Rainfall dynamics in Sri Lanka: A Review of Present Variability, Trends and Responses to Climate Change

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Rainfall dynamics in Sri Lanka: A Review of Present Variability, Trends and Responses to Climate Change

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Abstract

Sri Lanka exhibits one of the strongest rainfall gradients in the tropics due to the interaction between complex topography, seasonally reversing monsoonal circulations and large-scale air-sea coupling. Accordingly, understanding recent changes in the spatial and temporal characteristics of rainfall is crucial for food security, water resource management and reducing disaster risk. This review synthesizes current understanding of rainfall variability, long-term trends, and climate change responses in Sri Lanka, integrating recent observational analyses (1981-2023) based on the high-resolution CHIRPS satellite-gauge blended dataset, station records, and reanalysis products. Seasonal climatology, interannual variability, and trends assessed using non-parametric Mann–Kendall and Sen's slope methods reveal pronounced spatial contrasts, with the Southwest Monsoon dominating the Wet Zone through orographic enhancement and the Northeast Monsoon controlling rainfall in the Dry Zone. The Second Inter-monsoon (October–November) emerges as the most intense and variable season, contributing disproportionately to annual totals and extreme flood events. Evidence indicates a statistically significant and spatially coherent increase in Second Inter-monsoon rainfall, alongside a post-1990s rise in wet-day frequency, suggesting a shift toward more frequent and intense rainfall episodes. Synthesized findings further demonstrate that positive phases of the Indian Ocean Dipole exert the strongest large-scale control on Sri Lankan rainfall, particularly during October–November, while the El Niño–Southern Oscillation plays a secondary and seasonally dependent role. These teleconnections operate within a rapidly warming tropical Indian Ocean, which enhances atmospheric moisture availability and amplifies rainfall extremes. Collectively, the reviewed evidence indicates increasing hydro-climatic volatility, especially in the Wet Zone, heightening risks of floods and landslides, and underscoring the urgent need for improved seasonal prediction and climate-adaptive water resource management in Sri Lanka.

Keywords:

Sri Lanka, Rainfall variability, Second inter-monsoon, Monsoon systems, Indian Ocean Dipole, El Niño-Southern Oscillation

1. Introduction

Tropical regions, extending between the Tropics of Cancer and Capricorn and supporting more than 40% of the world's population, are characterised by intense and highly variable precipitation regimes. Rainfall in these regions is primarily driven by strong atmospheric convection associated with high Sea Surface Temperatures (SSTs), high atmospheric instability, the seasonal migration of the Intertropical Convergence Zone (ITCZ), monsoon circulation, and tropical cyclones (IPCC, 2021). These processes produce pronounced seasonal rainfall contrasts, with distinct wet and dry periods observed across major tropical landmasses, including Africa, South America, and South and Southeast Asia (Lau & Wu, 2011; Geen et al., 2020; IPCC, 2021).

These well-established rainfall regimes are now exhibiting pronounced changes responding to anthropogenic climate warming (Utsumi & Kim, 2022). While global mean precipitation is projected to increase modestly (approximately 1-3% per 1°C of warming), extreme precipitation events are expected to intensify at a much higher rate, approximately 7% per 1°C, consistent with the Clausius-Clapeyron relationship (high confidence; IPCC, 2021; Seneviratne et al., 2021). The amplification of rainfall extremes is expected to be particularly pronounced in the tropics, where increased convective activity and intensifying tropical cyclones are predicted to dominate future changes in precipitation (Allan et al., 2014; IPCC, 2021). Such shifts will have a substantial impact on tropical societies that depend on rainfall for rain-fed agriculture, freshwater access, hydropower generation, ecosystem services, and livelihoods (IPCC, 2022). Consequently, these societies will become more vulnerable to floods, droughts, landslides, and food insecurity (Seneviratne et al., 2021; IPCC, 2022). In this context, Sri Lanka, a tropical island nation located at the southern tip of the Indian subcontinent (5°55'- 9°51' N and 79°42'- 81°53' E; Fig. 1), exemplifies this vulnerability (Zubair et al., 2008; Hapuarachchi & Jayawardena, 2016; IPCC, 2022). Moreover, Sri Lanka's geographic position at the confluence of the South Asian monsoon system and the tropical Indian Ocean makes it a natural laboratory for diagnosing coupled ocean-atmosphere feedbacks of relevance to the broader Indo-Pacific climate system, providing scientific value that extends well beyond its modest territorial extent.

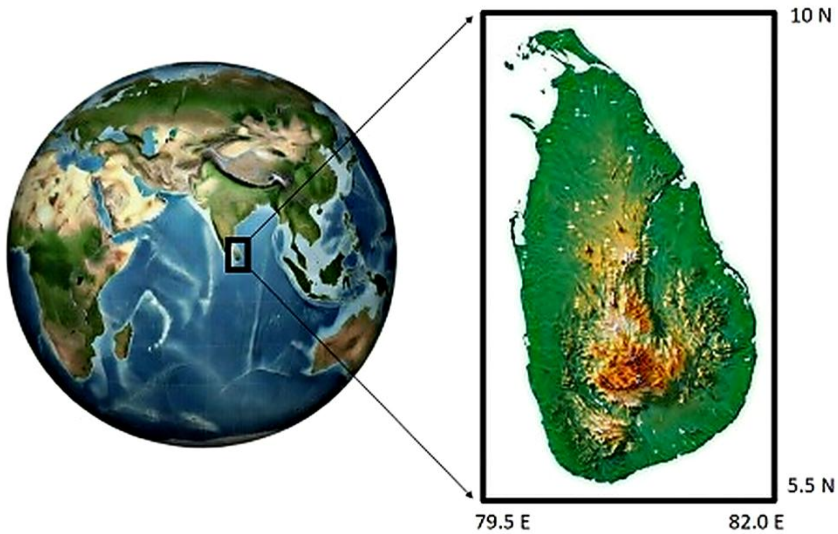


Fig. 1 Geographical Location of Sri Lanka

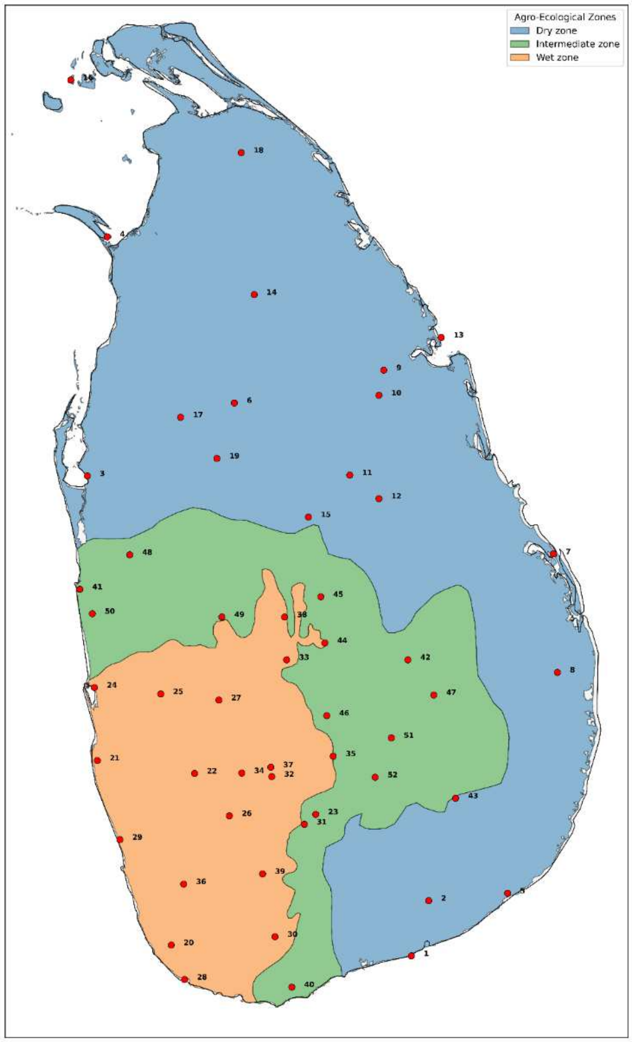


Fig. 1 Agro-ecological/climatic zones of Sri Lanka (Wet, Intermediate, and Dry) with locations of 52 long-term rainfall gauging stations. Each station is assigned a number from 1 to 52. (1. Hambantota, 2. Lunugamwehera, 3. Puttalam, 4. Mannar, 5. Yala, 6. Anuradhapura, 7. Batticaloa 8. Irakkamam, 9. Kannukkanei_tank, 10. Kantalai_tank, 11. Minneriya_tank, 12. Polonnaruwa, 13. Trincomalee, 14. Vavuniya, 15. Kandalama, 16. Nainativu, 17. Nochchiyagama, 18. Iranamadu_tank, 19. Mediyawa_tank, 20. Baddegama_estate, 21. Colombo, 22. Eheliyagoda, 23. Aluthnuwara, 24. Negombo, 25. Pasyala, 26. Ratnapura, 27.Undugoda, 28. Galle, 29. Kalutara, 30. Mawarella_estate, 31.Balangoda, 32. Maskeliya_hospital, 33. Kandy, 34. Helbodde_estate, 35. Hakgala, 36. Pelawatte, 37. Castereigh, 38. Matale_PWD, 39. Depedena_group, 40. Dandeniya_tank, 41. Chilaw_PWD, 42. Mapakadawewa, 43. Okkampitiya, 44. Duckwari_estate, 45. Illukumbura, 46. Kurundu_oya, 47. Bibile, 48. Polonthalawa, 49. Kurunegala, 50. Mellawa_estate, 51. Badulla, and 52. Bandarawela_estate)

Sri Lanka, though modest in its territorial extent, exhibits pronounced spatial and temporal heterogeneity in rainfall attributes due to its geographic position, complex topography, and exposure to multiple atmospheric and oceanic drivers (Zubair et al., 2008; Punyawardena, 2010; Basnayake, 2023). Rainfall over Sri Lanka arises from a combination of physical mechanisms, including convectional, monsoonal, cyclonic, depressional, and orographic processes (Punyawardena, 2010; Basnayake, 2023). The interaction between moist monsoon winds and the island's central highlands creates strong orographic uplift, resulting in sharp rainfall gradients over small areas. Consequently, based on long-term rainfall climatology, Sri Lanka is conventionally divided into three agro-climatic zones: the Wet Zone (>2,500mm/year), Intermediate Zone (1750 -2500mm/year), and Dry Zone (<1,750mm/year; Punyawardena, 2010; Nisansala et al., 2019; Figs 2 and 3). These zones differ substantially in their hydro-climatic characteristics and sensitivities to climate variability, making rainfall a critical determinant of agriculture, irrigation planning, and disaster risk management (Zubair et al., 2008; Jayawardena et al., 2018; IPCC, 2022).

The seasonal distribution of rainfall across these climatic zones is primarily governed by the South Asian monsoon system (Zubair et al., 2008; Punyawardena, 2010; Karunathilaka et al., 2017). Sri Lanka experiences four distinct rainfall seasons: the NEM (December–February, DJF), First Inter-Monsoon (FIM: March–April, MA), SWM (May–September, MJJAS), and SIM (October–November, ON) (Karunathilaka et al., 2017; Punyawardena & Abeysekera, 2020; Abeysekera et al., 2021; Fig. 3). Each season exhibits unique rainfall characteristics linked to large-scale circulation patterns. Among these four seasons, the SWM is the most dynamically active season, delivering moisture-laden southwesterly winds that generate intense orographic rainfall over the southwestern slopes of the central highlands. In contrast, the NEM predominantly affects the northern and eastern Dry Zone. At the same time, the Inter-monsoonal seasons are associated with widespread convective rainfall, particularly during the SIM when daily rainfall intensities are highest across much of the island (Punyawardena & Abeysekera, 2020; Abeysekera et al., 2021, Fig. 3).

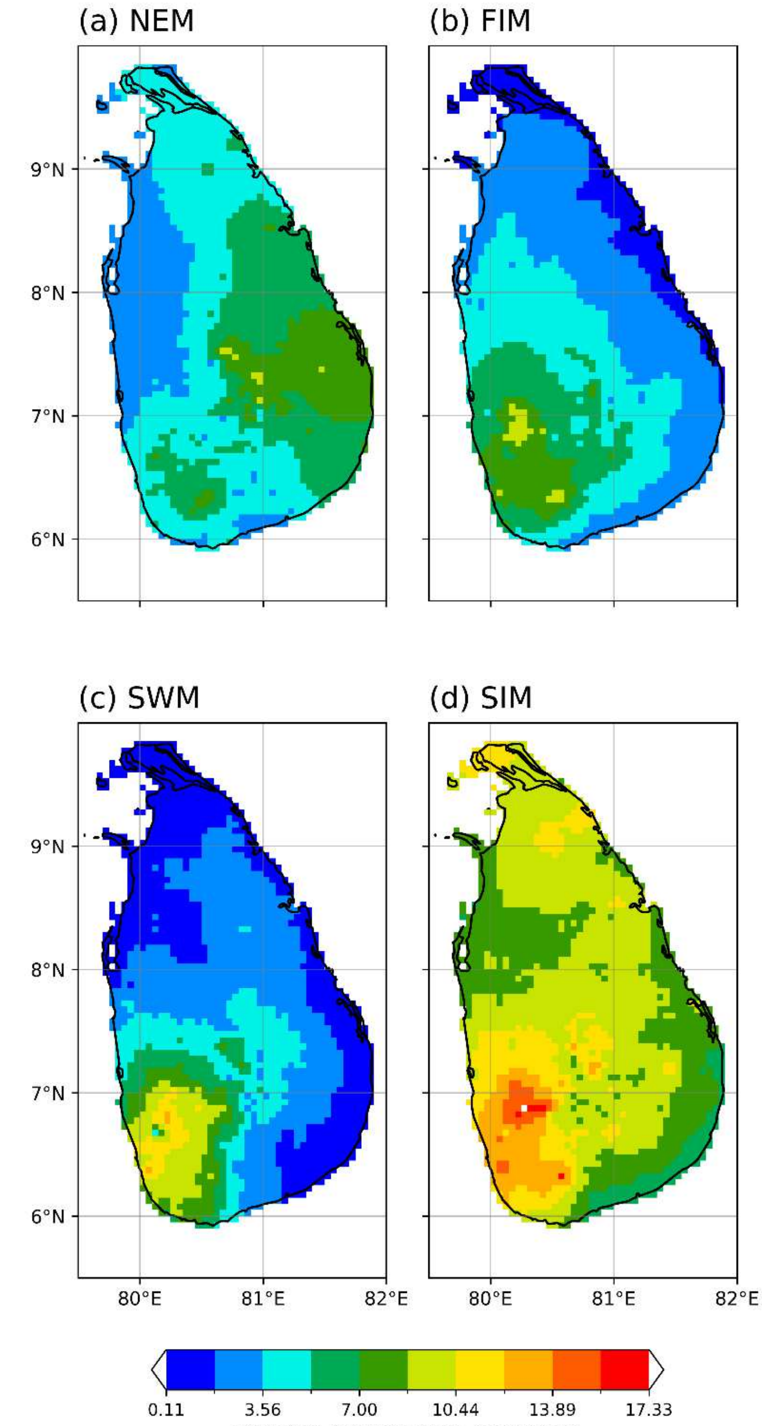


Fig. 2 Spatial distribution of Seasonal Rainfall Climatology (mm/day) of Sri Lanka during the (a) NEM, (b) FIM, (c) SWM, and (d) SIM derived from CHIRPS data (1981-2023). Seasonal means are computed from daily accumulations averaged over the respective monsoon months

