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Spatiotemporal Hydroclimatic Heterogeneity Across Odisha, India (1981–2025): Changing Rainfall–Temperature Regimes, Drought and Climate Extremes

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Abstract

Changes in rainfall and temperatures are basic elements of a regional climate system, but they are not often spatially uniform over time. This is relevant in monsoon-dependent regions where atmospheric moisture and thermal conditions affect agriculture and water resources, as well as exposure to climatic extremes. In this study, the hydroclimatic variability has been assessed at the district level over a 45-year period (1981-2025) for observations from the India Meteorological Department (IMD) that are gridded on a daily basis. The analysis considers three 15-year periods: 1981–1995, 1996–2010, and 2011–2025, across all 30 districts. Standard deviation and the coefficient of variance were used to assess the patterns and variability of annual rainfall, annual maximum temperature (Tmax) and annual minimum temperature (Tmin). The trend direction was evaluated with the Mann–Kendall test, and the magnitude of the trend was estimated by Theil-Sen's slope. The annual rainfall (mean) is consistent in the west–east gradation, about 1200–1300 mm per year in the interior and almost 1700 mm per year at the north-eastern coastal district. The number of districts with positive annual rainfall trends decreased from seven in 1981-1995 to one in 2011-2025. Tmax depicts an intensifying warm core over north-central and western interior districts (Sundargarh, Jharsuguda and Sambalpur), with an overall spatial warm pattern persisting. The 1-month SPI shows a drying trend, particularly during 1996-2010, which was somewhat moderated during 2011-2025. Tmax shows an intensifying warm core over north-central and western interior districts, particularly Sundargarh, Jharsuguda, and Sambalpur. Hythergraph analysis indicates persistent hot–dry pre-monsoon conditions and increasing thermal stress in interior districts, together with shifts in monsoon rainfall concentration. These findings indicate significant hydroclimatic variability in the State of Odisha and the need for district-wise climate risk mapping and adaptation planning, especially in rain-fed agricultural areas. The study also offers a unified approach to investigating changing rainfall–temperature regimes in monsoon-dependent regions.

Keywords: *Odisha, Mann–Kendall, Sen's slope, 15-year period analysis, Standardised Precipitation Index, Hythergraph, Spatio-temporal heterogeneity.*

1. Introduction

Climate change has moved beyond a theoretical concern and has become an increasingly evident contemporary reality, underscoring the need to understand its implications for regional environmental conditions. Eventually, it becomes one of the most significant scientific and policy issues, as it directly affects hydrology, agricultural productivity, ecosystem function, public health, and disaster risk (IPCC, 2023; Trenberth, 2011). The concentration of tropospheric greenhouse gases (GHGs) alters temperature and precipitation records at the global, regional, and local scales (Alexander et al., 2006; Seneviratne & Zurich, 2012). Changes in frequency, intensity, and the geographic distribution of such extremes (i.e., dry spells) are among the most essential. Measurement of such changes/alternations provides crucial information for policy-making in change-induced adaptation, and thus becomes essential for measures across geographies (IPCC, 2023) .

India is also experiencing recent shifts in climate trends and extremes, and is moving towards a more climate-sensitive state (Guhathakurta & Rajeevan, 2008; Parthasarathy et al., 1994). Previous studies over India have shown that relatively stable or weakly changing seasonal rainfall totals can coexist with substantial changes in the frequency, intensity and spatial variability of extreme rainfall events (Roxy et al., 2017; Ghosh et al., 2016). The case of Odisha is no different and is very relevant, as its climate is strongly controlled by the south-west monsoon and characterised by substantial spatial and seasonal variability in precipitation and temperature. Erratic precipitation behaviour, dry spells, drought, and heat waves cumulatively pose a threat to people and their livelihoods. The recurrent floods, droughts, heat waves, and other hydroclimatic extremes are becoming frequent in Odisha, making it essential to study both long-term gradual changes and short-duration extremes. The implications of such studies are manyfold – changes in temperature and precipitation have direct impacts on rainfed agriculture, ecosystem functioning, and socio-economic conditions. For example, Panda & Sahu (2019) identified the sensitivity of agriculture to climate fluctuations in the Kalahandi – Bolangir–Koraput region. At the state scale, long-term analyses have also identified substantial spatial heterogeneity in rainfall behaviour, including changes in dry-day frequency and heavy-to-extreme rainfall characteristics (Mohapatra et al., 2021; Swain et al., 2019). Similarly, Mishra (2017) examined Odisha, which is particularly vulnerable to multiple climate-related hazards – cyclones, floods, droughts and heat waves. Thus, robust spatio-temporal characterisation of climatic behaviour is essential for understanding the hydro-climatic

environment of Odisha and supporting agricultural planning, water resources management, disaster risk reduction, and adaptation.

Previous literature has substantially explored precipitation and temperature variability over Odisha; however, considerable variation persists in their spatial coverage, time period, and the elements of climate in focus (Nayak et al., 2013; Pai et al., 2013). At the grid scale, substantial spatio-temporal heterogeneity, including increasing and decreasing rainfall trends, was found by Prabhakar et al. (2019) using the Mann-Kendall, Modified Mann-Kendall, and Theil-Sen slope tests. Nageswararao et al.(2019) reported increasing frequencies of high-intensity rainfall events in several districts (i.e., Bolangir, Kalahandi, Nuapada, Koraput), though notable decreases in monsoonal rainfall (JJAS). Contrastingly, Panda & Sah (2019) reported significant increasing trends in monsoonal precipitation and in maximum and minimum temperatures, and notable precipitation variability in the Kalahandi, Bolangir, and Koraput regions during 1980 – 2017. District-level analyses from western and southern Odisha similarly indicate that rainfall and temperature trends can differ substantially among neighbouring regions (Panda & Sahu, 2019). Evidence from the eastern coastal region also indicates significant warming in both maximum and minimum temperature, while changes in rainfall totals are comparatively less coherent (Vijayakumar et al., 2021). Singh & Rath (2024) also identified persistent, prevailing mild drought and variability in the intensity and frequency of precipitation over the last 34 years in Sundargarh district. A recent study by Kumari et al. (2026) found an increasing trend in monsoonal precipitation (Sen's slope of +17.48 mm per decade) and a decreasing trend in pre-monsoon precipitation (up to -2.64 mm per decade) in the Tal basin, Odisha. Contrastingly, heavy rainfall days increased before 2000 and decreased after 2010, with an overall decline in the CWD and significant increases in the CDD and drought severity in the Tel Basin, Odisha (Kumari et al., 2026). More recent evidence further suggests that changes in Odisha rainfall may be expressed more strongly through event frequency, intensity and spell structure than through a uniform change in seasonal or annual totals (Kumari et al., 2026; Malayalam et al., 2026)

The literature therefore shows substantial spatio-temporal variability in Odisha, but remains fragmented across climatic variables, study areas, and observation periods. Few studies have jointly examined rainfall, Tmax, Tmin, drought/wetness conditions, and multiple extreme indicators at a common state-wide district scale through the recent period. An integrated assessment is therefore needed to examine the shifting hydroclimatic regime and the combined temperature–precipitation behaviour of Odisha.

Hence, the present study focuses on an integrated assessment of spatiotemporal evolution of rainfall and temperature over Odisha during 1981–2025. Specifically, the objectives of the present study are to; (i) characterise the spatial and temporal distribution of precipitation, maximum (T_{max}) and minimum temperature (T_{min})**;** (ii) quantify their spatial and interannual variability, monotonic trends and trend magnitude; (iii) assess selected hydro-climatic and temperature extremes, such as consecutive wet days (CWD), consecutive dry days (CDD), heavy-rainfall events, Standardised Precipitation Index (SPI), warm nights and heat-wave days; (iv) integrate precipitation–temperature behaviour to examine the hydrothermal regime of Odisha.

