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Precipitation Isotopes' Response to the Convective Activities over the Bay of Bengal

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ABSTRACT

Isotopic analysis of precipitation over an island located in the Bay of Bengal was carried out from 2012 to 2018 to understand the atmospheric controls on rainwater isotopic variabilities. It was observed that the precipitation isotopes undergo systematic depletions in response to the organized convection occurring over a large area and are driven by the integrated effect of convective activities. Precipitation isotopes appear to be modulated by the monsoon intraseasonal oscillation as well as by the Madden Julian Oscillation. Amount effect is typically low and shows considerable inter-annual variability

Keywords: *Precipitation isotopes, Indian monsoon, MJO, Andaman Islands and Bay of Bengal.*

1. Introduction

The Andaman and Nicobar Islands are a group of islands belonging to the northern Indian Ocean, located in the southeast portion of the Bay of Bengal (10–14 °N, 92.5–93.5 °E) (Figure 1). The island is characterized by several ridges and mountains with moderate elevation and slopes. Saddle peak situated in the northern portion of the island is the highest point (ca. 732 m). The total geographical area of the island is about 8250 km^2, most of which (92.2%) is covered by forest. The maximum and minimum temperatures vary from 31 to 23°C. The monsoon rain starts around the middle of May, which continues until October. The area-averaged mean annual rainfall is ca. 3180 mm. About 90% of the yearly rainfall takes place during the boreal summer (May to September), and the remaining 10% precipitate in the post-monsoon/winter season (mid-October to December). January to April period is mainly the dry season.

2. Bay of Bengal Climate

The Bay of Bengal (BOB) possesses certain unique climate characteristics; for example, (i) it experiences relatively high SST during the monsoon season compared to other Indian Ocean regions, which enhances convection (Parekh et al. 2016). During the boreal summer monsoon season (typically June to September or JJAS), the basin receives intense precipitation (see Figure 1), exceeding local evaporation. Hence, most of the moisture in this region is believed to originate from the Indian Ocean and the Arabian Sea. Nevertheless, a significant amount of local moisture also causes rainfall in the north and the central Indian region, driven by low-pressure systems. (ii) The area is strongly influenced by the Monsoon Intra Seasonal Oscillation (MISO), which manifests in the form of monsoon active and break phases. (iii) This region typically experiences high cyclonic activities during the pre- and post-monsoon seasons. (iv) The Madden Julian Oscillation (MJO), strongly influences convective activity and rainfall totals in the Bay of Bengal (Murty, 2021) and the Maritime Continent.

Therefore, the isotopic composition of rainwater in this region is expected to be strongly modulated by the above-mentioned ocean-atmospheric processes. With this perspective, a systematic study of the isotopic composition of precipitation was initiated at the Andaman Islands in the Bay of Bengal, where no significant rainfall isotopic record existed before. The objective was to determine whether the rainfall isotopic records carried the signature of the above-mentioned atmospheric processes and, if so, how these records could be used to study the monsoon system.

