Moisture transport associated with southwest monsoon rainfall over Sri Lanka in relatively wet and dry rainfall years

Sherly Shelton, Ross D. Dixon

Abstract
Atmospheric moisture transport is the most important part of the atmospheric branch of the water cycle, and its anomalies strongly influence rainfall variability. Atmospheric moisture transportation associated with southwest monsoon (SWM) years over Sri Lanka is still not fully understood. Using ERA5 daily data, we investigated the role of moisture transport in relatively wet (SWM\textsubscript{Wet}) and dry (SWM\textsubscript{Dry}) SWM years. Based on composite analysis, seven wet (SWM\textsubscript{Wet}) and nine dry (SWM\textsubscript{Dry}) years were selected from 1985 to 2015. We observe positive (negative) anomalous rainfall in SWM\textsubscript{Wet} (SWM\textsubscript{Dry}) years, while the strong anomalous rainfall is concentrated on the western and southwest parts of Sri Lanka. In SWM\textsubscript{Wet} years, strengthened moisture-laden low-level jets from the Arabian Sea bring excess moisture toward Sri Lanka, while a contrasting pattern is observed in SWM\textsubscript{Dry} years. As a consequence, the climatological mean of net moisture flux (9.46 × 10^5 kg s\(^{-1}\)) over the study domain is increased by 12.37 × 10^5 kg s\(^{-1}\), resulting in above-average rainfall in SWM\textsubscript{Wet} years. The results show a decrease in the net moisture flux (5.37 × 10^5 kg s\(^{-1}\)), prescribed below-average rainfall in SWM\textsubscript{Dry} years. The strong relationship (\(r = 0.63\)) between net moisture flux and SWM rainfall may explain the observed SWM rainfall variability over the country. Compared to the climatological Vertically Integrated Moisture Flux Convergence (VIMFC, 8.56 × 10^{-4} kg m\(^{-2}\) s\(^{-1}\)), positive anomalous VIMFC (2.63 × 10^{-4} kg m\(^{-2}\) s\(^{-1}\)) in SWM\textsubscript{Wet} years and negative anomalous VIMFC (−3.70 × 10^{-5} kg m\(^{-2}\) s\(^{-1}\)) in SWM\textsubscript{Dry} years are recorded. These results indicate that the free-tropospheric moisture and moisture flux convergence contributes to strong SWM rainfall by creating environments favorable for producing and maintaining moist absolutely unstable layers. This study helps us understand that the dynamic processes of the atmosphere are more important in regulating the variability of SWM rainfall over the country.

1 Introduction
According to the Clausius–Clapeyron relation, moisture-holding capacity is increased by approximately 7% with a degree temperature rise (Held and Soden 2006; Skliris et al. 2016), which implies that the ability to hold moisture in the atmosphere is increased under the warming climate. Consequently, the enhanced moisture content in the atmosphere and continuous transport of huge amounts of water vapor and its associated convergence intensify the occurrence of heavy rainfall events (Liu et al. 2020; O’Gorman 2015; Rayner and Chen 2010). For instance, Rajeevan et al. (2008) found that the increase in extreme rainfall events over central India was directly associated with an increase in the moisture content due to the rapid warming of the equatorial Indian Ocean. These prompt extreme rainfall events cause flooding landslides, soil erosion (Trenberth et al. 2003), and high streamflow (Neiman et al. 2013). On the other hand, less moisture transport for long periods and large horizontal moisture flux divergence are the main causes of drought (Held and Soden 2006).

The Southwest Monsoon (SWM) over the Indian monsoon region is generally referred as the Indian Summer Monsoon (ISM) (Dar and Ghosh 2017) and is considered one of the most active components of the climate system as part of the large-scale Asian monsoon (AM) circulation system (Kathayat et al. 2016; Rai and Raveh-Rubin 2023). The availability of moisture transported from the warm waters of the Arabian Sea and Bay of Bengal (Turner and Annamalai 2012), high moisture convergence over the monsoon trough (Pathak et al. 2017), and the effects of topography (Konwar...
et al. 2012; Turner and Annamalai 2012; Ullah and Gao 2012) play a key role in originating the SWM rainfall over the Indian subcontinent including Sri Lanka. For instance, Roxy et al. (2017) quantify the total moisture contribution for extreme rainfall events in India and found that moisture comes from the Arabian Sea, the Bay of Bengal, and the central Indian Ocean contributing to 36%, 26%, and 9% of the, respectively. Both the moisture already in the atmosphere, and local surface evaporation, contribute to SWM rainfall variability (Pathak et al. 2017; Wang et al. 2017). However, Rayner and Chen (2010) and Trenberth (1999) revealed that moisture contribution to heavy and moderated rainfall events is associated with large-distance transport, not local evaporation.

In tropical and subtropical regions, low-level jets (LLJs) and atmospheric rivers (ARs) are two major mechanisms of atmospheric moisture transport. LLJs can be defined as the wind corridors of the lower atmosphere, which carry moisture transport from warm oceans toward continental areas or low to high latitudes (Gimeno et al. 2016). In the Indian subcontinent, the strengthening of monsoon LLJ results in large-scale moisture advection, a prerequisite for heavy rainfall (Rai and Raveh-Rubin 2023; Xavier et al. 2018). On the other hand, a decrease in the strength of cross-equatorial LLJ that exists over the Indian Ocean is favourable for drought development (Joseph and Simon 2005). Typically, active phases are associated with strong low-level cyclonic circulation over India and the Bay of Bengal and moisture convergence over the monsoon core region, whereas break phases are marked by anticyclonic circulation and moisture divergence (Singh et al. 2014). Joseph and Sijikumar (2004) also observed the movement of the core of LLJ from the Arabian Sea through 15° N during the active monsoon season. Based on these facts, wind convergence and water vapor advection by the movement of the LLJs from the Arabian Sea play a significant role in moisture convergence or divergence over the Indian monsoon region.