2. Study Area

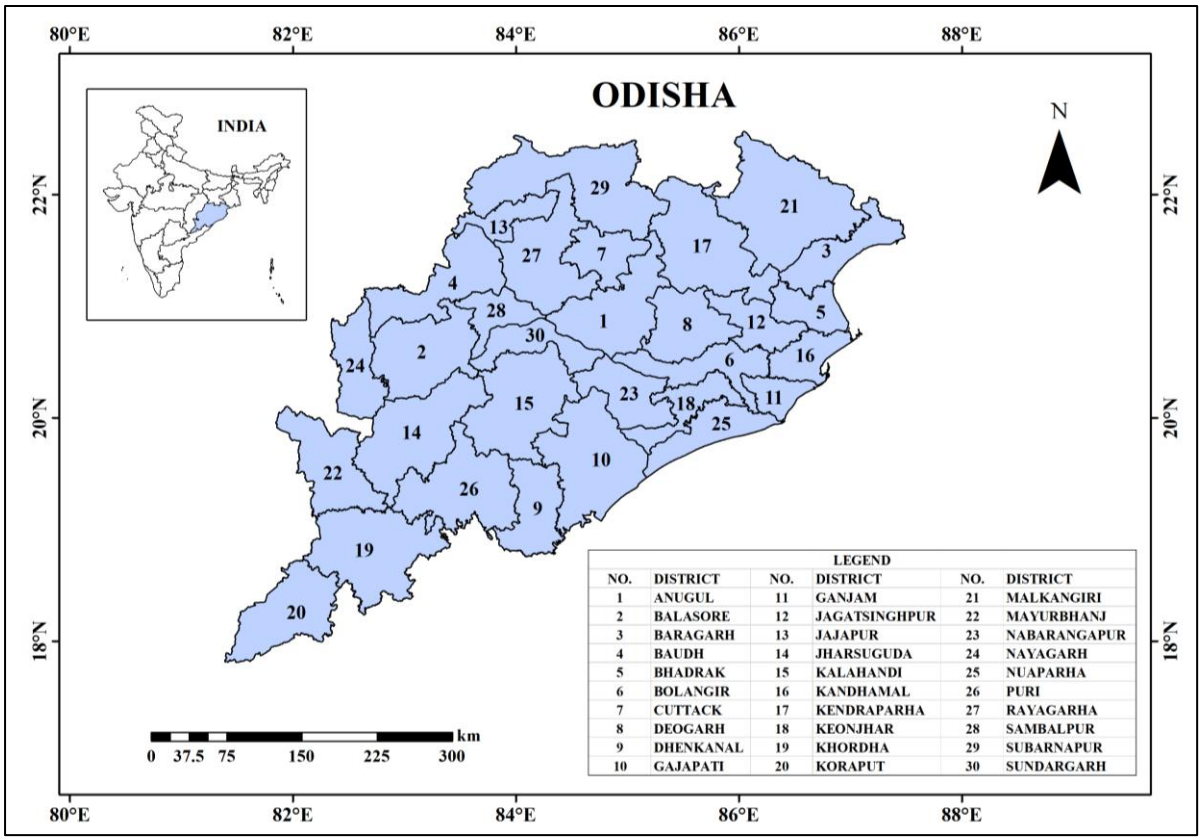


Fig.1. Location and physiographic setting of Odisha on the eastern coast of India (17°49′N–22°34′N, 80°29′E–87°29′E), showing the 30 administrative districts.

The state of Odisha, located along the eastern coast of peninsular India, extends between 17°49’N and 22°34’N latitude and 80°29’E and 87°29’E longitude, covering a total geographical area of 155,707 sq. km across 30 administrative districts. The state exhibits a

diverse physical landscape, transitioning from narrow coastal plains and deltaic lowlands in the east to undulating river valleys and densely forested plateaus toward the west, with the Eastern Ghats functioning as the dominant physiographic element and the primary driver of the west-to-east rainfall gradient. The mean annual precipitation follows a latitudinal and topographical gradient- 1,247 mm in the moisture-deficient western interior to 1,674 mm in the windward eastern and north-eastern coastal regions (Prabhakar et al., 2019; Sahu et al., 2025). About 78% of total rainfall occurs during the monsoon period, while the remaining months are relatively dry. Summer temperatures range from 30 – 45 °C, winter temperatures from 10 – 22 °C, and summer heat waves are very common.

3. Data and Methodology

3.1 Database

In the present study, long-term daily gridded meteorological data (25km) have been collected from the Indian Meteorological Department (IMD) for the period 1981 to 2025 (Pai et al., 2014 and Srivastava et al., 2009). In the dataset, three variables have been considered: daily precipitation in millimetres (mm), maximum temperature in degrees Celsius (Tmax), and minimum temperature in degrees Celsius (T_{min}). Gridded climate data were selected instead of station observations because of their consistent spatial coverage and temporal continuity over the study period. The use of gridded data minimizes gaps and inconsistencies associated with changes in station location, observation practices, and data availability, thereby providing a more homogeneous long-term dataset suitable for state-wide and district-level spatio-temporal analysis (Srivastava et al., 2009; Pai et al., 2014).

3.2 Methodology

3.2 15-Year Period Stratification

The entire 45-year period has been stratified into three equal 15-year periods: Period 1 (P1): 1981–1995; Period 2 (P2): 1996–2010; and Period 3 (P3): 2011–2025. These equal-length periods facilitate comparison of climatological characteristics while reducing sensitivity to individual short-lived climate anomalies**.**

3.3 Spatial Analysis

District-level thematic maps of precipitation, $T_{max,}$ and T_{min} were generated for all 30 districts of Odisha for the entire study period (1981-2025) and for each 15-year period sub-period using ArcGIS and R software. Spatial mapping enables the recognition of geographic patterns and

their changes over time, which cannot be captured using district-level average values. This is in line with methods used in the study of extreme events in India .

3.4 Descriptive Statistics

For each district and period, the arithmetic mean ($\bar{x}$), standard deviation (SD) and coefficient of variation (CV) of annual precipitation, T_{max} and T_{min} were computed as follows:

$$\bar{x} = (1/n)\, \Sigma_{i=1}^{n}\, x_i \qquad \text{Eq. 1}$$

$$SD\ (\sigma) = \sqrt{[(1/(n-1))\, \Sigma_{i=1}^{n}\, (x_i - \bar{x})^2]} \qquad \text{Eq. 2}$$

$$CV\ (\%) = (\sigma\ /\ \bar{x}) \times 100 \qquad \text{Eq. 3}$$

where x_i denotes the annual value of the variable in year i and n is the number of years in the period under consideration. The coefficient of variation (CV) provides a unit-free measure of relative dispersion that allows comparisons between different districts and variables, irrespective of the magnitudes of precipitation, Tmax, and Tmin.

3.5 ETCCDI Extreme Climate Indices

Extreme events were quantified using indices defined by the Expert Team on Climate Change Detection and Indices (ETCCDI), formulated under the joint auspices of WMO, WCRP, and the Commission for Climatology (Klein et al.,2003).Three precipitation-based and temperature-based indices were computed. **Consecutive dry days (CDD)** refers to the maximum number of consecutive days in a year when precipitation is less than 1 mm, serving as an index of drought duration. **Consecutive wet days (CWD)** refers to the maximum number of consecutive days per year with precipitation equal to or exceeding 1 mm, providing a measure of sustained wet spell duration. **Heavy Rainfall Days (HRD)** measure the number of days in the year when rainfall falls in the range of 64.5 to 115.5 mm, as defined by the Indian Meteorological Department (IMD, 1971) (Kumar et al., 2020) . HRD indicates the intensity of rainfall delivery, with an increase in HRD despite stable or decreasing annual rainfall (Rajeevan et al., 2008).

Heat Wave Days (HWD) were identified following the IMD operational criteria, whereby a heat wave is declared when the maximum temperature at a station departs by 4.5°C–6.4°C or more above the long-period normal, or when T_{max} exceeds 40°C in absolute terms, persisting for at least two consecutive days (Pai et al., 2013; Pattanaik et al., 2017; India Meteorological Department [IMD], 2026). Annual HWD counts were subsequently aggregated and analysed

for pre-monsoon and monsoon sub-seasonal totals. **Warm Night Days (WND)** were identified when the minimum temperature departure exceeded the long-period station normal by 4.5°C–6.4°C or above (Alexander et al., 2006; FAQ on Heat Wave, n.d.). The frequency of warm nights serves as an indicator of asymmetric warming, reflecting the well-documented global pattern in which Tmin rises faster than Tmax

3.6 Standardised Precipitation Index (SPI-1)

The one-month Standardised Precipitation Index (SPI-1) was computed for each district across the full 1981–2025 record following McKee et al. (1993), in which monthly precipitation totals are fitted to a gamma probability distribution and transformed to the standard normal variate:

$$G(x) = [1 / (\beta\hat{}\alpha\, \Gamma(\alpha))] \int_0^x t\hat{}(\alpha - 1)\, e\hat{}(-t/\beta)\, dt \qquad \text{Eq. 4}$$

where α and β stand for the shape and scale parameters of the gamma distribution obtained from the precipitation data, respectively, and Γ(α) is the gamma function. Then the cumulative probability G(x) was converted to the standard normal variable (SPI) by using the approximation developed by Abramowitz & Stegun 1964). The SPI-1 index was preferred over longer accumulation periods because it focuses on short-term moisture anomalies affecting monsoon-based agricultural activities. Still, it is a precipitation component of the moisture stress and does not account for potential evapotranspiration.

