



Observed southwest monsoon rainfall changes in Sri Lanka and possible mechanisms

Sherly Shelton^{1,2,3} · Buddhi Pushpawela⁴

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Abstract

Southwest monsoon (SWM) is one of the major monsoon systems that brings significant rainfall over western and south-western parts of Sri Lanka. Therefore, this study investigates the SWM rainfall trend for 1980–2013 using monthly rainfall data from 19 meteorological stations and an associated mechanism by analyzing moisture transport and related atmospheric variables. The influence of the Indian Ocean sea surface temperature (SST) on SWM rainfall is also evaluated. The results show a statistically non-significant decreasing trend of SWM rainfall in most stations, while the regional average rainfall in the wet, intermediate and dry climate zones decreased by -21.3 , -19.3 , and -5.3 mm for the 34 years, respectively. It is further evidenced by the decreasing trend of precipitable water content, especially over the southwest, south, and eastern parts of Sri Lanka. The observed decreasing rainfall is attributed to the decreasing trends of total moisture transport over the study domain ($-7.14 \text{ kg m}^{-1} \text{ s}^{-1}$), resulting from the weakening of low-level westerlies at 850 hPa and decreasing specific humidity at 850 hPa in the Arabian sea (AB), Central Indian Ocean (CI, and Bay of Bengal (BB) regions. This study found that SST in CI, AB, and BB regions are increasing by 0.48°C , 0.31°C , and 0.32°C for the study period. As a results, the weakening of the SST gradients between AB and BB can deteriorate the monsoon circulation untimely, which weakens SWM over Sri Lanka.

Keywords Southwest Monsoon · Rainfall Trend · Moisture Flux · Indian Ocean · Sea Surface Temperature

Introduction

Indian summer monsoon (ISMR) also known as the Southwest Monsoon (SWM) (Singh et al. 2012), is considered as one of the energetic monsoon circulations (Di Sante et al. 2019), fully coupled with the ocean-land atmosphere process (Turner and Annamalai 2012). ISMR rainfall from May to September provides a significant contribution (80%) of annual rainfall over the Indian peninsula (Hari et al. 2020; Ihara et al. 2007; Sahai et al. 2003). In the last decades, a

weakening of the sea surface temperature (SST) gradients in the Indian Ocean (Roxy et al. 2015) can deteriorate the ISMR circulation by developing a weak cross-equatorial (south to north) surface pressure gradient and north-to-south mid-and upper troposphere pressure gradient (Rajeevan et al. 2008; Yadav and Roxy 2019). For instance, summer monsoon rainfall over north India decreased during the last two decades (1996–2017) due to the warming of SST in the eastern equatorial Indian Ocean (Yadav and Roxy 2019).

Moisture transport from the ocean by summer monsoon wind is the principal feature of the observed ISMR over the Indian subcontinent and Sri Lanka (Pathak et al. 2017; Sinha et al. 2019). During the ISMR season, the low-level south-westerly monsoon flow (LLJ) transports moisture from the Indian Ocean toward the Indian landmass (Pathak et al. 2017; Sinha et al. 2019; Wilson et al. 2018). Atmospheric transport of oceanic water vapor is mainly due to the cross-equatorial pressure gradient between south of the equator (1015 Mb) and warmer north Indian Ocean (1005 Mb) (Fasullo and Webster 2003). In addition, SST gradient develops the reverse pressure gradient in the mid-and upper troposphere that maintains the upper-level monsoon outflow

✉ Sherly Shelton
sherly@mail.iap.ac.cn

¹ International Center for Climate and Environment Sciences, Institute of Atmospheric Physics, Chinese Academy of Sciences, P.O. Box 9804, Beijing 100029, China

² University of Chinese Academy of Sciences, Beijing 100049, China

³ Industrial Technology Institute, 363 Bauddhaloka Mawatha, Colombo, Sri Lanka

⁴ Division of Chemistry and Chemical Engineering, California Institute of Technology, Pasadena, CA, USA

(Webster et al. 1998) resulting the deep ocean convection during the ISMR season.

Decreasing moisture transport and associated monsoon rainfall reduction have been linked to drought propagation (Herrera-Estrada et al. 2019). For example, a decrease in the strength of cross-equatorial LLJ over the Indian Ocean has been linked to the drought conditions over the Indian subcontinent during the SWM season (Gimeno et al. 2016; Joseph and Simon 2005). In addition, the decrease in the upward motion could cause a decrease in the amount of moisture over the Arabian Sea, and thus a further reduction of summer rainfall over the Indian landmass (Ratna et al. 2016). On the other hand, Xavier et al. (2018) reported that the strengthening of monsoon LLJ brought a large flow of moisture and resulted in heavy rainfall over the Indian subcontinent. Swapna et al. (2014) have identified a decreasing trend of the summer monsoon rainfall by analyzing the long-term trends of the winds at a surface level during the SWM seasons and the meridional pressure gradient between sea levels, respectively.

In terms of analyzing the long-term trend of SWM rainfall, Das et al. (2014) reported that some regions of the Indian subcontinent close to Sri Lanka, such as the west coast of Kerala and Karnataka, exhibited significant negative trends. Similarly, part of the western coastal region of southern India exhibited a decreasing trend of summer monsoon precipitation and the south-westerly LLJ (Fukushima et al. 2019). The previous studies on SWM rainfall in Sri Lanka have observed positive trends in the lowlands and negative trends in the highlands (Malmgren et al. 2003; Ratnayake and Herath 2005; Suppiah 1996; Wickramagamage 1998, 2016). However, the mechanism and relevant processes for decreasing SWM rainfall are not fully confirmed. Meanwhile, the influence of SST warming in the Indian Ocean on SWM over Sri Lanka has not been previously studied.

