

Tropical Cyclone Patterns Near Sri Lanka and Their Environmental Controls: A 45-Year Analysis (1980–2024)

Warnasooriya Mudiyanseelage Ishini Tecla Warnasooriya^a, Hironori Fudeyasu^b,
Garu Muni Wathsala Lakpriya Gunawardena^{b,c,*}, Anjana Junius Vidanaralage^a

^a Sri Lanka Institute of Information Technology, Faculty of Computing, Sri Lanka

^b Typhoon Science and Technology Research Center, Institute for Multidisciplinary Sciences, Yokohama National University, Japan

^c Department of Town and Country Planning, Faculty of Architecture, University of Moratuwa, Sri Lanka

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Abstract

Tropical cyclones (TCs) are infrequent but potentially high-impact hazards for Sri Lanka. Using IBTrACS best-track data and ERA5 reanalysis for 1980–2024, a Sri Lanka-centered climatology was developed to characterize storms approaching the island and the large-scale environmental conditions associated with their occurrence. Storms were identified using proximity thresholds within a 700 km screening domain; 67 TCs satisfied the ≤ 100 km direct-impact criterion, corresponding to approximately $1.5 \text{ events yr}^{-1}$. Sri Lanka-influencing tracks were dominated by Bay of Bengal systems propagating westward to west-northwestward at low latitudes. Peak-intensity timing near Sri Lanka was strongly seasonal, with a primary maximum in October–December and a secondary peak in May, consistent with the broader bimodal seasonality of North Indian Ocean TC activity. Storm-event rainfall over Sri Lanka, accumulated within a fixed ± 48 h window centered on closest approach, showed substantial overlap between direct-impact storms and near-miss storms, defined here as systems whose minimum center-to-coast distance was > 100 km and ≤ 300 km. This result indicates that offshore storms can still produce notable rainfall over land even when their centers remain away from the coast. Trend analysis indicated no statistically significant long-term change in direct-impact frequency or genesis location over 1980–2024. Wavelet analysis further suggested that variability in annual direct-impact counts is weighted more strongly toward interannual than lower-frequency timescales, although no robust long-period oscillation is inferred because of the short record length and edge effects. Environmental changes were selective rather than uniform: storm-peak deep-layer shear increased significantly; OND mean SST and RH700 also increased significantly, whereas OND lower-tropospheric wind extremes, low-level vorticity, and upper-level divergence showed no significant long-term trends. Overall, the results show that near-miss storms remain rainfall-relevant for Sri Lanka and provide a Sri Lanka-focused hazard climatology linking storm proximity, rainfall-footprint relevance, and environmental conditions.

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1. Introduction

Sri Lanka experiences relatively few TCs compared with many other coastlines of the North Indian Ocean (NIO), yet infrequent events have still caused serious damage through strong winds, storm surge, flooding, and heavy rainfall (Wijetunge, 2013; Jayasekara et al., 2024). This apparent contrast between relatively low event frequency and continuing hazard relevance is important for Sri Lanka, because island-scale impacts can occur not only from direct

* Corresponding author. Typhoon Science and Technology Research Center, Institute for Multidisciplinary Sciences, Yokohama National University, Japan. Email:

E-mail addresses: teclaishini442@gmail.com (W.M. Ishini Tecla Warnasooriya), fudeyasu-hironori-dt@ynu.ac.jp (H. Fudeyasu), gunawardena-wathsala-hv@ynu.ac.jp (G.M.W.L. Gunawardena), junius.a@slit.lk (A.J. Vidanaralage).

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coastal passages but also from nearby offshore systems whose rainfall footprints extend across the island. Sri Lanka is located at the southern margin of the NIO, with the Bay of Bengal (BoB) to the east and the Arabian Sea (AS) to the west. Within this regional setting, storms affecting Sri Lanka are more commonly associated with the BoB than with the AS, and the surrounding NIO remains a densely populated and highly exposed basin in terms of TC impacts (Wahiduzzaman et al., 2017; Webster et al., 2005). Recent regional studies have likewise shown that TC-related extreme weather over Sri Lanka is closely linked to broader NIO cyclone activity and associated moisture transport processes (Jayasekara et al., 2024; Kabir et al., 2022; Srisangeerthan et al., 2015).

The seasonal climatology of the NIO is strongly bimodal, with a primary post-monsoon peak in October–December (OND) and a secondary pre-monsoon peak in April–May. By contrast, the boreal-summer monsoon season is generally less favorable for cyclogenesis because strong vertical wind shear and less favorable thermodynamic and moisture conditions suppress TC development (Evan et al., 2011; Gray, 1968; Mohanty et al., 2014; Osuri et al., 2013). Sri Lanka's historical experience broadly reflects this basin-scale seasonal structure, with the most substantial TC-related effects typically associated with post-monsoon BoB systems and a smaller number of late-spring events. This seasonal context is important for interpreting Sri Lanka-influencing storms, because the island's hazard exposure is embedded within the larger climatological controls of the NIO rather than operating as an isolated local system (Gray, 1968; Jayasekara et al., 2024).

In the broader climate context, recent studies have highlighted contrasting long-term changes across the NIO. In particular, the AS has been linked to an increase in extremely severe cyclonic storms in recent decades (Evan et al., 2011; Murakami et al., 2017; Pathaikara et al., 2025), whereas long-term changes in BoB cyclone frequency remain more sensitive to the analysis period, metric, and dataset used and are often weaker or more uncertain. In addition to these long-term tendencies, large-scale climate modes such as the El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole can modulate cyclone activity over the BoB by influencing storm occurrence, genesis location, and preferred track behavior (Roose et al., 2022). More generally, TC genesis and intensification depend on the combined influence of multiple environmental controls, including sea-surface temperature, mid-tropospheric humidity, low-level vorticity, upper-level divergence, and vertical wind shear, rather than on any single factor alone (Gray, 1968; Osuri et al., 2013). Global assessments similarly emphasize that observed and projected TC changes are basin-dependent and metric-dependent, with stronger confidence for some aspects of TC behavior than for others (Girishkumar and Ravichandran, 2012; Gray, 1968; Knutson et al., 2019; Murakami et al., 2017).

Despite this broader literature, most climatological and climate-change studies in the NIO have mainly emphasized basin-scale or sub-basin-scale measures such as cyclone counts,

exposure distributions, or landfall statistics for the larger coastlines of India, Bangladesh, and Myanmar (Murakami et al., 2017; Webster et al., 2005). Comparatively fewer studies have examined Sri Lanka specifically as a distinct island-centered tropical-cyclone setting in which storm-center proximity, offshore passage, rainfall footprint, and environmental context may interact differently from those of larger continental coastlines. This gap is important because TC-related hazards for Sri Lanka may remain substantial even when storm centers do not make direct landfall on the island. A Sri Lanka-centered perspective is therefore needed to clarify how cyclone occurrence, seasonality, approach characteristics, rainfall relevance, and associated environmental conditions have varied over recent decades in ways that are specifically meaningful for the island (Jayasekara et al., 2024; Kabir et al., 2022; Srisangeerthan et al., 2015).

