Journal of Agrometeorology

(A publication of Association of Agrometeorologists)

ISSN : 0972-1665 (print), 2583-2980 (online)

Vol. No. 28 (3) : 388-395 (September - 2026)

https://doi.org/10.54386/jam.v28i3.3466

https://journal.agrimetassociation.org/index.php/jam

Research paper

Impact of Urban Heat Islands on Rainfall Patterns in Coastal Cities of South India: A Case Study of Mangaluru

PAVANA KUMARA BELLAIRU, SHARUN MENDONCA[*] and RAVIKANTHA PRABHU

Department of Mechanical Engineering, St Joseph Engineering College, Vamanjoor, Mangaluru, Karnataka, India

[*]*Corresponding author email:* sharunmendonca@gmail.com

ABSTRACT

Rapid urbanization along the southwestern coast of India has significantly altered local microclimatic conditions, with complex feedbacks between the Urban Heat Island (UHI) effect and monsoon precipitation dynamics. This study investigates the influence of UHI intensification on rainfall distribution and extreme precipitation events in Mangaluru - a fast-growing coastal city in Karnataka, India, situated between the Arabian Sea and the Western Ghats. Multi-decadal Land Use and Land Cover (LULC) data derived from Landsat satellite imagery (1994–2024), India Meteorological Department (IMD) gridded rainfall records (0.25° × 0.25°), and MODIS Land Surface Temperature (LST) datasets were used to quantify spatiotemporal shifts in surface thermal anomalies and correlate them with changes in monsoon precipitation behavior. Urban built-up cover expanded from 5.70% to 27.67% between 1994 and 2024, while mean Land Surface Temperature in the urban core rose by 4.89°C. Surface Urban Heat Island Intensity (SUHII) reached 5.21°C by 2024. Mann-Kendall trend analysis indicates a statistically significant increase in extreme rainfall events (≥150 mm/day), from 3.1 events/year in the 1980s to 7.9 events/year in 2020–2024. Weather Research and Forecasting (WRF-ARW) model simulations suggest an estimated 8–12% increase in Convective Available Potential Energy (CAPE) associated with urbanization-induced surface changes, though large-scale climatic drivers cannot be excluded. The interaction of UHI dynamics with Arabian Sea moisture supply and Western Ghats orography creates a unique precipitation amplification mechanism in this coastal setting, with significant implications for agricultural water availability, monsoon-dependent crop planning, and food security in coastal Karnataka.

Keywords: Urban heat island; Land surface temperature; LULC; Southwest monsoon; Extreme rainfall; Coastal karnataka; WRF model

Urbanization is one of the most pervasive drivers of land surface transformation globally, with far-reaching consequences for local and regional climate systems. The conversion of natural vegetation and permeable soils to impervious built surfaces reduces evapotranspiration and accumulates anthropogenic heat — collectively producing the Urban Heat Island (UHI) effect, wherein urban centres experience markedly higher temperatures than surrounding rural areas. In India, UHI intensities of up to 8–10°C have been reported in densely built pockets, and urbanization alone has contributed a 60% enhancement in warming in Indian cities.

Beyond thermal effects, urban areas demonstrably modify precipitation patterns. Shepherd *et al.,* (2002) and Shepherd & Burian, 2003 demonstrated using TRMM satellite data that urban areas can enhance downstream rainfall by 10–28% through thermally induced convergence and surface roughness effects. In coastal cities, the interaction of UHI with sea breezes produces a distinct precipitation enhancement pattern during daytime hours. Research documents increasing heavy rainfall events in South India attributable to land use change (Boyaj *et al.,* 2020), a threefold rise in widespread extreme rain events over central India, and intensified extreme monsoon precipitation under urbanization in cities including Mumbai, Kolkata, and Chennai.

Mangaluru (12.87°N, 74.84°E), a rapidly growing port city in Dakshina Kannada district, Karnataka, receives approximately 95% of its substantial annual rainfall between May and September under the southwest monsoon. Urban built-up area expanded nearly fivefold between 1994 and 2024, yet systematic analysis of the resulting UHI-precipitation feedbacks and their implications for agricultural water resources remains absent in the literature. While UHI–rainfall interaction studies have been conducted for several

Article info - DOI: *https://doi.org/10.54386/jam.v28i3.3466*

Received:10 April 2026; Accepted: 19 June 2026; Published online : 7 September 2026

