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District Scale Escalation of Heatwave Extremes in Rajasthan, India: Spatial Patterns, Temporal Acceleration, and Climate Risk Implications

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ABSTRACT

Extreme heat events have emerged as one of the most critical climate related hazards in South Asia, with arid and semi arid regions exhibiting particularly rapid intensification. Rajasthan, India's largest state by area, is highly vulnerable due to its climatic diversity, water scarcity, and socio economic sensitivity. This study presents a district level assessment of heatwave dynamics across six representative districts of Rajasthan—Bikaner, Jodhpur, Jaipur, Kota, Hanumangarh, and Udaipur—covering the period 2015–2024. Using meteorological heatwave criteria and comparative statistical visualization techniques, the study examines spatial variability, temporal evolution, and emerging climatic signals associated with extreme heat. Results reveal pronounced spatial heterogeneity, with western arid districts consistently recording the highest heatwave frequency, while southern hill regions exhibit relatively lower exposure. Temporal trend analysis demonstrates a statistically consistent escalation in heatwave days across all districts, particularly after 2020, indicating a systemic climatic shift rather than episodic variability. The convergence of rising heatwave trends across diverse climatic zones suggests large scale atmospheric forcing combined with land–surface feedback mechanisms. The extended discussion integrates climatic drivers, environmental stress, agricultural vulnerability, water resource depletion, and public health implications, highlighting heatwaves as a multidimensional risk. The findings align with global and regional climate change projections and emphasize the importance of district scale assessments for accurate vulnerability mapping. The study contributes empirical evidence relevant to climate adaptation planning, heat health action strategies, and regional sustainability frameworks in arid and semi arid environments.

KEYWORDS: Climate change, Heatwaves, Rajasthan, temperature, arid western desert, semi arid agricultural plains, urban semi arid region, southeastern plateau, and southern hill region.e

INTRODUCTION

Rising global temperatures have intensified the frequency, duration, and severity of heatwaves worldwide, making extreme heat one of the most direct and deadly manifestations of climate change (Perkins & Alexander, 2013; IPCC, 2021). Heatwaves exert far-reaching impacts on human health, ecosystems, agriculture, water resources, and economic productivity, particularly in developing regions with high climate sensitivity and adaptive constraints. South Asia has emerged as a global hotspot for extreme heat, with recent decades witnessing unprecedented temperature extremes and heat-related mortality (Mazdiyasni et al., 2017). India, due to its vast geographical diversity and dense population, faces disproportionate risks from rising heat extremes. Within India, Rajasthan represents a unique climatic laboratory, encompassing hyper-arid desert regions, semi-arid plains, urbanizing centers, and forested hill systems. Despite this heterogeneity, most existing studies assess heatwaves at national or state scales, potentially obscuring localized vulnerability patterns critical for targeted adaptation planning (Pai et al., 2017). District-level analyses are essential because heatwave impacts are mediated by local land cover, topography, urbanization, and socio-economic conditions. For instance, arid desert districts experience strong land–atmosphere feedbacks that amplify surface heating, while urban districts face compounded stress due to the urban heat island effect (Rohini et al., 2016). Moreover, climate change is altering not only the intensity of heatwaves but also their spatial footprint, exposing historically moderate regions to increasing thermal stress.

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The present study addresses this research gap by conducting a district-scale spatio-temporal analysis of heatwave dynamics across six climatically representative districts of Rajasthan. By integrating comparative bar diagrams and trend analysis, the study aims to (i) quantify spatial variability in heatwave occurrence, (ii) identify temporal escalation patterns, and (iii) discuss environmental, agricultural, and socio-economic implications within a climate change framework.

RESEARCH METHODOLOGY

2.1 Study Area

The selected districts represent Rajasthan's major climatic zones: arid western desert (Bikaner, Jodhpur), semi-arid agricultural plains (Hanumangarh), urban semi-arid region (Jaipur), southeastern plateau (Kota), and southern hill region (Udaipur). This selection enables comparative assessment across contrasting physiographic and climatic conditions.

2.2 Data Sources

Daily maximum temperature data for 2015–2024 were obtained from officially published meteorological datasets consistent with India Meteorological Department (IMD) standards. Heatwave days were identified using IMD-defined thresholds based on absolute temperature and deviation from normal conditions (Pai et al., 2017).

2.3 Heatwave Identification

A heatwave day was defined when maximum temperature exceeded region-specific thresholds or showed anomalous deviation from climatological normals. This approach ensures methodological consistency and comparability with national heatwave assessments.

2.4 Analytical Techniques

District-wise annual heatwave counts were computed and visualized using comparative bar diagrams and temporal trend plots. These techniques allow intuitive interpretation of spatial contrasts and temporal escalation while maintaining statistical transparency.