The SWM is one of the major monsoon systems that bring significant rainfall over the western and southwestern parts of Sri Lanka (Shelton and Pushpawela 2022). Therefore, understanding the variability of SWM rainfall and key drivers plays a vital role in daily life, especially for hydropower generation and agricultural production in Sri Lanka (Shelton et al. 2021), because the SWM rainfall feeds major rivers and most of the reservoirs in the wet zone. For instance, more than 29% of the total rainfall is received during the SWM season over the upper Mahaweli River basin, where the seven major hydropower plants are located (Shelton 2021). The reduced SWM rainfall and the number of wet days during the SWM season will influence agriculture in Sri Lanka, especially in the Yala season (Shelton et al. 2021), where the frequencies of hydrometeorological extremes during the monsoon seasons are increasing.

Though SWM rainfall is important, the role of moisture transport and moisture convergence/divergence during the contrast SWM years over Sri Lanka is not well-understood. A recent study investigated rainfall extremes in the Mahaweli River Basin (MRB) of Sri Lanka and found that above-average rainfall was characterized by stronger southwestern LLJ, such as the Somali jet from the Arabian Sea directing more moisture into the Indian subcontinent between latitudes 5° N and 15° N (Shelton and Pushpawela 2023). It also connects variability in extreme precipitation across the MRB with large-scale atmospheric variability (ENSO, IOD). In this paper, we build upon the findings of Shelton and Pushpawela (2023) by considering the whole domain of Sri Lanka and focus on identifying the pathways of abnormal water vapor transport associated with the relatively wet and dry SWM years.

The rest of the paper is organized as follows: Section 2 describes the general characteristics of the study area, data, and methodology. Section 3 is allocated for the result. Section 4 presents the discussion, and the conclusion of the study is presented in Sect. 5.

2 Study site, data, and methodology

2.1 Study site

Sri Lanka is a tropical island country lying (5° 55′–9° 51′ N and 79° 41′–81° 53′ E) in the Indian Ocean and located in the circulation of the Indian monsoons. The rainfall pattern in Sri Lanka is seasonally well-distributed due to the intertropical convergence zone (ITCZ) movement over the equatorial region. As a result, seasonal variation in rainfall is strongly impacted by the southwest monsoon (SWM: June to September) and the northeast monsoon (NEM: December to February). In between two monsoon periods, the first inter-monsoon (FIM: March to May) and second inter-monsoon (SIM: October to November) seasons are identified (Malmgren et al. 2003). Three climatic zones, known as the wet zone, intermediate zone, and semi-arid dry zone, have been well-demarcated (Fig. 1a) based on the regional differences in the amount of rain and rainfall variability in different seasons (Rubasinghe et al. 2015). In addition, winds, temperature, relative humidity, and other climatic elements show significant differences between the three climate zones. The mean annual temperature in Sri Lanka demonstrates largely homogeneous temperatures in the lowlands. The mean annual average temperature is 27 °C from the lowlands, up to 100–150 m altitude. The temperature is abruptly decreasing as the altitude increases in the highlands (Shelton et al. 2022). For instance, the mean annual temperature at an altitude of about 1800 m is 15 °C (Marambe et al. 2015).
2.2 Data

Monthly rainfall data for 20 meteorological stations ranging from 1985 to 2015 were collected from the Department of Meteorology Sri Lanka. According to geographical distribution, 7, 3, and 10 meteorological stations are located in the wet, intermediate, and dry climate zones, respectively (Fig. 1a).

In addition, GPCC V6 data set with 0.5° × 0.5° grid resolution were obtained from the Global Rainfall Climatology Centre (Schneider et al. 2011), covering the study period for investigating the spatial distribution of rainfall anomaly in contrasting SWM years. For reproducing and interpreting the atmospheric branch of the hydrological cycle, ERA5-reanalysis data (Hersbach et al. 2020), more specifically, four times daily zonal and meridional wind, specific humidity, and surface pressure with 0.3° × 0.3° grid resolution data set have been used.

2.3 Methodology

In this study, we used composite sampling techniques for identifying the relatively wet and dry rainfall years. We first calculated the area average SWM rainfall using station-based observation using the Thiessen polygon (TP) method with the elevation regression method (Limin et al. 2015). We also calculated the area average SWM rainfall using the GPCC data. We then derived normalized anomalous SWM rainfall time series and used it to identify relatively wet and dry rainfall years. If the normalized SWM rainfall anomaly is above +0.8, it was identified as a relatively wet SWM year (hereinafter SWMWet). In contrast, a relatively dry SWM year (hereinafter SWMDry) is defined if the normalized anomaly is below −0.8 threshold levels in a particular year (Fig. 2). Finally, seven wet and nine dry SWM years were selected for further analysis (Table 1). Notably, we found that the SWM rainfall anomaly from GPCC well produces the interannual variation of SWM rainfall in Sri Lanka (Fig. 2) with a high correlation coefficient ($r_{\text{GPCC-Observed}} = 0.85$). Therefore, we used GPCC data to display the spatial rainfall climatology and anomalous rainfall distribution in the SWMWet and SWMDry years.

