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Precipitation isotopes' response to the atmospheric processes over the mainland and the island region in the northern Indian Ocean: Implications to the paleo-monsoon study

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सार – पश्चिमी भारत में एक स्थलीय वातावरण और बंगाल की खाड़ी में एक द्वीप क्षेत्र पर वर्षण की समस्थानिक संरचना का अध्ययन किया गया। हमने मॉनसून के दौरान सतह तापमान और क्षोभमंडलीय ऊष्णन के लिए जिम्मेदार वर्षण समस्थानिकों की जांच की। हमने देखा कि क्षोभमंडलीय तापमान और सतही तापमान समुद्र के ऊपर सकारात्मक रूप से जबकि भूमि पर नकारात्मक रूप से सहसंबद्ध होते हैं। परिणामस्वरूप, इन वातावरणों में वर्षण समस्थानिक सतह के तापमान परिवर्तिता के विपरीत व्यवहार करते हैं। इस अंतर के बावजूद, दोनों वातावरणों में वर्षण समस्थानिक क्षोभमंडलीय तापमान परिवर्तिता के प्रति सकारात्मक प्रतिक्रिया करते हैं, हालांकि स्थलीय वातावरण में संबंध कमजोर होता है। क्षोभमंडलीय तापमान के लिए वर्षण समस्थानिक प्रतिक्रिया पिछले मॉनसून पुनर्निर्माण में व्यापक रूप से उपयोग किए जाने वाले वर्षण और वर्षण समस्थानिक संबंध का विकल्प प्रदान कर सकती है।

ABSTRACT. The isotopic composition of precipitation was studied over a terrestrial environment in western India and an island region in the Bay of Bengal. We have examined the precipitation isotopes' response to the surface temperature and the tropospheric warming during the monsoon season. We observed that tropospheric temperature and surface temperature are positively correlated over the ocean while they are negatively correlated over the land. As a result, the precipitation isotopes in these environments show the opposite behavior to surface temperature variability. Despite this difference, precipitation isotopes in both environments respond positively to the tropospheric temperature variability, though the relationship is weaker in the terrestrial environment. The precipitation isotopic response to tropospheric temperature may provide an alternative to the precipitation and precipitation isotope relation widely used in past monsoon reconstruction.

Key words – Paleo-monsoon, Northern Indian Ocean, Terrestrial Environment.

1. Introduction

The stable isotopes of hydrogen and oxygen are widely used to study the atmospheric water cycle, including the monsoon processes (Rahul *et al*., 2016; Dong *et al*., 2016; Galewsky *et al*., 2016; Chakraborty *et al*., 2016; 2018; Chakraborty *et al*., 2022a; Sinha *et al*., 2019; Ansari *et al*., 2020; Ahmad *et al*., 2020; Saranya *et al*., 2021; He *et al*., 2021). Isotopic values of atmospheric moisture are mainly determined by the evaporation and condensation processes. In the vapor phase, the evaporation process produces relatively lighter isotopes (^{16}O and ^{1}H). In contrast, the condensation process preferentially removes the heavier isotopes (*i.e.*, ^{18}O and ^{2}H) from the moisture making the liquid phase isotopically enriched. Secondary processes, such as moisture transport and recycling and the mixing of air masses, also play varying roles. Several investigators have studied the precipitation isotopic characteristics in India. Kumar *et al*. (2010) analyzed precipitation isotopic data across India and presented an Indian Meteoric Water Line (IMWL, defined as $\delta^{2}H = 7.93\delta^{18}O + 9.94$, $n = 272$). Regional scale studies have also been carried out with specific objectives. For example, Dar *et al*. (2021) studied the precipitation isotopic composition in the western Himalayan region. They concluded that local meteorological factors play a minor role, but time-integrated large-scale convection over several days plays a more significant role. Lekshmy *et al*. (2014) made a similar observation in Kerala, a southern state of India. These authors analyzed rainwater across Kerala and observed large-scale convective activities rather than the individual rain events that played a decisive role in determining the rain isotopic composition. Midhun *et al*. (2018) studied the effect of monsoon circulation originating from the Bay of Bengal and the Arabian Sea on the precipitation isotopes in the central Indian region. Chakraborty *et al*. (2022a) investigated the effect of land-surface processes on the precipitation isotopic compositions in northeast India. Oza *et al*. (2020) collected samples from four climatic zones and redefined the IMWL. These authors presented a slightly different equation ($\delta^{2}H = 7.6\ \delta^{18}O + 8$; n = 556) than that of Kumar *et al*. (2010). Several other works in which various hydro-meteorological investigations were made involved precipitation isotopes. Despite these attempts, one fundamental issue, the role of the large-scale temperature change on precipitation isotopes, needed to be adequately investigated.