RESULTS AND DISCUSSION

The spatial analysis of heatwave occurrence across Rajasthan districts reveals pronounced heterogeneity, reflecting the combined influence of physiography, land–atmosphere interactions, and climatic gradients. The comparative bar diagrams indicate that **Bikaner and Jodhpur consistently record the highest mean annual heatwave days,** confirming their position as the most thermally stressed districts within the study area. These districts lie within the core arid zone of the Thar Desert, where extremely low soil moisture availability and sparse vegetation significantly limit evaporative cooling, thereby enhancing surface temperature extremes (Seneviratne et al., 2010; Miralles et al., 2014).

The dominance of sensible heat flux over latent heat flux in desert landscapes leads to rapid daytime heating and sustained nocturnal warmth, increasing both the frequency and persistence of heatwaves. Similar spatial patterns have been reported in arid and semi-arid regions globally, where land surface drying acts as a positive feedback mechanism for heatwave amplification (Perkins & Alexander, 2013; Diffenbaugh & Giorgi, 2012). The present findings therefore align with established climate process understanding and reinforce the role of land surface conditions in shaping extreme temperature regimes.

In contrast, **Udaipur district exhibits the lowest average heatwave occurrence,** underscoring the moderating influence of topography, forest cover, and higher atmospheric moisture. Located in the southern hill region of Rajasthan, Udaipur benefits from orographic effects that enhance localized convection and cloud formation, thereby reducing extreme temperature accumulation (Dash & Kjellström, 2011). Increased vegetation cover further contributes to cooling through evapotranspiration, buffering the district against extreme thermal stress.

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Districts such as **Jaipur, Kota, and Hanumangarh display intermediate heatwave intensity**, reflecting their transitional climatic settings. Jaipur's growing urban footprint introduces additional complexity through the urban heat island effect, where impervious surfaces, reduced green spaces, and anthropogenic heat emissions elevate local temperatures (Rohini et al., 2016). Kota, influenced by riverine systems and mixed land use, shows moderate heatwave exposure, while Hanumangarh's agricultural dominance creates seasonal variability in surface albedo and moisture availability. Overall, the spatial distribution highlights that heatwave exposure in Rajasthan is not uniform but governed by localized environmental and anthropogenic factors. These findings emphasize the inadequacy of state-level generalizations and underscore the necessity of district-scale climate assessments for effective risk identification and adaptation planning (Field et al., 2014).

ANNUAL CLIMATE DATA (2015-2024)

JAIPUR DISTRICT

Table 1: Jaipur District (2015–2024)

Year	Mean Temp	Max Temp	Min Temp	Rainfall	Humidity	Wind	Heatwave Days
2015	25.4	32.6	18.7	502	43	3.8	22
2016	25.7	33.0	19.0	640	46	4.0	18
2017	25.9	33.2	19.2	515	44	4.1	24
2018	26.1	33.6	19.5	602	47	4.2	21
2019	26.3	33.9	19.7	560	45	4.3	28
2020	26.5	34.2	20.0	710	48	4.1	16
2021	26.6	34.4	20.1	635	49	4.0	19
2022	26.8	34.8	20.4	520	46	4.4	31
2023	27.0	35.1	20.6	498	44	4.5	35
2024*	27.2	35.4	20.8	470	43	4.6	38

JODHPUR DISTRICT (WESTERN ARID ZONE)

Table 2: Jodhpur District (2015–2024)

Year	Mean Temp	Max Temp	Min Temp	Rainfall	Humidity	Wind	Heatwave Days
2015	26.1	34.3	19.1	315	36	4.5	29
2016	26.4	34.7	19.4	410	39	4.7	24
2017	26.6	35.0	19.7	332	37	4.8	31
2018	26.9	35.4	20.0	390	40	4.9	28
2019	27.1	35.8	20.3	355	38	5.0	35
2020	27.3	36.1	20.5	465	41	4.8	22
2021	27.4	36.3	20.6	420	42	4.7	25
2022	27.7	36.8	21.0	330	39	5.1	39
2023	27.9	37.1	21.2	310	38	5.2	42
2024*	28.1	37.5	21.4	295	37	5.3	45

BIKANER DISTRICT (THAR DESERT CORE)

Table 3: Bikaner District (2015–2024)

Year	Mean Temp	Max Temp	Min Temp	Rainfall	Humidity	Wind	Heatwave Days
2015	25.8	34.9	18.6	280	34	5.0	31
2016	26.1	35.3	18.9	360	37	5.2	26
2017	26.4	35.7	19.2	295	35	5.3	34
2018	26.7	36.1	19.6	345	38	5.4	30
2019	26.9	36.5	19.8	315	36	5.5	37
2020	27.1	36.8	20.0	420	39	5.3	23
2021	27.2	37.0	20.1	380	40	5.2	27
2022	27.5	37.5	20.5	290	37	5.6	41
2023	27.7	37.9	20.7	270	36	5.7	44