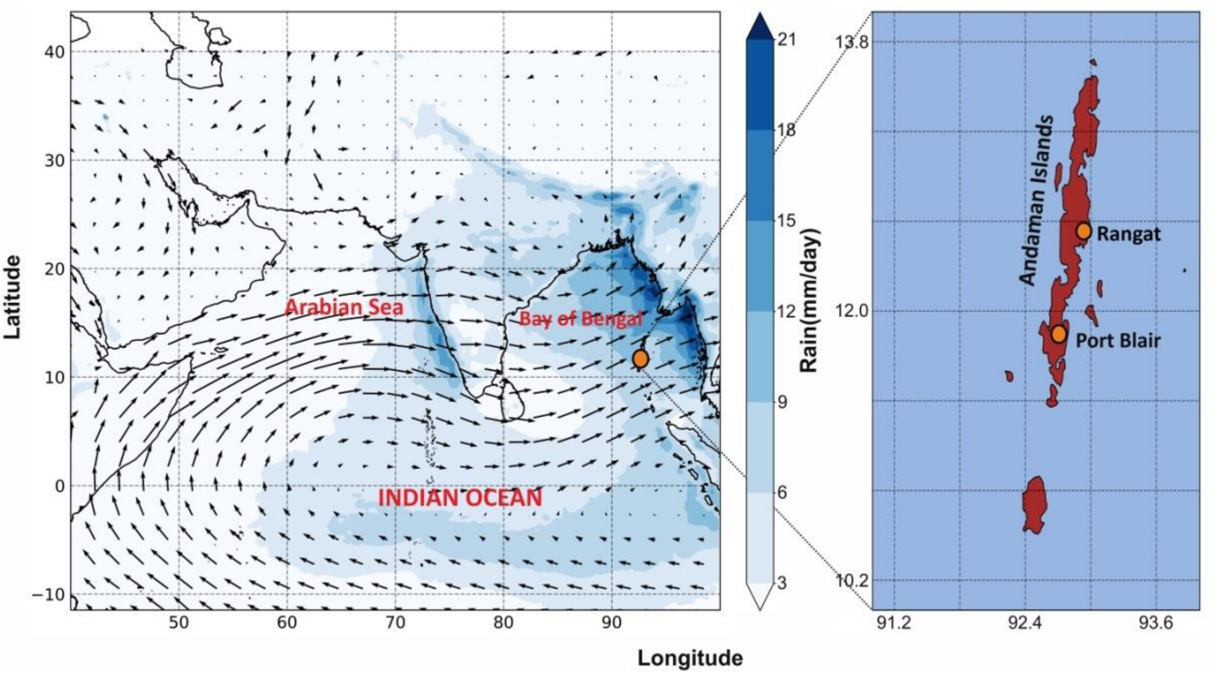

Figure 1: Figure shows the rainwater collection site, Port Blair (orange dot) at Andaman and Nicobar Islands. The arrows depict the climatological variation of southwest monsoon circulation (during the JJAS period; averaged from 2012 to 2018) at 850 hPa. The shading represents rainfall climatology. The right panel shows a zoom-in version of the Andaman Islands. The second site, Rangat, is also shown.

3. Data and Methods

3.1 Rainfall sampling and isotopic analysis

Rain samples were collected at the Pondicherry University campus (11.66°N, 92.73°E), Port Blair, Andaman Islands (Figure 1) on a daily basis (at 8:30 am local time) from 2012 to 2018. An ordinary rain gauge was used for sample collection, which also provided the rainfall data. We also collected rainwater samples from a site, Rangat, approximately 100km north of Port Blair. Precipitation isotope data at this site is available from 2015 to 2017, but rain gauge precipitation data were not available for this site. Samples were analyzed for their isotopic composition (oxygen and hydrogen) using an LGR Water and Water Vapour Isotope Analyzer (model: TWIA 45 EP). The isotopic ratios are reported in standard delta notation on the VSMOW scale. Measurement precision was typically ± 0.1‰ and ±0.5‰ for δ^{18}O and δ^{2}H, respectively.

3.2 Rainfall data

Apart from the rain-gauge data, we have also used the satellite-derived precipitation data; the Tropical Rainfall Measuring Mission (TRMM; Huffman et al. 2007) data to study the amount effect. This data is available daily with a spatial resolution of 0.25° × 0.25°.

We have also used the regional reanalysis data; the Indian Monsoon Data Assimilation and Analysis reanalysis (IMDAA), a high resolution (12 km) regional reanalysis of the atmospheric variables for the Indian region, available from 1979 to 2020 (Rani et al. 2021).

We have used the following grid boxes; the Port Blair site (11.625-12.125°N, 92.625-93.125°E); the Rangat site (12.125-12.625°N, 92.625-93.125°E). The precipitation data derived from these datasets were used to examine the amount effect.

4. Results

Table 1 shows the rainfall statistics and their isotopic values for all the sites. The annual average rainfall for Port Blair (ca. 2387 mm) during the observational period was much less than the climatological (30 year) value of 3180mm (WMO). Figure 2 shows Port Blair's rainfall δ^{18}O values (blackline) and the d-excess (magenta bar) variability from 2012 to 2018.Oneof the attributes of the δ^{18}O time series is the presence of systematic lows, which is believed to be associated

Table 1. Summary of rainfall amounts and their isotopic values at the two observational sites Port Blair and Rangat. The average values of the corresponding parameters are shown in the last three rows.