This study considers the top layer of vertical integration at 300 hPa, because the specific humidity above the 300 hPa level is very low. According to (Ratna et al. 2016), moisture transport above 300 hPa levels does not influence calculating Vertically Integrated Moisture Flux (VIMF).

$$\bar{Q} = \frac{1}{g} \int_{300}^{P_s} q \bar{V} dp$$  \hspace{1cm} (1)

The zonal ($Q_{\phi}$) and meridional ($Q_{\theta}$) components of the VIMF are calculated using Eqs. 2 and 3, respectively.
Vertically Integrated Moisture Flux Divergence \( VIMFD; \nabla \cdot \vec{Q} \) was computed using the following equation (Trenberth and Guillemot 1998):

\[
\begin{align*}
Q_v &= \frac{1}{g} \int_{300}^{P_S} q u dp \\
Q_z &= \frac{1}{g} \int_{300}^{P_S} q v dp
\end{align*}
\]

Vertically Integrated Moisture Flux Divergence \( \nabla \cdot \vec{Q} \) was computed using the following equation (Trenberth and Guillemot 1998):

\[
\nabla \cdot \vec{Q} = \nabla \cdot \left( \frac{1}{g} \int_{300}^{P_S} q \vec{V} dp \right).
\]

To understand the water vapor transports to cross the four boundaries (Fv), the Eastern boundary: 6° N–10° N (at 82° E), the western boundary: 6° N–10° N (at 79.5° E), the southern boundary: 79.5° E–82° E (at 6° N) and northern boundary: 79.5° E–82° E (at 10° N) were defined, and the following equation (Eq. 5) is used to calculate the moisture transport across a wall:

\[
F_v = \frac{1}{g} \int_{300}^{P_S} \int_0^l q \vec{V} dp dl
\]

The vertical distribution of regional moisture fluxes via each lateral boundary is calculated as follows:

\[
\vec{Q} = q \times \vec{V}
\]

where \( g, q, P_S, \vec{V}, u, v, \) and \( l \) are the acceleration of gravity, specific humidity, surface pressure, horizontal wind vector, zonal wind, meridional wind, and horizontal distance of section, respectively. The regional moisture budget is calculated as the net effect of moisture flux via each boundary. A positive regional moisture budget represents a net convergence of atmospheric water vapor transport from outside the region.

3 Results

3.1 Southwest monsoon rainfall in Sri Lanka

The seasonally varying monsoon system and the associated air masses and planetary wind regimes over South Asia greatly influence the rainfall climate of Sri Lanka (Ranatunge et al. 2003). In this section, we look at the SWM rainfall contribution to annual total rainfall in different climate zones in Sri Lanka using GPCC data. As shown in Fig. 1b, SWM rainfall contributes 31.6% to the
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...annual total rainfall (2382 mm) in the wet zone. For the intermediate zone, the annual total rainfall is 1974 mm, where it gets 19.3% during the SWM season (Fig. 1d). The annual total rainfall in the dry zone is 1360 mm; 13% of rainfall is from the SWM season (Fig. 1c). Considering the country average, the SWM rainfall contributes 23.1% to annual total rainfall (1845 mm) (Fig. 1e).

Furthermore, the spatial distribution of SWM rainfall climatology for 1985–2015 is shown in Fig. 3a. As shown in Fig. 3a, southwestern and southern parts of the country (wet zone) receive more rainfall from the SWM season. The observed spatial and temporal variability of SWM rainfall is associated with regional and local topographic influences. For instance, the central highlands of the country (Fig. 1a) act as an important physiographical climatic barrier that controls the prevailing moisture-laden monsoon winds by generating ‘fohn effect weather conditions’ among regions. Similarly, the South Asian monsoon is a fully coupled ocean–land–atmosphere system, also affected by fixed orography (Turner and Annamalai 2012). As an example, the contribution from the western Indian Ocean to the ISMR is limited due to the Western Ghats (Pathak et al. 2017), even most of the rainwater discharging during the IMSR is generated over the ocean (Ordóñez et al. 2012). Shashikanth et al. (2014) also revealed that the west coast and northeast India receive more precipitation during the summer monsoon because of the orographic effects of the Western Ghats and the Himalayas.

### 3.2 Monsoon rainfall distribution in relatively wet and dry years

This section presents the spatial distribution of anomalous rainfall distribution SWM in contrasting monsoon years (Fig. 3b, c) using GPCC data. Notably, we found that the whole domain receives above-average rainfall in SWM_Wet years, while large positive anomalous rainfall is more concentrated in the western and southwestern parts of the country (Fig. 3b). According to the long-term climatological mean (1985–2015), the seasonal average SWM rainfall (mm/month) in the wet, intermediate, and dry climate zones is 188 mm, 89 mm, and 42 mm, respectively. During the SWM_Wet years, we observed that rainfall in wet, intermediate, and dry zones increased by 21.2%, 24.1%, and 22.5%, respectively (Table 2). Figure 3c shows that the country experienced below-average rainfall during the SWM_Dry years, while the western and southwestern parts experienced more dry conditions than other regions. In contrast, rainfall in wet, intermediate, and dry zones decreased by 30.3%, 27.5%, and 35.5% in SWM_Dry years, respectively (Table 2).

To identify the monthly rainfall variation in SWM_Wet and SWM_Dry years, we calculate the long-term mean (1985–2015) and mean for contrast monsoon years using...
station-based observation (Table 2). The long-term average rainfall for June, July, August, and September is 214.3, 154.5, 151.6, and 232.7 mm, respectively, which indicates that June and September are relatively wet compared to other months in the SWM season. A similar observation is found for the intermediate zone; however, the dry zone receives more rainfall during August and September than the initial 2 months of the SWM season (Table 2).

In SWMWet years, the monthly mean rainfall over the wet zone increased by 22.2%, 39.5%, and 20.6% in June, July, and September, respectively. In contrast, all months of the season showed below-average rainfall during the SWMDry years, where the most considerable rainfall reduction is observed in June (32.4%) and September (34%), concerning the long-term mean value of the monthly rainfall. Similarly, results show that both dry and intermediate zones show a percentage increase (decrease) in monthly rainfall for SWMWet (SWMDry) years. For instance, in SWMWet years, the July rainfall increased by 70.8% over the intermediate and 85.2% over dry zones, respectively. In contrast, June (45.9%) and July (42.0%) in SWMDry years depict the largest rainfall dropping over intermediate and dry zones (Table 2).

