



Independent and combined impacts of ENSO and IOD on Maha season rainfall and paddy production in Sri Lanka

ARUNI ABEYSEKERA^{1*}, SHIROMANI JAYAWARDENA², RANJITH PUNYAWARDENA¹,

THAVANANTHAN SIVANANTHAWERL³ and BUDDHI MARAMBE³

¹Natural Resources Management Centre, Department of Agriculture, Peradeniya, Sri Lanka

²Regional Integrated Multi-Hazard Early Warning System (RIMES), Klong Luang, Pathumthani, Thailand

³Department of Crop Science, Faculty of Agriculture, University of Peradeniya, Sri Lanka

(Received 28 January 2026, Accepted 10 September 2026)

*Corresponding author's email: arunikasekera@gmail.com

सार – श्रीलंका सहित दक्षिण एशिया में वर्षा को प्रभावित करने वाले प्रमुख वृहद जलवायु कारकों में अल नीनो-दक्षिणी दोलन (ENSO) और हिंद महासागर द्विध्रुव (IOD) शामिल हैं। महा ऋतु (अक्टूबर से फरवरी) श्रीलंका में धान की खेती का मुख्य मौसम है, और इस पर वार्षिक जलवायु परिवर्तनशीलता का गहरा प्रभाव पड़ता है। हालांकि, मौसमी वर्षा की अनियमितताओं और धान उत्पादन पर ENSO और IOD के प्रभावों का मात्रात्मक विश्लेषण अभी तक पूरी तरह से नहीं किया गया है। इस अध्ययन में मुख्य रूप से महा ऋतु की वर्षा, विशेष रूप से द्वितीय अंतर-मानसून (SIM; अक्टूबर-नवंबर) के दौरान, और श्रीलंका में धान उत्पादन पर ENSO और IOD के स्वतंत्र और संयुक्त प्रभावों का विश्लेषण किया गया है। इसके लिए 41 मौसम विज्ञान केंद्रों से प्राप्त दैनिक वर्षा डेटा, ENSO और IOD घटनाओं की पहचान के लिए क्रमशः महासागर नीनो सूचकांक (ONI) और द्विध्रुवीय मोड सूचकांक (DMI), तथा 1979 से 2020 तक के जिलावार धान उत्पादन डेटा (उत्पादकता और खेती योग्य क्षेत्र दोनों को दर्शाते हुए) का उपयोग किया गया। सांख्यिकीय विश्लेषणों में एक-तरफा एनोवा, ची-स्क्वायर परीक्षणों के साथ क्रॉस-टैबुलेशन और एक-नमूना टी-परीक्षण ($p=0.05$) शामिल थे। 41 मौसम स्टेशनों पर किए गए सर्वेक्षणों में, आईओडी-सकारात्मक वर्षों से जुड़े अल नीनो वर्षों में, स्वतंत्र अल नीनो वर्षों (आईओडी से संबद्धता के बिना) की तुलना में एसआईएम वर्षा अवधि के दौरान औसत संचयी वर्षा में लगभग 85% अधिक सकारात्मक विचलन देखा गया। चयनित प्रमुख धान उत्पादक जिलों में से 87% में, आईओडी-सकारात्मक वर्षों से जुड़े अल नीनो वर्षों के दौरान महा ऋतु में धान की पैदावार तटस्थ वर्षों की तुलना में बढ़ी। आईओडी-नकारात्मक वर्षों से जुड़े ला नीना और स्वतंत्र ला नीना वर्षों (आईओडी से संबद्धता के बिना) में एसआईएम वर्षा में कमी देखी गई, जिसमें चयनित 15 प्रमुख धान उत्पादक जिलों में तटस्थ वर्षों की तुलना में आईओडी-नकारात्मक वर्षों के साथ ला नीना के अंतर्गत महा ऋतु में धान की पैदावार में 80% की कमी आई। अल नीनो घटनाओं से जुड़े IOD-सकारात्मक वर्षों में सभी चयनित मौसम स्टेशनों (100%) पर औसत संचयी SIM वर्षा में उल्लेखनीय वृद्धि देखी गई, जिसके परिणामस्वरूप सभी (100%) प्रमुख धान उत्पादक जिलों में धान उत्पादन में सकारात्मक विसंगतियाँ पाई गईं। अध्ययन अवधि के दौरान एकमात्र स्वतंत्र IOD-सकारात्मक घटना (ENSO संबंध के बिना), 2019/2020 के महा वर्ष में, SIM वर्षा में वृद्धि और 3.19 मिलियन मीट्रिक टन का उच्चतम दर्ज धान उत्पादन देखा गया। कुल मिलाकर, निष्कर्ष महा कृषि मौसम के पहले भाग और श्रीलंका में धान उत्पादन के दौरान SIM वर्षा परिवर्तनशीलता पर ENSO और IOD के स्पष्ट सहक्रियात्मक प्रभाव को दर्शाते हैं, जो मौसमी कृषि नियोजन और नीति निर्माण में इसके महत्व को रेखांकित करता है।

ABSTRACT. The *El Niño*-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) are among the dominant large-scale climate modes affecting rainfall in South Asia including Sri Lanka. The Maha season (October to February) is the principal paddy cultivation season in Sri Lanka, and its performance is strongly influenced by inter-annual climate variability. However, the influences of ENSO and IOD on seasonal rainfall anomalies and paddy production remain insufficiently quantified. This study mainly examined the independent and combined impacts of ENSO and IOD on Maha season rainfall, particularly during the Second Inter-monsoon (SIM; October-November), and the associated paddy production in Sri Lanka. Daily rainfall data from 41 meteorological stations, the Ocean Niño Index

(ONI) and Dipole Mode Index (DMI) for identifying ENSO and IOD events, respectively, and district-wise paddy production data (reflecting both productivity and cultivated extent) from 1979 to 2020 were studied. Statistical analyses included one-way ANOVA, cross-tabulation with chi-square tests, and one-sample t-tests ($p=0.05$). *El Niño* years associated with IOD-positive years showed approximately 85% higher positive deviations in mean cumulative rainfall across 41 weather stations compared to independent *El Niño* years (without IOD association) during SIM rainy period. Maha season paddy production increased during *El Niño* years associated with IOD-positive years compared to neutral years in 87% of the selected 15 major paddy-growing districts. *La Niña* associated with IOD-negative years and independent *La Niña* years (without IOD association) exhibited reduced SIM rainfall, with 80% reduction in Maha season paddy production under *La Niña* with IOD-negative years compared to neutral years among selected major paddy-growing districts. The IOD-positive years associated with *El Niño* events showed a significant increase in mean cumulative SIM rainfall across all selected weather stations (100%), resulting in positive paddy production anomalies in all (100%) major paddy-growing districts. The only independent IOD-positive event (without ENSO association) during the study period, in 2019/2020 Maha, showed significant increased SIM rainfall and the highest recorded paddy production of 3.19 million metric tons. Overall, the findings demonstrate a clear synergistic influence of ENSO and IOD on the SIM rainfall variability, during the first half of the Maha cultivation season and on paddy production in Sri Lanka, underscoring its importance of seasonal agricultural planning and policy formulations.

Key words – ENSO, IOD, Maha season, Paddy production, Second Inter-monsoon rains, Sri Lanka.

1. Introduction

The *El Niño*–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) are two climate drivers that arise from ocean–atmosphere interactions, leading to changes in wind patterns, ocean currents, and wave dynamics (Latif *et al.*, 1998; McPhaden *et al.*, 2006; Cai *et al.*, 2019). ENSO consists of two complementary phases in the tropical Pacific: *El Niño*, the warm phase, and *La Niña*, the cold phase (McPhaden, 2002). Similarly, the IOD cycle comprises two opposite phases: the IOD-positive (warm phase) and the IOD-negative (cold phase), in the context of the western Indian Ocean (Saji *et al.*, 1999; Webster *et al.*, 1999). These opposite phases of ENSO and IOD behave differently and result in significant variations in global weather patterns, including those over the Indian Ocean.

Before the discovery of the IOD, climate scientists believed that the tropical Indian Ocean did not possess an inherent mode of coupled variability. The conventional view suggested that the region passively responded to and amplified variations associated with ENSO (Wallace *et al.*, 1998). Saji *et al.* (1999) showed the independence of IOD in the Indian Ocean from ENSO in the Pacific Ocean and reported a moderately insignificant correlation between ENSO-IOD events. According to Jiang *et al.* (2021), the impact of IOD on the rainfall pattern of a specific country or location can be influenced by ENSO. Black *et al.* (2003) demonstrated that IOD cannot be considered in isolation as it is closely interconnected with ENSO and East African rainfall patterns, which are influenced by IOD and further amplified by ENSO.

The *El Niño* can trigger an IOD-positive event, characterized by positive SST anomalies in the western tropical Indian Ocean and negative SST anomalies along the Sumatra-Java coast (Saji *et al.*, 1999; Webster *et al.*, 1999; Allan *et al.*, 2001; Song *et al.*, 2007). Although the opposite sea-air interactions lead to the generation of

La Niña and negative IOD events, Sea Level Anomaly (SLA) signatures during negative IOD and *La Niña* events are much weaker (Aparna *et al.*, 2012).

A considerable number of IOD events also occur without triggering by ENSO. According to Vinayachandran *et al.*, (2009), about 50% of the IOD events in the past 100 years have co-occurred with ENSO, and the other half independently. However, Yamagata *et al.* (2004) reported that only one-third of IOD events are associated with ENSO events.