The objective of this study is to observe the changing pattern of SWM rainfall over Sri Lanka during the last few decades and identify the possible mechanism to explain the observed rainfall trend. The description of the data and methodology is presented in “Study site, Data, and Methodology”. The main results are described in “Result and Discussion”, followed by the discussion featuring. “Conclusion” is allocated for the conclusions of the study.

Study site, data, and methodology

Study site

The southwest (SW) and northeast (NE) monsoons play a crucial role in rainfall climatology in Sri Lanka because the country's location is directly located in the path of two monsoons (Shelton et al. 2021, 2022). The SWM rainfall

occurred from June to September to the southern and southwestern parts of Sri Lanka and the western slope of the central highlands (Burt and Weerasinghe 2014; Malmgren et al. 2003). Based on the rainfall received from two monsoon systems and two inter-monsoon systems, Sri Lanka is divided into three climate zones named wet, intermediate, and dry zones. The annual rainfall in the wet zone is over 2500 mm, while around 900 mm total rainfall is received over the dry zone. In between two climate zones, the intermediate zone is located where the annual rainfall is about 1500 mm. all three climate zones depict bimodal rainfall distribution (Rubasinghe et al. 2015; Wickramagamage 2016; Zubair and Ropelewski 2006; Zubair et al. 2008). Understanding the SWM rainfall events plays a vital role in daily life, especially for hydropower generation and agricultural production in Sri Lanka (Lin and Shelton 2020; 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 and Lin 2019).

Data

The monthly rainfall data of 19 meteorological stations in three climate zones (wet-7, intermediate-3, and dry-9) were obtained from the Department of Meteorology, Sri Lanka, from 1980 to 2013 (Fig. 1a). The GPCC V6 data with $0.5^\circ \times 0.5^\circ$ grid resolution was obtained for the same study period from the Global Rainfall Climatology Centre (Schneider et al. 2017) to depict the spatial rainfall

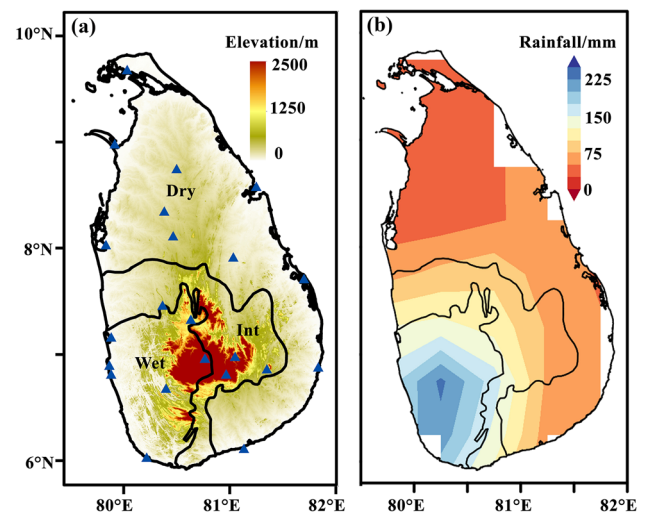


Fig. 1 The spatial distribution of **a** the meteorological stations over Sri Lanka (blue triangles) and **b** monthly mean southwest monsoon rainfall climatology (mm/month) for the 1980–2013 periods. The Wet, Int, and Dry terms represent the wet, intermediate, and dry climate zones demarcated by black lines, respectively

over the study domain (Fig. 1b). The present study has used $1^\circ \times 1^\circ$ resolution SST data (Rayner et al. 2003) from the Met Office Hadley Center Sea Ice and Sea Surface Temperature version 1.1 (HadISST1.1). The ERA-Interim (ERA-I) reanalysis data (Dee and Uppala 2009; Dee et al. 2011) represents the latest and the best third-generation atmospheric reanalysis (Trenberth et al. 2011) to investigate the atmospheric component of the hydrological cycle. In this study, four times daily horizontal wind (u), meridional wind (v), specific humidity (q), vertical velocity (ω) and surface pressure (p) data set with $0.5^\circ \times 0.5^\circ$ grid resolution from ERA-Interim was used to calculate the linear trend of water vapor flux, horizontal/ meridional wind, and vertical moisture advection during the study period.

Methodology

In this study, the area-weighted average rainfall over three climate zones was calculated by combining the Thiessen polygon method with the elevation regression method. This method has been previously used to estimate the rainfall in complex topography (Limin et al. 2015; Shelton and Lin 2019). Mann–Kendal test (MK) (Kendall 1975), and associated Sen’s slopes statistics (Sen 1968) were adopted to calculate rainfall trend in the individual stations and also for the trend in three climate zones. Before applying the MK test, Lag-1 serial correlation coefficient (r_1) was calculated for each time series using Ljung-Box Q -test. If the calculated r_1 is not significant at the 5% level, then the MK test and Sen’s slope estimator were applied to the original time series. If the calculated r_1 is significant at the 5% level, then the “pre-whitened” time series were obtained (Partal and Kahya 2006; Yue et al. 2002). Previous studies in different parts of the south Asia (Aawar et al. 2019; Baig et al. 2021; Hinge et al. 2021; Pathak and Dodamani 2020) also used MK test to identify the rainfall trends. This study calculated the linear trend of the selected atmospheric variables (specific humidity, horizontal wind, vertical velocity, and precipitable water) over the study domain to identify the causes for the observed SWM rainfall trend. Meanwhile, the relationship between Indian Ocean SST and SWM rainfall is also evaluated to understand the influence of SST on SWM rainfall in Sri Lanka.

As a result of very low specific humidity above 300 hPa level, moisture transports above this level are a negligible influence on the calculation of Vertically Integrated Total Moisture Flux (VITMF) (Ratna et al. 2016). Therefore, we considered the top layer of vertical integration up to 300 hPa level.