During the monsoon season, a significant amount of latent heat is released, which warms the troposphere over the Indian landmass. The monsoonal heat source represented by the upper tropospheric temperature gradient in the north-south direction shows a well-developed seasonal reversal. The evolution of this temperature gradient is an adequate representation of large-scale monsoonal moisture transport over the Indian region during monsoon time. Thus, it represents a more effective measure of local moisture source and sink. The isotopic composition of precipitation derives its signature from the moisture; hence we should better understand the moisture transport and the atmospheric thermodynamics that drives it.

Xavier *et al*. (2007) proposed that the monsoon circulation is driven by tropospheric temperature difference rather than the land-surface temperature gradient. These authors defined two boxes to quantify the tropospheric temperature gradient, denoted as ΔTT. The horizontal dimensions of these boxes are 5° N-35° N, 40° E-100° E (Northern box) and 15° S-5° N, 40° E-100° E (Southern box). To eliminate the effect of the surface temperature, the vertical dimensions of these boxes were chosen from 600 hPa to 200 hPa pressure levels.

How do the isotopic proxies respond to this tropospheric temperature difference? Some investigators opined that oxygen isotopic records of corals and foraminifera capture the ΔTT signal. Chakraborty *et al*. (2011) demonstrated that coral oxygen isotopic records of the equatorial Pacific strongly respond to the tropospheric temperature difference over the Indian region. Using this characteristic feature, these authors reconstructed the Indian summer monsoon rainfall of the seventeen century. Kumar *et al*. (2021) analyzed ocean sediment from the last deglaciation (approximately 20,000 to 14,000 yr ago). They observed that the tropospheric temperature difference of that time was strongly correlated to the monsoon intensity.

Natural proxies, such as speleothem, inherit the isotopic signal of past precipitation; hence it is essential to investigate how precipitation isotopes respond to this large-scale heating. Fousiya *et al*. (2022) investigated the effect of this heating on the precipitation isotopes over two island regions, *viz*., the Andaman Islands in the Bay of Bengal and the Minicoy Islands in the Arabian Sea. Most of the years showed a significant positive correlation. However, a weak negative correlation was found for a site in south peninsular India. These authors attribute the positive and negative correlation due to different feedback mechanisms operating between the land surface to the atmosphere and the marine environment to the atmosphere. The other result found in the case of the land region is based only on two years of precipitation isotope data collected from a coastal site (Trivandrum) in south India. A more extended dataset is required to ascertain their result. A paleo-monsoon perspective requires a better understanding of the precipitation isotopes' response to the atmosphere's thermodynamic characteristics. The conventional means of paleo-monsoon rainfall reconstruction relies on the premise that precipitation isotopic values are inversely related to the amount of rainfall, known as the 'amount effect. Modern days rainfall *vis-à-vis* precipitation isotopic analysis helps establish a linear relationship between these two parameters. Such a relation is assumed to be valid on a past time scale. The isotopic signal of past precipitation is recorded by some natural archives, such as the speleothems (Lachinet, 2009). Hence the isotopic analysis of speleothems is considered a reliable means of deciphering past monsoon variability. But the precipitation and precipitation isotope relation shows a wide variability