Several studies have revealed that the inter-basin SST anomalies are important in improving seasonal and inter-annual weather predictions (Cai *et al.*, 2019; Wang, 2019). ENSO is characterized by basin-wide ocean–atmosphere anomalies, resulting in coherent SST and sea-level pressure patterns across the Indian Ocean (Klein *et al.*, 1999; Vinayachandran *et al.*, 2009). In contrast, these anomalies during IOD events exhibit a distinct east–west dipole structure within the Indian Ocean (Saji *et al.*, 1999; Webster *et al.*, 1999). Supporting this distinction, Vinayachandran *et al.* (2009), through a comparison of ENSO events with IOD events, showed that IOD events are strongly phase-locked to the seasonal cycle with anomalies typically developing during boreal summer (June–August) and intensifying during boreal autumn (September–November).

Climate is one of the most important factors in crop cultivation, as it can significantly influences the growth, yield, and quality of the crop. Rainfall amounts, seasonal distribution, intensity, frequency of occurrence, and spatial and temporal variations are especially crucial for tropical agriculture (Jackson, 1977; Nieuwolt, 1982; Cline, 2007; Thomas and Joseph, 2024). The comprehensive analysis of existing literature has conclusively shown a significant shortfall in agricultural production, attributed to the impact of anomalous weather conditions experienced across the globe (Rosenzweig and

Parry, 1994; Lesk *et al.*, 2016). Several studies have demonstrated the relationship between large-scale climate drivers such as the ENSO and the IOD, and their impacts on crop yields globally (Zhang *et al.*, 2008; Apriyana *et al.*, 2019; Cherian *et al.*, 2021).

Sri Lanka is an island in the Indian Ocean, situated between 5°55' and 9°50' N latitude and 79°42' and 81°53' E longitude (Survey Department of Sri Lanka, 2007). Despite its relatively small land area, the country experiences considerable weather variability due to its diverse agro-ecological conditions. There are limited studies in Sri Lanka that examine the impacts of ENSO and IOD on crop production. According to the available studies, the paddy production, harvest, and average yield during the *Maha* season in Sri Lanka have exhibited a clear correlation with increased rainfall from October to December during *El Niño* and IOD-positive events (Zubair, 2002; Abeysekera *et al.*, 2023).

Rice (de-husked paddy; *Oryza sativa* L) is the staple food of about 22.2 million Sri Lankan community. (Department of Census and Statistics, 2025). About 34% of the total cultivated area of the country is occupied by paddy (Department of Agriculture, 2024). Water availability is the major limiting factor of paddy cultivation in the country. Sri Lanka has four distinct rainfall seasons, namely, the First Inter-monsoon (FIM), Southwest Monsoon (SWM), Second Inter-monsoon (SIM) and Northeast Monsoon (NEM) (Punyawardena, 2020). Based on these four rainfall seasons, paddy cultivation is being done in two cultivation seasons, namely, *Yala* (FIM + SWM; minor cultivating season; March – September) and *Maha* season (SIM + NEM; major cultivating season; October to February) (Punyawardena, 2020). A particular season is defined considering the sown period or land preparation activities during inter-monsoon rains and harvesting activities at the tail end of the monsoonal rains. The deviation in sown and harvested extent, the average yield thereby the paddy production in Sri Lanka is directly correlated with the deviations of the seasonal rainfall (Yoshino and Suppiah, 1983; Punyawardena, 2002; Marambe *et al.*, 2015). Therefore, a scientific assessment of the impacts of ENSO and IOD events, as well as their interactions, on seasonal rainfall climatology and national-scale paddy cultivation in Sri Lanka is of paramount importance for developing appropriate adaptation strategies to enhance paddy production under adverse weather conditions.

This study mainly focuses on the *Maha* season, the major paddy-growing season in Sri Lanka. Rainfall deviations associated with ENSO and IOD were assessed considering both independent events and combined events to determine the extent to which their interactions amplify

or suppress rainfall anomalies. Based on the observed rainfall responses, associated anomalies in paddy production were also analyzed. The findings provide insights for developing climate-adaptive agronomic strategies, including adjustments in cultivation extent, selection of suitable crop durations and varieties, improved water management and storage practices under water-scarce conditions, and enhanced drainage and flood-adaptive cultivation practices during flood-prone seasons. Such decisions can be supported through improved agrometeorological advisories, contributing to reduced production losses, optimized cultivation costs, enhanced national paddy production, and the development of appropriate policy instruments to strengthen food security.

2. Data and methodology

2.1. Sea Surface Temperature (SST) data

The Ocean Nino Index (ONI) and the Dipole Mode Index (DMI) are the indices used to identify ENSO and IOD events, respectively. ONI (https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php) and DMI (https://psl.noaa.gov/gcos_wgsp/Timeseries/DMI/) data were obtained from the National Oceanic and Atmospheric Administration (NOAA) of the United States Climate Prediction Centre (CPC).

2.2. Rainfall data

Daily rainfall data were collected from 41 weather stations for a 45-year period from 1976 to 2020. Fig. 1 illustrates the spatial distribution of the selected weather stations across the three major climatic zones and the 25 administrative districts of Sri Lanka.

2.2.1. Rainfall indices

Four rainfall indices were considered to compare the mean values of ENSO and IOD years with those of neutral years. Cumulative rainfall (mm) was defined as the total rainfall received during the season. The number of wet days was calculated as the total number of days receiving rainfall greater than 1 mm during the season (Nastos and Zerefos, 2009; Zhang *et al.*, 2011). The number of heavy rainfall events was defined as the total number of days with rainfall exceeding the 90th percentile threshold calculated for the standard average period of the study (IPCC, 2014; Camuffo *et al.*, 2020). The maximum consecutive dry days represented the longest sequence of consecutive days receiving less than 1 mm of rainfall during the season (Nastos and Zerefos, 2009; Zhang *et al.*, 2011). However, for the descriptive analysis, only the mean cumulative rainfall was considered.

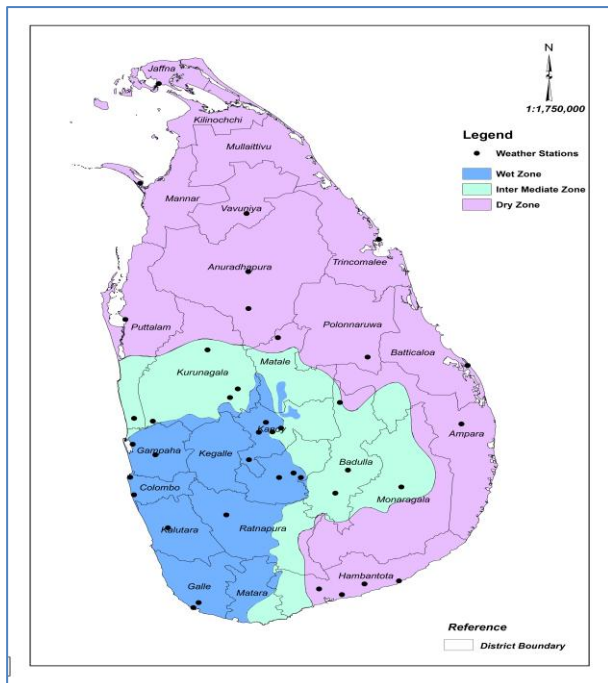


Fig. 1. Location map of the selected weather stations across the three major climatic zones and the 25 administrative districts in Sri Lanka (Source: Survey Department of Sri Lanka and NRM, Department of Agriculture, Sri Lanka)

2.3. Paddy production data

Since paddy production reflects the combined influence of cultivated extent and yield, this study focused on district-level paddy production data for the analysis. District-wise paddy production data were obtained from the Department of Census and Statistics (DCS) Sri Lanka, covering a 42-year period from 1979 to 2020 (DCS – various an array of publications).

Paddy is cultivated as a wetland crop in all 25 administrative districts but the area under cultivation differs among districts. (DCS, 2025). Among them the main paddy-growing districts were considered for further analysis. To obtain a threshold value of identifying major paddy-growing areas, the districts were sorted using several parameters such as percentage of paddy lands out of the total arable lands (>30%), the average yield in each district (>4.3 t/ha), the districts located in the Dry and Intermediate zones (if it is spread in more than one zone, the zone with the higher extent was considered), and the contribution to the national paddy production (>2%) (DCS, 2025 and Land Use Policy Planning Department, 2019). Based on the aforesaid parameters, 15 districts were identified as the major paddy-growing districts of the country, eleven from Dry zone namely, Anuradhapura, Polonnaruwa, Ampara, Batticaloa, Trincomalee,

Kilinochchi, Mullaitivu, Mannar, Vavuniya, Puttalam, Hambantota and four from Intermediate zone namely, Kurunegala, Badulla, Moneragala, and Matale (Abeysekera *et al.*, 2023).

2.4. ENSO and IOD relationships

The rainfall deviations associated with four selected rainfall indices, during the two opposite phases of the ENSO and the IOD were examined by composite analysis approach. Means of ENSO and IOD years across study period were compared, considering SIM rainfall, relative to the corresponding means of ENSO and IOD neutral years (considering the SST data mentioned under section 2.1). To assess the independent influence of ENSO and IOD, composite groups were constructed by eliminating the interactions of each other. The percentage deviations of mean rainfall values were calculated compared to neutral years to highlight the typical spatial and temporal deviations associated with each climate mode (Iizumi *et al.*, 2014; Abeysekera *et al.*, 2023).

2.5. Paddy production deviations

A similar composite analysis was applied to assess paddy production deviations associated with the two phases of ENSO and IOD during the Maha season. Mean paddy production during independent and combined ENSO–IOD years was compared with that during neutral years. Seasonal percentage deviations from neutral-year production were calculated for each category (Iizumi *et al.*, 2014; Abeysekera *et al.*, 2023). These deviations were used to quantify the impacts of ENSO and IOD on paddy production.