Meanwhile, we investigate spatial variation of rainfall in months of the SWM season. Figure 4a–d show the spatial distribution of rainfall climatology (1985–2015) for June, July, August, and September, while the middle (Fig. 4a1–d1) and lower (Fig. 4a2–d2) panels depict the anomalous rainfall in each month for SWMWet and SWMDry years (Table 2). Notably, we found that all the months of the SWM season bring a considerable amount of rainfall over the wet zone, where the rainfall peaks are observed in June and September. In general, the intermediate and dry zones receive less than 100 mm of rainfall in individual months of the season except for September (Fig. 4a–d).

During SWMWet years, all months of the season showed above-average rainfall, while strong positive anomalous rainfall was observed in July and September. The other remarkable feature of Fig. 4a1–d1 is that most of the positive anomalous rainfall is concentrated in the wet zone except in August in the SWM season. In SWMDry years, strong negative anomalous rainfall is observed in June and September while localized to the wet zone (Fig. 4a2–d2). To investigate the possible reason for the above-average and below-average rainfall in the SWM season, the moisture transports and associated moisture flux divergence/convergence in SWMWet and SWMDry years have been analyzed in the next section.

3.3 Vertically integrated moisture flux and its divergence

The ascending motion, the microphysics inside cloud droplets, and the moisture supply determine whether rain falls or not in a particular region (Gao and Sun 2016; Trenberth et al. 2003). It is noticed that the large-scale convergence rather than locally enhanced evaporation controls the precipitation patterns in the tropics (Allan and Soden 2007; Trenberth et al. 2003). Therefore, analysis of the moisture transport and its divergence/convergence provides insights into the major modes of rainfall variability over the country and the moisture sources themselves. Here, we investigate climatological vertical integrated moisture flux (VIMF; vector) and anomalous moisture fluxes in strong and weak SWM years (Fig. 5a–c), as well as the climatologically vertically integrated moisture flux divergence (VIMFD; shaded).

As shown in Fig. 5a, the VIMF vector from the Arabian Sea direction supplied moisture toward the convention center over Sri Lanka. Similarly, Pathak et al. (2017) found that moisture flux from the Western Indian Ocean (Arabian Sea) direction is the most important contributor to the initial phase of the Indian monsoon compared to moisture flux from the south of the equator direction. In the same study, they identified the regions with high vertically integrated moisture flux divergence as the potential sources of atmospheric moisture; meanwhile, regions with high convergence are considered potential sink regions. Figure 5a also shows climatological mean moisture flux divergence (positive value) over the Arabian Sea direction (source) as well as the Bay of Bengal, while more moisture convergence (negative
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divergence) over the western and southwestern parts (sink) of the country during the SWM season. We further note strong moisture divergence over the eastern and southeastern parts of the country.

Figure 5b shows the anomalous water vapor fluxes (vectors) and associated moisture flux divergence (shaded) for the SWM$_{\text{Wet}}$ years. Compared to the mean state, the excess moisture fluxes are observed over the study region, and vectors move towards the Arabian Sea direction. Furthermore, we detected cyclonic circulation of the VIMF over the Bay of Bengal during SWM$_{\text{Wet}}$ years, which injected moisture-laden wind toward the country. In contrast, the weakening
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of the westerly transport moisture flux can be observed over Sri Lanka and most of the eastern part of the Arabian Sea during SWM_{Dry} years (Fig. 5c), resulting in less moisture availability for cloud formation over Sri Lanka. Similar to our findings, Ratna et al. (2014) found that the weakening of westerlies reduced the moisture transport toward the southern part of the Western Ghats as well as local precipitation over India. Levine and Turner (2012) also pointed out that the strongest monsoon in the Indian subcontinent depended heavily on the moisture flux of the Arabian Sea.

Furthermore, we observed considerable spatial variations in the anomalous moisture flux divergence during the SWM_{Wet} and SWM_{Dry} years over Sri Lanka (Fig. 5b, c). For instance, an area with negative anomalous divergence has been observed over the western and southwestern parts of the country, while negative moisture flux divergence is observed over the Western Ghats and Bay of Bengal as well in SWM_{Wet} years (Fig. 5b). In SWM_{Dry} years, the study domain except for some parts of dry climate region depicts positive divergence fluxes anomaly, while strong divergence centers are located over the western and southwestern parts of the country. In addition, we observed positive anomalous moisture flux divergence over the Bay of Bengal (Fig. 5c). A closer look at the anomalous moisture divergence over Sri Lanka suggests that SWM rainfall is mostly concentrated over the western and southwestern parts of the country, which is attributed due to the orographic influence of the central mountain of Sri Lanka.

Monthly moisture flux and its convergence or divergence over the study domain were investigated for the SWM_{Wet} and SWM_{Dry} years (Fig. 6). As shown in Fig. 6a–d, the moisture flux from the Arabian Sea direction moves through Sri Lanka toward the Bay of Bengal direction in all the months of the season. In contrast, strong moisture fluxes (vectors) is observed in June. Another remarkable feature we observed is strong moisture flux convergence over the western/southwestern parts and moisture divergence in the northeast and east parts of the country (Fig. 6a–d). In SWM_{Wet} years, two cyclonic circulations over the Arabian Sea and the central Indian Ocean occurred in June, resulting in excess moisture transport toward Sri Lanka and strong moisture convergence over the country except for some isolated patches (Fig. 6a1). In July, the strongest moisture convergence centers are located in the Western Ghats and Sri Lanka (Fig. 6b1); however, moisture convergence gradually decreases in August and again increases in September (Fig. 6c1–d1), resulting in lower rainfall in August over Sri Lanka than in other months of the season. In SWM_{Dry} years, the strength of the VIMF is reduced in all the months and observed anticyclonic circulation in June, July, and September (Fig. 6c2–d2). As shown in Fig. c2, the strong moisture flux divergence anomaly is located over the country in August. Strong moisture flux divergence is concentrated in the south/southwestern parts of Sri Lanka in SWM_{Dry} years, especially in September, where divergence is stronger than the other 3 months of the season (Fig. 6d2).