The VITMF \vec{Q} in the troposphere from the surface to 300 hPa was calculated using the equation

$$\vec{Q} = \frac{1}{g} \int_{300}^{P_s} q \vec{V} dp \quad (1)$$

The horizontal moisture divergence $\nabla \cdot \vec{Q}$ was calculated using the equation (Trenberth and Guillemot 1998).

$$\nabla \cdot \vec{Q} = \nabla \cdot \frac{1}{g} \int_{300}^{P_s} q \vec{V} dp \quad (2)$$

Where g , q , P_s , and \vec{V} , are the acceleration of gravity, specific humidity, surface pressure and horizontal wind vector, respectively.

Result and discussion

Spatial distribution of SWM rainfall and associated trend

The mean rainfall climatology of SWM rainfall over Sri Lanka was investigated and found that more than 150 mm/month rainfall over the wet region (Fig. 1b). The rest of the country, especially the northern and eastern part of the central highland, received less rainfall (less than 120 mm/month) due to the orographically influenced low-level wind circulation, which generates ‘Foehn effect weather conditions’ among wet and dry zones. Similar to our findings, previous studies also found the largest magnitude of rainfall over the wet zone (Malmgren et al. 2003; Shelton et al. 2021).

As shown in Fig. 2a, we observed decreasing SWM rainfall in most stations and increasing SWM rainfall in a few stations (Galle, Hambanthota, and Pottuvil) near the coastal belt. Similarly, Malmgren et al. (2003) found increased rainfall in three coastal stations and decreased in two highland stations during the SWM season. Table 1 depicts the MK test results and Sen Slopes of monthly average SWM rainfall in selected 19 stations for 1980–2013. The monthly average rainfall in Nuwara-Eliya recorded the highest decreasing trend of -22.33 mm/34 years, while the lowest negative trend is observed in Ratnapura (-4 mm/34 years). In the wet region, only one station showed increasing SWM rainfall (Galle, 2.25 mm/34 years), while most stations located in high elevation attributed negative rainfall trend. All stations in the intermediate zone showed a statistically non-significant negative trend of monthly average SWM rainfall during the study period. Most of the stations exhibit a negative rainfall trend in the dry zone, while two stations recorded a positive trend in rainfall (Table 1) during the monsoon season. The findings suggest that decreasing and increasing rainfall patterns are not spatially coherent across distinct coastal and highland areas. As shown in

Fig. 2 The southwest monsoon (SWM) rainfall trend for **a** selected metrological stations. The downward (upward) arrow indicates the negative (positive) rainfall trend, while the black dot indicates the statistically significant trend at a 90% significant level. The Wet, Int, and Dry terms represent the wet, intermediate, and dry zones. The SWM rainfall trends for **b** dry, **c** intermediate, and **d** wet zones are shown. The blue dash line displays the linear regression line

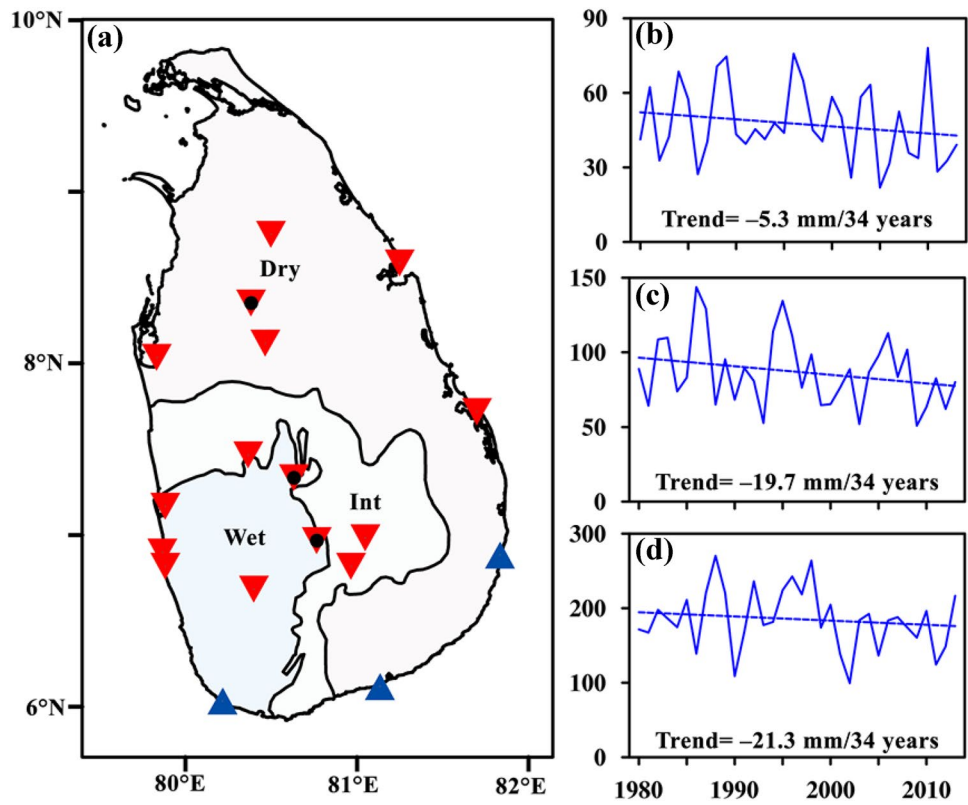


Table 1 Mann–Kendell’s Test statistics and associated Sen’s Slopes for the monthly average SWM rainfall from 1983 to 2013