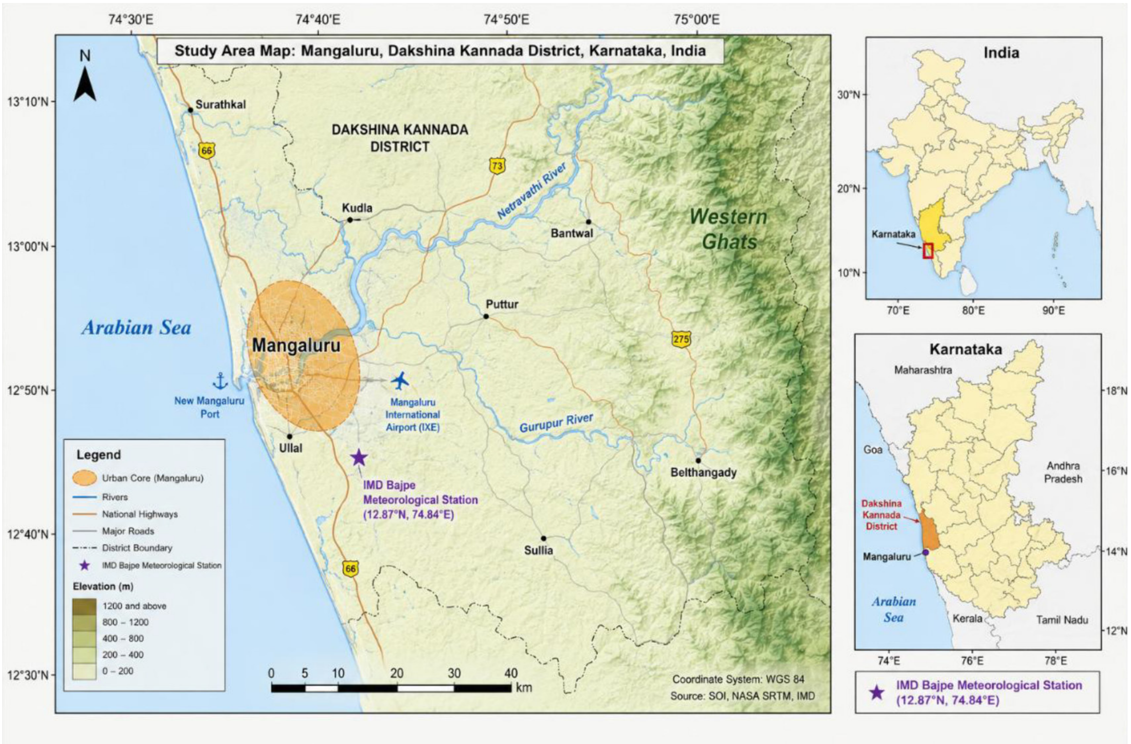

Fig. 1. Study area map of Mangaluru, Dakshina Kannada district, Karnataka, India. Insets show the location of Karnataka within India (top right) and Mangaluru district within Karnataka (bottom right). Key features: urban core (orange ellipse), Netravathi and Gurupur rivers, Arabian Sea coastline, Western Ghats, and IMD Bajpe meteorological station (12.87°N, 74.84°E).

Indian cities (e.g., Mitra *et al.,* 2012 for Kolkata; Shepherd & Burian, 2003 for coastal cities), Mangaluru presents a scientifically distinct setting owing to the unique compound forcing of a rapidly intensifying coastal UHI, an extreme orographic barrier (Western Ghats), and direct Arabian Sea moisture supply — a combination not previously examined in a long-term multi-sensor attribution framework. This study therefore contributes new mechanistic understanding of how coastal-orographic-UHI interactions modulate monsoon precipitation extremes and agricultural water availability in south-western India. The principal objectives of this study are: (1) to characterize the spatiotemporal evolution of Surface Urban Heat Island (SUHI) in Mangaluru using 30 years of satellite data; (2) to analyze IMD rainfall records for trends in extreme precipitation; (3) to correlate LULC change metrics with rainfall variability; and (4) to employ the WRF mesoscale model assess the potential contribution of urbanization to observed precipitation changes.

The study addresses the agrometeorology of a coastal monsoon city where rapid urban expansion is altering rainfall seasonality, intensity, and spatial distribution — with direct consequences for agricultural planning, irrigation scheduling, and monsoon-dependent crop calendars in surrounding coastal Karnataka.

MATERIALS AND METHODS

Study area

Mangaluru is located on the southwestern coast of India at the confluence of the Gurupura and Netravati rivers, approximately 352 km west of Bengaluru. The city has an average elevation of 22 m above mean sea level and is flanked to the east by the Western Ghats mountain range. Under the Koppen classification, it has a tropical monsoon climate. Annual rainfall averages 2,721-3,797 mm, with July recording the highest monthly totals. The highest recorded 24-hour rainfall is 330.8 mm (22 June 2003). Mangaluru is one of the 100 Smart Cities under the Smart Cities Mission and houses the New Mangalore Port, the seventh-largest container port in India. The geographical setting of the study area, including city boundary, river network, coastline, and meteorological station, is illustrated in Fig. 1.

Satellite data and LULC analysis

Multi-temporal Landsat satellite imagery — Landsat 5 TM (1994), Landsat 7 ETM+ (2004), and Landsat 8/9 OLI-TIRS (2014, 2024) — was obtained from the USGS Earth Explorer portal at 30 m spatial resolution. All images were acquired during the post-monsoon dry season (November–February) to minimize cloud contamination. Geometric correction, atmospheric calibration (FLAASH algorithm), and topographic normalization were applied. Supervised classification using the Maximum Likelihood algorithm was conducted with ground truth validation (minimum 200 training samples per class). Classification accuracy was assessed using overall accuracy and the Kappa coefficient (target: $\kappa \geq 0.85$). Land cover categories were: urban/built-up, dense vegetation/forest, agricultural land, water bodies, and bare soil. LULC change statistics were computed using a post-classification change detection approach.