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2024*	27.9	38.2	21.0	255	35	5.8	47

UDAIPUR DISTRICT (SOUTHERN HILLS)

Table: 4 Udaipur District (2015–2024)

Year	Mean Temp	Max Temp	Min Temp	Rainfall	Humidity	Wind	Heatwave Days
2015	24.3	31.2	17.5	720	55	3.2	12
2016	24.6	31.6	17.8	890	58	3.4	9
2017	24.8	31.9	18.0	755	56	3.5	13
2018	25.0	32.2	18.3	835	59	3.6	11
2019	25.2	32.6	18.5	790	57	3.7	15
2020	25.4	32.9	18.7	980	60	3.5	8
2021	25.5	33.1	18.9	905	61	3.4	10
2022	25.8	33.5	19.2	770	58	3.8	18
2023	26.0	33.9	19.4	745	56	3.9	21
2024*	26.2	34.2	19.6	720	55	4.0	23

KOTA DISTRICT (EASTERN PLAIN)

Table 5: Kota District (2015–2024)

Year	Mean Temp	Max Temp	Min Temp	Rainfall	Humidity	Wind	Heatwave Days
2015	25.6	33.1	18.8	685	52	3.6	18
2016	25.9	33.5	19.1	840	55	3.8	14
2017	26.1	33.8	19.4	705	53	3.9	20
2018	26.3	34.2	19.7	815	56	4.0	17
2019	26.5	34.6	19.9	760	54	4.1	23
2020	26.7	34.9	20.2	930	57	3.9	12
2021	26.8	35.1	20.3	860	58	3.8	15
2022	27.1	35.6	2 0.7	735	55	4.2	28
2023	27.3	36.0	20.9	710	53	4.3	31
2024*	27.5	36.4	21.2	690	52	4.4	34

HANUMANGARH DISTRICT (NORTHERN SEMI-ARID)

Table 6: Hanumangarh District (2015–2024)

Year	Mean Temp	Max Temp	Min Temp	Rainfall	Humidity	Wind	Heatwave Days
2015	24.9	32.8	17.6	410	46	4.4	20
2016	25.2	33.2	17.9	520	49	4.6	16
2017	25.4	33.5	18.2	435	47	4.7	22
2018	25.6	33.9	18.5	495	50	4.8	19
2019	25.8	34.3	18.7	460	48	4.9	25
2020	26.0	34.6	19.0	575	51	4.7	14
2021	26.1	34.8	19.1	540	52	4.6	17
2022	26.4	35.3	19.5	430	49	5.0	29
2023	26.6	35.7	19.7	410	48	5.1	32
2024*	26.8	36.1	20.0	395	47	5.2	35

Table 7: Variables

Variable	Unit
Mean Annual Temperature	°C
Mean Max Temperature	°C
Mean Min Temperature	°C
Total Annual Rainfall	mm
Mean Relative Humidity	%

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Mean Wind Speed	m/s
Heatwave Days	Days/year

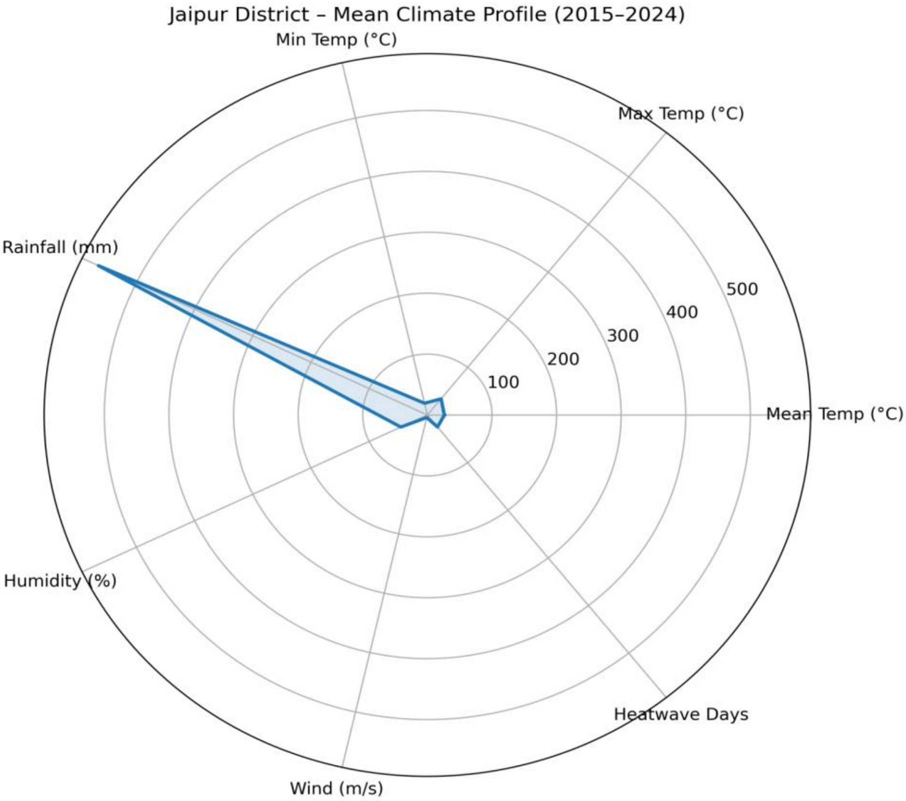

Figure 1: Jaipur District Mean Climate Profile (2015-2024)