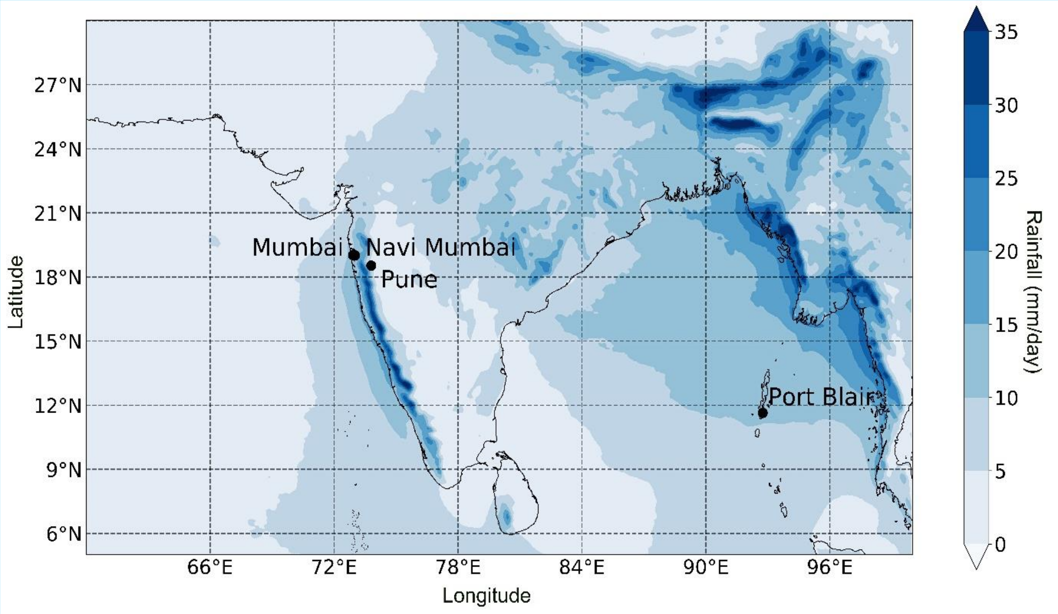


Fig. 1. The precipitation sampling station is shown as black dots. The land region consists of Pune, Mumbai and Navi Mumbai. Due to scaling issues, Mumbai and Navi Mumbai coincide. The marine environment site is Port Blair, the Andaman Islands. The shading depicts the composite rainfall variability of the summer season from 2012 to 2019, which approximately matched the sampling period

across the region. Secondly, the precipitation isotopes show a weak correlation with the precipitation amount resulting in limited success in quantitative monsoon rainfall reconstruction. Fousiya *et al*. (2022) proposed an alternative to circumvent this issue. These authors demonstrated that the precipitation isotopes in the marine environment respond to the tropospheric temperature stronger than the all-India rainfall amount. Hence it is essential to understand better the precipitation isotopic response to the atmospheric temperature variability during the monsoon season, especially for the land region. In this work, we investigate the precipitation isotope data from the Pune region and examine their characteristics in response to the surface and tropospheric temperature variability.