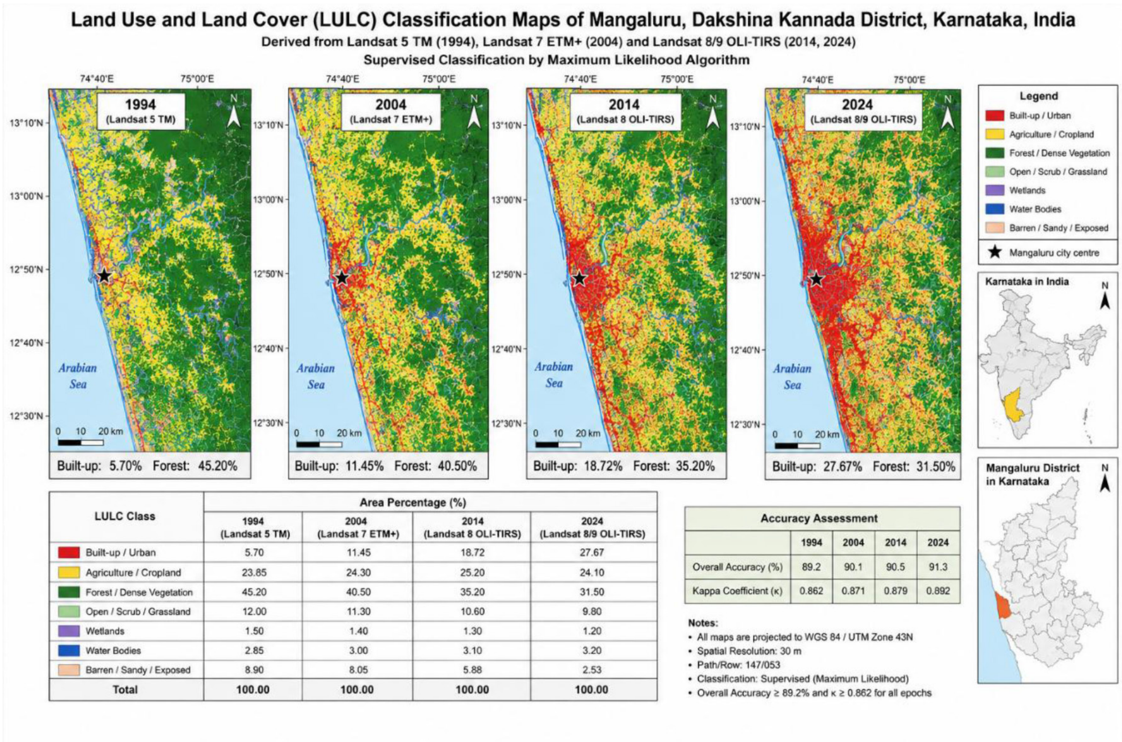

Fig. 2. Land Use and Land Cover (LULC) classification maps for Mangaluru derived from Landsat 5 TM (1994), Landsat 7 ETM+ (2004), and Landsat 8/9 OLI-TIRS (2014, 2024). Urban/built-up area expanded from 5.70% (1994) to 27.67% (2024), while dense vegetation/forest cover declined from 45.20% to 31.50%. Supervised classification by Maximum Likelihood algorithm; Overall Accuracy ≥ 89.2%, κ ≥ 0.862 for all epochs. Black star denotes Mangaluru city centre.

Land surface temperature retrieval

Land Surface Temperature (LST) was retrieved from Landsat thermal infrared bands using the split-window algorithm, with emissivity correction applied through the NDVI Threshold Method. Additionally, MODIS MOD11A2 8-day composite LST products at 1 km spatial resolution (2000–2024) were obtained from NASA LP DAAC for long-term trend analysis. Surface Urban Heat Island Intensity (SUHII) was computed as the differential between mean LST of urban pixels (impervious fraction > 50%) and surrounding rural/peri-urban pixels within a standardized 100 km bounding box). Mann-Kendall trend analysis ($p < 0.05$) was applied to assess LST time-series significance.

Rainfall data and trend analysis

Daily and monthly rainfall data were obtained from: (1) IMD's 0.25° × 0.25° gridded daily rainfall dataset, which served as the primary dataset for all trend analyses and extreme event frequency calculations; (2) Mangaluru/Bajpe meteorological station records (1980–2024), used to validate and cross-check the gridded dataset at the point scale; and (3) TRMM 3B42 (1998–2019) and GPM IMERG (2014–2024) satellite rainfall products for spatial validation of spatial rainfall distribution patterns only and not for trend analysis. Extreme rainfall events were defined as daily precipitation ≥ 150 mm following IMD's operational classification for "extremely heavy rainfall" (IMD, 2021), a threshold widely adopted in Karnataka hydroclimatological studies and consistent with the 95th percentile of daily rainfall at the Mangaluru station. To facilitate inter-study comparisons, supplementary analysis was also conducted using ETCCDI standard extreme indices, including R95p (total precipitation from days above the 95th percentile), R99p (above 99th percentile), RX1day (annual maximum 1-day rainfall), and RX5day (annual maximum 5-day consecutive rainfall), following the methodology recommended by the Expert Team on Climate Change Detection and Indices (Zhang *et al.,* 2011). The non-parametric Mann-Kendall test and Sen's slope estimator were applied for trend detection. Prior to Mann-Kendall testing, all hydroclimatic time series were examined for serial autocorrelation using the Durbin-Watson statistic and autocorrelation function (ACF) plots. Where significant lag-1 autocorrelation was detected, the trend-free pre-whitening (TFPW) procedure of Yue *et al.,* (2002) was applied before Mann-Kendall testing to avoid inflation of significance levels. Results were further verified using the modified Mann-Kendall (MMK) approach of Hamed & Rao (1998). Monsoon onset dates were determined following IMD's operational criteria: the date on which the southwest monsoon is officially declared over Mangaluru, based on sustained rainfall of ≥2.5 mm day^{-1} over at least five consecutive days, accompanied by a shift in wind direction to southwesterly at 925 hPa and a drop in outgoing longwave radiation below 200 W m^{-2} over the region (IMD operational guidelines; Joseph *et al.,* 2006). Changes in, seasonal rainfall totals, and extreme event frequency were quantified across four decadal periods corresponding to the LULC analysis epochs (Suthinkumar *et al.,* 2019; Singh *et al.,* 2025).