3.7 Mann–Kendall Trend Test and Sen's Slope Estimation

Period-specific monotonic trends in annual rainfall**,** Tmax and Tmin were evaluated using the non-parametric Mann–Kendall (MK) test (Kendall, 1948; Mann, 1945), which tests the null hypothesis (H_0) of no monotonic trend against the alternative (H_1) that a trend is present, without requiring the series to be normally distributed (Hamed & Rao, 1998**)**. The test statistic S is derived as:

$$S = \Sigma_{i=1}^{n-1} \Sigma_{j=i+1}^{n} sgn(x_j - x_i) \qquad \text{Eq. 5}$$

where $sgn(x_j - x_i)$ takes the values +1, 0 or −1 according to whether the difference is positive, zero or negative. For $n \geq 8$, the variance of S was determined while considering tied values:

$$Var(S) = [n(n-1)(2n+5) - \Sigma_k\, t_k(t_k - 1)(2t_k + 5)] / 18 \qquad \text{Eq. 6}$$

where t_k represents the number of tied values in the k^{th} group of ties. The standardised test statistic Z is then given by:

$$Z = (S - 1) / \sqrt{Var(S)}, if\ S > 0 \quad \text{Eq.7}$$

$$Z = 0, if\ S = 0 \quad \text{Eq.8}$$

$$Z = (S + 1) / \sqrt{Var(S)}, if\ S < 0 \quad \text{Eq. 9}$$

At significance of 5 % level, a trend was considered statistically significant where $|Z| \geq 1.96$ (two-tailed, $p < 0.05$). Kendall's tau (τ), signifying the strength of association independent of magnitude, was computed as

$$\tau = S / [n(n-1)/2] \quad \text{Eq. 10}$$

The magnitude and direction of any monotonic trend were quantified using Sen's slope estimator (Sen, 1968; Hirsch et al., 1982), computed as the median of all pairwise slopes:

$$Q_k = (x_j - x_i) / (j - i), for\ all\ i < j \quad \text{Eq. 11}$$

Sen's slope $\beta = \text{median}(Q_k)$. A positive β indicates an increasing trend and a negative β indicates a decreasing trend, expressed in the variable's native units per year (e.g., mm year^{-1} for rainfall, °C year^{-1} for temperature). Trends were considered statistically significant only when the Mann–Kendall test rejected H_0 at $p < 0.05$; all other districts were characterised descriptively.

3.8 Compound hydro-climatic behaviour - Hythergraph

Hythergraph (or hygrothermal diagram) is a bivariate plot method which describes the relation between temperature and precipitation of a site for a year using an annual cycle of twelve consecutive points of mean monthly coordinates ($\bar{T}_m$, $\bar{R}_m$), where m=1,…,12, beginning from January to December (Mishra, 2017; Thornthwaite, 1948) For each chosen district, three loops for P1, P2 and P3 were created to understand and visualise the changes of the moisture–temperature regime through time.

4. Results.

4.1 Spatial and Temporal Pattern of Annual Rainfall, T_{max} and T_{min}

Mean annual rainfall variation across the thirty districts of Odisha shows a geographically consistent pattern over the study period (**Fig.2.a-c**). In all three 15-year period phases, the lowest rainfall class, between 1,200 and 1,300 mm, appears to be confined to a group of districts in the western and north-western interior region. In contrast, the highest rainfall class, close to 1,700 mm, consistently occurs in a district on the north-eastern coastal margin. Such geographic variation aligns with the orographic effects of the Eastern Ghats and the moderating

influence of the Bay of Bengal, and its persistent presence for 45 years indicates that the west-east rainfall gradient is an enduring element of Odisha's climatic regime rather than a transient or phase-specific phenomenon.

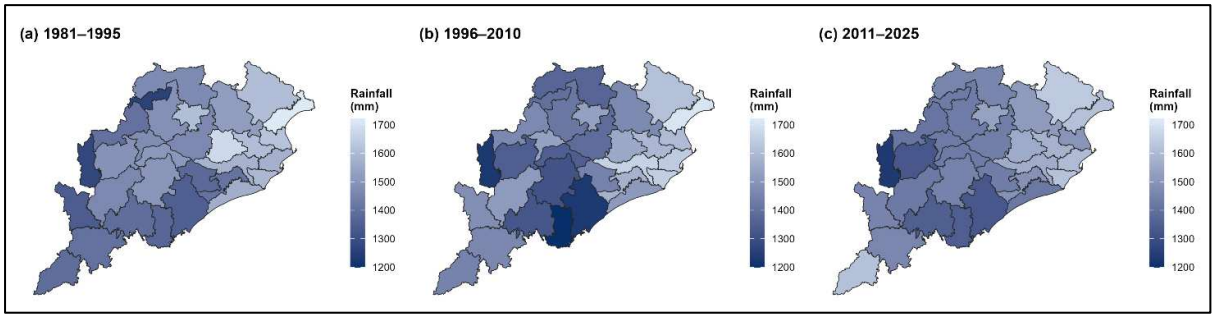


Fig.2. District-wise mean annual rainfall (mm) across Odisha for (a) P1 (1981–1995), (b) P2 (1996–2010), and (c) P3 (2011–2025.

While such structural stability exists, there is also a shift among the intermediate rainfall classes across phases. In P2 (1996-2010), more northern districts belong to the lower rainfall classes than in P1 (1981-1995), whereas in P3 (2011-2025) the mid-range rainfall classes become dominant in northern and central regions.

The T_{max} shows a spatially concentrated warm core located over the north-central and western interior districts for all three periods (**Fig.3.a-c**). This warm core region corresponds to the Sundargarh-Jharsuguda-Sambalpur regional belt and its vicinity, where high interior continentality, coupled with a lesser influence of the maritime effect, leads to high pre-monsoon and summer temperatures. There is a notable enhancement in the extent and intensity of the warm core from P1 to P3: the region occupied by the highest T_{max} category is much larger in 2011-2025 than in 1981-1995, implying an increased spatial intensity of the thermal environment over the 45-year study period.

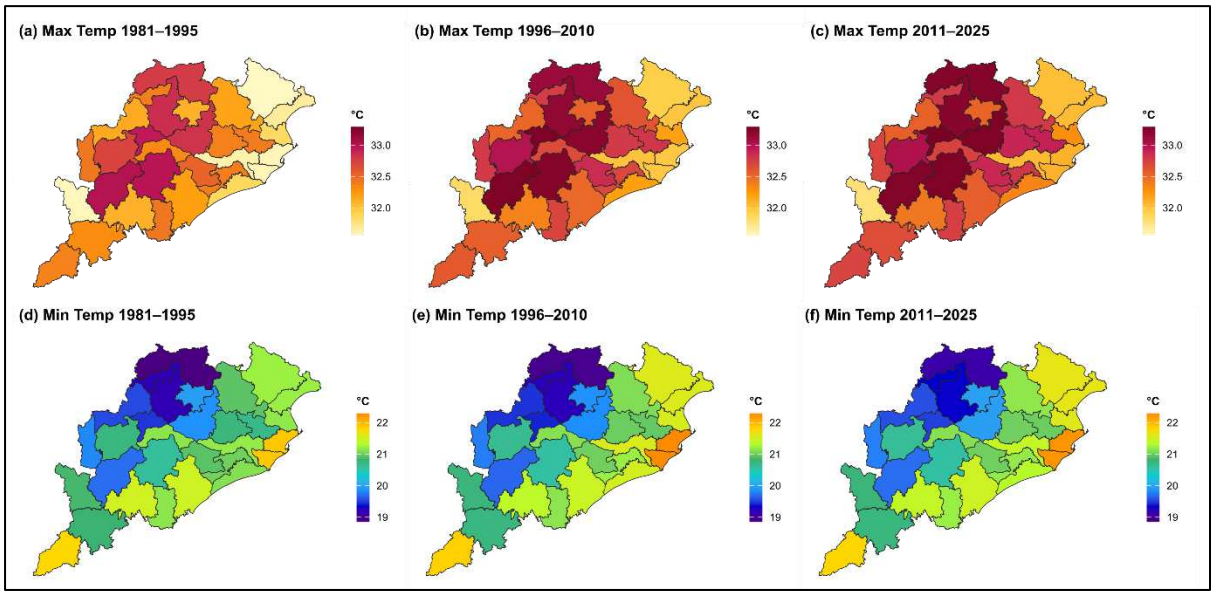


Fig. 3. District-wise mean maximum temperature (Tmax, °C) for (a) P1, (b) P2, and (c) P3; and mean minimum temperature (Tmin,°C) for (d) P1, (e) P2, and (f) P3.

The spatial pattern of Tmin is very different from that of Tmax and is relatively stable (**Fig. 3.d-f**). Low Tmin values are always present in the same north-western interior cluster as those of Tmax. In contrast, high Tmin values are found in coastal and northeast districts such as Mayurbhanj, Balasore & Bhadrak due to the thermal effect of the Bay of Bengal. Unlike Tmax, there is relatively weak variation in the extent or intensity of the Tmin spatial distribution from P1 to P3, implying a relatively homogeneous spatial behaviour of the Tmin trend over time.

4.2 Spatio-temporal Variability of Precipitation, Tmax and Tmin

Fig. 4 represents the standard deviation (SD) and coefficient of variation (CV) of the rainfall distribution. In the period P1, the high rainfall CVs (close to 300–350%) are located in a cluster of districts in the west-central belt, while the low rainfall CVs (less than 250%) are found in the far north-eastern region of Odisha. In period P2, it changes, with the high rainfall CV cluster moving southwards and eastwards and expanding into the adjoining districts, and again in period P3, when the district with the highest CV moves to the south-western interior. Therefore, rainfall unpredictability, rather than its volume, operates as a mobile property of the region's climatic system rather than a stationary property of the driest districts.