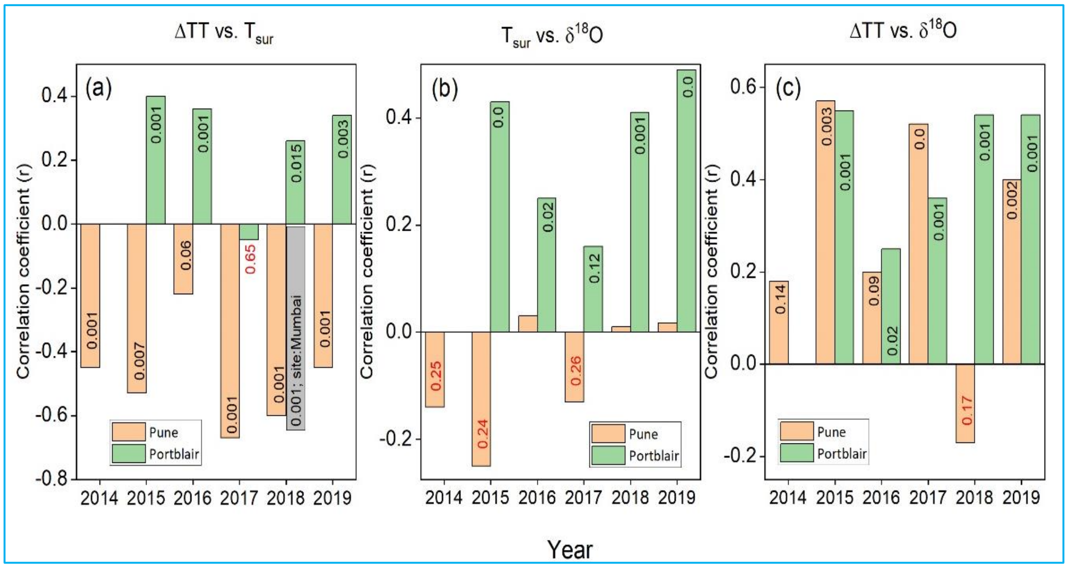
2. Methods

Pune (18°43′ N, 73°51′ E, 559 m AMSL) is an urban area situated in western peninsular India (Fig. 1). The city is approximately 200 km off the Arabian Sea coast. Since it is located on the lee side of the Western Ghats Mountain, the rainfall is significantly less than in the coastal areas, such as Mumbai. Most (>90%) of the rain is received during the summer monsoon season, from June to September. The mean annual rainfall is about 740 mm (India Meteorological Department; IMD). We have also collected rainwater samples from Mumbai/Navi Mumbai; isotopic data from this site is available only for 2018. Basic characteristics of precipitation isotopic composition of Pune and neighboring areas are reported in Chakraborty *et al*. (2018); Chakraborty *et al*. (2022a); Bajaj *et al*. (2019); Datye *et al*. (2022).

The other sampling site is Port Blair, the Andaman Islands (Fig. 1). Daily-scale rainwater was collected here from 2012 to 2019. Some investigators have already reported the isotopic values of this site (Chakraborty *et al*., 2016; Sinha *et al*., 2019; Munksgaard *et al*., 2019; Sinha and Chakraborty, 2020; Fousiya *et al*., 2022). We will be using these data to understand the moisture dynamical processes in two different environments: terrestrial and marine.

2.1. *Rainwater collection*

Rain samples were collected at the campus of the Indian Institute of Tropical Meteorology, Pune, from 2014 to 2019. We collected rainwater on a daily scale accumulated during the last 24 hour. The collection time was 8.30 am (local time). An ordinary rain gauge was used for this purpose which also provided the rainfall record. After each collection, the sample was transferred to leak proof bottles. A total of 393 samples were collected during the observation period from 2014 to 2019. Isotopic analysis of samples was carried out using a laser-



Figs. 2(a-c). Linear correlation coefficients calculated between (a) the surface temperature and the tropospheric temperature gradient (ΔTT), (b) surface temperature and precipitation δ^{18}O and (c) ΔTT versus precipitation d^{18}O during the summer monsoon season. Numbers on the bars depict the significance level. When the numbers are in red, the correlation values are not significant. Yellow and green represent Pune and PortBlair, grey stands for Mumbai

based isotope analyzer (Model-TIWA-36EP, Make: LGR,USA). Secondary laboratory standards were used for analysis purposes. These secondary standards were calibrated using primary standards supplied by the International Atomic Energy Agency (IAEA), Vienna. The isotopic values were reported against the Vienna Standard Mean Ocean Water and expressed in permille (‰) notation. The measurement precision was 0.1 and 1.0‰ for δ^{18}O and δ^{2}H, respectively.

2.2. *Moisture flux divergence*

We have computed the moisture flux divergence (unit kg. kg^{-1}. s^{-1}) at 850 hPa using the zonal (u) and meridional (v) wind components and specific humidity (q; kg.kg^{-1}) derived from the ERA5 data portal (Hersbach *et al.*, 2020). A scaling factor of 10^9 was used. To calculate the MFD,following equation was used (Wallace and Hobbs, 2006).

$$\text{Moisture flux divergence } (s^{-1}) = \frac{\partial(qu)}{\partial x} + \frac{\partial(qv)}{\partial y} \quad (1)$$

To calculate the precipitation climatology, we have used the rainfall data obtained from the Indian Monsoon Data Assimilation and Analysis (IMDAA) project (Rani *et al.*, 2021). Precipitation data was downloaded with a spatial resolution of 0.125° latitude × 0.125° longitude over the Indian subcontinent and created a contour map, as shown in Fig. 1.

2.3. *Surface and tropospheric temperature*

To calculate the tropospheric temperature gradient (ΔTT), we have used the temperature data from the mid to upper troposphere. ERA5 reanalysis data (Hersbach *et al*. 2020) from 600hPa to 200 hPa were downloaded and the ΔTT time-series were generated. We have also used the ERA5 temperature data at the 1000hPa level representing the surface temperature variability over a 1° × 1° spatial region over the respective sites.