2.6. Test of statistical significance

Statistical analyses were performed using one-way analysis of variance (ANOVA), cross-tabulation Chi-square tests, and one-sample t-tests implemented in Minitab 18 statistical software, with statistical significance evaluated at $p = 0.05$ level. When the number of events in a given category was fewer than three, formal statistical testing was not conducted; instead, descriptive analyses were used to examine the behavior of the specific event(s) and to identify apparent trends.

3. Results and discussion

The Maha season in Sri Lanka begins with the SIM rains (October to November) and continues with the NEM rains (December to February). The influence of ENSO persists throughout the Maha season, as it affects both SIM and NEM rainfall (Punyawardena and Cherry, 1999; Zubair *et al.*, 2008; Hapuarachchi and Jayawardena, 2015;

TABLE 1

Independent and combined ENSO and IOD events during the SIM rainfall season over the study period

SIM rainfall season							
ENSO events				IOD events			
El	IEl	La	ILa	IODp	IIODp	IODn	IIODn
1976	1976	1983	1983	1982	2019	1980	1980
1977	1977	1984	1988	1994		1984	1996
1979	1979	1988	1995	1997		1996	
1982	1986	1995	1999	2006		1998	
1986	1987	1998	2000	2011			
1987	1991	1999	2007	2015			
1991	2002	2000	2010	2018			
1994	2004	2007	2011				
1997	2009	2010	2016				
2002	2014	2011	2017				
2004		2016					
2006		2017					
2009							
2014							
2015							
2018							

SIM: second inter-monsoon; ENSO: *El Niño*–Southern Oscillation; IOD: Indian Ocean Dipole; El: *El Niño* years; IEl: Independent *El Niño* years (without IOD years); La: *La Niña* years; ILa: Independent *La Niña* years (without IOD years); IODp: IOD-positive years; IIODp: Independent IOD-positive years (without ENSO years); IODn: IOD-negative years; IIODn: Independent IOD-negative years (without ENSO years). Source: CPC (NOAA)

Abeysekera *et al.*, 2017; Abeysekera *et al.*, 2019). In contrast, the impact of the IOD during the *Maha* season is predominantly observed during the SIM period and taper-off by early December (Zubair *et al.*, 2003; Jayawardena *et al.*, 2015; Abeysekera *et al.*, 2020; Abeysekera *et al.*, 2021; Kajakokulan *et al.*, 2023). Therefore, the SIM rainy period was selected to examine the combined impacts of ENSO and IOD in comparison with their independent impacts. Previous studies have reported positive rainfall anomalies for *El Niño* years and negative rainfall anomalies for *La Niña* years during the SIM season, in Sri Lanka (Suppiah, 1989; Kane, 1998; Punyawardena and Cherry, 1999; Zubair *et al.*, 2008; Hapuarachchi and Jayawardena, 2015; Abeysekera *et al.*, 2017; Abeysekera *et al.*, 2019). The limited studies conducted on the influence of the IOD also showed an increase in SIM rainfall. (Zubair *et al.*, 2003; Abeysekera *et al.*, 2020; Abeysekera *et al.*, 2021; Kajakokulan *et al.* 2023). The present study examined the impacts of ENSO and the IOD by eliminating the interactions of each other.

The *El Niño* years were predominantly observed in association with IOD-positive years, however, without a notable association with IOD-negative years. Similarly, *La Niña* years were mainly associated with IOD-negative

years. Associations of *La Niña* years with IOD-positive years were rare and when present, were weak and short-lived (Bureau of Meteorology, 2024; National Oceanic and Atmospheric Administration, 2024). Therefore, for the analysis, *El Niño* years associated with IOD-positive events and *La Niña* years associated with IOD-negative events were considered.

According to Table 1, among the 16 *El Niño* years observed during the study period, 10 *El Niño* years remained after removing the combined *El Niño* and IOD-positive events during the SIM rainfall period. Similarly, among the 12 *La Niña* years, 10 remained after removing the combined *La Niña* and IOD-negative events to assess the independent impact of *La Niña* years in the SIM rainfall season (Table 1).

During the 45-year period, only one IOD-positive year (2019) remained after excluding *El Niño*–associated years from the list of IOD-positive years during the SIM season (Table 1). Among the four IOD-negative years, only two independent IOD-negative years remained after excluding *La Niña*–associated events. Consequently, statistical testing could not be performed for these remaining individual IOD-positive and negative years due

TABLE 2

Percentage of positive and negative SIM rainfall deviations during *El Niño* and *La Niña* years associated with corresponding IOD phases and independent ENSO years (without association with IOD years), relative to neutral years across selected weather stations [numbers in parentheses indicate statistically significant events ($p < 0.05$) out of 41 weather stations]

Rainfall index	Mean cumulative rainfall	Number of wet days	Number of heavy rainfall events	Mean maximum consecutive dry days
<i>El Niño</i> years associated with IOD-positive years	95% (06)	100% (34)	83% (13)	-100% (06)
Independent <i>El Niño</i> years (without association with IOD years)	66% (00)	98% (26)	51% (04)	-93% (00)
<i>La Niña</i> years associated with IOD-negative years	-90% (09)	-95% (27)	-88% (16)	88% (01)
Independent <i>La Niña</i> years (without association with IOD years)	-83% (04)	-93% (27)	-93% (13)	76% (00)

to the limited sample size. Therefore, a descriptive analysis was conducted for the IOD-positive event in 2019 and the two independent IOD-negative events, focusing on mean cumulative rainfall values.

3.1. The impact of ENSO years associated with corresponding IOD phases over independent *El Niño* and *La Niña* years (without association with IOD years) on SIM rainfall deviations compared to neutral years

Across all four considered rainfall indices, the rainfall deviations during *El Niño* years associated with IOD-positive events showed an apparent increase during the SIM period across 41 selected weather stations compared to neutral years (Table 2). Independent *El Niño* years (without association with IOD years) were also observed above-normal rainfall during the SIM season, compared to neutral years even without counting very strong *El Niño* years or Super *El Niño* 's, during the study period namely, 1982/83, 1997/98, and 2015/16 (National Aeronautics and Space Administration, 2023).

The SIM period is the least drought-prone period of the year in Sri Lanka (Jayamaha, 1976). Consequently, the observed increase in rainfall with statistically significant events (Table 2), during *El Niño* years is of considerable importance for agricultural planning. Higher rainfall is beneficial for land preparation, crop establishment, and increased reservoir storage. However, heavy rainfall events accompanied by an increased number of wet days may lead to crop damage, necessitating re-establishment of the crop, mainly by re-sowing. Hence, understanding the strength of ENSO impacts, particularly when ENSO is associated with other climate drivers such as the IOD, is essential for impact-based agricultural decision-making.

During both *La Niña* years associated with IOD-negative years and independent *La Niña* years (without

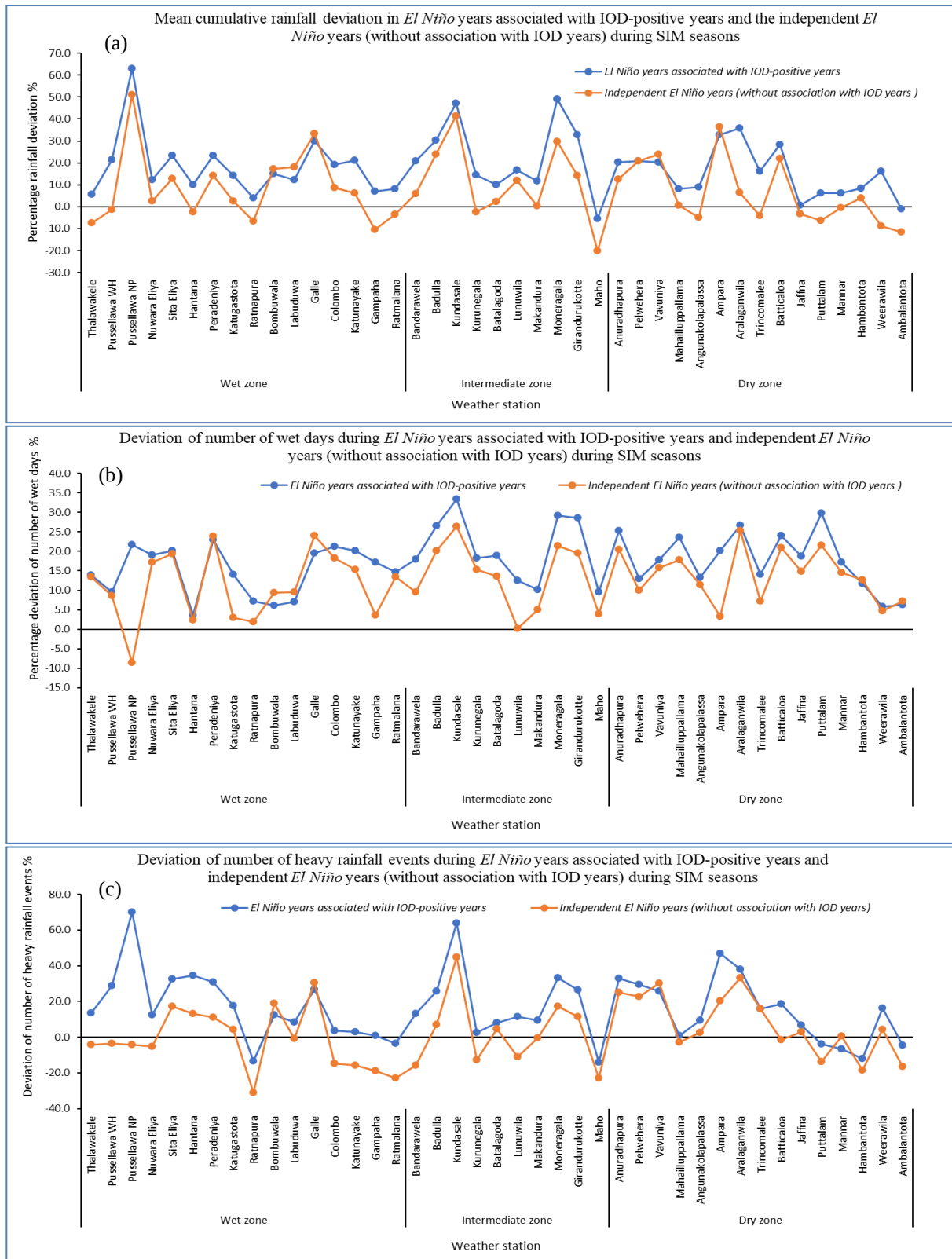
association with IOD years), an apparent reduction of rainfall was observed compared to the neutral years (Table 2).