	Port Blair (island)	**Rangat (island)**
	Daily	Daily
Sampling Period	2012–2018	2015–2017
N	791	214
slope	7.11	7.22
intercept	5.65	2.80
Av. Annual rainfall; raingauge (mm)	2387.0	Not available
Av. Annual rainfall; TRMM (mm)	1680.0	1405.41
Av. Annual rainfall; IMDAA (mm)	2577.0	2601.0
Mean $\delta^{18}O$ (‰)	-3.14±2.65	-2.38±2.15
Mean $\delta^{2}H$ (‰)	-16.64±19.33	-17.65±16.01
Mean d-excess (‰)	8.45±5.01	5.00±4.11

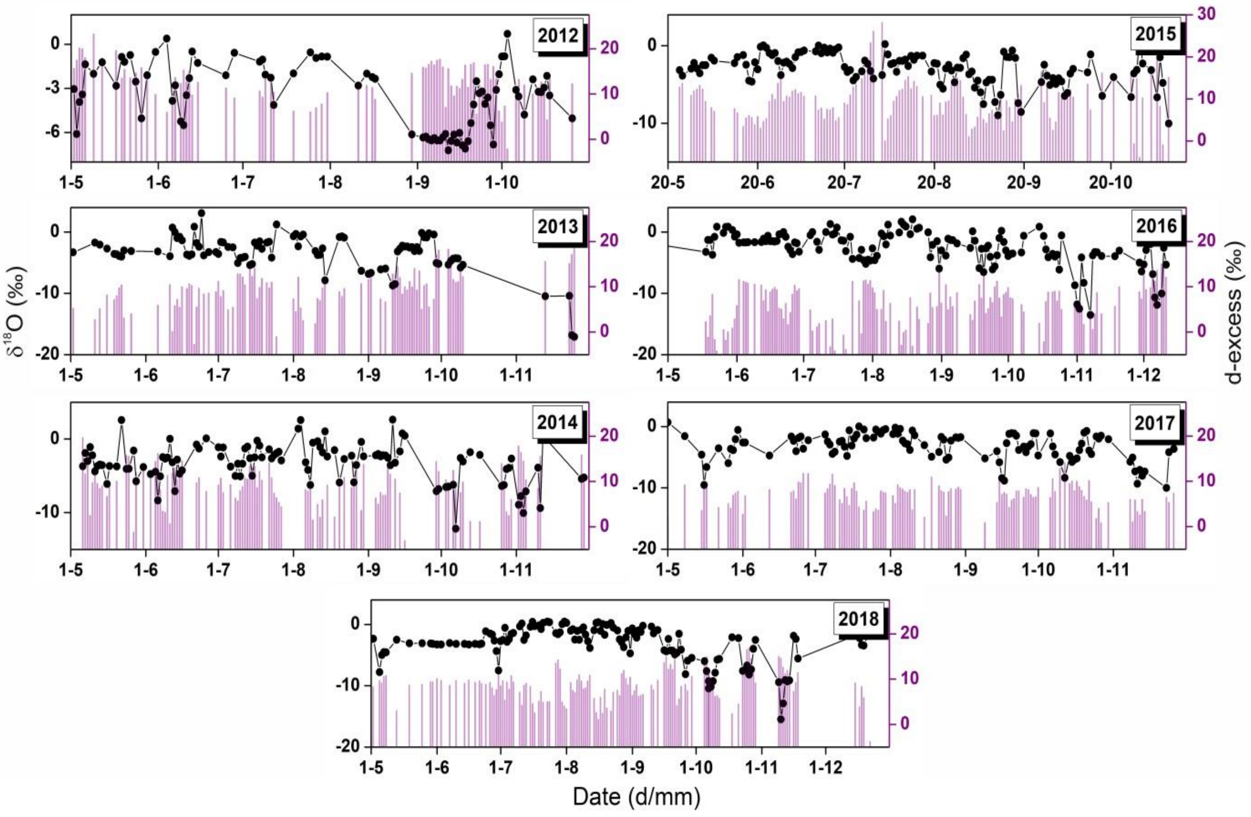

Figure 2: Time series of precipitation $\delta^{18}O$ (black line) and d-excess (bars) from 2012 to 2018 at Port Blair, Andaman Islands.

with the 10 – 20-day periodicity characterizing the monsoon intra-seasonal oscillation (Chakraborty et al. 2016, Sinha et al. 2019). Starting from the early to middle phase of the monsoon (May to early August) the $\delta^{18}O$ values typically vary from +2 to -4‰. From late August, the values usually decrease, sometimes to values as low as -17‰ during the post-monsoon or winter season. The low $\delta^{18}O$ values during the post-monsoon/winter time are usually associated with low-pressure systems and tropical cyclones in the Bay of Bengal (Chakraborty et al. 2016).

