Final Report

ASSESSMENT OF THE POSSIBLE IMPACT OF CLIMATE CHANGE ON EVAPOTRANSPIRATION FOR DIFFERENT CLIMATIC REGIONS OF INDIA

NATIONAL INSTITUTE OF HYDROLOGY
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ROORKEE - 247 667

April 2025

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ACKNOWLEDGMENT

The Principal Investigator expresses sincere gratitude to Dr. M.K. Goel, Director, National Institute of Hydrology (NIH), Roorkee, for his continuous encouragement, administrative support, and valuable guidance throughout the course of this study titled “Assessment of the Possible Impact of Climate Change on Evapotranspiration for Different Climatic Regions of India.”

The support and insightful suggestions from Dr. S.D. Khobragade, Scientist ‘G’ and Head, Hydrological Investigations Division (HID), are gratefully acknowledged. His role as Divisional Head and Co-Investigator has been instrumental in shaping the direction and quality of the study.

The meteorological datasets used in the study, procured from the India Meteorological Department (IMD), Pune, are thankfully acknowledged. The study also benefited from ancillary datasets and reports from various national and regional agencies, whose contributions are duly appreciated.

The Principal Investigator extends heartfelt thanks to all the scientists, technical staff, and administrative personnel at NIH, Roorkee, who have directly or indirectly contributed to the successful completion of this work.

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SUMMARY

India, with its vast geographic spread and climatic diversity, is highly sensitive to climate variability and change, particularly with respect to its water resources. Evapotranspiration (ET), representing the combined process of evaporation and plant transpiration, is a key component of the hydrological cycle and is directly influenced by atmospheric demand. Changes in ET more specifically, Potential Evapotranspiration (PET) serve as critical indicators of shifts in climate, with profound implications for irrigation demand, agriculture, groundwater recharge, and overall water resource management. Given the increasing concerns about rising temperatures and erratic rainfall under global warming scenarios, this study aimed to assess the present and future trends of PET across different climatic regions of India, thereby contributing to scientific understanding and practical adaptation planning.

The study adopted a station-based approach, selecting eight representative locations from distinct agro-climatic zones: Jammu (Northwestern Himalayas), Guwahati (Humid Northeast), Patna (Eastern Indo-Gangetic Plains), Bhopal (Central India), Jodhpur (Arid West), Roorkee (Sub-Himalayan Foothills), Kakinada (Eastern Coastal Plains), and Belgaum (Western Plateau). These locations were chosen to reflect India's wide climatic and geographic variability, allowing for a robust understanding of how climate change may influence atmospheric water demand across diverse landscapes.

To quantify PET, the study utilized the FAO Penman-Monteith method, a globally accepted and physically based model that integrates multiple meteorological variables: air temperature, relative humidity, solar radiation, and wind speed. For the historical period (2001–2024), maximum and minimum temperature data were sourced from the India Meteorological Department (IMD), while other required variables were obtained from NASA POWER. For future projections (2025–2100), statistically downscaled climate data from NASA NEX-GDDP, based on three CMIP6 global climate models (ACCESS-CM2, ACCESS-ESM1-5, and EC-Earth3), were used under two greenhouse gas concentration trajectories: SSP2-4.5 (intermediate scenario) and SSP5-8.5 (high emissions scenario).

Historical analysis revealed significant seasonal and interannual variability in PET across all locations, with the Pre-Monsoon season (March–May) consistently exhibiting the highest PET values due to elevated temperatures and intense solar radiation. Years such as 2002, 2015, and 2016 were identified as high-PET periods, aligning with known drought episodes and heat anomalies, thus affirming the sensitivity of PET to temperature and humidity changes. Even during the monsoon season, which typically experiences reduced PET due to cloud cover and rainfall, significant interannual differences were noted, pointing to complex atmospheric interactions.

The future projections presented a compelling narrative. Under SSP2-4.5, PET shows a gradual upward trend, becoming more prominent after 2050, whereas under SSP5-8.5, the increase is rapid, substantial, and sustained across all stations and seasons, particularly after 2060. This stark contrast between scenarios underscores the influence of emission pathways on hydrological responses. The study found that Bhopal, Patna, and Roorkee are likely to experience the most significant increases in PET, especially during

the non-monsoon months. Even traditionally humid stations like Guwahati and Kakinada exhibit rising PET trends, indicating that no region is immune to atmospheric drying under warming conditions.

Seasonal analysis further emphasized the dominance of the Pre-Monsoon season, where the PET is highest and most variable, often coinciding with crucial agricultural activities such as land preparation and sowing. However, winter and post-monsoon seasons, which currently experience lower PET levels, are projected to see disproportionately higher percentage increases, potentially extending the periods of water stress. These findings point toward a year-round intensification of evaporative demand, raising concerns about soil moisture deficits, increased irrigation requirements, and greater pressure on freshwater resources.

The ensemble-based approach, which averaged outputs from multiple climate models, added robustness to the projections by accounting for model-specific uncertainties and ensuring consistency in trends. The analysis also highlighted the expansion of interquartile ranges and more frequent extreme PET values under SSP5-8.5, suggesting growing unpredictability and higher risks of extreme atmospheric demand events in the future.

In conclusion, this study presents a comprehensive and regionally nuanced picture of how climate change is expected to impact potential evapotranspiration in India. By combining high-quality observed datasets with advanced climate model projections, the study offers valuable insights for water resource planning, agricultural adaptation, and climate resilience building. The findings highlight the urgency of integrating PET projections into sectoral policies and underscore the need for climate-smart practices, especially in vulnerable regions poised to face the sharpest increases in evaporative demand. With rising PET likely to exacerbate the gap between water supply and demand, particularly in already water-stressed zones, this research serves as a timely input to inform adaptive decision-making at national and regional levels.

1 INTRODUCTION

Climate change is exerting profound and multifaceted impacts on the hydrological cycle, with evapotranspiration (ET) emerging as one of the most sensitive components. Evapotranspiration, which encompasses both evaporation from land and water surfaces and transpiration from vegetation, is a critical link between the land surface and atmospheric processes. It plays a key role in regulating regional water availability, soil moisture dynamics, and agricultural productivity. Any alterations in ET due to changing climate patterns can substantially influence water resources, ecosystem sustainability, and food security, especially in climate-sensitive regions such as India. Climate change significantly influences hydrological processes like evapotranspiration, altering regional water demand and supply dynamics (Huntington, 2006; Jain & Kumar, 2012; IPCC, 2014)

India is characterized by a diverse range of climatic conditions from arid deserts in the west to humid tropics in the south and northeast, and temperate highlands in the north. This variability in climate, coupled with strong seasonality driven by the monsoon, results in highly heterogeneous evapotranspiration regimes across the country. Moreover, a significant portion of India's economy and livelihoods is heavily dependent on agriculture, which in turn is directly influenced by climatic parameters such as temperature, solar radiation, humidity, wind speed, and precipitation. Therefore, understanding how evapotranspiration patterns respond to current and projected climate scenarios is essential for adaptive water resource planning and climate-resilient agriculture.

Recent studies and climate models indicate a rising trend in surface temperatures across India, accompanied by increased variability in rainfall and extreme weather events. These climatic shifts are likely to enhance atmospheric demand for moisture, potentially leading to higher evapotranspiration rates, especially during already water-stressed seasons such as summer and post-monsoon. Enhanced ET could exacerbate the pressure on limited water resources, especially in regions with high irrigation demands or limited water availability. However, the nature and magnitude of ET changes vary considerably across space and time, necessitating detailed regional analyses.

In the context of global climate change projections, the Coupled Model Intercomparison Project Phase 6 (CMIP6) provides future climate data under multiple Shared Socioeconomic Pathways (SSPs), which consider both greenhouse gas emission trajectories and socioeconomic developments. Among these, SSP2-4.5 represents a moderate emissions scenario, while SSP5-8.5 represents a high-emissions pathway. Assessing evapotranspiration changes under these scenarios is crucial for anticipating future climate risks and developing appropriate mitigation and adaptation strategies.

This study aims to assess the present and future trends of potential evapotranspiration (PET) across diverse climatic regions of India using both observed and climate model data. Specifically, the study focuses on eight representative locations spread across different climate zones Jammu (north-western Himalayas), Guwahati (humid northeast), Patna (eastern Indo-Gangetic plain), Bhopal (central India), Jodhpur (arid west), Roorkee (sub-Himalayan belt), Kakinada (eastern coastal plain), and Belgaum (western plateau). These stations were selected to capture a wide range of climatic variability, geographical diversity, and agro-ecological conditions.

For the historical analysis, high-resolution meteorological data from the India Meteorological Department (IMD) were used to compute seasonal PET using the FAO-recommended Penman-Monteith method. This method integrates multiple climatic variables and is widely accepted for its accuracy in estimating reference evapotranspiration. The seasonal analysis was conducted for four distinct periods summer (March–May), monsoon (June–September), post-monsoon (October–November), and winter (December–February) to understand the seasonal sensitivity of ET to climatic drivers.

To assess the impact of climate change on future ET regimes, projected climate data from the NASA NEX-GDDP CMIP6 dataset were employed. This dataset offers downscaled daily climate projections at a spatial resolution of 0.25°, derived from an ensemble of global climate models. For robustness, three CMIP6 models ACCESS-CM2, ACCESS-ESM1-5, and EC-Earth3 were used to estimate future PET under SSP2-4.5 and SSP5-8.5 scenarios. These projections extend to the end of the 21st century, allowing for the detection of both near- and long-term trends in evapotranspiration.

The selection of multiple seasons and emission pathways provides a comprehensive understanding of how different regions in India may experience changes in evapotranspiration patterns under a changing climate. Seasonal PET estimates were analyzed to evaluate not only the magnitude of change but also its direction, spatial consistency, and variability across climate zones. The implications of these changes were then interpreted in the context of water resource management, crop planning, and regional hydrological balance.

Preliminary findings from this study indicate a clear and consistent increase in PET across all stations, particularly under the high-emission SSP5-8.5 scenario. The rate of increase is most pronounced post-2050, aligning with the expected intensification of climate warming. Summer and monsoon seasons exhibit the highest susceptibility to PET rise, which could critically affect soil moisture retention, irrigation needs, and drought severity during key crop growth stages. Even in regions with traditionally ample rainfall, such as Guwahati and Kakinada, increased PET could offset rainfall gains, leading to net moisture stress.

Furthermore, the analysis highlights that the rise in PET is not uniform across regions; it is modulated by local climatic and geographic factors such as elevation, proximity to the coast, land use, and prevailing wind patterns. For instance, the arid region of Jodhpur and central highland city Bhopal show markedly higher increases in PET during summer, reflecting the combined effect of high solar radiation and elevated temperatures. In contrast, stations like Roorkee and Belgaum show significant winter and post-monsoon PET rises, underscoring the season-specific nature of climate impacts.

The findings of this study have significant implications for policy formulation, particularly in water-stressed and drought-prone areas. Anticipated increases in evapotranspiration could aggravate existing water scarcity issues, heighten agricultural vulnerability, and strain irrigation infrastructure. As such, integrating PET projections into regional water planning and crop advisories will be crucial for enhancing resilience in the face of climate change.

In summary, this study provides a regionally disaggregated assessment of the potential impacts of climate change on evapotranspiration across diverse Indian climates. Through the integration of historical meteorological observations and future climate projections, it offers valuable insights into how evapotranspiration patterns are likely to evolve over the 21st century. This work contributes to the growing body of knowledge necessary for proactive and science-based adaptation in India's water and agricultural sectors.

2 STUDY AREA

India, a geographically diverse country extending from 8°4′N to 37°6′N latitude and from 68°7′E to 97°25′E longitude, experiences a wide spectrum of climatic regimes from arid deserts in Rajasthan to humid tropics in the northeastern states. Its hydro-climatic variability is shaped by a combination of monsoonal patterns, physiographic features, land cover, and anthropogenic pressures. India's vast geographical extent and complex climatic systems make it essential to evaluate climate change impacts regionally. To capture the spatial and climatic diversity of the country, this study focuses on eight representative stations, each located in a distinct climatic zone of India. These stations were strategically selected to reflect regional variability in temperature, rainfall, humidity, and land use, which directly influence Potential Evapotranspiration (PET) patterns. The selected stations span a broad spectrum of agro-ecological and hydro-climatic conditions, making them suitable proxies for their respective zones.

Jammu (North-Western Himalayas)

Situated in the western Himalayan region, Jammu experiences a temperate to sub-humid climate, with cold winters and warm summers. The region receives moderate rainfall (~1000 mm annually), mostly from the southwest monsoon and some western disturbances. Snowfall in higher elevations and complex topography influence seasonal PET dynamics.

Guwahati (Humid Northeast India)

Located in Assam, Guwahati represents the humid subtropical climate of Northeast India. The region is characterized by high annual rainfall (2000–2500 mm), lush vegetation, and frequent monsoonal storms. ET in this zone is largely influenced by dense forest cover and high humidity levels.

Patna (Eastern Indo-Gangetic Plains)

Patna lies in the fertile Indo-Gangetic Plain, which features a sub-humid to humid climate with annual rainfall of 1000–1200 mm, concentrated in the monsoon season. The region is agriculturally intensive, with high groundwater use and irrigation, making it significant for PET analysis under changing climatic conditions.

Bhopal (Central India)

Located in Madhya Pradesh, Bhopal represents the Central Indian Highlands, with a semi-humid climate and annual rainfall of 1000–1300 mm. The area is a mix of forests, agricultural lands, and urban areas. Seasonal variability in rainfall and temperature significantly influences PET patterns.

Jodhpur (Arid Western India)

Jodhpur lies in the Thar Desert region of Rajasthan and exemplifies hot arid conditions with very low annual rainfall (~300–500 mm) and high potential evapotranspiration throughout the year. Sparse vegetation and high temperatures make it highly vulnerable to water stress under climate change.

Roorkee (Sub-Himalayan Belt)

Roorkee, in Uttarakhand, represents the sub-Himalayan foothills, where the climate is humid subtropical, and annual rainfall is approximately 1200–1400 mm. The region lies near the Ganga plains and features both agricultural and forested landscapes. ET here is driven by seasonal variability and land cover.

Kakinada (Eastern Coastal Region)

Located in Andhra Pradesh along the Bay of Bengal, Kakinada has a humid tropical climate, receiving 1000–1300 mm of rainfall annually. The area is influenced by both southwest and northeast monsoons, as well as occasional cyclonic activity. Coastal proximity and high humidity affect ET rates.

Belgaum (Western Plateau/Western Ghats Transition Zone)

Belgaum in Karnataka is located in a transitional climatic zone between the Western Ghats and the Deccan Plateau. The region has a moderate to high rainfall regime (900–1200 mm) and a semi-humid climate, with mixed land use including agriculture, forest, and pasture, making it a representative station for western peninsular India.

These eight locations collectively represent India’s diverse climatic zones, ranging from cold highlands to arid deserts and humid coasts. This selection enables a detailed assessment of regional patterns in potential evapotranspiration and how these may evolve under projected climate change scenarios. The zonal insights derived from these stations provide valuable information for regional water resource planning and climate resilience strategies (**Figure 1**).