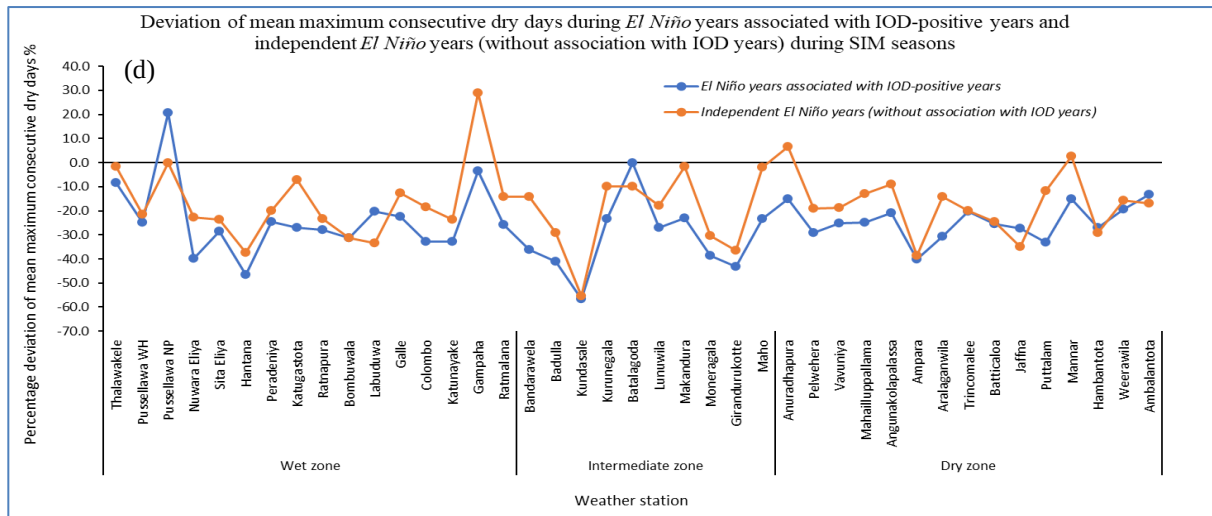
Among the four rainfall periods in Sri Lanka, SIM is the period that experiences low-pressure systems, depressions and cyclones, especially in the Bay of Bengal (Yoshino and Suppiah, 1984; Punyawardena, 2008; Hapuarachchi and Jayawardena, 2015). Heavy rainfall generated by these systems can occur during SIM periods irrespective of specific climate phases such as ENSO or IOD conditions. This is evident from observations of intense rainfall during SIM periods influenced by ENSO and IOD events as well as during ENSO and IOD neutral conditions. For example, the ENSO and IOD neutral SIM period in 2024, experienced intense rainfall in late November due to Cyclone Fengal, while the *La Niña* affected SIM period in 2025 was strongly influenced by heavy rainfall associated with Cyclone Ditwah during late November and early December.

Despite such rainfall events occurring due to the activation of weather systems during the study period, the overall reduction in rainfall observed during *La Niña* years remains an important consideration for agricultural planning.

3.2. Comparative impact of ENSO years associated with corresponding IOD phases over independent *El Niño* and *La Niña* years (without association with IOD years) on SIM rainfall

A further comparison was conducted between *El Niño* years associated with IOD-positive years and independent *El Niño* years (without association with IOD years; Fig. 2[a-d]).





Figs. 2(a-d). Rainfall deviations in (a) mean cumulative rainfall, (b) number of wet days, (c) number of heavy rainfall events and (d) maximum consecutive dry days during the SIM period, comparing *El Niño* years associated with IOD-positive years to independent *El Niño* years (without association with IOD years)

During *El Niño* years associated with IOD-positive years, over 85%, 88%, and 90% of the 41 selected weather stations showed higher positive deviations in mean cumulative rainfall, number of wet days, and number of heavy rainfall events, respectively, compared to the independent *El Niño* years (without association with IOD years; Fig. 2[a-c]). The mean maximum consecutive dry days showed negative deviations over 85% of the 41 selected weather stations during *El Niño* years associated with IOD-positive years, compared to independent *El Niño* years (without association with IOD-positive years; Fig. 2[d]). The observed results, clearly revealed that when *El Niño* years are associated with IOD-positive years, it leads to synergize the above-normal rainfall received during the SIM period. Independent *El Niño* years (without association with IOD years) show increased SIM rainfall; however, the weak to moderate strength of these events limits the occurrence of heavy rainfall events.

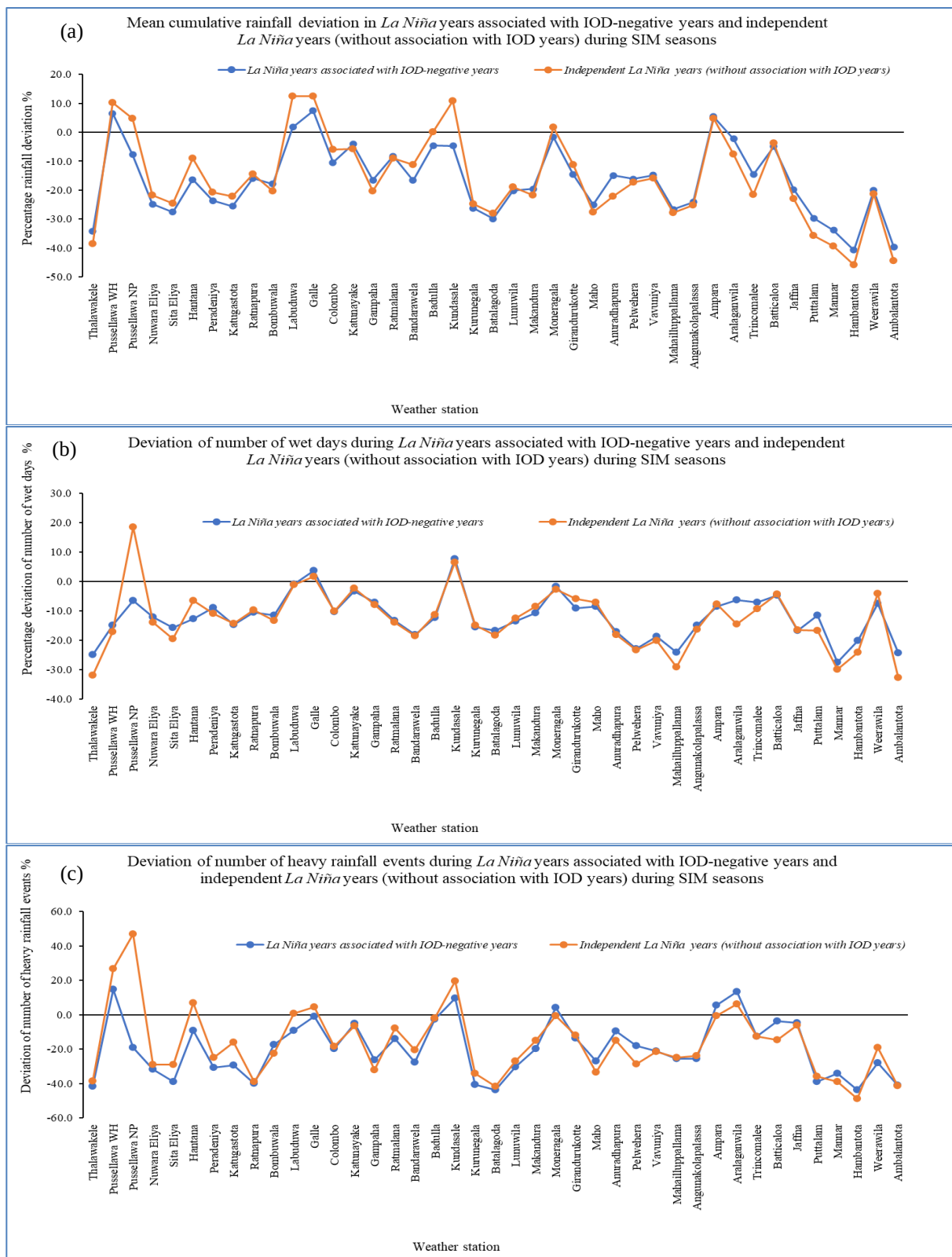
However, the comparison of *La Niña* years associated with IOD-negative years with independent *La Niña* years (without association with IOD years) shows only a marginal deviation in SIM rainfall (Fig. 3[a-d]). The mean cumulative rainfall received during the SIM season and number of wet days during independent *La Niña* years (without association with IOD years) did not show any detectable deviations in almost all selected weather stations, compared to *La Niña* years associated with IOD-negative events (Fig. 3[a-b]). Over 63% of selected weather stations showed higher negative deviations in the number of heavy rainfall events (Fig. 3[c]) and over 61% positive deviations in mean maximum consecutive dry days (Fig. 3[d]), during *La Niña* years associated with IOD-negative events compared to