3. Results and discussion

3.1. *Precipitation isotopes and temperature*

The relationship between surface temperature and the precipitation isotopes is usually positive, especially in the high latitude regions (Tian *et al.*, 2018). In the tropical region, the precipitation isotopes' temperature dependency is usually weak and the relationship does not show a coherent behavior. For example, Kumar *et al*. (2010) found a weak negative correlation between these parameters in most parts of India. However, the relationship was positive in the case of an eastern Indian site, Kolkata. Fousiya *et al.* (2022) analyzed the relationship with the precipitation isotopic data in a Bay of Bengal Island, the Andaman Islands. They observed positive correlations for the isotopic data collected from 2015 to 2019. Where we compare the isotope-temperature relationships between the mainland *versus* island regions. In doing so, first, we examine the relation between the surface temperature and the tropospheric temperature gradient.

We have performed a linear correlation analysis between the surface temperature (T_{sur}) and the tropospheric temperature gradient (ΔTT). Figs. 2(a-c) show the results of the linear correlation analysis among the atmospheric variables *vis-à-vis* the precipitation isotopes. Panel (a) in this figure shows the correlation values between surface temperature and the tropospheric temperature gradient for Pune (yellow bar) and Pot Blair (green bar), respectively. The correlation value for the coastal region of Mumbai is also shown (grey bar).

Interestingly, these two parameters always show a significant negative correlation for the land region (Pune, Mumbai). Still, the marine environment, *i.e.*, the Andaman Islands region, shows a positive correlation. The correlation values mostly remain significant, except for 2016 and 2017 in the case of Pune and Port Blair, respectively. This analysis shows that the land and oceanic regions respond differently to the troposphere's thermodynamical processes. Hence, the precipitation isotopes are expected to react differently in these regions.

Panel (b) shows the correlation values between surface temperature and precipitation δ^{18}O. The land region (Pune) shows a weak negative correlation, though the values are not significant, implying that surface temperature has little role in modulating the precipitation isotopic values. But Port Blair, an oceanic region, maintains a positive correlation between these parameters. Panel (c) shows the correlation values for ΔTT versus precipitation isotope relationship. In this case, these two parameters generally show a positive correlation, though it is weaker for the land region and is not significant in the case of 2014, 2017 and 2019.

The above analysis shows that precipitation isotopes are almost always positively correlated with the tropospheric temperature gradient both in land and oceanic environment. However, it responds differently to the surface temperature. Over the marine region, precipitation isotopes are usually positively correlated with the surface temperature. However, this relationship is nearly non-existent over the land region, implying that surface temperature has little control over the precipitation isotopes for the land region. This observation probably explains why the earlier investigators did not find a coherent relation between temperature and precipitation isotopes across the Indian region (Kumar *et al*., 2010). It is to be noted that surface temperature and tropospheric temperature show different behavior in these environments. As revealed in Fig. 2(a), ΔTT is positively correlated with the surface temperature over the ocean but negatively associated with the Pune region. We performed partial correlation analysis to understand better the effect of tropospheric temperature versus the surface temperature on precipitation isotopes. Table 1 presents the linear correlation analysis results, while Table 2 summarizes the result of the partial correlation analysis.

Since ΔTT and surface temperature are not entirely independent, it is necessary to examine the effect of one parameter on precipitation δ^{18}O while the other one is kept invariant. Partial correlation analysis provides a means to explore the impact of a specific variable when other parameters remain constant. The details are outlined in Kendall & Stuart (1973). Table 1 shows the linear correlation coefficients calculated between the atmospheric variables. Table 2 shows the partial correlation coefficient values. The second and third columns in Table 1 show the linear correlation coefficients; the same columns in Table 2 show the importance of the partial correlation coefficients. The parameter r (ΔTT, δ^{18}O – T_{sur}) represented the correlation values between ΔTT and δ^{18}O when the effect of surface temperature was disregarded.

For the Pune region, in the case of 2014, δ^{18}O showed a weak positive correlation with ΔTT; the correlation value remained nearly the same when the effect of T_{sur} was removed. Similar behavior was observed in all other years. This analysis suggests that T_{sur} played a minor role in controlling the precipitation δ^{18}O over the Pune region.