Deuterium excess showed an inverse correlation with $\delta^{18}O$ (Figure 2). The correlation is reasonably strong, with a typical r-value of -0.55, indicating a sizeable number of raindrops evaporated, resulting in an amount effect. But the evaporation process was very much subdued in the year 2013 when the r value was reduced to -0.22. The amount effect was also found to be negligible in this year (discussed later). d-excess was relatively high during the winter and spring but remained low during the monsoon season. Infrequent large-scale convective systems during the summer monsoon season could have been the reason for positive d-excess anomalies (Chakraborty et al. 2016)

Rainfall isotopic compositions in this region also seemed to be affected by the MJO. The MJO is known to affect the tropical Indian Ocean climate (on an intra-seasonal timescale) and, in particular, the Bay of Bengal and Maritime Continents during its phase-2 and phase-3 transitions (Wheeler and Hendon, 2004). Realtime, Multivariate MJO index 1 or the RMM1 component of the MJO index (Wheeler and Hendon, 2004) has been plotted in Figure 3 in association with the rainfall time series (bar) and its isotopic ratios (standardized form). It is obvious from this plot that precipitation $\delta^{18}O$ in this region is in general inversely correlated with the RMM1 component of the MJO index. This is expected since RMM1 describes the situation when the MJO produces enhanced convection at the longitudes of the Maritime Continents (Wheeler and Hendon, 2004), and enhanced convective activity (i.e. negative OLR) has depleted isotopic values (Rahul et al. 2016).

4.1 Seasonality in rainfall isotopic composition

Another characteristic of the rainfall isotopic record in this region is the presence of strong seasonality, higher isotopic values in the summer, and relatively lower values during the post-monsoon and early winter. This results in a few per mil differences between the mean summer and the winter values.

The $\delta^{18}O$ values of rainwater at Port Blair are shown in the form of a box diagram (Figure 4). As shown in this figure, the mean isotopic values in the summer are usually higher than the mean values in the winter. Except for 2012, all the years (2013 to 2018) show similar behavior. The discrepancy (opposite behavior) observed in 2012 is possibly due to the sampling artifact, as the number of samples collected in the winter months of 2012 was less than in other years. Other investigators also observed a similar pattern of seasonal variability. For example, Lekshmy et al. (2021) reported a summer to winter isotopic gradient of surface-level vapor collected onboard during oceanic cruises over the Bay of Bengal. These observations indicate that the isotopic compositions of rainwater in this latitude range (ca. 11-13°N) show an opposite behavior to that observed in the neighboring regions. For example, precipitation $\delta^{18}O$ in Bangladesh (Ahmed et al., 2020) shows lower values during the summer and higher in winter. One of the reasons for the low isotopic values in the post-monsoon/winter period is the occurrence of tropical cyclones, which are known to produce anomalously low isotopic ratios in rainwater in this region (Chakraborty et al. 2016). Transport of moistures depleted in heavy isotopes from the maritime continent is also believed to contribute to yielding the seasonal contrast (Lekshmy et al. 2021; Fousiya et al. 2022).

4.2 Local meteoric water line

The local meteoric water lines were calculated and are shown in Figure 5. The data sets consist of precipitation isotopic values of summer (June to September) and winter (October to December). The slope and intercepts for each line are given in Table 1.