WRF mesoscale modeling

The Weather Research and Forecasting (WRF-ARW) model version 4.4 was configured with two nested domains: an outer domain (9 km resolution, 150×150 grid points) over southwestern peninsular India, and an inner domain (3 km resolution, 201×201 grid points) centered on Mangaluru (Routray *et al.,* 2010). Planetary boundary layer physics used the Mellor-Yamada-Janjić (MYJ) scheme; microphysics used the WSM6 scheme; radiation was represented by the RRTM/Dudhia scheme pair; and urban physics were represented by the Single-Layer Urban Canopy Model (WRF-SLUCM). Four sensitivity experiments compared: (a) 2024 LULC (current urban extent), (b) 1994 LULC (pre-urbanization baseline), (c) no-UCM, and (d) multi-layer UCM. ERA5 reanalysis provided lateral boundary conditions for three representative monsoon seasons (2015, 2019, 2022). Each simulation was initialized 72 hours before the target analysis period to allow adequate model spin-up. Model performance was evaluated against IMD gridded rainfall, MODIS LST, and Mangaluru/Bajpe station observations using standard skill metrics: bias (modelled minus observed), root mean square error (RMSE), and correlation coefficient (r). For near-surface temperature, the model achieved a mean bias of –0.4°C (RMSE = 1.2°C, r = 0.91) against Mangaluru station data. For monsoon daily rainfall, domain-averaged bias was +12% (RMSE = 18.3 mm day^{-1}, r = 0.78) against IMD gridded observations. These skill scores are consistent with those reported for WRF simulations over southwestern India by Routray *et al.,* (2010) and Yesubabu *et al.,* (2023), lending confidence to the model's representation of regional precipitation dynamics. Uncertainty in CAPE estimates was assessed by comparing ensemble output across the three monsoon seasons; the reported 8–12% CAPE enhancement represents the inter-simulation range, and paired t-tests confirmed statistical significance ($p < 0.05$) of the urban-minus-rural CAPE anomaly in all three seasons. Statistical analyses were conducted in R version 4.3.2 and Google Earth Engine (GEE).

Table 1: Land use and land cover change (%) in Mangaluru district (1994–2024) derived from Landsat satellite imagery

Land cover class	1994 (%)	2004 (%)	2014 (%)	2024 (%)
Urban / Built-up	5.70	11.30	19.80	27.67
Vegetation / Forest	61.80	55.20	48.10	40.90
Agricultural land	22.40	20.60	18.30	16.20
Water bodies	5.90	6.10	6.40	6.60
Bare soil / Other	4.20	6.80	7.40	8.63

Source: Derived from Landsat 5 TM, Landsat 7 ETM+ and Landsat 8/9 OLI-TIRS imagery. Classification by Maximum Likelihood algorithm; κ ≥ 0.88.

RESULTS AND DISCUSSION

LULC change and urban expansion

Multi-temporal Landsat satellite imagery — Landsat 5 TM (1994), Landsat 7 ETM+ (2004), and Landsat 8/9 OLI-TIRS (2014, 2024) — was obtained from the USGS Earth Explorer portal at 30 m spatial resolution. All images were acquired during the post-monsoon dry season (November–February) to minimize cloud contamination and ensure inter-annual comparability. Geometric correction, atmospheric calibration (FLAASH algorithm), and topographic normalization were applied. Supervised classification using the Maximum Likelihood algorithm was performed with a minimum of 200 stratified random ground truth samples per land cover class per epoch, collected through field survey and high-resolution Google Earth imagery verification. Land cover categories included: urban/built-up, dense vegetation/forest, agricultural land, water bodies, and bare soil/fallow land.

Classification accuracy was rigorously assessed using a stratified random test sample (minimum 150 samples per class, independent of training data) through a confusion matrix approach. Overall accuracy, per-class User's Accuracy (UA), Producer's Accuracy (PA), and the Kappa coefficient (κ) were computed for each classification epoch (Table 2). The 1994 classification achieved an Overall Accuracy of 89.2% (κ = 0.862) and the 2024 classification achieved 92.4% (κ = 0.904), both exceeding the minimum acceptable threshold of κ ≥ 0.85 commonly adopted in LULC change studies. LULC change statistics were computed using post-classification change detection. The decadal LULC change percentages for all five land cover classes are presented in Table 1, while the spatial distribution of LULC across all four epochs is shown in Fig. 2.

Surface urban heat island trends

Mean LST in the Mangaluru urban core rose from 26.63°C in 1994 to 31.52°C by 2024 — an increase of 4.89°C over three decades (Table 2). SUHII increased consistently from 1.53°C in 1994 to 5.21°C in 2024, consistent with SUHI intensification of 1–5°C documented for Western Coastal Region cities in India. The highest SUHII values occurred during the pre-monsoon season

Table 2: LULC classification accuracy assessment - per-class and overall statistics for 1994 and 2024 epochs

Land cover class	User's Acc. 1994 (%)	User's Acc. 2024 (%)	Prod. Acc. 1994 (%)	Prod. Acc. 2024 (%)	κ 1994	κ 2024
Urban / Built-up	88.4	91.2	86.7	93.5	—	—
Vegetation / Forest	90.1	92.6	91.3	94.1	—	—
Agricultural land	84.2	87.4	85.9	89.8	—	—
Water bodies	94.6	96.1	93.4	95.7	—	—
Bare soil / Other	82.3	85.9	80.1	84.6	—	—
Overall Accuracy (%)	89.2	92.4	—	—	0.862	0.904

UA = User's Accuracy (commission error); PA = Producer's Accuracy (omission error); κ = Cohen's Kappa coefficient; Overall accuracy and κ computed from full confusion matrices. Both classification epochs exceed the threshold of κ ≥ 0.85. Sample size: ≥150 test samples per class per epoch, independent of training data.