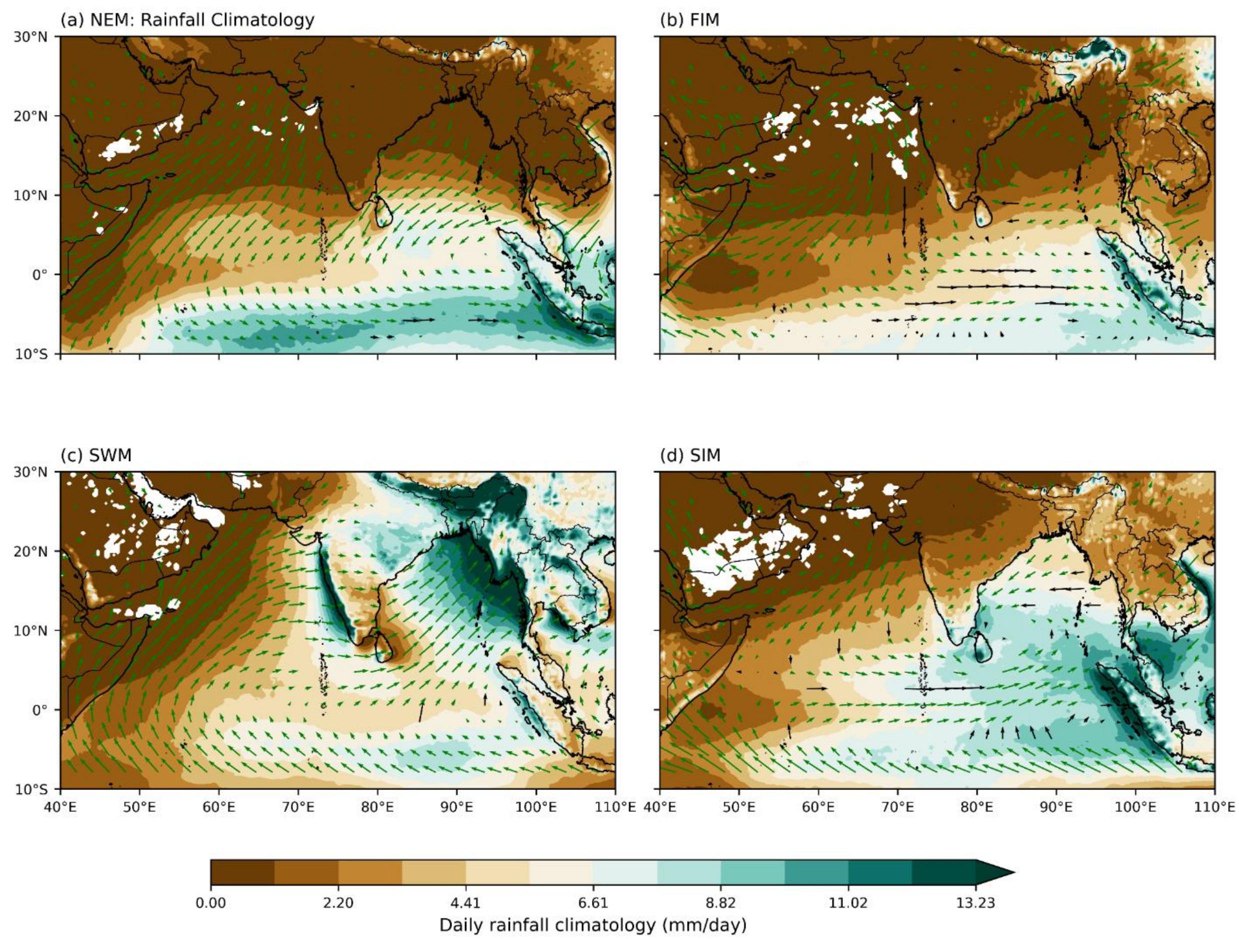


Fig.4 Spatial distribution of Seasonal Rainfall Climatology (mm/day) and associated low-level wind patterns over the Indian Ocean region during the (a) NEM, (b) FIM, (c) SWM, and (d) SIM. Rainfall is derived from ERA5 reanalysis data and represents long-term seasonal averages, while arrows indicate low-level wind circulation patterns (1981 – 2023). Seasonal means are computed from daily accumulations averaged over the respective monsoon months. The results highlight the seasonal reversal of monsoon winds and their influence on rainfall distribution across the Indian Ocean and the Sri Lankan region

Beyond the seasonal monsoon cycle, interannual-to-decadal variability in Sri Lanka's rainfall is strongly modulated by large-scale climate modes. Statistically robust influences from the ENSO, the IOD, and regional ocean–atmosphere interactions have been well described in the literature (Zubair et al., 2003; Abeysekera et al., 2019, 2021). More recently, attention has focused on the

Indo-Pacific Warm Pool (IPWP), a region of persistently high SSTs that acts as a major heat source for the global climate system (Weller et al., 2016; Kim et al., 2020). Variability and long-term warming of the IPWP, often mediated by ENSO and the IOD, have been shown to significantly alter atmospheric circulation patterns and rainfall distribution over South Asia, including Sri Lanka (Kajakokulan et al., 2023a, 2025a). Critically, the IOD's influence on Sri Lankan rainfall is not symmetric: recent evidence demonstrates that positive IOD (pIOD) events exert substantially stronger rainfall anomalies than their negative counterparts across the tropical Indian Ocean and surrounding regions, including Sri Lanka, with implications for seasonal prediction and extreme event attribution (Werellapatha et al., 2026). These findings collectively highlight the significance of examining rainfall variability in Sri Lanka within a coupled ocean-atmosphere framework.

A robust understanding of these complex rainfall dynamics requires high-quality observational data. Although research on the rainfall in Sri Lanka has a long history, dating back to the late nineteenth and early twentieth centuries (Suppiah & Yoshino, 1984; Jayawardene et al., 2005), those studies, based largely on gauge observations, revealed pronounced spatial heterogeneity and temporal variability. While gauge data remain essential for assessing long-term trends, their sparse spatial coverage, particularly in mountainous and remote regions, poses limitations (Naveendrakumar et al., 2018). To overcome these constraints, recent studies increasingly rely on satellite-derived precipitation products and climate reanalysis datasets, which offer improved spatial and temporal resolution (Huang et al., 2023). Integrating multiple observational datasets with statistical analysis techniques has improved the characterisation of rainfall variability, long-term trends and extreme events across Sri Lanka (Alahacoon & Edirisinghe, 2021; Kajakokulan et al., 2023a, 2023b).

Evidence from both ground-based and satellite observations indicates a recent increase in rainfall extremes over Sri Lanka, with serious socio-economic and environmental consequences. Extreme rainfall events have triggered widespread flooding, landslides, and prolonged droughts, affecting livelihoods, infrastructure, and ecosystem stability (Naveendrakumar et al., 2018; Wijemannage et al., 2018). For example, extreme rainfall in late 2024 displaced 468,732 people and 139,512 households across the island, causing loss of life (~18 deaths) and extensive damage to housing

(~2,600) and infrastructure (Disaster Management Centre, 2024). Such events underscore the growing exposure of Sri Lanka to hydro-climatic extremes under a changing climate.

Despite substantial progress in understanding monsoon variability and large-scale climate influences, the contribution of tropical cyclones to Sri Lankan rainfall dynamics remains largely unexamined in the peer-reviewed literature. The Northern Indian Ocean accounts for approximately 7% of global tropical cyclone activity, with nearly 75% originating in the Bay of Bengal (BoB) and the remainder in the Arabian Sea (WMO, 2008; Mohanty et al., 2012). Given Sri Lanka's proximity to both basins, cyclone-induced rainfall can be spatially extensive and exceptionally intense. While operational disaster management records and rapid post-disaster assessments document the immediate human and economic impacts of such events, their systematic incorporation into long-term rainfall climatology and trend analyses has not yet been achieved, a gap that is increasingly consequential as cyclone tracks and intensities respond to ongoing ocean warming. Recent events vividly illustrate this threat. Cyclonic Storm Ditwah, which struck Sri Lanka on 27-28 November 2025, became the deadliest weather-related disaster in the country since the 2004 Indian Ocean tsunami (Kew et al., 2025). The storm produced record-breaking 24-hour rainfall totals exceeding 500 mm in parts of the central highlands. Gammaduwa and Matale recorded 540.66 mm and 421.0 mm, respectively, with adjoining provinces receiving 300-400 mm, triggering catastrophic flooding and landslides across all 25 districts. The disaster resulted in approximately 644 fatalities and 175 unaccounted individuals, with an estimated 2 million persons adversely affected (Disaster Management Centre, 2025). A substantial proportion of the displaced population was subsequently accommodated in temporary shelters. The event caused extensive infrastructure deterioration, including the destruction and partial damage to thousands of residential structures, significant disruption to major network and bridge systems, and considerable impact on agricultural assets (particularly paddy, tea, and vegetable crops). According to the World Bank's Global Rapid Post-Disaster Damage Estimation (GRADE) report, a standardised, model-based institutional assessment released on 18 December 2025, estimated direct physical damage at US$4.1 billion (equivalent to ~4% of GDP), with total economic losses potentially reaching US$6-7 billion (World Bank GRADE, 2025). These devastating outcomes highlight the increasing threat posed by intensifying cyclone-related extremes in a warming climate.

In light of these considerations, it is both timely and necessary to produce a comprehensive, up-to-date synthesis of rainfall dynamics in Sri Lanka. While numerous studies have examined individual drivers, such as monsoon variability, ENSO and IOD influences, and long-term rainfall trends, no previous synthesis has jointly addressed the full seasonal cycle, interannual climate mode interactions, emerging extreme event trends, and the role of cyclone-induced rainfall within a unified observational and analytical framework. This review addresses that gap by integrating, for the first time, observational analyses spanning 1981-2023 from the high-resolution CHIRPS satellite-gauge-blended dataset with station records and ERA5 reanalysis products, applying nonparametric MK and Sen's slope trend detection simultaneously across all four rainfall seasons. It further synthesises recent findings on the asymmetric influence of positive versus negative IOD (nIOD) phases on Sri Lankan rainfall, an emerging but underexamined dimension of regional climate variability, alongside ENSO teleconnections and IPWP dynamics. By connecting historical variability, observed recent changes including the post-1990s intensification of the SIM, and projected climate responses, the review provides a coherent, evidence-based assessment across Sri Lanka's three climatic zones. The synthesised findings aim to support the development of improved seasonal prediction frameworks, climate-resilient water resource management strategies, and disaster risk reduction measures in one of South Asia's most hydro-climatically sensitive regions, with broader implications for monsoon dynamics across Indo-Pacific.

2. Data and Methods

This section summarises the main data sources and analytical methods used in rainfall studies in Sri Lanka, including ground-based observations, satellite-derived datasets, geospatial techniques, and climate model-based approaches, emphasising their development, strengths, and limitations. Since the late 1990s, Sri Lankan researchers have increasingly adopted rigorous statistical, geospatial, and climate-diagnostic approaches to examine seasonal variability, long-term trends, and extreme rainfall events associated with the SWM and NEM, and the two inter-monsoon periods (Chithranayana & Punyawardena, 2008; Zubair et al., 2008). This methodological progression has been driven by the country's strong dependence on monsoon rainfall for agriculture, hydropower generation, and flood management, as well as the growing need for climate information relevant to policy under a warming climate (Naveendrakumar et al., 2018; Alahacoon & Edirisinghe, 2021). Consequently, rainfall studies in Sri Lanka now span a broad spectrum of analytical approaches, ranging from station-based statistical analyses to satellite-based, geospatial, and climate model-driven investigations.

2.1. Ground-Based Observations and Statistical Analyses.

The earliest and most widely used analyses of rainfall variability in Sri Lanka are based on long-term in situ observations from meteorological stations operated by the Department of Meteorology and the Department of Irrigation, Sri Lanka. These records, many of which span 30–50 years, provide invaluable temporal depth for assessing interannual variability, seasonal cycles, and long-term trends across the Wet, Intermediate, and Dry Zones (Jayawardene et al., 2005; Karunathilaka et al., 2017; Nisansala et al., 2019). However, early studies reported weak or inconsistent rainfall trends, whereas more recent analyses increasingly highlight rising variability and intensification of inter-monsoon rainfall over Sri Lanka (Table 1).

Table 1 Evolution of scientific understanding of rainfall variability and trends in Sri Lanka.

Study Period	Key findings on rainfall variability and trends	Reference
1869-1998	No clear long-term monotonic trend in annual rainfall across Sri Lanka, but strong inter-annual and decadal variability linked to monsoon fluctuations and large-scale circulation.	Jayawardena et al., 2005
1881-1980	Strong spatial contrast between wet and dry zones and pronounced seasonal monsoon control were identified as dominant features of Sri Lanka rainfall climatology.	Suppiah & Yoshino, 1984
1971-1985	Distinct regional rainfall regimes and high seasonal variability were observed, with rainfall strongly modulated by monsoon circulation and topography.	Domroes & Ranathunga, 1993
1869-2004	Sri Lankan rainfall variability linked to ENSO and large-scale ocean-atmosphere variability; interannual predictability is strongest during the October-December season.	Zubair et al., 2008

1961-2010	The cumulative annual or seasonal rainfall in Sri Lanka's major climatic zones during the analysed period has not changed significantly. However, the variability of seasonal rainfall during the 2001-2010 period has increased compared to the previous decade, 1991-2000, across the climatic zones.	Nissanka et al., 2011
1989-2019	Significant increase in annual rainfall from 1989 to 2019 in all climatic zones of Sri Lanka, with the maximum increase in the wet zone.	Alahacoon & Edirisinghe, 2021

Initial analyses relied primarily on descriptive and inferential statistics to characterise rainfall variability. Commonly used metrics include mean rainfall, standard deviation (SD), coefficient of variation (CV), standardised rainfall anomaly index (SRAI), and precipitation concentration index (PCI). These indices have been widely applied to quantify rainfall seasonality, variability, and concentration, thereby enabling comparative assessments across climatic zones and seasons. Such metrics remain fundamental for diagnosing baseline rainfall characteristics and identifying anomalous wet and dry periods.

The most commonly used metrics and their formulas are presented below:

1. Mean Rainfall ($\bar{X}$)

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} \mathrm{X}_{\mathrm{i}}$$

Where;

n - Total number of years

X_{i} - Rainfall of the i year

2. Standard Deviation

$$SD = \sqrt{\left\{\frac{1}{n}\sum_{i=1}^{n}(X_i - \bar{X})^2\right\}}$$

Where;

n - Total number of years

X_i - Rainfall of the i year

$\bar{X}$ - Mean rainfall

3. Coefficient of Variation (CV)

$$CV = \left(\frac{SD}{\bar{X}}\right) \times 100$$

4. Standardised Rainfall Anomaly Index (SRAI, Van Rooy,1965)

$$SRAI = \frac{\{X_i - \bar{X}\}}{SD}$$

5. Precipitation Concentration Index (PCI, Oliver,1980)

$$PCI_{\{\{annual\}\}} = \frac{\left\{\sum_{\{i=1\}}^{\{12\}} P^2{}_{\mathrm{i}}\right\}}{\left(\sum_{\{i=1\}}^{\{12\}} P_{\mathrm{i}}\right)^2} X\ 100$$

$$PCI_{\{\{Seasonal-SWM\}\}} = \frac{\left\{\sum_{\{i=1\}}^{\{12\}} P^{2}{}_{\mathrm{i}}\right\}}{\left(\sum_{\{i=1\}}^{\{12\}} P_{\mathrm{i}}\right)^{2}} X\ 41.66$$

$$PCI_{\{\{Seasonal-NEM\}\}} = \frac{\left\{\sum_{\{i=1\}}^{\{12\}} P^{2}{}_{\mathrm{i}}\right\}}{\left(\sum_{\{i=1\}}^{\{12\}} P_{\mathrm{i}}\right)^{2}} X\ 25$$

Where;

P_{i} − Precipitation in the i^{th} month

To overcome the limitations of pattern-based indices alone, subsequent studies increasingly incorporated trend detection techniques to assess temporal changes in rainfall. Non-parametric methods have gained prominence for their robustness to non-normal distributions, missing values, and outliers, which are common features of long-term climatic records. The MK test has become the most widely used tool for detecting monotonic trends in annual and seasonal rainfall series across Sri Lanka (Jayawardene et al., 2005; Pawar et al., 2022). Furthermore, the Sen's slope estimator is often used in conjunction with the MK test to quantify the magnitude of detected trends (Naveendrakumar et al., 2018). Together, these methods have revealed statistically significant spatially heterogeneous rainfall trends across different climatic zones.

Other techniques, such as Least Squares Regression (LSR) and Spearman's rank correlation, have also been employed to assess linear and monotonic relationships in rainfall time series (Nisansala et al., 2019). While these methods provide intuitive estimates of trend direction and strength, their applicability is often constrained by assumptions of linearity and stationarity, as well as by the uneven spatial distribution of rain gauges. To address spatial gaps, researchers have employed interpolation techniques such as Inverse Distance Weighting (IDW) and kriging to generate continuous rainfall surfaces from point-based observations (Wijemannage et al., 2018). Although these approaches improve spatial representation, their reliability remains sensitive to station density, topographic complexity, and data quality, emphasising the need to complement ground-based analyses with spatially continuous datasets.

2.2 Satellite-Based, Geospatial, and Model-based Approaches

In response to the limitations of sparse station networks, recent decades have witnessed a marked shift towards satellite-based and model-integrated rainfall analyses in Sri Lanka. This transition has been facilitated by the increasing availability of high-resolution gridded precipitation datasets and reanalysis products, which provide spatially continuous coverage essential for regional climate assessments.