Against this background, the present study develops a Sri Lanka-centered climatological assessment of TCs during 1980–2024, with emphasis on storm occurrence, seasonality, approach characteristics, rainfall-hazard relevance, and associated large-scale environmental conditions. The study is framed as a hazard-oriented climatological analysis rather than a formal risk assessment, because explicit exposure, vulnerability, and loss data are not quantified. Accordingly, the objective is not to estimate risk directly, but to clarify how TCs approaching Sri Lanka are distributed in time and space, how rainfall relevance differs between closer and offshore storm passages, and how selected environmental conditions near Sri Lanka have varied over the study period.

2. Data and methods

2.1. Study domain and cyclone selection

This study examines TCs influencing Sri Lanka and its surrounding oceanic environment within the NIO. Here, the NIO follows the IBTrACS North Indian basin designation, and the AS and BoB identifiers are taken from the IBTrACS MAIN best-track fields. Because the aim was to develop a Sri Lanka-centered climatological framework rather than a basin-wide inventory of all NIO storms, storm selection was based on proximity to Sri Lanka.

A Sri Lanka-centered circular screening domain with a radius of 700 km, centered near 9°N, 81°E and spanning approximately 3–15°N and 75–87°E, was used to identify storms with plausible hazard relevance for the island. This circle was used only for Sri Lanka-focused storm screening and does not represent the boundary of the NIO basin. The 700 km radius was adopted as a practical island-centered domain that captures storms approaching sufficiently close to produce direct or nearby offshore effects on Sri Lanka, while excluding the much larger NIO storm population that is less likely to influence the island in a direct Sri Lanka-centered sense. It should therefore be interpreted as an analytical screening choice rather than as a universal physical cutoff (National Hurricane Center, n.d.; National Hurricane Center, 2023).

Within this screening domain, storms were classified by the minimum great-circle distance between the storm center and the Sri Lankan coastline using three thresholds: ≤ 100 km, ≤ 200 km, and ≤ 300 km. Storms with minimum coastline distance ≤ 100 km were defined as direct-impact cyclones. The ≤ 200 km and ≤ 300 km thresholds were retained as contextual sensitivity brackets around the direct-impact definition and to distinguish very close passages from somewhat more distant offshore passages that could remain meteorologically relevant to Sri Lanka. In this framework, near-miss storms were defined as offshore systems whose centers remained outside the direct-impact class but passed within 300 km of the Sri Lankan coastline, that is, storms with minimum coastline distance > 100 km and ≤ 300 km. The term “near-miss” is therefore used here in a Sri Lanka-focused hazard sense to identify offshore storms that may still produce notable rainfall over land.

Using IBTrACS best-track data for 1980–2024, 67 cyclones satisfied the ≤ 100 km direct-impact criterion, whereas 84 and 94 satisfied the ≤ 200 km and ≤ 300 km criteria, respectively (Fig. 1b; Fig. 2a). Storm selection was based only on this coastline-distance framework so that the same storm set could be used consistently across the rainfall and environmental analyses. Environmental variables were treated as explanatory context rather than as event-selection criteria.

Although IBTrACS includes some storm-structure information, such as agency-reported wind radii and, in some cases, radius of maximum wind, these variables are not consistently available across agencies and decades and are therefore less suitable for a temporally homogeneous long-term climatology (Avenas et al., 2023; NOAA National Centers for Environmental Information, 2025). Accordingly, the present approach should be interpreted as a reproducible, hazard-oriented storm-selection framework for Sri Lanka, and the coastline-distance thresholds should be regarded as Sri Lanka-centered analytical categories rather than universal physical cutoffs for all TC settings.

2.2. Data

2.2.1. IBTrACS best-track data

TC track positions and intensity estimates were obtained from the International Best Track Archive for Climate Stewardship (IBTrACS), version 4 (Knapp et al., 2010). Track positions used in this study were taken from the MAIN best-track record. Because contributing agencies use different sustained-wind averaging periods, IBTrACS preserves agency-specific wind information rather than fully homogenizing all wind estimates into a single convention. Wind speeds reported in knots were converted to m s^{-1} for consistency. IBTrACS data were used here to characterize storm tracks, timing, and best-track intensity within the Sri Lanka-influencing storm sample.

2.2.2. ERA5 atmospheric reanalysis

Large-scale environmental fields and rainfall diagnostics were derived from the ERA5 global atmospheric reanalysis. ERA5 is a global reanalysis produced by ECMWF and widely used for climate and weather diagnostics (Hersbach et al., 2020). ERA5 hourly data on the 0.25° latitude–longitude grid were sampled at 6-hourly synoptic times to align with best-track timing as closely as practicable.

Two complementary sampling approaches were used. First, storm-centered peak sampling was applied at the nearest ERA5 grid point and time corresponding to each storm's peak intensity to derive 850-hPa wind speed as a large-scale wind diagnostic (ws850) and deep-layer vertical wind shear $|V_{200} - V_{850}|$. Second, fixed-domain OND sampling over $5\text{--}15^\circ\text{N}$ and $75\text{--}90^\circ\text{E}$ was used to derive background environmental indices, including p95 (ws850), OND mean SST, RH700, η_{850} , and $\nabla \cdot V_{200}$. These variables were treated within a common OND fixed-domain framework, with variable-specific calculations applied only where necessary. SST was converted from kelvin to $^\circ\text{C}$, absolute vorticity was computed as $\eta = \zeta + f$, and ERA5 total precipitation

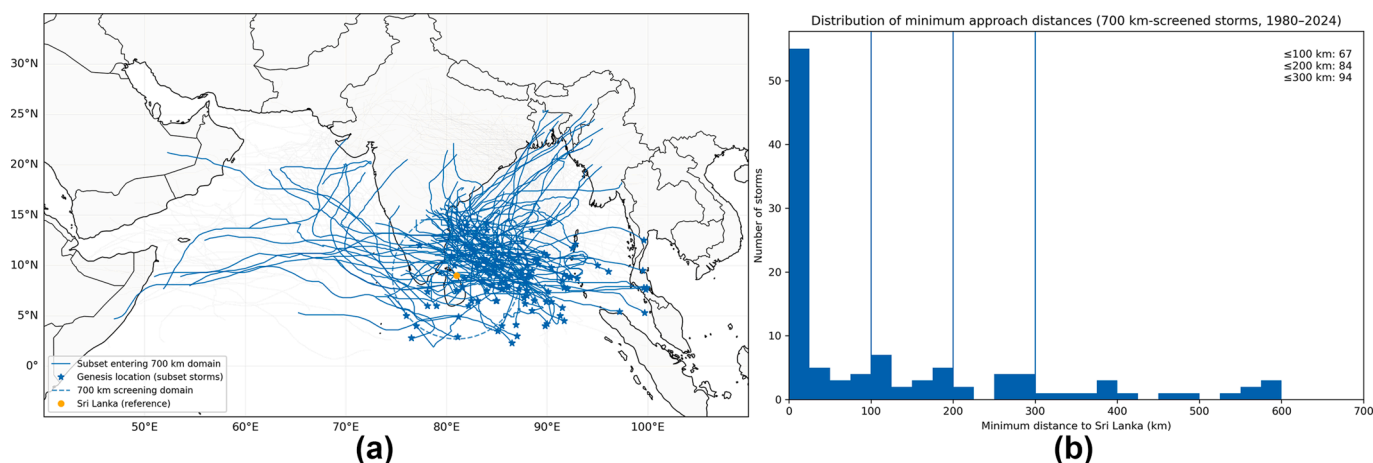


Fig. 1 Sri Lanka-centered tropical cyclone screening framework for 1980–2024. (a) Tracks of tropical cyclones entering the 700 km screening domain around Sri Lanka; blue stars indicate genesis locations and the orange circle marks the Sri Lanka reference point ($\sim 9^\circ\text{N}$, 81°E). (b) Distribution of minimum approach distances to Sri Lanka for the 700 km-screened storms. Vertical lines mark the 100, 200, and 300 km thresholds used to define the direct-impact and near-miss classes.