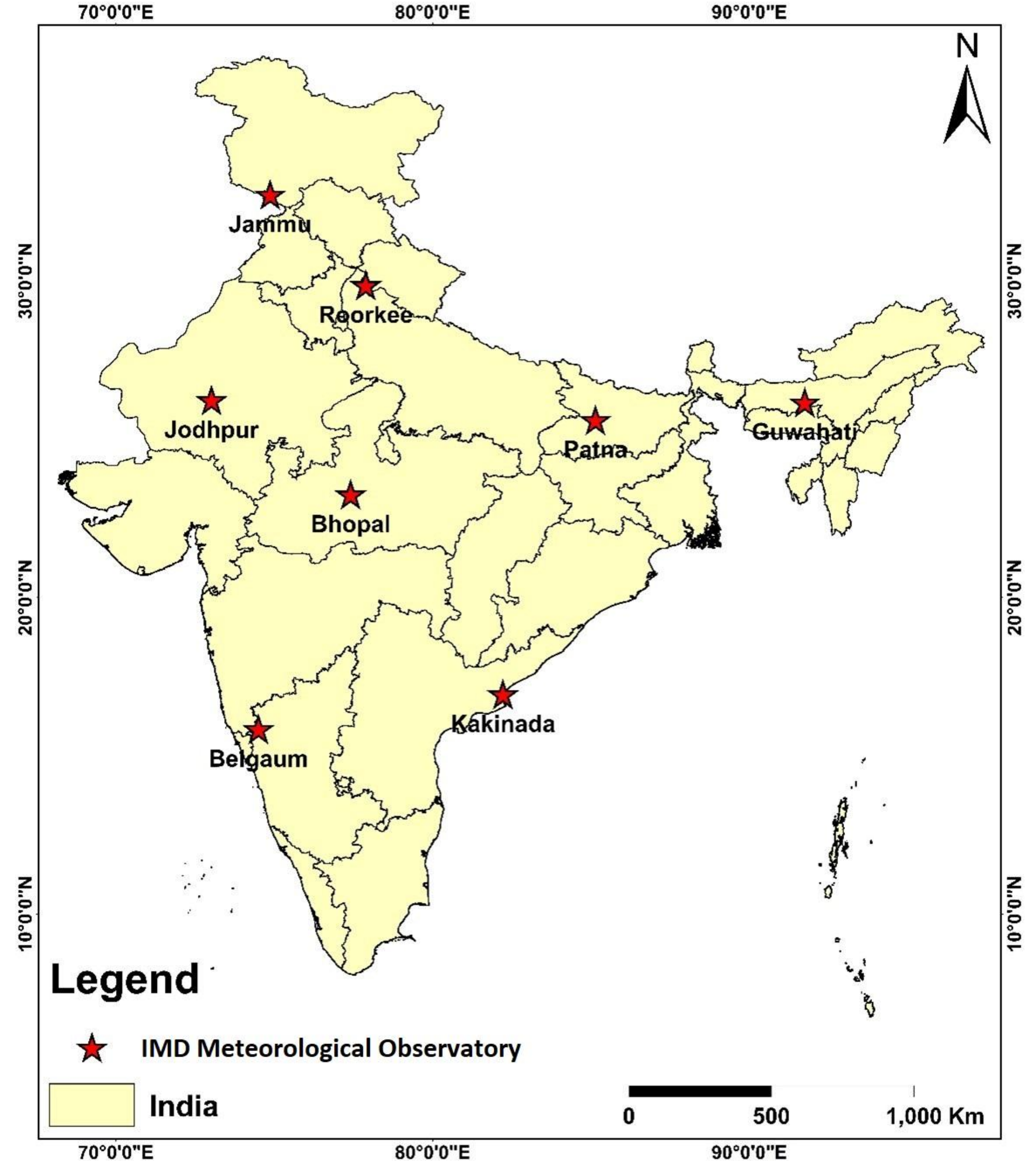

Figure 1 Location Map of the observation sites

3 MATERIALS AND METHODS

3.1 Datasets

To analyze evapotranspiration patterns under current and future climatic conditions, the study utilizes a combination of observed meteorological datasets and downscaled climate projections from Coupled Model Intercomparison Project Phase 6 (CMIP6) under two Shared Socioeconomic Pathways: SSP2-4.5 (intermediate scenario) and SSP5-8.5 (high emissions scenario). The datasets are selected based on spatial resolution, temporal availability, consistency, and relevance to evapotranspiration modeling using the FAO Penman-Monteith equation. The FAO Penman-Monteith method (Allen et al., 1998) was applied due to its robustness in estimating reference evapotranspiration under varying climatic conditions

Table 1. Summary of Datasets Used

Dataset	**Variable (s)**	**Source**	**Resolution**	**Temporal Coverage**	**Purpose**
IMD Station Data	Tmax, Tmin	India Meteorological Department (IMD)	Station-level	2001–2024	Historical PET (Penman-Monteith)
NASA POWER	Solar Radiation, Relative Humidity	NASA POWER (https://power.larc.nasa.gov/)	Point (Global Grid)	2001–2024	Supplementary PET inputs
CMIP6 - NASA NEX-GDDP	Tmax, Tmin, Solar Radiation, RH, Wind Speed	NASA NEX-GDDP (downscaled CMIP6)	0.25° × 0.25°	2025–2100	Future PET under climate scenarios
Climate Models (Ensemble: 3 GCMs)	ACCESS-CM2, ACCESS-ESM1-5, EC-Earth3	CMIP6, downscaled	0.25° × 0.25°	2025–2100	Ensemble PET projections

3.2 Methodology

The methodology adopted for achieving various objectives is given in **Figure 2.**

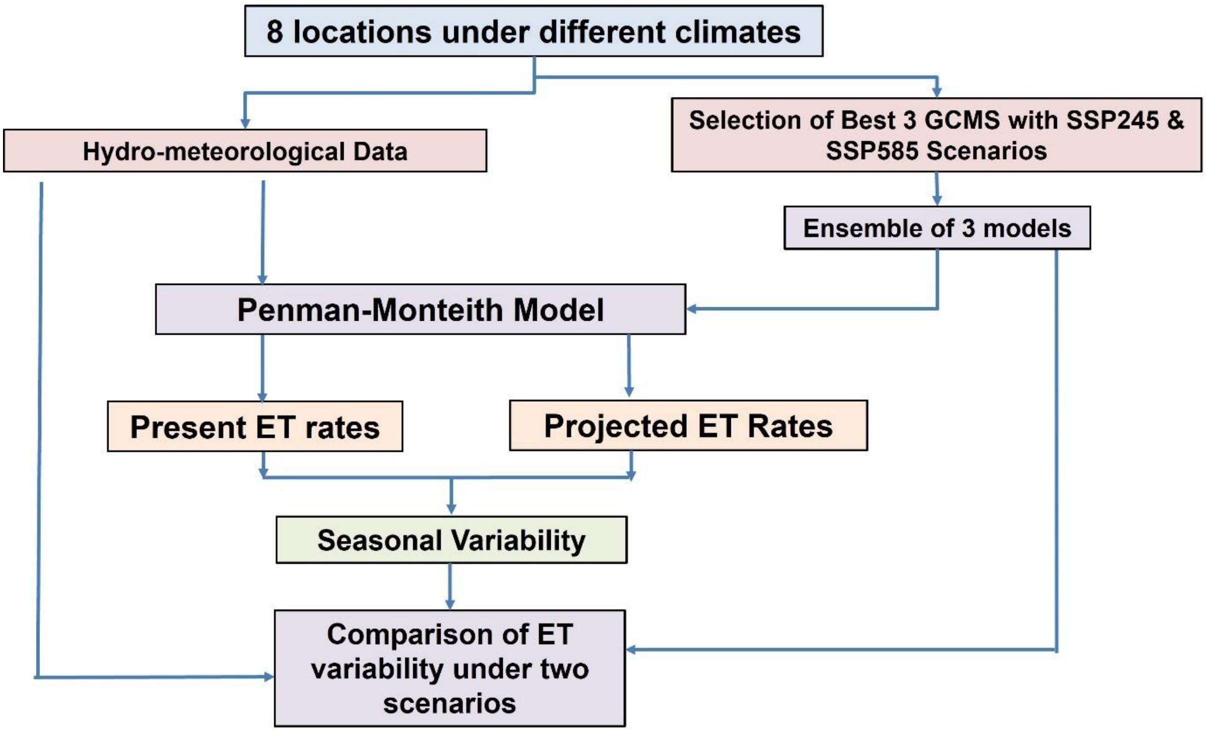

Figure 2 Flowchart of methodology

To evaluate the changing patterns of Potential Evapotranspiration (PET) under current and future climatic conditions across diverse climatic zones in India, this study integrates high-resolution observed meteorological data and statistically downscaled climate projections. The methodology involves the systematic computation of PET using the FAO Penman-Monteith equation, analysis of historical trends from 2001 to 2024, and future projections from 2025 to 2100 under two Shared Socioeconomic Pathways (SSP2-4.5 and SSP5-8.5) of CMIP6. Eight representative stations Jammu, Guwahati, Patna, Bhopal, Jodhpur, Roorkee, Kakinada, and Belgaum were selected to represent a wide range of hydro-climatic zones across the country.

Observed temperature data (maximum and minimum) for these stations were obtained from the India Meteorological Department (IMD) for the period 2001–2024. Additional meteorological parameters such as solar radiation and relative humidity were sourced from the NASA POWER database to supplement the Penman-Monteith equation. For future projections, downscaled climate data from NASA NEX-GDDP, based on three CMIP6 models (ACCESS-CM2, ACCESS-ESM1-5, and EC-Earth3), were utilized at a spatial resolution of 0.25° × 0.25°. These datasets provided daily values of Tmax, Tmin, relative humidity, wind speed, and solar radiation for the period 2025–2100 under two scenarios: SSP2-4.5, representing an intermediate emissions trajectory, and SSP5-8.5, representing a high emissions pathway. The future PET was calculated for each model and subsequently ensemble-averaged to reduce model-specific biases and enhance robustness.

The core of the PET estimation relies on the FAO Penman-Monteith equation **(i),** which combines both energy balance and aerodynamic principles to represent atmospheric evaporative demand. The equation is expressed as:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \cdot \frac{900}{T+273} \cdot u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34 \cdot u_2)} \tag{i}$$

Where:

ET_o = Potential evapotranspiration (mm/day)

Δ = Slope of the vapor pressure curve (kPa/°C)

R_n = Net radiation at the crop surface ($MJ/m^2/day$)

G = Soil heat flux density ($MJ/m^2/day$), assumed negligible for daily time step

γ = Psychrometric constant (kPa/°C)

T = Mean daily air temperature (°C)

u_2 = Wind speed at 2 m height (m/s)

e_s = Saturation vapor pressure (kPa)

e_a = Actual vapor pressure (kPa)

$(e_s - e_a)$ = Vapor pressure deficit (kPa)

This method accounts for multiple influencing factors of evapotranspiration including temperature, humidity, radiation, and wind speed. All required variables were either directly available or derived from the input datasets. Calculations were performed on a daily time step and later aggregated into monthly and seasonal values for trend analysis.

For the historical period (2001–2024), computed PET values were analyzed for each station to determine mean monthly climatology, seasonal distribution, and interannual variability. Anomalously high PET years such as 2002, 2015, and 2016 were examined in detail to understand the relationship between PET peaks and climatic anomalies (e.g., El Niño events or regional droughts). The Pre-Monsoon period (March to May) consistently showed the highest PET values due to elevated temperatures and high solar radiation, highlighting its importance in agricultural water management.

For the future period (2025–2100), PET was computed under both SSP scenarios to assess the impact of projected climate change. Under SSP2-4.5, PET showed a modest increasing trend, especially after 2050. However, under SSP5-8.5, the PET values increased substantially throughout the century, particularly during the Pre-Monsoon season. This rise is primarily attributed to projected temperature increases, declining relative humidity, and enhanced net radiation, all of which intensify atmospheric evaporative demand. Seasonal analysis revealed that the Pre-Monsoon period remains the most sensitive and vulnerable, while the Monsoon season exhibits relatively lower PET due to increased cloud cover and rainfall.

An ensemble approach was adopted for future projections by averaging PET outputs from three CMIP6 models. This ensemble method reduces individual model uncertainty and ensures more reliable trend detection. Seasonal PET changes were assessed for each station under both SSP scenarios, with special attention given to the expansion of interquartile ranges and the emergence of extreme PET values, particularly under the high-emission pathway.

In summary, the methodology provides a comprehensive framework to assess historical trends and future trajectories of PET across India’s diverse climate zones. By integrating observed data, downscaled climate model projections, and a robust PET estimation method, this study enables informed decision-making for irrigation planning, drought preparedness, and climate adaptation in water resource management.

4 RESULTS

4.1 Belgaum

The temporal and seasonal variability of Potential Evapotranspiration (PET) in Belgaum, computed using the FAO Penman-Monteith method, reveals critical insights into the evolving evaporative demand under changing climatic conditions. The historical PET heatmap from 2001 to 2024 **(Figure 3)** shows substantial interannual variability, with peak PET values consistently occurring during the Pre-Monsoon months (March to May), when solar radiation and temperature are highest. Interspersed high PET years, notably during 2002, 2015, and 2016, coincide with historically dry periods and reflect increased atmospheric evaporative demand, likely exacerbated by temperature anomalies and reduced humidity. These peaks suggest potential stress on crop water requirements and groundwater recharge during dry spells.

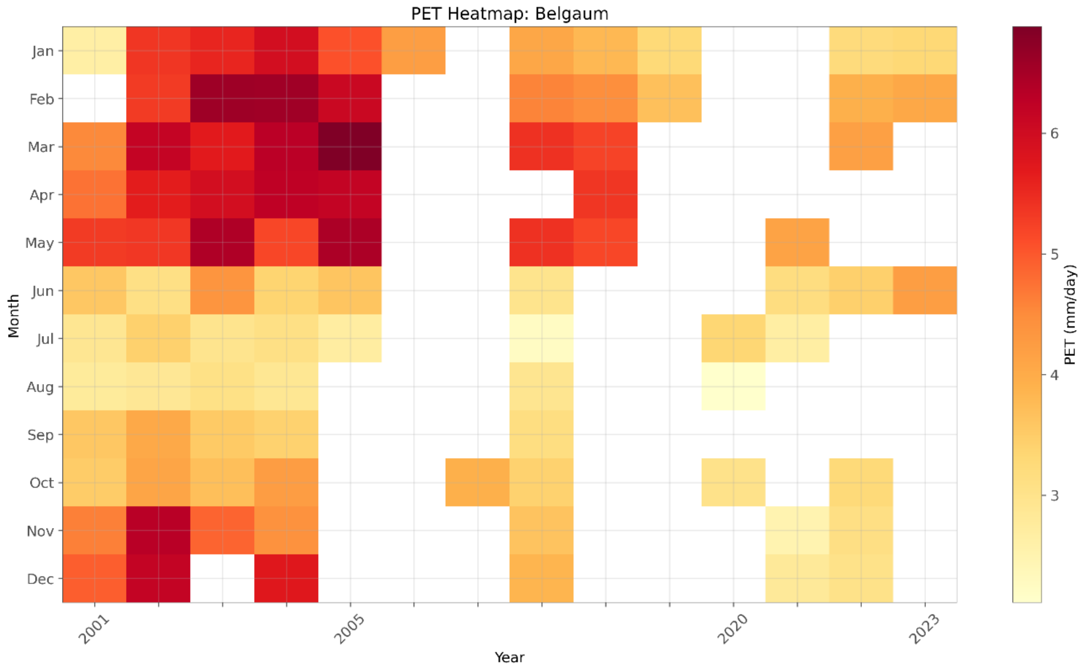

Figure 3 Historical Mean Monthly PET from 2001-2024 for Belgaum

Seasonal PET distribution **(Figure 4)** further highlights the dominance of the Pre-Monsoon season, which exhibits the highest median PET and variability. This indicates that this season imposes the greatest atmospheric water demand on agricultural and hydrological systems. The Monsoon season shows relatively moderate PET due to increased cloud cover and precipitation, while Winter and Post-Monsoon seasons experience lower PET levels due to cooler temperatures and reduced solar input.