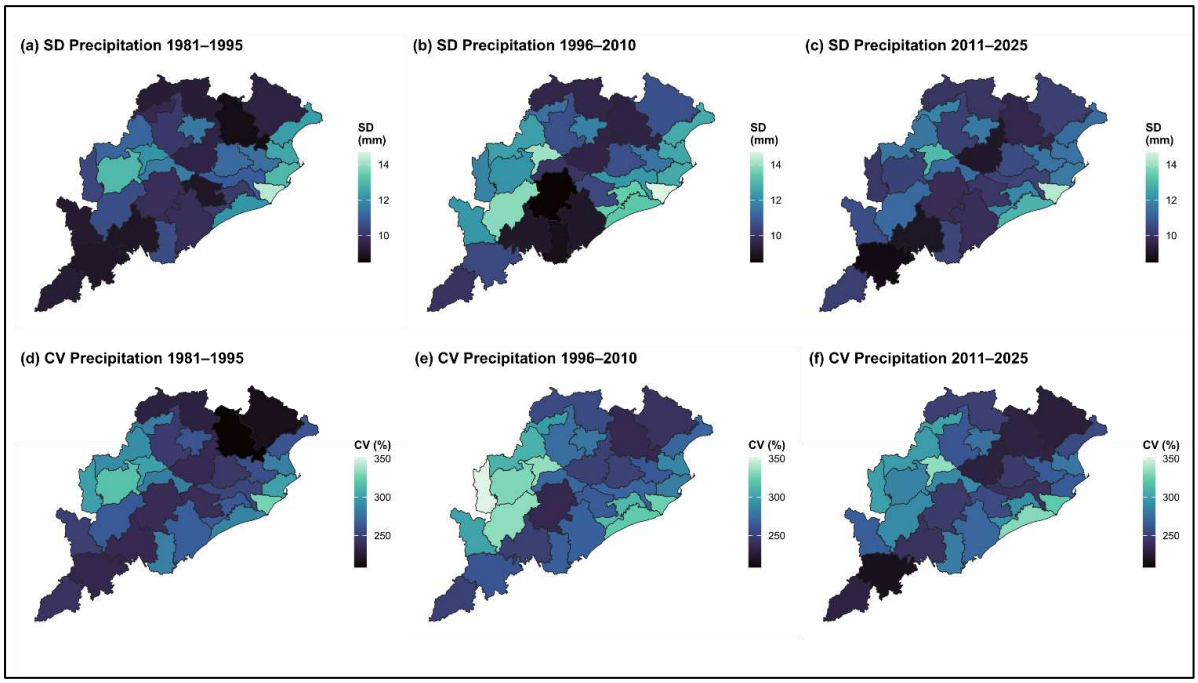


Fig. 4. District-wise standard deviation (mm; a–c) and coefficient of variation (%; d–f) of annual rainfall for P1, P2 and P3, respectively

The variability of Tmax and Tmin follows a substantially more stable spatial distribution than that of rainfall (**Fig. 5 & 6**). In every period considered, the highest SD and CV of Tmax (SD of approximately 4.5–5.0°C; CV of approximately 13–15%) and Tmin (SD of approximately 5.0–5.5°C; CV of approximately 25–29%) are recorded in a cluster of northern and north-western interior districts, while the low values – in the districts of the south and south-western parts of the region. The consistency of this pattern across all periods indicates the structural nature of this temperature-variability hotspot in the western interior.

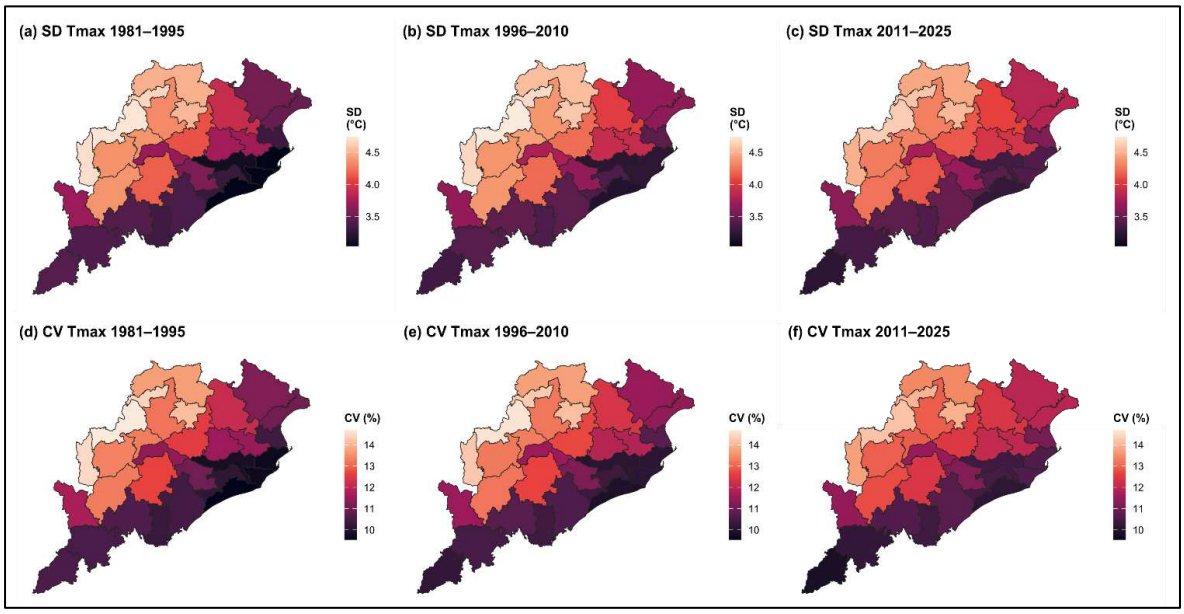


Fig.5.District-wise standard deviation (°C; a–c) and coefficient of variation (%; d–f) of maximum temperature (T_{max}) for P1, P2 and P3, respectively.

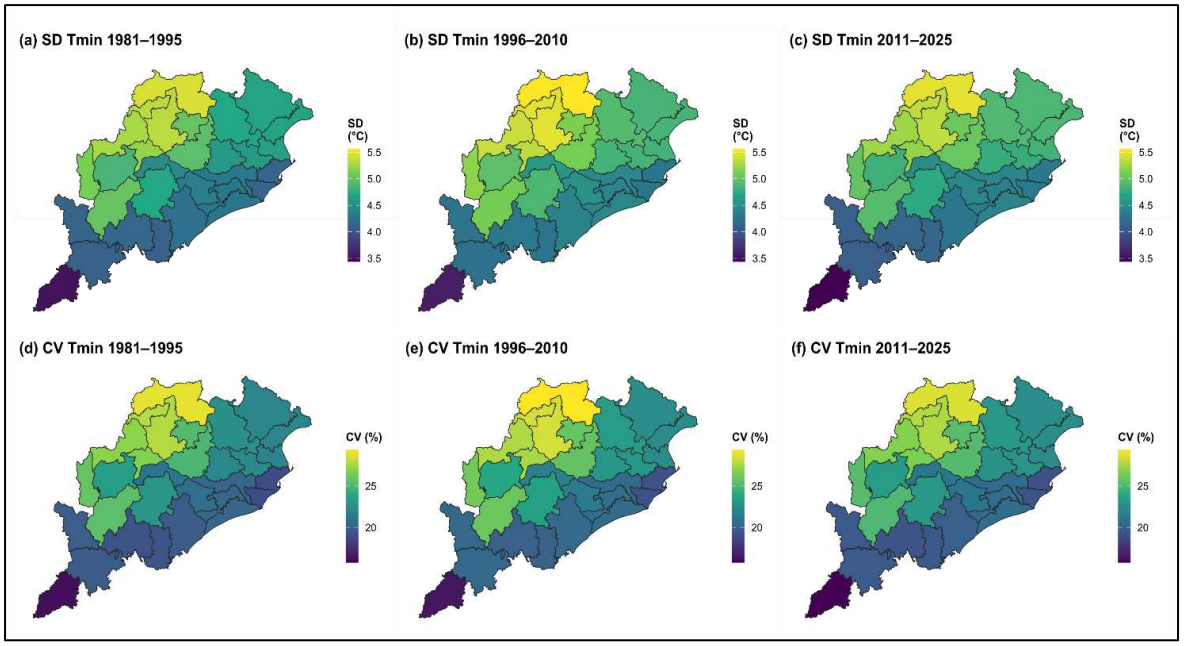


Fig.6.District-wise standard deviation (°C; a–c) and coefficient of variation (%; d–f) of minimum temperature (*Tmin*) for P1, P2 and P3, respectively.

The persistent warming signal identified here is broadly consistent with evidence of increasing temperature extremes across India, including pronounced changes during the pre-monsoon season (Kothawale et al., 2010; Panda et al., 2014; Wagholikar et al., 2014)

4.3. Extreme Events in Odisha

4.3.1 Consecutive Dry Days, Consecutive Wet Days, and Heavy Rainfall Days

Fig. 7 highlights spatiotemporal variations in CDD, CWD, and HRD across the three periods. Western and interior Odisha record the highest CDD values (250–270 days), with the 260–270-day category occurring across more districts in P3 than in P1.