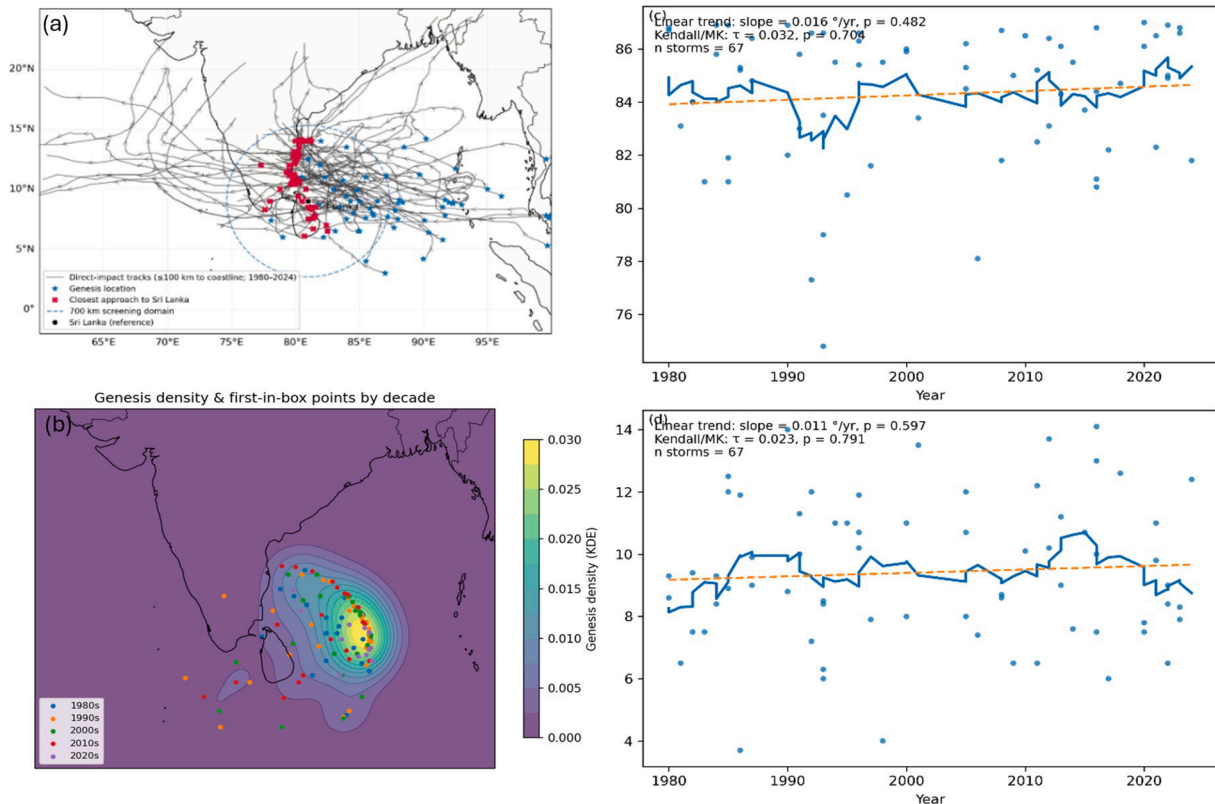


Fig. 2. **Characteristics of tropical cyclones passing within ≤ 100 km of the Sri Lankan coastline during 1980–2024 ($n = 67$).** (a) Direct-impact storm tracks with genesis locations (blue stars), closest-approach points (red X markers), and the 700 km Sri Lanka-centered screening domain. (b) Spatial density and decadal distribution of genesis and early-track positions. (c) Interannual variation in genesis longitude. (d) Interannual variation in genesis latitude.

was converted to millimeters for event-total rainfall. Land-only rainfall statistics were derived using the ERA5 land–sea mask with a land fraction threshold of $lsm \geq 0.5$.

Because reanalyses do not resolve TC inner-core structure with the same fidelity as best-track archives, ERA5-derived winds were interpreted here as large-scale environmental and circulation diagnostics rather than as direct substitutes for best-track storm intensity.

2.2.3. Satellite precipitation data (TRMM/GPM)

To assess the robustness of the storm-event rainfall analysis, the same event-based rainfall metrics were also calculated from satellite precipitation products. TRMM TMPA 3B42_Daily was used for 1998–2019, and GPM IMERG Final Daily was used from 2020 onward (Huffman et al., 2023). These products were used only as independent rainfall datasets to test whether the contrast between direct-impact and near-miss storms was consistent across precipitation products (Huffman et al., 2007, 2020).

2.3. Methods

2.3.1. Track, proximity, seasonality, and genesis metrics

Using the storm set defined in Section 2.1, cyclone frequency and seasonality were characterized from monthly and annual counts for the ≤ 100 km direct-impact class. The ≤ 200 km and ≤ 300 km classes were retained only as contextual sensitivity

brackets around this primary definition. For each direct-impact storm, the month of peak intensity within the screening domain was identified and summarized as a histogram (Fig. 5; $n = 66$ storms with available wind data). Track characteristics and minimum coastline approach distances were derived from great-circle geometry applied to IBTrACS positions.

Genesis location was defined as the first available position in the IBTrACS MAIN track. Direct-impact storm characteristics were summarized using the composite shown in Fig. 2, including storm tracks and closest-approach points (Fig. 2a), the spatial density and decadal distribution of genesis and early-track positions (Fig. 2b), and the interannual variation of genesis longitude and latitude with fitted linear trends and running means (Fig. 2c and d). The spatial density field in Fig. 2b was computed from genesis locations of the direct-impact subset ($n = 67$).

2.3.2. Trend analysis

Trend statistics were computed for annual direct-impact counts, genesis longitude, genesis latitude, and the ERA5-derived environmental indices summarized in Table 1. Linear trends were estimated using ordinary least squares regression (OLS), and monotonic tendencies were evaluated using Kendall's rank-based statistic within the Mann–Kendall framework (Hamed, 2008; Kendall, 1975; Mann, 1945). Uncertainty in trend estimates was assessed using bootstrap resampling (Efron and Tibshirani, 1994). These methods are widely used for climatological trend detection and uncertainty estimation.

Table 1

Trend statistics for Sri Lanka direct-impact tropical cyclones and associated environmental indices (1980–2024).

