RESEARCH ARTICLE OPEN ACCESS

Rainfall Anomalies Over the South-West of Sri Lanka During the Second Intermonsoon Season and its Relationship to IOD

K.L. Pasqual

Department of Atmospheric Science, Nanjing University of Information Science and Technology, Nanjing, China

Email: kasun.pasqual@yahoo.com

----------**********----------

Abstract:

The temporal and spatial characteristics of monthly rainfall anomalies in the southwest region of Sri Lanka at different Indian Ocean Dipole (IOD) phases during the second intermonsoon (SIM) season in Sri Lanka were investigated using composite analysis and significance testing. ERA5 monthly rainfall data from 1972 to 2021 was used for this purpose. The results revealed that the highest impact of the IOD phenomenon on rainfall anomalies during the SIM season occurs in October. In October, there is a significant increase in rainfall over Sri Lanka during positive IOD (PIOD) events and a significant decrease in rainfall over Sri Lanka during negative IOD (NIOD) events. In particular, IOD extremes have a greater impact on rainfall anomalies in the southwest region. In November, during the PIOD, rainfall significantly increased in the southwest region of Sri Lanka, and during the NIOD period, rainfall in the Kegalle and Ratnapura districts was reduced. The mechanism of the IOD influence on SIM seasonal rainfall anomalies was studied. Western and eastern Indian Ocean SSTs play a critical role in this mechanism. The positive SST anomaly over the western Indian Ocean region and the Arabian Sea during the PIOD period during the SIM season enhances evaporation and convection. The low-level pressure difference between the western and eastern Indian Oceans, the easterly wind, weakens the monsoon wind across Sri Lanka, and the moisture convergence, the effect of the low-level cyclonic circulation, intensifies the convective process and gives more rain. In contrast, during the NIOD period, the negative SST anomaly over the western Indian Ocean and the Arabian Sea reducess evaporation and convection. During this season, the westerly wind flow caused by the pressure difference between the western and eastern Indian oceans strengthens the monsoon winds over Sri Lanka. The moisture divergence and strong monsoon flow across Sri Lanka disrupt the convection process and significantly reduce rainfall. The study will help researchers understand specific impacts on local meteorological patterns and provide warnings for disaster mitigation. For further research, I propose the combined effect of homogeneous phases of ENSO and IOD.

Keywords **—IOD, Sri Lanka, Rainfall, Second intermonsoon.**

----------**********----------

I. INTRODUCTION

Sri Lanka is a small island in the Indian Ocean, south of the Indian peninsula. It is located between latitudes 5°55′ and 9°51′ N and longitudes 79°42′ and 81°53′ E [1]. Sri Lanka is characterized by a rainfall pattern with two main monsoons and two intermonsoons[2], and it is consistently affected by various weather-related hazards, including floods, strong winds, thunderstorms, lightning, and droughts. Due to its topography, hydro-meteorological hazards such as floods, flash floods, and landslides are widely reported in the areas on the southwestern slopes of the Central Hills. Apart from causing loss of life and property, these hazards have caused significant damage to the ordinary lives of the public, services, and industries such as agriculture, fisheries, and tourism.

 ©IJSRED:All Rights are Reserved

It is reasonable to assume that Indian Ocean SST influences these rainfall anomalies. However, Abeysekera [3]has shown that Sri Lanka has a tropical climate that is constantly influenced by the Indian Ocean climatic phenomena.Previous studies have found a relationship between rainfall and SST in the Indian Ocean. This relationship was found to be independent of ENSO and was later identified as the IOD [3, 4]. The IOD is an air-sea coupled phenomenon occurring in the tropical Indian Ocean [4,6] and, it's associated with the east-west gradient of SST anomalies in the tropical Indian Ocean [7]. Saji[4]called this gradient the Dipole Mode Index (DMI). Also, they defined the SST difference between the tropical western Indian Ocean (50E–70E, 10S–10N) and the tropical southeast Indian Ocean (90E-110E, 10S-0) as an index to quantify the IOD. SST anomalies above +0.4 °C are considered positive IOD (PIOD) events, and anomalies below -0.4 °C are negative IOD (NIOD) events. A DMI range of -0.4 °C to +0.4 °C is considered neutral IOD. PIOD events are characterized by anomalous cooling of SST in the southeastern equatorial Indian Ocean and anomalous warming of SST in the western equatorial Indian Ocean, while the opposite is for the NIOD[8].

The SIM is a crucial rainy season that affects Sri Lanka during October and November [2]. It contributes 30% to Sri Lanka's annual rainfall. SIM rainfall is very important for the southwest region, and Chitranayana and Punyawardena [9]showed that in southwestern Sri Lanka, non-irrigated rice cultivation and cultivation of tea, rubber, coconut, export crops, and vegetables depend mainly on rainfall patterns. Jayawardene [10] stated that hydropower is the main energy source in Sri Lanka, and SIM season rainfall is very important for hydropower generation. Rainfall in the SIM season is associated with the ITCZ and is characterized by convective rains[2]. Thevakaran [11] indicated that weather systems such as convergence, convection, and depressions bring heavy rainfall during the SIM season (October to November). The agricultural "Maha" season is associated with the SIM season [12]. Thunderstorms affect the southern region of Sri Lanka during the SIM period, which belongs to the "Maha" season [9,10]. Therefore, to improve the accuracy of weather forecasts, it is very important to determine the IOD effect on rainfall before the "Maha" season to make decisions about cropping and hydropower management.

The frequency of IOD has increased in the last few decades due to global warming, and authors [14,15,16]point out that the weakening of both equatorial westerly winds and eastward oceanic currents creates a favorable environment for IOD development.Zubair [17] pointed out that the IOD is a seasonally phase-locked phenomenon that initiates in May, peaks in October, and decreases by December. However, Lim and Hendon [18] have shown that the IOD starts developing around June, peaks in September and October, and decays rapidly during the austral summer.Therefore, it can be inferred that different IOD phases will affect the SIM season rainfall anomalies. However, limited studies have shown that IOD influences the SIM seasonal rainfall in Sri Lanka. Abeysekera [3] showed from a statistical analysis that there is a clear increase in accumulated seasonal rainfall with PIOD events during the SIM season and the opposite with NIOD events. Jayawardene [10], in their analysis of cyclical rainfall patterns in Sri Lanka, revealed significant relationships between rainfall and IOD in the 2-3 year period and thus showed IOD also plays an important role as a modulator of rainfall in Sri Lanka. However, Zubair [17] pointed out that during the "Maha" agricultural rainy season in Sri Lanka from September to December, PIOD events increase rainfall over Sri Lanka, while NIOD events decrease rainfall. They further pointed out that the mechanism caused by SST anomalies in the western Indian Ocean also contributes significantly to this. The general climate pattern in Sri Lanka may change due to IOD, a global phenomenon, and rainfall in Sri Lanka is directly influenced by SST in the Indian Ocean [12,13]. Abeysekera [3]showed that only the SIM season yielded statistically significant observations with IOD, which was the peak of IOD events within a year. Further, they indicate that if a positive IOD phase is predicted in a given year, excess soil moisture conditions in the highlands and flooding in the lowlands can be expected during the SIM season.Zubair [17]pointed out that "Maha" season rainfall mainly increases with El Niño and PIOD

 ©IJSRED: All Rights are Reserved

phases and decreases during opposite periods. They further indicated that the IOD influence on the "Maha' seasonal rainfall exceeded that of ENSO, except in the 1920s.

This study also explored the impact of different IOD phases on SIM seasonal rainfall anomalies in Sri Lanka and, a possible mechanism. The study results are useful tools for SIM seasonal and monthly climate forecasting.

Authors[6,12,15]have shown that the IOD cannot be viewed separately from ENSO, and they also showed that in some years, strong ENSO forcing may create a bias in the Indian Ocean-coupled system. However, as Zubair[17]further points out, that the effects of IOD and ENSO are statistically interrelated, and even if the impact of ENSO is removed, the IOD effect is significant and dominant over the ENSO effect. Several studies have shown that different ENSO phases also impact rainfall anomalies during the SIM season in Sri Lanka[14,15,16]. Therefore, examining the combined effect of IOD and ENSO on rainfall anomalies during SIM season is suggested to merit further study.

The paper is organized as follows: Section 2 describes the data and methods used. Section 3 describes the results, and Section 4 presents the conclusions.

II. Data and Methodology

A. Observation and reanalysis data

Monthly observational rainfall data were obtained from the Meteorological Department, Sri Lanka (from 1972 to 2021). District-level average rainfall values were used for this study. ERA5 [25] high-resolution rainfall reanalysis data (horizontal resolution 0.1° x 0.1°) from 1972 to 2021 were used. ERA5 monthly rainfall data are processed by ECMWF's Copernicus Climate Change Service (C3S)and data are available at https://cds.climate.copernicus.eu/cdsapp#!/home. The necessary reanalysis data, such as vertical velocity, vertical integral of divergence of moisture flux, horizontal wind components, mean sea-level pressure (MSLP), and SST, were obtained with a horizontal resolution of 0.25° x 0.25° by ERA5. The Outgoing longwave radiation (OLR) (W/m2) gridded monthly data (1974 - 2021) used in this study were obtained from NCEP-NCAR with a 0.25° x 0.25° spatial coverage, anddata are available at https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html.