Among these datasets, the CHIRPS product has emerged as the most widely used satellite-based rainfall dataset in Sri Lankan studies. CHIRPS offers quasi-global coverage at approximately 5 km spatial resolution with a long-term temporal record, achieved by blending satellite estimates with in-situ observations (Funk et al., 2015; Alahacoon & Edirisinghe, 2021). Its hybrid nature makes it particularly suitable for monsoon-dominated regions such as Sri Lanka. Several studies have successfully combined CHIRPS with station data and reanalysis products such as ERA5 to improve trend detection and validate rainfall extremes (Hersbach et al., 2020; Kajakokulan et al., 2023a, 2023b).

The integration of satellite rainfall products with Geographic Information System (GIS) techniques has further enhanced the spatial analysis of rainfall variability. GIS-based approaches allow rainfall data to be examined alongside topography, land use, and administrative boundaries, enabling detailed assessments of zonal and watershed-scale rainfall changes (Wijemannage et al., 2018; Alahacoon & Edirisinghe, 2021). The use of daily raster datasets derived from blended satellite products has enabled finer-scale spatial analyses than traditional station-based methods (Amarasinghe, 2020). Nevertheless, satellite rainfall estimates remain subject to uncertainties arising from cloud properties, sensor limitations, and algorithmic biases, particularly during intense rainfall events (Alahacoon & Edirisinghe, 2021). These limitations highlight the importance of systematic validation against ground observations.

Hybrid analytical frameworks combining satellite-derived rainfall fields with statistical trend detection methods, such as the MK test and Sen's slope, have proven particularly effective in identifying spatial patterns of rainfall trends and extremes across Sri Lanka (Naveendrakumar et al., 2018; Amarasinghe, 2020; Abeysinghe, 2022). These approaches are especially valuable in tropical island settings, where rainfall variability is strongly influenced by localized convection, monsoonal flows, and orographic effects.

Beyond observational analyses, climate model-based studies have contributed notably to understanding future rainfall dynamics under climate change. Simulations from global climate model ensembles, particularly CMIP6 (Eyring et al., 2016; IPCC, 2021), have been used to examine projected changes in rainfall responding to warming of the IPWP and associated increases in atmospheric instability (Pathirana et al., 2023, 2024). Earlier multi-model studies using PCMDI (Program for Climate Model Diagnosis and Inter-comparison, Lee et al., 2024) archives provided evidence for mechanisms such as "wet-get-wetter," whereby regions with high climatological rainfall may experience further intensification under global warming (Chou et al., 2009; Xie et al., 2010; Chadwick et al., 2013). Emerging data sources, such as rainfall estimates derived from Commercial Microwave Links (CMLs) within telecommunication networks, represent a novel and promising complement to traditional gauges and satellites, offering high temporal and spatial resolution, particularly in urban environments (Overeem et al., 2021).

2.3 Linking Rainfall Variability to Large-Scale Climate Phenomena

Advances in observational and analytical methods have enabled a substantial body of research to focus on linking Sri Lankan rainfall variability to large-scale climate variabilities. Sri Lanka's rainfall variability is strongly modulated by coupled ocean-atmosphere modes operating across the Indo-Pacific region, particularly ENSO, IOD, and Madden-Julian Oscillation (MJO). While these drivers were briefly introduced earlier, this section provides a focused synthesis of their dynamical influence on seasonal rainfall distribution, variability, and extremes across the island. Early studies used composite analysis to examine rainfall anomalies associated with different ENSO phases (Zubair et al., 2008). Subsequent research has built on these approaches by integrating correlation analysis, contingency tables, and regression techniques in order to assess the predictability of Sri Lankan rainfall based on ENSO states (Chandimala & Zubair, 2007; Yahiya et al., 2009; Kajakokulan et al., 2025b). These studies have consistently demonstrated reduced rainfall during

El Niño events and increased rainfall during La Niña phases, particularly during the SWM and NEM seasons.

Quantitative assessments commonly rely on correlation and regression analyses between rainfall anomalies and climate indices such as Niño 3.4, the Southern Oscillation Index (SOI), and the Dipole Mode Index (DMI) (Suppiah & Yoshino, 1984; Abeysekera et al., 2021; Kajakokulan et al., 2023a, 2025b). Spatial stratification into homogeneous rainfall zones has proven particularly useful for identifying region-specific climate–rainfall relationships. More recent studies have adopted regression mapping and coupled ocean–atmosphere diagnostics to explore spatial linkages between SST anomalies, atmospheric circulation, and moisture transport pathways (Kajakokulan et al., 2023a, 2023b). While these statistical approaches have greatly enhanced understanding of teleconnections, they are limited by nonlinear interactions and phase combinations among climate modes, underscoring the need for more advanced multivariate and machine-learning frameworks in future research (Saubhagya et al., 2024).

Table 2 summarises the major rainfall datasets employed in key Sri Lankan rainfall studies reviewed in this paper. Ground-based observations from the Department of Meteorology and the Department of Irrigation remain the backbone of long-term trend analyses, offering robust temporal coverage but limited spatial density. This spatial sparsity has driven the rapid adoption of blended satellite–gauge products, particularly CHIRPS, which now dominate recent regional analyses. The complementary use of long-term station data for temporal consistency and satellite and reanalysis datasets (e.g. ERA5) for spatial continuity represents a critical methodological advancement in Sri Lankan rainfall research.

Table 2 Summary of the data used in the review

Data	Period	Data Source	Link	Reference
Rainfall data (In Situ)	1990 – 2019	Department of Meteorology Sri Lanka	https://doi.org/10.1155/2022/6456761	Pawar et al., 2022

	1966 - 2015	Department of Meteorology Sri Lanka	https://doi.org/10.4038/engineer.v50i2.7251	Karunathilka et al., 2017
	1961 - 2015	Department of Meteorology Sri Lanka	https://doi.org/10.1155/2018/4217917	Naveendrakumar et al., 2018
Rainfall data (CHIRPS)	1989 - 2019	Climate Hazard Center	https://www.academia.edu/download/107300439/F2113444.pdf	Amarasinghe, 2020
Cyclone Wind speed data	1900 - 2020	International Best Track Archive for Climate Stewardship (IBTrACS)	https://doi.org/10.4038/engineer.v57i4.7663	Daranagama et al., 2024
Commercial Microwave Links	12.09.2019 – 31.12.2019	Cellular Telecommunication Network	https://doi.org/10.1088/1748-9326/ac0fa6	Overeem et al., 2021
Historical Data (Precipitation)	1854 - 2014	Coupled Model Inter-comparison Project Phase 6 (CMIP6)	https://doi.org/10.1007/s00382-023-06918-0	Pathirana et al., 2023

Rainfall Data (Satellite-based)	2001 - 2019	Integrated Multi-Satellite Retrievals for GPM (IMERG version 6)	https://doi.org/10.1016/j.atmosres.2023.106692	Huang et al., 2023
Rainfall Data (Reanalysis)	1979 - 2024	ERA5 (ECMWF)	https://doi.org/10.1002/qj.3803	Hersbach et al., 2020

3. Results

Although this article is structured as a review, we incorporate updated statistical diagnostics using a harmonised CHIRPS 1981-2023 dataset to provide an internally consistent comparison of seasonal rainfall variability and climate drivers across Sri Lanka. Previous studies have often employed different time periods, datasets, and methodological frameworks, making direct comparison challenging. The analyses presented here are therefore intended to synthesise, verify and clarify existing findings within a unified framework rather than to introduce entirely novel mechanisms. This approach enables a more coherent assessment of historical variability, recent trends, and dataset-dependent uncertainties.

3.1 Spatial and Temporal Variability of Sri Lankan Rainfall

Sri Lanka’s rainfall climatology exhibits one of the sharpest spatial gradients in the tropics as a result of the country, which interacts with oscillatory monsoonal circulations (Alahacoon & Edirisinghe, 2021; Kajakokulan et al., 2023a). Analysis of the high-resolution CHIRPS dataset for the period 1981–2023 reveals robust seasonal variations in rainfall magnitude and spatial distribution across the island (Figs 3, 5, and 6). The SWM season (MJJAS) represents the dominant rainfall season for the Wet Zone. Mean daily rainfall frequently exceeds 8 – 16 mm/day along the windward slopes of the central highlands, locally surpassing 20 mm/day in elevated regions such as the Adam's Peak and Rakwana Hills, where strong orographic uplift enhances moisture convergence (Bandurathna et al., 2021; Kajakokulan et al., 2023b; Fig. 3). In contrast, the NEM (DJF) reverses the rainfall pattern, delivering 6 – 10 mm/day to the Northern and Eastern Dry zone, while much of the Southwestern lowlands receive only 2 - 6 mm/ day (Punyawardena & Abeysekera, 2020; Abeysekera et al., 2021; Fig. 3).

The two Inter-monsoon seasons play a critical transitional role. The FIM (MA) produces moderate and relatively uniform rainfall across the island (6 – 10 mm/day; Fig. 3), reflecting widespread convective activity under weak background winds. In contrast, the SIM (ON) emerges as the season of maximum convective intensity, with localised mean daily rainfall exceeding 16–20 mm/day over the southwestern lowlands and central highlands (Fig. 3). Despite its short duration, SIM contributes a substantial share of Sri Lanka's annual rainfall. Quantitative assessment using gridded reanalysis data indicates that the SIM accounts for approximately 30-33% of the annual rainfall at the national scale, with an even larger proportional contribution in the dry zone, where it represents the dominant rainfall season (Fig. 5). In the wet and intermediate zones, the SIM contribution is comparable to that of the SWM, confirming its critical role in the island's annual hydrological balance. This pronounced seasonal concentration helps explain why a large proportion of flood and landslide events occur in October-November despite the season's short duration.

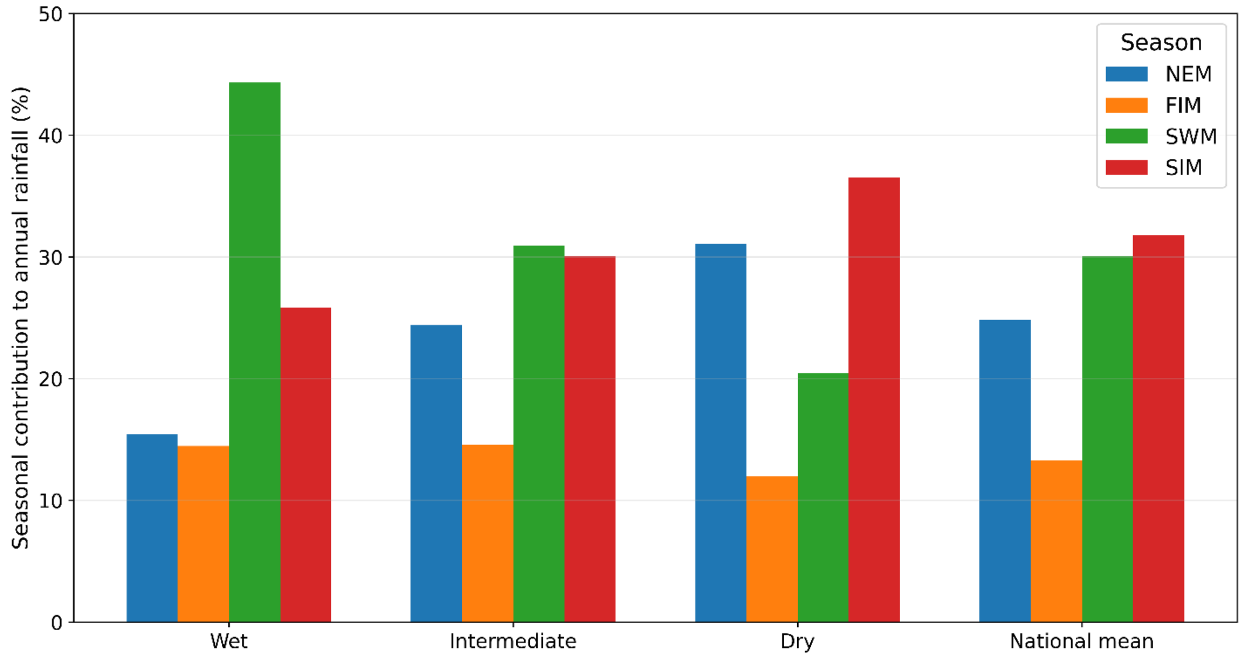


Fig. 5 Seasonal contribution (%) of the NEM, FIM, SWM, and SIM to the annual rainfall total over Sri Lanka for the period 1990-2023. Contributions are calculated as the percentage of seasonal rainfall relative to annual rainfall using daily reanalysis data. Values represent averages across the stations within the wet, dry and intermediate zones, with the national mean shown for comparison

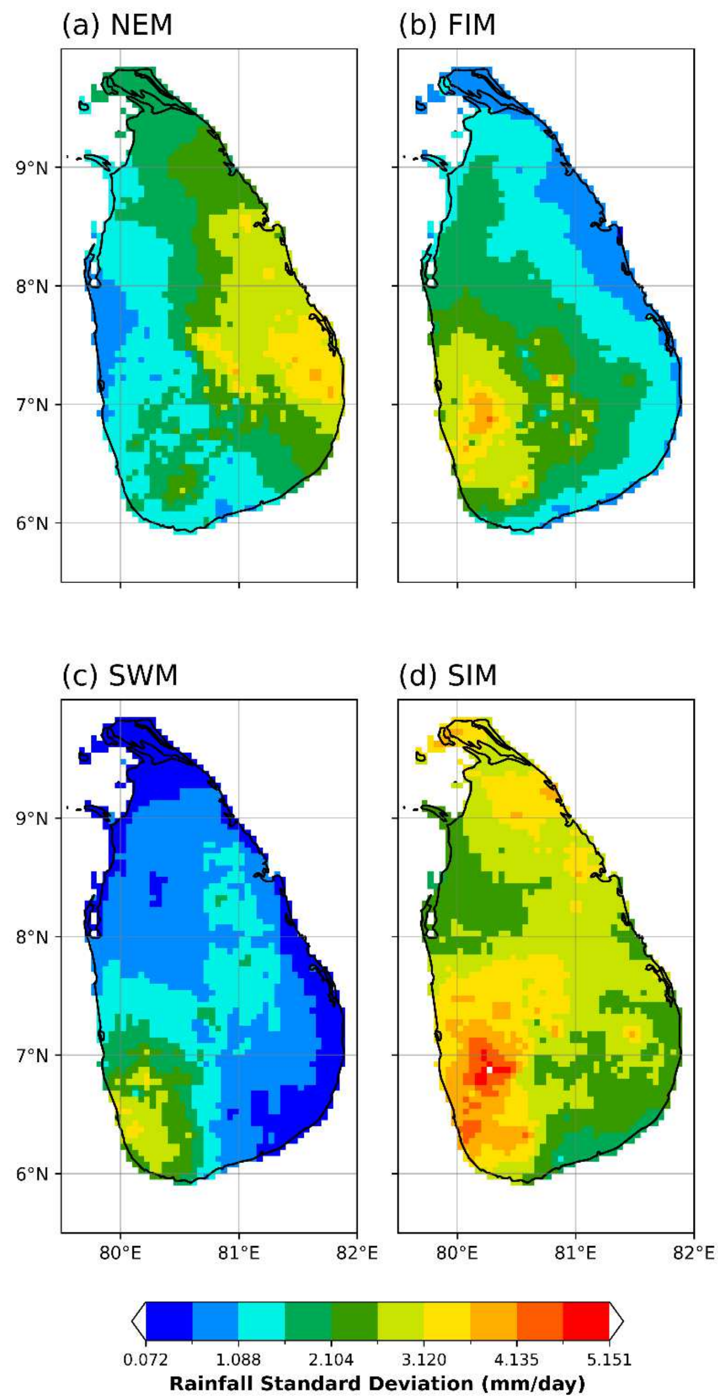


Fig. 6 Spatial distribution of Seasonal rainfall variability (SD of seasonal mean rainfall; mm/day) in Sri Lanka during the (a) NEM, (b) FIM, (c) SWM, and (d) SIM, derived from CHIRPS data (1981 – 2023). Variability is calculated as the inter-annual SD of seasonal rainfall totals

Interannual variability, quantified using the SD of seasonal rainfall (Fig. 6), further reveals distinct seasonal behaviour. Variability during the core SWM remains comparatively low (2 – 3 mm/day) over the wet zone, reflecting the relative stability of the large-scale southwesterly flow and persistent orographic forcing (Nisansala et al., 2019). In contrast, rainfall variability increases sharply during the SIM, frequently exceeding 5 mm/day, confirming that October–November rainfall is the most intense and exhibits the largest interannual variability among the four seasons (Karunathilaka et al., 2017; Naveendrakumar et al., 2018).