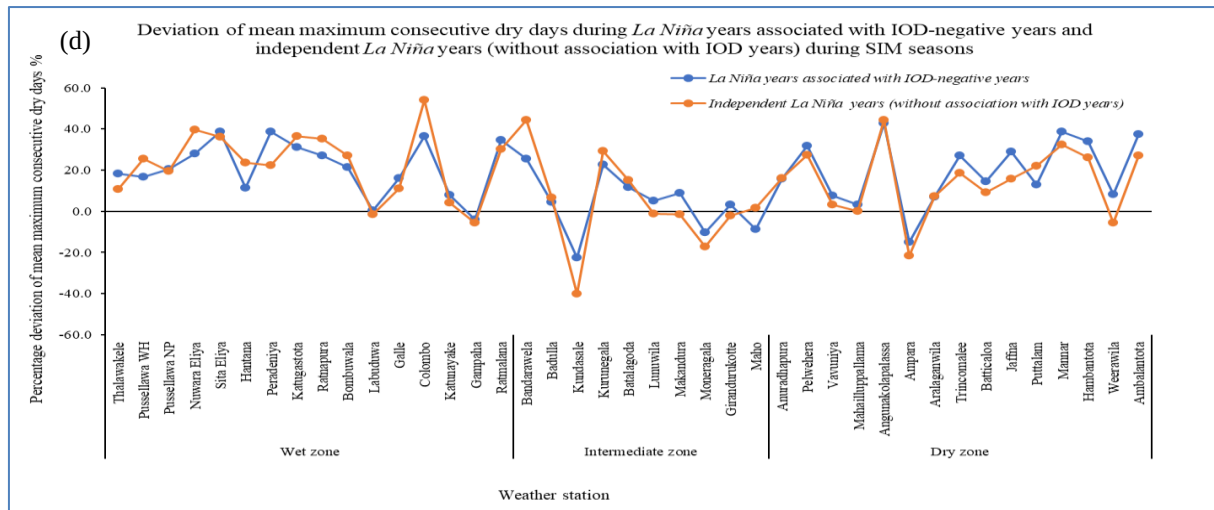
independent *La Niña* years (without association with IOD years) out of 41 selected weather stations. As shown in Table 1, only two of the 12 *La Niña* years were associated with IOD-negative events, and among these two only 1998 was a strong *La Niña* event. This limited number of associated events may explain the marginal differences observed.

3.3. The impact of positive and negative SIM rainfall deviations during ENSO years associated with corresponding IOD events and independent *El Niño* and *La Niña* years (without association with IOD years) on paddy production during Maha seasons

Over 87% of 15 major paddy-growing districts showed positive anomalies in paddy production during *El Niño* years associated with IOD positive years compared to neutral years (Fig. 4). In contrast, the percentage anomalies in paddy production during the Maha season, influenced by independent *El Niño* years (without association with IOD events), showed negative deviations in 53% of selected major paddy-growing districts compared to neutral years (Fig. 4). The absence of clear percentage production anomalies during independent *El Niño* years may be attributed to the fact that, after excluding IOD-positive events, the remaining *El Niño* events were predominantly weak to moderate in intensity and therefore had a lower impact on paddy production.

The percentage anomalies in Maha season paddy production during *La Niña* years associated with IOD-negative years (67%), compared with independent *La Niña* years (without association with IOD years), showed similar negative deviations in most of the selected major





Figs. 3(a-d). Rainfall deviations in (a) mean cumulative rainfall, (b) number of wet days, (c) number of heavy rainfall events and (d) maximum consecutive dry days during the SIM period comparing La Niña years associated with IOD-negative years to independent La Niña years (without association with IOD years)

paddy-growing districts relative to neutral years under the SIM rainfall variations. A marginal exception was observed in Ampara District. (Fig. 4). Positive deviations were observed only in the Polonnaruwa, Hambantota, and Moneragala districts.

A study conducted to find the ENSO and IOD impact on annual coffee production in Indonesia, including five major production centres, has shown that the effects of ENSO and IOD were different in each region. However, the highest decline in production occurred in the *La Niña* year in almost all production centres (Sarvina *et al.*, 2021).

3.4. The impact of IOD years associated with corresponding ENSO phases over independent IOD-positive and IOD-negative years (without association with ENSO years) on SIM rainfall deviations compared to neutral years.

The comparison of rainfall deviations in the IOD-positive years associated with *El Niño* years across all 41 selected weather stations showed a significant increase during the SIM period compared to neutral years (Table 3).

The SIM period, which receives the highest rainfall within two months, shows the most widespread rainfall distribution across the country (Department of Meteorology, 2023). However, during IOD-negative years associated with *La Niña* years, a significant reduction in SIM rainfall has been reported by more than 85% of weather stations related to all four rainfall indices (Table 3).

The only independent IOD-positive event, (without association with ENSO) which occurred in 2019, showed positive mean cumulative rainfall deviations at over 88% of the selected 41 weather stations compared to neutral years. The IOD-positive event in 2019, considered as a "Super IOD event" (Takaya, *et al.*, 2020), was notable for being the only one to persist without triggering an *El Niño*. The IOD-positive event observed in 2019 was an extreme and prolonged event a phenomenon not seen since the 1960s (Zhang and Du, 2021). Furthermore, the 2019 IOD-positive event is the first extreme IOD-positive event reported in the 21st century based on a rainfall metric and the DMI (Wang *et al.*, 2020). During the peak phase of the event, the SST anomaly in the western tropical Indian Ocean reached about 1 °C (NOAA, 2022).

Among the observed four IOD-negative years, the independent IOD-negative years (without association with ENSO years) in 1980 and 1996, showed negative deviations in mean cumulative rainfall over 78% of the 41 weather stations, compared to neutral years (Table 3).

3.5. Comparative impact of IOD years associated with corresponding ENSO phases over independent IOD-positive and IOD-negative years (without association with ENSO years) on SIM rainfall

Among the selected 41 weather stations, over 63%, showed higher positive deviations in mean cumulative rainfall during IOD-positive years associated with *El Niño* years, compared to the independent IOD-positive year (without association with ENSO) in 2019 (Fig. 5[a]). This increase was mainly due to the rainfall deviation in the

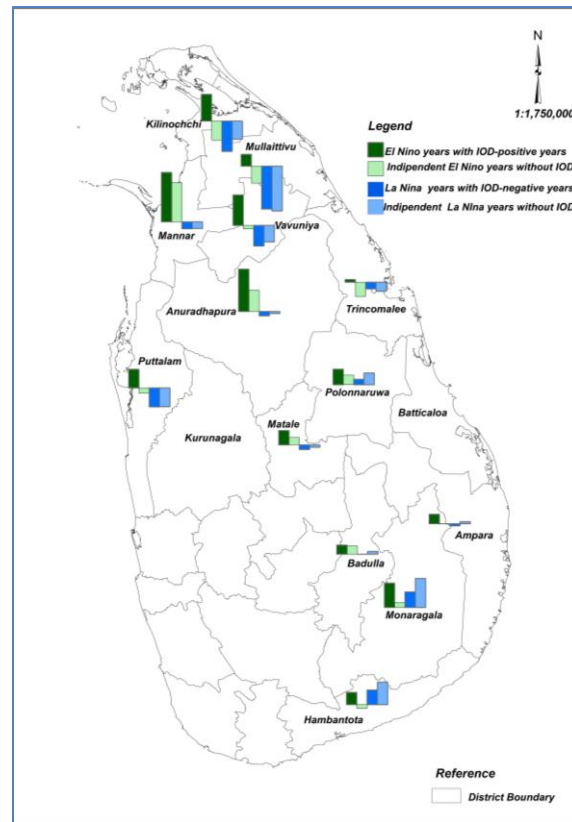


Fig. 4. The mean paddy production anomalies in Maha seasons, during to ENSO years associated with corresponding IOD events compared to independent *El Niño* and *La Niña* years (without association with IOD years)