Climate zone	Meteorological station	Kendell’s test statistics		Sen’s slope (mm/34 year)	
		Tau	P value		
Wet	Colombo	-0.07	0.57	- 5.0	
	Galle	0.04	0.77	2.2	
	Katugasthota	-0.27	0.02	- 13.4	
	Katunayaka	-0.14	0.24	- 11.2	
	Nuwara-Eliya	-0.27	0.03	- 22.3	
	Rathmalana	0.03	0.84	1.8	
	Rathnapura	-0.07	0.57	- 4.2	
	Intermediate	Badulla	-0.12	0.33	- 3.8
		Diyathalawa	-0.12	0.33	- 5.9
Kurunagala		-0.19	0.13	- 7.8	
Dry	Anuradhapura	-0.21	0.08	- 6.2	
	Bataloa	-0.05	0.68	- 1.9	
	Hambanthota	0.04	0.77	1.2	
	Maha-Ilupallama	-0.15	0.21	- 4.0	
	Mannar	-0.19	0.19	- 4.0	
	Pottuvil	0.07	0.59	1.4	
	Puttalama	-0.10	0.41	- 3.0	
	Trinco	-0.15	0.22	- 6.1	
Vavniya	-0.05	0.68	- 2.2		

Figs.2b, c, and d, area average SWM rainfall in the dry, intermediate, and wet regions decreases by 5.3, 19.3, and 21.3 mm for 34 years (Fig.2d), respectively

The causes for changes in SWM rainfall

SWM rainfall and Indian Ocean temperature

The principle component one (PC1) from EOF analysis of SWM rainfall explains 52% of the total variance. PC1 shows positive loadings of the SWM rainfall for the whole landmass, and the most potent positive lording can be seen in the western/ southwestern part of Sri Lanka (Figure is not shown). The SST in the Bay of Bengal (BB), spanning from 83 to 95° E; 6–15° N (Fig.3b) has a positive correlation ($r \geq 0.3$ at 90% significant level) with PC1 time series of SWM rainfall. In contrast, SST in the Arabian Sea (AB) and Central Indian Ocean (CI) negatively correlate with ($r \leq -0.3$) with PC1 time series of SWM rainfall, suggesting that lower SST in AB and CI and high SST in BB are associated with more than rainfall over the study domain (Fig.3a).

The linear trend of area average SST in AB, CI, and BB regions is shown in Figs. 3b–d, where the SST in CI, AB, and BB regions show an increasing trend by 0.48 °C 0.31°C, and 0.32°C for the 34 years, respectively (Figs.3b–d). The enormous SST anomaly difference between the western and eastern parts of Indian Ocean develops large-scale SWM

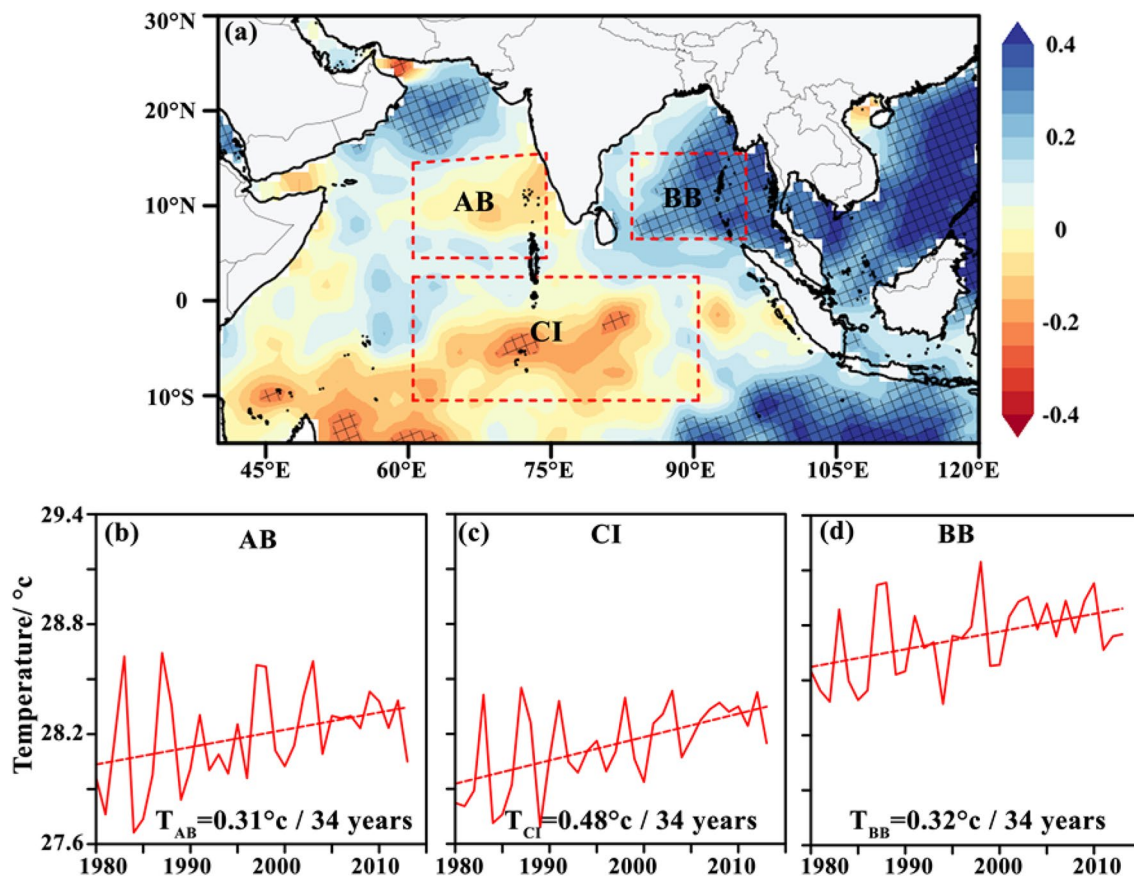


Fig. 3 a Correlation coefficient of Principal component 1 (PC1) of southwest monsoon rainfall with de-trended mean sea surface temperature during June to September. The Arabian Sea (AB), Central Indian Ocean (CI), and the Bay of Bengal (BB) are demarcated by red dashed boxes, respectively. The shaded area showed a statisti-

cally significant correlation at a 90% significant level (one tail). The linear trend of mean sea surface temperature (SST; °C/34 year) for b AB, c CI, and d BB regions during the southwest monsoon season are depicted in lower panels, where the red dash line shows the linear regression fit

circulation (Ratna et al. 2021). However, the increase of both ends of Indian Ocean SST warming weakens large-scale SWM circulation, which directly links to reduce moisture transport towards Indian sub-continent and nearby Sri Lanka.