CWD shows the opposite spatial pattern: eastern and coastal Odisha experience the longest wet spells (30–35 days), whereas western Odisha records shorter spells (10–20 days). The reduction in maximum CWD in western Odisha from P1 to P3 indicates a shift toward more intermittent rainfall separated by longer dry spells.

HRD remains low across most districts (generally 1–3 days year^{-1}), with intermittent increases in P2 in some coastal and north-eastern districts and higher values in P3 in several western districts, including Kalahandi, Bolangir, and Baragarh.

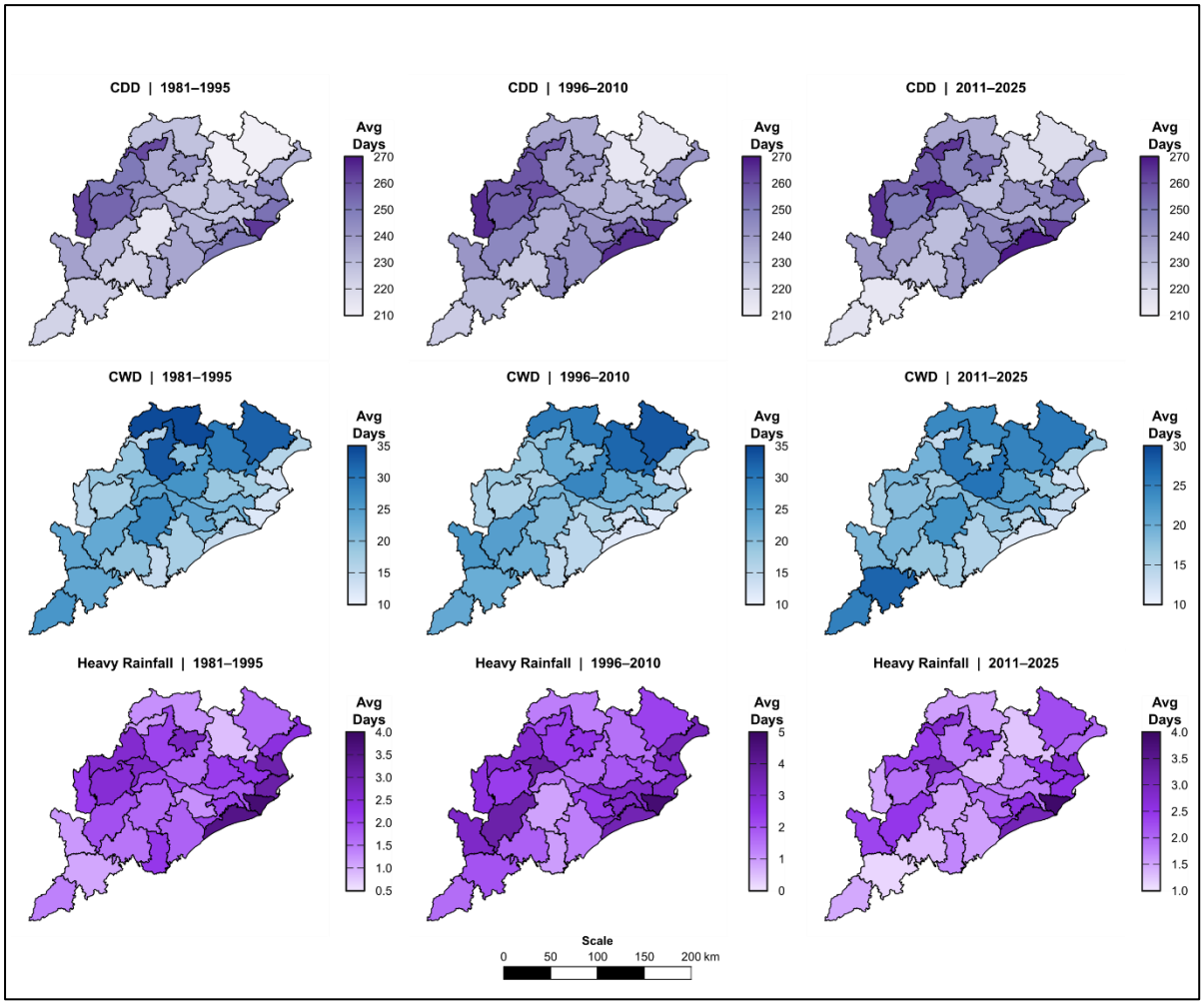


Fig.7 15-year-period spatial distribution of precipitation extreme indices across Odisha districts for three periods — P1 (1981–1995), P2 (1996–2010), and P3 (2011–2025) — showing **(a)** mean Consecutive Dry Days (CDD, days), **(b)** mean Consecutive Wet Days (CWD, days), and **(c)** mean Heavy Rainfall Days (HRD, days per year). Darker shading in panel **(a)** indicates longer dry spells.

4.3.2. Spatio-temporal distribution of Standardised Precipitation Index (SPI-1)

The spatial distribution of one-month SPI-1 reveals a period-based, rather than homogeneous, pattern across Odisha's 30 districts (Fig. 8a–c). During Period 1 (1981–1995), most districts exhibit a slightly positive mean SPI-1, with a maximum positive anomaly occurring in a west-central district in the Bolangir–Subarnapur region, while negative SPI-1 values are confined to a few districts in the Ganjam–Gajapati region. The spatial pattern is largely reversed during Period 2 (1996–2010), where a majority of districts show a negative mean SPI-1, which is

highly pronounced in a northern group of districts in Sundargarh and Jharsuguda, and also in a few districts in the Boudh–Kandhamal region, while the coastal districts of Kendrapara and Bhadrak continue to have a near-neutral value. However, during Period 3 (2011–2025), there is a partial return toward positive anomalies in western and central districts, dominated by Malkangiri in the south-west, with a solitary district in the north-east, the Balasore–Bhadrak region, exhibiting a highly negative SPI-1 value. This implies that the spatial distribution of the moisture deficit changes over time, from the southern parts during Period 1 to the northern interior during Period 2, and finally to the north-eastern coastal areas during Period 3.

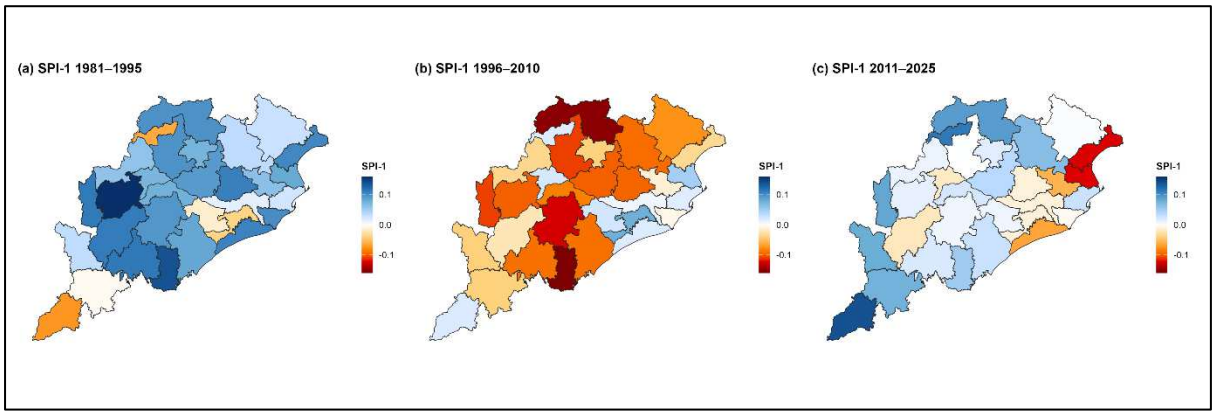


Fig. 8. District-wise mean one-month Standardised Precipitation Index (SPI-1) for (a) P1 (1981–1995), (b) P2 (1996–2010), and (c) P3 (2011–2025).

4.3.3 Extreme Temperature Indices: Warm Nights & Heat Wave Days

The spatial distribution of warm night days (**Fig. 9)** shows the shifting of Warm Night Day intensity across Odisha over different periods, despite the phenomenon's increasing magnitude. The maximum Warm Night Day intensity (12-13 days/year) in P1 (1981-1995) is found in two areas: the north-central (Sundargarh, Jharsuguda, Sambalpur, Deogarh) and south-west districts (Koraput, Malkangiri, Nabarangpur, Rayagada), while the east coast region is characterised by the lowest intensity (8-9 days/year). For P2 (1996-2010), the intensity ranges from 8-16 days/year, and the highest intensity is in the northeast region (Mayurbhanj, Kendujhar, Balasore, Bhadrak), while the previous hotspots in the west and south-west regions are now mid-range intensity locations. In P3 (2011-2025), the intensity range narrows to 7-15 days/year, and the maximum intensity is highly concentrated in Mayurbhanj, while the west-southern & central districts, including Kandhamal-Boudh, experience the lowest intensity.