In the case of Port Blair (2015), the ΔTT-δ^{18}O correlation (0.56) decreased to 0.45 when the effect of $T_{sur}$was removed. Similar behavior was observed in the case 2016. For 2017, the correlation value between them (0.35) remained nearly the same (0.37) when the effect of T_{sur} was disabled. For 2018 and 2019, the correlation values decreased slightly when the effect of T_{sur} was removed. This result indicates that except for 2017, T_{sur} indeed played a role in the precipitation isotopes over the oceanic region.

On the other hand, when the effect of ΔTT was removed, the correlation values changed significantly in many cases. For example, in 2015, the correlation value (-0.25 for Pune) became insignificant (r = 0.072) and in the case of Port Blair, the correlation value (r = 0.43) reduced to 0.27, implying a strong role of ΔTT on the precipitation isotope variability over both the land and

TABLE 1

Linear correlation analysis

Year	Pune	Port Blair	Pune	Port Blair	Pune	Port Blair
	r (ΔTT vs. δ^{18}O)		r (ΔTT vs. T_{sur})		r (T_{suf} vs. δ^{18}O)	
2014	0.18 (0.14)	-	-0.45 (0.14)		-0.14 (0.26)	-
2015	**0.56** (0.003)	**0.55** (0.0)	**-0.53** (0.01)	**0.40** (0.0)	-0.25(0.23)	**0.43**(0.0)
2016	0.22 (0.06)	0.25 (0.02)	-0.22 (0.06)	**0.36** (0.0)	0.03(0.8)	0.25(0.02)
2017	**0.52** (0.00)	**0.35** (0.0)	**-0.67** (0.0)	-0.05 (0.65)	-0.13(0.25)	0.16(0.12)
2018	-0.17 (0.17)	**0.54** (0.0)	**-0.6** (0.0)	0.26 (0.02)	0.01(0.88)	**0.41**(0.0)
2019	**0.40** (0.002)	**0.54** (0.0)	0.017 (0.9)	**0.34** (0.003)	0.02(.9)	**0.49**(0.0)

Linear correlation coefficients calculated between the precipitation isotopes and the thermodynamic parameters, *viz*., surface temperature and tropospheric temperature gradient. The correlation values are shown and their significance level is provided in parentheses. The significant values at 0.01 level or better are shown in bold.

TABLE 2

Partial correlation analysis

Year	Pune	Port Blair	Pune	Port Blair
	r (ΔTT, δ^{18}O – T_{sur})		r (T_{sur}, δ^{18}O – ΔTT)	
2014	0.18 (0.14)	-		-
2015	**0.53** (0.007)	**0.45** (0.0)	0.07(0.74)	**0.27**(0.01)
2016	0.23 (0.05)	0.17 (0.11)	0.08(0.48)	0.17(0.11)
2017	**0.59** (0.0)	**0.37** (0.0)	**0.35**(0.002)	0.19(0.08)
2018	-0.21 (0.10)	**0.49** (0.0)	-0.11(0.40)	**0.33**(0.001)
2019	**0.46** (0.00)	**0.45** (0.00)	0.24(0.08)	**0.38**(0.00)

Partial correlation analysis calculated among the parameters as shown in Table 1. Columns 2 and 3 show the correlation values between ΔTT and δ^{18}O when the effect of surface temperature was removed. The last two columns show the correlation values between surface temperature and precipitation δ^{18}O while the impact of ΔTT was disabled. The significant values at 0.01 level or better are shown in bold. Partial correlation values between ΔTT and T_{sur} were not carried out since these parameters do not depend on the precipitation isotopic values

oceanic regions. Similar behavior was observed in other years.

In this context, it may be mentioned that the surface – atmosphere interactions differ significantly in the terrestrial and marine environments. For example, the turbulent exchange of heat through sensible heat (temperature) and latent heat (moisture) fluxes differs in these two environments. The ratio of these two fluxes, or the Bowen ratio, is typically high in the land region and low in the oceanic environment. Secondly, the oceanic moisture flux is high and evaporative; that is, the land contribution of moisture is significantly less than marine moisture. It also consists of a significant amount of transpired vapor which is negligible in the oceanic region. Because of such behavior, the precipitation isotopes behave differently in these two environments. A quantitative analysis, however, is beyond the scope of this work.