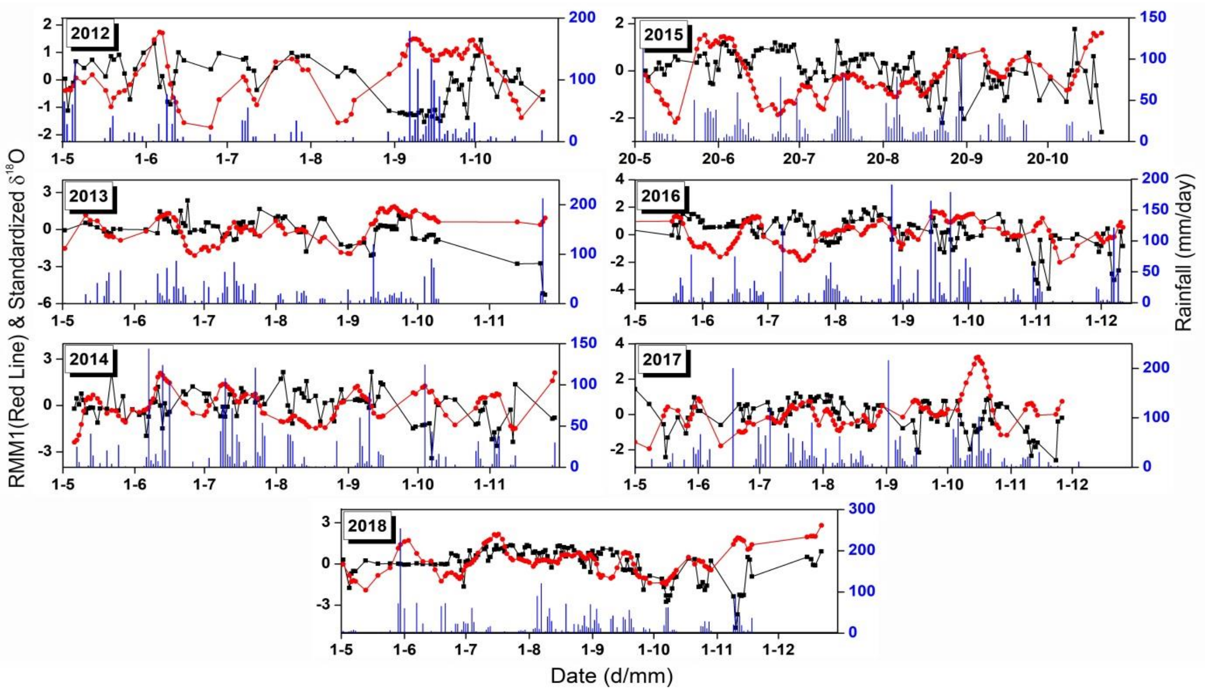

Figure 3: Time series of rainwater δ^{18}O (black line; standardized values) and the MJO index (red line: are shown for the observational years. The rainfall data are shown as bar diagrams (blue). The precipitation isotopic record typically shows an inverse correlation with the MJO variability.