### 3.4 Moisture flux through different boundaries

This section quantifies the climatological moisture transport via different boundaries and investigates the anomalous moisture flux in SWM_{Wet} and SWM_{Dry} years. In addition, the regional average net moisture flux is calculated by getting the difference between moisture influx and outflux from the different boundaries of the study domain. The long-term climatology of moisture transport from each boundary and associated anomalous moisture fluxes for SWM_{Wet} and SWM_{Dry} years are depicted in Fig. 7a–c.
Based on the long-term climatology for moisture fluxes for the SWM season, the western \((38.42 \times 10^7 \text{ kg s}^{-1})\) and southern \((27.11 \times 10^7 \text{ kg s}^{-1})\) boundaries act as moisture influx boundaries, while eastern \((36.80 \times 10^7 \text{ kg s}^{-1})\) and northern \((19.27 \times 10^7 \text{ kg s}^{-1})\) boundaries are considered as the main moisture outflux boundaries (Fig. 7a).

The anomalous moisture influx from the western and southern boundaries during the SWM\textsubscript{Wet} years is \(1.07 \times 10^7\) and \(6.91 \times 10^7 \text{ kg s}^{-1}\), respectively. However, the moisture influx from western \((- 4.66 \times 10^7 \text{ kg s}^{-1})\) and southern \((- 2.30 \times 10^7 \text{ kg s}^{-1})\) boundaries decreased in SWM\textsubscript{Dry} years. As a moisture outflux boundary, the eastern boundary showed \(- 9.19 \times 10^7 \text{ kg s}^{-1}\) and \(2.92 \times 10^7 \text{ kg s}^{-1}\) anomalous moisture flux for the SWM\textsubscript{Wet} and SWM\textsubscript{Dry} years, respectively. Moisture outflux through the northern boundary showed a negative anomalous moisture outflux in SWM\textsubscript{Wet}.

**Fig. 6** Vertically integrated moisture flux divergence (VIMFD, shaded, unit: \(10^{-6} \text{ kg m}^{-2} \text{ s}^{-1}\)) superimposed with vertically integrated moisture flux (VIMF, vector, unit: \(\text{kg m}^{-1} \text{ s}^{-1}\)) for a long-term average (1985–2015) of a June, b July, c August, and d September.

The middle (a1–d1) and right (a2–d2) columns are the same as the left column but for the anomalous VIMFD and VIMF for relatively wet (SWM\textsubscript{Wet}) and dry (SWM\textsubscript{Dry}) SWM years, respectively.
(−11.88 × 10^7 kg s^{-1}) and SWMDry (−1.09 × 10^7 kg s^{-1}) years (Fig. 7b, c). Similar to our findings, Ratna et al. (2014) found that the main moisture influx and outflux for the Indian subcontinent are the southern boundaries of the Arabian Sea and the eastern boundary, respectively. Considering the moisture influx and outflux, the area-average net moisture budget (hereinafter, NetMB) for the 1985–2015 period over the study domain is 9.46 × 10^7 kg s^{-1}. Compared to the climatological mean of the NetMB, the positive (2.91 × 10^7 kg s^{-1}) and negative (−4.09 × 10^7 kg s^{-1}) anomalous NetMB is observed in SWMWet and SWMDry years, respectively.

We further analyze the moisture influx, outflux through different boundaries, and NetMB in each month of the season (Fig. 8). Compared to the moisture influx boundaries, moisture influx from the western boundary is much higher than the southern boundary. In June, the highest moisture influx from the western (44.72 × 10^7 kg s^{-1}) and southern (30.12 × 10^7 kg s^{-1}) boundaries are observed. The moisture influx from both boundaries decreases with time, and lowers moisture influx from western (30.57 × 10^7 kg s^{-1}) and southern (23.04 × 10^7 kg s^{-1}) boundaries are recorded in September. In terms of magnitude, the eastern boundary is a major outflux boundary for each month of the SWM season. The outflux from the eastern and northern boundaries decreases with time; for instance, the outflux in June (42.04 × 10^7 kg s^{-1}) from the east boundary gradually decreased to 30.35 × 10^7 kg s^{-1} in September (Fig. 8a–d).

In SWMWet years, positive anomalous net moisture influx for the western boundary is observed in June and July, while August and September showed below-average moisture influx. However, the southern boundary showed positive anomalous net moisture flux for all the months in the SWM season. With respect to the long-term mean influx from the southern boundary, July (0.38 × 10^7 kg s^{-1}) and August (0.88 × 10^7 kg s^{-1}) show the lowest and highest influx anomaly, respectively. The moisture outflux from the eastern boundary shows a negative anomaly in all the months except for June (0.53 × 10^7 kg s^{-1}) (Fig. 9a1–d1). During the SWMWet years, the northern boundary also acts as a moisture outflux boundary, where negative outflux anomalies are recorded in all the months, and the largest negative anomaly is observed in July (−1.61 × 10^7 kg s^{-1}).