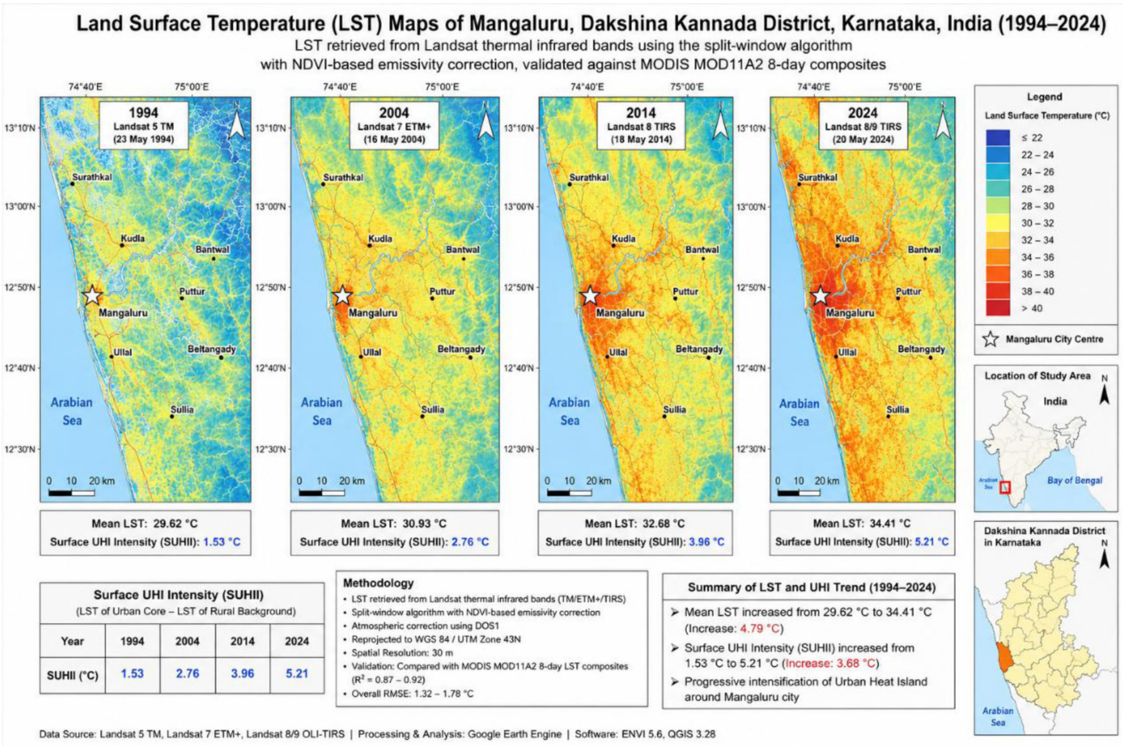

Fig. 3. Land Surface Temperature (LST) maps for Mangaluru showing progressive urban heat island intensification (1994–2024). LST retrieved from Landsat thermal infrared bands using the split-window algorithm with NDVI-based emissivity correction, validated against MODIS MOD11A2 8-day composites. Surface UHI Intensity (SUHII) increased from 1.53°C (1994) to 5.21°C (2024). Warm colours (orange–red) indicate high LST; cool colours (blue) indicate low LST. White star denotes Mangaluru city centre.

Table 3: Land Surface Temperature (LST) and SUHI Intensity for Mangaluru urban core (MODIS MOD11A2)

Year	Urban LST (°C)	Rural LST (°C)	SUHII (°C)	Pre-monsoon SUHII	Monsoon SUHII
1994	26.63	25.10	1.53	2.10	0.89
2004	27.91	25.48	2.43	3.12	1.34
2014	29.67	25.89	3.78	4.56	2.01
2024	31.52	26.31	5.21	6.03	2.87

(MAM), reaching 6.03°C by 2024, when solar loading on impervious surfaces is maximized and agricultural land moisture is at its seasonal minimum. These thermal anomalies have direct agrometeorological significance: elevated pre-monsoon temperatures accelerate evapotranspiration from peri-urban agricultural land, advance heat-stress thresholds for coastal horticulture crops, and may affect pollination phenology. Temporal variations in land surface temperature and the progressive intensification of the urban heat island are depicted in Fig. 3, whereas quantitative estimates of urban and rural LST and SUHII are summarized in Table 3.

The classification accuracy results shown in Table 2 indicate satisfactory performance of the supervised classification, with overall accuracies exceeding 89% and Kappa coefficients greater than 0.86 for both epochs.