Heat Wave Days (**Fig.10**) depict relatively more consistent spatial distribution across all the three periods as well, with the same northwest cluster — consisting of Bargarh, Jharsuguda, Sambalpur, Sundargarh, Deogarh, Sonepur, Bolangir, Nuapada and Kalahandi – recording the maximum number of HWDs, while the central cluster – consisting of Angul, Dhenkanal and Boudh – depicts an intermediate value while the coastal district cluster including Ganjam, Gajapati, Rayagada, Koraput and coastal regions consistently depicts the minimum value. While Warm Nights depict a peak magnitude at the P2 period only, HWDs depict peak magnitude during the P2 period as well and then decline slightly in the P3 period.

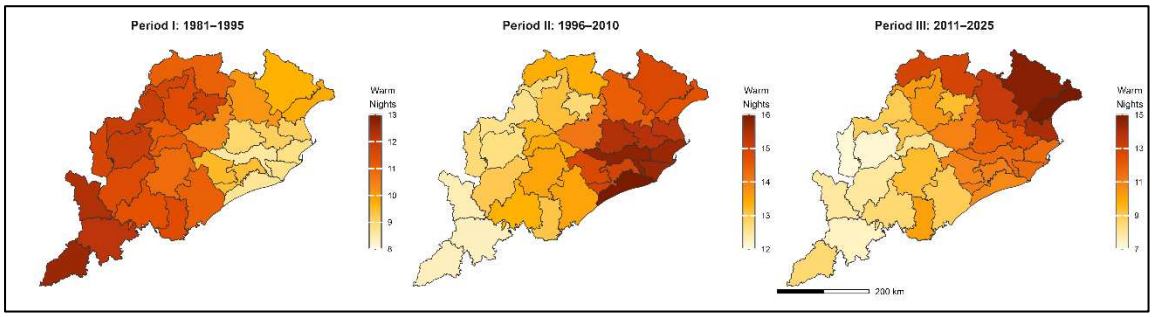


Fig.9. 15-year-period spatial distribution of mean annual Warm Night Days across Odisha districts for P1 (1981–1995), P2 (1996–2010), and P3 (2011–2025).

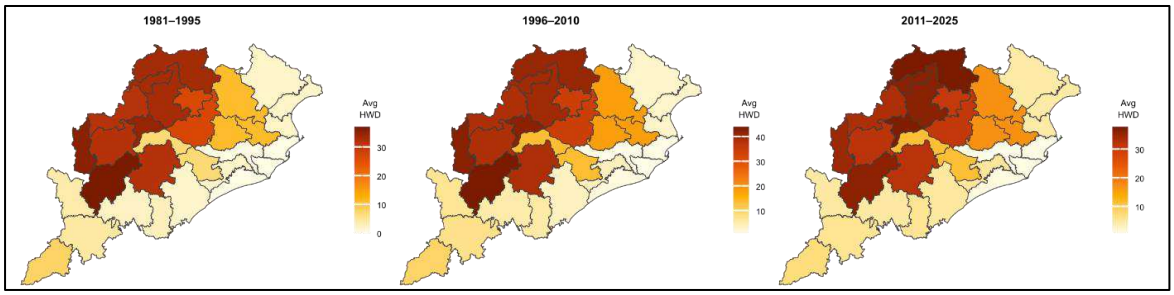


Fig.10 Spatial distribution of Annual Heat Wave Days (HWD) extreme indices across Odisha districts for P1 (1981–1995), P2 (1996–2010), and P3 (2011–2025),

4.4 Period-Specific Trends: Mann–Kendall Test and Sen's Slope Estimator

The analysis of the Mann-Kendall (MK) test and Sen's slope test on rainfall, shown in Fig. 11, shows a consistent pattern of a reduction in the spatial coverage of trends with statistical significance across the three periods (Fig. **11 (a-c)**).

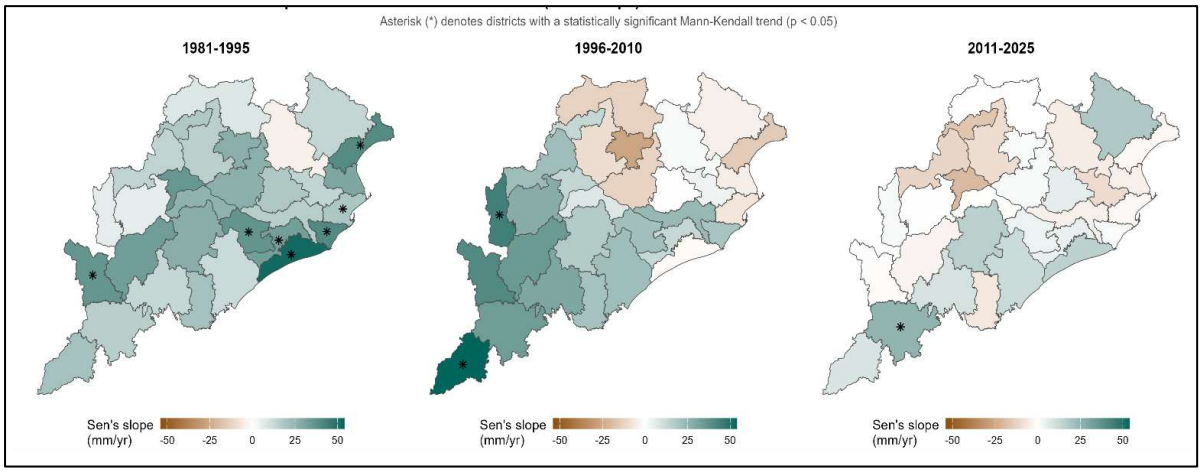


Fig.11. District-wise rainfall trends were estimated using Sen's slope (mm year^{-1}). Positive values indicate increasing annual rainfall, whereas negative values indicate decreasing annual rainfall. The colour gradient represents the magnitude and direction of the trend, with brown shades indicating negative trends and green shades indicating positive trends. Asterisks (*) denote districts exhibiting statistically significant Mann–Kendall trends at $p < 0.05$.

During Period 1 (1981-1995), seven districts show a statistically significant positive trend ($p<0.05$), including Balasore (Baleshwar), Jagatsinghpur, Kendrapara, Khordha, Nabarangpur, Nayagarh, and Puri. Among them, Sen's slope values in these districts range from 18.99 mm year^{-1} (Kendrapara) to 52.37 mm year^{-1} (Puri). In contrast, Kendall's τ varies from 0.39 to 0.50, which demonstrates a moderate to strong positive monotonic relationship in all cases. Puri shows the maximum Sen's slope value (52.37 mm year^{-1}) and one of the maximum values of τ (0.4667) among all districts in all periods, whereas Nayagarh has the maximum τ (0.5048) with the Sen's slope value of 36.46 mm year^{-1}. The remaining 23 districts in Period 1 show a non-significant trend ($p\geq0.05$), as their S-statistics and Z-values are less than the critical value of ±1.96.

During Period 2 (1996-2010), only two districts show a statistically significant positive trend ($p\leq0.05$), including Malkangiri (Sen's slope = 53.91 mm year^{-1}, τ = 0.4857, p=0.0133) and Nuaparha (Sen's slope = 43.99 mm year^{-1}, τ = 0.4286, p=0.0294). Malkangiri has the highest Sen's slope value in the entire dataset. Several districts show almost statistically significant positive trends during Period 2 ($0.05>p\geq0.01$) such as Nabarangapur (p=0.0748, Sen's slope = 40.27 mm year^{-1}) and Rayagarha (p=0.0748, Sen's slope = 29.94 mm year^{-1}). This indicates the weakening of an underlying positive signal rather than its complete disappearance. The remaining 28 districts are not significant in this period.

By Period 3 (2011–2025), only a single district, Koraput, retains a statistically significant positive trend (Sen's slope = 25.27 mm year^{-1}, τ = 0.4476, p = 0.0228), while the remaining

twenty-nine districts exhibit a non-significant trend, with several districts, including Sambalpur, Jharsuguda, Subarnapur, Baragarh and Sundargarh, showing a negative, though statistically non-significant, Sen's slope during this period.

Across all three periods, the relationship between Kendall's τ and Sen's slope (**Fig. 12**) confirms the expected monotonic association between the two statistics: significant districts consistently occupy the upper portion of the Sen's slope distribution, generally at or above 19 mm year^{-1}, showing that statistical significance is concentrated among observations with stronger positive trend magnitudes. A notable feature of the dataset is the complete absence of a statistically significant negative trend in annual rainfall in any district in any of the three periods; all districts classified as "decreasing" in trend direction fail to reach statistical significance (p ranging from 0.3223 to 1.000), and the corresponding Z-statistics remain within the non-rejection region of the test. This indicates that while the number of districts exhibiting a statistically confirmed wetting trend has declined markedly, from seven districts in 1981–1995 to a single district in 2011–2025, this contraction has not been accompanied by the emergence of a statistically confirmed drying trend anywhere in the state; rather, the majority of districts in the most recent period show a Sen's slope close to zero with wide statistical uncertainty.