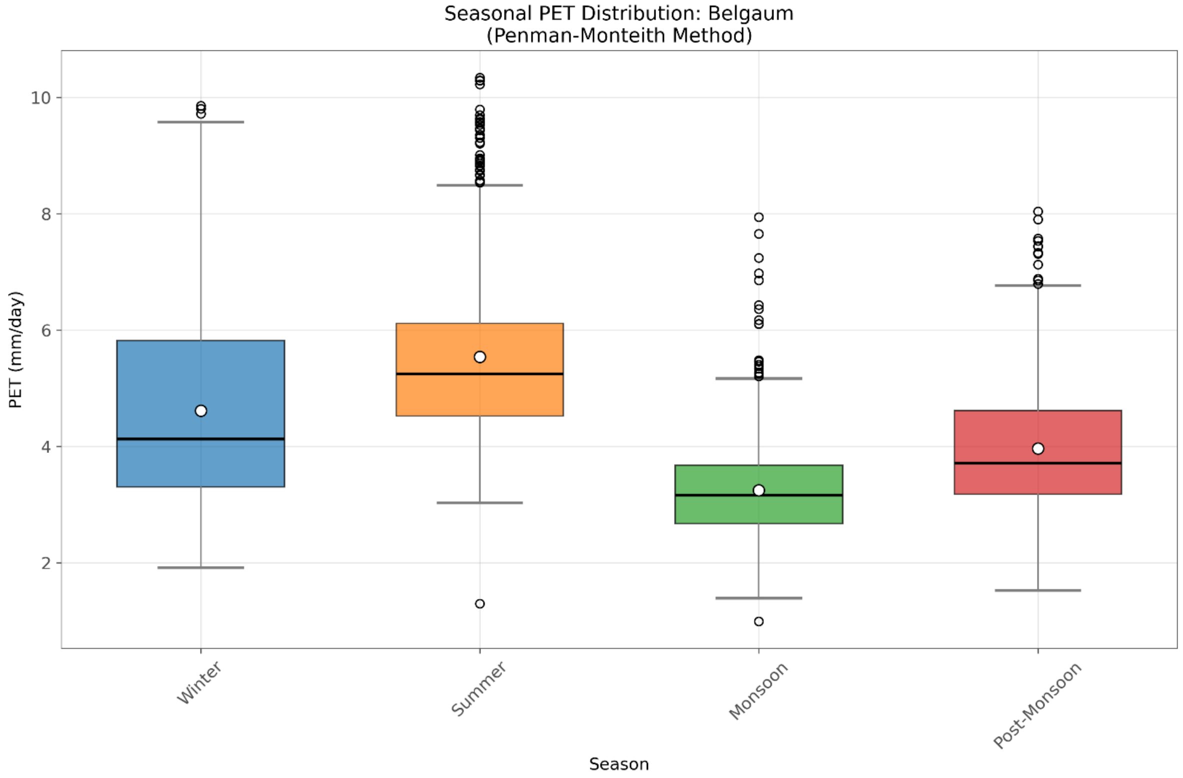

Figure 4 Historical seasonal PET distribution through boxplot for Belgaum

Figure 5 presents seasonal PET projections under both SSP2-4.5 and SSP5-8.5 scenarios. Future projections under different emission scenarios portray diverging PET trajectories. Under the intermediate emission pathway SSP2-4.5, PET remains relatively stable until mid-century, with a modest increasing trend thereafter. However, the high-emission scenario SSP5-8.5 shows a stark and persistent rise in PET across the 21st century, particularly after 2060. This sharp increase reflects the compounded effect of projected temperature rise, reduced relative humidity, and possible shifts in net radiation factors that directly influence PET in the Penman-Monteith framework. The amplified evaporative demand under SSP5-8.5 raises concerns about intensified water stress in the region, especially if not matched by proportional increases in precipitation.

A significant upward trend is evident in all seasons under SSP5-8.5, with the Pre-Monsoon period emerging as the most vulnerable to extreme PET increases. The trend is more subdued but still rising under SSP2-4.5. The widening interquartile range and more frequent extreme values under the high-emission scenario underscore the growing evaporative burden, which may lead to soil moisture depletion, increased irrigation demand, and stressed freshwater resources.

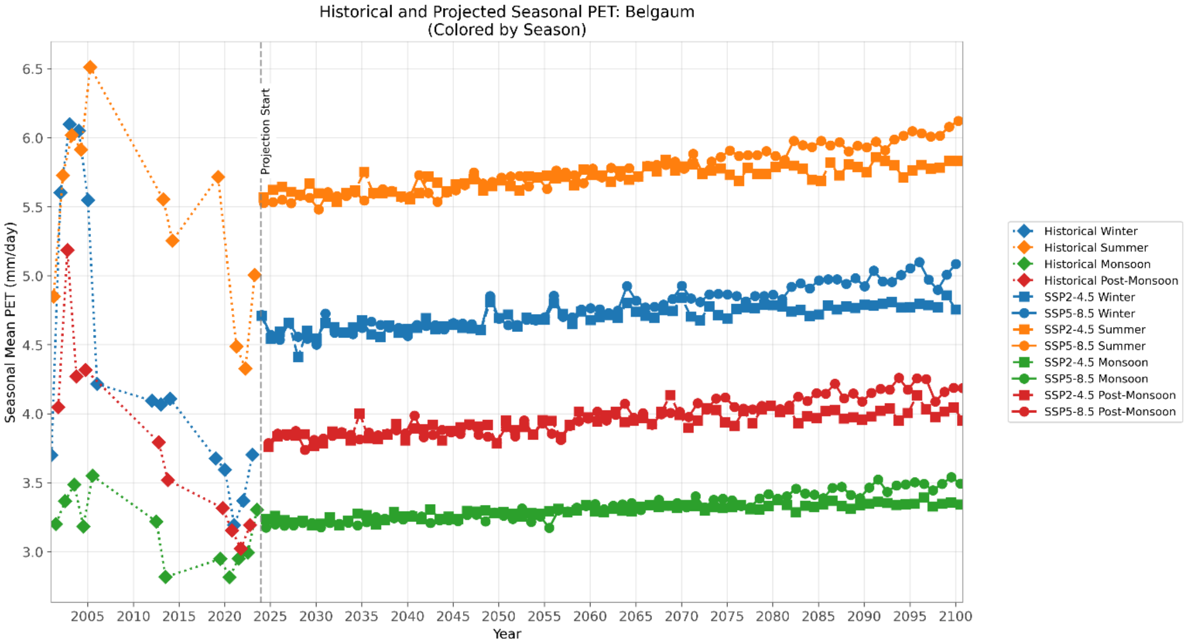

Figure 5 Temporal distribution of historical and projected seasonal PET over Belgaum

Overall, the Penman-Monteith based PET assessment reveals that Belgaum is poised to face a substantial increase in atmospheric water demand, especially under high-emission scenarios. These trends, if not addressed through adaptive irrigation planning, crop selection, and water resource management, could undermine agricultural productivity and exacerbate regional hydrological stress in the coming decades.

4.2 Bhopal

The historical assessment of Potential Evapotranspiration (PET) in Bhopal illustrates well-defined seasonal dynamics consistent with the region’s subtropical climate. The heatmap of historical PET from 2001–2024 **(Figure 6)** reveals that the highest PET values occur during the pre-monsoon and summer months (March to June), with monthly means typically ranging between 8 and 10 mm/day. This peak aligns with elevated temperatures, high solar radiation, and low humidity characteristic of this season. In contrast, winter months (December to February) consistently record the lowest PET values, averaging around 3.5 to 5 mm/day, due to lower temperatures, reduced solar insolation, and shorter photoperiods.

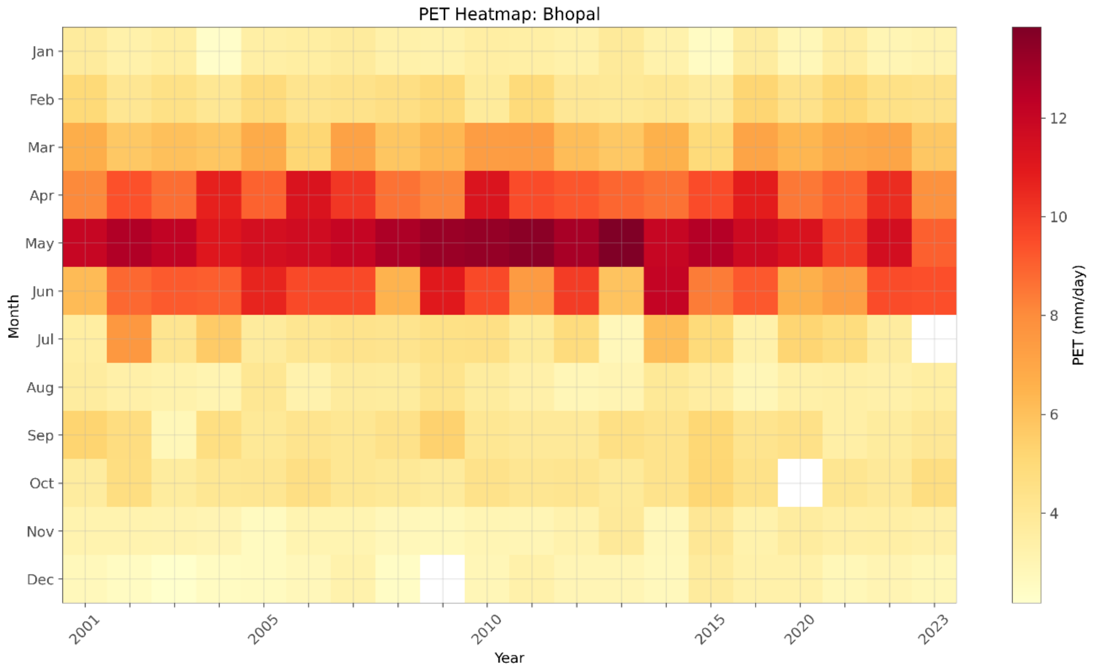

Figure 6 Historical Mean Monthly PET from 2001-2024 for Bhopal

The historical seasonal boxplot reinforces these trends **(Figure 7)**. The pre-monsoon season shows the highest median PET, approaching 9.5 mm/day, while winter exhibits the lowest, near 4 mm/day. The monsoon season, influenced by variable rainfall and cloud cover, presents a broader interquartile range (approximately 6 to 8.5 mm/day), indicating notable inter-annual variability. This variability likely stems from fluctuations in rainfall intensity, cloudiness, and wind patterns during the monsoon.

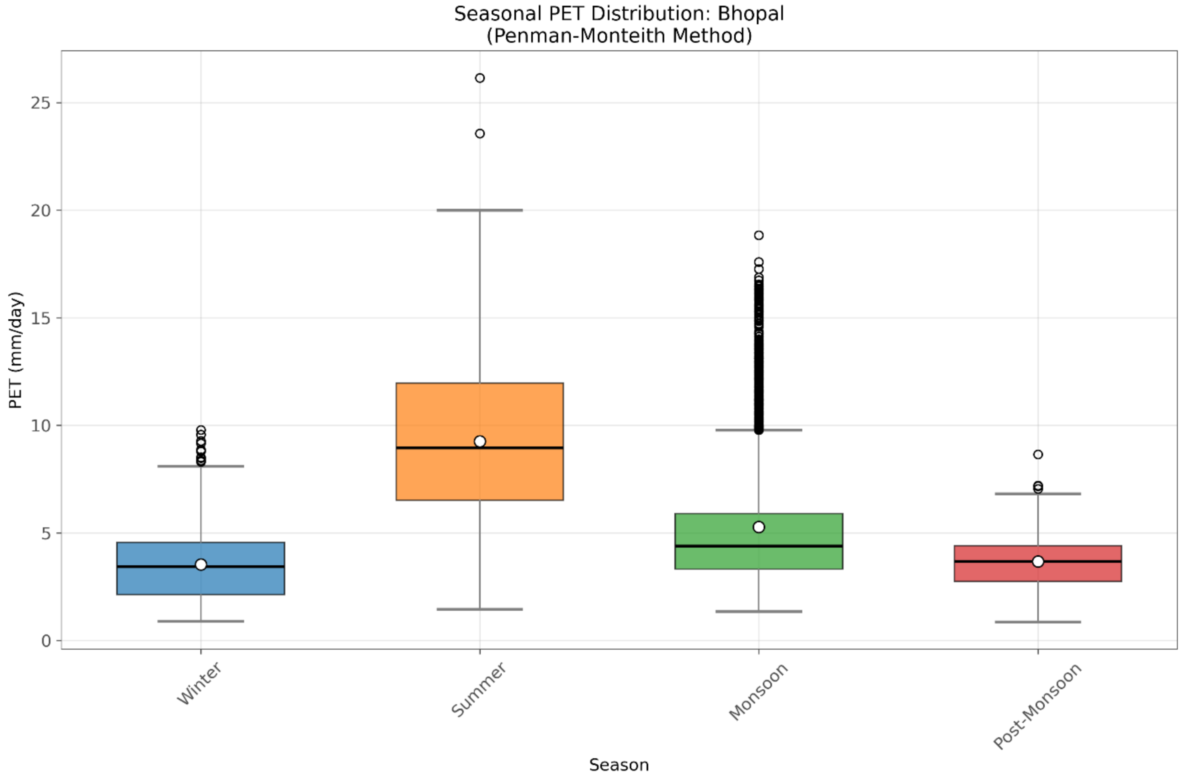

Figure 7 Historical seasonal PET distribution through boxplot for Bhopal

Projected PET changes under future climate scenarios show a consistent and intensifying trend of increasing PET across all seasons **(Figure 8)**. Under SSP2-4.5, pre-monsoon PET values are projected to increase to around 10.5–11 mm/day by the late century, with winter PET rising to approximately 5.5 mm/day. In contrast, the SSP5-8.5 scenario projects more extreme increases, with pre-monsoon PET values reaching 12–13 mm/day, and winter PET exceeding 6 mm/day. These shifts are driven not only by warming temperatures but also by changes in related meteorological parameters such as humidity, solar radiation, and wind speed.

Under SSP2-4.5, median pre-monsoon PET increases to around 10.5 mm/day, winter medians to 5.5 mm/day, and monsoon medians from about 7 mm historically to 8.5 mm/day. Under the high-emission SSP5-8.5 pathway, these shifts are even more pronounced: pre-monsoon PET medians rise to 12.5 mm/day, monsoon PET to 9.5 mm/day, and post-monsoon PET increases from a historical median of 5.5 mm/day to nearly 7.5 mm/day. These findings underscore that even traditionally cooler or less water-demanding seasons will face heightened atmospheric evaporative demand.

The seasonal PET time series from 2005 to 2100 further confirms a clear and consistent upward trajectory across all seasons. Under both SSP2-4.5 and SSP5-8.5, PET shows a steady rise, with a more pronounced slope under SSP5-8.5. For example, pre-monsoon PET increases from approximately 9.5 mm/day in 2005 to nearly 13 mm/day by 2100 under SSP5-8.5. Similarly, winter PET rises from around 4.5 mm/day to over 6 mm/day, and post-monsoon PET from about 5.5 to nearly 7.5 mm/day. These changes highlight a shift in seasonal water demands, suggesting that increased irrigation requirements will not be limited to the summer alone.