B. Indian Ocean Dipole (IOD)

For this study, DMI values greater than +0.4 °C were considered positive IOD events, and values less than -0.4 °C were considered negative IOD events. IOD years were obtained from the BoM (Bureau of Meteorology: http://www.bom.gov.au/climate/enso/#tabs=Indian-Ocean), Australia. PIOD and NIOD years are shown in Table 1.

Table 1. PIOD and NIOD years from 1972 to 2021 were used for this study

Events	Year
Positive IOD years	1972 1987 1994 1997 2006 2015 2019
Negative IOD years	1974 1975 1992 1996 1998 2010 2016

C. Composite analysis (CA) and Significance test

This study used CA to identify the changes in various climate parameters during different IOD events. Suppiah [23] used a t-test to examine the

 ©IJSRED: All Rights are Reserved

variation in rainfall during different ENSO phases and deviations from normality. Xie [26] points out that CA is a useful tool to help understand the relationships between different phenomena.

Student's t-test was used to determine whether there was a significant difference between PIOD and NIOD events in each parameter considered in this study. The formula for the t-test is as follows:

$$t = \frac{\bar{x} - \bar{y}}{\sqrt{\frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2}} \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}}$$

Where $\bar{x}$ and $\bar{y}$ are the mean of samples 1 and 2 n_1 and n_2 are the corresponding sample sizes of samples 1 and 2, S_1 and S_2 are the standard deviations of samples 1 and 2, respectively. t follows the t-distribution of the degree of freedom (n1+n2-2).

III. RESULT AND DISCUSSION

1) Temporal and spatial characteristics of rainfall in Sri Lanka during the SIM season in different IOD phases

The SIM season is a main rainy season in Sri Lanka, active from October to November. Thunderstorms mainly occur in the evening or night over the country due to local convective activity during this season. Rainfall during this season is associated with the Intertropical Convergence Zone and contributes to 30% of Sri Lanka's annual rainfall. Although there is widespread rainfall over Sri Lanka during the SIM season, the southwest region receives more rainfall, mainly the western slopes of the Central Hills. During the SIM period, weather systems such as convergence, convection, and depressions bring heavy rain [11].Frequent floods, flash floods, landslides, and droughts during this season have caused considerable damage to human lives and the economy.

A temporal and spatial analysis of rainfall anomalies during the SIM period at different IOD phases was carried out using composite analysis. Figure 1 shows the composite anomalies of monthly rainfall in PIOD and NIOD for October to November 1972–2021 using the ERA5 gridded reanalysis rainfall dataset with a high resolution of 0.1° x 0.1°. At PIOD, there is a statistically significant positive rainfall anomaly over Sri Lanka in October (Fig. 1a). A significant high positive rainfall anomaly exists, especially in the southwestern part (Kegalla, Ratnapura, Nuwara Eliya, and Kandy districts). It poses a severe flood risk to the districts of Kegalle and Ratnapura, located on the southwestern slopes. However, at NIOD, there is a statistically significant negative rainfall anomaly in Sri Lanka in October (Fig. 1b). Kegalle, Ratnapura, Nuwara Eliya, and Kandy districts have significantly high negative rainfall anomalies. However, the significant negative rainfall anomaly in the northern and eastern parts of Sri Lanka, which receive less rainfall, will cause a severe drought. During PIOD, in November, there will be a significant positive rainfall anomaly only in the southwestern part of Sri Lanka, creating flood threats in southwestern slopes. At NIOD, there is a negative rainfall anomaly in the Kegalle and Ratnapura districts in November.

According to the above results, it is clear that the IOD phenomenon has affected the rainfall anomalies of the SIM season in Sri Lanka. Rainfall anomalies during SIM season show contrasting spatial patterns during different IOD phases, and an increase in SIM seasonal rainfall during PIOD events and a decrease in SIM seasonal rainfall during NIOD events occur in most parts of the island, especially in the southwest region. According to Figure 1, the highest impact of SIM season in different IOD phases was in Kegalle and Ratnapura districts. The most substantial impact of IOD extremes occurred in October.These results are consistent with the conclusion that seasonal rainfall in the SIM increases during the PIOD period and decreases during the NIOD period[2,9].Additionally, this study has uncovered October and November monthly rainfall anomalies and associated regions.

A comparison of averagerainfallin different districts of Sri Lanka in PIOD, NIOD, and Neutral years during SIM is shown in Figure 2, using observation data sets from 1972 to 2021A. There is a significant increase in mean rainfall in October during PIOD years over Sri Lanka (Fig. 2a).

 ©IJSRED: All Rights are Reserved

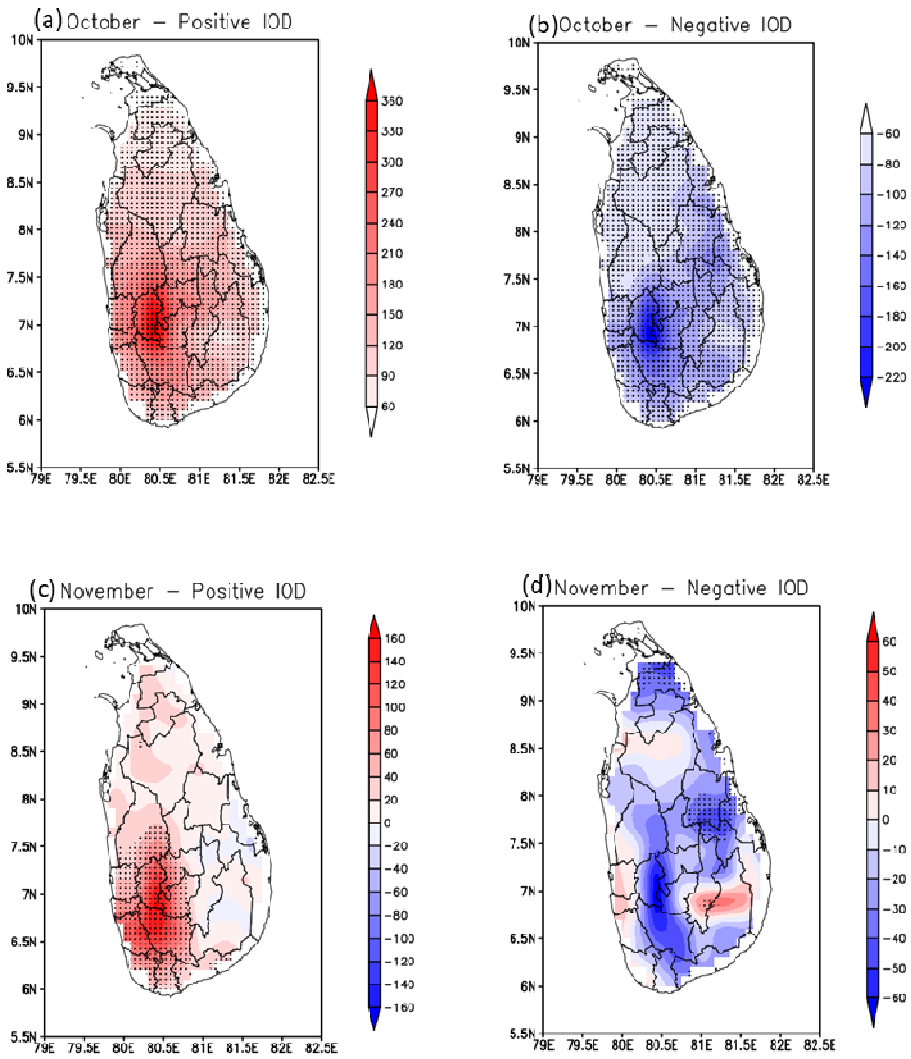

Figure 1. Composite anomalies in the monthly rainfall (mm) in PIOD and NIOD years from ERA5 dataset from (a, b) October and (c, d) November 1972-2021. Black dotted regions represent the anomalies are statistically significant at the 95% confidence level according to the student's t-test