Variable	Season	Domain/subset	Linear slope (per yr)	p-value (linear)	Kendall τ	p-value (MK)	n (years/storms)	Trend significance
Annual direct-impact TC count (≤ 100 km)	All	Sri Lanka direct-impact	−0.0016	0.896	−0.028	0.805	45 years	Not significant
Genesis longitude ($^{\circ}$ E)	All	Sri Lanka direct-impact storms	0.016	0.482	0.032	0.704	N storms = 67	Not significant
Genesis latitude ($^{\circ}$ N)	All	Sri Lanka direct-impact storms	0.011	0.597	0.023	0.791	N storms = 67	Not significant
Deep-layer vertical wind shear V200–V850 at TC peak (within 700 km)	All	Sri Lanka direct-impact storms (annual medians)	0.140	0.021	0.264	0.021	37 years; 66 storms	Significant increase
ERA5 OND p95 (ws850)	OND	Sri Lanka region (5–15 $^{\circ}$ N, 75–90 $^{\circ}$ E)	0.0153	0.216	0.0848	0.411	45 years	Not significant
ERA5 OND p95 (ws850)	OND	Arabian Sea sub-domain	0.00872	0.518	0.0707	0.493	45 years	Not significant
ERA5 OND p95 (ws850)	OND	Bay of Bengal sub-domain	0.0160	0.169	0.115	0.265	45 years	Not significant
ERA5 OND mean SST ($^{\circ}$ C)	OND	Sri Lanka region (5–15 $^{\circ}$ N, 75–90 $^{\circ}$ E)	0.0152	2.77×10^{-7}	0.493	1.81×10^{-6}	45 years	Significant increase
ERA5 OND mean RH700 (%)	OND	Sri Lanka region (5–15 $^{\circ}$ N, 75–90 $^{\circ}$ E)	0.160	0.000315	0.347	0.000765	45 years	Significant increase
ERA5 OND mean η_{850} (absolute vorticity) (s^{-1})	OND	Sri Lanka region (5–15 $^{\circ}$ N, 75–90 $^{\circ}$ E)	3.06×10^{-9}	0.910	0.0303	0.769	45 years	Not significant
ERA5 OND mean $\nabla \cdot V_{200}$ (divergence) (s^{-1})	OND	Sri Lanka region (5–15 $^{\circ}$ N, 75–90 $^{\circ}$ E)	1.43×10^{-8}	0.202	0.184	0.0750	45 years	Not significant

ERA5 diagnostics were analyzed in two groups: storm-centered peak shear (Fig. 3a) and fixed-domain OND background indices (Fig. 3b–f; Fig. 4a and b). The latter included OND p95 (ws850) over the Sri Lanka region and adjacent sub-domains (ETCCDI Expert Team on Climate Change Detection and Indices, 2014; Klein Tank et al., 2009; Zhang et al., 2011).

2.3.3. Spectral analysis of annual direct-impact cyclone counts

To examine whether variability in annual Sri Lanka direct-impact TC counts is concentrated at interannual or lower-frequency timescales, a continuous wavelet transform was applied to the annual count series for 1980–2024 using a Morlet mother wavelet. Wavelet power spectra, global wavelet spectra, and 95% significance levels against a red-noise background were computed following the Torrence–Compo framework, and the cone of influence was used to identify regions potentially affected by edge effects (Torrence and Compo, 1998). Variability was summarized by comparing mean global wavelet power in the 2–8-year interannual band with that in the >8-year lower-frequency band (Chan, 2005; Frank and Young, 2007).

2.3.4. Storm-event rainfall metrics and land masking

Storm-event rainfall was defined as the accumulated precipitation over a fixed ± 48 h window centered on each storm's closest approach to Sri Lanka. ERA5 total precipitation was summed over a Sri Lanka bounding box, converted to millimeters, and masked to land grid cells using a

land fraction threshold of $lsm \geq 0.5$. For each storm, land-mean, land-95th-percentile, and land-maximum event-total rainfall were then calculated and compared between direct-impact (≤ 100 km) and near-miss (> 100 km and ≤ 300 km) storms. The same event definition and summary metrics were applied to TRMM TMPA 3B42_Daily (1998–2019) and GPM IMERG Final Daily (2020 onward) to assess cross-product consistency in the rainfall comparison (Huffman et al., 2023).

The ± 48 h window was adopted as a pragmatic storm-centered interval for island-scale rainfall comparison because rainfall over Sri Lanka may occur both before and after the time of closest approach as outer rainbands and broader cyclone-circulation effects pass across the island (National Hurricane Center, 2023; Yu et al., 2023). For a relatively small island situated near common offshore storm tracks, a fixed event window centered on closest approach provides a reproducible way to compare integrated rainfall relevance across storms with different approach geometries. At the same time, this window does not isolate purely TC core precipitation and may include some rainfall associated with the broader monsoonal or synoptic environment. The resulting metric should therefore be interpreted as an integrated storm-centered rainfall-hazard footprint measure rather than as a pure cyclone-core rainfall diagnostic. Accordingly, the rainfall comparison is intended to evaluate whether offshore near-miss storms remain rainfall-relevant for Sri Lanka within a consistent Sri Lanka-centered event-definition framework, not to claim that the exact rainfall amounts are insensitive to alternative window lengths.