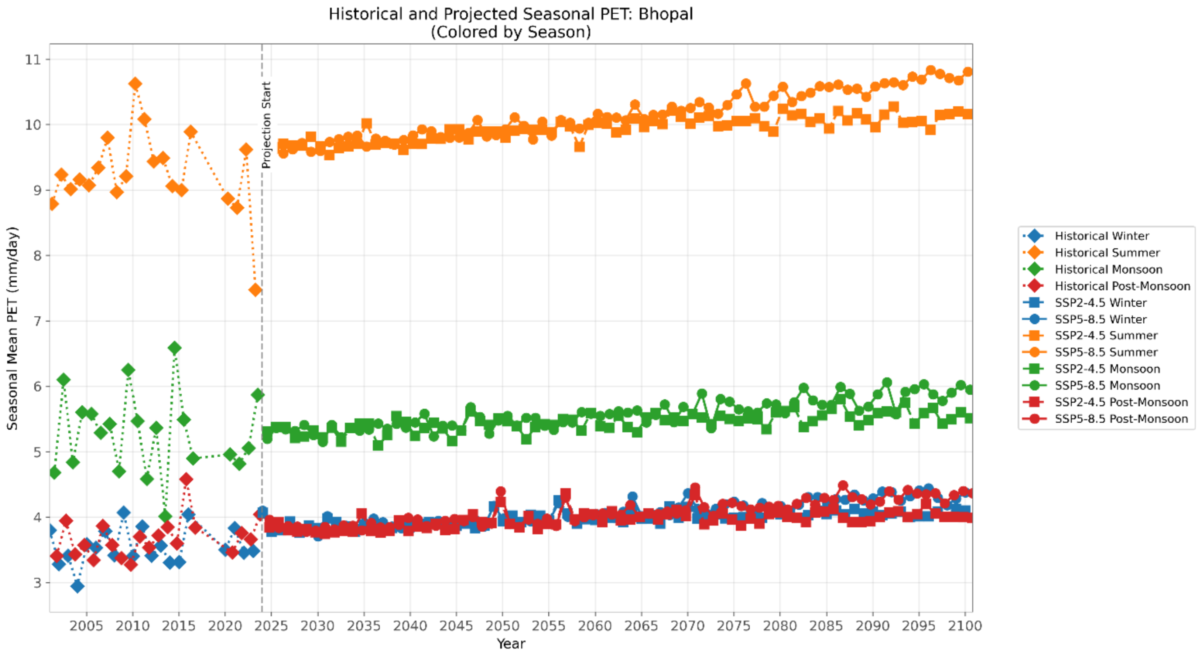

Figure 8 Temporal distribution of historical and projected seasonal PET over Bhopal

These trends have important implications for water resources and agriculture in Bhopal. As PET increases across all seasons, agricultural water demand is expected to rise, particularly affecting both rabi (winter) and kharif (monsoon) cropping systems. Under the SSP5-8.5 scenario, the combination of increased PET and potential climate-induced variability in precipitation could heighten the risk of water stress and drought, especially during the pre-monsoon and post-monsoon seasons. These challenges necessitate adaptive measures, including the adoption of efficient irrigation methods (e.g., drip, sprinkler), adjusted sowing calendars, and climate-resilient cropping strategies. Further, watershed management, groundwater recharge, and urban water planning will be essential to build resilience against these projected changes.

In conclusion, Bhopal's PET projections under future climate scenarios underscore the urgent need for integrated and proactive climate adaptation, especially in water-intensive sectors. Addressing these changes will be crucial to ensuring long-term agricultural productivity, water sustainability, and climate resilience for the region.

4.3 Guwahati

The climate analysis for Guwahati, based on both historical and projected scenarios, reveals significant seasonal and long-term variations in temperature and precipitation patterns. The historical heatmap **(Figure 9)** clearly shows that Guwahati experiences a strong monsoonal influence, with the bulk of annual rainfall concentrated between June and September, peaking in July. These months coincide with the Southwest Monsoon, which dominates the hydrological cycle of Northeast India.

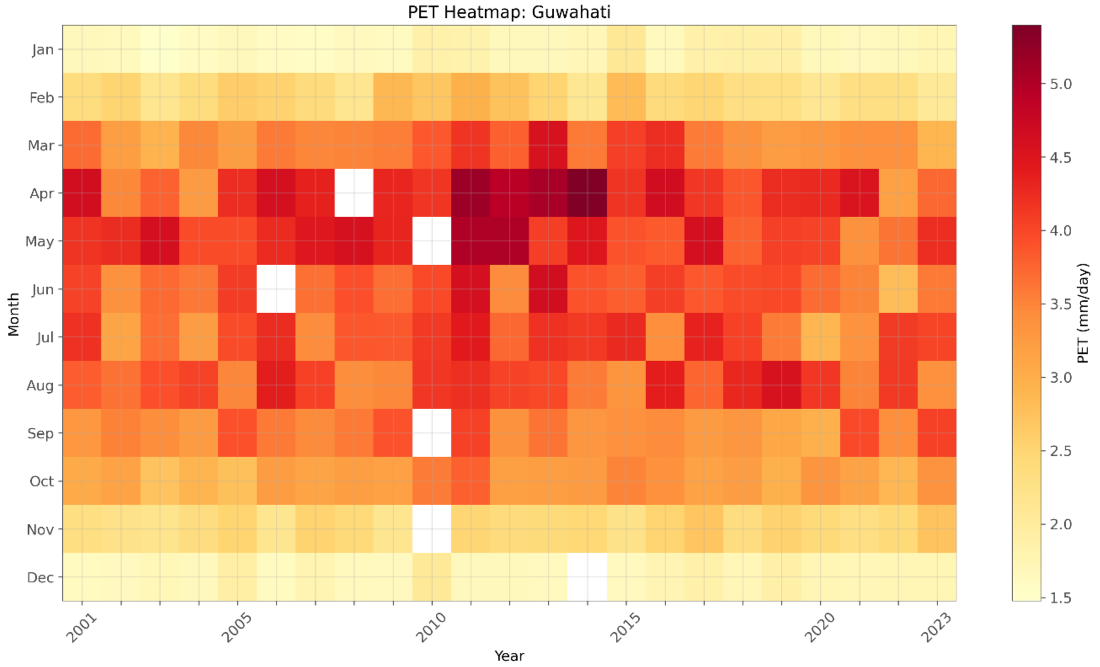

Figure 9 Historical Mean Monthly PET from 2001-2024 for Guwahati

The temperature pattern displays a typical subtropical trend, with maximum temperatures recorded between May and August, often exceeding 30°C. The seasonal boxplots **(Figure 10)** for the baseline period further affirm this, indicating a stable climatic regime with predictable monsoon and dry seasons.

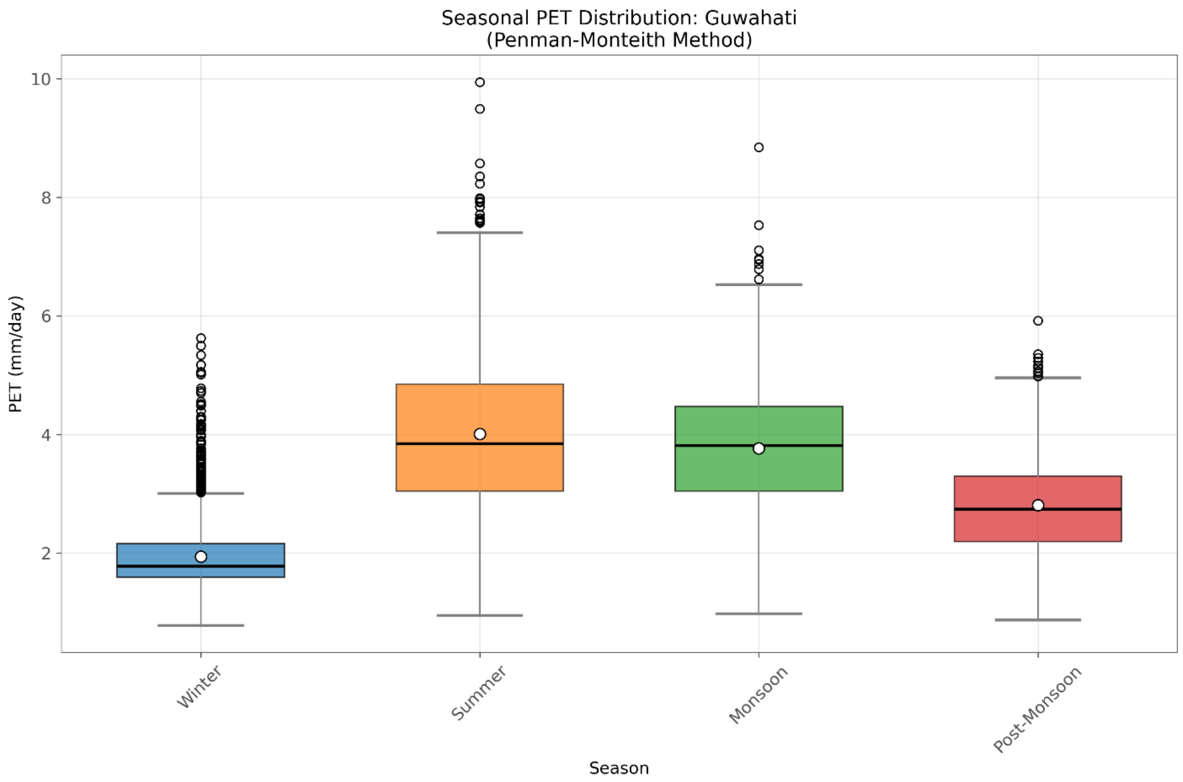

Figure 10 Historical seasonal PET distribution through boxplot for Guwahati

Projections under the ssp245 scenario indicate noticeable warming across all months, with the most pronounced temperature increases occurring in the pre-monsoon (March–May) and post-monsoon (October–November) periods. Temperatures in these months are projected to rise by approximately 1.5°C to 2.5°C. Rainfall remains primarily monsoonal, but there are subtle changes in its distribution, with indications of shifting monsoon onset and retreat, especially in June and September. These shifts could affect crop planning, groundwater recharge, and urban water management. The increase in temperature during the pre-monsoon period may also enhance heat stress and energy demand for cooling, compounding urban climate risks.

Under the high-emission ssp585 scenario, the projected changes are more severe. Temperatures are expected to rise by more than 3°C across most months, with the greatest warming observed during the pre-monsoon season, where the temperature anomaly reaches up to 3.5°C to 4°C. This increase poses a significant risk of more frequent and intense heatwaves, particularly in urban areas like Guwahati, which are vulnerable due to high population density and limited adaptive infrastructure. Rainfall under ssp585 also exhibits greater variability, with some months, such as August and September, potentially experiencing reduced or more erratic precipitation. This variability introduces uncertainty into water resource planning and heightens the risk of both droughts and short-term flooding events due to extreme rainfall bursts.

Both ssp245 and ssp585 show a clear upward shift in seasonal median temperatures **(Figure 11)**, with increased interquartile ranges, suggesting a trend toward greater temperature variability and more frequent extreme temperature events. In terms of precipitation, while the monsoon remains the dominant wet season, the projections for the pre-monsoon and post-monsoon periods show increased variability, especially under ssp585. This points to a possible redistribution of rainfall across seasons, making water availability more unpredictable and potentially exacerbating seasonal drought risks.

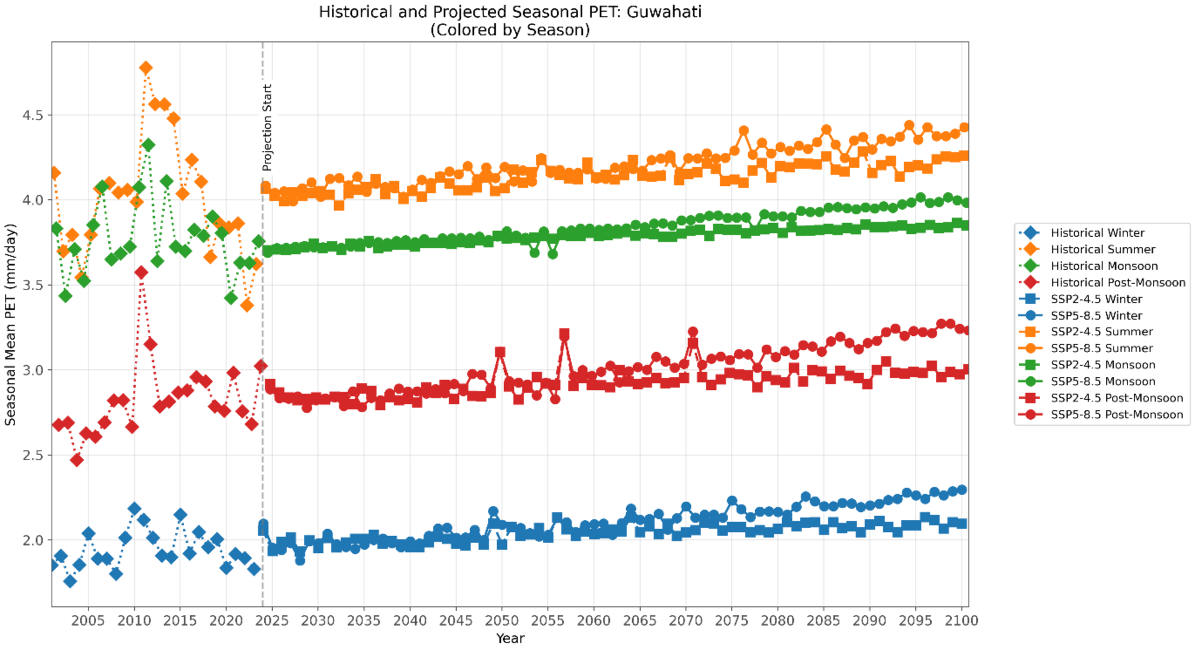

Figure 11 Temporal distribution of historical and projected seasonal PET over Guwahati

Overall, the visualizations and statistical analyses of the future climate projections underscore the importance of integrating climate adaptation into regional planning. The increasing temperatures and variability in rainfall suggest a need for early warning systems for heatwaves, enhanced urban planning to mitigate heat island effects, and robust water resource management strategies. Guwahati's vulnerability to both excess rainfall and dry spells highlights the urgency of developing flexible and forward-looking policies. Adaptation strategies should prioritize climate-resilient infrastructure, improved agro-meteorological services, and enhanced coordination between urban planning and environmental management. These interventions will be critical to building climate resilience in the face of projected changes, particularly under a high-emissions trajectory.

4.4 Jammu

The historical assessment of Potential Evapotranspiration (PET) in Jammu highlights pronounced seasonal variability aligned with the region's subtropical climate and complex topography. The heatmap of historical PET from 2001–2024 **(Figure 12)** reveals the highest PET values during the pre-monsoon and summer months (March to June), with average daily PET typically ranging from 8 to 10 mm/day. This seasonal peak coincides with elevated air temperatures, high solar radiation, and low relative humidity conditions that strongly favor atmospheric evaporative demand. Conversely, the winter season (December to February) consistently exhibits the lowest PET values, averaging between 3.5 and 5 mm/day, driven by cooler temperatures, shorter daylight hours, and reduced solar intensity.