The pronounced interannual variability of the SIM arises from the coexistence and interaction of multiple large-scale and synoptic-scale atmospheric drivers during this transitional season. Unlike the SWM, which is dominated by relatively stable southwesterly low-level flow and persistent orographic uplift, the SIM occurs during a period of weak background monsoon circulation when the ITCZ migrates southward across Sri Lanka (Zubair et al., 2008; Punyawardena, 2010). This migration enhances deep convection and atmospheric instability, but the absence of steady monsoonal flow makes rainfall highly sensitive to short-lived disturbances. During October-November, Sri Lanka is simultaneously influenced by enhanced convective activities associated with ITCZ positioning (Burt et al., 2014; Ranasinghe et al., 2024), frequent low-pressure systems and depressions forming in the BoB (Burt et al., 2014), tropical cyclones and cyclonic storms (Burt et al., 2014), strong modulation from IOD events (Abeysekera et al., 2021; Kajakokulan et al., 2023a), and ENSO-related Pacific-Indian teleconnections (Burt et al., 2014).

The BoB cyclone season peaks during October-November, and even systems that do not make direct landfall can produce extreme rainfall over Sri Lanka when interacting with the island's steep central topography (WMO, 2008; Mohanty et al., 2012; Pathirana & Priyadarshani, 2022). Furthermore, pIOD events have become more frequent since the mid-1990s, inducing anomalous warming in the western Indian Ocean, strengthening low-level moisture convergence toward Sri Lanka, and enhancing convective rainfall during SIM (Zubair et al., 2003; Cai et al., 2014; Abeysekera et al., 2021). ENSO further modulates this variability, with El Niño years typically associated with wetter October-November conditions (Zubair et al., 2008). In addition, rapid basin-wide warming of the tropical Indian Ocean has increased atmospheric moisture-holding capacity in accordance with the Clausius-Clapeyron relationship, intensifying convective rainfall extremes during inter-monsoon periods (Roxy et al., 2014; Gulev et al., 2021).

Seasonal rainfall trends estimated using the non-parametric MK test combined with Sen's Slope estimator (Fig. 7) indicate near-zero or weak trends during the NEM, FIM, and SWM across most regions, consistent with previous studies (Alahacoon & Edirisinghe, 2021; Kajakokulan et al., 2023a). In contrast, a spatially coherent and statistically significant positive trend emerges during the SIM. Trend magnitudes range from approximately +0.08 mm/day/year in coastal regions to approximately +0.12–0.16 mm/day/year across a large part of the southwestern slopes and central highlands (Kajakokulan et al., 2023a), indicating a systematic intensification of October-November rainfall. Because SIM rainfall is primarily convection-driven rather than dynamically constrained by steady monsoonal flow, it responds strongly to thermodynamic amplification, thereby enhancing both rainfall intensity and interannual variability. This explains why statistically significant positive trends emerge during SIM across most of the country.

From a socioeconomic standpoint, the observed intensification of SIM-associated precipitation has significant implications, as the October-November rainfall regime coincides with the onset of the Maha cultivation season across much of Sri Lanka, making it a principal determinant of crop establishment dynamics, flood hazard exposure, and regional food security outcomes. (Marambe et al., 2015). Strengthening inter-monsoon rainfall, while beneficial for water storage in some years, increases exposure to flooding, landslides, and agricultural losses, particularly in the wet zone and central highlands. Therefore, the emerging positive trend in SIM rainfall represents both a hydrological intensification signal and growing climate risk.

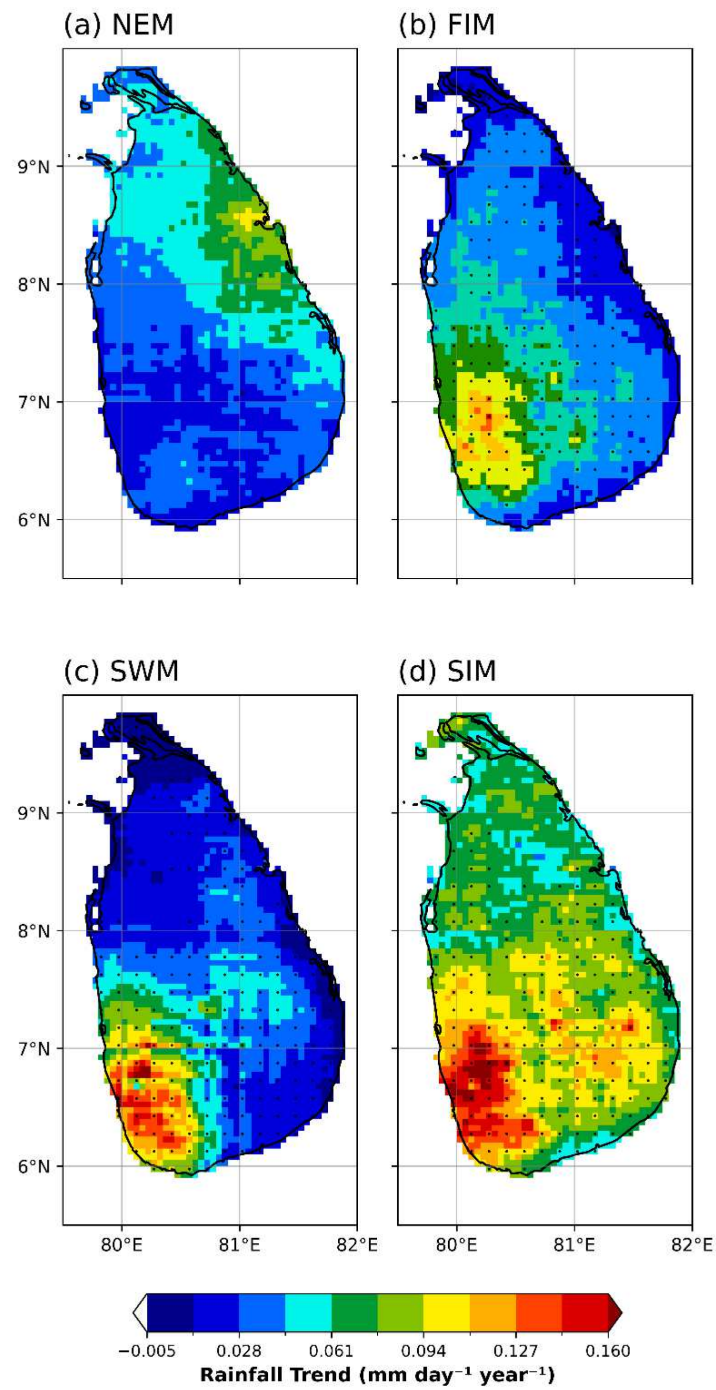


Fig. 7 Spatial distribution of seasonal rainfall trends (mm/day/year) across Sri Lanka during the (a) NEM, (b) FIM, (c) SWM, and (D) SIM, derived from CHIRPS 1981-2023 data. Trends are calculated using the non-parametric MK t-test (Mann, 1945; Kendall, 1975) with Sen's slope estimator (Sen, 1968). Statistical significance is assessed at the 95% confidence level

Changes in rainfall frequency further reinforce these findings. For instance, the comparison of inter-annnual variability of the annual number of wet days (≥ 1 mm/day) and dry days (≤ 1 mm/day) exhibit an increase of wet days (Fig. 8a) during the period from 1981 to 2023 where the number of annual wet days were typically ranged from 150 to 250 days per year (Fig. 8a). The long-term shift toward wet-day dominance is clearly reflected in the annual difference between number of wet days and the number of dry days (Fig. 8b). During the early period of record (1981-1990), this diffrence varies around zero or asumes slightly negative values, where as from the late 1990s onward it become persistantly positive and exhibits a marked increasing treand (Fig. 8b), with extreme positive anomalies recorded in 2018 (+173), 2020 (+145) and 2022 (+175). The fitted linear trend (Fig. 8b) indicates an increase of ~3.28 wet days per year, suggesting a gradual shift toward more frequent rainfall days at the national scale. These results contrast with Amarasinghe (2020), who reported only modest increases in wet days and no systematic change in dry days, highlighting the sensitivity of trend estimates to dataset choice and analysis period.

The apparent discrepancy between the present results and those of Amarasinghe (2020) primarily reflects differences in the rainfall indicators analysed rather than a true contradiction in long-term rainfall behaviour. Amarasinghe (2020) focused exclusively on trends in monthly, seasonal, and annual rainfall totals derived from CHIRPS data for the period 1989-2019, without explicitly examining daily rainfall occurrence or wet-day frequency (Fig. 8). In contrast, the present analysis evaluates changes in rainfall frequency using daily data, and thereby present study captured shifts in the number of rainfall events rather than total accumulated rainfall. These two metrics represent distinct dimensions of hydro-climatic variability. Rainfall totals represent the cumulative amount of precipitation received, whereas wet-day frequency reflects the occurrence and persistence of rainfall events (Zolina et al., 2010; Donat et al., 2013).

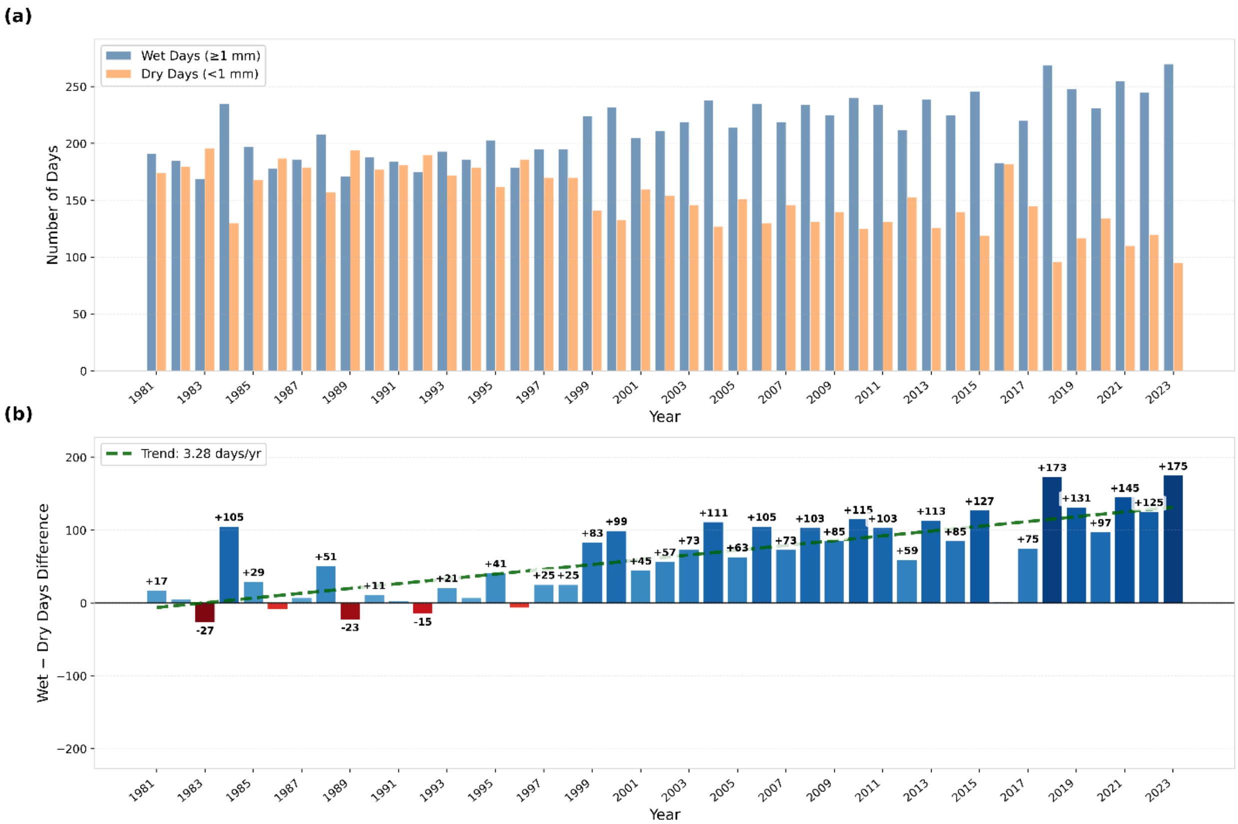
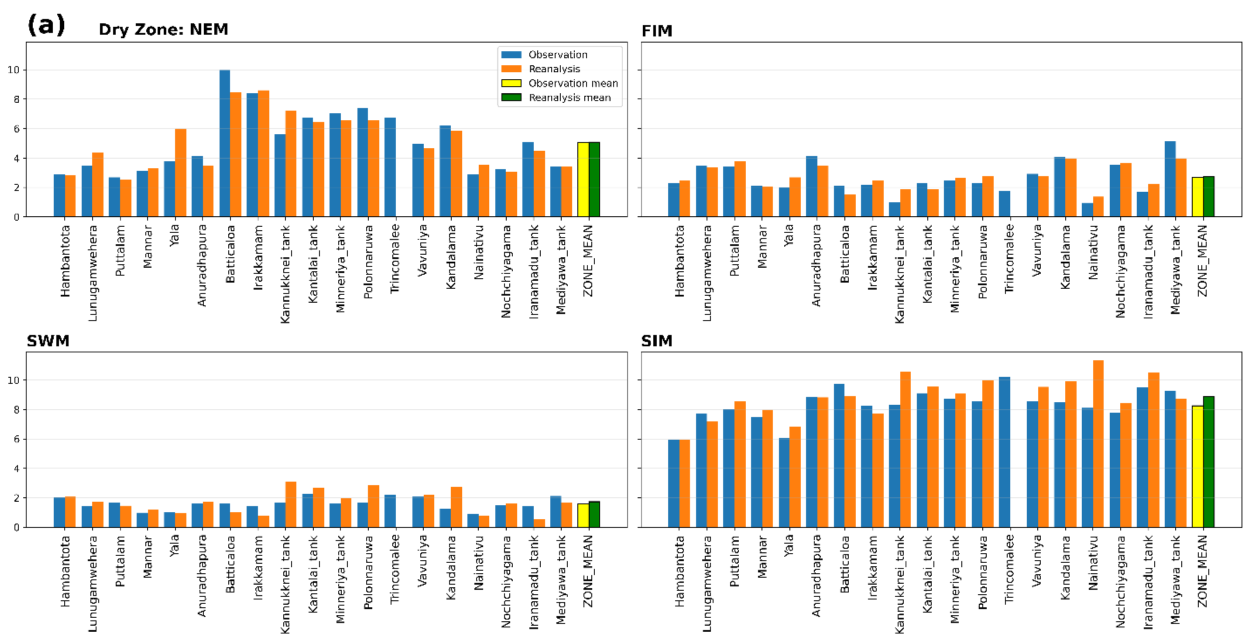
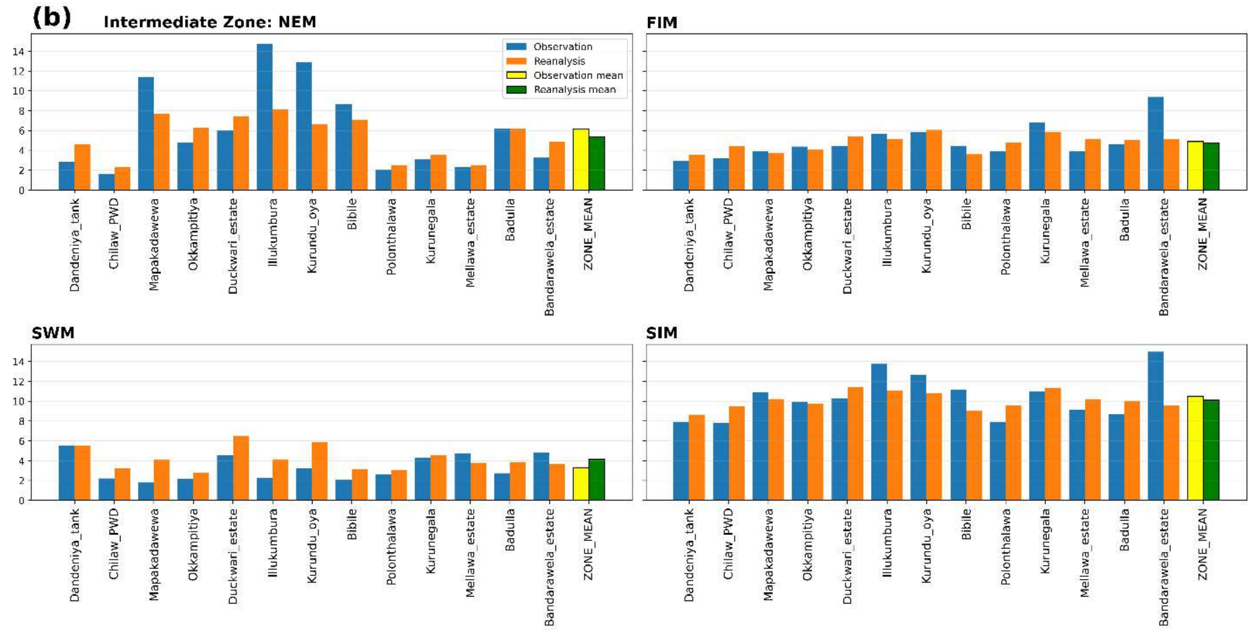


Fig. 8 (a) Annual number of wet days (blue bars; precipitation ≥ 1mm) and dry days (Orange bars; ≤ 1 mm/day) from 1981 to 2023. Total days per year are approximately 365/366. Therefore, wet days + dry days = total calendar days. (b) Corresponding annual difference (Wet days; Blue bars – Dry days; Brown Bars) for the same period (CHIRPS data from 1981-2023), with labelled anomalies relative to the long-term mean and linear trend line indicating an increase of 3.28 wet days per year. Positive values denote more wet days, while negative values denote more dry days. The ≥ 1mm threshold follows common precipitation frequency definitions used in climate indices

Changes in rainfall totals do not necessarily correspond to proportional changes in rainfall frequency. An increase in total rainfall may occur through fewer but more intense events, or through more frequent moderate rainfall events, depending on prevailing atmospheric and oceanic conditions (IPCC, 2021). Consequently, studies based solely on monthly or seasonal totals may not detect changes in rainfall events that become evident when daily frequency metrics are analysed. The stronger increasing trend in wet days identified in the present study, therefore complements, rather than contradicts, earlier findings of modest or inconsistent changes in rainfall totals.