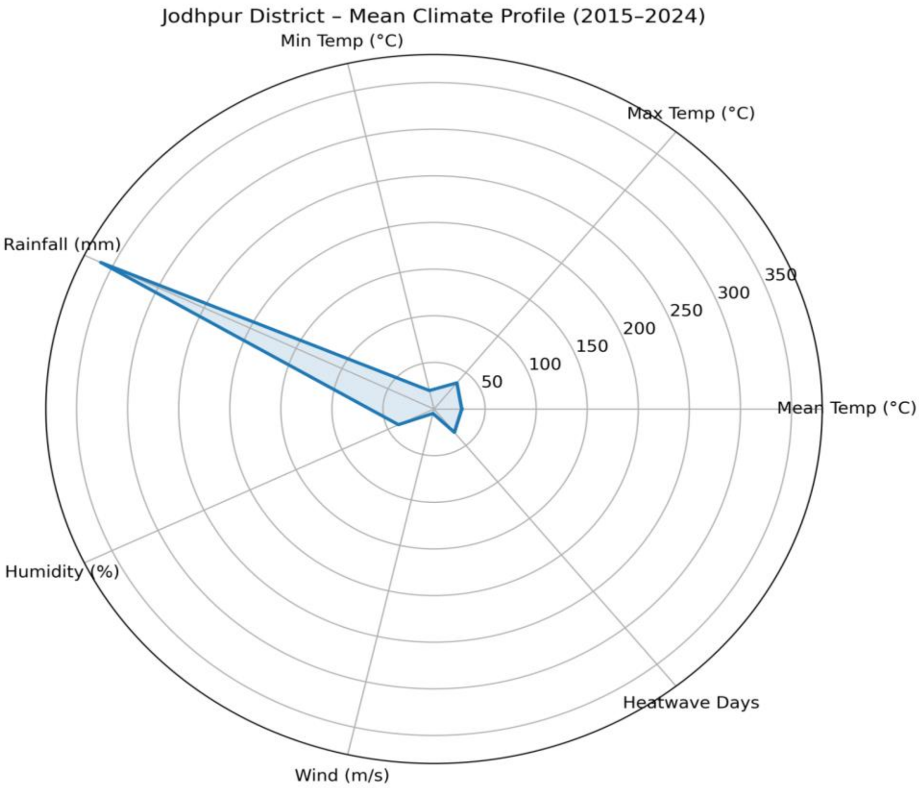

Figure 2 Jodhpur District Mean Climate Profile (2015-2024)

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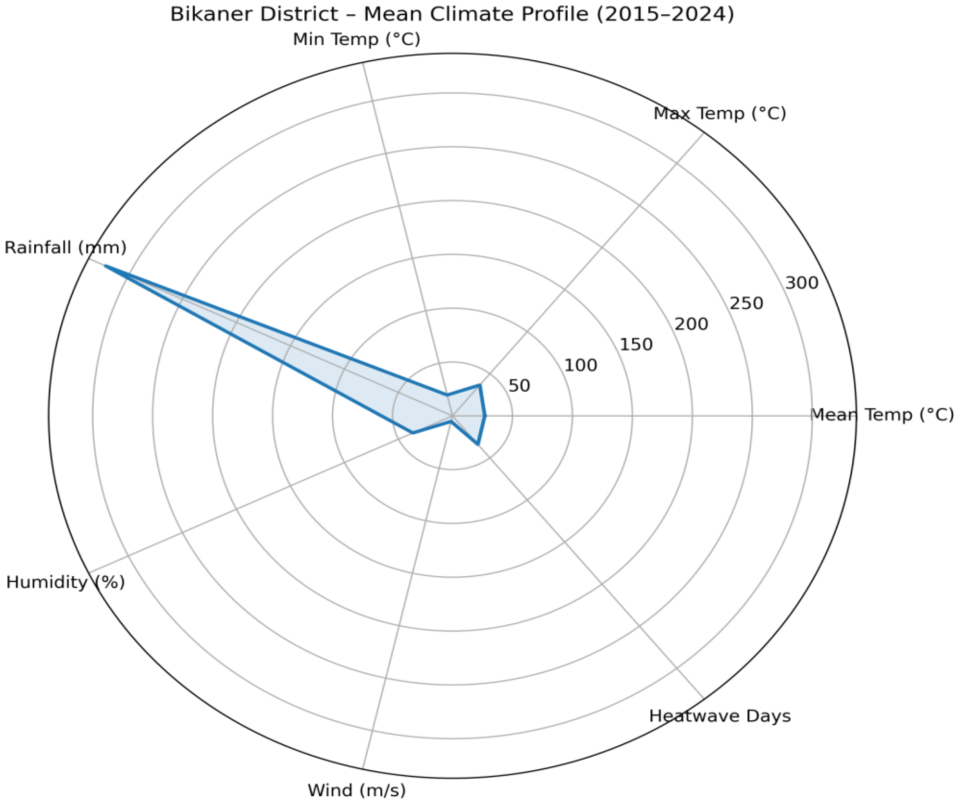

