Dhaka	− 7.28	935
	Sylhet	− 8.49	2909
Post-monsoon	Chittagong	− 9.29	205
	Dhaka	− 13.11	122
	Sylhet	− 15.94	188

For calculation of the weighted means, weighted by the amount of precipitation has been adopted

were observed in the pre-monsoon season, with the main source being identified as the ocean close to Bangladesh (i.e., the Arabian Sea and the Bay of Bengal). In contrast, remote vapor source regions (i.e., the Indian Ocean) contributed to precipitation over Bangladesh in the ISM season. The effect of the travel distance contributed to a reduction in $\delta^{18}O$ values of precipitation over Bangladesh. Additionally, the recycling of water reduced the $\delta^{18}O$ values of precipitation in the ISM and post-monsoon seasons because the values in the recycling of water were lower than those in precipitation. This effect resulted in a seasonally declining trend in the $\delta^{18}O$ values of precipitation (Fig. 2). The migration of organized convective activity caused an intraseasonal variation in the $\delta^{18}O$ values of precipitation around the Indian subcontinent (e.g., Lekshmy et al. 2014, 2015). The observed $\delta^{18}O$ values of precipitation dropped drastically in mid-May, late June, late July, late August, late September, and late October, with these events being linked to the existence of convective activity over Bangladesh (Fig. 4). Lekshmy et al. (2014) found similar depletion events in the $\delta^{18}O$ values of precipitation across nine sites in southern India. The migration of the convective activity affected the $\delta^{18}O$ values of precipitation around the Indian subcontinent. The origins of precipitation and migration of organized convective activity were important factors for better understanding and interpreting the terrestrial proxies of past precipitation around the Indian subcontinent.

Our simulation showed drastic changes in the vapor source regions in late March (pentad 17), early June (pentad 32), and late September (pentad 54). To investigate the factors that induce drastic changes around Bangladesh, Fig. 8 shows the spatial distribution of the difference between the amount of moisture originating from the ocean (the Bay of Bengal, the Arabian Sea, and the Indian Ocean) and the land surface divided by the TPW. Reddish shading indicated that ocean moisture was dominant. In pentads before the first drastic change event (pentad 16), the oceanic moisture was less than the land moisture, but this increased due to the transport of the oceanic moisture by a southerly moisture flux in pentad 17. The second drastic change event occurred in early June (pentad 32). The event corresponded to the time when the strong southwesterly moisture flux arrived in Bangladesh. The third drastic change event occurred in late September (pentad 54), when the land moisture gradually increased from pentad 53 to 55. The southwesterly moisture flux gradually weakened, while the easterly moisture flux was enhanced in pentad 55. These drastic change events were related to changes in atmospheric circulation patterns.

Previous studies have determined the timing of the monsoon onset and withdrawal using variations in the local precipitation amount (e.g., Matsumoto 1997). However, determining this timing is difficult in Bangladesh, especially in Sylhet (Fig. 2a). Some previous studies identified the onset and withdrawal of the monsoon using the origins of moisture in the Asian monsoon region (e.g., Yoshimura et al. 2004; Ichiyanagi et al. 2005; Hiraoka et al. 2011). For example, Ichiyanagi et al. (2005) defined the monsoon withdrawal in Thailand to be when the amount of moisture originating from the Java Sea and the Pacific Ocean exceeded that originating from the Indian Ocean. In Bangladesh, we found clear seasonal variation in the origins of moisture and precipitation (Figs. 4 and 5), and the timing of monsoon onset and withdrawal could be identified by comparing the amounts of the ocean and land moisture (e.g., Fig. 8). In addition, seasonal variations in the isotopic composition of precipitation also have the potential to identify the timing of monsoon onset and withdrawal because the ISM season is characterized by a seasonally declining trend in the $\delta^{18}O$ values of precipitation. Isotopic composition and the origins of precipitation are useful for identifying the timing of monsoon onset and withdrawal and for estimating its duration and long-term trend.