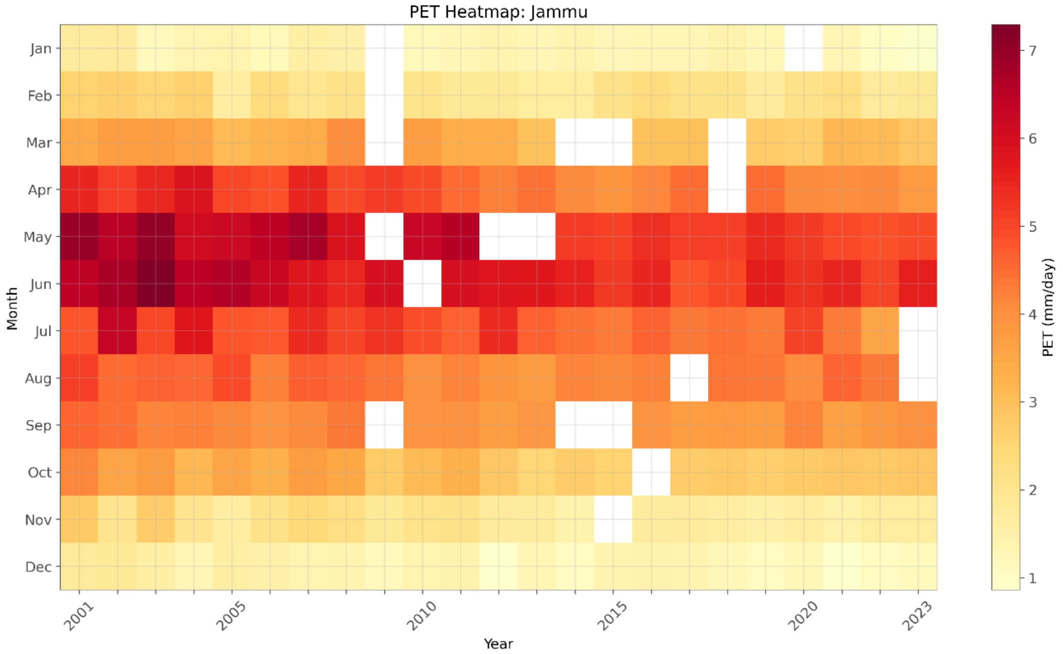

Figure 12 Historical Mean Monthly PET from 2001-2024 for Jammu

The historical seasonal boxplot **(Figure 13)** further substantiates these seasonal trends. The pre-monsoon season displays the highest median PET, around 9.5 mm/day, while winter shows the lowest median near 4 mm/day. The monsoon season (June to September) features a wider interquartile range, from approximately 6 to 8.5 mm/day, suggesting considerable inter-annual variability. This variability likely results from fluctuations in monsoonal rainfall, cloud cover, and wind dynamics that influence both energy availability and moisture conditions.

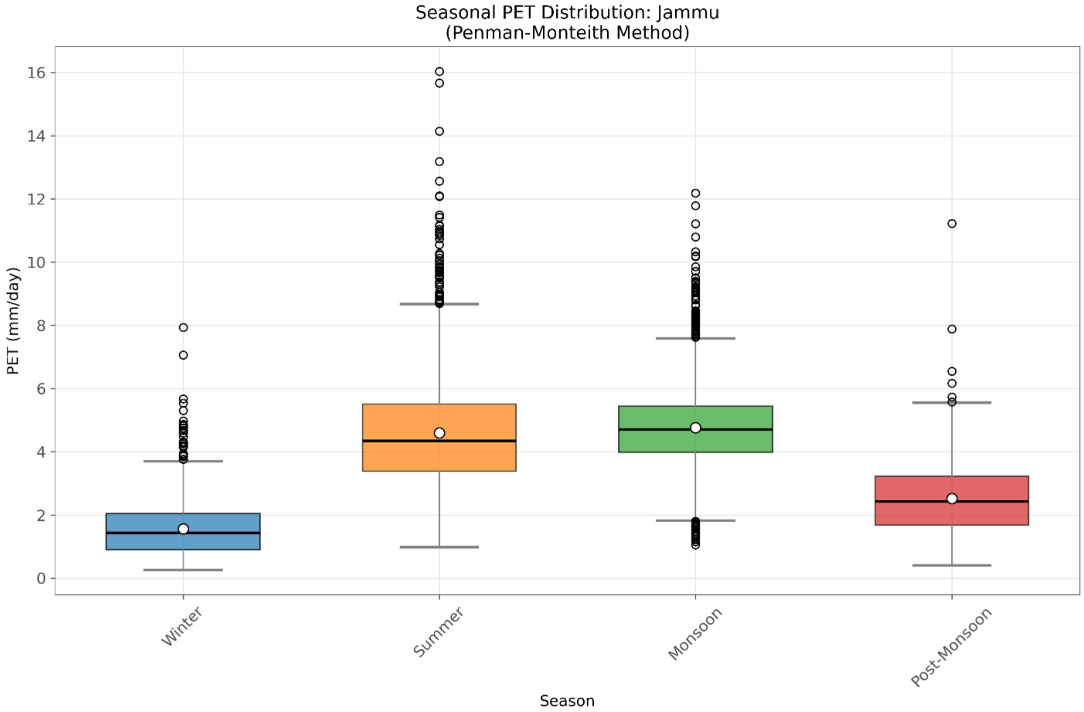

Figure 13 Historical seasonal PET distribution through boxplot for Jammu

Projections of PET under future climate scenarios indicate a clear intensification in evaporative demand across all seasons. The PET heatmaps for SSP2-4.5 and SSP5-8.5 scenarios exhibit a strong upward shift in PET values through the 21st century, with particularly notable increases during the pre-monsoon period. Under SSP2-4.5, pre-monsoon PET values are projected to reach approximately 10.5–11 mm/day by the century's end, while winter PET increases to around 5.5 mm/day. Under the more extreme SSP5-8.5 pathway, PET values surge further, with pre-monsoon PET reaching 12–13 mm/day and winter PET rising beyond 6 mm/day. These increases are driven not only by regional warming but also by compounding changes in solar radiation, humidity, and wind speed.

The future seasonal boxplots (2025–2100) provide additional insight. Under SSP2-4.5, the median pre-monsoon PET increases to about 10.5 mm/day, while monsoon and winter medians rise to approximately 8.5 mm/day and 5.5 mm/day, respectively. Under SSP5-8.5, these medians are substantially higher: pre-monsoon PET reaches 12.5 mm/day, monsoon PET rises to 9.5 mm/day, and post-monsoon PET climbs from its historical median of 5.5 mm/day to around 7.5 mm/day. These trends suggest an across-the-board increase in atmospheric water demand, extending even to traditionally cooler seasons.

The seasonal PET time series from 2001 to 2100 confirms a persistent upward trend across all seasons **(Figure 14)**. Both SSP2-4.5 and SSP5-8.5 scenarios demonstrate steady PET increases, with the latter showing a steeper trajectory. For instance, pre-monsoon PET rises from around 9.5 mm/day in 2005 to nearly 13 mm/day by 2100 under SSP5-8.5. Winter PET shows a similar upward shift from about 4.5 to over 6 mm/day, while post-monsoon PET climbs from roughly 5.5 to almost 7.5 mm/day. These increases underscore that rising PET will not be confined to summer months but will increasingly affect the entire seasonal cycle.

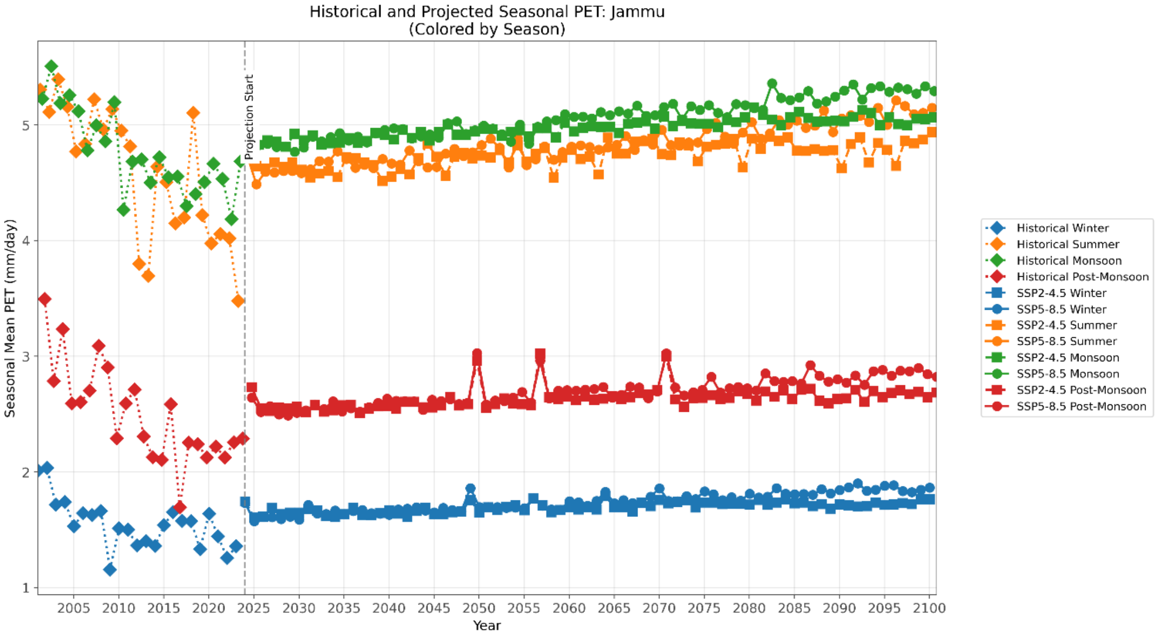

Figure 14 Temporal distribution of historical and projected seasonal PET over Jammu

These shifts have critical implications for water management and agriculture in Jammu. As PET intensifies, water requirements for crops are expected to grow across all growing seasons, including the rabi (winter) and kharif (monsoon) periods. Under the high-emission SSP5-8.5 scenario, rising PET coupled with potential changes in precipitation patterns could lead to heightened drought risk and water scarcity, especially during the pre-monsoon and post-monsoon periods. Effective adaptation strategies will be essential, such as implementing water-efficient irrigation systems, revising crop calendars, adopting climate-resilient crop varieties, and enhancing watershed and groundwater management.

In conclusion, projected PET increases for Jammu reflect a growing need for proactive adaptation in the face of climate change. Integrated water resource management, agricultural planning, and infrastructure development must account for these evolving climatic pressures to safeguard regional water security and agricultural sustainability.

4.5 Jodhpur

The seasonal and temporal analysis of Potential Evapotranspiration (PET) in Jodhpur, estimated via the FAO Penman-Monteith method, highlights significant patterns and changes that bear critical implications for regional water resources and drought management. The baseline PET heatmap **(Figure 15)**, representing historical or observed climatic conditions, indicates that PET values in Jodhpur vary prominently across seasons, with the highest values observed during the pre-monsoon and summer months (April to June). Specifically, PET during May frequently reaches values around 9.5–10.5 mm/day, reflecting intense solar radiation, high temperatures, and low relative humidity. In contrast, during the winter months (December–January), PET values drop significantly to about 2.0–2.5 mm/day, indicative of lower atmospheric demand.

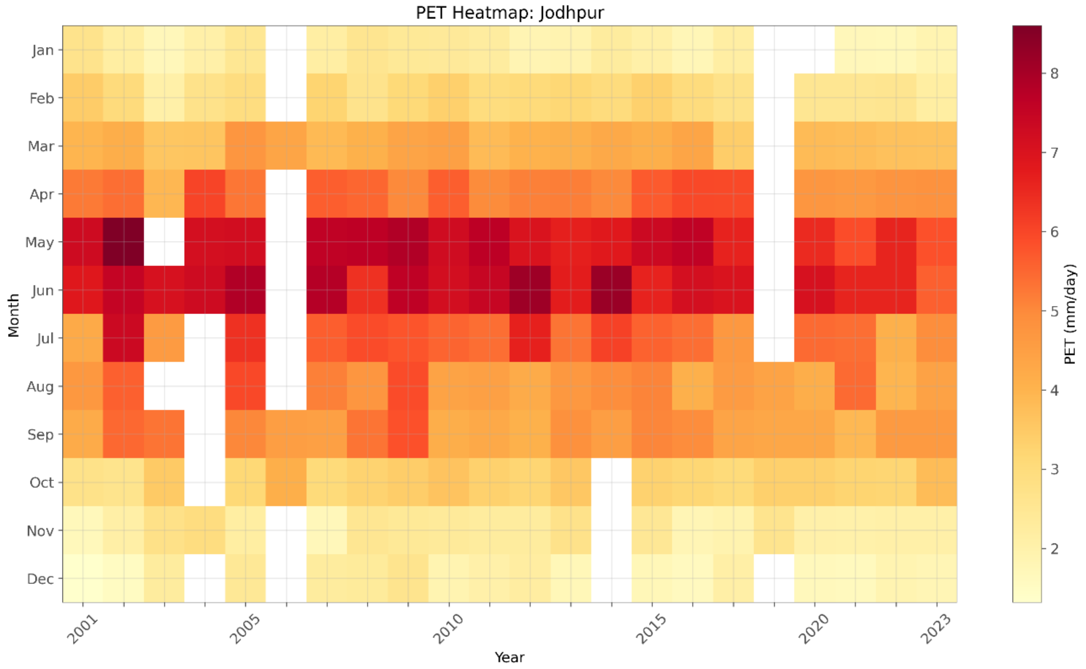

Figure 15 Historical Mean Monthly PET from 2001-2024 for Jodhpur

The seasonal boxplots for the baseline scenario **(Figure 16)** reinforce this trend, showing that the summer and monsoon seasons have the highest median PET values, with summer peaking near 9.8 mm/day, and monsoon medians ranging between 6.5 and 7.5 mm/day. Notably, the monsoon season still sustains high PET values due to persistent heat, despite the presence of rainfall. Winter exhibits the lowest PET medians of around 2.2 mm/day, while the post-monsoon period sees modest recovery to 3.5–4.5 mm/day.

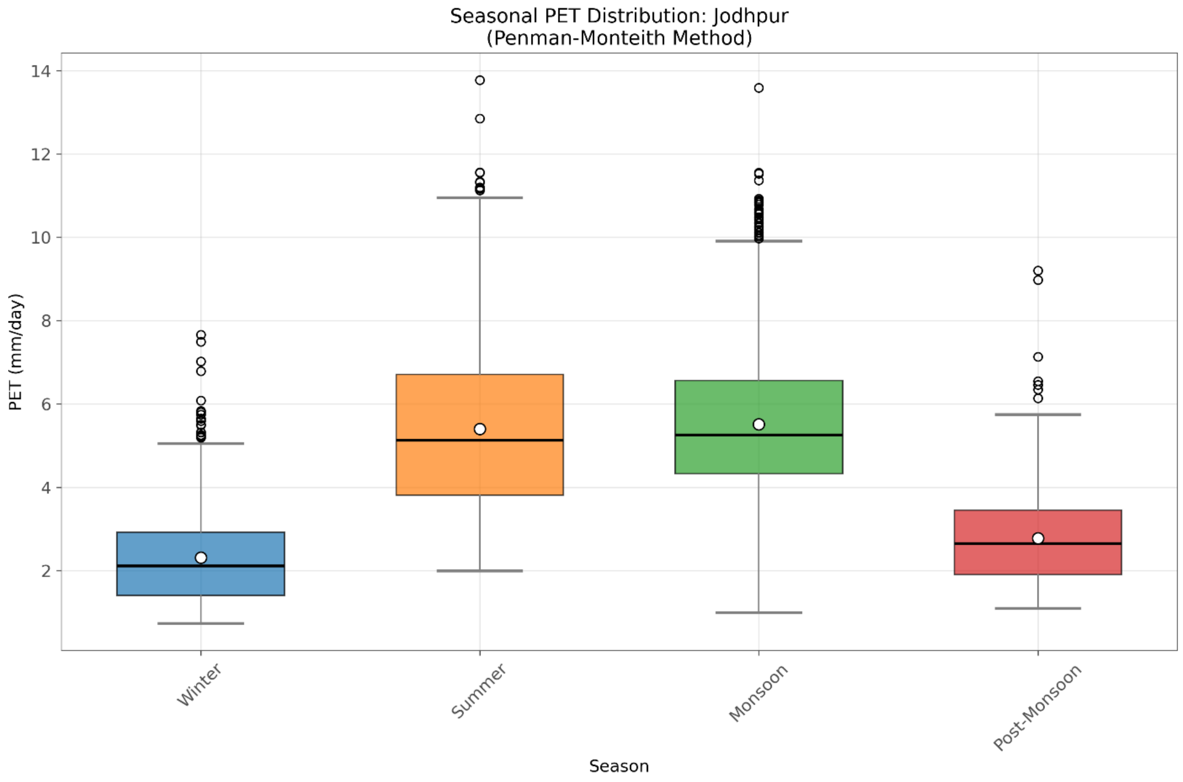

Figure 16 Historical seasonal PET distribution through boxplot for Jodhpur

Under future climate scenarios **(Figure 17)**, PET was scaled to reflect increased atmospheric demand Scenario -4.5 and Scenario -8.5 likely representing 4.5% and 8.5% increases in radiative and temperature forcing, respectively. These future projections show significant amplification in PET across all seasons. In Scenario -4.5, the maximum summer PET rises to approximately 11.2 mm/day, with median values in the monsoon and summer seasons increasing to 8.0 mm/day and 10.3 mm/day, respectively. Even winter PET shows a rise, with median values reaching around 2.8 mm/day.