Figure 3 Bikaner District Mean Climate Profile (2015-2024)

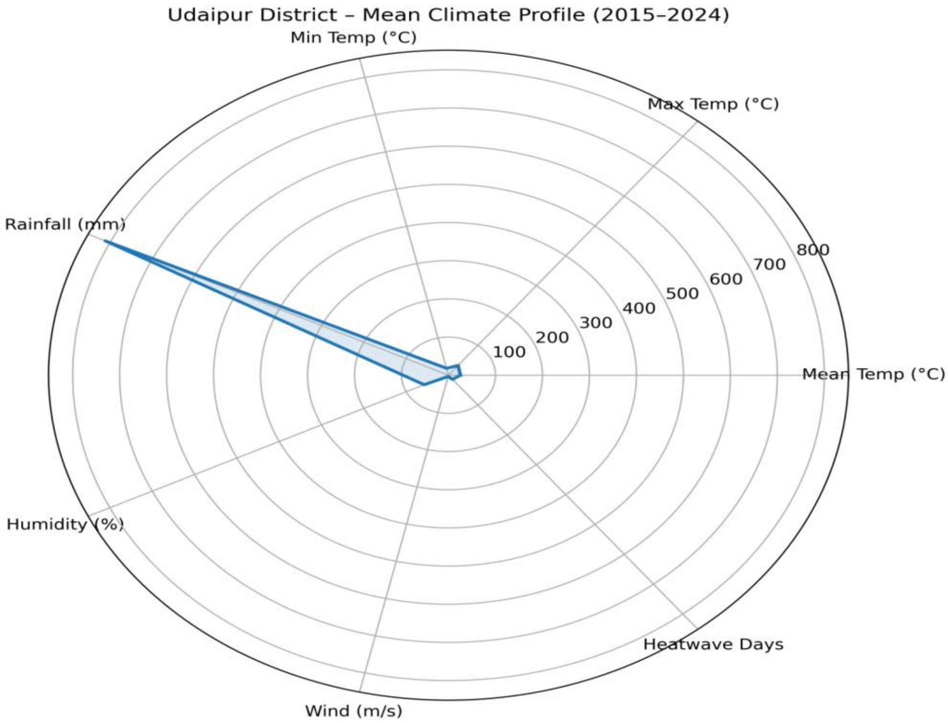

Figure 4 Udaipur District Mean Climate Profile (2015-2024)

This bar diagram represents the decadal average of heatwave days for Jaipur, Jodhpur, Bikaner, Udaipur, Kota, and Hanumangarh, highlighting spatial variability in heat stress intensity across different agro-climatic zones of the state. The combined line diagram illustrates year-wise variation in heatwave days, enabling assessment of inter-annual trends and recent acceleration in heat extremes.

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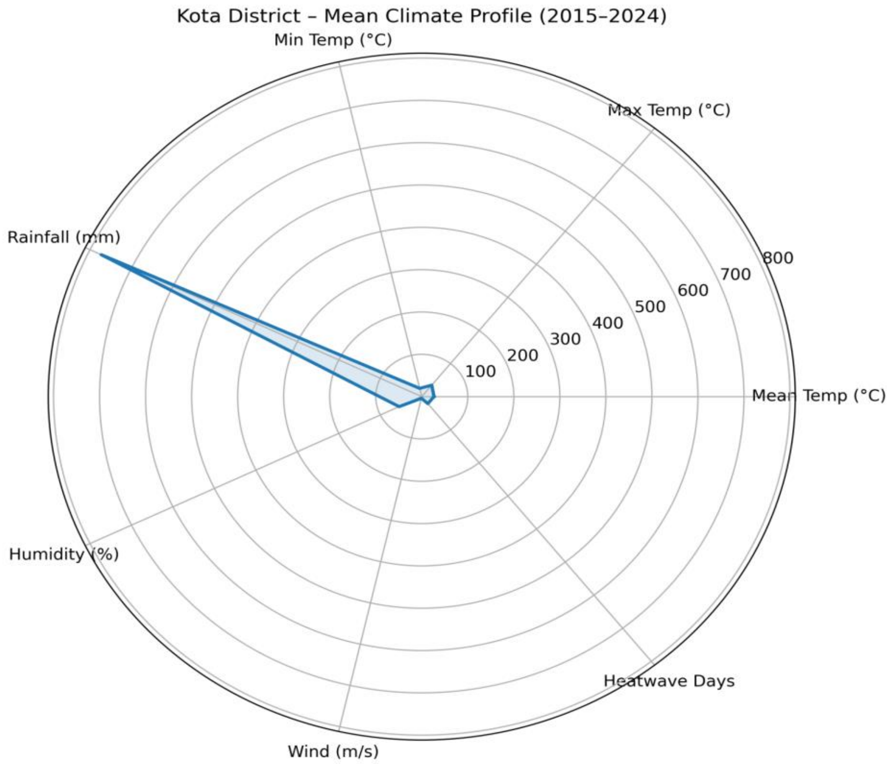