To compare the estimations of the origins of moisture based on the Lagrangian and Eulerian approaches, we conducted a backward trajectory analysis and investigated the E–P distribution for each season (Fig. 9). The trajectories of the IsoGSM simulation and JRA-55 were generally similar in the pre-monsoon and ISM seasons. In the pre-monsoon season, most trajectories originated from the region around the Red Sea and passed over the northern part of India or the south coast of peninsular India (Fig. 9a). A positive E–P value was found at the

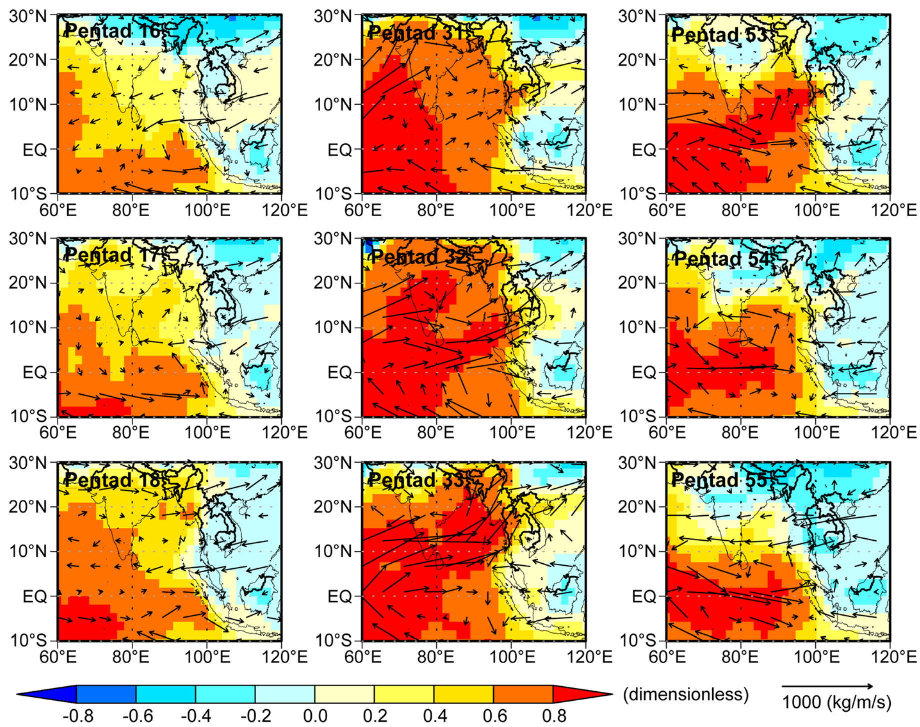

Fig. 8 The spatial distributions of the vertically integrated moisture flux and differences between the amount of moisture originating from the ocean (the Arabian Sea, the Bay of Bengal, the Indian Ocean) and land surface divided by the TPW in late March (pentad 16–18), early June (pentad 33–35), and late September (pentad 53–55). Red (blue) shaded indicated that moisture originating from the ocean (the land surface) was dominant

Bay of Bengal, the Arabian Sea, and the southern part of the Indian Ocean, while a negative *E*–*P* value was found in the northern part of the Indian Ocean (Fig. 9b). The main sources of moisture were identified as the Bay of Bengal and the Arabian Sea in this season. In the ISM season, air parcels transported from the western part of the Indian Ocean passed over the Arabian Sea and the Bay of Bengal (Fig. 9c). A positive *E*–*P* value was recognized in the western part of the Arabian Sea and the southern part of the Indian Ocean, and these oceans were determined to be the main sources of moisture in the ISM season (Fig. 9d). Because the value in the Bay of Bengal was less than − 2 mm/day, this region was clearly not the main source of moisture in the ISM season. In the post-monsoon season, most trajectories originated from East Asia and the Pacific Ocean in the JRA-55 simulation, whereas some trajectories originated from the northern part of the Indian Ocean and the Bay of Bengal in the IsoGSM simulation (Fig. 9e). The Arabian Sea and the western part of the Indian Ocean can be the main source of moisture over Bangladesh because a high positive *E*–*P* value was found in these regions, while the south coast of Vietnam, the Indian Ocean, and the Pacific Ocean are not the main vapor source regions over Bangladesh because a negative *E*–*P* value was found in these regions (Fig. 9f).