The impact is even more pronounced in Scenario -8.5. Here, PET values during May and June reach up to 12.5 mm/day, while median values during the summer season approach 11.0 mm/day. The monsoon median increases to approximately 9.2 mm/day, and the winter medians exceed 3.0 mm/day. This sharp upward trend signifies a stronger and longer evaporative pull, severely impacting crop water needs and irrigation efficiency.

Additionally, the seasonal boxplots demonstrate an increasing spread and interquartile range in PET values in future scenarios, especially under Scenario -8.5. This indicates that not only will PET increase on average, but the variability and frequency of extremely high PET days will also grow. Such conditions imply heightened risk of agricultural droughts, as increased PET could outpace rainfall, reducing effective soil moisture and increasing crop water stress.

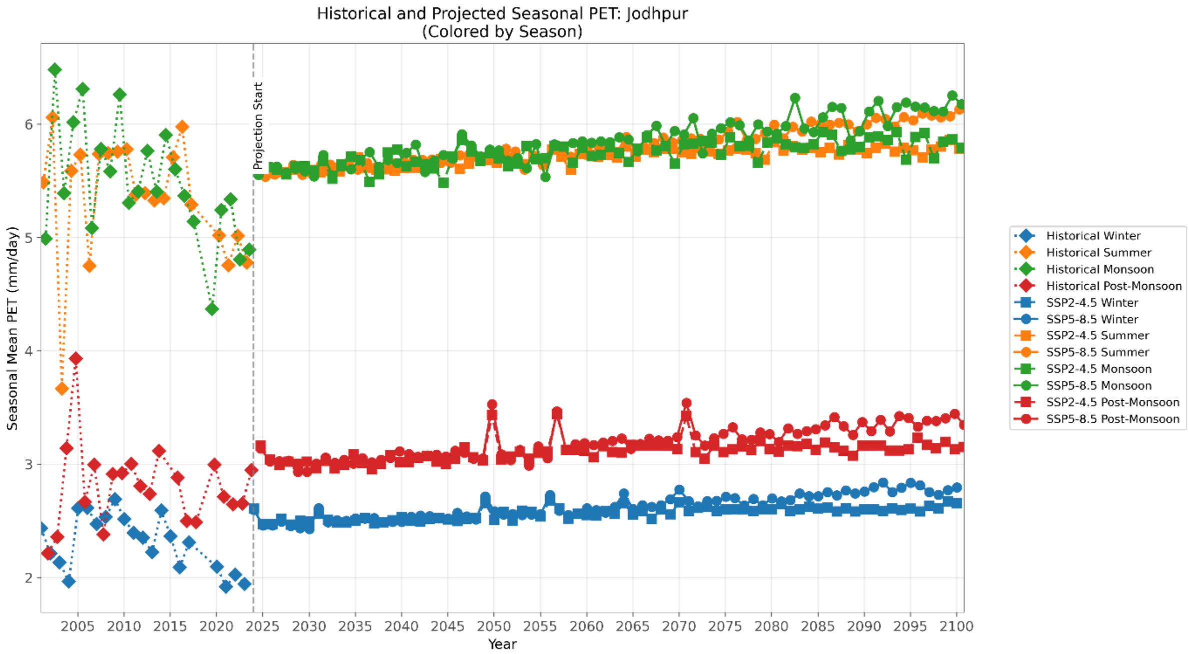

Figure 17 Temporal distribution of historical and projected seasonal PET over Jodhpur

In summary, the Penman-Monteith based PET analysis for Jodhpur clearly shows that the region is moving toward a future with significantly higher atmospheric water demand. With peak PET values projected to rise from ~10 mm/day to over 12.5 mm/day, and consistent increases across all seasons, proactive planning for irrigation scheduling, drought mitigation, and water conservation becomes imperative. These results emphasize the importance of integrating PET projections into regional climate adaptation and water resource management strategies.

4.6 Kakinada

The historical and projected patterns of Potential Evapotranspiration (PET) in Kakinada reveal significant seasonal and interannual variations, with clear indications of warming and increased atmospheric water demand under future climate scenarios. The trends by the temporal heatmap visualizations of monthly PET values from the historical period are shown in **Figure 18**. The historical heatmap reveals a seasonal rhythm, with maximum PET occurring between April and June, coinciding with the pre-monsoon heat. The pattern is relatively stable over years, indicating consistent seasonal cycles in the past. In contrast, the SSP2-4.5 shows a noticeable progression toward higher PET values over time, with the onset of peak PET months advancing into March and elevated values persisting into October, suggesting a lengthening of the high evaporative demand period. This indicates that future climate conditions may bring about earlier onset and delayed withdrawal of the dry-hot season, effectively altering the hydrological regime.

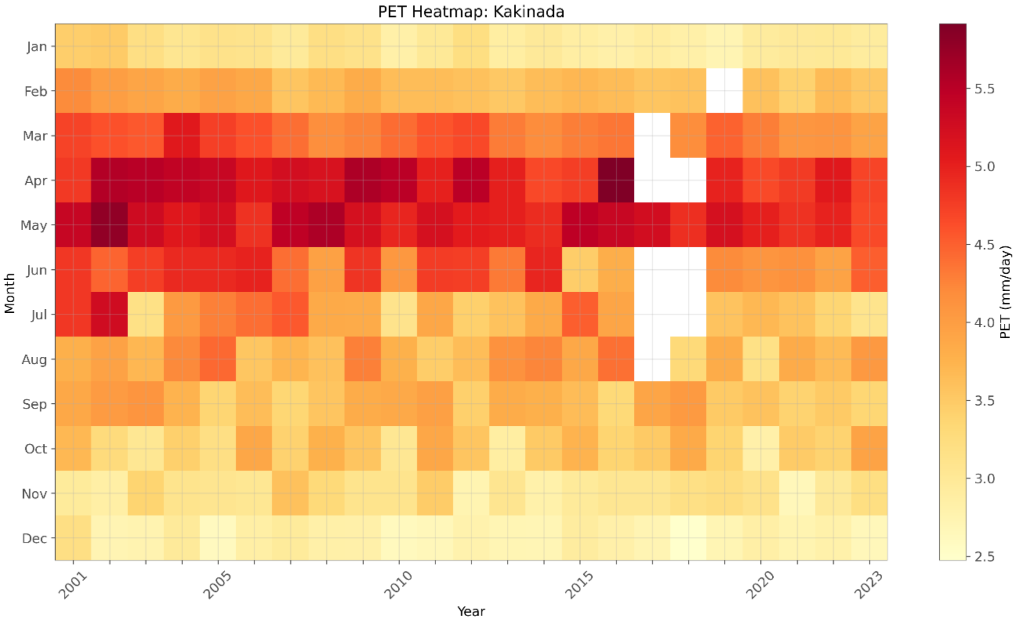

Figure 18 Historical Mean Monthly PET from 2001-2024 for Kakinada

The historical seasonal boxplot **(Figure 19)** of PET illustrates a well-defined climatological cycle, where summer (March–May) and monsoon (June–September) months exhibit the highest median PET values, peaking during May and June, reflecting intense solar radiation and high temperatures characteristic of coastal Andhra Pradesh. The winter season (December–February) shows the lowest PET values, with minimal variability, corresponding to cooler temperatures and lower insolation. The interquartile ranges (IQR) in the monsoon and summer seasons are noticeably broader than in winter and post-monsoon seasons, suggesting a greater intra-seasonal spread in atmospheric evaporative demand, potentially influenced by interannual rainfall variability and temperature anomalies during the monsoon period.

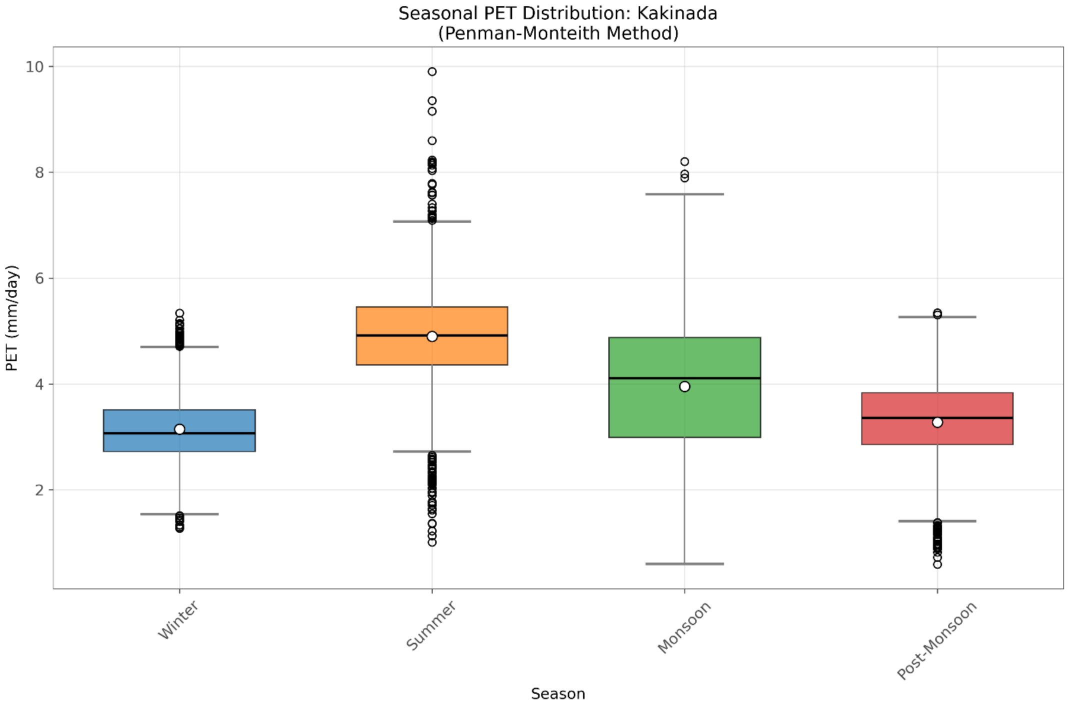

Figure 19 Historical seasonal PET distribution through boxplot for Kakinada

When future projections are considered **(Figure 20)**, based on CMIP6 simulations for SSP2-4.5 (medium emissions) and SSP5-8.5 (high emissions), a marked upward shift in PET is evident across all seasons. The seasonal boxplot under SSP2-4.5 shows a consistent rise in median PET across all four seasons compared to the historical period, with the summer and monsoon medians rising by approximately 10–15%, and even post-monsoon and winter seasons showing elevated values. This suggests that even under moderate mitigation, the evaporative demand in the region will intensify, potentially exacerbating water stress during the dry season and altering crop water requirements. The boxplots under SSP5-8.5, however, indicate a more alarming trend. PET values not only increase substantially, particularly during the summer (up to 20–25% higher median than historical) but also show a significant widening of the IQRs, indicating greater variability and an increased likelihood of extreme high PET events. Such elevated and fluctuating PET values can severely impact irrigation planning, groundwater recharge, and urban water security in Kakinada.

The SSP5-8.5 depicts the most intense changes, with large swathes of the annual cycle across many years showing extremely high PET values (above 6–7 mm/day in several months). The heat is no longer restricted to typical pre-monsoon months but increasingly dominates the post-monsoon (OND) and even parts of the winter season, pointing toward persistent atmospheric drying. These shifts suggest that Kakinada will face prolonged periods of high evaporative loss, with critical implications for agriculture, freshwater ecosystems, and urban infrastructure resilience. Increased PET without a proportional increase in precipitation would reduce effective moisture availability and raise crop water demand, necessitating the re-evaluation of existing irrigation schedules, cropping patterns, and water harvesting infrastructure.

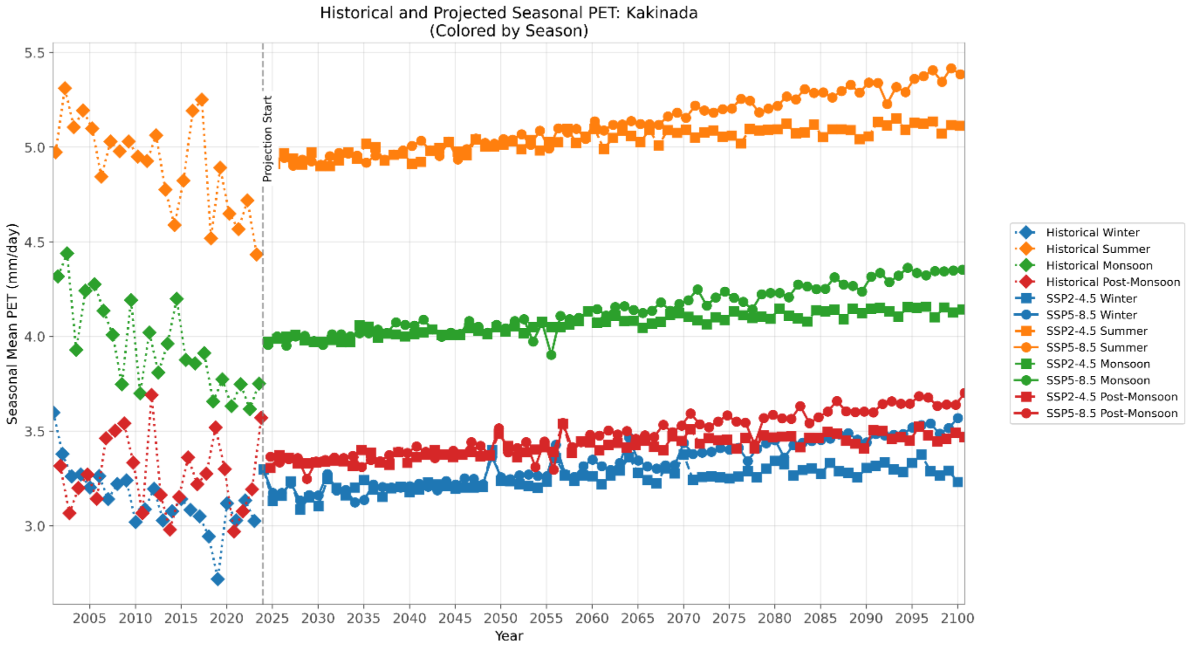

Figure 20 Temporal distribution of historical and projected seasonal PET over Kakinada

Overall, the consistent rise in PET across all seasons under both emission pathways, with significantly intensified effects under SSP5-8.5, underscores the urgent need for climate-resilient planning. Adaptation strategies should include enhancing water use efficiency, expanding rainwater harvesting capacity, and developing PET-informed early warning systems for drought. The insights from both boxplots and heatmaps collectively illustrate that Kakinada is poised to experience not only higher temperatures but also prolonged and intensified evaporative stress, with cascading impacts on agriculture, water resources, and urban sustainability unless effective mitigation and adaptation measures are implemented in time.

4.7 Patna

The historical assessment of Potential Evapotranspiration (PET) in Patna reveals distinct seasonal patterns. The heatmap of historical PET from 2001–2024 **(Figure 21)** demonstrates that the summer months (April to June) consistently record the highest PET values, with monthly means frequently ranging from 9 to 11 mm/day, indicative of the intense pre-monsoon heat and high solar radiation. In contrast, the winter months (December to February) show significantly lower PET values, generally between 3 to 5 mm/day, consistent with cooler temperatures and reduced daylight.