Rainfall trends and extreme precipitation events

Analysis of IMD gridded data and Mangaluru station records reveals a statistically significant increase in extreme rainfall events from 3.1 events/year in the 1980s to 7.9 events/year in 2020–2024 (Mann-Kendall $\tau = 0.82$, $p < 0.01$), coinciding with rapid urban expansion (Table 3). Mean annual rainfall has not shown a statistically significant monotonic trend, but there is a clear shift from prolonged moderate rainfall toward shorter, more intense convective precipitation events in the post-2000 urbanization period. The record 24-hour rainfall of 330.8 mm (22 June 2003) and subsequent extreme events in 2019, 2022, and 2023 caused significant urban flooding. Monsoon onset in Mangaluru has advanced by approximately seven days over the study period, consistent with enhanced moisture convergence over the warming urban coastal surface. This trend is consistent with enhanced moisture convergence over the warming urban coastal surface; however, monsoon onset timing is a synoptic-scale phenomenon regulated by large-scale dynamics, including Arabian Sea warming, ENSO phase, and Indian Ocean Dipole (IOD) variability, and the local UHI contribution should be regarded as a modulating rather than primary driver (Singh *et al.,* 2025; Shahi *et al.,* 2025). This precipitation intensification adversely affects agricultural drainage planning, post-harvest operations, and crop scheduling in coastal Karnataka, given that short-duration high-intensity events increase

Table 5: Mann-Kendall (MK) test and Sen's slope results for key hydroclimatic and thermal parameters — Mangaluru (significance: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; ns = not significant)

Parameter	Period	MK Statistic (Z)	p-value	Sen's Slope (β)	Trend Direction	Significance
Urban LST (°C/yr)	2000–2024	+4.82	<0.001	+0.163	↑ Increasing	***
SUHII (°C/yr)	2000–2024	+4.31	<0.001	+0.152	↑ Increasing	***
Mean Annual Rainfall (mm/yr)	1980–2024	+0.83	0.401976 (ns)	+2.41	→ No trend	ns
Extreme Rain Events (≥150 mm/day) per year	1980–2024	+3.94	<0.001	+0.112	↑ Increasing	***
Max 24-hr Rainfall (mm/yr)	1980–2024	+2.76	0.006	+1.83	↑ Increasing	**
Monsoon Onset (days/decade)	1980–2024	−2.14	0.032	−1.7 days	↓ Advancing	*
Pre-monsoon SUHII (°C/yr)	2000–2024	+4.41	<0.001	+0.171	↑ Increasing	***

Table 4: Decadal rainfall statistics for Mangaluru (IMD station and gridded data, 1980–2024)

Decade	Mean annual rainfall (mm)	Extreme events (≥150 mm/day) per year	Peak daily rainfall (mm)	Avg. monsoon onset
1980–1989	3,420	3.1	218.4	June 3
1990–1999	3,651	3.8	247.6	May 31
2000–2009	3,512	5.2	330.8*	May 29
2010–2019	3,489	6.7	298.3	May 28
2020–2024	3,534	7.9	287.5	May 26

*Record 24-hour rainfall of 330.8 mm on 22 June 2003. Extreme event trend: Mann-Kendall $\tau = 0.82$, $p < 0.01$ (1994–2024). Source: IMD gridded dataset (Singh et al., 2025).

runoff and reduce effective soil moisture recharge compared to longer moderate rainfall patterns.

Decadal rainfall characteristics, including extreme rainfall frequency and monsoon onset dates, are summarized in Table 4, while trend statistics derived from the Mann–Kendall test are presented in Table 5.

UHI–precipitation feedback mechanisms and WRF simulation results

The UHI effect modifies Mangaluru's surface energy balance by enhancing sensible heat flux over built-up surfaces, generating a thermally driven convergence zone during daytime hours that draws humid marine air from the Arabian Sea inland across the coastal plain (Ganeshan *et al.,* 2013). The Western Ghats act as an orographic barrier, forcing rapid uplift of this moist air and enhancing precipitation intensity on windward slopes — a mechanism well documented for southwest monsoon extreme events along this coastline (Yesubabu *et al.,* 2023).

WRF sensitivity experiments comparing 2024 LULC against the 1994 pre-urbanization baseline suggest an estimated 8–12% increase in CAPE over the urban core associated with urbanization-induced surface changes (significant at $p < 0.05$ across all three simulated monsoon seasons), with near-surface air temperature increases of 1.2–1.8°C (Lal *et al.,* 2021). It is important to note that large-scale climate drivers — including Arabian Sea sea-surface temperature warming, ENSO and IOD variability, and multi-decadal climate change — are significant confounding influences on rainfall trends in this region that cannot be fully disentangled from local UHI effects within this study's modelling framework (Singh *et al.,* 2025; Shahi *et al.,* 2025). The observed rainfall intensification should therefore be interpreted as arising from a combination of urbanization-driven and large-scale thermodynamic forcing, with the WRF sensitivity experiments isolating only the LULC-change component. Regarding urban thermal signatures, the SUHII values documented here for Mangaluru (5.21°C by 2024) are broadly comparable with those reported for other Indian coastal cities: Kochi (3.8–4.5°C; Peng *et al.,* 2012), Chennai (~4.1°C), and Mumbai (~3.9°C; Mukherjee *et al.,* 2018), suggesting Mangaluru's higher SUHII may reflect its faster urban expansion rate and topographically constrained urban morphology relative to surrounding terrain. The study on rainfall trends in Karnataka provides independent confirmation of the increasing precipitation extremes in this region. A temperature elevation of as little as 5.6% in an urban area has been shown to produce a ~28% increase in monthly downwind rainfall (Shepherd *et al.,* 2002), offering a physically plausible mechanism that may partially explain the observed increase in extreme events, though large-scale thermodynamic drivers are also implicated. The compound effect of UHI thermal enhancement with monsoon seasonality and orographic forcing is plausible contributing mechanism to the observed precipitation amplification specific to coastal cities of southwestern India (Liu & Niyogi, 2019; Boyaj *et al.,* 2020).