 ©IJSRED: All Rights are Reserved

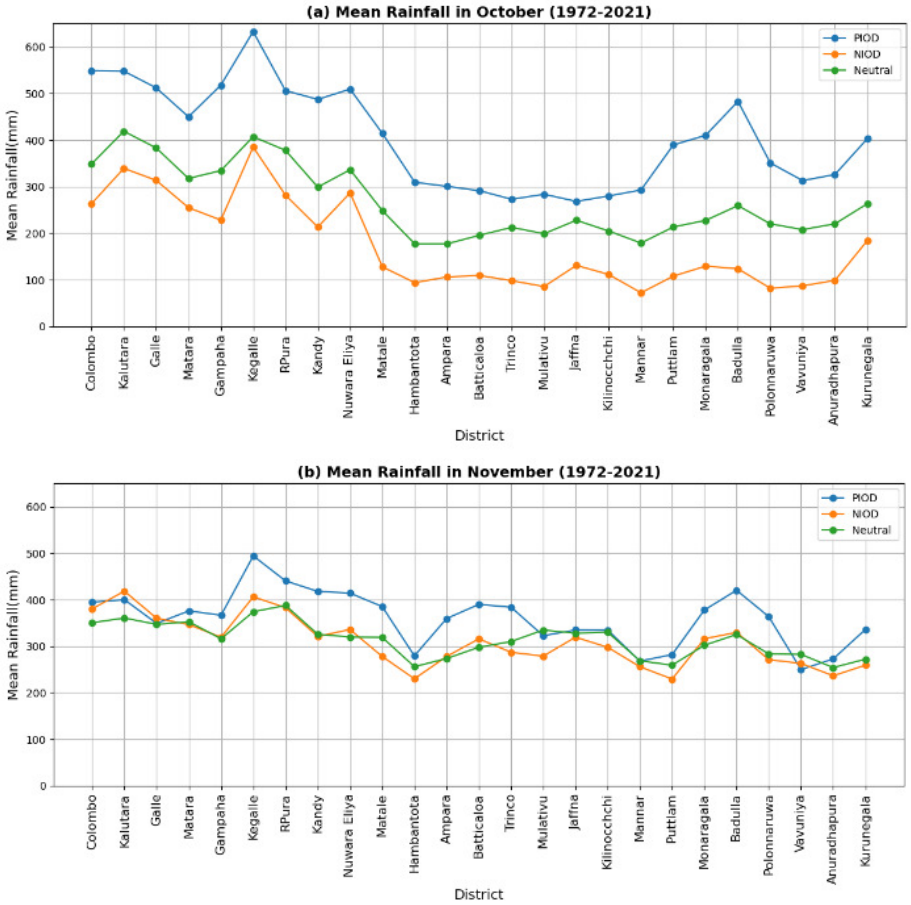

Figure 2. Monthly mean rainfall for PIOD (blue), NIOD (red), and neutral years for all districts in Sri Lanka from (a) October and (b) November. Monthly observational data from 1972 to 2021 was used

In contrast, there is a significant decrease in mean rainfall in October during NIOD years (Fig. 2a). Kegalle district has high mean rain, particularly in PIOD years.According to Figure 2b, there is an increase in average rainfall in most districts of Sri Lanka during November in PIOD years and a decrease in rainfall in most districts during the NIOD years.Thus, in the SIM season during PIOD years, rainfall in Sri Lanka is relatively high; therefore, floods can frequently occur in the southwest region; rainfall is relatively low in the NIOD years, and drought condition scan be expected in the northern and eastern areas. These results are almost consistent with the rainfall anomalies in Sri Lanka at different IOD phases during the SIM season, shown in Figure 1. However, the authors [22,23] state that the positive IOD often coincides with the positive phase of ENSO. They also state that the negative phases of IOD and ENSO often occur in the same years. Therefore, ENSO and IOD may have a combined effect on observed rainfall values during different IOD events.

Figure 3 shows the monthly rainfall anomaly graphs in PIOD and NIOD phases in all districts in the southwestern part of Sri Lanka. October and

 ©IJSRED: All Rights are Reserved

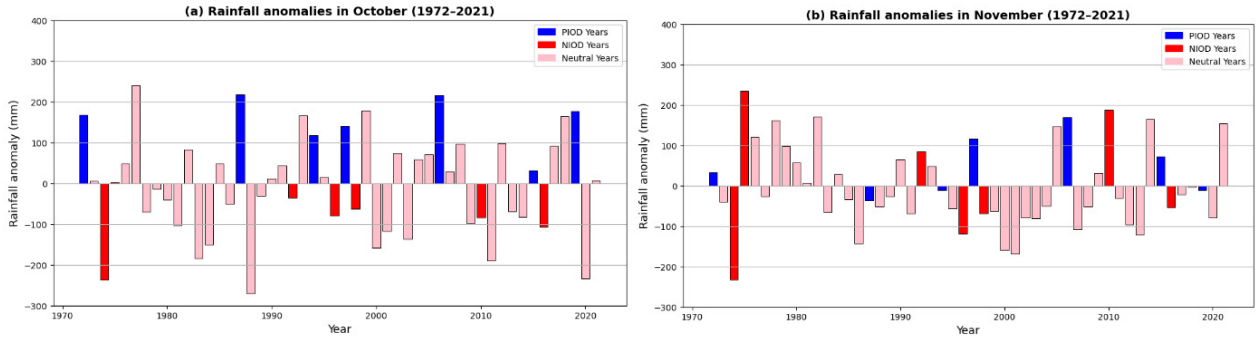

Figure 3. Monthly rainfall anomalies for PIOD (blue), NIOD (red), and Neutral years for all districts in southwestern Sri Lanka. From (a) October and (b) November. Monthly observational data from 1972 to 2021 was used

November observational rainfall data from 1972 to 2021 were used for this analysis. According to Figure 3a, October has a positive rainfall anomaly in PIOD years and a negative rainfall anomaly in NIOD years. However, there are some years in November when this is not the case and a positive rainfall anomaly can be observed in most PIOD years and a negative rainfall anomaly in most NIOD years(Fig. 3b). These results are almost consistent with the rainfall anomalies in the southwestern part of Sri Lanka in different IOD phases during the SIM season shown in Figure 1.

2) Mechanisms of how the IOD influences the rainfall during SIM season

A. Role of the vertical velocity

Vertical velocity plays a critical role in rainfall formation by supporting the lift and cooling the air. Vertical velocity anomalies were studied over Sri Lanka from 1972 to 2021 at different IOD phases in October and November. Figure 4 shows composite vertical velocity anomalies at the 500 mb level during different IOD phases at different periods. During PIOD, there is a statistically significant negative vertical velocity anomaly over Sri Lanka in October, which is higherin the southwesternpart (Fig. 4a).It indicated an upward motion and brought more rain. In contrast, there is a statistically significant positive vertical velocity anomaly over

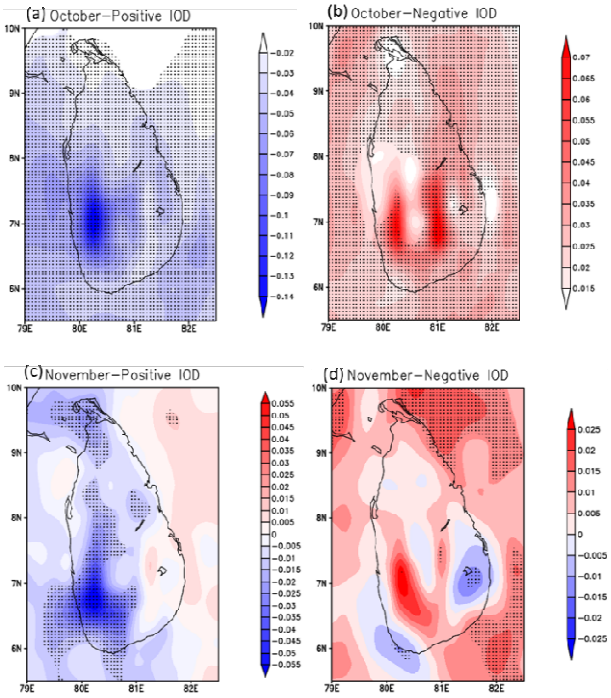

Figure 4. Composite anomalies in the monthly vertical velocity(Pas^{-1}) (shaded) at 500 mb level in PIOD and NIOD years from (a, b) October and (c, d) November 1972-2021 (ERA5). Black dotted regions represent the anomalies are statistically significant at the 95% confidence level according to the student's t-test

Sri Lanka during October during the NIOD, with ahigher value in the southwestern part (Fig. 4b). That parameter represents an upward motion and avoids the occurrence of rain.

 ©IJSRED: All Rights are Reserved

During PIOD, there is a statistically significant higher negative vertical velocity anomaly over the southwestern part of Sri Lanka in November, which will receive more rain (Fig. 1c). However, during NIOD November, there is a positive vertical velocity anomaly in the southwestern part of the Kegalle and Rathnapura districts, which resulted in reduced rainfall(Fig. 1d). These vertical velocity anomaly results are consistent with the rainfall anomalies over Sri Lanka during the PIOD and NIOD periods in the SIM season, shown in Figure 1.