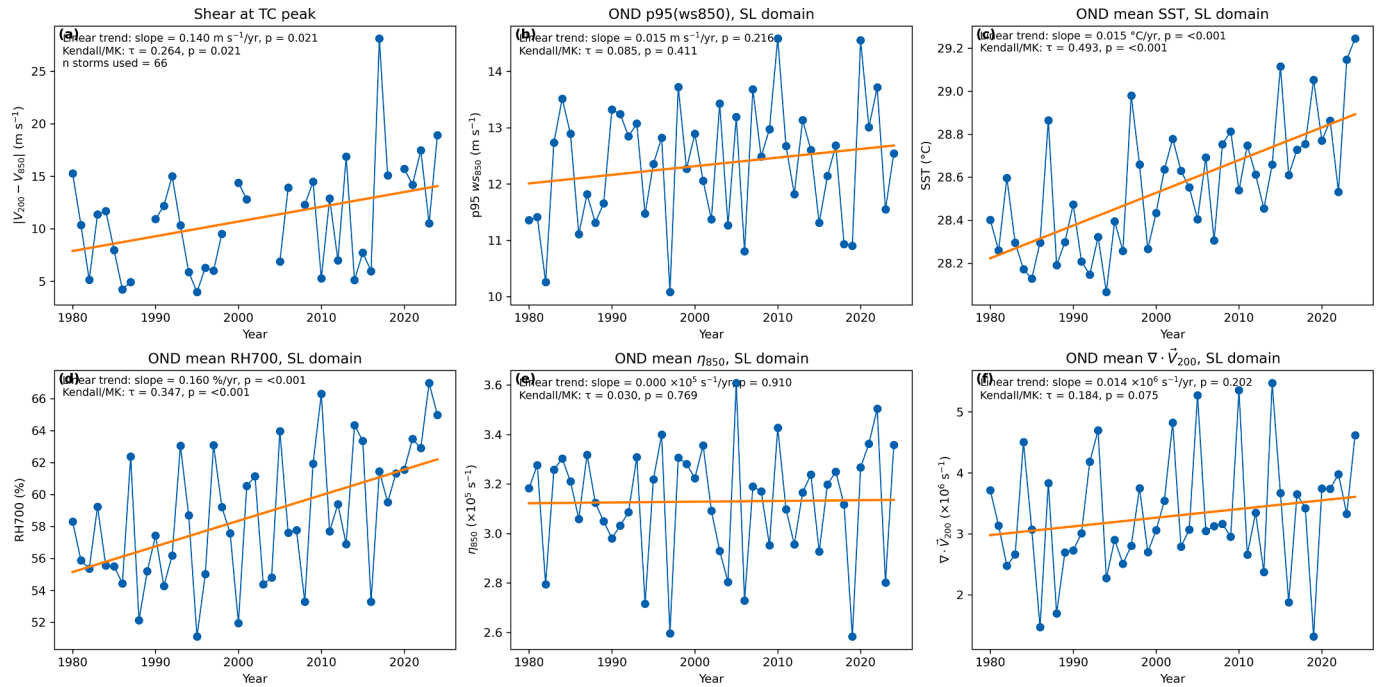


Fig. 3. Trends in environmental controls relevant to tropical cyclone development near Sri Lanka during 1980–2024. (a) Storm-peak deep-layer shear $|\bar{V}_{200} - \bar{V}_{850}|$ (annual median across direct-impact storms; $n = 66$). (b) OND p95 (ws850) over the Sri Lanka region. (c–f) OND mean SST, RH700, η_{850} , and $\nabla \cdot \bar{V}_{200}$ over $5\text{--}15^\circ\text{N}$, $75\text{--}90^\circ\text{E}$. Blue points show annual values and orange lines show OLS trends; trend statistics are summarized in Table 1.

3. Results

3.1. Climatology of cyclones near Sri Lanka

From 1980 to 2024, 67 TCs passed within 100 km of the Sri Lankan coastline, corresponding to an average of approximately $1.5 \text{ events yr}^{-1}$ over the 45-year record (Fig. 6a). When the proximity threshold is relaxed, 84 storms approached within 200 km and 94 within 300 km. The distribution of minimum approach distances is skewed toward smaller values, with the highest frequencies concentrated near the coast and a long tail extending toward the outer part of the 700 km screening radius (Fig. 1b). Annual counts of direct-impact storms range from 0 to 4 events yr^{-1} and show pronounced interannual variability (Fig. 6a). Decadal totals are 15 in the 1980s, 17 in the 1990s, 10 in the 2000s, 15 in the 2010s, and 10 during 2020–2024 (Fig. 6b). No statistically significant long-term trend is detected in annual direct-impact frequency (OLS slope = -0.0016 yr^{-1} , $p = 0.896$; Kendall $\tau = -0.028$, $p = 0.805$; Table 1).

Wavelet analysis of the annual direct-impact count series suggests that variability is weighted more strongly toward interannual than toward lower-frequency timescales (Fig. 6c). Mean global wavelet power is higher in the 2–8-year band (1.053) than in the >8 -year band (0.524). Although the global wavelet spectrum shows a broad maximum near 31 years, this feature is not interpreted as evidence of a robust long-period oscillation because the record is short relative to that period and the lowest-frequency part of the spectrum is strongly affected by edge effects and the cone of influence.

Peak-intensity timing for Sri Lanka direct-impact storms is concentrated in the post-monsoon season (Fig. 5; $n = 66$ storms with available wind data). October–December accounts for 55 of the 66 peak occurrences, with November (24/66) and December (21/66) contributing the largest shares. A smaller secondary maximum occurs in May (4/66), whereas peak occurrences are scarce during July–September (Fig. 5). Storms entering the 700 km screening domain are shown in Fig. 1a, and direct-impact storm tracks, closest-approach points, and the Sri Lanka-centered screening circle are shown in Fig. 2a. The direct-impact subset is dominated by low-latitude tracks extending westward to west-northwestward across the southern BoB toward Sri Lanka.

3.2. Rainfall relevance of near-miss storms

Storm-event rainfall over Sri Lanka shows substantial overlap between direct-impact ($\leq 100 \text{ km}$) and near-miss ($> 100 \text{ km}$ and $\leq 300 \text{ km}$) storms across land-mean, land-95th-percentile, and land-maximum rainfall metrics (Fig. 7). In the ERA5-based panels (Fig. 7a–c), storms in the 100–300 km offshore class include events with rainfall amounts overlapping those of the direct-impact class. The same qualitative overlap is present in the satellite-based panels (Fig. 7d–f). The satellite-based rainfall analysis uses a smaller event subset than the ERA5-based analysis because satellite precipitation coverage begins in 1998 and valid fields are required across the event window. Accordingly, the satellite panels include 36 direct-impact storms and 18 near-miss storms, compared with 67 direct-impact storms and 27 near-miss storms in the ERA5-based panels. Despite the smaller sample