Moisture Transport towards Sri Lanka and associated trend

Monsoon circulation dramatically affects the water vapor transport from over the ocean towards the monsoon region, significantly influencing rainfall in the monsoon region. The seasonal average VITMF over and around the Sri Lanka season are shown in Fig.4. The strong moisture flux transport during the SWM period is linked to the robust eastward channel of cross-equator Somali jet that brings abundant moisture towards the country (Fig.4a). Compared to the Arabian Sea direction, the VITMF magnitude is larger in the Bay of Bengal direction. The zonal moisture transport pattern has a dominant positive (eastward) correlation with rainfall over southern peninsular India. Based on the

results, it seems that the moisture transport by low-level jet and cross-equatorial flow over the Arabian Sea towards Sri Lankan are important factors for the SWM rainfall over the country. Figure 4b shows the linear trend of VITMF averaged over selected domains, highlighting the weakening trend ($-7.14 \text{ kg m}^{-1} \text{ s}^{-1}$) during the 1980–2013 period.

The VITMF over the region depends on the zonal and meridional wind component, surface pressure, and relative humidity, as shown in Eq. (1). Therefore, the observed negative trend of VITMF can be explained by separately investigating the abovementioned parameters. The zonal wind climatology during the SWM season and associated trend for 1980–2013 has been depicted in Figs. 5a-a1, where the strong zonal wind magnitude is observed in the Arabian Sea, close to the western part of Sri Lanka and the southern part of the Indian peninsula and Bay of Bengal direction has less zonal wind magnitude during the SWM season. In general, the whole study domain depicts the negative trend of zonal wind, while the wind magnitude in the central highland of

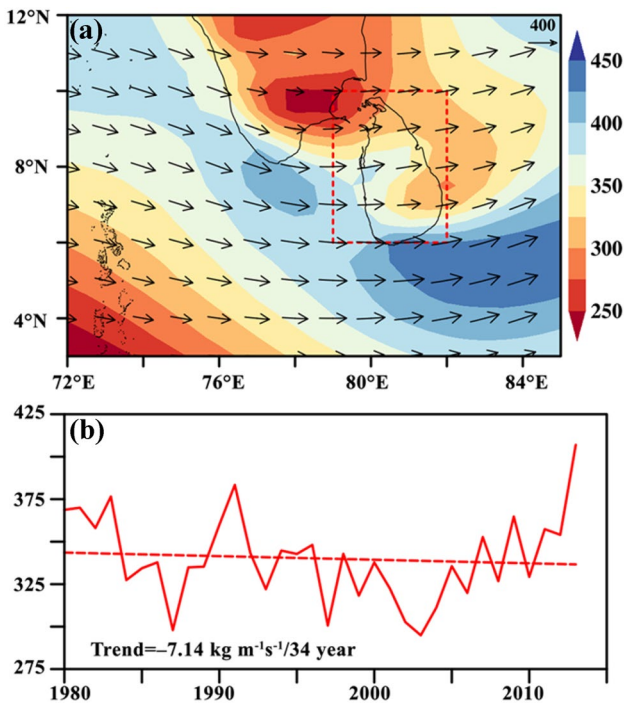


Fig. 4 **a** The climatology of vertically integrated moisture total transport (VITMF, shaded, unit: $\text{kg m}^{-1} \text{s}^{-1}$) during the southwest monsoon season for the 1980–2013 period, superimposed with vertically integrated wind component vectors. **b** The linear trends of the VITMF (units: $\text{kg m}^{-1} \text{s}^{-1}$) averaged over Sri Lanka (red box; $79\text{--}82^\circ \text{E}$; $6\text{--}10^\circ \text{N}$) where the red dash line shows the linear regression fit

Sri Lanka and the southeastern part of the Indian peninsula depicts a statistically significant decrease trend. These findings suggested that weakening of westerly flow reduces

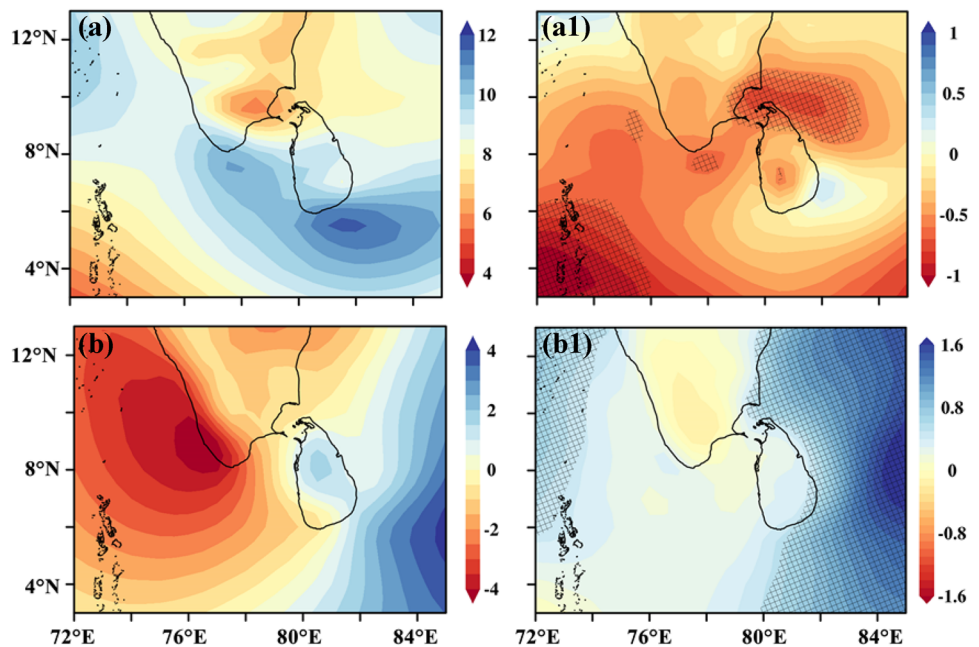
zonal moisture transport towards Sri Lanka during the 1980–2013 period.