The origins of moisture estimated by the Eulerian and Lagrangian approaches were almost identical, except for the post-monsoon season. In the post-monsoon season, the Eulerian approach identified the Pacific Ocean and recycling of water as the main sources of moisture, while the Lagrangian approach identified the Pacific Ocean and the Indian Ocean as the main sources of moisture. Although we could not directly identify the main sources of moisture based on any observations, this discrepancy likely arose from the inability of the Lagrangian approach to explain the local moisture source. In addition, because the approach adopted the assumption of an adiabatic process, it may be not adequate for analyzing the isotopic composition of precipitation. The Eulerian approach has the advantage of enabling investigation of the effect of recycling of water on the isotopic composition of precipitation.

Although the model could capture the seasonal and intraseasonal variations in the isotopic composition of precipitation reasonably well, there was room for improvement in the calculation of simulated isotopic composition. For example, the simulated precipitation amount was underestimated due to the insufficient horizontal resolution of IsoGSM for capturing the local precipitation system over Bangladesh. Recently, a regional isotope circulation model was developed (Yoshimura et al. 2010), which can resolve line-type precipitation systems over the western part of the

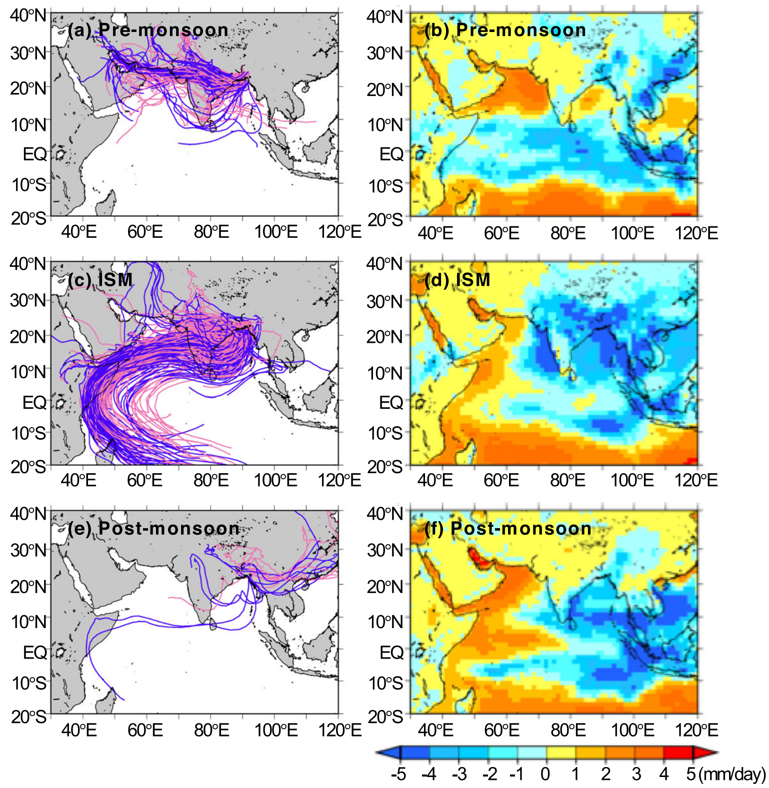

Fig. 9 Backward trajectory analysis for every precipitation sampling day in the pre-monsoon (**a**), Indian Summer Monsoon (ISM) (**c**), and post-monsoon seasons (**e**). Red and blue solid lines indicate the results of an IsoGSM simulation and JRA-55, respectively. The spatial pattern of the averaged *E–P* (mm/day) in the pre-monsoon (**b**), ISM (**d**), and post-monsoon seasons (**f**) derived from an IsoGSM simulation