B. Effect of moisture on rainfall anomalies

Investigating moisture convergence and divergence is critical in studying rainfall anomalies. Figure 5 shows the composite anomalies of the monthly vertical integral of divergence of moisture flux at different IOD phases in the upper atmosphere over Sri Lanka in different IOD phases. According to the definition, this parameter is positive for moisture divergence and negative for the opposite. During the PIOD phase, October shows a statistically significant negative anomaly over Sri Lanka, which can be identified as a moisture convergence (Fig. 5a). Greater moisture convergence can be detected over the western slopes of the central hills, and more rain will be received in those areas. In contrast, during the NIOD phase in October, there is a statistically significant positive anomaly in this parameter in most parts of Sri Lanka (Fig. 5b). It can be identified as moisture divergence, which will prevent rain and cause severe dry conditions. However, in PIOD, there is a negative anomaly in the monthly vertical integral of divergence of moisture flux that is statistically significant over the southwestern part of Sri Lanka in November (Fig. 5c), and the moisture convergence will increase the rain in the southwest region. A positive anomaly in moisture can be observed over the Kegalle and Rathnapura districts in the Southwestern region in November during the NIOD phase (Fig. 5d).Accordingly,a decrease in rainfall can be expected

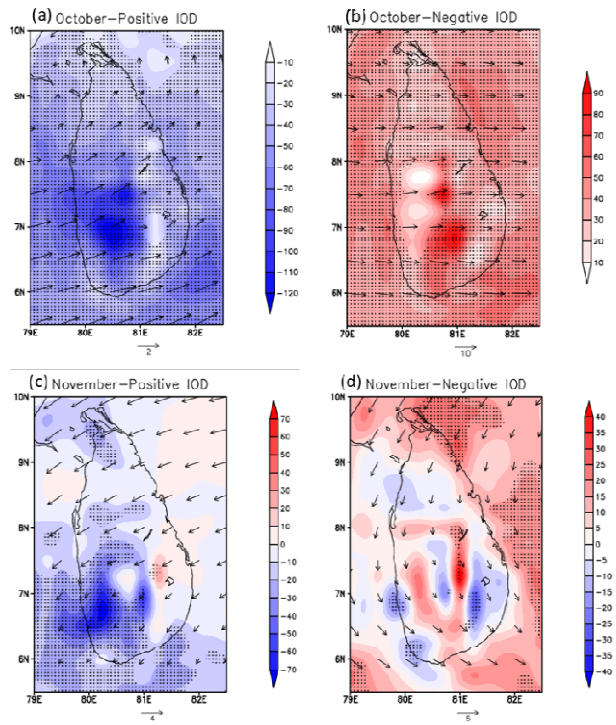

Figure 5. Composite anomalies in the monthly vertical integral of divergence of moisture flux ($kgm^{-2}s^{-1}*10^6$) (shaded) at 500 mb level in PIOD and NIOD years from (a, b) October and (c, d) November 1972-2021 (ERA5). Black dotted regions represent the anomalies are statistically significant at the 95% confidence level according to the student's t-test. The mean horizontal winds (ms^{-1}) in each PIOD and NIOD period are shown

in that area. These results are consistent with the rainfall anomalies of different IOD phases during SIM, shown in Figure 1.Since SIM season is the period between SWM and North-East monsoon (NEM), the wind direction is reversed from southwest to west and northeast. Therefore, in October and November, the direction of wind coming to Sri Lanka at lower levels changes.

C. Anomalies of SST in the Indian Ocean

During a PIOD phase, westerly winds weaken along the equator, allowing warm water to shift toward Africa. Wind changes also allow cooler water to rise from the deep ocean in the east. This causes a temperature change across the tropical

 ©IJSRED: All Rights are Reserved

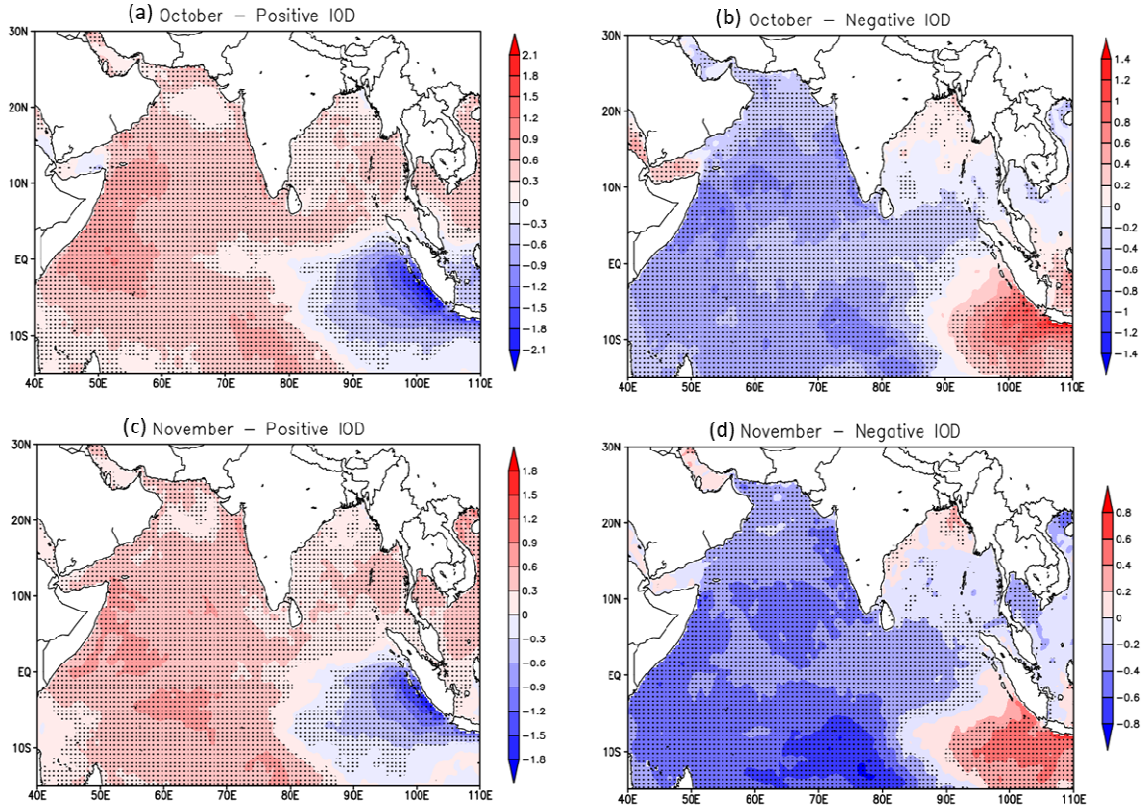

Figure 6. Composite anomalies in the monthly SST (^{0}C) (shaded) in PIOD and NIOD years from (a, b) October and (c, d) November 1972-2021 (ERA5). Black dotted regions represent the anomalies are statistically significant at the 95% confidence level according to the student's t-test

Indian Ocean[3]. Since Sri Lanka is an island in theIndian Ocean, it can be expected that the tropical Indian Ocean SST will influence its weather patterns. Figure 6 shows composite SST anomalies during different IOD phases at different periods. During the PIOD period in October and November, there is a statistically significant positive SST anomaly near the African coast in the western Indian Ocean. Also, the same situation can be observed around Sri Lanka (Fig. 6a,c).During this season, there is a statistically significant negative SST anomaly in the eastern Indian Ocean, near Indonesia and Australia, resulting in temperatures being cooler than normal in that sea area (Figure 6a, c). Here, the temperature gradient is towards the western Indian Ocean. The positive SST anomaly over Sri Lanka allows for good evaporation.

Due to increased moisture and convection, more rainfall can be expected in October and November during the PIOD period in Sri Lanka.During PIOD events, "Maha" rainfall (SIM season) is enhanced due to anomalously warm SST in the western Indian Ocean and large-scale convergence extending to Sri Lanka. Convection induced by this convergence increases rainfall over Sri Lanka, while the opposite mechanism operates during NIOD events[17].

During the negative IOD phase, westerly winds intensify along the equator, allowing warm water to concentrate near Australia, its creating a temperature difference[3]. According to Figures 6b and d, during NIOD years in October and November, there is a statistically significant negative SST anomaly near the African coast in the Western Indian Ocean. The same situation can be observed near Sri Lanka. During this season, there is a statistically significant positive SST anomaly in

 ©IJSRED: All Rights are Reserved

the eastern Indian Ocean, near Indonesia and Australia, resulting in cooler-than-normal temperatures in that sea area (Figure 6b, d). Here, the temperature gradient is towards the east Indian Ocean. The significant negative SST anomaly over Sri Lanka inhibits evaporation and thus reduces moisture over Sri Lanka. It's one of the reasons for the substantial decrease in rainfall in October and November during the NIOD period. These results are consistent with the rainfall anomalies over Sri Lanka during the PIOD and NIOD periods in the SIM season, shown in Figure 1.

high positive MSLP anomaly in the eastern Indian Ocean and a negative MSLP anomaly near the African coast in the western Indian Ocean (Fig. 7a, c).This low-level pressure difference causes an east-to-west wind flow across the Indian Ocean, which weakens the normal west-to-east monsoon flow. The weakening monsoon flow over Sri Lanka intensifies the convective process and brings more rain. In contrast, during the NIOD period in October and November, there is a significant positive MSLP