Figure 5b-b1 show meridional wind climatology over the 1980–2013 period and associate linear trend for 34 years, respectively. The Arabian Sea direction showed southward meridional wind flow while the Bay of Bengal side recorded northward wind flow (Fig.5b). The meridional wind over the Bay of Bengal direction showed a statistically significant positive trend during the study period (Fig.5b1). At the same time, southerly flow (northerly flow) strengthens over the Arabian Sea (Bay of Bengal) direction. As a result, moisture transport from the meridional wind is increased over the country.

Compared to the nearby Arabian Sea, the Bay of Bengal, and the south Indian Ocean, a large moisture concentration at 850 hPa is observed over Sri Lanka (Fig.6a). Interestingly, we found a decreased moisture over AS and in the southern part of the Bay of Bengal. Moisture concentration in southwestern, south and eastern parts showed statistically significant decreasing trends (Fig.6a1).

As moisture over the AS and the south Indian Ocean decreases, it will likely contribute to the decrease in precipitation over the Sri Lankan landmass. Similarly, Ratna et al. (2016) revealed that the area-averaged moisture at 850 hPa level decreased over the East Africa/Arabian Sea during the 1951–2004 period. Figure 6b-b1 shows the summer PW climatology and the linear trend for 1980–2013. As shown in figure, PW content over the Indian Ocean is larger than it's over Sri Lankan landmass. Meanwhile, we found the PW in the western and southwestern parts of the country is higher than the eastern, southeastern part of the county. The results indicate decreasing PW over the Arabian Sea and the South

Fig. 5 **a** The climatology of zonal wind at 850 hPa during the southwest monsoon season and **a1** associated linear trend for 1990–2013. **b** and **b1** are the same as top panels but for the meridional wind at 850 hPa. The statistically significant trend at a 90% significant level is shaded in **a1** and **b1**



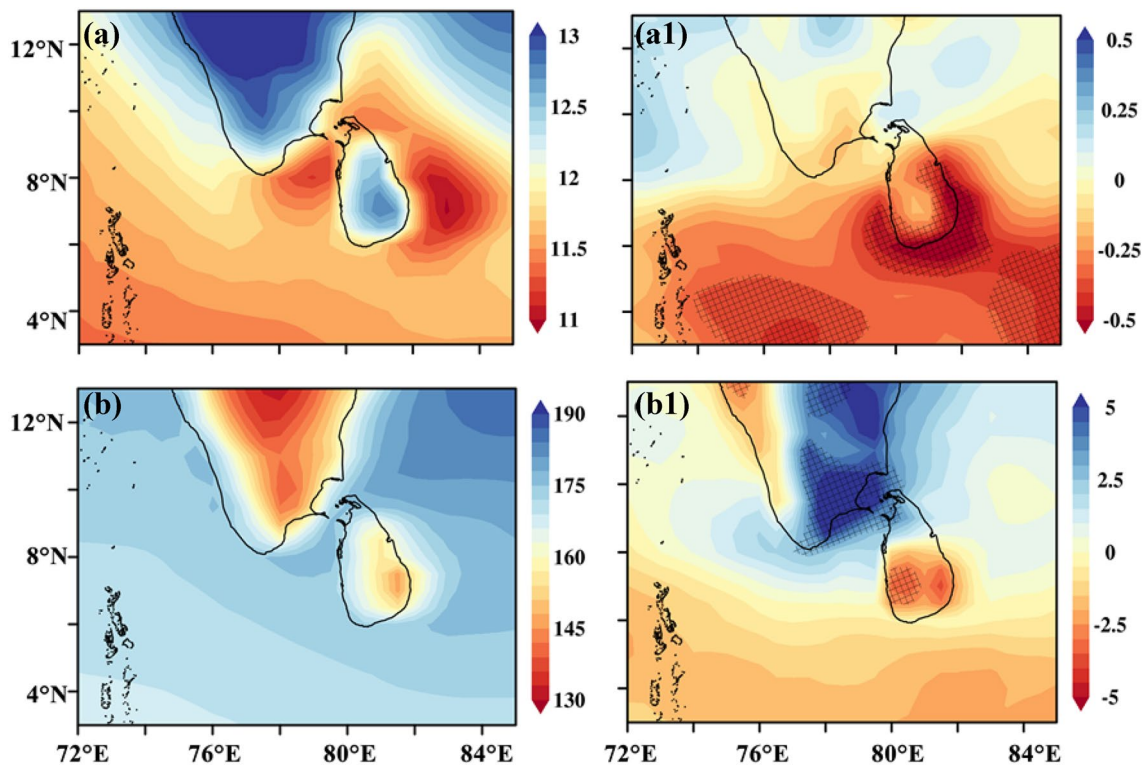


Fig. 6 The climatology of **a** specific humidity at 850 hPa during the southwest monsoon season and **a1** associated linear trend for 1980–2013. **b** and **b1** are the same as top panels but for the vertically inte-

grated perceptible water (1000 hPa to 300 hPa) and associated trend, respectively. The statistically significant trend at a 90% significant level is shaded in **a1** and **b1**

Indian Ocean. The PW over the west, southwest, south and eastern part of the country exhibits a statistically significant decreasing trend (Fig. 6b1).