TABLE 3

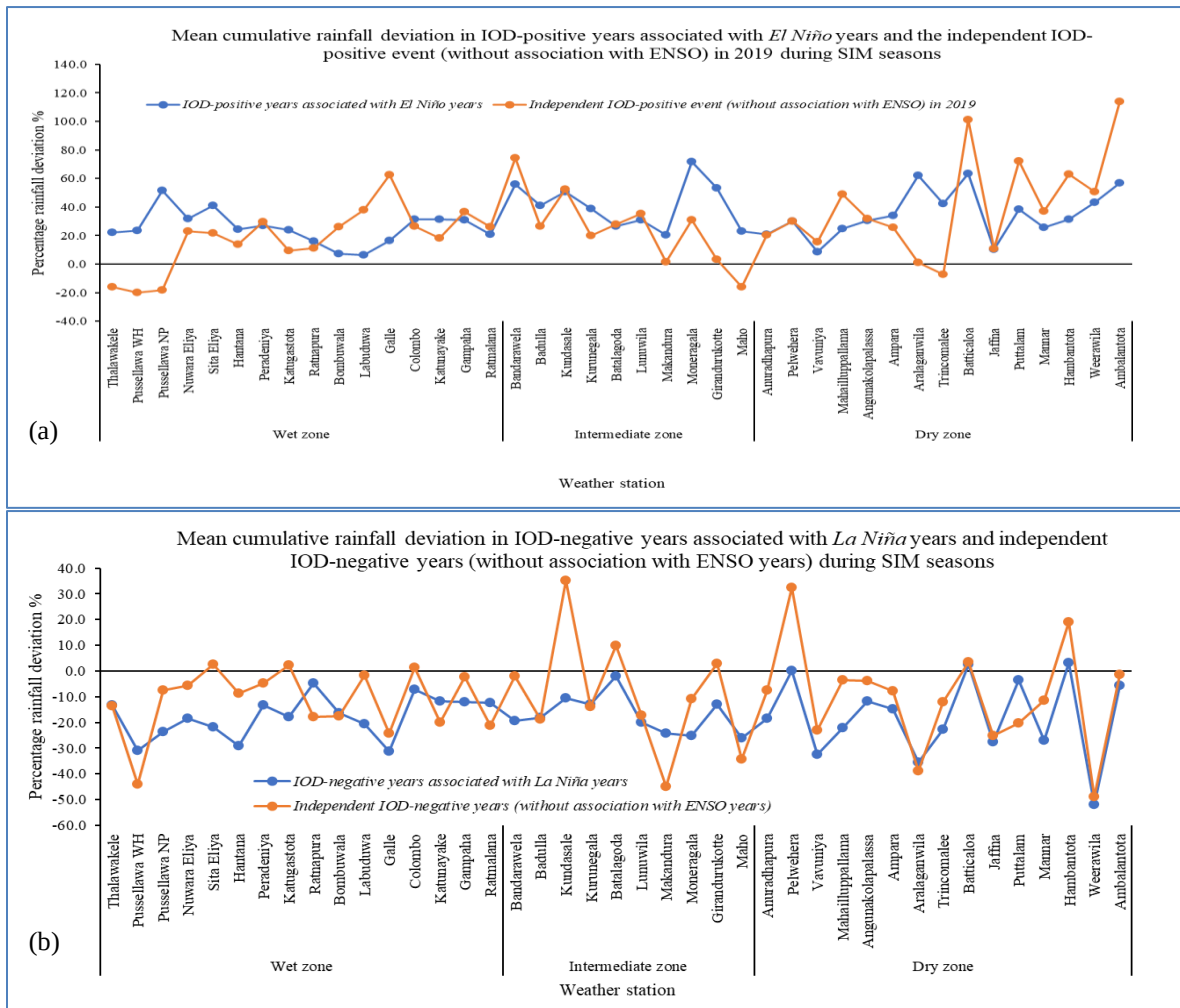
Percentage of positive and negative SIM rainfall deviations during IOD-positive and IOD-negative years associated with corresponding ENSO phases relative to neutral years across selected weather stations [numbers in parentheses indicate statistically significant events ($p < 0.05$) out of 41 weather stations]

Rainfall index	Mean cumulative rainfall	Number of wet days	Number of heavy rainfall events	Mean maximum consecutive dry days
IOD-positive years associated with <i>El Niño</i> years	100% (15)	95% (33)	100% (30)	-100% (09)
IOD-negative years associated with <i>La Niña</i> years	-93% (01)	-88% (17)	-85% (04)	95% (07)

SIM season caused by IOD-positive events synergized with *El Niño*.

The results of the study further revealed that, strong independent IOD events can also result in considerable positive deviations in SIM rainfall in Sri Lanka. However, the impact of such events may vary with the strength of the event. Therefore, it is difficult to draw definitive conclusions based on this single occurrence.

More than 66% of the selected weather stations out of 41, showed higher negative deviations in mean cumulative rainfall during IOD-negative years associated with *La Niña* years compared to independent IOD-negative years in 1980 and 1996 (without association with ENSO years; Fig. 5[b]). Therefore, descriptive analysis of this study indicates that independent IOD - negative years (without association with ENSO years) lead to reduced rainfall during the SIM season, and this effect is amplified



Figs. 5(a&b). Rainfall deviations in SIM rains comparing IOD years associated with corresponding ENSO years to the independent IOD-positive and IOD-negative events (without association with ENSO)

when these IOD- negative events are associated with *La Niña* years.

3.6. The impact of positive and negative SIM rainfall deviations during IOD years associated with corresponding ENSO events and independent IOD-positive and IOD-negative years (without association with IOD years) on paddy production during Maha seasons

All selected major paddy-growing districts in Sri Lanka showed positive anomalies in paddy production during the *Maha* season, influenced by IOD-positive years associated with *El Niño* years, compared to neutral years, under the SIM rainfall deviations (Fig. 6). Furthermore, all selected districts showed higher production anomalies during the independent IOD-positive event in 2019 (without association with ENSO) than during neutral years and IOD-positive years associated with *El Niño*. (Fig. 6).

This was proven by the observed data with the paddy production during the 2019/20 *Maha* season reaching 3.19 million metric tons, the highest recorded during the study period. However, this increase is not only attributed to the rise in SIM rainfall but also the general increasing trend of paddy cultivation in the country with the aid of improved agronomic practices, timely provision of agricultural inputs, etc. Due to the government's policy decision to ban chemical fertilizers and other socio-economic conflicts, this upward trend in paddy production dropped after 2019/20 *Maha* season (DCS, 2025). Therefore, further independent IOD-positive events are needed in future to draw definitive conclusions.

All selected major paddy-growing districts in Sri Lanka showed negative anomalies in paddy production during the *Maha* season, influenced by both IOD-negative years associated with *La Niña* years and independent

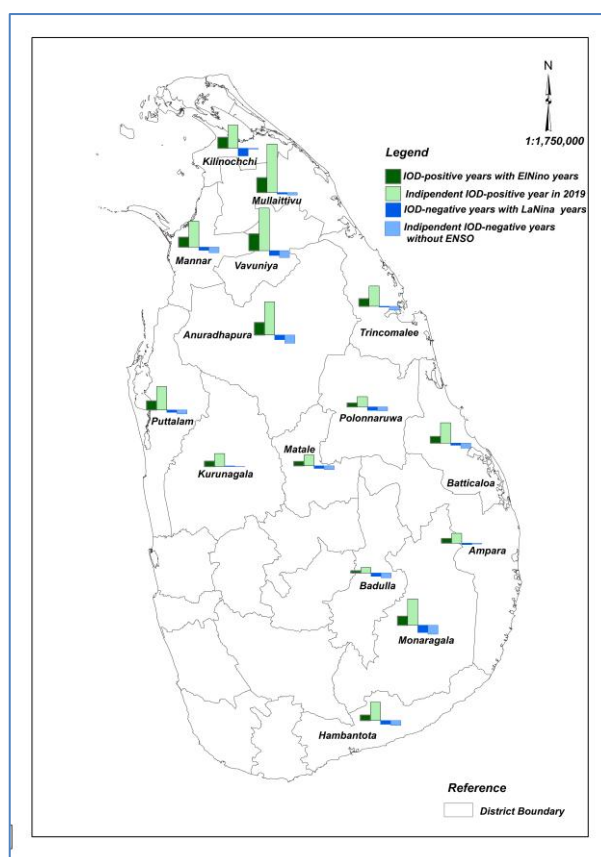


Fig. 6. The mean paddy production anomalies in Maha seasons, during to IOD years associated with corresponding ENSO events compared to the independent IOD-positive event in 2019 and independent IOD-negative years (without association with ENSO years)

IOD-negative years (without association with ENSO years), compared to neutral years, under the SIM rainfall deviations (Fig. 6).

However, definitive conclusions are difficult to draw because of the limited occurrence of IOD-negative events, which restricts the applicability of statistical testing. Furthermore, the overall increasing trend in paddy cultivation in the country, supported by advances in agricultural technology and increased farmer awareness, may also have influenced the results. Nevertheless, composite analyses comparing IOD years with neutral years, or IOD phases with independent IOD years (IOD events without an association with ENSO), can provide meaningful insights into the potential influence of IOD variability on rainfall and paddy production.

4. Conclusions

This study mainly focused on rainfall deviations associated with combined and independent ENSO and

IOD years, and their influence on paddy production during the *Maha* season in Sri Lanka. Considering the occurrence of ENSO and IOD events during the first half of the *Maha* season, SIM rainfall deviations were considered for the analysis.

During the study period, *El Niño* years associated with IOD-positive years and *La Niña* years associated with IOD-negative years were observed during the SIM season. According to the results, both *El Niño* years associated with IOD-positive years and independent *El Niño* years (without association with IOD years) led to increase the mean cumulative rainfall in SIM, about 95% and 66% respectively, across the 41 selected weather stations. However, when IOD-positive events are associated with *El Niño* years, they synergize the positive impact showing approximately 85% higher positive deviations in mean cumulative rainfall across 41 weather stations compared to independent *El Niño* years (without IOD association) during SIM rainy period. Correspondingly, paddy production during the *Maha*

season showed an increase in 87 % of selected major paddy-growing districts during *El Niño* years associated with IOD-positive years compared to neutral years. However, independent *El Niño* years (without association with IOD-positive years) showed a mixed trend compared to neutral years, likely due to the weak or moderate intensity of the remaining independent *El Niño* events.

Both *La Niña* years associated with IOD-negative years and independent *La Niña* years (without association with IOD years) showed 90% and 83% reduction in mean cumulative SIM rainfall respectively. About 80% reduction in *Maha* season paddy production under *La Niña* years associated with IOD-negative years was observed among 15 selected major paddy-growing districts. *La Niña* years without association with IOD years did not show considerable deviations from the above-mentioned results, except the marginal variations in Ampara district.

The IOD-positive years associated with *El Niño* years showed significant increase in mean cumulative SIM rainfall in all selected weather stations (100%), while IOD-negative years associated with *La Niña* years revealed 93% reduction. Parallely, all (100%) selected major paddy-growing districts in Sri Lanka showed positive anomalies in paddy production during the *Maha* season, influenced by IOD-positive years associated with *El Niño* years and 100% negative impact during IOD-negative years associated with *La Niña* years.

There were insufficient independent IOD-positive and IOD-negative years to carry out statistical testing during the study period. However, the independent IOD-positive event in 2019 (without association with ENSO) enhanced SIM rainfall, which contributed to the 2019/20 *Maha* season paddy production reaching 3.19 million metric tons, the highest recorded during the study period. Paddy production during the *Maha* season showed negative anomalies in 87% of the 15 selected major paddy-growing districts during independent IOD-negative years (without association with ENSO years), likely due to reduced SIM rainfall.