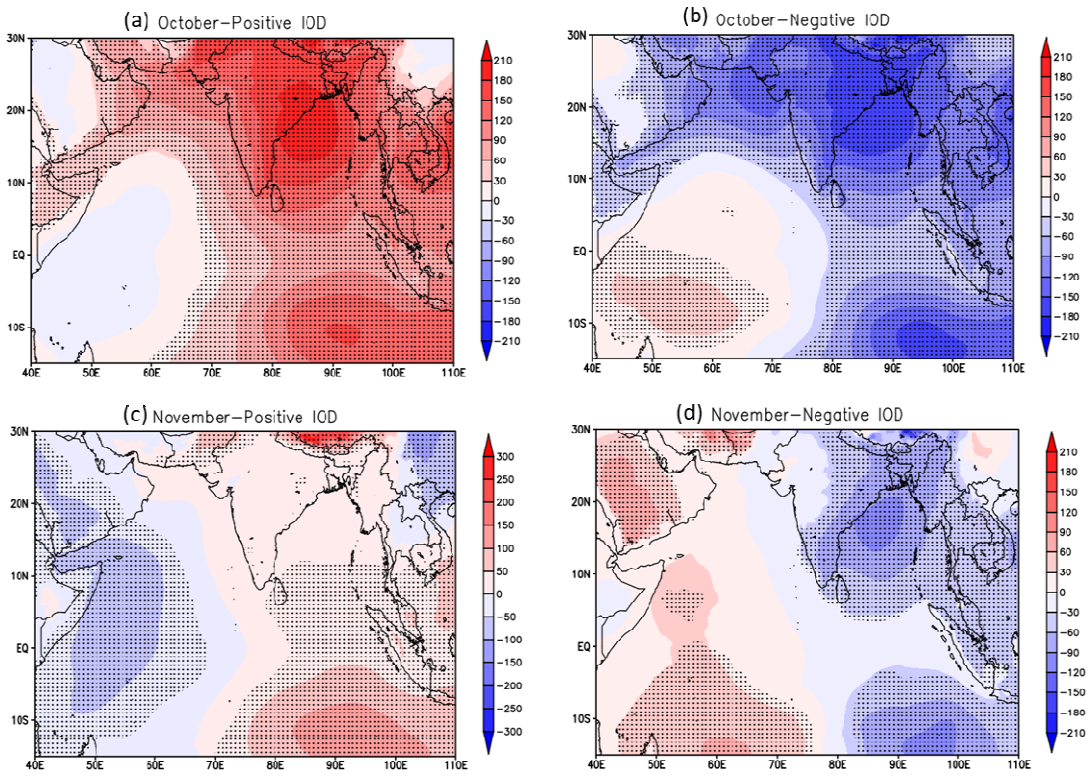

Figure 7. Composite anomalies in the monthly mean sea level pressure (Pa) (shaded) in PIOD and NIOD years from (a, b) October and (c, d) November 1972-2021 (ERA5). Black dotted regions represent the anomalies are statistically significant at the 95% confidence level according to the student's t-test

D. Mean Sea Level Pressure (MSLP)

Figure 7 shows composite mean sea pressure (MSLP) anomalies at different IOD phases in the SIM season. During the PIOD period in October and November, there is a statistically significant anomaly near the African coast in the western Indian Ocean and a statistically significant higher negative

MSLP anomaly in the eastern Indian Ocean (Fig. 7b, d). This low-level pressure difference further strengthens the west-to-east monsoon flow through

 ©IJSRED: All Rights are Reserved

the west-to-east wind flow across the Indian Ocean. The strengthening monsoon flow over Sri Lanka interferes with the convective process and significantly reduces the convective rainfall during the SIM season. These MSLP anomaly results are consistent with the rainfall anomalies over Sri Lanka during the PIOD and NIOD periods of the SIM season, as shown in Figure 1.

E. The role of horizontal winds over the Indian Ocean

Figure 8 shows the composite anomalies in monthly horizontal winds in PIOD and NIOD periods during the SIM season at 850 mb and 200mb levels. The IOD is characterized by the difference in sea surface temperature between the western and eastern parts of the Indian Ocean, which causes changes in the atmospheric circulation in the Indian Ocean region. During the PIOD phase of October and November, there is a negative wind anomaly over Sri Lanka at the 850 mb and 200 mb levels (Fig. 8a, c, e, and g). During this season, due to the pressure gradient caused by the temperature difference between the west and east of the Indian Ocean, the easterly winds over the western Indian Ocean strengthen.Cai [14] also showed that due to the weakening of the Pacific Walker circulation and the strong land-ocean temperature difference in the Asian monsoon region during the PIOD period, easterly winds in the equatorial Indian Ocean are strengthened.As a result, the south-westerly monsoon winds across Sri Lanka from the Arabian Sea are weakened.Therefore, low horizontal wind speed promotes the formation of convective clouds and thunderstorms, creating atmospheric instability over Sri Lanka during the SIM season. It will bring above-normal rainfall over most parts of Sri Lanka, especially the southwestern slopes of the central hills.

In contrast, during the NIOD phase of October and November, there is a positive wind anomaly over Sri Lanka at the 850 mb and 200 mb levels (Figs. 8b, d, f, and h). During this season, due to the pressure gradient caused by the temperature difference between the west and east of the Indian Ocean, the monsoon wind flow over Sri Lanka is further strengthened due to the eastward wind flow across the western Indian Ocean. Due to this, the high horizontal wind speed disturbs the convection process over Sri Lanka during SIM. As a result, drought conditions can be expected in most parts of Sri Lanka, with a significant reduction in rainfall.These horizontal wind anomaly results are consistent with the rainfall anomalies over Sri Lanka during the PIOD and NIOD periods of the SIM season, as shown in Figure 1.

Figure 9 shows the composite anomalies in monthly horizontal winds in PIOD and NIOD periods during the SIM season at 850 mb level, and the mean wind streamlines at 850 mb level are overlaid. According to Figure 6a, the October wind pattern of PIOD periods is directly influenced by a cyclonic (anticlockwise) wind pattern at a low level (850 mb) over Sri Lanka.The negative wind speed during that season further intensifies the convective process, giving more rainfall over much of the country (Fig. 9a). Webster and Yang [28] have also shown that a strong monsoon is characterized by strong low-level inflow from the ocean and high-level outflow toward the Ocean in the form of an anticyclone. Also, in an earlier study based on 1964 and 1965 data, Lockwood [29] reported a well-developed low-level circulation (700 mb) over the Bay of Bengal during October and November. According to Figures 9b and d, it is clear that such wind patterns had no direct effect on Sri Lanka during the NIOD period of October and November. During that season, the positive wind speed associated with Sri Lanka interferes with the convection process, which causes the rain to decrease across the country.