USA (Yoshimura et al. 2010) and orographic winter precipitation patterns over Japan (Tanoue et al. 2016, 2017). The Eulerian approach combined with a regional isotope circulation model can obtain the origins of moisture and precipitation at a fine horizontal resolution (10 to 180 km). The RMSE between the observed and simulated isotopic composition of precipitation in the coastal region (i.e., Chittagong) was smaller than that in the inland region (i.e., Sylhet), with the large RMSE in the inland region likely caused by the recycling of water. The IsoGSM assumes no fractionation when water vapor is evaporated from the land surface (Yoshimura et al. 2008). Assuming isotopic fractionation, the isotopic values could be low because the isotopic enrichment of water during evaporation is lower than that during transpiration. This suggests that understanding the isotopic variation associated with the recycling of water could improve the overestimation of the isotopic enrichment of precipitation simulated by IsoGSM in the ISM and post-monsoon seasons over Bangladesh.

Summary and conclusions

We observed the isotopic composition of precipitation at three sites (Sylhet, Dhaka, and Chittagong) over Bangladesh in 2010 and estimated the origin of precipitation using the Eulerian approach combined with IsoGSM.

The temporal characteristics of the observed precipitation amount differed among sites, while the observed δ^{18}O values of precipitation displayed clear and similar seasonal variation. Across the region, the intraseasonal variation in the δ^{18}O values of precipitation was found, which was linked to the migration of organized convective activity. The model could capture seasonal and intraseasonal variations in the observed δ^{18}O values of precipitation reasonably well; however, the overestimation of the simulated δ^{18}O values was found in the ISM and post-monsoon seasons, especially in the inland region (i.e., Sylhet).

The main sources of precipitation were the Bay of Bengal and the Arabian Sea in the pre-monsoon season. In the ISM season, these sources gradually decreased, while the Indian Ocean contributed more to precipitation over Bangladesh. These oceanic moisture sources contributed less to precipitation in the post-monsoon season, as the Pacific Ocean, the Bay of Bengal, and land surface were the main sources of precipitation at that time.

Our results indicated that the main sources of precipitation and the migration of organized convective activity were the dominant factors controlling the isotopic composition of precipitation over Bangladesh. The origins of precipitation, particularly the Indian Ocean and land surface, controlled seasonal variation in the isotopic composition of precipitation. The migration of organized convective activity controlled intraseasonal variation in the isotopic composition.

Our results indicated that the isotopic composition and origins of precipitation could be used to identify monsoon onset and withdrawal. These variations drastically changed in the timing after pre-monsoon, ISM, and post-monsoon seasons over Bangladesh. These drastic changes were found not only in Bangladesh but also in the Asian monsoon region (e.g., Araguás-Araguás et al. 1998; Ichiyanagi et al. 2005); we would investigate the relation between these variations and the monsoon onset and withdrawal for future study.

Abbreviations
AGCM: Atmospheric General Circulation Model; ISM: Indian summer monsoon; IsoGSM: Isotope-enabled Global Spectral Model; NCEP/DOE R2: National Centers for Environmental Prediction/Department of Energy Reanalysis 2; NOAA: The National Oceanic and Atmospheric Administration; OLR: Outgoing Longwave Radiation; TPW: Total precipitable water; USGS: The United States Geological Survey

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Availability of data and materials
All of the data used in this study are available from the first author upon request.

Authors' contributions
MT carried out the analysis and wrote the manuscript. KI planned the observations. MK, TT, and TH helped conduct the observations. KY supported the model experiment. All authors read and approved the final manuscript.

Competing interests
The authors declare that they have no competing interests.

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