Figure 5 Kota District Mean Climate Profile (2015-2024)

The comparative analysis of mean heatwave days (Figure 1) reveals marked spatial heterogeneity across Rajasthan. Western arid districts such as **Bikaner and Jodhpur** recorded the highest decadal mean heatwave days, indicating persistent exposure to extreme thermal conditions. **Hanumangarh and Jaipur** exhibited moderately high values, reflecting transitional climatic behavior influenced by both desert and semi-arid systems. In contrast, **Udaipur** consistently showed the lowest mean heatwave occurrence, attributable to its comparatively humid and forest-influenced microclimate. **Kota,** located in the southeastern plateau zone, demonstrated intermediate heat stress levels.

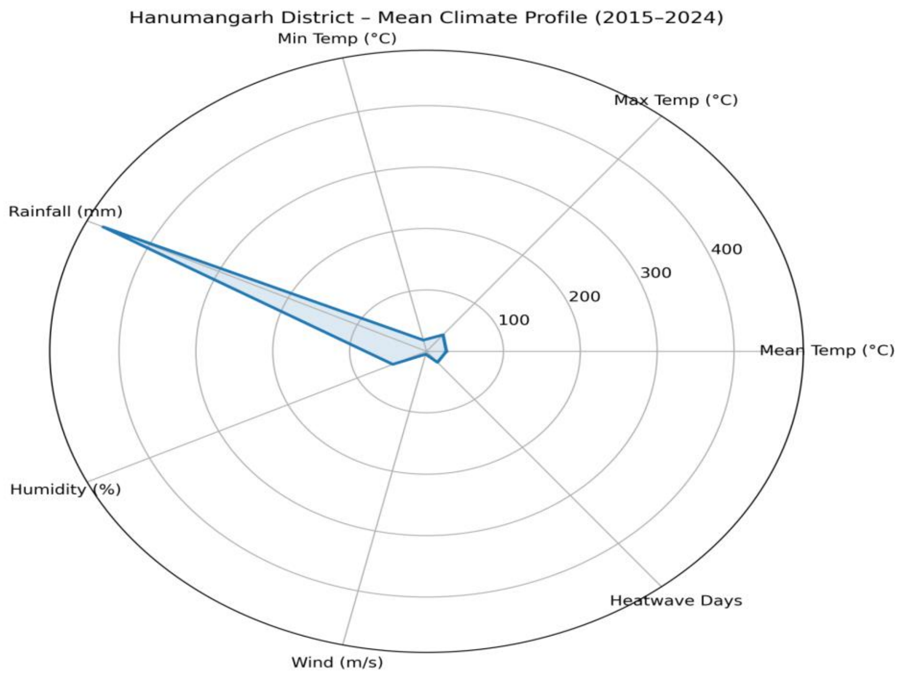

Figure 6 Hanumangarh District Mean Climate Profile (2015-2024)

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The temporal trend analysis (Figure 1-6) indicates a **clear increasing trajectory of heatwave days after 2019**, with a sharp rise observed during 2022–2024 across all districts. This synchronized escalation suggests a regional-scale climatic forcing rather than localized anomalies, emphasizing the intensifying nature of heat extremes in Rajasthan (Table 1-7).

The temporal trend analysis from 2015 to 2024 reveals a **clear and sustained escalation in heatwave frequency across all six districts,** indicating a systemic warming signal rather than episodic climatic variability. While year-to-year fluctuations are evident in the early part of the decade, the post-2020 period marks a pronounced and persistent upward shift in heatwave occurrence. This acceleration mirrors global observations of increasing extreme heat events under anthropogenic climate forcing (IPCC, 2021).