 ©IJSRED: All Rights are Reserved

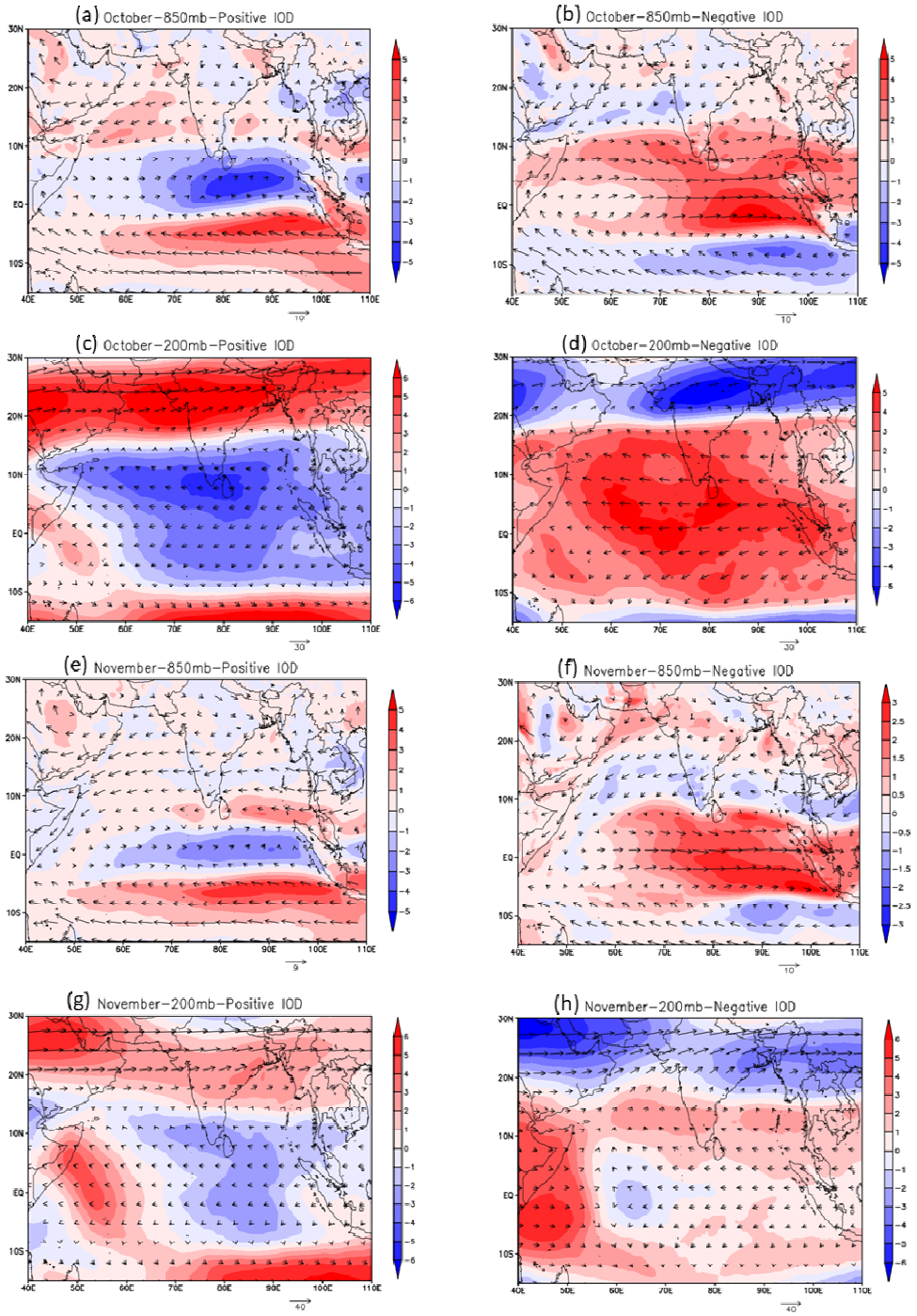

Figure 8. Composite anomalies in the monthly mean horizontal winds (ms^{-1}) (shaded) in PIOD and NIOD years from (a, b) October at 850 hPa, (c, d) October at 200 hPa, (e, f) November at 850 hPa, and (g, h) Novemberat 200 hPa 1972-2021 (ERA5). Mean wind directions from each level are shown

 ©IJSRED: All Rights are Reserved

However, according to Figure 9c, the wind pattern during PIOD periods in November is somewhat influenced by a cyclonic (anticlockwise) pattern near Sri Lanka at a low level (850 mb), which causes a slight increase in rainfall. These results are consistent with the rainfall anomalies over Sri Lanka during the PIOD and NIOD periods of the SIM season, as shown in Figure 1.

F. Role of Moisture over the Indian Ocean in Different IOD Phases

Figure 10 shows the composite anomalies of the monthly vertical integral of divergence of moisture flux at different IOD phases over the Indian Ocean during the SIM season. There is a statistically significant negative anomaly in the vertical integral of the divergence of the moisture flux parameter over the West Indian and Sri Lanka regions during the PIOD phase of October and November (Fig. 10a, c). This negative discrepancy seems to be relatively higher in October. The convergence of moisture in the region is indicated, and the convective process will bring more rainfall to Sri Lanka. Atmospheric moisture increases with increased evaporation due to positive SST in the western Indian Ocean during the PIOD phase in October and November (Fig. 6a, c). Simultaneously, the PIOD phase weakens the Walker circulation. However, cross-equatorial winds flow along the African coast and, although weakened by PIOD activity, transport that moisture across the Arabian Sea toward Sri Lanka. This circulation pattern affects moisture entry and rainfall in Sri Lanka.

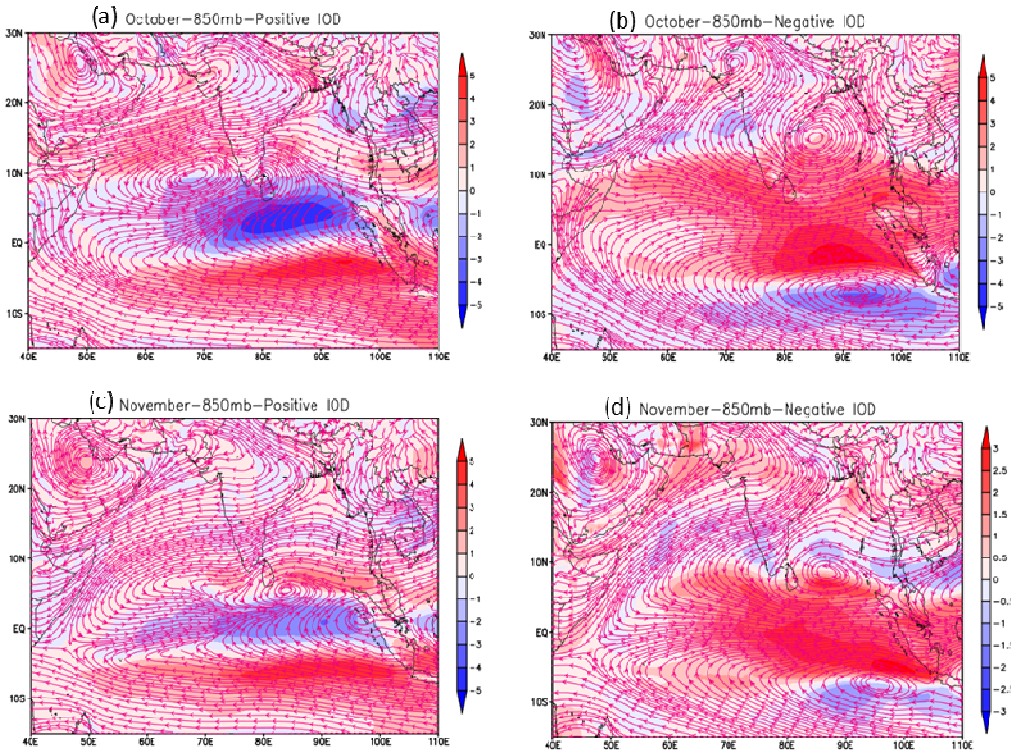

Figure 9. Composite anomalies in the monthly mean horizontal winds (ms^{-1}) (shaded) in PIOD and NIOD years from (a, b) October and (c, d) November at 850 hPa 1972-2021 (ERA5). The mean wind streamlines at 850mb level are shown

 ©IJSRED: All Rights are Reserved

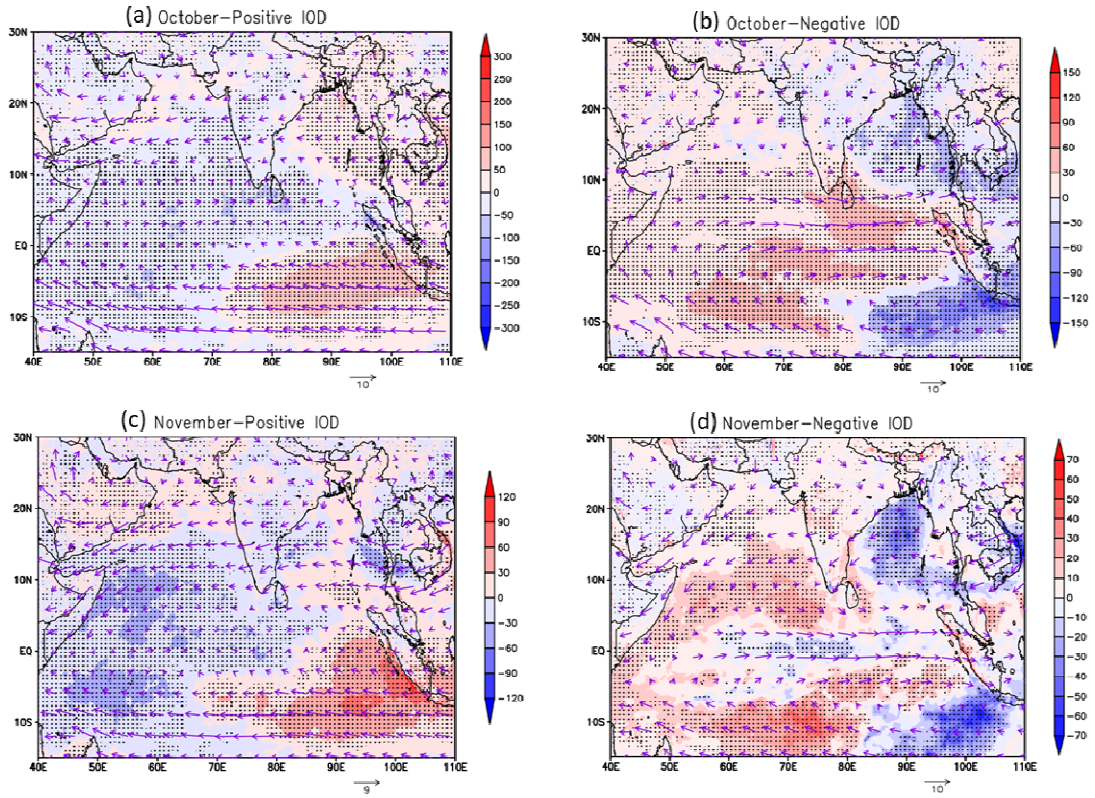

Figure 10. Composite anomalies in the monthly vertical integral of divergence of moisture flux ($kgm^{-2}s^{-1}*10^6$) (shaded) at 500 mb level over the Indian Ocean during PIOD and NIOD years from (a, b) October and (c, d) November 1972-2021 (ERA5). Black dotted regions represent the anomalies are statistically significant at the 95% confidence level according to the student's t-test. The mean horizontal winds (ms^{-1}) at 850 mb level in each PIOD and NIOD period are shown.