Figure 7 shows the SWM season climatology and the linear trend of vertical velocity at 500 hPa and its vertical integral in the troposphere (from 1000 to 300 hPa) from 1980 to 2013. The wet zone shows negative vertical velocity at 500 hPa and integrated vertical velocity compared to the dry zone, proving that the west and southwestern part of the country received more SWM rainfall (Figs. 7a, b). In addition, the nearby Arabian Sea and Bay of Bengal depict negative vertical velocity, while associate trends indicate strengthen of vertical motion. The linear trend of omega at 500 hPa and integrate omega from 1000 to 300 hPa over the country except the eastern part has a statistically significant positive trend which discloses that weakening upward motion (Figs. 7a, b).

The linear trend of the height-longitudinal cross-section of vertical velocity (omega) and specific humidity averaged over the latitude 4–10° N for 1980–2013 were further analyzed as shown in Figs. 8a, b. The increase of omega from 1000 to 700 hPa is observed nearby the AB direction, while a significant decreasing omega is recorded from 600 to 300 hPa. In addition, the longitude bands of the country (79.5°E–83°E) showed an increasing trend of omega from

1000 to 300 hPa level. The increasing omega denotes the weakening of upward motion, which negatively influences SWM rainfall over the country. Furthermore, we notice decreasing trend of omega over the Bay of Bengal direction (Fig. 8a). Figure 8b shows the trend of the height-longitudinal cross-section of specific humidity. It indicates a negative trend of specific humidity from the surface (1000 hPa to 750 hPa level) over the AB and BB.

In contrast, the statistically significant positive trend of specific humidity is observed over AB after 750 hPa level. Meanwhile, we observed a decreasing trend of specific humidity from 1000 to 300 hPa levels except for 750–500 hPa levels over the Sri Lanka domain. The negative specific humidity from the surface to 750 hPa coincides with the weakening upward motion (Figs. 8a, b).

Discussion

Understanding the trend of the SWM rainfall is helpful in further hydrological analysis, which is essentially at finer scales and can be used for water availability studies for water resources management. The spatial patterns of the SWM rainfall trend over Sri Lanka and the drivers behind the observed rainfall trend have been investigated. Based

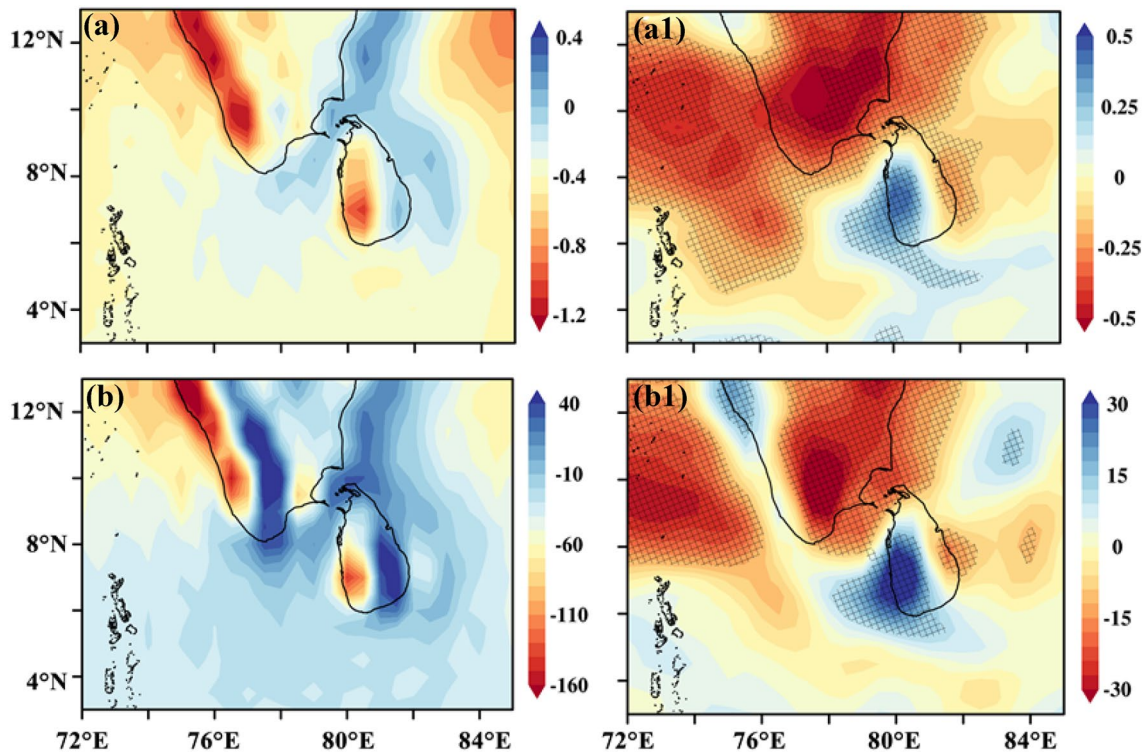
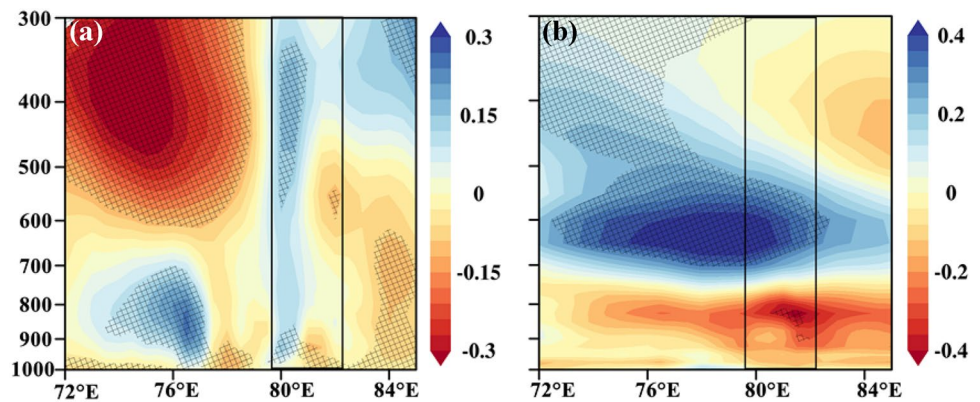