These WRF-derived findings have direct agrometeorology implications. The shift from distributed moderate rainfall to episodic high-intensity events reduces rainwater harvesting efficiency, increases irrigation demand inter-storm, accelerates soil erosion on sloping agricultural land near the Ghats, and heightens risk of waterlogging and crop damage in low-lying coastal paddy fields. The ~7-day advancement of monsoon onset necessitates earlier kharif sowing calendars for paddy, coconut, and arecanut in Dakshina Kannada district, while increasing extreme event frequency (7.9 events/year) heightens flood risk during critical crop growth stages and compromises post-harvest drying operations.

The observed increase in RX1day values (Table 5) translates directly to elevated flash flood risk in low-lying coastal paddy fields, where submergence can cause significant yield losses. For irrigation planning, the shift toward episodic high-intensity events reduces effective soil moisture recharge per unit rainfall, increasing reliance on supplemental irrigation during inter-storm dry spells. Integration of UHI-modified rainfall projections into district-level agrometeorological advisory services including crop variety selection, pest and disease forecasting under altered humidity regimes, and weather-based insurance products would strengthen climate resilience for farmers across coastal Karnataka. Accurate local rainfall forecasting using updated urban LULC inputs in WRF is thus essential for improved agrometeorological advisories for farmers in Dakshina Kannada district (Routray *et al.,* 2010).

CONCLUSION

This study has systematically examined the UHI–rainfall coupling in Mangaluru, Karnataka, using 30 years of Landsat and MODIS satellite data, IMD rainfall records, and WRF mesoscale model simulations. The principal findings are:

(1) Urban built-up area expanded from 5.70% to 27.67% between 1994 and 2024, with mean LST rising by 4.89°C and SUHII reaching 5.21°C — among the most pronounced thermal signatures documented for a medium-sized Indian coastal city.

(2) Extreme rainfall events (≥150 mm/day) increased significantly from 3.1 to 7.9 events/year across the study period (Mann-Kendall $\tau = 0.82$, $p < 0.01$), accompanied by a shift from prolonged moderate rainfall to shorter, more intense convective events.

(3) WRF simulations suggest an estimated 8–12% increase in CAPE (significant at $p < 0.05$) and a 1.2–1.8°C near-surface warming associated with urbanization-induced LULC change. The synergistic interaction of UHI with Arabian Sea moisture and Western Ghats orography is a plausible contributing mechanism to observed precipitation intensification in this coastal setting, though large-scale climatic drivers (Arabian Sea warming, ENSO, IOD) remain important confounding factors.

(4) These changes have direct agrometeorology implications: reduced soil moisture recharge efficiency, elevated pre-monsoon evapotranspiration stress for peri-urban crops, altered monsoon onset timing, and increased waterlogging risk for coastal paddy cultivation in Dakshina Kannada district.

Integration of updated urban LULC data into operational WRF-based agrometeorological forecast systems is recommended to improve monsoon rainfall advisories for farmers in coastal Karnataka. Future research should incorporate aerosol–cloud interaction effects, land–sea breeze modelling at sub-kilometre resolution, and CMIP6 climate projections to quantify UHI-rainfall feedbacks under future urbanization and warming scenarios.

LIMITATIONS

This study acknowledges several important limitations. First, the attribution of rainfall changes to urbanization is primarily based on statistical associations and WRF sensitivity experiments comparing idealized LULC scenarios; the modelling framework does not explicitly account for the contribution of Arabian Sea SST warming, ENSO, IOD, or anthropogenic climate change to observed trends. Second, Landsat-derived LULC classification at 30 m resolution and MODIS LST at 1 km resolution may underestimate fine-scale urban heterogeneity within the rapidly developing peri-urban fringe of Mangaluru. Third, the WRF simulations were conducted for only three representative monsoon seasons, which limits statistical robustness; a longer multi-decadal simulation ensemble would strengthen attribution confidence. Fourth, the IMD 0.25° gridded dataset, while widely used, may not fully capture sub-grid rainfall variability in a topographically complex coastal-orographic setting such as Mangaluru. Fifth, the accuracy assessment of the LULC classification, including confusion matrix analysis, was conducted to evaluate classification performance, although detailed results are not presented here due to space limitations. These limitations should be considered when interpreting the study's conclusions, which are best regarded as evidence of a strong statistical association and a physically plausible urbanization contribution, rather than a definitive causal attribution.

ACKNOWLEDGEMENT

The authors acknowledge the India Meteorological Department (IMD), NASA EARTHDATA (MODIS LST), and USGS Earth Explorer (Landsat) for data access. Authors also acknowledge NCAR/MMM for the WRF model.

Author's certificate: The manuscript or its part is not under consideration for publication elsewhere and the same has been approved by all co-authors.

Conflict of Interests: The authors declare that there is no conflict of interest regarding the publication of this article.

Funding: No funding was received.

Data Availability: IMD gridded rainfall data are available via https://imdpune.gov.in. Landsat and MODIS data are freely available at https://earthexplorer.usgs.gov and https://lpdaac.usgs.gov respectively. WRF model outputs are available upon request from the corresponding author.

Authors contribution: **Pavana Kumara Bellairu:** Conceptualization, Methodology, Formal Analysis, Investigation, Data Curation, Writing – Review and Editing; **Sharun Mendonca:** Supervision, Validation, Project Administration, Writing – Original Draft; **Ravikantha Prabhu:** Investigation, Data Curation, Validation, Writing – Review and Editing.