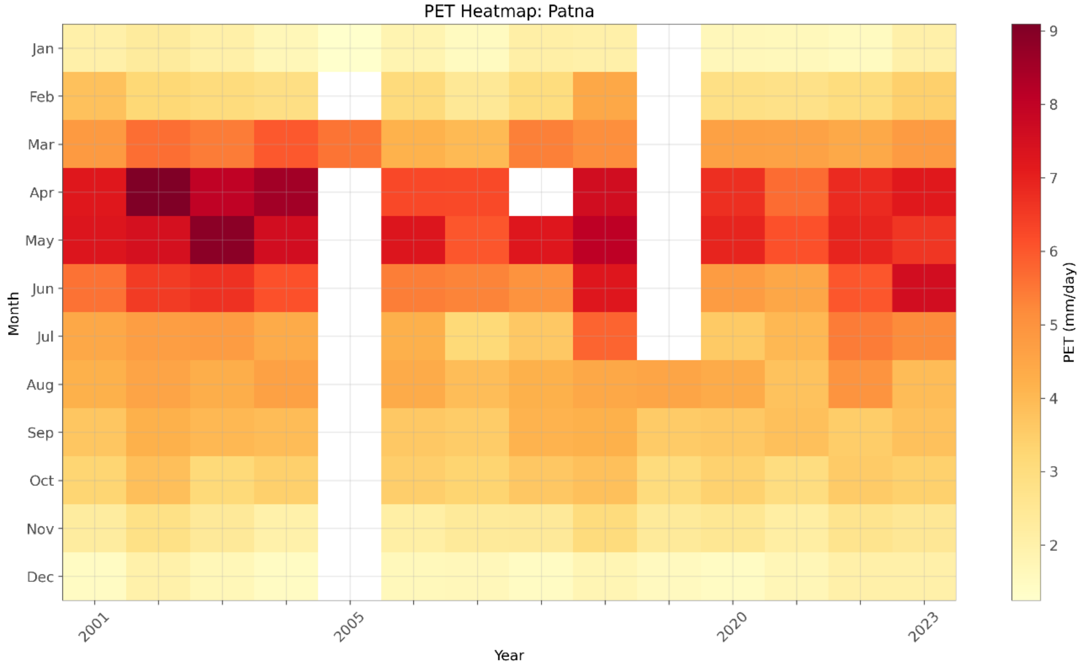

Figure 21 Historical Mean Monthly PET from 2001-2024 for Patna

This seasonal variability is further emphasized in the historical seasonal boxplot **(Figure 22),** which aggregates data across years and clearly shows that the summer season has the highest median PET, exceeding 10 mm/day, while the winter season exhibits the lowest median, around 4 mm/day. The monsoon season, despite higher humidity, presents a wide interquartile range in PET values, typically ranging from 6 to 9 mm/day, suggesting inter-annual variability due to fluctuating cloud cover, rainfall intensity, and solar input.

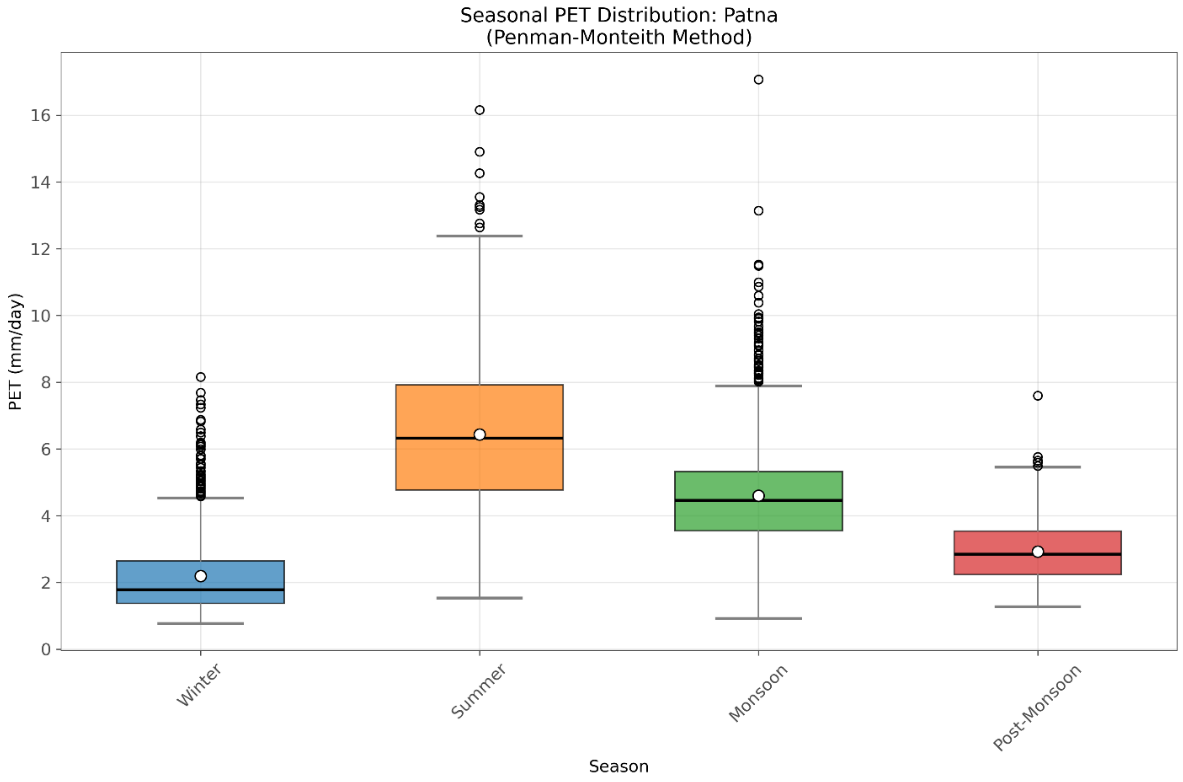

Figure 22 Historical seasonal PET distribution through boxplot for Patna

Projected changes in PET under future climate scenarios reveal a concerning intensification. The PET heatmaps for SSP2-4.5 and SSP5-8.5 scenarios show a progressive increase in PET values across most months during the 21st century. Under SSP2-4.5, which assumes moderate mitigation efforts, PET increases are visible but relatively moderate; for example, summer PET values shift upwards to 11–12 mm/day, while winter values climb to 5–6 mm/day by late-century. However, under SSP5-8.5, representing a high-emissions trajectory, the increase is more pronounced and persistent across all months. By the late 21st century, summer PET under SSP5-8.5 reaches 13–14 mm/day, and winter values exceed 6 mm/day, indicating a substantial rise in atmospheric evaporative demand across the year. This intensification of PET under a warming climate could substantially increase crop water requirements and challenge water resource sustainability in the region.

Seasonal boxplots for the future period (2025–2100) further highlight this **trend (Figure 23)**. Under SSP2-4.5, the median PET in summer increases to around 11 mm/day, and winter values rise to approximately 5.5 mm/day. For SSP5-8.5, the median summer PET approaches 13 mm/day, and monsoon season PET also increases significantly, with medians near 10 mm/day. The post-monsoon season, traditionally more stable, also shows a marked rise, from historical medians around 5 mm/day to future values nearing 7 mm/day under the high-emissions pathway. These shifts indicate that all seasons in the future will experience higher evaporative demand, likely driven by rising temperatures and potential changes in wind speed, humidity, and radiation regimes.

Further insights are drawn from the seasonal PET time series spanning from 2005 to 2100, which shows a clear and steady upward trend in PET across all seasons for both scenarios. The rate of increase is more pronounced under SSP5-8.5, where summer PET rises from about 10 mm/day in 2005 to nearly 14 mm/day by 2100. Similarly, winter PET increases from around 4.5 mm/day to more than 6 mm/day over the same period. Notably, post-monsoon PET, which remained relatively unchanged historically, shows a significant increase under both scenarios, indicating that even traditionally low-demand seasons will become more water-intensive in the future.

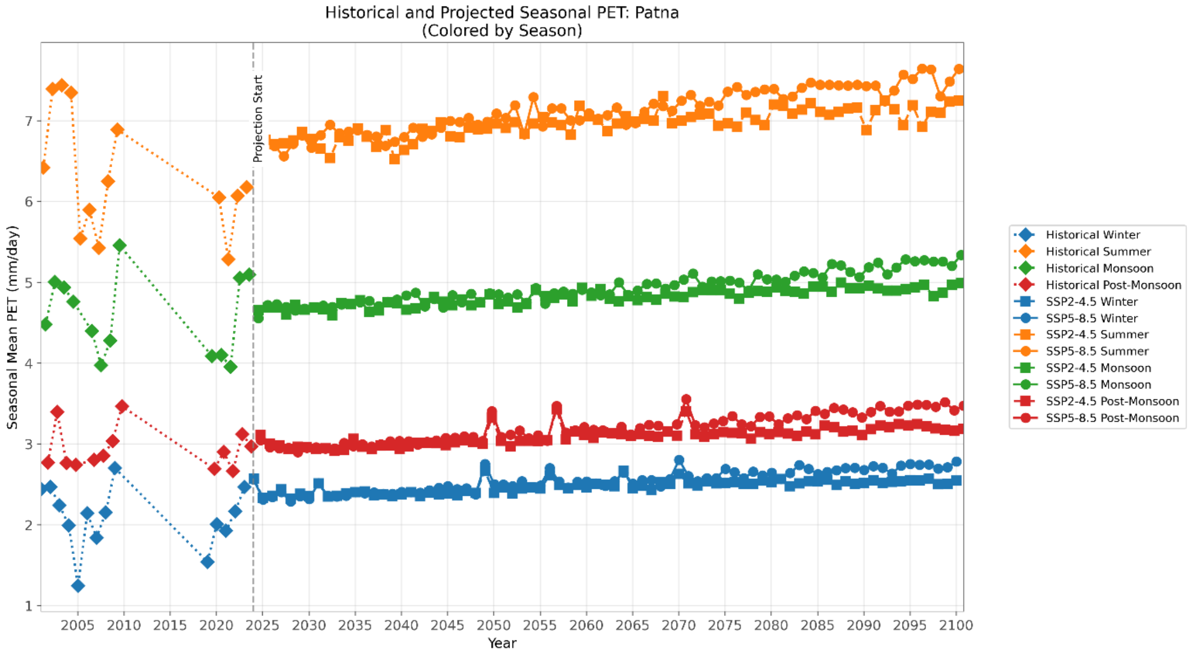

Figure 23 Temporal distribution of historical and projected seasonal PET over Patna

These findings have substantial implications for water management and agriculture in Patna. Increased PET translates directly to higher crop water requirements, especially during the rabi (winter) and kharif (monsoon) cropping seasons. Under the SSP5-8.5 scenario, the compounding effects of elevated temperatures and increased PET could lead to more frequent and severe agricultural droughts and water stress episodes. Adaptation strategies will be essential and may include implementation of micro-irrigation technologies such as drip and sprinkler systems, adjustment of cropping calendars and crop varieties, and watershed management approaches aimed at enhancing groundwater recharge and surface water retention. In summary, PET projections for Patna under future climate scenarios underscore the urgent need for proactive climate adaptation in the water and agriculture sectors.

4.8 Roorkee

The historical assessment of Potential Evapotranspiration (PET) in Roorkee reveals distinct seasonal patterns that align with the region's climatic regime. The heatmap of historical PET from 2001–2024 **(Figure 24)** shows that the highest PET values are concentrated during the summer months (April to June), with monthly means typically ranging from 8 to 10 mm/day. This seasonal peak corresponds to elevated temperatures and high solar radiation during the pre-monsoon season. Conversely, the winter months (December to February) consistently show the lowest PET values, averaging around 3 to 5 mm/day, which aligns with reduced temperatures, shorter daylight hours, and lower solar input.

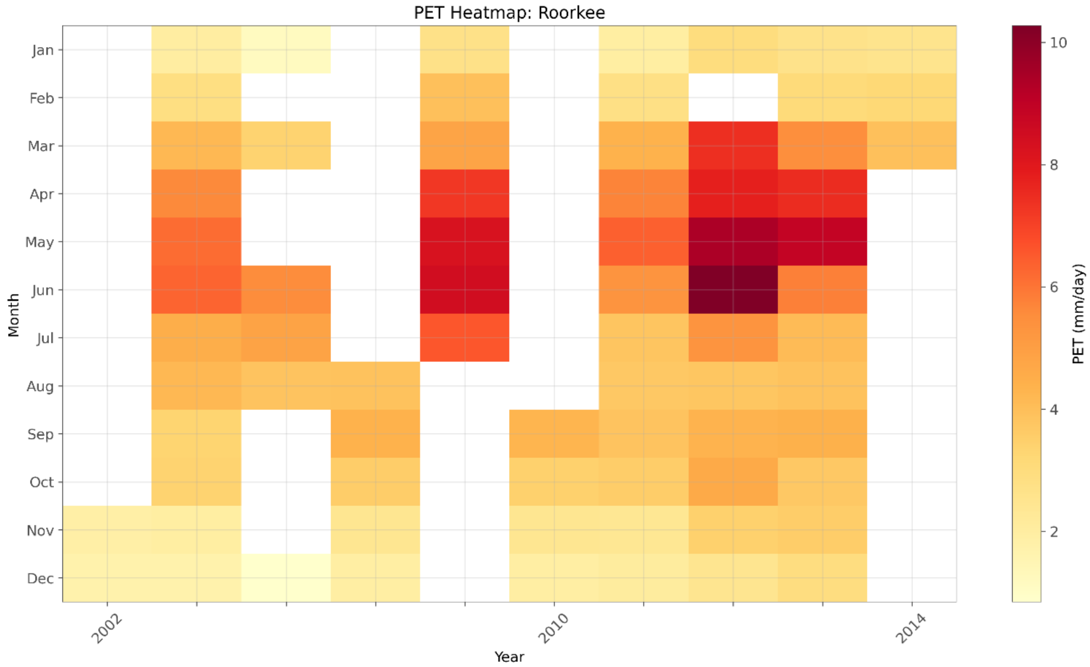

Figure 24 Historical Mean Monthly PET from 2001-2024 for Roorkee

The historical seasonal boxplot further reinforces these observations **(Figure 25)**, with the summer season showing the highest median PET of approximately 9.5 mm/day, and the winter season displaying the lowest median near 4 mm/day. The monsoon season presents a broader interquartile range of PET values (roughly 6 to 8.5 mm/day), suggesting greater inter-annual variability influenced by fluctuations in rainfall, cloud cover, and atmospheric humidity.