During the SWMDry years, the moisture influx and outflux in June and July depicts below-average compared to their climatological mean (Fig. 8a2–b2). However, positive anomalous moisture influx and outflux were observed in August (Fig. 8c2). For instance, moisture outflux in August recorded the most prominent positive anomaly for both eastern (1.17 × 10^7 kg s^{-1}) and northern (0.95 × 10^7 kg s^{-1}) boundaries compared to the rest of the months (Fig. 9d2). The moisture influx from the western and outflux from the northern boundary showed a below averaged moisture during dry years, but a contrast pattern is observed in the eastern and southern boundaries (Fig. 8d2). We find considerable month-to-month variations in the moisture influx and outflux transport through the boundaries, where they play a cooperative role in amplifying the moisture content available for precipitation and total precipitable water.
The long-term climatology of the NetMB in June, July, August, and September are $10.39 \times 10^7$ kg s$^{-1}$, $10.50 \times 10^7$ kg s$^{-1}$, $7.93 \times 10^7$ kg s$^{-1}$, and $9.01 \times 10^7$ kg s$^{-1}$, respectively (Fig. 9a–d). In relatively wet SWM years, all months of the season showed positive anomalous NetMB with respect to the long-term climatology, as shown in Fig. 9a1–d1, where the largest positive anomaly was observed in June ($3.46 \times 10^7$ kg s$^{-1}$) relative to the long-term mean. However, the lowest NetMB is observed in June ($1.73 \times 10^7$ kg s$^{-1}$), followed by September ($3.02 \times 10^7$ kg s$^{-1}$) and August ($3.41 \times 10^7$ kg s$^{-1}$). In SWMDry years, the long-term mean of NetMB for June, July, August, and September is $-0.19 \times 10^7$ kg s$^{-1}$, $-0.75 \times 10^7$ kg s$^{-1}$, $-1.08 \times 10^7$ kg s$^{-1}$, and $0.32 \times 10^7$ kg s$^{-1}$, respectively (Fig. 9a2–d2), which evident that all the months of the season except for September showed below-average moisture availability.

Based on the results, we can explain the observed rainfall variability in relatively wet and dry monsoon years in terms of NetMB over the study domain. For instance, positive NetMB is one of the reasons for the relatively wet monsoon rainfall events in Sri Lanka, because larger clouds occurring in a moist environment may be better able to protect their updrafts from entrainment effects, increasing their chances of rain. To further prove this, the relationship between seasonal rainfall anomalies over Sri Lanka and NetMB has been evaluated, as shown in Fig. 9. The normalized NetMB shows a statistically significant correlation with the normalized SWM rainfall anomaly calculated using station-based observations ($r = 0.62$), GPCC product ($r = 0.59$) and CRU ($r = 0.54$) dataset (Fig. 8).

### 3.5 Vertical distribution of moisture in contrast monsoon years

According to Anderson et al. (2009), the role of low-level flow is critical in the moisture flux fluctuations and precipitation, where they found positive moisture advection by the LLJ and evaporative water occurring below 950 hPa, which was then redistributed into higher levels by the LLJs-enhanced subgrid vertical turbulent transport. In this study, we also investigate the vertical distribution of regional moisture fluxes via each lateral boundary for SWM seasons. Climatological moisture fluxes (black line; shaded) and the anomalous moisture fluxes for SWMWet (blue line) and SWMDry (red line) years (bottom x-axis) for each boundary are plotted in Fig. 10.

The climatological eastward total moisture influxes through the western boundary in the lower troposphere decreases gradually with height and the largest moisture flux observed between 1000 and 900 hPa level. The southern boundary also acts as moisture input, although the moisture influx via the southern boundary is smaller in magnitude compared to the western boundary (Fig. 10c). According to the vertical structure across the southern boundary, the largest moisture transport occurs below 900 hPa and decreases with height. In the eastern and northern boundaries, the maximum moisture outflux is also observed below 900 hPa levels and gradually decreases with height (Fig. 10b–d). The most striking feature of these figures is the large moisture peak in the lower troposphere compared to the middle and higher troposphere.

In SWMWet years, we observe positive anomalous moisture fluxes via the western boundary from 1000 to 700 hPa level (Fig. 10a). Above 700 hPa, there is a negative anomalous moisture flux up to around 450 hPa level. In contrast, during the SWMDry years, the negative anomalous moisture influx through the western boundary from 900 to 300 hPa levels dominates (Fig. 10a). The negative anomalous influx from western and southern boundaries was mainly attributed due to the weakening of moisture transport from the Arabian Sea and Central Indian Ocean direction. The negative anomalous moisture outflux from the northern and eastern boundaries in SWMWet years is mainly due to strong convergence over the study domain, affecting less moisture availability for transport through outflux boundaries.

### 3.6 Moisture fluxes divergence in contrast monsoon years

Moisture flux from each of the domain edges can give us an idea of sources and sinks of moisture; however, the convergence/divergence of moisture is another useful metric which allows us to determine the available moisture in an area which can increase the probability of intensifying rainfall (Wei et al. 2015). Therefore, we calculate the long-term mean of vertically integrated Total Moisture Flux Convergence (TMFC), Zonal Moisture Flux Convergence (ZMFC), and Meridional Moisture Flux Convergence (MMFC) over the total averaged area of Sri Lanka for the SWM season, as well as the anomalous TMFC, ZMFC, and MMFC for each month and SWM season (Fig. 11a–c). In SWMWet years, the enhanced moisture transport brings more water vapor from the Arabian Sea to Sri Lanka, forming the maximum MFC core inside the country (Fig. 6a–d).