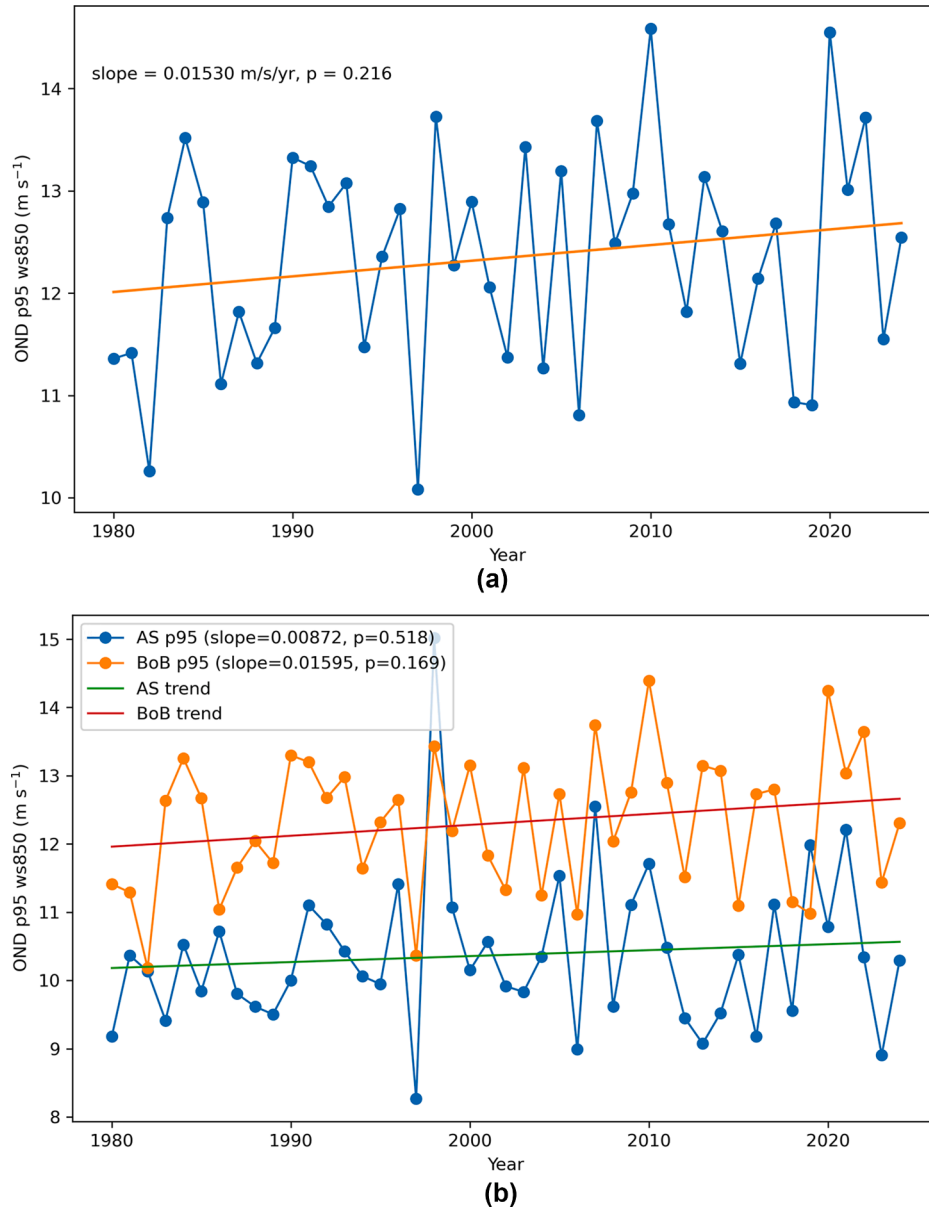


Fig. 4 OND lower-tropospheric wind extremes over the Sri Lanka region and adjacent sub-domains during 1980–2024. (a) OND p95 (ws850) over the Sri Lanka region (5–15°N, 75–90°E) with fitted linear trend. (b) OND p95 (ws850) over the Arabian Sea (5–15°N, 65–75°E) and Bay of Bengal (5–15°N, 75–95°E) sub-domains with fitted linear trends.

size, overlap between the two proximity classes remains evident in both rainfall products.

3.3. Genesis locations and long-term shifts

Genesis locations of Sri Lanka direct-impact TCs are concentrated in the southern BoB, with the highest density clustered near approximately 85–90°E and predominantly south of 15°N (Fig. 2b). The spatial distribution of genesis and early-track positions shows interdecadal variability but no coherent long-term displacement of the Sri Lanka-relevant genesis region (Fig. 2b).

Year-by-year genesis coordinates likewise show no statistically significant long-term shift over 1980–2024 (Fig. 2c and

d; Table 1). Genesis longitude shows a small, non-significant linear trend ($+0.016^\circ \text{ yr}^{-1}$, $p = 0.482$) and no significant monotonic trend ($\tau = 0.032$, $p = 0.704$). Genesis latitude also shows no significant change ($+0.011^\circ \text{ yr}^{-1}$, $p = 0.597$; $\tau = 0.023$, $p = 0.791$). Although some genesis and early-track positions extend episodically toward the eastern AS sector, this does not correspond to a statistically significant shift in mean genesis position over the analysis period.

3.4. Environmental conditions associated with Sri Lanka-influencing storms

Storm-peak deep-layer shear $|V_{200} - V_{850}|$ shows a statistically significant increasing trend over 1980–2024 (Table 1:

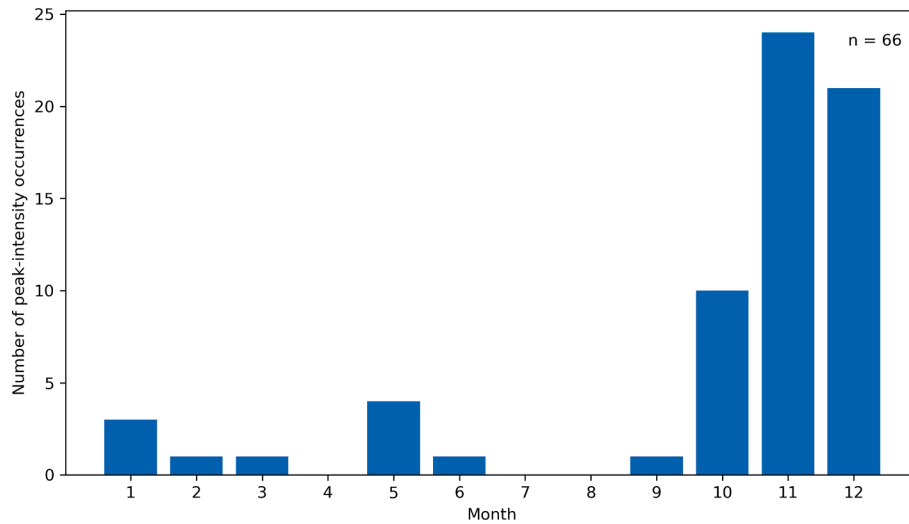


Fig. 5. Seasonality of tropical cyclone peak intensity near Sri Lanka during 1980–2024. Bars show the month in which each direct-impact storm (≤ 100 km) attains its maximum best-track wind within the 700 km Sri Lanka screening domain ($n = 66$). Peak occurrences are concentrated in October–December, with a smaller secondary maximum in May.

slope = 0.140 yr^{-1} , $p = 0.021$; Kendall $\tau = 0.264$, $p = 0.021$). In contrast, OND lower-tropospheric wind extremes, represented by p95 (ws850), show no statistically significant long-term trends over the Sri Lanka region (slope = 0.0153 yr^{-1} , $p = 0.216$), the AS sub-domain (slope = 0.00872 yr^{-1} , $p = 0.518$), or the BoB sub-domain (slope = 0.0160 yr^{-1} , $p = 0.169$) (Fig. 4a and b; Table 1).

Over the Sri Lanka region, OND mean SST and RH700 both show statistically significant increases, with slopes of $0.0152 \text{ }^{\circ}\text{C yr}^{-1}$ ($p = 2.77 \times 10^{-7}$) and $0.160 \text{ \% yr}^{-1}$ ($p = 0.000315$), respectively. By contrast, OND mean η_{850} and $\nabla \cdot \mathbf{V}_{200}$ do not show statistically significant long-term trends (Table 1). Thus, among the circulation-related indicators examined here, storm-peak deep-layer shear is the only variable showing a statistically significant long-term increase, whereas the OND background thermodynamic and circulation indices display a mixed pattern of significant and non-significant change.

4. Discussion

The results support a Sri Lanka-centered TC climatology characterized by relatively infrequent but persistent direct-impact storms, strong post-monsoon seasonality, a stable southern BoB genesis corridor, and substantial rainfall overlap between direct-impact and offshore near-miss storms. Under the ≤ 100 km direct-impact definition, Sri Lanka-influencing TCs occur at a rate of about 1.5 yr^{-1} , and neither annual frequency nor genesis location exhibits a statistically significant long-term trend over 1980–2024. The wavelet analysis further indicates that this occurrence record is weighted more strongly toward interannual than toward lower-frequency variability, but the short record length and cone-of-influence limitations do not support strong inference regarding multi-decadal periodicity.

The seasonal structure identified here is consistent with the established bimodal climatology of NIO cyclogenesis, with

major activity during the monsoon transition seasons and reduced activity during the boreal-summer monsoon, when stronger vertical wind shear is generally less favorable for development. The concentration of Sri Lanka direct-impact storm peaks in October–December, together with the smaller May secondary maximum, therefore places the Sri Lanka-focused results within the broader basin-scale seasonal framework rather than implying a locally unique seasonal regime.