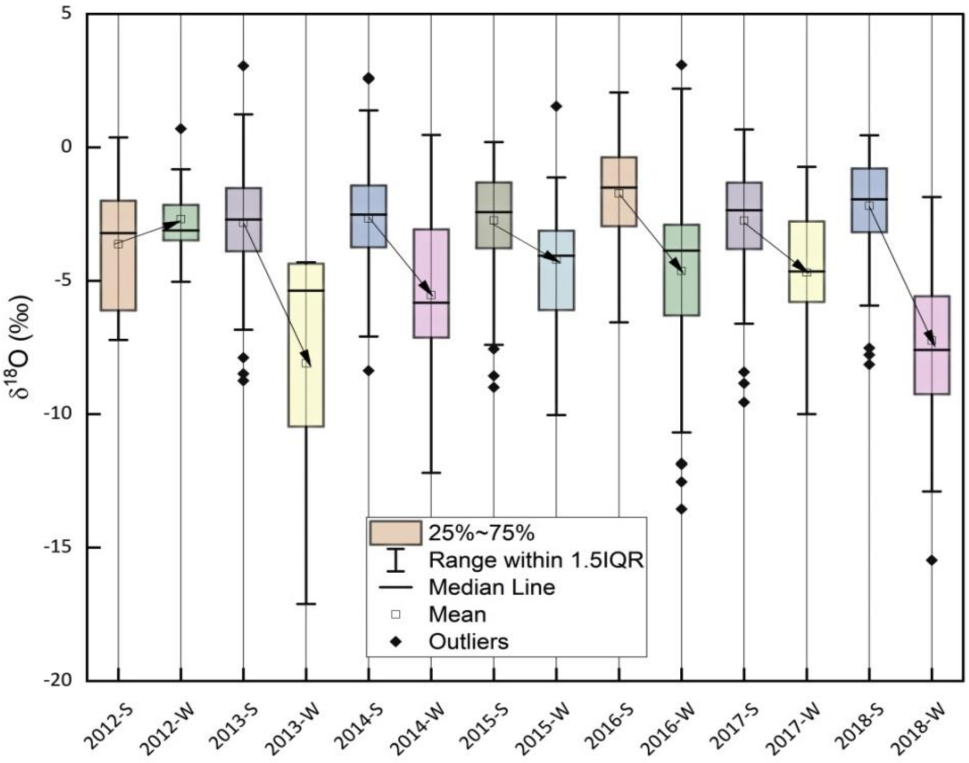

Figure 4: Box and Whisker diagram showing δ^{18}O of precipitation at Port Blair from 2012 to 2018. S and W in x axis stand for summer (June to September) and winter (October to December) respectively. The inset box explains the statistical parameters. IQR stands for inter-quartile range. Typically, the summer values are high, and the winter values are low. Arrows show the mean difference of the isotopic values in the two seasons.

4.3 Amount effect

The Andaman Island region shows a weak amount effect on a daily time scale. A negative correlation (r= -0.24) between rainfall amount and δ^{18}O was observed in 2012, correlations were also negative in other years; 2014 (r = -0.23), 2015 (-0.20), 2016 (-0.22), 2017 (r = -0.26) and 2018 (r = -0.22). Year 2013 shows the highest correlation (-0.39) of all years. The r-value for the entire observational years (2012 to 2018) was -0.25 (n=791, $p<0.0001$).

The northern Indian Ocean experiences heavy convective activity throughout the monsoon season, Chakraborty et al. (2016) used OLR and rainfall data to show that this strongly modulates rainfall δ^{18}O. In this context, we note that the precipitation δ^{18}O of the southwestern parts of India (the Kerala state) also showed a strong dependency on convective activity; however, unlike the Andaman region, the Kerala site did not show any significant amount effect (Lekshmy et al. 2014). The amount effect for the Rangat site was r= -0.27, n=214, encompassing three years of data (2015 to 2017).

5. Discussion and Conclusions

The rainwater isotopic compositions over the Andaman Island region showed systematic low isotopic values, which seem to be associated with the seasonal monsoon cycle and seasonality of the intra- seasonal oscillation. Relatively low humidity during the early phase of the monsoon most likely resulted in a moderate level of raindrop evaporation, contributing to the amount effect. However, as the monsoon progressed to its mature stage and relative humidity increased, the extent of sub-cloud evaporation diminished. Moisture flux convergence increased (bringing in moisture from outside the Bay of Bengal domain; see Chakraborty et al. 2021) and the importance of local moisture became less at this stage (Sinha and Chakraborty 2020). Deuterium excess shows a variation on a seasonal scale, i.e. relatively lower values during the monsoon and higher values during the non-monsoon season. This is likely the result of a shift in moisture source from the equatorial Indian Ocean during the monsoon to the continental and non-Indian Ocean region during the non-monsoon seasons. However, higher values of d-excess may also result from the recycling of water vapor associated with large-scale convective systems. The time scale of the positive d-excess anomalies during the monsoon appears to be modulated by the monsoon intra-seasonal oscillation (Sinha et al. 2019).

We have estimated the amount effect with the raingauge, satellite, and reanalysis data. The correlation coefficients (Table 2) computed using the rain gauge, and TRMM data are similar (~ -0.24), but the same with the IMDAA derived reanalysis data is reasonably higher (-0.36). The possible reason for getting higher values in the case of the reanalysis data is as follows. The reanalyses provide comprehensive snapshots of atmospheric conditions at regular intervals over long periods. At the same time, the observed data provide only a limited understanding of the meteorological conditions. In other words, the reanalysis data integrate the large-scale processes. When the precipitation isotopes respond better to the reanalysis data than the raingauge data, they represent the large scale better than the local scale processes.

The precipitation isotope data from the Andaman region revealed that the isotopic composition of rainfall was mainly controlled by regional atmospheric dynamical processes rather than rainfall amount alone (Chakraborty et al. 2021). This maritime site sampling program has provided a better means to study the moisture transport processes over the Bay of Bengal (Sinha et al., 2019). Very low δ^{18}O and δ^{2}H values of Andaman rainwater were found to be associated with intense cyclonic activities (Chakraborty et al. 2016). We expect that this anomaly may have its imprint in the oxygen isotopic composition of speleothems that are found in the Andaman Islands group (Laskar et al., 2013) and Peninsular India (Sinha et al. 2018).