The difference in temporal coverage may further contribute to the divergence of the observed rainfall trends between the present study and previous studies. Amarasinghe (2020) analysed a 30-year period ending in 2019, whereas the present study further extends to 2023 and includes several recent extreme rainfall years. Trend detection in hydro-climatic time series is known to be sensitive to record length and to the inclusion of anomalously wet or dry periods (Donat et al., 2013). The inclusion of recent high-rainfall years may therefore enhance the detectability of an increase in rainfall frequency. Taken together, these methodological differences indicate that the observed increase in wet-day frequency represents an additional dimension of rainfall change in Sri Lanka. While previous studies highlight modest or spatially variable trends in rainfall totals, the present findings suggest a gradual shift to more frequent rainfall events at the national scale, consistent with broader evidence of intensifying hydrological cycle variability in a warming tropical climate (IPCC, 2021).





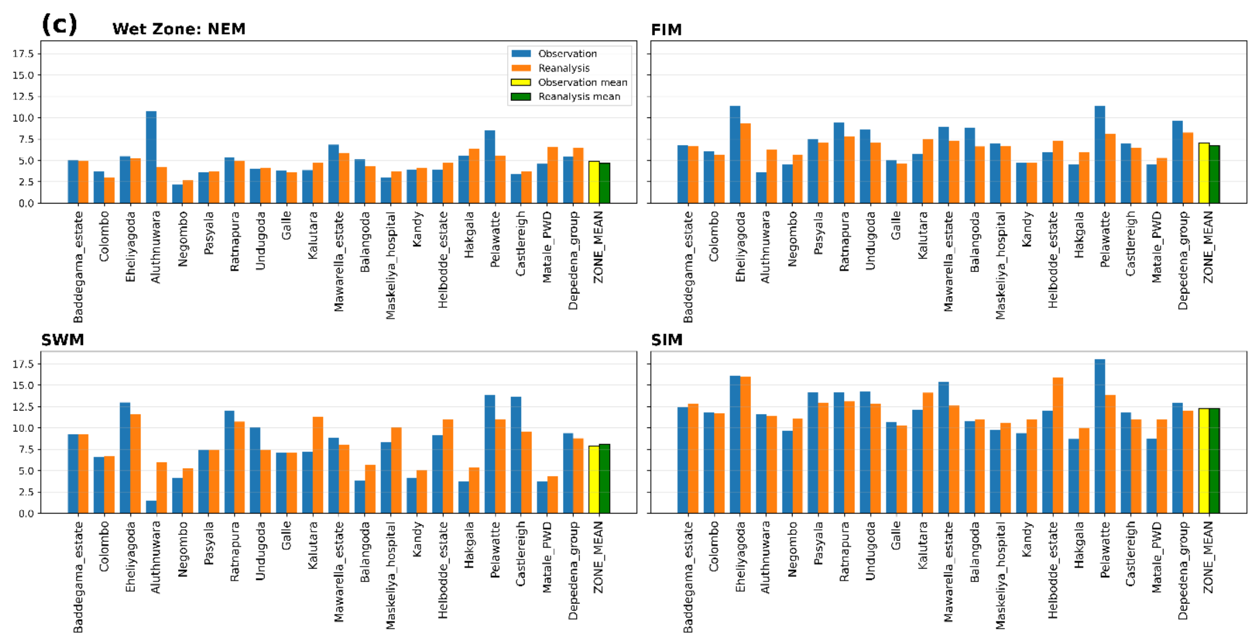


Fig. 9 Station-wise seasonal rainfall climatology in mm/day (1990-2023), across Sri Lanka's (a) Dry zone, (b) Intermediate zone, and (c) Wet zone. Bars represent mean monthly rainfall (in arbitrary units scaled for comparison) during the four main rainfall seasons: Northeast Monsoon (NEM), First Inter-monsoon (FIM), Southwest Monsoon (SWM), and Second Inter-monsoon (SIM). Blue bars show gauge observations, orange bars show reanalysis data, yellow lines indicate

observational zonal means, and green lines indicate reanalysis zonal means. Stations are ordered approximately west to east/south to north within each zone

Both in-situ observed and reanalysis data exhibit a clear spatial heterogeneity among station-wise seasonal rainfall across three major climatic zones of Sri Lanka (dry, intermediate, and wet) (Fig. 9). Agreement between the observations (yellow) and reanalysis (green) rainfall was further evaluated using season-wise statistical comparison at individual stations (Table. 3). Correlation is generally high across most seasons and zones, particularly in the dry zone ($r = 0.67 – 0.91$) and during the inter-monsoon periods in the wet zone ($r = 0.70 – 0.82$). Larger RMSE and lower correlation values in the intermediate zone, especially during the SWM and SIM, likely reflect localised convective variability and complex topographic influences that are smoothed in grid products. Despite these localised differences, mean bias remains small across all zones (generally within ± 1 mm/day), confirming that the reanalysis dataset reliably captures the broad seasonal rainfall structure over Sri Lanka.

Table. 3 Season-wise statistical agreement between observations and reanalysis datasets (1990-2023). Statistical comparison between station observations and reanalysis rainfall based on seasonal mean values at individual stations. (Bias represents reanalysis minus observations)

Climatic Zone	Season	r value	p-value	Bias (mm/day)	RMSE (mm/day)
Wet	NEM	0.45	0.047	-0.27	1.76
	FIM	0.82	0.000	-0.34	1.53
	SWM	0.82	0.000	0.23	2.10
	SIM	0.70	0.001	0.02	1.77
Intermediate	NEM	0.83	0.000	-0.79	2.90
	FIM	0.55	0.052	-0.12	1.40
	SWM	0.54	0.057	0.86	1.43
	SIM	0.38	0.205	-0.37	2.07
Dry	NEM	0.91	0.000	0.01	0.85
	FIM	0.90	0.000	0.05	0.51
	SWM	0.51	0.029	0.16	0.66
	SIM	0.67	0.002	0.61	1.18

In the Dry zone (Fig. 9a), rainfall is relatively dominated by the NEM, with peak intensities concentrated along the northeastern coast, reflecting direct moisture transport from the BoB. Inland regions receive comparatively lower rainfall, though localized enhancements are evident in some interior parts. The FIM and SWM contribute to relatively weak rainfall. In contrast, the SIM emerges as the primary rainfall season, characterized by widespread and intense precipitation across both coastal and inland stations. Spatial variability is evident, with coastal and northeastern stations generally receiving higher rainfall than inland regions. Reanalysis data broadly capture these spatial patterns but tend to underestimate the peak rainfall at high-intensity locations while slightly overestimating rainfall at some inland stations.

The Intermediate zone (Fig. 9b), rainfall shows greater spatial variability compared to the Dry zone, particularly during the NEM, reflecting strong topographic influences. The FIM is characterised by relatively uniform rainfall, consistent with the widespread convective activity. Rainfall during the SWM remains moderate, while the SIM is the dominant season, with the highest intensities at most stations. Reanalysis data reproduce the overall spatial structure but tend to underestimate peak rainfall in high-elevation regions, highlighting limitations in resolving localised orographic effects.

In the Wet zone (Fig. 9c), rainfall is more evenly distributed across seasons but shows clear dominance of the SWM and SIM. The SWM produces sustained high rainfall through orographic uplift along the windward slopes of the central highlands, while the SIM contributes equally intense, convection-driven rainfall across both highland and lowland regions. FIM also delivers appreciable rainfall, whereas NEM plays a relatively minor role. Reanalysis data also capture the seasonal rainfall distribution in the Wet Zone, although peak intensities remain slightly underestimated due to the smoothing of extreme values.

Together, these station-level patterns reinforce the sharp spatial gradients evident in gridded climatology (Fig. 3) and emphasise the important influence of topography on large-scale monsoonal flows. The Dry Zone's reliance on NEM rainfall and also SIM contrasts markedly with the Wet Zone's dependence on SWM and SIM convective activity, while the Intermediate Zone bridges these extremes. These distinct regimes have direct implications for agricultural (e.g. alignment of the *Maha* season with NEM rainfall in the Dry Zone and the *Yala* season with SWM rainfall in the Wet zone) and hazard exposure, with the Wet zone particularly vulnerable to SWM, and SIM-related floods and landslides, and the Dry zone sensitive to NEM failures and droughts. The close correspondence between observational and reanalysis zonal means further supports the robustness of these spatial-temporal patterns across different data sources.

3.2 Role of Tropical Cyclones

Tropical Cyclones and depressions originating in the BoB exerts a disproportionate influence on Sri Lanka's rainfall extremes, particularly during the NEM and SIM periods (Jayasekara et al., 2024; Ranasinghe et al., 2024). Although direct cyclone landfalls are relatively rare, even distant or weakening systems can deliver 200 – 500 mm of rain within 24-48h when their circulation interacts with Sri Lanka's steep topography (Pathirana & Priyadarshani, 2022). The eastern and northeastern coasts are most frequently affected by cyclones, though intense events occasionally impact the southwestern region as well. Recent observational and modelling studies indicate an eastward shift in cyclone genesis locations in the BoB, along with an increase in rapid intensification events, linked to warmer SSTs and enhanced mid-tropospheric humidity (Jayasekara et al., 2024). These changes increase the likelihood of heavier rainfall and stronger storm surges affecting the northern and eastern (Dry Zone) Sri Lanka, a region historically less exposed to cyclonic extremes than the southwest. While a detailed cyclone-specific analysis is beyond the scope of this study and will be addressed in a separate review. This brief overview highlights the important role of weather systems in the BoB in shaping Sri Lanka's most severe precipitation events and highlights the need for enhanced monitoring and preparedness.

3.3 Impact of dominant Air- Sea Coupled Modes and Ocean Warming

Global mean SST has increased by approximately 0.60 °C since 1980, with the majority of excess anthropogenic heat absorbed by the oceans (Gulev et al., 2021). The Tropical Indian Ocean has warmed faster than the global average, exhibiting a basin-wide increase of nearly 1 °C since the 1950s, with stronger warming in the western basin (Roxy et al., 2014). The differential warming enhances atmospheric moisture availability and alters large-scale circulation, creating a thermodynamic background for intensified convection and rainfall extremes over Sri Lanka, particularly during the Inter-monsoon periods (Roxy et al., 2014; Gulev et al., 2021).

Beyond its direct thermodynamic influence, sustained ocean warming can also alter the behaviour, frequency, and intensity of tropical air–sea coupled climate modes that regulate regional rainfall variability. In the Indian Ocean sector, changes in background SST gradients influence the amplitude and occurrence of modes such as the IOD, while Pacific variability associated with the ENSO continues to modulate atmospheric circulation through inter-basin teleconnections. Several studies suggest an increased frequency of extreme pIOD events since the late 1990s (Cai et al., 2014), alongside enhanced variability in regional climate extremes (Pathirana et al., 2024). This intensification of air–sea coupled variability, superimposed on a warmer and moister atmospheric background, provides a physically consistent explanation for the observed upward trend in inter-monsoon rainfall over Sri Lanka.

3.3.1 Indian Ocean Dipole

The Indian Ocean Dipole (IOD), measured by the Dipole Mode Index (DMI), is a dominant mode of inter-annual variability influencing Sri Lankan rainfall, especially during the SIM (Zubair et al., 2003; Abeysekera et al., 2021; Werellapatha et al., 2026). PIOD events, characterised by warmer western Indian Ocean SSTs relative to the east, enhance low-level convergence and moisture transport toward Sri Lanka's southwestern topography, leading to increased rainfall. Regression analysis of seasonal rainfall anomalies against the SON (September-October-November) DMI (Fig. 10) reveals the strongest response during the SIM, with positive slopes of +1.94 to +3.88 mm/day/°C over the Wet zone and central highlands (Fig. 10d), many of which are statistically significant ($p < 0.05$). Other seasons show weaker or mixed responses, confirming the seasonal selective influence of the IOD. The increased frequency and intensity of extreme pIOD events since the mid-1990s have amplified SIM variability and contributed to positive rainfall trends, with anomalies reaching 6–10 mm/day during strong events (Cai et al., 2014; Abeysekera et al., 2021).