The rainfall comparison is the most important hazard-oriented result of the study. Although the 100–300 km near-miss class remains offshore by definition, both the ERA5-based and satellite-based analyses show substantial overlap in event-total rainfall with the direct-impact class. This indicates that storm-center proximity alone does not fully capture rainfall relevance for Sri Lanka. In a Sri Lanka context, offshore passage does not preclude substantial land rainfall, so the near-miss class is best interpreted as a Sri Lanka-focused rainfall-hazard category rather than merely a geometric offshore subset. This interpretation is also physically plausible because outer rainbands and broader cyclone-circulation effects can extend well away from the storm center, even though their spatial extent varies across storms (National Hurricane Center, 2023; Yu et al., 2023). This conclusion should nevertheless be interpreted within the present Sri Lanka-centered event-definition framework, because the magnitude of event-total rainfall could vary under alternative proximity bins or shorter and longer accumulation windows, even if the qualitative finding of offshore rainfall relevance remains plausible.

The environmental diagnostics point to a selective rather than uniform pattern of change. Storm-peak deep-layer shear increases significantly, whereas OND lower-tropospheric wind extremes do not. At the same time, OND mean SST and RH700 both increase significantly, whereas OND mean η_{850} and $\nabla \cdot \mathbf{V}_{200}$ do not. This combination suggests that the environmental setting near Sri Lanka has become warmer and moister over the study period without showing corresponding increases in all circulation-related indicators. The results therefore do not support a simple narrative of uniformly

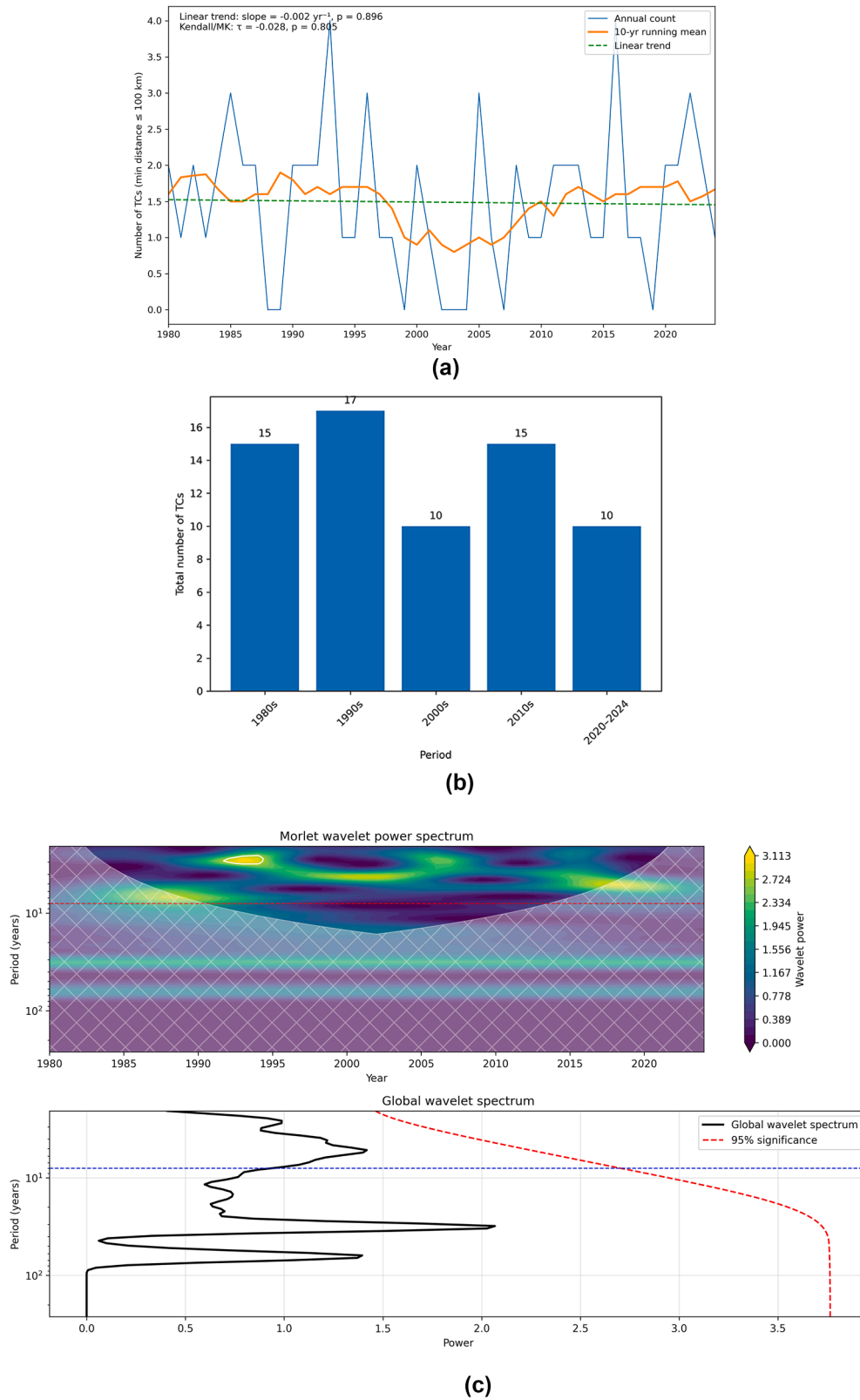


Fig. 6 Annual and spectral characteristics of Sri Lanka direct-impact tropical cyclones during 1980–2024. (a) Annual counts of storms passing within 100 km of the Sri Lankan coastline, with a 10-year running mean and fitted linear trend. (b) Decadal totals for the same direct-impact storm set. (c) Morlet wavelet analysis of the annual direct-impact count series, showing the wavelet power spectrum and global wavelet spectrum with the 95% significance level against a red-noise background. The cross-hatched region denotes the cone of influence.