One of the key issues is the origin of seasonality in isotopic time series, which cannot be explained by the traditional amount effect alone. The cyclonic events, especially during the post-monsoon season, are known to produce isotopically light anomalies. Still, the effect of MJO-induced moisture supply may also augment this process, thereby producing

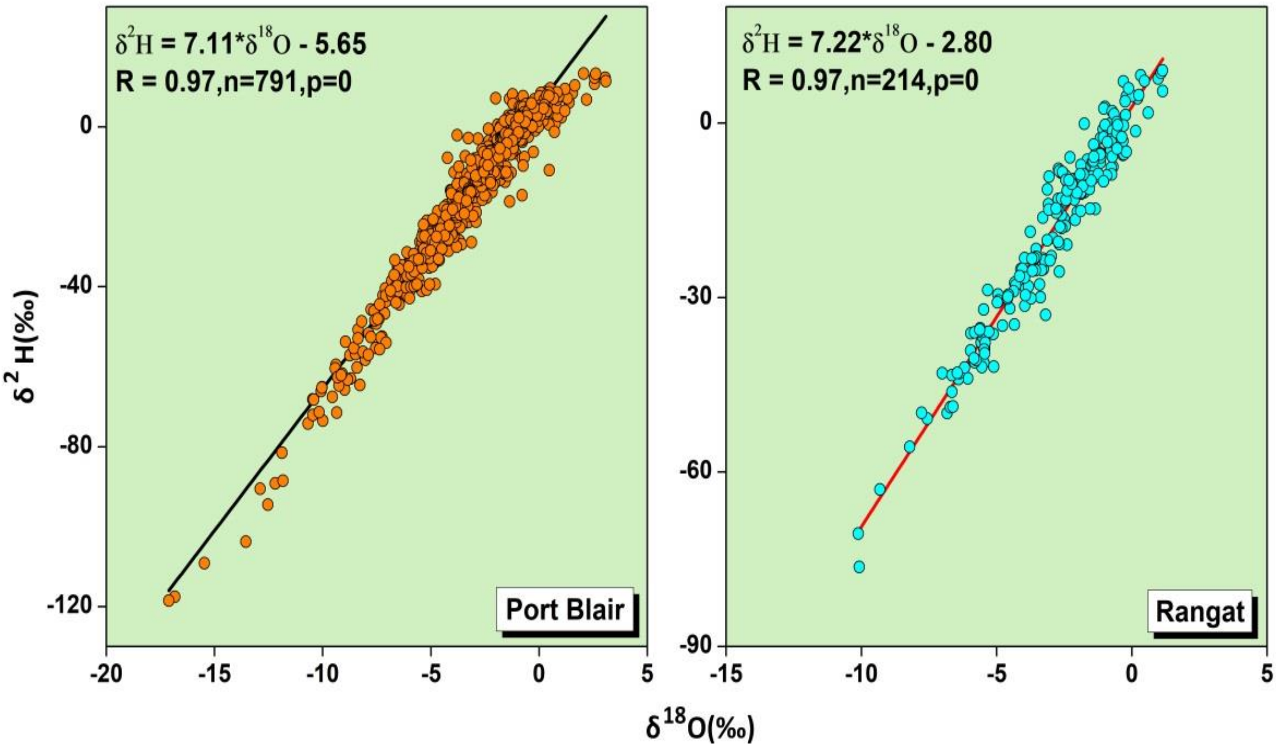

Figure 5: Local Meteoric Water lines for the observational sites.

Table 2. Summary of the amount effect. The statistical parameters are shown for the regression lines drawn between the precipitation amount and the precipitation isotopes on a daily scale.

Sampling Site	Data type	Slope	Intercept	r	p	n
Port Blair	Rain-gauge data	-0.021	-2.65	-0.25	0.0	791
	TRMM Data	-0.037	-2.78	-0.23	0.0	791
	IMDAA Data	-0.064	-2.22	-0.36	0.0	791
Rangat	TRMM Data	-0.00	-2.81	0	-	214
	IMDAA Data	-0.055	-2.06	-0.27	0.0	214

lower isotopic values during the boreal winter than summer. This aspect has not been studied before in this region; hence it is essential to quantify the extent of isotopic depletion due to the MJO. This may be potentially useful in paleo-monsoon studies, paving the way for a qualitative reconstruction of the past MJO activities in this region using proxy records such as speleothems.

Acknowledgments

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