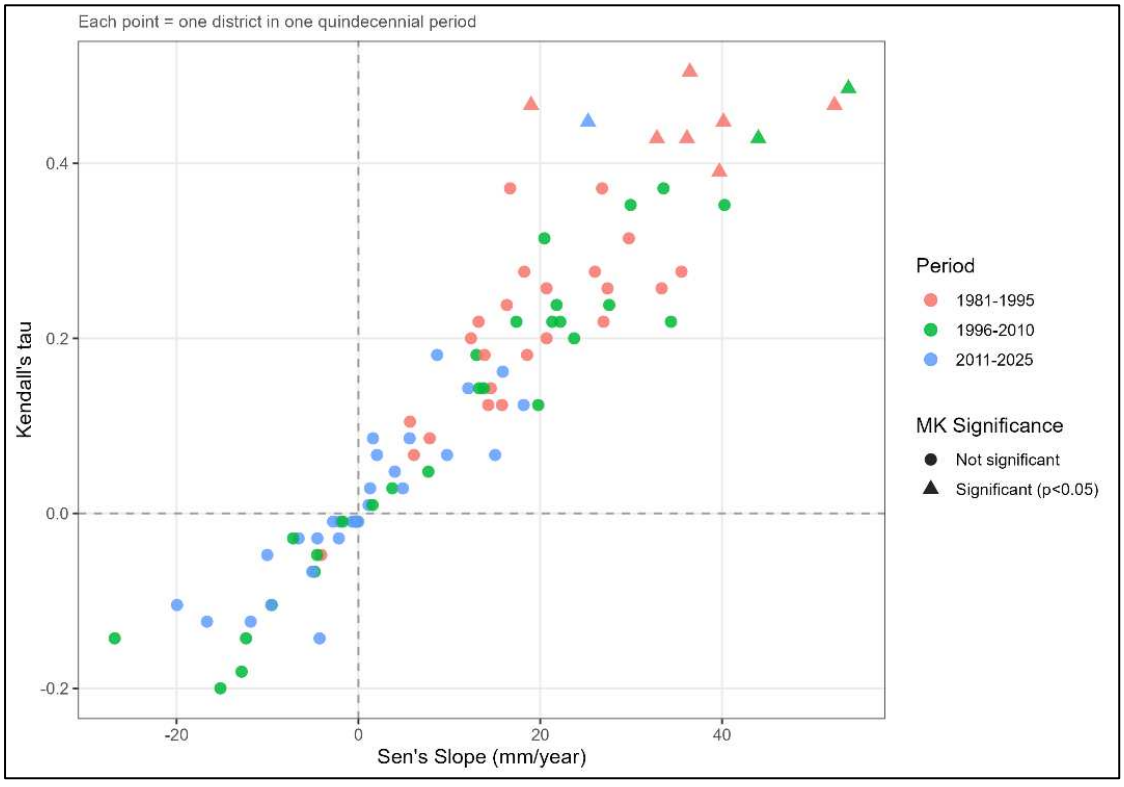


Fig.12. District-wise rainfall trends across Odisha for the three 15-year periods: P1 (1981–1995), P2 (1996–2010), and P3 (2011–2025). Each point represents a district–period observation. The x-axis shows Sen's slope (mm year^{-1}) and the y-axis shows Kendall's tau (τ). Colours represent the three periods; circles indicate non-significant trends ($p \geq 0.05$) and triangles significant trends ($p < 0.05$). Dashed lines indicate zero Sen's slope and Kendall's tau.

The geographic distribution of significant trends also shifts across periods. In Period 1, significant districts are concentrated along the eastern coastal belt (Balasore, Kendrapara, Jagatsinghpur, Puri, Khordha), together with two districts in the southern and south-western interior (Nabarangpur, Nayagarh), suggesting that the early positive rainfall signal was strongest in the coastal and southern sectors of the state. In Period 2, the locus of significance shifts to the far south (Malkangiri) and the western interior (Nuaparha), spatially overlapping with the districts identified in Section 4.4.2 as exhibiting the least negative SPI-1 departure during this generally drier period. In Period 3, the sole significant district, Koraput, lies in the southern interior, adjoining Malkangiri and Nabarangapur, suggesting the possible persistence of a locally positive rainfall regime in this southern corridor, even as significance elsewhere in the state has disappeared.

4.5 Integrated Climatic Behaviour based on Hythergraph

The hythergraph analysis was performed for all the 30 districts of Odisha to identify any variation in the hydrothermal regime of the area for all three periods (Fig. S1). The five districts that show pronounced change in temperature and precipitation relationship were selected for detailed presentation, include five districts named Boudh, Jharsuguda, Sundargarh, Koraput, and Malkangiri. There are noticeable variations in the coupling and seasonal distribution of the hydrothermal regime during the period 1981–2025. In all districts, the climate is hot-dry (March-May), warm-wet (June–September), and cooler and increasingly dry (October-December). The most prominent feature is the significant variation in temperature and precipitation during the pre-monsoon season (April-May), when temperatures are at their annual peak and rainfall is comparatively low. This combination suggests a higher risk of moisture stress in the atmosphere and higher evaporation demand during the warmest period of the year.

The three periods highlight that the fundamental seasonal pattern has not changed, but the amount and inter-seasonal distribution of rainfall have changed in relation to the thermal regime. The magnitude of the July-August rainfall peak shows significant differences between the periods in Boudh, Jharsuguda, and Sundargarh. The inter-month variability in rainfall distribution in July, August, and September is significant in Koraput and Malkangiri as well. Therefore, the recent climate variability does not appear to be a consistent tendency in the precipitation signature toward either wetter or drier conditions, but rather a shift in the precipitation signature within the monsoon season. This is similar to the recent trend indicating

an increase in rainfall variability across Odisha and differences in rainfall frequency and intensity (Behera et al., 2025; Mohanty et al., 2026).

Importantly, the later period (2011–2025) is not necessarily the wetter period; in some districts, precipitation is more concentrated, while the pre-monsoon temperature remains high. This altered hydrothermal regime, along with the observed warming over interior parts of Odisha, indicates an increase in climatic variability and a moisture imbalance, which may lead to increased drought stress, reduced water availability, and greater vulnerability of the agriculture sector (Kar & Sahu, 2026).

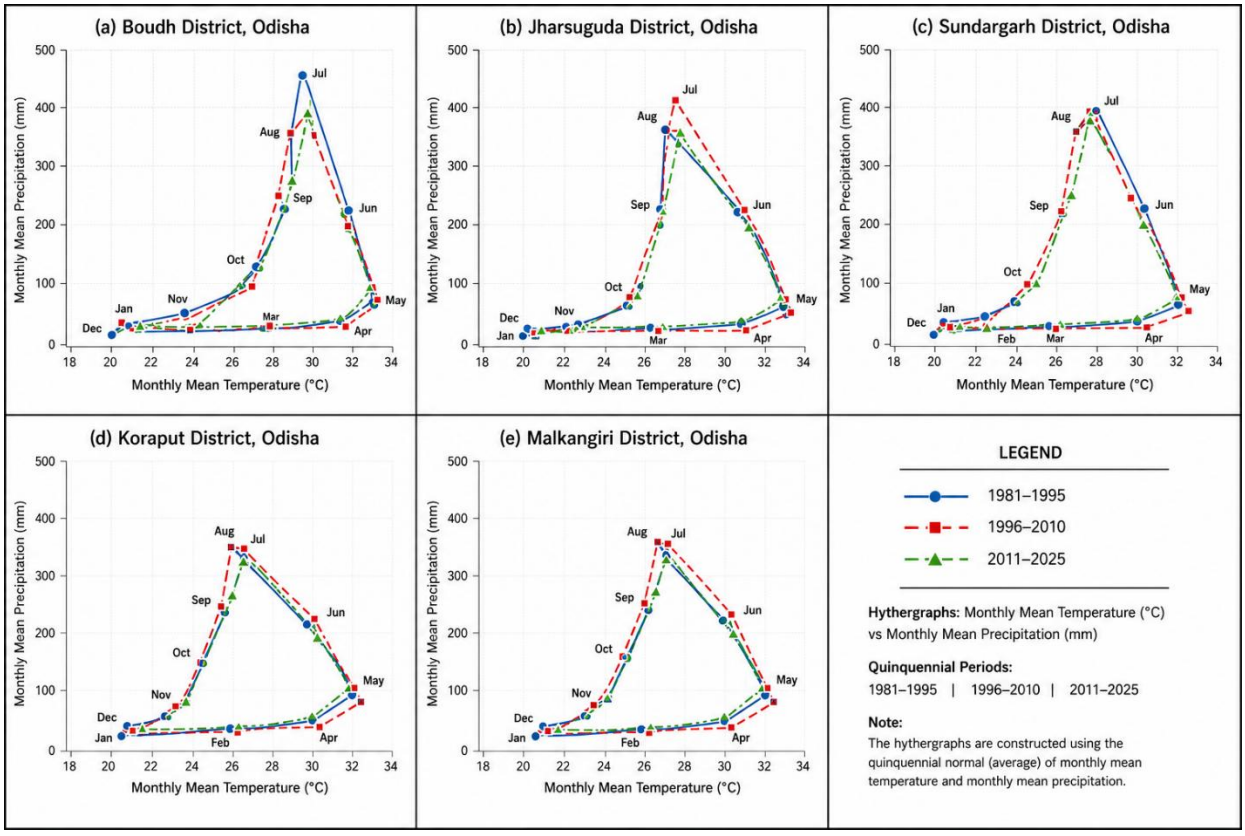


Fig. 13. Hythergraphs showing the relationship between monthly mean temperature and precipitation for Boudh, Jharsuguda, Sundargarh, Koraput, and Malkangiri districts of Odisha across three 15-year periods: 1981–1995, 1996–2010, and 2011–2025. Each curve represents the monthly hydrothermal regime for the respective period.