In contrast, there is a statistically significant positive anomaly in the vertical integral of divergence of moisture flux parameter over the western Indian and Sri Lankan regions during the NIOD phase in October and November (Fig. 10b, d). It indicates a moisture divergence. During this season, the decrease in evaporation with the negative SST in the western Indian Ocean (Fig. 10b, d) has reduced the atmospheric moisture. It significantly reduces the rain across Sri Lanka. During the NIOD phase, due to the warming of theeastern Indian Ocean, the Walker circulation over the Indian Ocean strengthens, resulting in a downward motion over the western Indian Ocean and an upward motion over the east Indian Ocean. The descending motion over the west of the Indian Ocean limits rainfall and prevents moisture convergence. The flow of dry monsoon winds passing through Sri Lanka at this stage from the South Indian Ocean through the Arabian Sea also contributes to the reduction of this rainfall.These anomaly results of the vertical integral of divergence of moisture flux parameter are consistent with the rainfall anomalies over Sri Lanka during the PIOD and NIOD periods of the SIM season, as shown in Figure 1.

 ©IJSRED: All Rights are Reserved

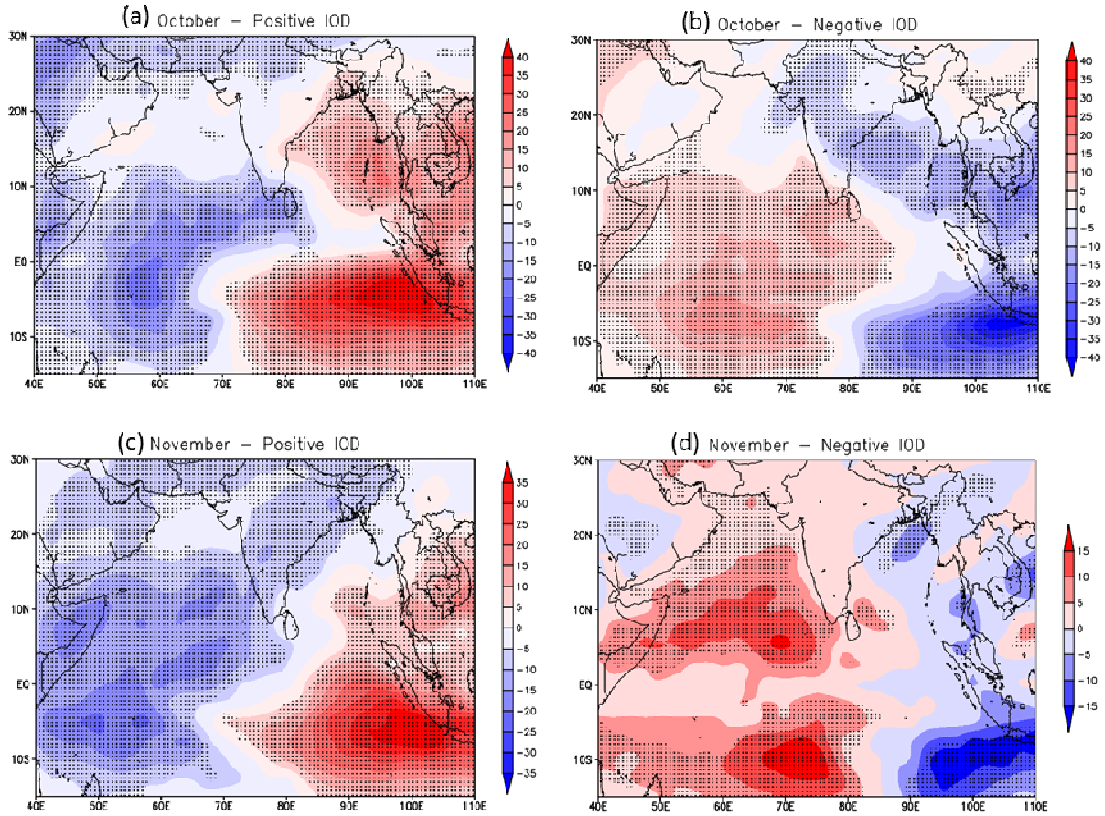

Figure 11. Composite anomalies in the monthly OLR (Wm^{-2}) (shaded) in PIOD and NIOD years from (a, b) October and (c, d) November 1972-2021 (ERA5). Black dotted regions represent the anomalies are statistically significant at the 95% confidence level according to the student's t-test

G.Anomalies of Outgoing Longwave Radiation (OLR) during different IOD Phases

During SIM season, Figure 11 shows the composite anomalies of the monthly outgoing longwave radiation (OLR) anomalies at different IOD phasesover the Indian Ocean. During the PIOD phase in October, there is a statistically significant negative OLR anomaly over Sri Lanka (Fig. 11a). November also shows negative OLR anomalies, but less than October (Fig. 11c). According to Figures 6a and c, there is a significant positive SST anomaly in the Indian Ocean adjacent to Sri Lanka during that period, which may enhance the atmospheric instability. And warmer ocean temperatures lead to moreevaporation and latent heat release, which leads to increased convection, cloud growth, and rainfall. Strong convection can lead to the formation of dense clouds that absorb and emit infrared radiation, resulting in a decrease in OLR. Negative OLR anomalies are associated with stronger convection [30]. They further pointed out that the largest OLR negative anomaly values occurbetween longitude 70Eand 120E. Greater cloud cover results in a negative OLR anomaly and more rain can be expected.However, in contrast, there are statistically significant positive OLR anomalies during the NIOD wake in October (Fig. 11b). November also has positive OLR anomalies, but less than October. According to Figures. 6b and d, there is a significant negative SST anomaly in the Indian Ocean near Sri Lanka, and the amount of OLR emitted is also low. It strongly inhibits convection and inhibits cloud growth and rainfall. However,

 ©IJSRED: All Rights are Reserved

the OLR anomaly is higher than the PIOD season due to the decrease in cloud cover. That is, the presence of a positive OLR anomaly was confirmed by low cloud cover.

These OLR anomaly results are consistent with the rainfall anomalies over Sri Lanka during the PIOD and NIOD periods of the SIM season, as shown in Figure 1.

IV. CONCLUSIONS

The impact of positive and negative extremes of the IOD phenomenon on the rainfall anomalies over the southwest region of Sri Lanka during the SIM season was studied. This study used 1972–2021 observational and ERA5 reanalysis data, and analysis was performed using a significance test with composite analysis.

The highest impact of the IOD phenomenon on rainfall anomalies during the SIM season occurred in October. SIM seasonal precipitation anomalies show opposite spatial patterns during different IOD phases. In most parts of the island, especially in the southwest region, there was an increase in SIM seasonal rainfall during PIOD events and a decrease in SIM seasonal rainfall during NIOD events. It was revealed that the Kegalle and Rathnapura districts are most affected.

The mechanism of the IOD influence on SIM seasonal rainfall anomalies was studied. This study used reanalysis data from 1972–2021, and analysis was performed using a significant test with composite analysis. Western and eastern Indian Ocean SSTs play a critical role in the occurrence of this mechanism. A positive SST anomaly over the western Indian Ocean region and the Arabian Sea in the PIOD period during the SIM season enhances evaporation and convection. The easterly wind flow, caused by the low-level pressure anomaly between the western and eastern Indian Oceans, weakens the monsoon winds over Sri Lanka. Weak monsoon winds transport moisture from the west (Arabian Sea) and southwest Indian Ocean towards Sri Lanka, resulting in moisture convergence. Due to the increase in moisture, the influence of low-level cyclonic circulation, and the intensification of the convection process, Sri Lanka receives more rainfall. In contrast, during the NIOD period, the negative SST anomaly over the western Indian Ocean region and the Arabian Sea reduces evaporation and convection. The westerly wind flow caused by the pressure difference between the western and eastern Indian oceans strengthens the monsoon winds over Sri Lanka. It interferes with the convection process, and the rainfall is significantly reduced due to the moisture diverging over Sri Lanka.

The results revealed that IOD significantly influences rainfall anomalies during the SIM season in Sri Lanka. The study will help researchers understand and address specific impacts on local meteorological patterns. For further study, I suggest the combined effect of homogeneous phases of ENSO and IOD.

ACKNOWLEDGMENT

I would like to thank the Nanjing University of Information Science and Technology for allowing this study. I also sincerely thank Professor Hu Dingzhu, who has been dedicated to overseeing my study, for her support and encouragement. I thank the Director General of the Department of Meteorology, Sri Lanka, for providing rainfall data.