3.2. *Precipitation isotopes and moisture flux divergence*

The precipitation isotopes respond strongly to the dynamical moisture process over the Bay of Bengal (Sinha *et al*., 2019). Chakraborty *et al*. (2016) demonstrated that when moistures converge over this region, the precipitation isotopic values deplete. Precipitation isotopic values are believed to maintain a strong correlation with moisture flux convergence, *i.e*., negative of divergence (Chakraborty *et al*., 2022b). Where we examine the precipitation isotopes' response to moisture flux divergence over

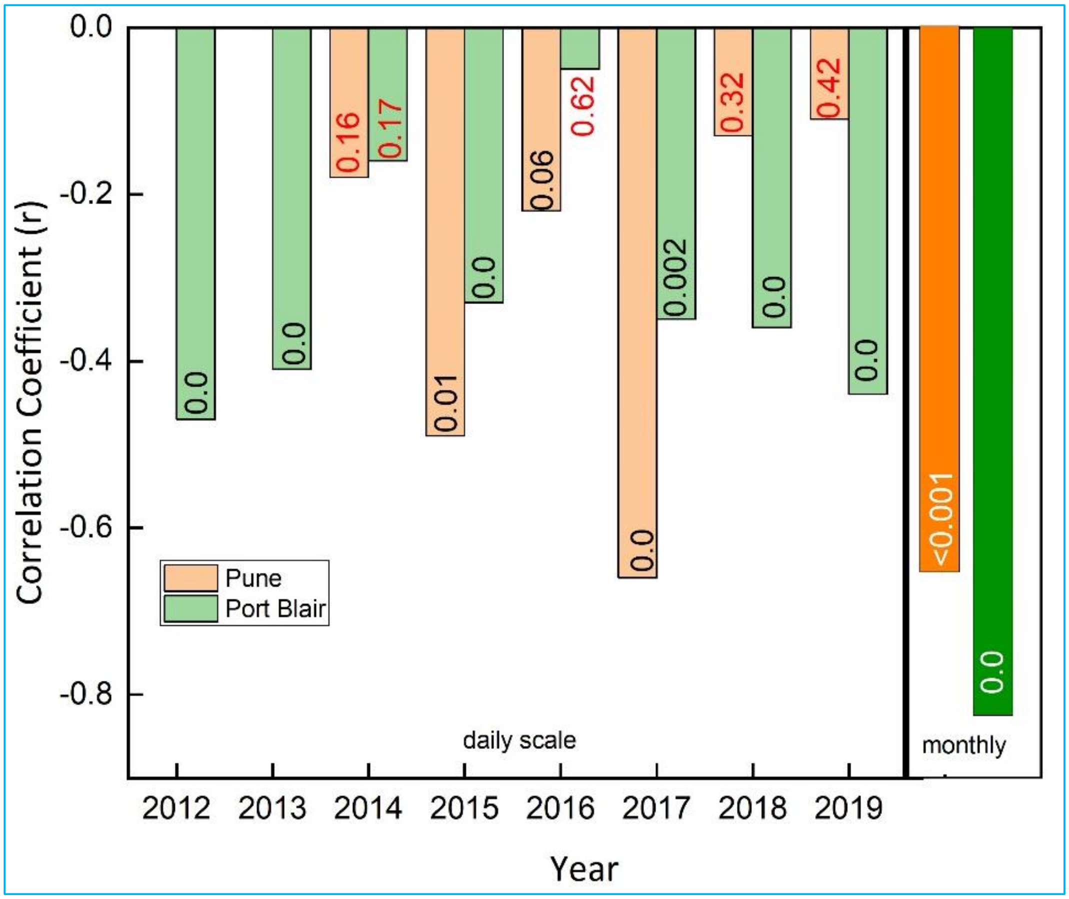


Fig. 3. Linear correlation coefficients calculated by regressing the moisture flux divergence and the precipitation isotopes, on a daily scale, at Pune and Port Blair. The light color bars (orange and green) show these values for Pune and Port Blair, respectively. The dark color bars in the right panel show the correlation values on a monthly scale. The numbers on the bars indicate the significance level. When the numbers are in red, the correlation values are not significant at at 0.1 level

the land region and compare the result with that of the oceanic region.