5. Discussion

The climatology of Odisha for the period 1981-2025 shows a clear warming signal**,** along with an increasingly scattered spatial-temporal distribution of rainfall. The evidence presented indicates that changes in temperature regimes show an evolutionary trend in which the formation of the warm interior became increasingly evident and common in Period 3 compared to Period 1. In contrast, minimum temperatures retained a relatively stable spatial structure,

while warm-night occurrence increased in recent periods. The trends in rainfall data are inconsistent: despite no change in the long-term gradient of mean precipitation over the last four decades, the number of districts with statistically significant positive trends decreased from seven to two and, finally, to one.

In contrast, the moisture characteristics (SPI-1) shifted from the Ganjam-Gajapati to the Sundargarh-Jharsuguda region and, eventually, to the coast of Balasore-Bhadrak district. These findings indicate an asymmetric evolution of two climate parameters, with one becoming increasingly coherent and the other showing spatial variability. This imbalance is reflective of statistically significant trend in temperature variables, and weak, statistically insignificant trend in precipitation variables as found by Vijayakumar et al., (2021) in coastal districts of Odissa.

Unlike any uniform warming trend, the warming signals in Odisha are spatially clustered along a belt extending across the western interior regions of the state. The warm core formed by T_{max} in the districts of Sundargarh, Jharsuguda, Sambalpur and its adjoining regions like Anugul, Bolangir remains intact across all three periods while expanding in terms of spatial extent and magnitude from P1 to P3. Furthermore, the observed spatial heterogeneity in Tmax is supported by the findings from the latest district-level study on Odisha, which identified significant regional variations in the trend of Tmax in the state (Sree et al., 2026). However, the Warm Night Days do not follow this pattern, although 4-5 days above the 90th percentile were restricted only to a certain number of districts lying in P1; the highest category in P3 changes its position and sharpens in Mayurbhanj, indicating that the peak WND has shifted from the central-north and south-western areas in P1 to the north-eastern areas (Mayurbhanj, Kendujhar, Balasore, Bhadrak) in P2-P3. This implies that whereas the T_{max} warm core stays fixed in the western regions, the minimum temperature extreme is mobile. (Pai et al., 2013; Rohini et al., 2016) Consistent occurrence of Sundargarh, Jharsuguda and Sambalpur across four different thermal indicators, including mean T_{max}, T_{max} variability, warm nights and heat wave frequency, suggests a structural attribute of the region's climatic conditions, which is in accordance with the asymmetric warming documented for the Indian subcontinent by Alexander et al. 2006) as well as recent assessments by IPCC (2023).

In contrast to temperature, rainfall variation in Odisha seems to occur predominantly through spatial variability, spell structure, and intensity rather than an overall shift in annual totals. Despite the lack of change in the mean annual rainfall gradient across periods P1-P3, the pattern revealed by the extreme events indices is quite different: Firstly, the number of CDD increases

both spatially and temporally in the western and interior tract – the region centered on Sundargarh, Jharsuguda, Sambalpur, Baragarh and Subarnapur that is repeatedly identified in this study as the thermally and hydrologically stressed part of the state – with 260-270 day category becoming more frequent here in P3 compared to P1. Secondly, CWD decreases in the western tract, while the eastern coastal tract sustains longer wet spells. Thirdly, HRD remains spatially widespread but low in frequency, with higher values occurring in several western districts in P3. This phenomenon is in line with the findings of a similar station and gridded data analysis of Odisha, where a similar trend of increase in heavy-to-extreme rainfall and dry days, while light-to-moderate rainfall and wet days are decreasing, was observed, especially in urban and Eastern Ghats districts like Khordha (Nageswararao et al., 2019). All these indices, therefore, describe a rainfall pattern characterised by similar or even constant seasonal totals, interspersed with long dry spells and short but intense rainfall episodes; the latter redistribution is invisible on an annual total basis but is important for the soil moisture regime and irrigation scheduling in the western interior districts of Odisha(Kumar et al., 2021).

The observational decline in the number of districts showing a statistically significant positive rainfall trend is from seven (Balasore, Kendraparha, Jagatsinghpur, Puri, Khordha, Nabarangapur and Nayagarh) in Period 1, to two (Malkangiri and Nuaparha) in Period 2, to one (Koraput) in Period 3, which should not be interpreted as evidence of a drying trend**.** This variation in the position of significant rainfall zones corresponds to the observed spatial heterogeneity in previous rainfall studies carried out for the whole state of Odisha (Behera et al., 2025; Prabhakar et al., 2019). A notable observation is that no district in any of the periods exhibits a statistically significant negative Sen's slope; the districts that exhibit negative trends, such as Sambalpur, Jharsuguda, Subarnapur, Baragarh, and Sundargarh in Period 3, exhibit p-values between 0.32 and 1.00. Thus, the decline observed is not due to a reduction in rainfall quantity but to a loss of spatial consistency in the previously positive rainfall trend. This shifting pattern is therefore better interpreted as spatial rainfall variability rather than a reversal from wet to dry. (Guhathakurta & Rajeevan, 2008)

Together, temperature and rainfall indicate a transformation in Odisha's hydrothermal regime, most clearly reflected in changes in the intensity of monsoon rainfall. Among the thirty districts assessed, the strongest signal of such a change is in Boudh, Jharsuguda, Sundargarh, Malkangiri and Koraput districts, where the rainfall peak shows a marked shift/compression during July-August in Period 3 (2011-2025) as compared to other periods, most markedly in Boudh, where peak rainfall changes from approximately 440mm to 300mm across the entire

period. Notably, Jharsuguda and Sundargarh exhibit their maximum monsoon peak in Period 2 (1996-2010), as opposed to Period 3, thus indicating that monsoon intensity changes are not always progressive in nature. These kinds of temporal variabilities in monsoon rainfall features are similar to what has been observed recently in rainfall trend and change point studies over Odisha(Behera et al., 2025). Thus, the hydrothermal reorganization identified here is primarily a regional monsoon-season signal rather than a state-wide shift**.** Taken together, the findings indicate redistribution of hydroclimatic stresses rather than uniform intensification. Thermal-stress reduction should be prioritised in the Sundargarh–Jharsuguda–Sambalpur belt, drought and soil-moisture management in western districts with longer dry spells, and flexible water management in coastal districts where moisture deficits recur. Such district-level differentiation is more informative for climate-sensitive agriculture and disaster-risk reduction than reliance on state-wide averages (Singh & Rath, 2024).

6. Limitations

The present study is based on the daily records maintained by the India Meteorological Department, and possible discontinuity or inhomogeneity during the earliest sub-period, 1981–1995, may affect the validity of the 15-year period analysis, especially in the less-densely observed interior districts (Srivastava et al., 2009). The Mann-Kendall and Sen's slope trends for T_{max} and T_{min} at the district level are still being processed and are therefore not reported quantitatively in this paper; the spatial distribution presented for these parameters must therefore be viewed as descriptive only. Numerical state-wide trends for the ETCCDI precipitation and temperature extremes are not reported in this paper. The SPI-1 index only takes into account the precipitation component of moisture stress without taking potential evaporation into account, an omission that is likely to matter in the case of the high T_{max} interior districts identified in the present study (Pattanaik et al., 2017) . Hythergraph shift is described descriptively and does not, in itself, constitute reclassification of the climate type.

7. Conclusion

Forty-five years of district-level observations show that Odisha is not experiencing uniform warming and drying; instead, warming and rainfall variability exhibit contrasting spatial structures. The Sundargarh–Jharsuguda–Sambalpur belt emerges as a persistent thermal hotspot, characterised by high Tmax, temperature variability, warm nights, and heat-wave occurrence, whereas rainfall retains its broad west–east gradient but changes in wet/dry spell structure and the location of moisture anomalies. The results therefore point to a geographically

persistent thermal signal alongside a spatially mobile hydrological signal. This heterogeneity means that state-level averages can obscure locally concentrated hydroclimatic stresses. Adaptation should consequently differentiate heat stress in the northwestern interior, drought and soil-moisture management where dry spells lengthen despite stable annual rainfall, and water management in coastal districts experiencing recurring moisture deficits.

Conflict of Interest

The authors declare that they have no conflict of interest.

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Author Contributions

SS: Conceptualization, Formal analysis, Writing—original draft, Writing—review and editing.

SP: Conceptualization, Methodology, Writing—original draft, Writing—review and editing, Supervision

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