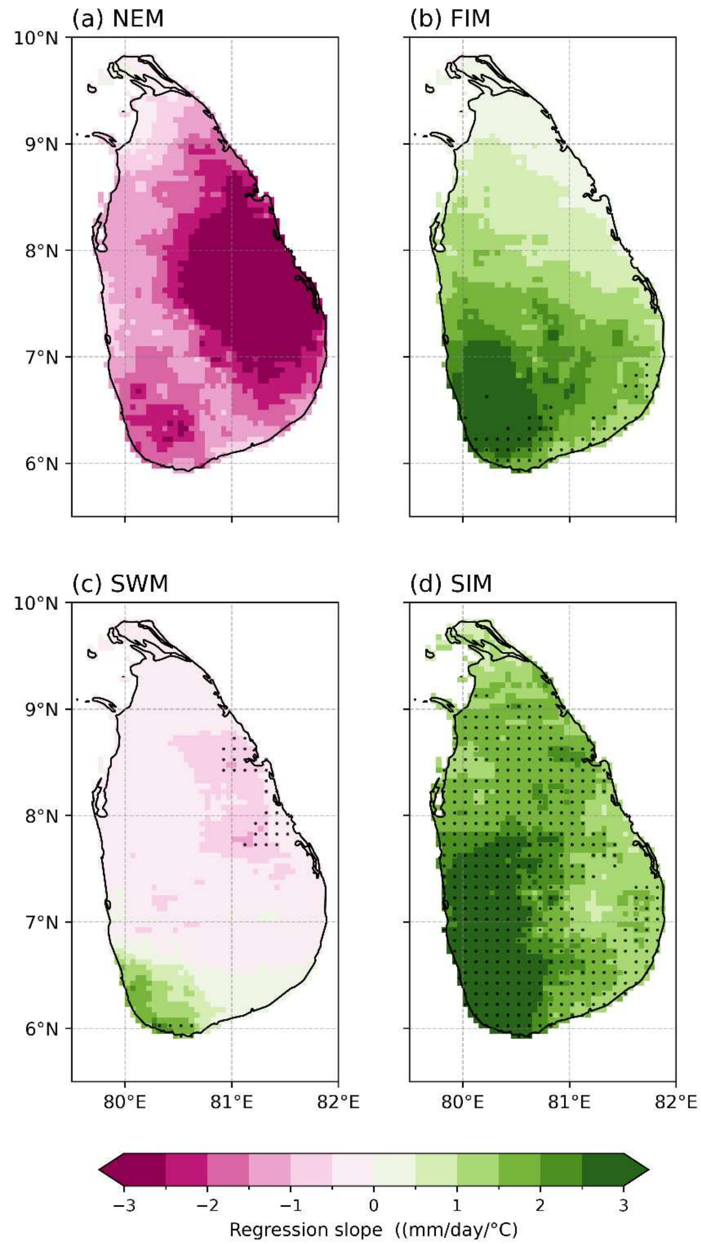
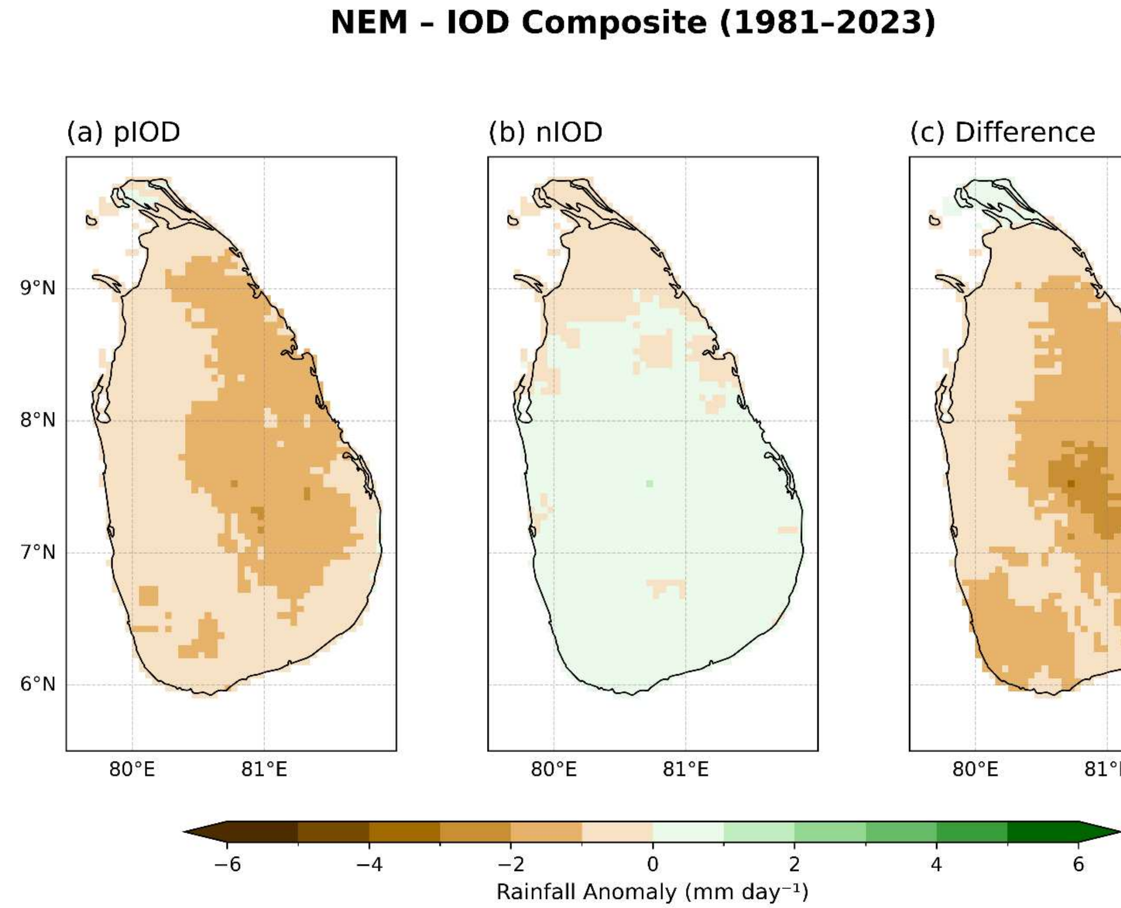
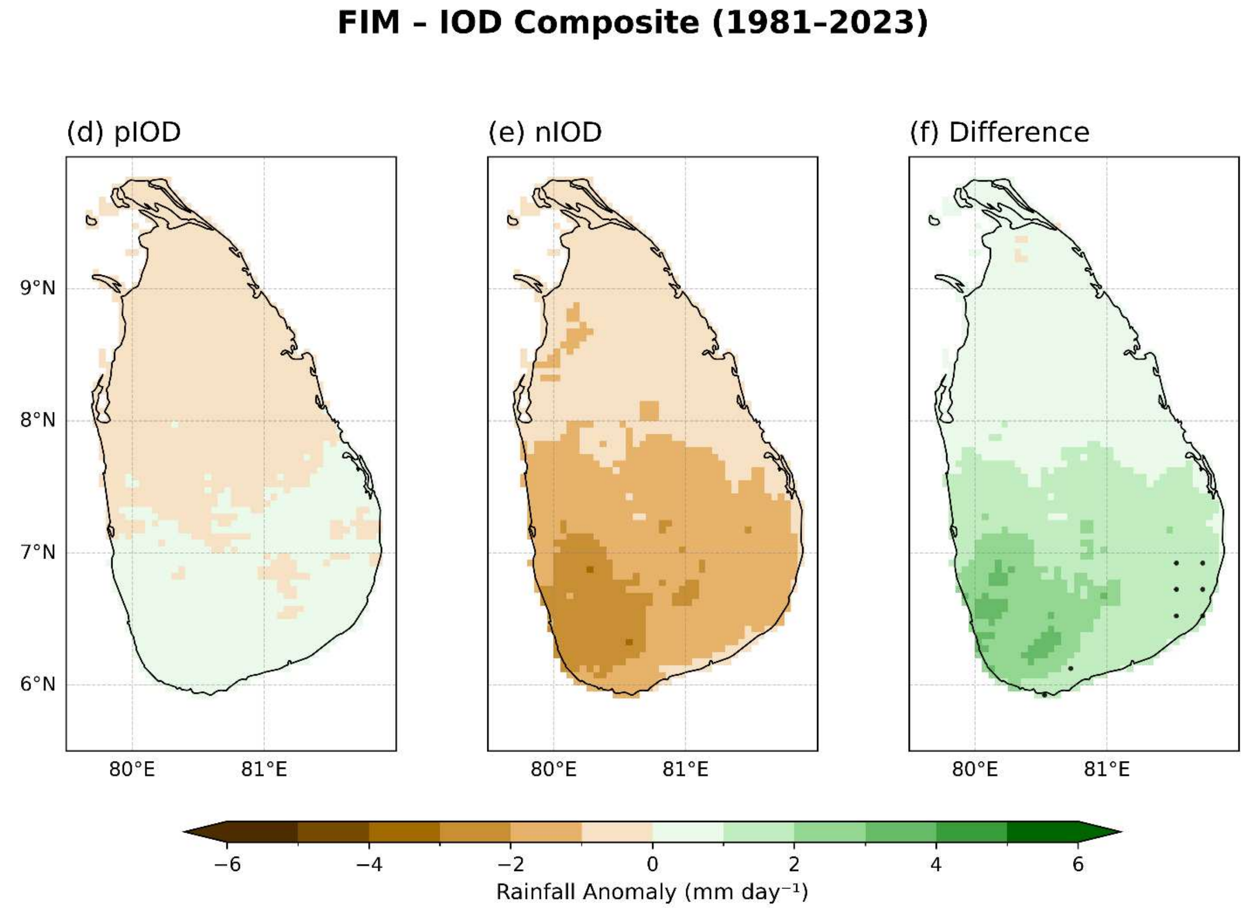
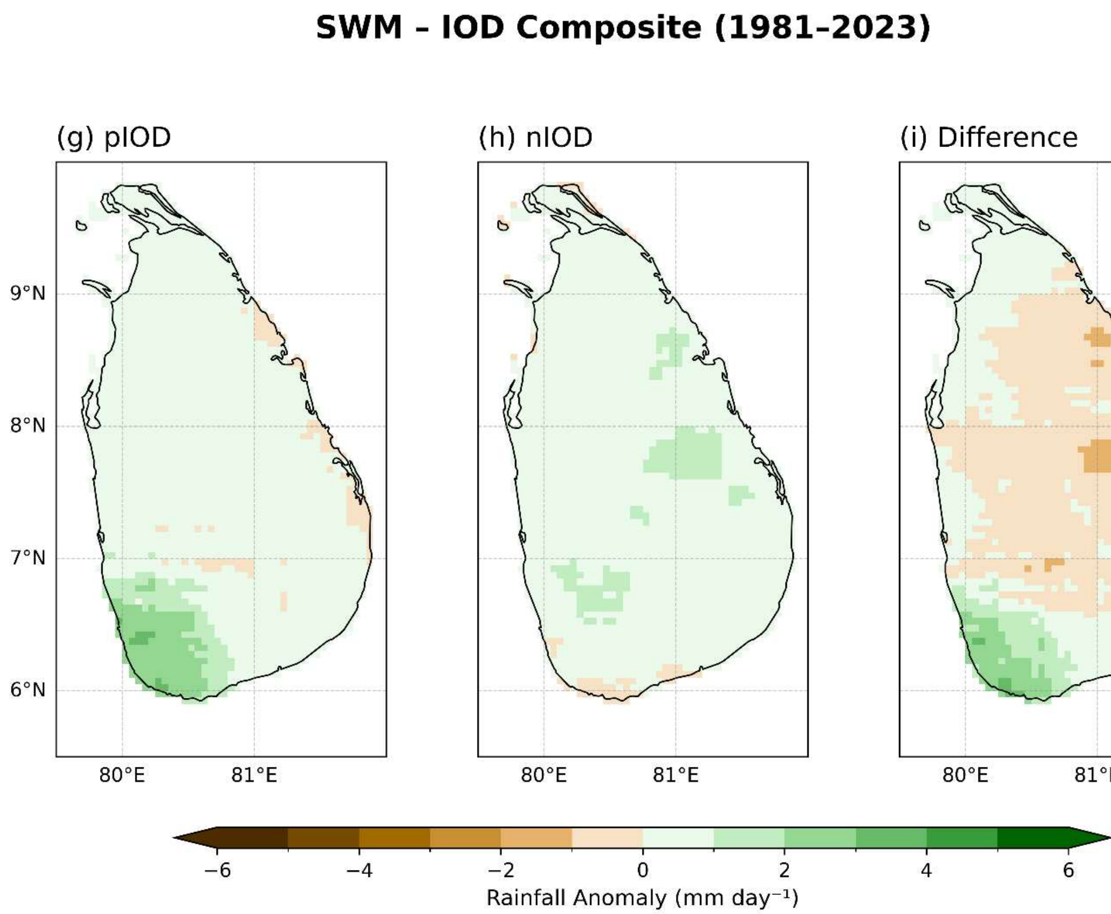


Fig. 10 Spatial patterns of the regression coefficients between seasonal rainfall anomalies and the SON (September-October-November) DMI (Saji et al., 1999) over Sri Lanka. Panels show the linear regression slope (mm/day/°C), (a) NEM, (b) FIM, (c) SWM, and (d) SIM. Positive values (green color) indicate increased rainfall associated with IOD, while negative values (Pink color) indicate decreased rainfall associated with IOD. Black stippling indicates grid cells where the regression is statistically significant at the 95% confidence level based on two-tailed student's t-test (Wilks, 2011)


NEM – IOD Composite (1981–2023)
(a) pIOD
(b) nIOD
(c) Difference
9°N
8°N
7°N
6°N
80°E
81°E
−6
−4
−2
0
2
4
6
Rainfall Anomaly (mm day⁻¹)


FIM – IOD Composite (1981–2023)
(d) pIOD
(e) nIOD
(f) Difference
9°N
8°N
7°N
6°N
80°E
81°E
−6
−4
−2
0
2
4
6
Rainfall Anomaly (mm day⁻¹)


SWM – IOD Composite (1981–2023)
(g) pIOD
(h) nIOD
(i) Difference
9°N
8°N
7°N
6°N
80°E
81°E
−6
−4
−2
0
2
4
6
Rainfall Anomaly (mm day⁻¹)

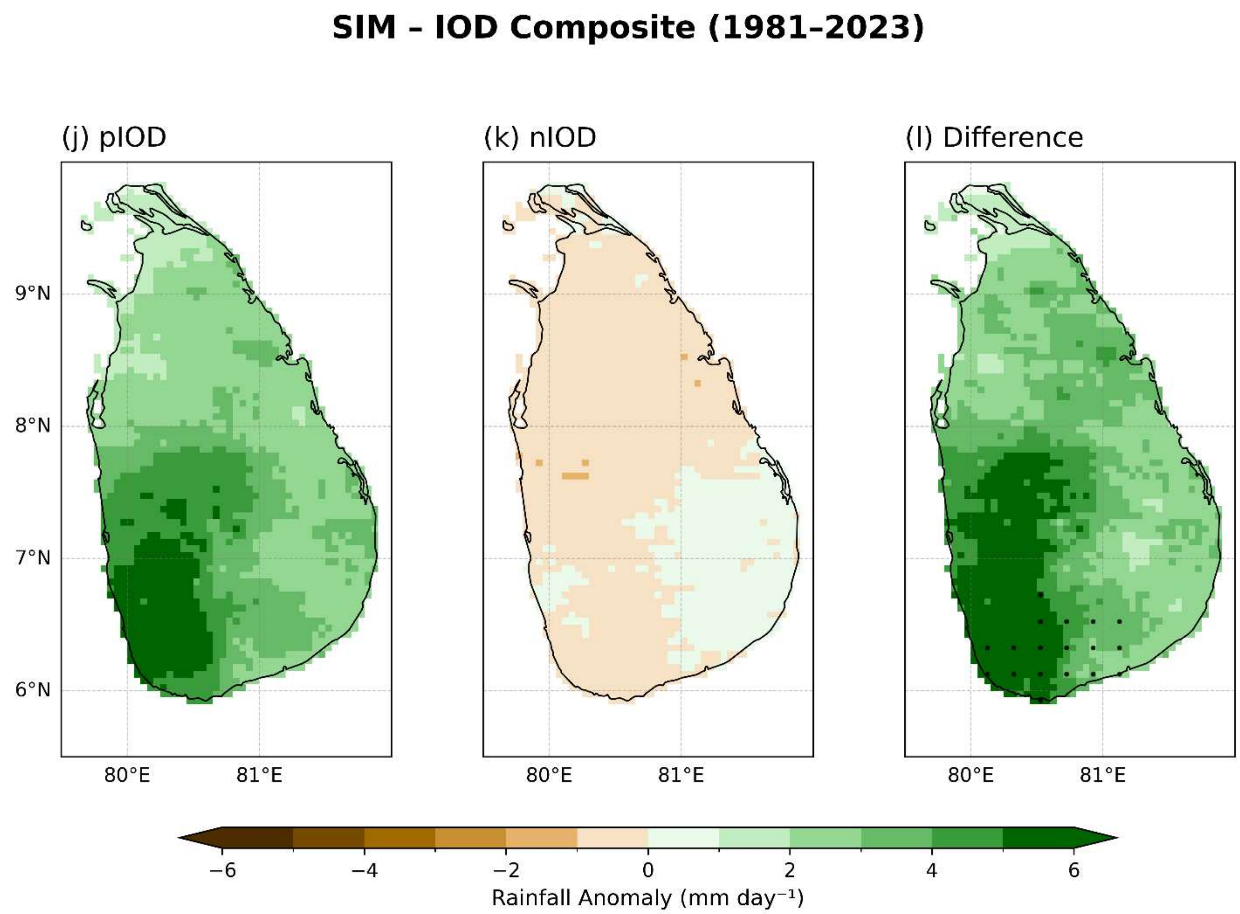


Fig. 11 Composite rainfall anomalies (mm/day) over Sri Lanka during pIOD, nIOD and their difference. (a) NEM pIOD, (b) NEM nIOD, (c) NEM Difference, (d) FIM pIOD, (e) FIM nIOD, (f) FIM Difference, (g) SWM pIOD, (h) SWM nIOD, (i) SWM Difference, (j) SIM pIOD, (k) SIM nIOD, and (l) SIM Difference. Positive anomalies indicate above-average rainfall, while negative anomalies indicate below-average rainfall during the respective IOD phases. The difference panel highlights enhanced rainfall in pIOD relative to nIOD. Black stipplings indicate grid cells where the composite anomalies are statistically significant at the 95% confidence level based on two-tailed student's t-test (Wilks, 2011). Positive and Negative IOD years are defined using ± 0.4°C DMI thresholds (Saji et al., 1999; Cai et al.,2014)

There is a clear spatial heterogeneity in relationship between rainfall and IOD (pIOD, nIOD and the difference) across four monsoon seasons during the period of 1981-2023 (Fig. 11). Composite analysis of rainfall anomalies (Fig. 11) further highlights the asymmetric influence of the IOD on Sri Lanka's seasonal rainfall (Saji et al., 1999; Abeysekera et al., 2021). During the SIM (ON), pIOD years exhibit widespread rainfall enhancement exceeding 4–6 mm/day over the Wet zone and central highlands, while nIOD years show comparable deficits. The difference map highlights anomalies exceeding 6 mm/day in the wet zone, confirming the strong enhancement of convective rainfall during positive phases and its suppression during negative phases (Abeysekera et al., 2021). The difference map of SIM indicates the dominance of pIOD and a dominant wetter period. This aligns well with foundational work showing a positive correlation between pIOD and enhanced rainfall via anomalous western Indian Ocean warming, which induces lower-tropospheric convergence and convection extending to Sri Lanka (Zubair et al., 2003). Recent analyses confirm significant positive anomalies in SIM cumulative rainfall, wet days, and heavy events during pIOD, with opposite drying and more consecutive dry days in nIOD (Abeysekera et al., 2021). These patterns demonstrate asymmetric IOD responses throughout the seasons. As a result, the SWM (MJJAS) shows modest positive anomalies in the Wet zone during pIOD, but a weaker overall response; the NEM (DJF) reveals slight drying in the north; and the FIM (MA) displays diffuse positive anomalies without strong spatial coherence. Thus, the asymmetry is weaker in other seasons, reinforcing the IOD's dominant role in driving extreme wet conditions during October-November. The dominance of pIOD events in modulating rainfall over Sri Lanka is consistent with recent findings highlighting the asymmetric nature of the IOD-induced rainfall variability across the tropical Indian Ocean (Werellapatha et al., 2026).