REFERENCES

[1] S. F. M. Sulaiman, "Pineapple production and research in Sri Lanka," *Acta Hortic.*, no. 529, pp. 89–92, May 2000, doi: 10.17660/ActaHortic.2000.529.9.

[2] B. V. R. Punyawardena, "Climate," in *The Soils of Sri Lanka*, R. B. Mapa, Ed., in World Soils Book Series. , Cham: Springer International Publishing, 2020, pp. 13–22. doi: 10.1007/978-3-030-44144-9_2.

[3] A. B. Abeysekera, B. V. R. Punyawardena, B. Marambe, I. M. S. P. Jayawardena, T. Sivananthawerl, and V. N. M. Wickramasinghe, "Effect of Indian Ocean Dipole (IOD) Events on the Second Inter-monsoonal Rainfall in the Wet Zone of Sri Lanka," *Trop. Agric. Res.*, vol. 32, no. 3, p. 287, Jul. 2021, doi: 10.4038/tar.v32i3.8492.

[4] N. H. Saji, B. N. Goswami, P. N. Vinayachandran, and T. Yamagata, "A dipole mode in the tropical Indian Ocean," *Nature*, vol. 401, no. 6751, pp. 360–363, Sep. 1999, doi: 10.1038/43854.

[5] P. J. Webster *et al.*, "Monsoons: Processes, predictability, and the prospects for prediction," *J. Geophys. Res.*, vol. 103, no. C7, pp. 14451–14510, Jun. 1998, doi: 10.1029/97JC02719.

 ©IJSRED: All Rights are Reserved

[6] P. J. Webster, A. M. Moore, J. P. Loschnigg, and R. R. Leben, "Coupled ocean–atmosphere dynamics in the Indian Ocean during 1997–98," *Nature*, vol. 401, no. 6751, pp. 356–360, Sep. 1999, doi: 10.1038/43848.

[7] K. Ashok, Z. Guan, and T. Yamagata, "Impact of the Indian Ocean dipole on the relationship between the Indian monsoon rainfall and ENSO," *Geophysical Research Letters*, vol. 28, no. 23, pp. 4499–4502, Dec. 2001, doi: 10.1029/2001GL013294.

[8] S. Sun, J. Lan, Y. Fang, Tana, and X. Gao, "A Triggering Mechanism for the Indian Ocean Dipoles Independent of ENSO," *J. Climate*, vol. 28, no. 13, pp. 5063–5076, Jul. 2015, doi: 10.1175/JCLI-D-14-00580.1.

[9] R. Chithranayana and B. Punyawardena, "Identification of drought prone agro-ecological regions in Sri Lanka," *J. Natn. Sci. Foundation Sri Lanka*, vol. 36, no. 2, p. 117, Jun. 2008, doi: 10.4038/jnsfsr.v36i2.143.

[10] H. Jayawardene, D. Jayewardene, and D. Sonnadara, "Interannual variability of precipitation in Sri Lanka," *J. Natn. Sci. Foundation Sri Lanka*, vol. 43, no. 1, p. 75, Mar. 2015, doi: 10.4038/jnsfsr.v43i1.7917.

[11] A. Thevakaran, R. Suppiah, and U. Sonnadara, "Trends in extreme rainfall events in Sri Lanka, 1961 - 2010," *J. Natn. Sci. Foundation Sri Lanka*, vol. 47, no. 3, p. 285, Sep. 2019, doi: 10.4038/jnsfsr.v47i3.9280.

[12] L. Zubair, "El Niño–southern oscillation influences on rice production in Sri Lanka," *Intl Journal of Climatology*, vol. 22, no. 2, pp. 249–260, Feb. 2002, doi: 10.1002/joc.714.

[13] L. Zubair, "Diurnal and seasonal variation in surface wind at Sita Eliya, Sri Lanka," *Theoretical and Applied Climatology*, vol. 71, no. 1–2, pp. 119–127, Jan. 2002, doi: 10.1007/s704-002-8212-2.

[14] W. Cai, A. Sullivan, and T. Cowan, "Climate change contributes to more frequent consecutive positive Indian Ocean Dipole events," *Geophysical Research Letters*, vol. 36, no. 23, p. 2009GL040163, Dec. 2009, doi: 10.1029/2009GL040163.

[15] W. Cai *et al.*, "Increased frequency of extreme Indian Ocean Dipole events due to greenhouse warming," *Nature*, vol. 510, no. 7504, pp. 254–258, Jun. 2014, doi: 10.1038/nature13327.

[16] Y. Du, W. Cai, and Y. Wu, "A New Type of the Indian Ocean Dipole since the Mid-1970s," *Journal of Climate*, vol. 26, no. 3, pp. 959–972, Feb. 2013, doi: 10.1175/JCLI-D-12-00047.1.

[17] L. Zubair, S. A. Rao, and T. Yamagata, "Modulation of Sri Lankan *Maha* rainfall by the Indian Ocean Dipole," *Geophysical Research Letters*, vol. 30, no. 2, p. 2002GL015639, Jan. 2003, doi: 10.1029/2002GL015639.

[18] E.-P. Lim and H. H. Hendon, "Causes and Predictability of the Negative Indian Ocean Dipole and Its Impact on La Niña During 2016," *Sci Rep*, vol. 7, no. 1, p. 12619, Oct. 2017, doi: 10.1038/s41598-017-12674-z.

[19] Y. E. Zambrano Mera, J. F. Rivadeneira Vera, and M. Á. Pérez-Martín, "Linking El Niño Southern Oscillation for early drought detection in tropical climates: The Ecuadorian coast," *Science of The Total Environment*, vol. 643, pp. 193–207, Dec. 2018, doi: 10.1016/j.scitotenv.2018.06.160.

[20] V. P. I. S. Wijeratne, G. Li, M. S. Mehmood, and A. Abbas, "Assessing the Impact of Long-Term ENSO, SST, and IOD Dynamics on Extreme Hydrological Events (EHEs) in the Kelani River Basin (KRB), Sri Lanka," *Atmosphere*, vol. 14, no. 1, p. 79, Dec. 2022, doi: 10.3390/atmos14010079.

[21] S. C. Chan, S. K. Behera, and T. Yamagata, "Indian Ocean Dipole influence on South American rainfall," *Geophysical Research Letters*, vol. 35, no. 14, p. 2008GL034204, Jul. 2008, doi: 10.1029/2008GL034204.

[22] B. V. R. Punyawardena and N. J. Cherry, "Assessment of the predictability of seasonal rainfall in Ratnapura using the southern oscillation and its two extremes," *J. Natn. Sci. Foundation Sri Lanka*, vol. 27, no. 3, p. 187, Sep. 1999, doi: 10.4038/jnsfsr.v27i3.3059.

[23] R. Suppiah, "Extremes of the southern oscillation phenomenon and the rainfall of Sri Lanka," *Int. J. Climatol.*, vol. 17, no. 1, pp. 87–101, Jan. 1997, doi: 10.1002/(SICI)1097-0088(199701)17:1<87::AID-JOC95>3.0.CO;2-X.

[24] R. P. Kane, "ENSO relationship to the rainfall of Sri Lanka," *Int. J. Climatol.*, vol. 18, no. 8, pp. 859–871, Jun. 1998, doi: 10.1002/(SICI)1097-0088(19980630)18:8<859::AID-JOC264>3.0.CO;2-W.

[25] H. Hersbach *et al.*, "The ERA5 global reanalysis," *Quart J Royal Meteoro Soc*, vol. 146, no. 730, pp. 1999–2049, Jul. 2020, doi: 10.1002/qj.3803.

[26] Z. Xie, A. Duan, and Q. Tian, "Weighted composite analysis and its application: an example using ENSO and geopotential height," *Atmospheric Science Letters*, vol. 18, no. 11, pp. 435–440, Nov. 2017, doi: 10.1002/asl.786.

[27] X. Wang and C. Wang, "Different impacts of various El Niño events on the Indian Ocean Dipole," *Clim Dyn*, vol. 42, no. 3–4, pp. 991–1005, Feb. 2014, doi: 10.1007/s00382-013-1711-2.

[28] P. J. Webster and S. Yang, "Monsoon and Enso: Selectively Interactive Systems," *Quart J Royal Meteoro Soc*, vol. 118, no. 507, pp. 877–926, Jul. 1992, doi: 10.1002/qj.49711850705.

[29] J. G. Lockwood, "700□mb Contour charts for south□east asia and neighbouring areas," *Weather*, vol. 21, no. 9, pp. 325–334, Sep. 1966, doi: 10.1002/j.1477-8696.1966.tb02889.x.

[30] A. L. Kijazi and C. J. C. Reason, "Relationships between intraseasonal rainfall variability of coastal Tanzania and ENSO," *Theor. Appl. Climatol.*, vol. 82, no. 3–4, pp. 153–176, Sep. 2005, doi: 10.1007/s00704-005-0129-0.

 ©IJSRED: All Rights are Reserved