Based on the findings of this study, agricultural decision-making that considers the influence of climatic drivers such as ENSO and IOD should first determine whether these events occur independently or in combination, as well as their respective strengths. This approach enables more accurate prediction of their impacts on seasonal rainfall and paddy production during *Maha* seasons, the major growing season for national food security.

Acknowledgements

The authors gratefully acknowledge the Natural Resource Management Center (NRMCC), Department of Agriculture (DoA), Sri Lanka and the Postgraduate Institute of Agriculture, University of Peradeniya, for provision of essential research facilities and institutional support. Authors also wish to express their sincere gratitude to Mr. A. K. Hettiarachchi, NRMCC, DoA, Sri Lanka for developing the location map of the selected weather stations in Sri Lanka and paddy production anomaly maps.

Authors' contributions

Aruni Abeysekera: Data curation, Data analysis, Data interpretation & Manuscript writing.

Ranjith Punyawardena: Overall supervision and guidance, Revision of the manuscript and editing. (email: batugedara_vrp@yahoo.com).

Buddhi Marambe: Supervision and guidance, Revision of the manuscript and editing. (email: bmarambe@gmail.com).

Shiromani Jayawardena: Supervision and guidance, Revision of the manuscript and editing. (email: shirojaya2000@yahoo.com).

Thavananthan Sivananthawerl: Supervision and Statistical guidance in the analysis and interpretation of the data. (email: sivawerl@agri.pdn.ac.lk).

Disclaimer: The contents and views expressed in this research article are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

Reference

- Abeysekera, A.B., Punyawardena, B.V.R., Sivananthawerl, T. and Premalal, K.H.M.S., 2017, "Inter-seasonal variability of the rainfall pattern in the Dry Zone of Sri Lanka with the influence of El Niño–Southern Oscillation (ENSO)", *Ann. Sri Lanka Dep. Agric.*, **19**(1), 139–167.
- Abeysekera, A.B., Punyawardena, B.V.R., Marambe, B., Jayawardena, I.M.S.P., Wickramasinghe, V.N.M., Senarathna, E.D.D.L. and Wijerathna, W.M.V.S., 2019, "Effect of El Niño–Southern Oscillation (ENSO) events on inter-seasonal variability of rainfall in Wet and Intermediate zones of Sri Lanka", *Trop. Agriculturist*, **167**(1), 14–27, doi: <https://doi.org/10.4038/ta.v167i1.65>.
- Abeysekera, A.B., Punyawardena, B.V.R., Marambe, B., Jayawardena, I.M.S.P., Sivananthawerl, T. and Wickramasinghe, V.N.M., 2020, "The effect of Indian Ocean Dipole (IOD) events on the second inter-monsoonal rainfall in the Dry Zone of Sri Lanka", *Proc. 6th Int. Conf. Dry Zone Agric., Fac. Agric., Univ. Jaffna*, **6**, 32.
- Abeysekera, A.B., Punyawardena, B.V.R., Marambe, B., Jayawardena, I.M.S.P., Sivananthawerl, T. and Wickramasinghe, V.N.M., 2021, "Effect of Indian Ocean Dipole (IOD) events on the second inter-monsoonal rainfall in the Wet Zone of Sri Lanka",

- Trop. Agric. Res., **32**(3), 287–297, doi: <https://doi.org/10.4038/tar.v32i3.8492>.
- Abeysekera, A.B., Punyawardena, B.V.R., Marambe, B., Jayawardena, I.M.S.P. and Sivananthawerl, T., 2023, “Relationship between the Indian Ocean Dipole (IOD) and paddy cultivation during Maha season in Sri Lanka”, Trop. Agriculturist, **171**(3), 55–68, doi: <https://doi.org/10.4038/ta.v171i3.18>.
- Allan, R., Chambers, D., Drosowsky, W., Hendon, H., Latif, M., Nicholls, N. and Tourre, Y., 2001, “Is there an Indian Ocean Dipole and is it independent of the *El Niño*–Southern Oscillation?”, CLIVAR Exch., **21**, 18–22.
- Aparna, S.G., McCreary, J.P., Shankar, D. and Vinayachandran, P.N., 2012, “Signatures of Indian Ocean Dipole and *El Niño*–Southern Oscillation events in sea level variations in the Bay of Bengal”, J. Geophys. Res. Oceans, **117**(C10), C10012, doi: <https://doi.org/10.1029/2012JC008055>.
- Apriyana, Y., Aldrian, E., and Koesmaryono, Y., 2019, “The dynamics of rice cropping calendar and its relation with the ENSO (*El Niño*–Southern Oscillation) and IOD (Indian Ocean Dipole) in Monsoon and Equatorial Regions of Indonesia”, In IOP conference series: earth and environmental science (Vol. 363, No. 1, p. 012013). IOP Publishing, doi: <https://doi.org/10.1088/1755-1315/363/1/012013>.
- Black, E., Slingo, J. and Sperber, K.R., 2003, “An observational study of the relationship between excessively strong short rains in coastal East Africa and Indian Ocean SST”, Mon. Wea. Rev., **131**(1), 74–94, doi: [https://doi.org/10.1175/1520-0493\(2003\)131%3C0074:AOSOTR%3E2.0.CO;2](https://doi.org/10.1175/1520-0493(2003)131%3C0074:AOSOTR%3E2.0.CO;2).
- Bureau of Meteorology (BOM), 2024, “Understanding the Indian Ocean Dipole (IOD)”, Bureau of Meteorology, Australia (online), accessed 25 July 2023.
- Cai, W., Wu, L., Lengaigne, M., Li, T., McGregor, S., Kug, J.S. and Chang, P., 2019, “Pan-tropical climate interactions”, Science, **363**(6430), eaav4236, doi: <https://doi.org/10.1126/science.aav4236>.
- Camuffo, D., Becherini, F. and della Valle, A., 2020, “Relationship between selected percentiles and return periods of extreme events”, Acta Geophys., **68**, 1201–1211, doi: <https://doi.org/10.1007/s11600-020-00452-x>.
- Cherian, S., Sridhara, S., Manoj, K. N., Gopakali, P., Ramesh, N., Alrajhi, A. A., ... and Mattar, M. A., 2021, “Impact of *El Niño* Southern Oscillation on rainfall and rice production: A micro-level analysis”, Agronomy, **11**(6), 1021, doi: <https://doi.org/10.3390/agronomy11061021>.
- Cline, W.R., 2007, *Global warming and agriculture: Impact estimates by country*, Center for Global Development and Peterson Institute for International Economics, Washington, DC.
- Department of Agriculture (DoA), 2024, “Rice – general information”, Department of Agriculture, Sri Lanka (online), accessed 17 January 2024.
- Department of Census and Statistics (DCS), 2025, “Agriculture”, Department of Census and Statistics, Sri Lanka (online), accessed 14 August 2024.
- Department of Meteorology (DoM), 2023, “Climate of Sri Lanka”, Department of Meteorology, Sri Lanka (online), accessed 24 August 2023.
- Hapuarachchi, H.A.S.U. and Jayawardena, I.M.S.P., 2015, “Modulation of monthly rainfall in Sri Lanka by ENSO and ENSO Modoki extremes”, Sri Lanka J. Meteorol., **1**, 3–9.
- Iizumi, T., Luo, J.J., Challinor, A.J., Sakurai, G., Yokozawa, M., Sakuma, H. and Yamagata, T., 2014, “Impacts of *El Niño*–Southern Oscillation on the global yields of major crops”, Nat. Commun., **5**(1), 3712, doi: https://doi.org/10.1038/ncomms4712?utm_source=chatgpt.com.
- IPCC, 2014, *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects*, Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, USA, doi: <https://doi.org/10.1017/CBO9781107415379>.
- Jackson, I.J., 1977, “Climate, water and agriculture in the tropics”, Longman, London.
- Jayamaha, G.S., 1976, “An analysis of droughts in Sri Lanka”, Proc. Indian Natl. Sci. Acad., **42**, 133–148.
- Jayawardene, H.K.W.I., Jayewardene, D.R. and Sonnadara, D.U.J., 2015, “Interannual variability of precipitation in Sri Lanka”, J. Natl. Sci. Found. Sri Lanka, **43**(1), 75–82, doi: <https://doi.org/10.4038/jnsfr.v43i1.7917>.
- Jiang, Y., Zhou, L., Roundy, P.E., Hua, W. and Raghavendra, A., 2021, “Increasing influence of Indian Ocean Dipole on precipitation over Central Equatorial Africa”, Geophys. Res. Lett., **48**, e2020GL092370, doi: <https://doi.org/10.1029/2020GL092370>.
- Kajakokulan, P., Pathirana, G., Dheerasinghe, M. and Edirisooriya, I., 2023, “Influence of Indian Ocean warming on rainfall of Sri Lanka”, Int. J. Climatol., **43**, 1–10, doi: <https://doi.org/10.1002/joc.8124>.
- Kane, R.P., 1998, “ENSO relationships to the rainfall of Sri Lanka”, Int. J. Climatol., **18**, 859–871, doi: [https://doi.org/10.1002/\(SICI\)1097-0088\(19980630\)18:8%3C859::AID-JOC264%3E3.0.CO;2-W](https://doi.org/10.1002/(SICI)1097-0088(19980630)18:8%3C859::AID-JOC264%3E3.0.CO;2-W).
- Klein, S.A., Soden, B.J. and Lau, N.C., 1999, “Remote Sea surface temperature variations during ENSO: Evidence for tropical atmospheric bridge”, J. Climate, **12**(3), 917–932, doi: [https://doi.org/10.1175/1520-0442\(1999\)012%3C0917:RSSTVD%3E2.0.CO;2](https://doi.org/10.1175/1520-0442(1999)012%3C0917:RSSTVD%3E2.0.CO;2).
- Land Use Policy Planning Department (LUPPD), 2019, “Land use and land cover of Sri Lanka”, Land Use Policy Planning Department, Narahenpita, Colombo 05.
- Latif, M., Anderson, D., Barnett, T., Cane, M., Kleeman, R., Leetmaa, A., O’Brien, J., Rosati, A. and Schneider, E., 1998, “A review of the predictability and prediction of ENSO”, J. Geophys. Res. Oceans, **103**(C7), 14375–14393, doi: <https://doi.org/10.1029/97JC03413>.
- Lesk C., Rowhani P. and Ramankutty N. 2016, “Influence of extreme weather disasters on global crop production”, Nature, **529**, 84–87, doi: <https://doi.org/10.1038/nature16467>.
- Marambe, B., Punyawardena, R., Silva, P., Premalal, S., Rathnabharathie, V., Kekulandala, B., and others, 2015, “Climate, climate risk, and food security in Sri Lanka: The need for strengthening adaptation strategies”, In *Handbook of climate change adaptation* (pp. 1759–1789). Springer, doi: https://doi.org/10.1007/978-3-642-38670-1_120.
- McPhaden, M.J., 2002, “*El Niño* and *La Niña*: causes and global consequences”, Encycl. Global Environ. Change, **1**, 353–370.
- McPhaden, M.J., Zebiak, S.E. and Glantz, M.H., 2006, “ENSO as an integrating concept in earth science”, Science, **314**(5806), 1740–1745, doi: <https://doi.org/10.1126/science.1132588>.