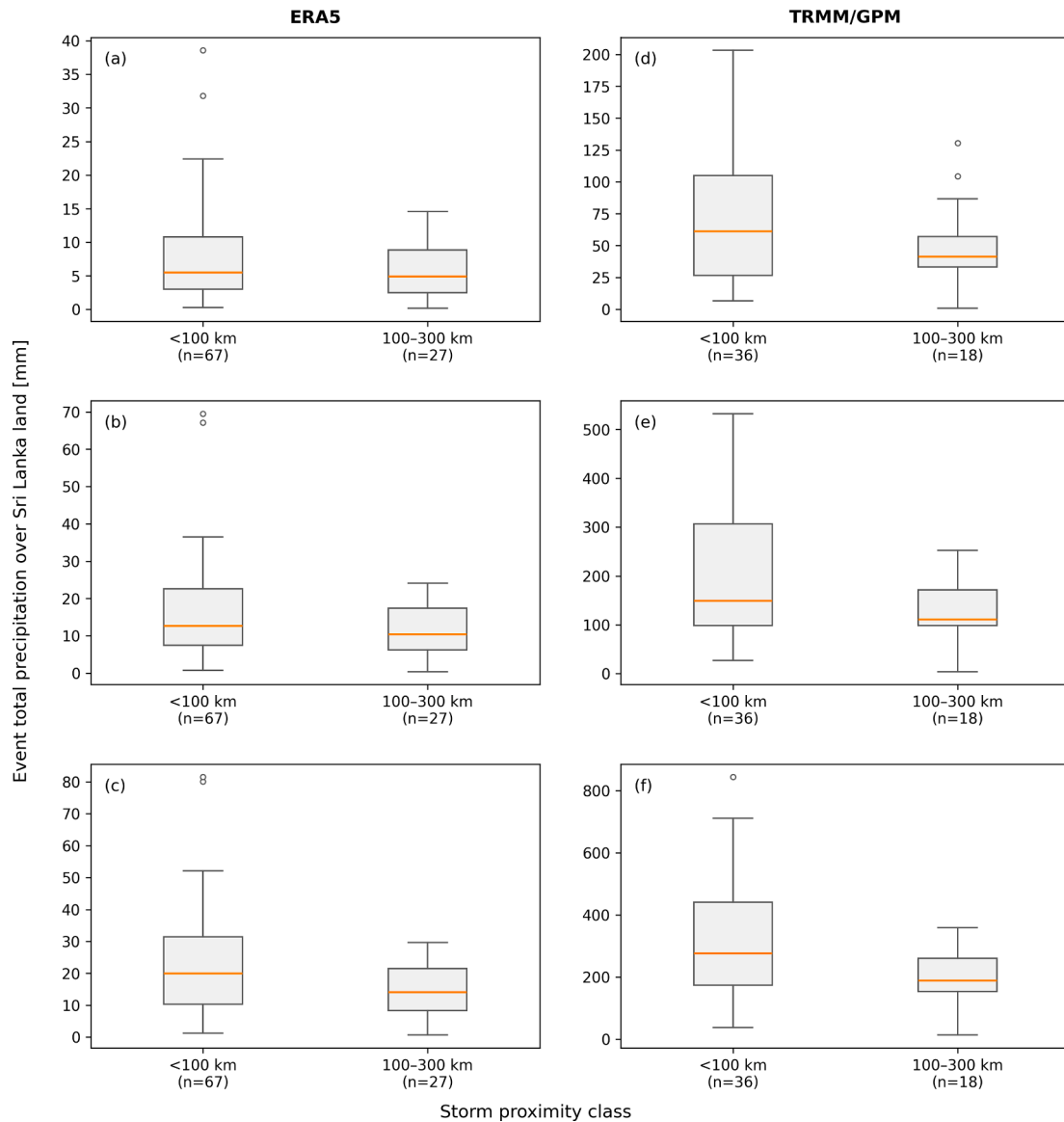


Fig. 7. Storm-event rainfall over Sri Lanka for direct-impact and near-miss tropical cyclones during 1980–2024. (a–c) ERA5-based land rainfall metrics for direct-impact (≤ 100 km) and near-miss (>100 – ≤ 300 km) storms, showing event-total (a) land-mean, (b) land-95th-percentile, and (c) land-maximum rainfall. (d–f) Corresponding TRMM/GPM-based land rainfall metrics for the same two proximity classes, showing (d) land-mean, (e) land-95th-percentile, and (f) land-maximum rainfall. Event rainfall was accumulated over a ± 48 h window centered on each storm's closest approach to Sri Lanka.

increasing TC favorability. Instead, they suggest a mixed environmental evolution in which some background conditions have become more supportive for moist convection while others have remained unchanged or become more constraining.

The increase in storm-peak deep-layer shear deserves careful interpretation. Vertical wind shear is widely recognized as a key control on TC structure and intensification because stronger shear tends to promote asymmetry and disrupt vertical alignment, although the observed effects can vary with storm structure and environmental context (Gray, 1968; Yu et al., 2023). More broadly, recent basin-comparative satellite analysis has also shown that tropical-cyclone structure varies systematically by basin and life-cycle stage, reinforcing the idea that storm organization and asymmetry can vary

substantially across cases (Gunawardena et al., 2026). In the present study, the increasing shear signal is not accompanied by corresponding increases in coastline-defined event frequency, nor by significant increases in OND lower-tropospheric wind extremes. This combination reinforces the conclusion that the long-term environmental changes relevant to Sri Lanka are mixed rather than uniformly intensifying.

From a Sri Lanka-focused hazard perspective, the present findings support an interpretation framework that considers both coastline-distance class and rainfall-footprint relevance. The absence of significant trends in direct-impact counts or lower-tropospheric wind extremes does not imply that offshore storms are unimportant for the island. Rather, the rainfall results indicate that storms remaining outside the direct-impact class may still be relevant for flood-related hazard planning,

especially during the post-monsoon season when Sri Lanka-influencing storms are most common.

5. Conclusions

This study provides a reproducible, Sri Lanka-focused framework for identifying IBTrACS NI basin TCs that influence the island and for examining their associated large-scale environmental context using IBTrACS best tracks and ERA5 for 1980–2024. By combining a Sri Lanka-centered screening domain, coastline-distance storm classes, and event-scale rainfall and environmental diagnostics, the analysis clarifies the climatological characteristics and rainfall-hazard relevance of Sri Lanka-influencing storms. Because exposure, vulnerability, and observed losses were not explicitly quantified, the study should be interpreted as a hazard-oriented climatology rather than a formal risk assessment.

Several main findings emerge. First, the Sri Lanka-influencing storm set is dominated by BoB systems propagating westward to west-northwestward at relatively low latitudes, with peak occurrences concentrated in October–December and a smaller secondary maximum in May. This indicates that Sri Lanka's TC hazard context is closely tied to the broader bimodal seasonal structure of the North Indian Ocean. Second, storm-event rainfall over Sri Lanka shows substantial overlap between direct-impact and near-miss storms, indicating that offshore storms can still produce notable land rainfall and that storm-center proximity alone does not fully represent rainfall-hazard relevance for the island. This interpretation is physically plausible because outer rainbands and associated hazardous weather can extend a few hundred kilometers from the storm center, although their extent varies substantially from storm to storm. Third, the environmental diagnostics indicate a mixed rather than uniform pattern of long-term change. Storm-peak deep-layer vertical wind shear increases significantly, whereas OND lower-tropospheric wind extremes show no significant long-term trend. Over the Sri Lanka region, OND mean SST and RH700 increase significantly, while OND mean η_{850} and $\nabla \cdot V_{200}$ do not. Thus, the multidecadal environmental evolution near Sri Lanka appears selective rather than uniformly more favorable or unfavorable for TC related hazards.

No statistically significant long-term change is detected in coastline-defined direct-impact frequency or genesis location over 1980–2024. The added wavelet analysis further indicates that the annual occurrence record is weighted more strongly toward interannual than toward lower-frequency variability, although the 45-year record is too short to support strong inference regarding long-period oscillations and interpretation near the cone of influence requires caution.

Several limitations should be recognized. Storm relevance was defined using storm-center screening and coastline-distance thresholds, which are transparent and reproducible but cannot fully represent storm size, asymmetry, rainfall and wind footprints, storm surge, wave setup, or impact severity. Best-track intensity and timing contain agency- and era-dependent uncertainties, and ERA5, while valuable for large-

scale environmental diagnostics, does not resolve TC inner-core structure at best-track intensity scales. In addition, the rainfall comparison depends on the Sri Lanka-centered coastline-distance classes and the fixed ± 48 h window around closest approach; these choices provide a consistent storm-centered hazard framework but do not isolate purely TC-core precipitation.

Future work should move beyond proximity-based definitions toward impact-oriented metrics that better represent the hazards experienced on the island, including rainfall footprint, wind footprint, storm surge, and waves, and should incorporate storm-size information where available. Additional storm-centered environmental sampling, higher-resolution regional modeling, and climate-model ensemble analysis would also help translate this climatology into more forward-looking hazard scenarios and planning-relevant applications.

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