The long-term climatology of TMFC, ZMFC, and MMFC for the SWM season are $8.56 \times 10^{-4}$, $2.43 \times 10^{-4}$ kg m$^{-2}$ s$^{-1}$, and $7.10 \times 10^{-4}$ kg m$^{-2}$ s$^{-1}$, respectively suggesting that MMFC contributes largely to the total moisture convergence during the season (Fig. 11a). According to the monthly analysis, the long-term mean of TMFC in June ($9.40 \times 10^{-4}$), and July ($9.50 \times 10^{-4}$), larger than TMFC in other 2 months while lower TMFC in August resulting lowest rainfall compared to rainfall in June, July, and September. MMFC is dominant in all months, while ZMFC in August and September is much
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June

(a) VIMF_{Clim}
\[\begin{array}{c}
22.42 \\
10^\circ N \\
44.72 \\
8^\circ N \\
(10.39) \\
6^\circ N \\
30.12 \\
\end{array}\]

(a1) VIMF_{Strong} - VIMF_{Clim}
\[\begin{array}{c}
0.28 \\
1.15 \\
0.02 \\
1.34 \\
-0.71 \\
-1.34 \\
-0.34 \\
\end{array}\]

(a2) VIMF_{Weak} - VIMF_{Clim}
\[\begin{array}{c}
0.82 \\
(1.73) \\
(3.46) \\
-1.44 \\
(-0.19) \\
(-1.75) \\
-0.85 \\
\end{array}\]

(b) VIMF_{Clim}
\[\begin{array}{c}
21.32 \\
10^\circ N \\
41.77 \\
8^\circ N \\
(10.50) \\
6^\circ N \\
28.90 \\
\end{array}\]

(b1) VIMF_{Strong} - VIMF_{Clim}
\[\begin{array}{c}
-1.61 \\
0.02 \\
3.46 \\
-1.46 \\
-0.40 \\
-1.46 \\
-0.86 \\
\end{array}\]

(b2) VIMF_{Weak} - VIMF_{Clim}
\[\begin{array}{c}
0.38 \\
(3.46) \\
(-1.08) \\
-1.26 \\
-0.75 \\
-1.17 \\
-0.86 \\
\end{array}\]

(c) VIMF_{Clim}
\[\begin{array}{c}
19.11 \\
10^\circ N \\
36.61 \\
8^\circ N \\
(7.93) \\
6^\circ N \\
26.39 \\
\end{array}\]

(c1) VIMF_{Strong} - VIMF_{Clim}
\[\begin{array}{c}
-1.47 \\
-0.19 \\
-1.09 \\
-1.04 \\
0.95 \\
-1.08 \\
0.42 \\
\end{array}\]

(c2) VIMF_{Weak} - VIMF_{Clim}
\[\begin{array}{c}
0.88 \\
(3.41) \\
-1.60 \\
0.42 \\
0.88 \\
0.54 \\
0.42 \\
\end{array}\]

(d) VIMF_{Clim}
\[\begin{array}{c}
14.25 \\
10^\circ N \\
30.57 \\
8^\circ N \\
(9.01) \\
6^\circ N \\
23.04 \\
\end{array}\]

(d1) VIMF_{Strong} - VIMF_{Clim}
\[\begin{array}{c}
-1.39 \\
-0.54 \\
-0.54 \\
-1.51 \\
0.54 \\
-0.26 \\
0.69 \\
\end{array}\]

(d2) VIMF_{Weak} - VIMF_{Clim}
\[\begin{array}{c}
0.66 \\
(3.02) \\
0.66 \\
0.69 \\
0.66 \\
0.32 \\
0.69 \\
\end{array}\]
smaller than ZMFC in the other 2 months. The magnitude of MMFC in June–August does not show much variation, and it gradually increases in September (Fig. 11a).

In SWMWet years, TMFC and its two components depict positive anomalous moisture flux in each month and season, as shown in Fig. 11b. Compared to the seasonal climatology, We found a positive anomalous TMFC (2.63 × 10^{-4} kg m^{-2} s^{-1}), ZMFC (0.92 × 10^{-4} kg m^{-2} s^{-1}) and MMFC (1.70 × 10^{-4} kg m^{-2} s^{-1}). It suggests that excess MMFC is the key component contributing to positive anomalous TMFC in SWMWet years. The anomalous TMFC and its components were lowest in June, while anomalous ZMFC in June (1.30 × 10^{-4} kg m^{-2} s^{-1}) and MMFC in August (2.12 × 10^{-4} kg m^{-2} s^{-1}) exhibited the largest anomaly. Furthermore, we notice that MMFC in each month is higher than ZMFC in SWMDry Years (Fig. 11b).

Figure 11c shows seasonal and monthly anomalous TMFC, ZMFC, and MMFC in SWMDry years. As shown in Fig. 11c, seasonal average TMFC (0.370 × 10^{-4} kg m^{-2} s^{-1}) and ZMFC (− 0.45 × 10^{-4} kg m^{-2} s^{-1}) in SWMDry years are lower than long-term climatology. However, seasonal-average MMFC (0.08 × 10^{-4} kg m^{-2} s^{-1}) showed a positive anomaly during weak monsoon years. We observed negative anomalous TMFC in all the months except September, while the lowest TMFC was recorded in August (− 0.98 × 10^{-4} kg m^{-2} s^{-1}). With respect to the long-term mean of MMFC, June and September show positive anomalous MMFC, where the largest convergence is observed in September (0.87 × 10^{-4} kg m^{-2} s^{-1}). In July and August, zonal and meridional convergence got weaker than long-term climatology, ending up with a reducing TMFC compared to their monthly mean. Interestingly in SWMDry years, we found positive anomalous TMFC in September due to above-average MMFC. These findings suggest that excess TMFC may be more important for the above-average rainfall in the regions, while other factors, such as local topography conditions, may strongly impact localized rainfall during the SWM season. Rajeevan et al. (2010) found break events during August, in which the normalized anomaly of the rainfall is below the normal summer monsoon rainfall due to weak moist convective regimes. Similarly, we found less moisture convergence in August resulted in less rainfall compared to other months of the season.

4 Discussion

It is noticed that around 60% of the terrestrial precipitation directly originates as a result of moisture transported from the ocean (Gimené et al. 2012), while excessive transports are usually primary sources for extreme weather and flood events (Galarran et al. 2010), as well as interrupted transports, can lead to droughts and subsequent socioeconomic stresses. Therefore, a clear understanding of the mechanisms that force observed changes to the hydrological cycle over Sri Lanka is crucial for water management and mitigation of meteorological-induced disasters. Hence, the present study has been focused on finding out a relationship between the variability of the oceanic moisture source and monsoon rainfall (SWM) variability during relatively wet and dry monsoon years over Sri Lanka.