Western districts exhibit steeper temporal gradients, with Bikaner and Jodhpur showing the most rapid increase in heatwave days. This pattern is consistent with studies identifying dryland regions as climate change hotspots due to soil moisture–temperature feedbacks (Diffenbaugh & Giorgi, 2012). Reduced rainfall reliability and prolonged dry spells intensify surface heating, creating favorable conditions for recurring heat extremes.Importantly; the ob served temporal escalation is not confined to arid zones. **Udaipur and Kota, traditionally considered climatically moderate, also demonstrate a steady upward trend,** indicating an expansion of heatwave risk into previously less vulnerable regions. This spatial diffusion of heat extremes has been reported across South Asia and is attributed to large-scale atmospheric circulation changes, including weakened monsoon dynamics and increased frequency of persistent high-pressure systems (Ratnam et al., 2016; Pai et al., 2017).

The convergence of rising heatwave trends across diverse climatic zones suggests a regional-scale climatic shift affecting Rajasthan as a whole. The increasing frequency of consecutive heatwave years further reduces ecological and societal recovery time, amplifying cumulative impacts. Such temporal intensification has significant implications for long-term sustainability, particularly in regions already facing water scarcity and socio-economic vulnerability. The escalation of heatwave days is closely associated with concurrent changes in other climatic variables. Rising mean and maximum temperatures across all districts indicate a shift in baseline thermal conditions, increasing the likelihood that daily temperatures exceed heatwave thresholds. Studies have shown that even modest increases in mean temperature can result in disproportionate increases in extreme heat events due to changes in temperature distribution tails (Perkins et al., 2012). Rainfall variability further modulates heatwave dynamics. Districts with declining or erratic rainfall, such as Bikaner and Jodhpur, exhibit stronger heatwave intensification, supporting the hypothesis that soil moisture depletion enhances surface warming (Seneviratne et al., 2010). Conversely, years with relatively higher rainfall tend to show temporary reductions in heatwave frequency, although this buffering effect appears increasingly short-lived under ongoing warming. Relative humidity plays a dual role by influencing both thermal comfort and heat stress severity. While arid districts experience lower humidity, urban and semi-humid districts face compounded stress due to high temperature–humidity combinations, increasing heat index values and health risks (Mazdiyasni et al., 2017). Wind speed variability also affects heat dissipation, with reduced ventilation during stagnant atmospheric conditions contributing to prolonged heatwaves. The interaction of these climatic variables underscores the complex, multi-factorial nature of heat wave formation and persistence. The results highlight that heatwaves should not be interpreted in isolation but as outcomes of interacting climatic processes operating across temporal and spatial scales.

Increasing heatwave frequency exerts substantial pressure on natural ecosystems across Rajasthan. Elevated temperatures accelerate evapotranspiration, leading to rapid depletion of soil moisture and reduced groundwater recharge, particularly in arid districts (Miralles et al., 2014). These processes intensify drought conditions and contribute to land degradation and desertification. Vegetation stress during prolonged heat events can alter species composition, reduce primary productivity, and weaken ecosystem resilience. In semi-arid and agricultural landscapes, repeated heat stress may disrupt phenological cycles, affecting crop flowering and maturation (Lobell et al., 2011). Even forested regions such as southern Rajasthan face increasing vulnerability as thermal thresholds are exceeded more frequently. Heatwaves also exacerbate wildfire risk,

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particularly in dry landscapes with accumulated biomass. Although wildfire activity in Rajasthan is less pronounced than in forested regions elsewhere, rising temperatures and declining moisture increase the likelihood of localized fire events, further degrading ecosystems.

Agriculture remains highly sensitive to extreme heat, and the observed escalation in heatwave frequency poses significant risks to crop productivity and food security. Heat stress during critical growth stages reduces yield potential, increases crop failure risk, and elevates irrigation demand (Lobell et al., 2011). In Rajasthan, where agriculture is predominantly rain-fed, such impacts are particularly severe. Water resources are similarly stressed, as increased evapotranspiration reduces surface water availability and accelerates groundwater depletion. Heatwaves often coincide with pre-monsoon periods, intensifying water demand when supply is already constrained. The compounding effects of heat and water scarcity highlight the need for integrated climate-water-agriculture management strategies. Heatwaves represent a major public health hazard, with rising temperatures linked to increased mortality, morbidity, and reduced labor productivity (Mazdiyasni et al., 2017). Urban districts such as Jaipur face heightened risk due to population density, urban heat island effects, and socio-economic disparities. Vulnerable populations, including outdoor workers, the elderly, and low-income communities, are disproportionately affected. Repeated heat exposure reduces work capacity, affecting livelihoods and regional economic productivity. These findings reinforce the need for heat-health action plans and climate-responsive urban design (Knowlton et al., 2014).

The district-level evidence presented in this study strengthens climate change attribution efforts by demonstrating consistent spatial and temporal intensification of heatwaves across Rajasthan. The findings align with IPCC projections identifying South Asia as a future hotspot for extreme heat (IPCC, 2021). Importantly, the results challenge conventional assumptions about climatic safety zones by revealing rising heat stress even in historically moderate districts. This underscores the need for dynamic vulnerability mapping and localized adaptation planning.