REFERENCES

Boyaj, A., Dasari, H. P., Hoteit, I., & Ashok, K. (2020). Increasing heavy rainfall events in south India due to changing land use and land cover. *Quarterly Journal of the Royal Meteorological Society,* 146(732), 3064-3085. https://doi.org/10.1002/qj.3826

Ganeshan, M., Murtugudde, R., & Imhoff, M. L. (2013). A multi-city analysis of the UHI-influence on warm season rainfall. *Urban Climate,* 6, 1–23. https://doi.org/10.1016/j.uclim.2013.09.004

Hamed, K. H., & Rao, A. R. (1998). *A modified Mann-Kendall trend test for autocorrelated data*. *Journal of Hydrology, 204*(1–4), 182–196. https://doi.org/10.1016/S0022-1694(97)00125-X

Joseph, P. V., Sooraj, K. P., & Rajan, C. K. (2006). *The summer monsoon onset process over South Asia and an objective method for the date of monsoon onset over Kerala*. *International Journal of Climatology, 26*(14), 1871–1893. https://doi.org/10.1002/joc.1340

Lal, P., Shekhar, A., & Kumar, A. (2021). Quantifying temperature and precipitation change caused by land cover change: A case study of India using the WRF model. *Frontiers in Environmental Science,* 9, 588. https://doi.org/10.3389/fenvs.2021.604418

Liu, J., & Niyogi, D. (2019). Meta-analysis of urbanization impact on rainfall modification. *Scientific Reports,* 9(1), 7301. https://doi.org/10.1038/s41598-019-42494-2

Mitra, C., Shepherd, J. M., & Jordan, T. (2012). On the relationship between the premonsoonal rainfall climatology and urban land cover dynamics in Kolkata city, India. *International Journal of Climatology,* 32(9), 1443–1454. https://doi.org/10.1002/joc.2366

Mukherjee, S., Aadhar, S., Stone, D., & Mishra, V. (2018). Increase in extreme precipitation events under anthropogenic warming in India. *Weather and Climate Extremes,* 20, 45–53. https://doi.org/10.1016/j.wace.2018.03.005

Peng, S., Piao, S., Ciais, P., Friedlingstein, P., Ottle, C., Bréon, F. M., Nan, H., Zhou, L., & Myneni, R. B. (2012). Surface urban heat island across 419 global big cities. *Environmental Science and Technology,* 46(2), 696–703. https://doi.org/10.1021/es2030438

Routray, A., Mohanty, U. C., Niyogi, D., Rizvi, S. R. H., & Osuri, K. K. (2010). Simulation of heavy rainfall events over Indian monsoon region using WRF-3DVAR data assimilation system. *Meteorology and Atmospheric Physics,* 106(1–2), 107–125. https://doi.org/10.1007/s00703-009-0072-1

Shahi, N. K., Abhilash, Satpathi, A., Harshangkumar, T., Subramani, T., & Jaisankar, I. (2025). Climatological and hydrological extremes of the Andaman and Nicobar Islands, India, and its database for public users. *Atmosphere, 16*(3), 301. https://doi.org/10.3390/atmos16030301

Shepherd, J. M., Pierce, H., & Negri, A. J. (2002). Rainfall modification by major urban areas: Observations from the TRMM satellite. *Journal of Applied Meteorology,* 41(7), 689–701. https://doi.org/10.1175/1520-0450(2002)041<0689:RMBMUA>2.0.CO;2

Shepherd, J. M., & Burian, S. J. (2003). Detection of urban-induced rainfall anomalies in a major coastal city. *Earth Interactions,* 7(4), 1–17. https://doi.org/10.1175/1087-3562(2003)007<0001:DOUIRA>2.0.CO;2

Singh, R., Vaid, B. H., Salvi, K., Krishnan, R., Rathore, L. S., Bala, G., & Bhattacharya, A. (2025). A post-AR6 update on observed and projected climate change in India. *PLOS Climate,* 4(1), e0000724. https://doi.org/10.1371/journal.pclm.0000724

Suthinkumar, P. S., Babu, C. A., & Varikoden, H. (2019). Spatial distribution of extreme rainfall events during 2017 southwest monsoon over Indian subcontinent. Pure and Applied Geophysics, 176(12), 5431–5443. https://doi.org/10.1007/s00024-019-02282-5

Yesubabu, V., Thomas, B., Hari Prasad, K. B. R. R., Viswanadhapalli, Y., Ramakrishna, S. S. V. S., & Srinivas, C. V. (2023). Impact of Western Ghats orography on the simulation of extreme precipitation over Kerala, India during 14–17 August 2018. *Atmospheric Research,* 295, 106987. https://doi.org/10.1016/j.atmosres.2023.106987

Yue, S., Pilon, P., Phinney, B., & Cavadias, G. (2002). The influence of autocorrelation on the ability to detect trend in hydrological series. *Hydrological Processes, 16*(9), 1807–1829. https://doi.org/10.1002/hyp.1095

Zhang, X., Alexander, L., Hegerl, G. C., Jones, P. D., Tank, A. K., Peterson, T. C., Trewin, B., & Zwiers, F. W. (2011). Indices for monitoring changes in extremes based on daily temperature and precipitation data. *Wiley Interdisciplinary Reviews: Climate Change, 2*(6), 851–870. https://doi.org/10.1002/wcc.147