Precipitation isotopes over the Bay of Bengal typically correlate negatively with the moisture flux divergence. On a daily scale, the correlation value on an average was 0.4, significant at 0.01 level or better. The years, 2014 and especially 2016 showed poor correlation. Fig. 3 shows the correlation values; the green bars represent the marine site, Port Blair. We have also performed a similar analysis for the Pune region; the yellow bars depict the correlation value. In this case, correlation values were weak and insignificant, but 2015 and 2017 showed a strong negative correlation with a significance level of 0.01 or better.

The right panel of this figure shows the correlation values between precipitation δ^{18}O and the moisture flux divergence, wherein these parameters were averaged on a monthly scale. In either land or ocean, the monthly average of δ^{18}O showed a strong negative correlation with the moisture fluxes. Though the correlation value in caseof Port Blair (r=0.83, p=0.0) was significantly higher than that of the Pune region (r=0.65; p=0.001). The reason for getting a higher correlation on a monthly scale than that on a daily scale is because the moisture balance closure equation works better on a longer time scale, exceeding the moisture residence time of ~10 days (Moore *et al*., 2014); as a result, the precipitation isotopes are better coupled with the moisture fluxes on a monthly scale.

The above findings may have strong implications for paleo-monsoon studies. First, monsoon reconstruction primarily relies on the amount effect; that is, how well the precipitation isotopes correlate with the rainfall amount. On a monthly scale, the isotopic values typically decrease by 1.5‰ for every 100mm of rainfall. However, this parameter varies significantly over the Indian region, ranging from 1 to 2‰ (Chakraborty *et al*., 2022b). Hence, quantitative rainfall reconstruction is subjected to a high level of uncertainty. Secondly, precipitation shows wide variability in terms of the type of rainfall (mainly stratiform and convective) and the quantity of rain across the Indian landmass. Each of these processes may have its distinct isotopic signature. For example, a heavy downpour, such as an intense convective activity or an extreme rainfall event, would significantly reduce the isotopic values of rainfall more than a stratiform type of rainfall. All such kinds of processes typically characterize the monsoon season. Hence a well-constrained single isotopic value representing all kinds of rain across India may not be plausible. This situation necessitates searching for an alternative means by which the precipitation isotopes would respond to a coherent process and operate on a large spatial scale. Monsoon has different attributes: low-level circulation, precipitation and tropospheric warming. Precipitation isotopes show different sensitivity to these processes. As discussed above, precipitation isotopic sensitivity to rainfall varies widely and their relationship may not be generalized in a single quantitative framework.

Similarly, the precipitation isotopes' response to circulation also differs. It is known that intense vertical circulations associated with deep convective activities reduce the isotopic values of rainfall (Cai and Tian, 2016). But the low-level horizontal circulation plays a small role in determining the isotopic values of rain (Fousiya *et al*., 2022). So, a unified effect of these two kinds of circulation on the precipitation isotopes may not be effectively quantified. On the other hand, the third component, tropospheric warming and the associated moisture dynamics may provide a viable means in this regard. Fousiya *et al*. (2022) demonstrated that precipitation isotopes over the oceanic region strongly respond to tropospheric warming. This study shows that precipitation isotopes over the western Indian part similarly react to the tropospheric process, albeit with slightly different efficiency. We have also demonstrated that precipitation isotopes strongly respond to moisture fluxes in marine and terrestrial environments. Hence, we propose that a well-constrained relation between the precipitation isotopes and the tropospheric temperature and moisture flux divergence, rather than rainfall, would provide a better means of monsoon research. Long-term isotopic data is required to realize the goal.

4. Conclusions

This study analyzed the precipitation isotopic records from two different environments, a terrestrial region in western India and a marine site in the Bay of Bengal. We have examined the isotopic response to the atmospheric processes, namely with the surface temperature and the tropospheric temperature difference. Precipitation isotopes in the marine region significantly correlate with the surface temperature, but no correlation was found in the land region. However, they show a positive correlation with the tropospheric temperature difference in both environments, though the correlation is somewhat weak in the land region. The isotopic values show a strong dependency on the advected moisture fluxes, which increases from daily scale to monthly scale. These characteristics may have the potential to better reconstruct past monsoon variability than the existing technique.

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