- National Aeronautics and Space Administration (NASA), 2023, “*El Niño/La Niña* watch and PDO”, National Aeronautics and Space Administration (online), accessed 15 May 2024.
- Nastos, P. T. and Zerefos, C. S., 2009, “Spatial and temporal variability of consecutive dry and wet days in Greece”, *Atmos. Res.*, **94**(4), 616–628, doi: <https://doi.org/10.1016/j.atmosres.2009.03.009>.
- Nieuwolt, S., 1982, “Tropical rainfall variability—The agroclimatic impact”, *Agric. Environ.*, **7**(2), 135–148.
- National Oceanic and Atmospheric Administration (NOAA), 2022, “Global impacts”, (online), accessed 19 January 2022.
- National Oceanic and Atmospheric Administration NOAA, 2024, “Climate forcing”, National Oceanic and Atmospheric Administration (online), accessed 15 June 2023.
- Punyawardena, B.V.R. and Cherry, N.J., 1999, “Assessment of the predictability of seasonal rainfall in Ratnapura using the Southern Oscillation and its two extremes”, *J. Natl. Sci. Counc. Sri Lanka*, **27**(3), 187–196, doi: <https://doi.org/10.4038/jnsfr.v27i3.3059>.
- Punyawardena, B. V. R., 2002, “Identification of the potential of growing seasons by the onset of seasonal rains: a study in the DL region of the north central Dry zone”, *J. Natl. Sci. Found. Sri Lanka*, **30**(1-2), doi: <https://doi.org/10.4038/jnsfr.v30i1-2.2557>.
- Punyawardena, B.V.R., 2008, *Rainfall and agro-ecological regions of Sri Lanka* (in Sinhala), Department of Agriculture, Sri Lanka.
- Punyawardena, B.V.R., 2020, “Climate”, in *The Soils of Sri Lanka*, ed. R.B. Mapa, Springer, pp. 13–22, doi: https://doi.org/10.1007/978-3-030-44144-9_2.
- Rosenzweig C. and Parry M.L. 1994, “Potential impact of climate change on world food supply”, *Nature*, **367**, 133–138, doi: <https://doi.org/10.1038/367133a0>.
- Saji, N.H., Goswami, B.N., Vinayachandran, P.N. and Yamagata, T., 1999, “A dipole mode in the tropical Indian Ocean”, *Nature*, **401**(6751), 360–363.
- Sarvina, Y., June, T., Sutjahjo, S.H., Nurmalina, R. and Surmaini, E., 2021, “The impacts of climate variability on coffee yield in five Indonesian coffee production centers”, *Int. J. Climatol.*, **41**, 1–15, doi: <https://doi.org/10.25186/v16i.1917>.
- Song, Q., Vecchi, G.A. and Rosati, A.J., 2007, “Indian Ocean variability in the GFDL coupled climate model”, *J. Climate*, **20**(13), 2895–2916, doi: <https://doi.org/10.1175/JCLI4159.1>.
- Suppiah, R., 1989, “Relationship between the Southern Oscillation and the rainfall of Sri Lanka”, *Int. J. Climatol.*, **9**, 601–618, doi: <https://doi.org/10.1002/joc.3370090605>.
- Survey Department of Sri Lanka, 2007, *The National Atlas of Sri Lanka*, 2nd edition, Survey Department of Sri Lanka, pp. 36–56.
- Takaya, Y., Ishikawa, I., Kobayashi, C., Endo, H. and Ose, T., 2020, “Enhanced Meiyu–Baiu rainfall in early summer 2020: Aftermath of the 2019 super IOD event”, *Geophys. Res. Lett.*, **47**(22), e2020GL090671, doi: <https://doi.org/10.1029/2020GL090671>.
- Thomas, J., and Joseph, S., 2024, “Impacts of recent rainfall changes on agricultural productivity and water resources within the Southern Western Ghats of Kerala, India”, *Environ. Monit. Assess.*, **196**(2), 115, doi: <https://doi.org/10.1007/s10661-023-12270-x>.
- Vinayachandran, P.N., Saji, N.H. and Yamagata, T., 1999, “Response of the equatorial Indian Ocean to an unusual wind event during 1994”, *Geophys. Res. Lett.*, **26**(11), 1613–1616, doi: <https://doi.org/10.1029/1999GL900179>.
- Wallace, J.M., Rasmusson, E.M., Mitchell, T.P., Kousky, V.E., Sarachik, E.S. and Von Storch, H., 1998, “On the structure and evolution of ENSO-related climate variability in the tropical Pacific: Lessons from TOGA”, *J. Geophys. Res. Oceans*, **103**(C7), 14241–14259, doi: <https://doi.org/10.1029/97JC02905>.
- Wang, B., Lu, J., Yan, Z., Luo, H., Li, T., Zheng, Y. and Zhang, G., 2019, “Deep uncertainty quantification: A machine learning approach for weather forecasting”, *Proc. 25th ACM SIGKDD Int. Conf. Knowl. Discov. Data Min.*, 2087–2095, doi: <https://doi.org/10.1145/3292500.3330704>.
- Wang, G., Cai, W., Yang, K., Santoso, A. and Yamagata, T., 2020, “A unique feature of the 2019 extreme positive Indian Ocean Dipole event”, *Geophys. Res. Lett.*, **47**(18), e2020GL088615, doi: <https://doi.org/10.1029/2020GL088615>.
- Webster, P.J., Moore, A.M., Loschnigg, J.P. and Leben, R.R., 1999, “The great Indian Ocean warming of 1997–98: Evidence of coupled oceanic–atmospheric instabilities”, *Nature*, **401**(6751), 356–360.
- Yamagata, T., Behera, S.K., Luo, J.J., Masson, S., Jury, M.R. and Rao, S.A., 2004, “Coupled ocean–atmosphere variability in the tropical Indian Ocean”, *Geophys. Monogr.*, **147**, 189–212, doi: <https://doi.org/10.1029/147GM12>.
- Yoshino, M. M., and Suppiah, R., 1983, “Climate and paddy production: a study on selective districts in Sri Lanka.” *Clim. Notes*, **33**, 33–50.
- Yoshino, M.M. and Suppiah, R., 1984, “Rainfall and paddy production in Sri Lanka”, *J. Agric. Meteorol.*, **40**(1), 9–20, doi: <https://doi.org/10.2480/agrmet.40.9>.
- Zhang, T., Zhu, J., Yang, X., and Zhang, X., 2008, “Correlation changes between rice yields in North and Northwest China and ENSO from 1960 to 2004”, *Agric. For. Meteorol.*, **148**(6-7), 1021–1033, doi: <https://doi.org/10.1016/j.agrformet.2008.01.018>.
- Zhang, Q., Singh, V.P., Li, J. and Chen, X., 2011, “Analysis of the periods of maximum consecutive wet days in China”, *J. Geophys. Res. Atmos.*, **116**(D23), doi: <https://doi.org/10.1029/2011JD016088>.
- Zhang, Y. and Du, Y., 2021, “Extreme IOD induced tropical Indian Ocean warming in 2020”, *Geosci. Lett.*, **8**(1), 37, doi: <https://doi.org/10.1186/s40562-021-00207-6>.
- Zubair, L., 2002, “*El Niño*–southern oscillation influences on rice production in Sri Lanka”, *Int. J. Climatol.*, **22**(2), 249–260, doi: <https://doi.org/10.1002/joc.714>.
- Zubair, L., Rao, S.A. and Yamagata, T., 2003, “Modulation of Sri Lankan *Maha* rainfall by the Indian Ocean Dipole”, *Geophys. Res. Lett.*, **30**(2), doi: <https://doi.org/10.1029/2002GL015639>.
- Zubair, L., Siriwardhana, M., Chandimala, J. and Yahiya, Z., 2008, “Predictability of Sri Lankan rainfall based on ENSO”, *Int. J. Climatol.*, **28**(1), 91–101, doi: <https://doi.org/10.7916/D84JOMBQ>.