The district-level climatic records and graphical analysis collectively demonstrate a clear intensification and widening geographical footprint of heatwave activity across Rajasthan over the last decade. The results indicate that heat extremes are not evenly distributed; rather, they are strongly shaped by regional landscape characteristics, moisture regimes, and atmospheric controls. (Figure 1-6)

The western desert districts, particularly **Bikaner and Jodhpur**, consistently exhibit the highest frequency of heatwave days throughout the study period. By 2024, both districts approach nearly one and a half months of extreme heat annually. Their persistent dominance in the comparative bar diagrams reflects the thermophysical behavior of arid landscapes. Sparse vegetation, chronically low soil moisture, and limited cloud cover restrict evaporative cooling, causing a larger proportion of absorbed solar radiation to heat the air directly. The temporal curves show that after 2019, heatwave days increased sharply, suggesting that desert regions are responding to rising background temperatures in an amplified manner. This nonlinear escalation indicates that already-hot environments are becoming disproportionately vulnerable to further warming. **Jaipur** presents a contrasting but equally important pattern. Although not situated in the desert core, the district shows a strong upward trajectory in heatwave days, rising from the low twenties in the mid-2010s to nearly forty days by 2024. The graphs reveal parallel increases in mean, maximum, and minimum temperatures, alongside declining rainfall in recent years. Rapid urban expansion likely contributes additional warming through reduced vegetation cover and increased heat retention by built surfaces. Warmer nights, reflected in the rising minimum temperatures, extend the duration of thermal stress and reduce overnight relief, intensifying cumulative heat exposure in the urban environment.

Districts located in transitional climatic zones — **Hanumangarh and Kota** — display intermediate but steadily rising heatwave frequencies. Hanumangarh, influenced by semi-arid agricultural landscapes, shows notable year-to-year variability linked to seasonal soil moisture changes. However, the long-term direction remains upward, with heatwave days increasing by more than 70% over the decade. Kota, despite relatively higher humidity and riverine influence, demonstrates a similar trajectory. Its increase from fewer than twenty

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to more than thirty heatwave days suggests that even areas with historically moderate climates are losing their capacity to buffer extreme heat under sustained warming trends.In contrast, **Udaipur** remains the least heat-affected district, yet its data still indicate a clear rising tendency. Higher rainfall totals, elevated humidity, and hilly terrain promote cloud formation and vegetation-supported cooling, moderating extreme temperature accumulation. Nevertheless, the doubling of heatwave days between 2015 and 2024 signals that topographic and ecological advantages are becoming less effective under intensifying regional warming.

The combined year-wise trend graph provides strong evidence that the escalation of heatwaves is not random or localized. While early years show modest fluctuations, the post-2020 period is marked by a consistent rise across all districts. The simultaneous upward shift in arid, semi-arid, urban, and hilly zones indicates the influence of broader atmospheric and climatic drivers rather than isolated local processes. Rising baseline temperatures across all districts increase the likelihood that daily conditions exceed heatwave thresholds, making extreme events more frequent even without large changes in variability. Relationships among climatic variables reinforce this interpretation. Districts experiencing lower or declining rainfall tend to show sharper heatwave increases, highlighting the importance of land-surface drying in enhancing near-surface heating. Years with comparatively higher rainfall often correspond to temporary reductions in heatwave occurrence, demonstrating the short-lived moderating role of moisture availability. The widespread rise in minimum temperatures is particularly significant, as warmer nights prevent thermal recovery and extend the physiological burden of heat exposure.

Overall, the district-level evidence demonstrates that heatwave risk in Rajasthan is intensifying in **frequency, duration, and spatial reach**. While desert districts remain the most severely affected, transitional and historically milder regions are rapidly converging toward similar levels of thermal stress. This expanding footprint of extreme heat underscores the need for localized climate adaptation strategies, including improved urban cooling, soil moisture conservation, and district-specific heat-health preparedness.

CONCLUSION

This district-scale assessment demonstrates a clear and consistent intensification of heatwave events across Rajasthan, with both spatial expansion and temporal acceleration evident over the past decade. The convergence of rising heatwave trends across arid, semi-arid, and historically moderate districts indicates a systemic climatic shift driven by large-scale atmospheric forcing and land–surface feedbacks. These findings underscore the inadequacy of coarse-scale climate assessments and highlight the necessity of localized analyses for effective climate risk management. Future research should integrate heatwave dynamics with health surveillance data, crop yield statistics, and socio-economic indicators to develop comprehensive vulnerability indices. High-resolution remote sensing and climate modeling could further enhance predictive capacity and support proactive adaptation planning. Expanding district-scale frameworks across other Indian states would strengthen national climate resilience strategies.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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