Based on the results, the cross-equatorial flux entering the west Indian Ocean from the southern hemisphere is one of the most important sources of moisture for Sri Lanka during the relatively wet monsoon SWM years. Furthermore, we noticed that the deficiency of westerly moisture flux from the Arabian Sea results in below-average SWM rainfall over the country. Gimené et al. (2010) and Pathak et al. (2016) found the Indian Ocean, and the Arabian Sea as the major oceanic sources for the Indian monsoon, which is consistent with this study. Konwar et al. (2012) also revealed an increasing trend of low and medium rainfall in the western parts due to increasing vertically integrated moisture transport (VIMT) over the Arabian Sea (AS).

This study revealed that the Sri Lankan summer monsoon also originated from the sea; particularly, a strong cross-equatorial low-level jet stream is close to the 850 hPa level over the Indian Ocean. Similar to our findings, Liu et al. (2023), the combination of the enhanced LLJs centered around 950 hPa and the increase of moisture below 850 hPa were the main drivers for the continuous strengthening of moisture transport in the Henan province of China. For instance, Ordoñez et al. (2012) found that the Arabian Sea and the Indian Ocean, through the action of Somali Low-Level Jets, are the most crucial source during the summer monsoon season. In particular, Malik et al. (2015) observe the most considerable moisture flux convergence at 925 hPa level in summer and at 850 hPa level in winter over central southwest Asia. This study highlights the relative contribution of zonal and meridional moisture fluxes and moisture convergence in contrasting years and found that meridional moisture transport and its convergence play a key role in observed SWM rainfall variability. Similar to our findings, Bansod et al. (2012) revealed that the low level meridional
winds at 850 hPa over Arabian Sea leads to the more supply of moisture over the Indian sub-continent resulted into good rainfall activity during the monsoon months that.

The vertically integrated moisture flux computation showed that the net positive divergence over the western Indian Ocean and moisture flux convergence over Sri Lanka, mainly convergence centers, are concentrated to the west/southwest parts of the country during the SWM$_{Wet}$ years. Because the central mountain constrains the moisture transport in the basin, favoring moisture gathering at the mountain foothills and the valleys. Moreover, the elevated terrain provides dynamic lifting to the convergent moist air masses, triggering convection. Zhao et al. (2020) also found that it strengthens the extreme precipitation over north China due to The interactions between moisture convergence and topographic settings. These positive moisture divergence developments were enhanced by the strong westerly winds over the West Indian Ocean, while abundant moisture was located over Sri Lanka, which contributes to enhancing convection as well as cloud formation, thunderstorms, and rainfall during the SWM$_{Wet}$ years. In contrast, the negative VIMFC during the relatively dry SWM years caused below-average SWM rainfall over the country.

Previous studies (Pandey et al. 2019; Varikoden and Preethi 2013) suggest that sea surface temperature also influences to enhancement and subsidence of SWM rainfall over India. For instance, above-average (below-average) SWM rainfall occurred during the La Nina (El Nina) years over India. We also believe that SST over the Indian and Pacific oceans modulates relatively wet and dry SWM years. According to the previous study, the SWM variability associated with moisture indices is unaffected by El Niño Southern Oscillation (Nair et al. 2021). Thus, it is imperative to understand what drives the large-scale circulation and moisture transport relating to the year-to-year variations of the SWM. Therefore, we will investigate how SST changes and large-scale oceanic circulation modulate moisture transport that affects the occurrence of above and below-average SWM events in Sri Lanka.

Shelton and Pushpawela (2023) observed above-average (below-average) SWM rainfall and associated rainfall extremes in the largest river basin in Sri Lanka due to strengthening (weakening) moisture flux from the Arabian Sea direction and strong (weak) convergence over the study domain. In parallel with the above study, this moisture transport analysis assists in explaining the occurrence of extreme rainfall events in the SWM season in Sri Lanka, because many extreme rainfall events originate with high moisture and an atmospheric disturbance.
moisture transport associated with southwest monsoon rainfall over Sri Lanka in relatively…

Conclusion

The present study attempts to find a relationship between moisture transport and SWM variability during strong and weak monsoon years. We find that the strong monsoon years are associated with a predominant moisture transport from the Arabian Sea. The weak monsoon years have less contributions from oceanic sources and might be sustained by the evapotranspiration from land surface processes. Therefore, future studies must quantify the importance of terrestrial moisture on monsoonal precipitation. The net moisture convergence over Sri Lanka is primarily driven by the balance between the incoming and outgoing fluxes of moisture through the strong lower atmospheric winds. The decomposition shows significant differences between the TMFC and its zonal and meridional components between wet and dry years. Based on the long-term climatology, MMFC components dominate in the SWM season. In SWMWet years, the contribution of MMFC to TMFC is larger than zonal convergence. However, in SWMDry years, negative anomalous ZMFC in all the months contributes to below-average TMFC over the study domain. This study confirms that the dynamic processes of the atmosphere are more important in regulating the variability of SWM rainfall over the country. However, it is valuable to further investigate moisture transport process based on precipitation changes in Sri Lanka using numerical moisture tracking and regional climate models.

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Author contributions

SS and RD research conceptualization and methodology, SS formal analysis, data curation, and writing original draft, SS and RD writing—review, and editing. All authors equally collaborated in the research presented in this publication by making the following contributions.

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Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request. The reanalysis data of ERA5 are from https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5.

Code availability

The codes used during the current study are not available.

Declarations

Conflict of interest

The author reported no potential conflict of interest.

Ethics approval

Not applicable.

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