3.3.2 El Niño Southern Oscillation (ENSO)

The ENSO, indexed by Niño 3.4 anomalies, exerts a secondary influence on Sri Lankan rainfall through Pacific–Indian Ocean teleconnections (Zubair & Ropelewski, 2006; Zubair et al., 2008). Regression patterns (Fig. 12) show modest rainfall enhancement during the SIM under El Niño conditions, particularly over western and southeastern regions, while NEM and FIM exhibit rainfall suppression. SWM responses are generally weak and insignificant (Zubair et al., 2008). According to rainfall composites for El Niño, La Niña, and their difference across the four seasons (Fig. 13), there is a clear spatial pattern across the island, highlighting orographic influences specifically during the inter-monsoon period. These composites robustly align with and extend findings from Yahiya et al. (2009), who analysed ENSO modulation of Sri Lankan rainfall using historical data and seasonal composites. El Niño leads to wetter conditions in October- November and drier conditions in January-February (Yahiya et al., 2009; Fig. 13), while the La Niña effects are generally inverse. The results are statistically significant for SIM across Sri Lanka. During SIM, the difference map shows strong positive values ranging from 4 to 6 mm/day, indicating El Niño dominance. During NEM, El Niño shows widespread dry anomalies, while La Niña shows wetter conditions (Yahiya et al., 2009; Fig. 13). Together, rapid Indian Ocean warming, increased pIOD frequency, and ENSO modulation provide a coherent explanation for the observed intensification and growing unpredictability of SIM rainfall, particularly in Sri Lanka's Wet Zone, with direct implications for heavy rainfall and flood risk (Cai et al., 2014; Roxy et al., 2014).

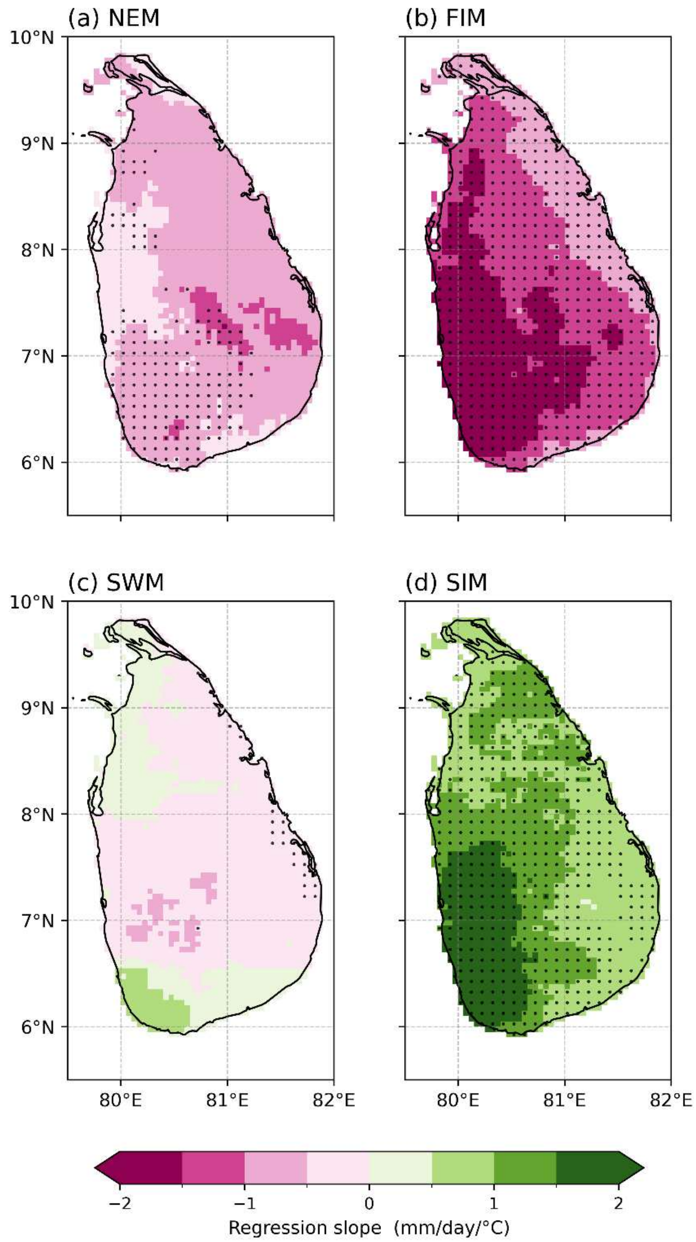
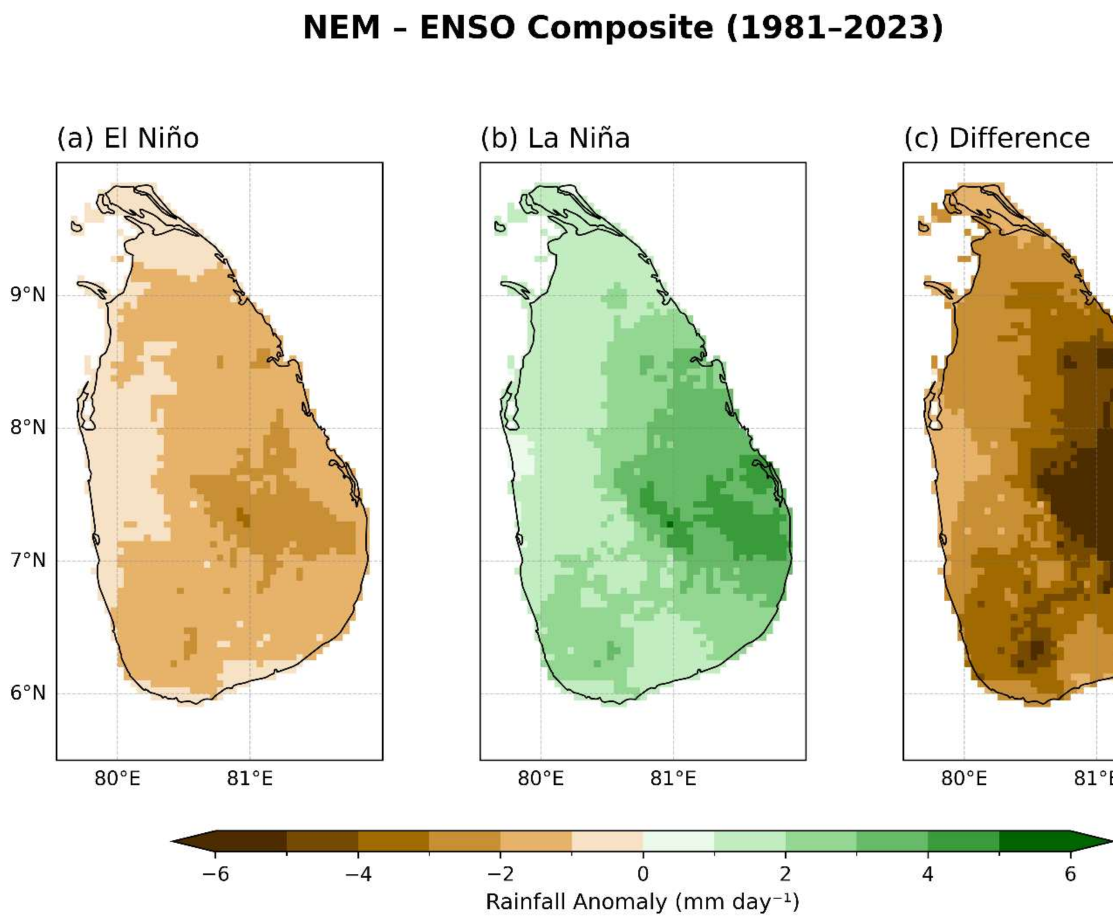
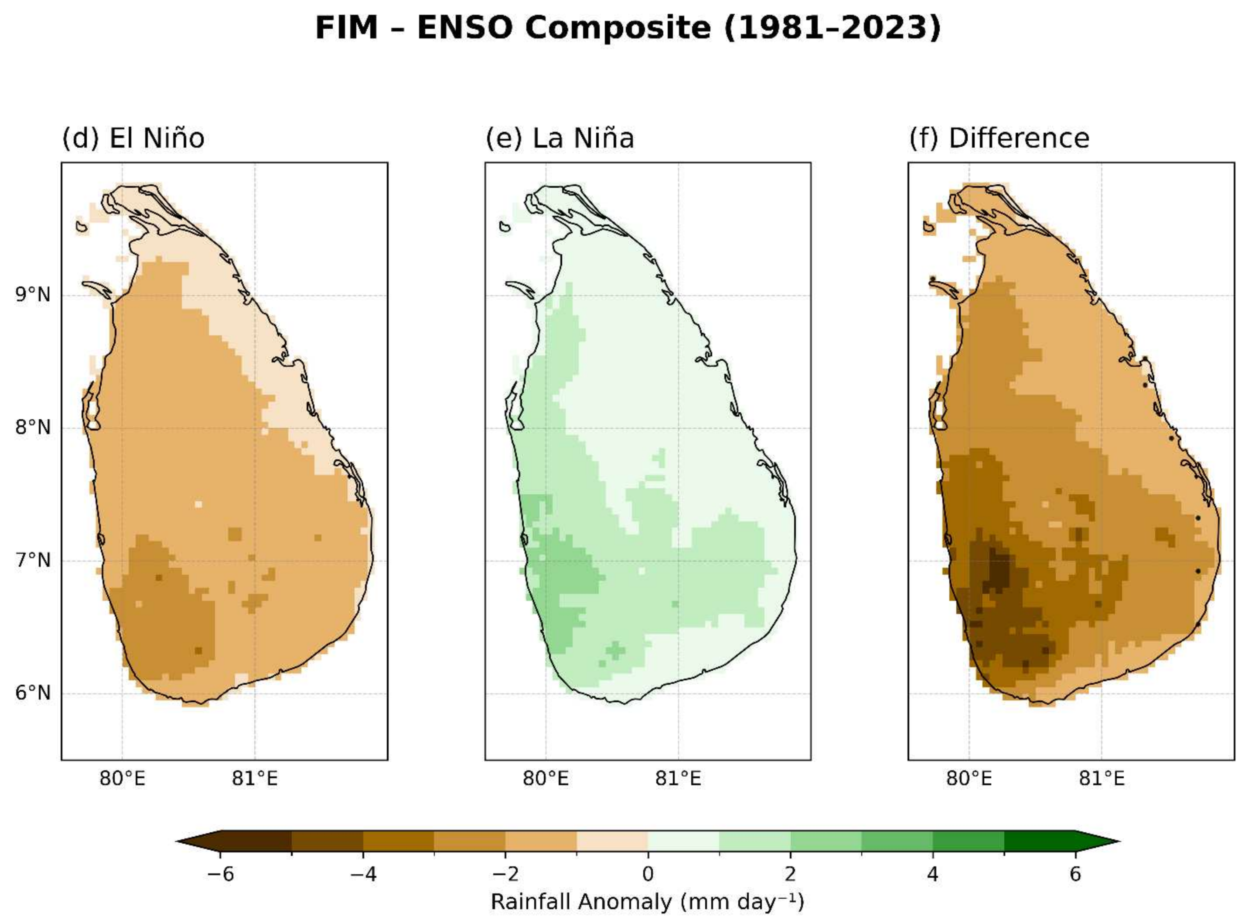
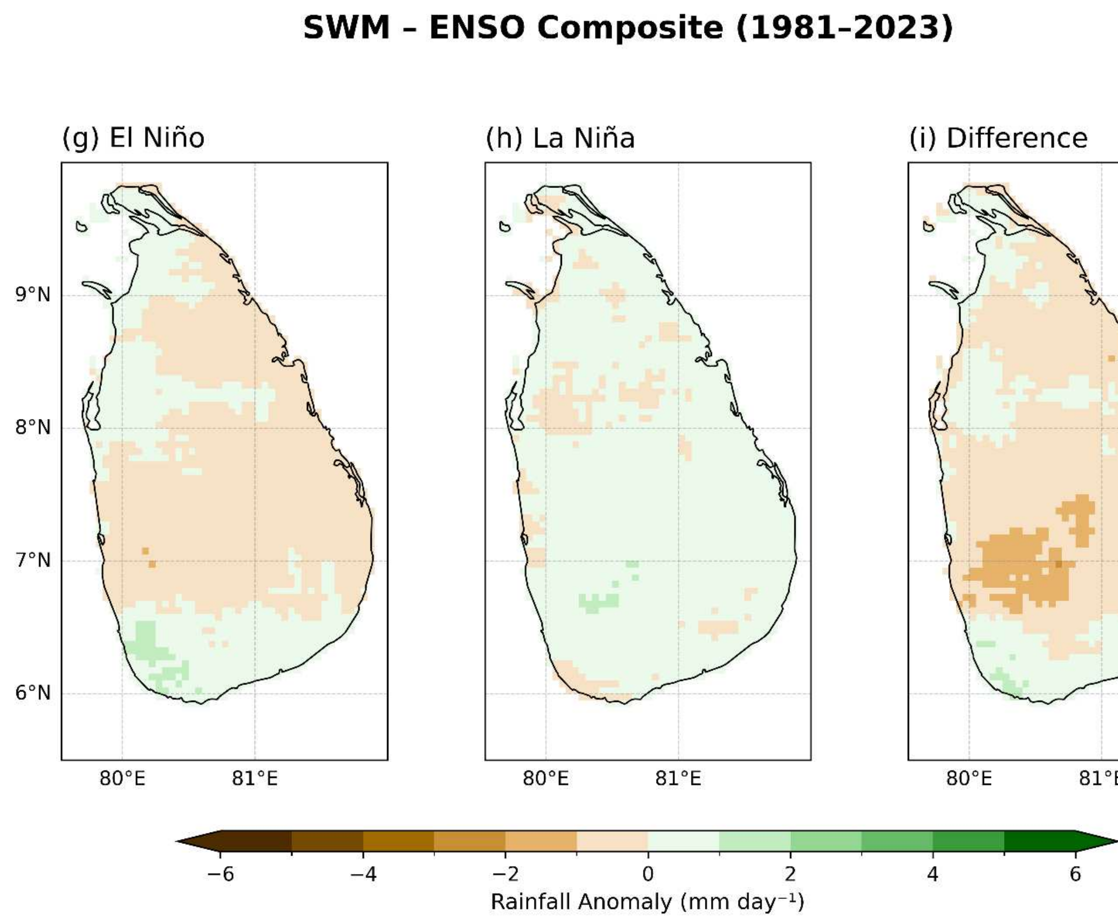


Fig. 12 Spatial patterns of the regression coefficients between seasonal rainfall and the Niño 3.4 index (Trenberth, 1997) over Sri Lanka. Panels show the linear regression slope (mm/day/°C), (a) NEM, (b) FIM, (c) SWM, and (d) SIM. Positive values (green color) indicate increased rainfall associated with Niño 3.4 index, while negative values (Pink color) indicate decreased rainfall associated with Niño 3.4 index. Black stippling indicates grid cells where the regression is statistically significant at the 95% confidence level based on two-tailed student's t-test (Wilks, 2011)


NEM – ENSO Composite (1981–2023)
(a) El Niño
(b) La Niña
(c) Difference
9°N
8°N
7°N
6°N
80°E
81°E
−6
−4
−2
0
2
4
6
Rainfall Anomaly (mm day⁻¹)


FIM – ENSO Composite (1981–2023)
(d) El Niño
(e) La Niña
(f) Difference
9°N
8°N
7°N
6°N
80°E
81°E
−6
−4
−2
0
2
4
6
Rainfall Anomaly (mm day⁻¹)


SWM – ENSO Composite (1981–2023)
(g) El Niño
(h) La Niña
(i) Difference
9°N
8°N
7°N
6°N
80°E
81°E
−6
−4
−2
0
2
4
6
Rainfall Anomaly (mm day⁻¹)