Fig. 7 The climatology of **a** Omega at 500 hPa during the southwest monsoon season and **a1** associated linear trend for the period 1980–2013. **b** and **b1** are the same as top panels but for the vertically

integrated omega (1000 hPa to 300 hPa) and associated trend, respectively. The statistically significant trend at a 90% significant level is shaded in **a1** and **b1**

Fig. 8 The linear trend of height-longitude cross-section (4°N – 10°N) of mean **a** Omega ($10^{-1} \times \text{Pa s}^{-1}$) and **b** specific humidity (g kg^{-1}) during the southwest monsoon season 1980–2013. The black box represents the longitude band of the study domain (Sri Lanka). The statistically significant trend at a 90% significant level is shaded in **a1** and **b1**



on the station observation and spatial analysis, we found a decreasing SWM rainfall during the 1980–2013 period. Similar to our findings, previous studies (Ranatunge et al. 2003; Suppiah 1996; Wickramagamage 1998, 2016) also found decreasing rainfall trends over central highlands, while Naveendrakumar et al. (2018) observed a decrease in the number of wet days during the SWM season. 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). Similar to our findings, Satyanarayana et al. (2020) found a decrease in SWM

seasonal rainfall over Myanmar for 1951–2010. (Duhan and Pandey 2013); Fukushima et al. (2019) observed decreasing trend of summer monsoon precipitation around central and eastern India. In the Indian subcontinent, the cities of dry winter humid subtropical areas recorded a decrease in SWM rainfall (Mohammad and Goswami 2019).

It was noticed that the increasing Arabian Sea and Bay of Bengal SST warming are accompanied by the weakening of the large-scale summer monsoon circulation and rainfall over Indian sub-continent and the nearby Sri Lanka. Similar to our findings, Roxy et al. (2015) found that changes in

SWM rainfall may be attributed to a warming of the western Indian Ocean and a subsequent weakening of the temperature gradient in SST over the Indian Ocean. The decrease of the north–south SST gradient in the Indian Ocean is attributed to a decrease in the strength of the monsoon westerlies over the Indian subcontinent and Myanmar (Chung and Ramanathan 2006; Naidu et al. 2009).

Prasanna and Yasunari (2008) revealed that atmospheric circulation and moisture transport are responsible for precipitation generation in peninsular India, the Arabian Sea, and the Bay of Bengal during early and late summer. Ratna et al. (2016) also found that the moisture over the Arabian Sea through the strong low-level winds during the monsoon season is vital for the Indian summer monsoon rainfall. The low-level Somali jet has two channels; the northward channels of moisture transport appear to move to the Arabian Sea while the other curves toward the Bay of Bengal (Latif et al. 2015). Similarly, Latif et al. (2015) pointed out that the moisture over Central-North India is supplied by the eastward expansion of the Somali jet from the Arabian Sea. We also identified that moisture availability and its advection by prevailing summer monsoonal winds are the principal aspects of the observed rainfall over the Sri Lanka.

Sandeep and Ajayamohan (2015) found that low-level jet seems to weaken below 15° latitude over the Arabian Sea while strengthening above the latitude. For instance, the linear trend of the meridional winds flow is weakening along the eastern Arabian Sea and over the Bay of Bengal (Ratna et al. 2011). As we observed, the zonal wind magnitude over Sri Lanka and the southeastern part of the Indian peninsula decreased, which ascribed weakling of zonal moisture transport towards Sri Lanka during the 1983–2013 period.

Seasonal rainfall and PW have positive correlations in regions where water vapor increases much more than temperature, mainly monsoon regions (Bretherton et al. 2004; Lu et al. 2009). The results highlighted a declining trend of PW over Sri Lanka, leading to a weakening of the drawn draft, affecting the reduction of SWM rainfall during the study period. Vertical moisture advection is the most critical term determining the changes in precipitation (Ma and Zhou 2015; Oueslati et al. 2019). Large negative vertical velocity values correspond to areas of heavy rainfall if moisture is available because precipitation is likely to be far better correlated with available moisture than with vertical motion (Rose and Lin 2003). Ratna et al. (2016) found that the Arabian Sea, Bay of Bengal, and Asian landmass have strong upward motion associated with enhanced convection and high moisture values during the summer monsoon. Similarly, we also observed the weakening of vertical motion over Sri Lanka and the Arabian Sea caused the reduction of moisture. This analysis quantifies the processes leading to low SWM rainfall rates and can be extended for further attribution studies. Most importantly, a complete understanding of the SWM

rainfall pattern in the changing environment will help in better decision-making and improve the adapting capacity of the communities to sustain the extreme weather events.

Conclusion

On different time and spatial scales, seasonal rainfall decreases over three climate regions where a largest decreasing trend is observed for the wet zone. The decreasing trends of moisture, moisture transport, and zonal wind over the Arabian Sea have aggravated the decreasing southwest monsoon rainfall over the country. Understanding whether these changes continue in the future or estimated future projections of SWM is crucial for further hydrological analysis, which can be used for water availability studies for water resources management in the country. Therefore, identifying the future changes of SWM using coupled General Circulation Models (GCMs), including Coupled Model Intercomparison Project Phase 6 (CMIP6) model results, is timely needed. The parameters associated with large-scale monsoon circulation cannot fully explain the spatial variation of rainfall trends in a small island like Sri Lanka. It is suggested to study land-use change, soil moisture, evaporation that affects the spatial variation of rainfall trends, mainly convective rains, through changes to the heat and moisture fluxes.

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