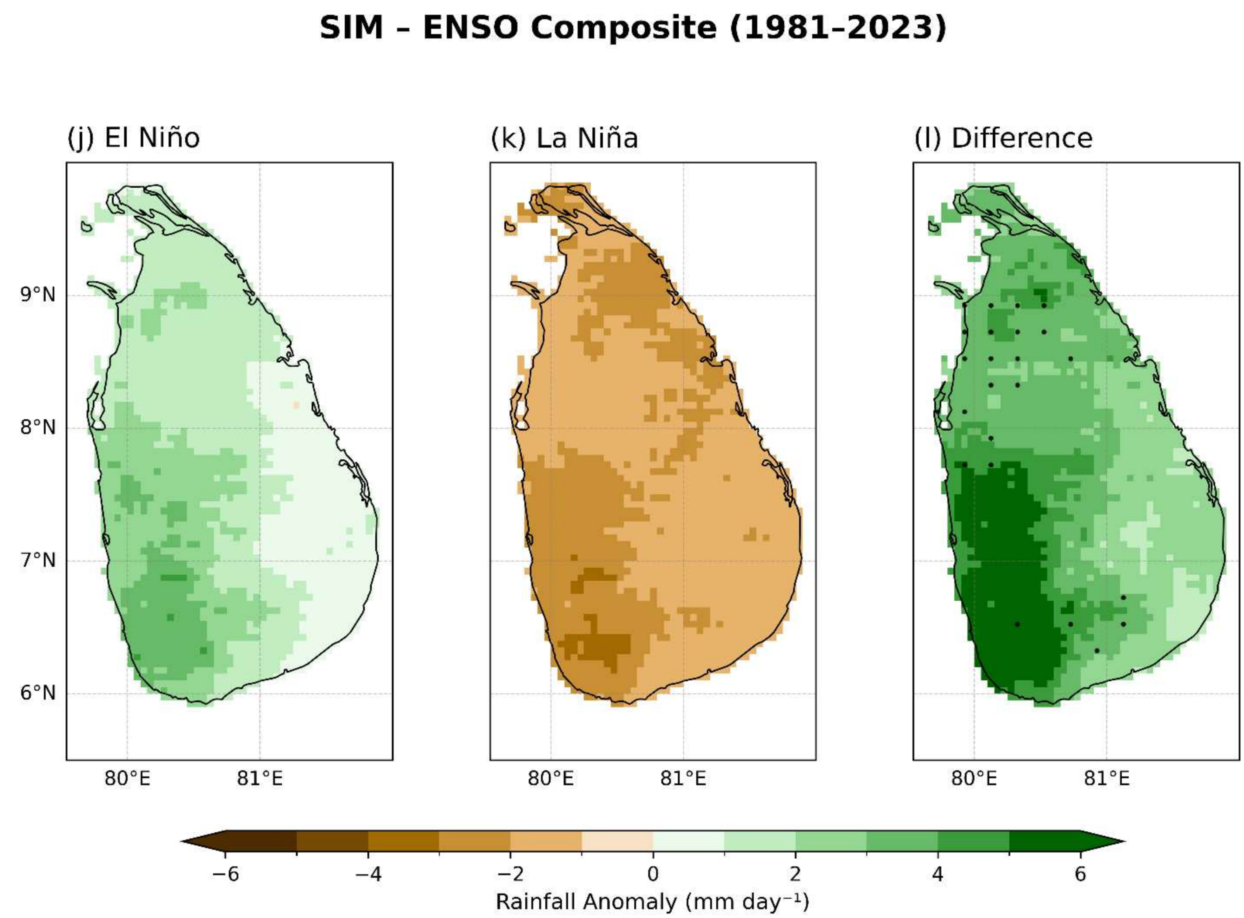


Fig. 13 Composite rainfall anomalies (mm/Day) over Sri Lanka during EL Niño, La Niña and their difference. (a) NEM EL Niño (b), NEM La Niña (c), NEM Difference (d), FIM EL Niño (e), FIM La Niña (f), FIM Difference (g), SWM EL Niño (h), SWM La Niña (i), SWM Difference (j), SIM EL Niño (k), SIM La Niña (l), SIM Difference. Positive anomalies indicate above-average rainfall, while negative anomalies indicate below-average rainfall during the respective ENSO phases. The difference panel highlights increased rainfall during El Niño relative to La Niña. Black stippling indicates grid cells where the composite anomalies are statistically significant at the 95% confidence level based on a two-tailed Student's t-test (Wilks, 2011). EL Niño and La Niña years are defined using the Niño 3.4 SST anomaly threshold of ± 0.5 °C (Trenberth, 1997)

4. Discussion

4.1. Challenges and Limitations

Rainfall studies in Sri Lanka employ a diverse array of analytical approaches (summarised in Table 4), which compare the main methodological categories by their common techniques, strengths, and limitations. Conventional gauge-based analyses remain the benchmark for station-level trend detection due to their direct observational accuracy and robustness to outliers (e.g. MK t-test), but the network has declined considerably since the 1990s, particularly in the north and east, leading to large spatial gaps (Naveendrakumar et al., 2018; Ranasinghe et al., 2024).
In contrast, satellite-gauge blended products such as CHIRPS, IMERG, and GSMaP have largely filled these gaps. They are now the dominant data source for spatial analyses, offering superior coverage in data-sparse and topographically complex regions. However, they may underestimate light orographic rainfall and occasionally smooth extreme convective events (Alahacoon & Edirisinghe, 2021). Non-parametric trend tests (MK, Sen's Slope) are widely used because of their robustness to non-normality and outliers, making them well-suited for hydro-climatic data. However, their ability to detect weak trends may be limited with relatively short records, such as 40–50 years, particularly when accounting for autocorrelation and applying field-significance corrections, which can reduce effective sample size and statistical power (Karunathilaka et al., 2017). Teleconnection analyses using linear regression provide insights into identifying teleconnections but assume stationarity of teleconnections, an assumption increasingly challenged by rapid Indian Ocean warming (Roxy et al., 2014). Despite substantial progress in observational datasets and statistical analyses, several key uncertainties remain in understanding Sri Lanka's rainfall dynamics under a warming climate.

First, most existing studies rely primarily on statistical trend detection and correlation-based teleconnection analyses. While these approaches identify associations between rainfall and large-scale drivers such as ENSO and the IOD, they provide limited insight into nonlinear interactions among multiple climate modes or the underlying dynamical mechanisms that govern extreme rainfall events. Compound interactions between ENSO, IOD, MJO, and tropical cyclones remain insufficiently quantified, despite growing evidence that such combined influences often determine the most severe rainfall extremes over Sri Lanka.

Second, current analyses are constrained by limitations in spatial and temporal resolution. Although satellite-gauge blended products such as CHIRPS provide improved spatial coverage, they may underestimate localised convective and/or orographic rainfall, particularly over the central highlands where steep topography strongly modulates precipitation. The declining density of ground-based observation networks since the 1990s further limits validation of high-resolution rainfall variability, especially in the northern and eastern regions. This restricts the ability to accurately detect sub-daily extremes and short-duration high-intensity rainfall events, which are critical for flood and landslide risk assessment.

Third, future rainfall projections for Sri Lanka remain highly uncertain due to the coarse spatial resolution of most global climate models and their limited ability to resolve meso-scale convective systems and orographic processes. While CMIP6 simulations suggest intensification of rainfall extremes under continued Indian Ocean warming, regional-scale projections vary widely in magnitude and spatial pattern. High-resolution regional climate modelling, convection-permitting simulations, and coupled ocean-atmosphere diagnostics focused on the northern Indian Ocean are therefore essential to improve confidence in future projections.

Finally, emerging observational technologies such as commercial microwave link rainfall retrievals, high-resolution reanalysis datasets, and machine-learning-based predictive frameworks offer promising opportunities but remain underutilised in Sri Lankan rainfall research. Integrating these approaches with traditional observations and satellite products could significantly enhance real-time monitoring, seasonal forecasting, and early warning capabilities. Addressing these research gaps will be crucial for improving predictive understanding of rainfall variability and strengthening climate-resilient water resource and disaster management strategies in Sri Lanka. Developing an integrated multi-scale observational and modelling framework remains the most critical priority for advancing rainfall predictability and climate risk assessment in Sri Lanka.

Table 4: Comparison of methods used in Rainfall Analysis in Sri Lanka.

Method/ Approach	Data Source	Strengths	Limitations	Key Applications	References
Basic Statistical Analysis	Ground-based rainfall stations	Simple to implement; useful for trend detection and descriptive statistics	Limited spatial coverage; inconsistent data quality in some regions	Historical trend analysis; variability assessment	Chithranayana & Punyawardena, 2008
Standardised Rainfall Anomaly Index (SRAI)	Ground-based observations	Identifies wet/dry periods; useful for inter-annual variability	Sensitive to missing data; station-dependent	Drought and flood monitoring	Karunathilaka et al., 2017
Precipitation Concentration Index (PCI)	Ground-based rainfall data	Quantifies seasonal concentration; useful for monsoonal climates	Cannot capture spatial variability; sensitive to monthly outliers	Seasonality analysis; hydrological risk assessment	Wickramagamage & Mohotti, 2016

Satellite-Based Rainfall Estimation (e.g., CHIRPS)	Satellite + gauge-blended datasets	High spatial and temporal resolution; covers data-sparse areas	Subject to cloud cover and sensor limitations; validation needed	Regional rainfall trend mapping; spatial variability analysis	Alahacoon & Edirisinghe, 2021; Kajakokulan et al., 2023a
GIS-Based Spatial Analysis	Integrated ground + satellite datasets + spatial layers	Enables spatial mapping and overlay with geographic features	Requires spatial expertise; dependent on data quality	Zonal trend analysis; watershed-level planning	Alahacoon & Edirisinghe, 2021
Hybrid Statistical Approaches (e.g., MK + Satellite)	Satellite products validated with ground data	Improved accuracy; combines spatial and temporal trend detection	Complex processing; subject to uncertainties from both sources	Fine-scale trend assessment; extremes identification	Naveendrakumar et al., 2018
Climate Model Simulations (e.g., CMIP6, PCMDI)	Global/regional climate models	Useful for future projections; enables scenario-based analysis	Coarse spatial resolution; model uncertainty; requires downscaling	Climate change impact studies; future rainfall projection	Pathirana et al., 2023

Commercial Microwave Links (CML)	Telecommunication network signals	High resolution spatial and temporal rainfall information in data-sparse tropical/subtropical regions, complementing gauges and satellites where infrastructure is limited	Still emerging; sensitive to environmental noise and calibration needs	Real-time tropical rainfall monitoring; agricultural planning; flood/landslide early warning in data-sparse developing region	Overeem et al., 2021

4.2. Implications for agriculture, fisheries and water resource management

Rainfall seasonality directly influences agricultural planning, inland fisheries, and water resource management across Sri Lanka. The strong dependence of the dry zone on NEM and SIM rainfall aligns closely with the *Maha* cultivation season, which accounts for the majority of national rice production. Variability or delayed onset of October-November rainfall can therefore significantly affect crop establishment, irrigation storage, and food security (Marambe et al., 2015; Punyawardena & Abeysekera, 2020). In contrast, the wet zone relies more heavily on SWM and inter-monsoon rainfall to sustain perennial crops such as tea and rubber, while also facing heightened exposure to flood and landslide hazards during intense rainfall episodes. Increasing variability and intensification of SIM rainfall observed in recent decades therefore present a dual challenge, enhancing water availability in some years while simultaneously increasing disaster risk and agricultural losses in others. Further, increasing wet-day dominance and intensifying rainfall trends pose dual risks: while enhanced precipitation during the *Maha* season may improve soil moisture availability and irrigation water supply, prolonged wet spells increase the risk of waterlogging, root rot, and crop failure. Furthermore, shift in rainfall onset, and cessation can disrupt the traditional crop calendars, threatening crop stability and yield. Thus, the findings in the present study would probably help in deciding and altering current management practices in this regard to avoid these circumstances.

Beyond agriculture, seasonal rainfall variability plays a crucial role in sustaining culture-based fisheries in seasonal tanks and reservoirs, particularly in the dry and intermediate zones where inland fisheries production is closely tied to monsoonal water availability. Seasonal tank filling during the *Maha* season determines fish stocking cycles, productivity, and rural livelihoods (Marambe et al., 2015). Increasing inter-annual variability in rainfall and shifts in seasonal distribution may therefore influence both crop calendars and fisheries productivity.

Specifically, extreme rainfall events significantly elevate the surface runoff and sediment loading into coastal and inland waters causing an array of disruption not only to cultured organisms but also to the aquaculture and fisheries practices. Flood induced inundation can cause structural damage, stock losses and pathogen out-brakes. Conversely, prolonged dry periods reduce aquaculture production due to insufficient water levels. Thus, the present findings will also help in adjusting current practices in stocking, harvesting and disaster resilience.

Furthermore, increasing variability in rainfall specifically, wet-day dominance has paramount validity in adjusting water resource planning in line with reservoir operation, flood forecasting, and drought management. As the extreme wet-year anomalies observed in 2018, 2020 and 2022 highlighted flood risk and may exceed the capacity of existing hydraulic structures, this analysis provides background and insight into deciding criteria to minimize flood and drought risk in future. On the other hand, inter annual variability detected in rainfall provides hint to revisit the current strategies practice in sustain irrigation demand, municipal supply and ecological flow regimes of major irrigation schemes. These linkages highlight the importance of integrating rainfall variability and seasonal forecasting into climate-resilient agricultural planning, reservoir management, fish stocking, and fisheries adaptation strategies across Sri Lanka.

5. Conclusion

Sri Lanka's rainfall regime is characterised by strong spatial contrasts and pronounced seasonal variability governed by monsoonal circulation, complex topography, and coupled ocean-atmosphere processes. Considering the geographical location of Sri Lanka, it provides a representative case for tropical island rainfall systems influenced by coupled monsoon-Indian Ocean variability. Analysis of observational and satellite-derived datasets since the early 1980s confirms that while the SWM and NEM continue to shape the island's primary rainfall structure, long-term trends remain weak or spatially inconsistent across most seasons. In contrast, the SIM emerges as the most dynamically significant season, exhibiting a spatially coherent and statistically significant increase in rainfall, along with the highest interannual variability. The increasing frequency of wet days and substantial contribution of this short season to annual rainfall totals highlight its growing influence on Sri Lanka's hydro-climatic system. The observed intensification of inter-monsoon rainfall is physically consistent with rapid warming of the tropical Indian Ocean and enhanced variability associated with the IOD and ENSO, which together modulate atmospheric moisture availability and convective activity over the region. These evolving rainfall characteristics have important implications for flood risk, water resource management, and climate-sensitive sectors such as agriculture and inland fisheries, which depend strongly on seasonal rainfall reliability. Strengthening seasonal forecasting, improving high-resolution regional climate projections, and integrating climate information into sectoral planning will be essential to enhancing climate resilience in Sri Lanka amid ongoing ocean-atmosphere warming.

Statements & Declarations

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Assistance and the facilities provided by the Department of Oceanography and Marine Geology, Faculty of Fisheries and Marine Sciences & Technology, University of Ruhuna, Sri Lanka is highly acknowledged. All open-source datasets used in this study are available from the links cited in the text. All plots and analysis are carried out using Python v.3.9 including supportive packages.

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Conflict of Interest statement

The authors declare that they have no conflicts of interest, financial or otherwise, related to the research, authorship, and/or publication of this article.

Author Contributions

All authors contributed to the conception and design of this study. Material preparation, data collection and analysis were performed by PG and CP. GP contributed to the conception, design and supervision of the study. The first draft of the manuscript was written by PG and revised by CP, GP, JSK, KSSA, XG, YKW, DW, UP, PNR and PHCDS. All authors discussed the study results and reviewed earlier versions of the manuscript. All authors read and approved the final version of the manuscript.

Data Availability Statement

The rainfall data used in this study include the CHIRPS, which is publicly available at https://data.chc.ucsb.edu/products/CHIRPS-2.0. Reanalysis rainfall and wind datasets used for large-scale circulation analysis were obtained from the ECMWF ERA5 reanalysis, available through the Copernicus Climate Data Store (https://cds.climate.copernicus.eu/). Daily total precipitation (tp) and near-surface wind components (u10 and v10) were used to analyze rainfall patterns and atmospheric circulation over the Indian Ocean region. The SST data were obtained from the NOAA Extended Reconstructed SST Version 5 (ERSSTv5) dataset, available at https://www.ncei.noaa.gov/products/extended-reconstructed-sst. In-situ rainfall observations for Sri Lanka were obtained from the Department of Meteorology, Sri Lanka, and are available upon reasonable request from the data provider.

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