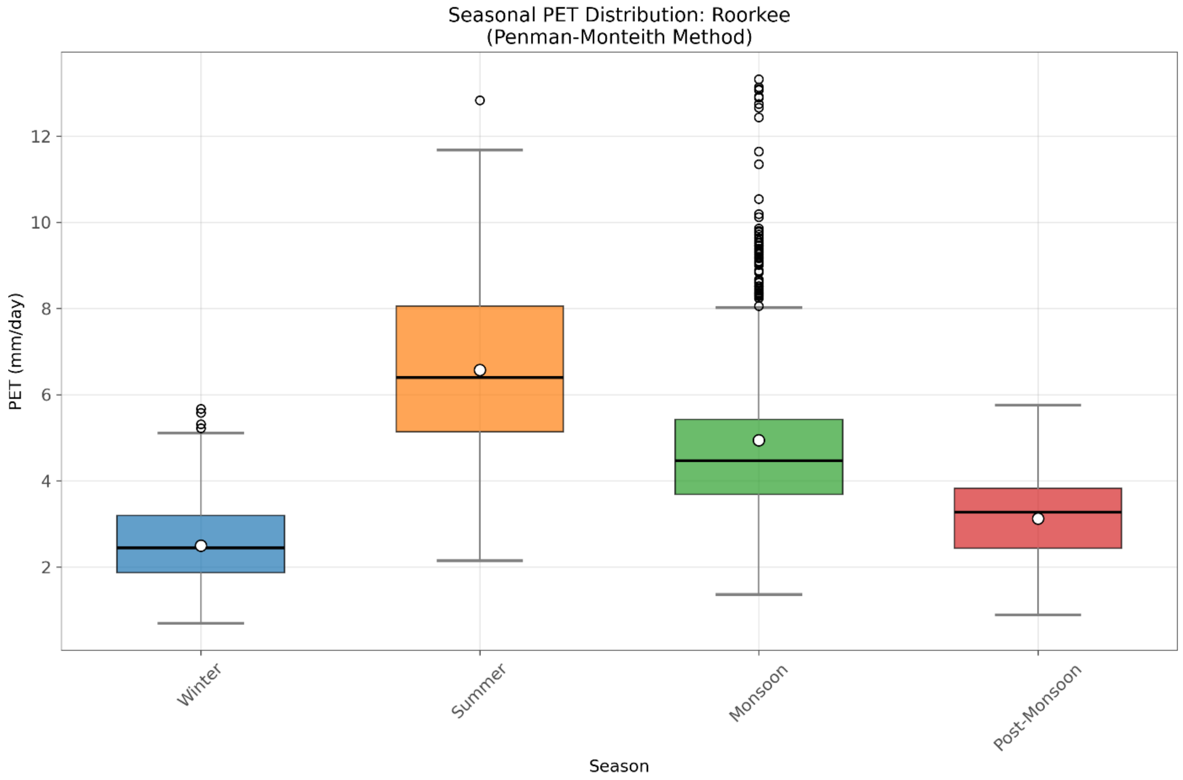

Figure 25 Historical seasonal PET distribution through boxplot for Roorkee

Projected changes in PET under future climate scenarios highlight a persistent and intensifying trend of increasing evaporative demand across all seasons. The PET heatmaps for SSP2-4.5 and SSP5-8.5 scenarios show an upward shift in PET values over the 21st century, with significant increases in the summer and post-monsoon periods. Under SSP2-4.5, summer PET values are projected to rise to around 10.5–11 mm/day by the late century, while winter values increase modestly to about 5.5 mm/day. However, under the high-emissions SSP5-8.5 scenario, the increase is more pronounced, with summer PET rising to 12–13 mm/day and winter PET reaching over 6 mm/day. These changes reflect not only rising temperatures but also shifts in associated climatic variables such as solar radiation, humidity, and wind speed, all of which contribute to higher atmospheric evaporative demand.

The seasonal boxplots for the future period (2025–2100) offer a clearer comparative visualization of these shifts **(Figure 26)**. Under SSP2-4.5, summer PET medians rise to about 10.5 mm/day, while winter medians increase to around 5.5 mm/day. The monsoon season also experiences an increase, with PET medians shifting from around 7 mm/day historically to approximately 8.5 mm/day. Under SSP5-8.5, these increases are more significant summer PET medians approach 12.5 mm/day, monsoon values near 9.5 mm/day, and post-monsoon PET increases from a historical median of 5.5 mm/day to almost 7.5 mm/day. These rising PET values suggest that even the cooler or previously less water-demanding seasons will experience increased atmospheric demand, potentially placing stress on water resources throughout the year.

The time series of seasonal PET from 2005 to 2100 further elucidates this long-term trend. For both SSP2-4.5 and SSP5-8.5 scenarios, there is a steady upward trajectory in PET values for all seasons, with the slope of increase markedly steeper under SSP5-8.5. Summer PET, for example, rises from approximately 9.5 mm/day in 2005 to nearly 13 mm/day by 2100 under SSP5-8.5. Similarly, winter PET increases from around 4.5 mm/day to over 6 mm/day during the same period. The post-monsoon season, historically more stable in PET, also shows a significant rise under both scenarios, reflecting a shift in seasonality and increasing the overall water demands during this period.

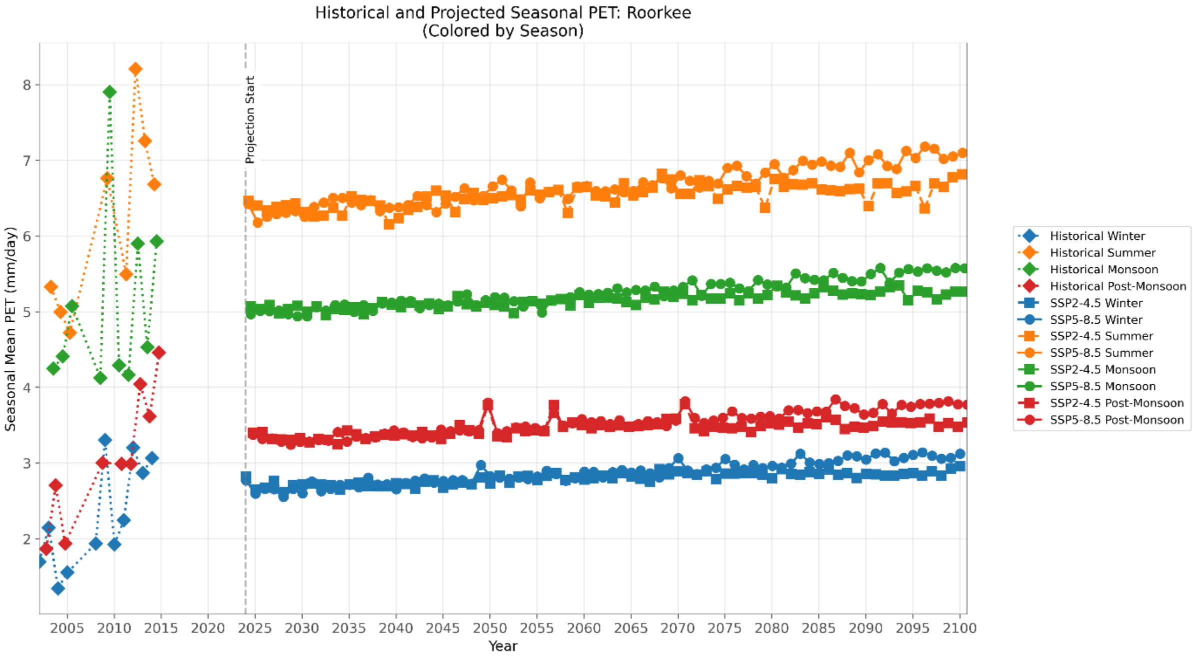

Figure 26 Temporal distribution of historical and projected seasonal PET over Roorkee

These findings carry critical implications for water management and agriculture in Roorkee. Higher PET across all seasons means that crop water requirements will rise significantly, affecting both rabi (winter) and kharif (monsoon) cropping systems. Under the SSP5-8.5 scenario, elevated PET combined with potential reductions in water availability could exacerbate the frequency and severity of agricultural droughts and water stress events. This calls for targeted adaptation measures, including the adoption of water-efficient irrigation technologies such as drip and sprinkler systems, optimization of cropping patterns and planting calendars, and investment in watershed development and groundwater recharge strategies. In conclusion, PET projections for Roorkee under future climate scenarios emphasize the urgent need for proactive and integrated climate adaptation planning in both the water resource and agricultural sectors to ensure long-term sustainability.

5 DISCUSSION

The percentage changes in seasonal mean Potential Evapotranspiration (PET) from the baseline year 2025 to the late 21st century (2095–2100), under two emission scenarios (SSP2-4.5 and SSP5-8.5), reveal important spatial and seasonal trends across the eight study locations. These percentage changes, already calculated and presented in **the table 2**, provide insight into how atmospheric evaporative demand may evolve under future climatic conditions.

Table 2 Percentage Change (%) in mean daily PET for different seasons under ssp245 and ssp585

	Summer		Monsoon		Post-Monsoon		Winter	
Station	**ssp245**	**ssp585**	**ssp245**	**ssp585**	**ssp245**	**ssp585**	**ssp245**	**ssp585**
Jammu	4.78	11.3	5.88	11.34	6.35	13.49	10.9	19.23
Guwahati	5.49	9.48	1.86	6.1	6.41	15.3	8.25	17.01
Patna	11.41	17.81	6.94	14.1	8.84	18.03	15.98	25.11
Bhopal	9.31	16.34	5.31	12.33	9.78	17.93	14.69	22.32
Jodhpur	7.64	13.22	6	12	12.81	20.28	13.85	20.35
Kakinada	4.29	9.8	4.81	9.87	6.1	11.59	4.76	12.06
Roorkee	7.77	14.72	5.01	11.22	12.1	20.7	20.5	29.71
Belgaum	7.21	11.83	6.35	10.79	5.77	9.97	10.11	15.4

Across all stations, PET is projected to increase in every season under both SSP2-4.5 and SSP5-8.5, confirming that warming temperatures and associated climate shifts will drive higher evapotranspiration demands. The magnitude of increase, however, varies by location and season, indicating strong geographic and seasonal sensitivity. Trends of increasing PET across India have also been observed by previous studies (Patle & Mahajan, 2021; Rangarajan et al., 2014; Singh & Kaushal, 2022)

Under the high-emissions scenario SSP5-8.5, winter PET shows the largest percentage increase at most stations. For example, Roorkee shows a dramatic rise in winter PET by 29.71%, compared to 20.5% under SSP2-4.5. Patna and Guwahati also show large increases in winter PET (25.11% and 17.01%, respectively). This shift suggests that cooler seasons, which traditionally had lower evapotranspiration, will experience significant warming and dryness, potentially altering the hydrological balance during off-peak periods. Similar to findings by Mukherjee et al. (2020) and Goyal & Ojha (2021), the current analysis shows sharper PET increases under high emission scenarios (SSP5-8.5)

Post-monsoon PET also increases notably at several locations. Jodhpur shows a rise of 20.28%, and Roorkee and Patna follow closely with increases of 20.7% and 18.03%, respectively, under SSP5-8.5. These trends suggest a lengthening of the dry season, with higher evaporative losses even after the monsoon ends.

Table 3 Key observations

Location	Historical PET Trend	Future PET Trend (SSP2-4.5 vs SSP5-8.5)	Seasonal Highlights	Key observations
Jammu	Moderate PET	Rising PET, more under SSP5-8.5	Summer > Post-Monsoon > Winter	Winter PET also increasing noticeably
Guwahati	Stable to slight rise	Small rise, relatively lower difference between scenarios	Summer > Post-Monsoon > Monsoon	Coastal humidity buffers PET rise
Patna	Gradual PET rise	Significant PET rise post-2050 under SSP5-8.5	Summer > Post-Monsoon	Longer dry seasons projected
Bhopal	High summer PET historically	Steady strong rise, especially summer PET	Summer > Post-Monsoon > Monsoon	Peak PET intensifying sharply
Jodhpur	Highest PET historically	Steepest PET rise among all	Summer > Post-Monsoon >> Winter	High water stress risk
Kakinada	Mild PET changes	Moderate PET increase, less aggressive	Summer > Post-Monsoon > Monsoon	Coastal effect moderates trends
Roorkee	High summer PET	Sharp rise across seasons, steeper under SSP5-8.5	Summer > Post-Monsoon > Winter	Semi-arid vulnerabilities
Belgaum	Moderate PET historically	Moderate to strong PET rise post-2050	Summer > Winter > Post-Monsoon	Summer season PET getting longer

While summer PET values are high in absolute terms, the percentage increases are more moderate compared to winter and post-monsoon. For instance, in Bhopal, summer PET increases by 16.34%, in Patna by 17.81%, and in Roorkee by 14.72% under SSP5-8.5. This reflects the fact that PET during summer is already high, and therefore even substantial absolute increases result in more modest percentage growth.

Interestingly, monsoon PET also shows substantial increases, especially in locations like Guwahati (6.1%), Bhopal (12.33%), and Patna (14.1%) under SSP5-8.5. Traditionally, monsoon months are associated with lower PET due to higher humidity and rainfall. However, these results indicate that future monsoon periods may become warmer and more evaporatively active, possibly due to intermittent dry spells, less cloud cover, or more intense solar radiation.

Spatially, Roorkee, Patna, and Bhopal emerge as PET hotspots, showing consistently high percentage increases across all seasons. In contrast, Kakinada and Belgaum show comparatively lower increases, especially in summer and post-monsoon, which may be due to coastal moderation and humid climate conditions. However, even these locations exhibit noticeable rises in winter and monsoon PET, suggesting a region-wide trend.

In summary, the percentage increases presented in the table reflect a clear signal: PET is rising significantly across seasons and scenarios, with the greatest changes often occurring during cooler and transitional periods. This suggests a shift toward year-round evaporative stress, which will have implications for irrigation planning, water resource allocation, and climate adaptation strategies. The importance of integrating evapotranspiration trends in water planning is also highlighted by studies focused on western India and arid regions (Kundu et al., 2019; Kharol et al., 2013). The results underscore the importance of emissions mitigation as SSP5-8.5 consistently shows higher PET increases than SSP2-4.5 and highlight the need for region-specific responses to these evolving climate-water dynamics.

6 CONCLUSIONS AND RECOMMENDATIONS

This study provides a detailed assessment of the changing patterns of Potential Evapotranspiration (PET) across India in the context of climate change, using both historical observations and future climate model projections. By analyzing PET trends at eight geographically and climatically diverse locations Jammu, Guwahati, Patna, Bhopal, Jodhpur, Roorkee, Kakinada, and Belgaum this research offers crucial insights into the spatial and seasonal variability of atmospheric evaporative demand across India. The application of the FAO Penman-Monteith method, using reliable datasets from the India Meteorological Department (IMD), NASA POWER, and NASA NEX-GDDP downscaled CMIP6 climate models, enabled robust and consistent computation of PET across both historical (2001–2024) and future (2025–2100) periods.

The findings reveal that evaporative demand is increasing across all regions and seasons, but with varying intensities. The Pre-Monsoon season consistently shows the highest PET values, placing significant stress on water resources during the early stages of crop growth. Alarmingly, the winter and post-monsoon seasons, traditionally characterized by lower PET, are projected to experience disproportionately higher percentage increases, especially under the high-emission scenario SSP5-8.5. This implies a possible shift toward year-round elevated evaporative demand, which can severely affect water availability for irrigation, groundwater recharge, and ecosystem sustainability. Regions such as Bhopal, Patna, and Roorkee are particularly vulnerable, showing steep upward trends in future PET. Even humid zones like Guwahati and Kakinada demonstrate a rising PET trajectory, confirming that the impacts of climate change on atmospheric water demand are widespread and not confined to arid or semi-arid regions.

The divergence between SSP2-4.5 and SSP5-8.5 pathways in PET projections underlines the importance of global mitigation efforts. Under SSP5-8.5, the increase in PET is sharper, persistent, and more extreme, indicating that high-emission futures could place a severe and prolonged burden on water systems. This rising PET, when not matched by proportional increases in precipitation, will likely lead to enhanced irrigation requirements, reduced agricultural productivity, and increased vulnerability to drought. The findings of this study underscore the critical need to integrate PET projections into climate-resilient water management, irrigation planning, and policy development.

In conclusion, evapotranspiration a process often overlooked in national water policymust be treated as a central climate impact indicator. This study emphasizes that proactive adaptation strategies, such as climate-smart agriculture, efficient irrigation systems, groundwater recharge enhancement, and rainwater harvesting, are essential to counter the growing atmospheric demand for water. Integrating scientific tools such as PET modeling into mainstream planning can significantly strengthen India’s preparedness to face future climate-induced water challenges.

Key Recommendations

- **Integrate PET Projections into Water Planning:** Regional and national water resource strategies should incorporate PET trends to better estimate irrigation needs, reservoir operation, and groundwater sustainability.
- **Prioritize High-Risk Zones:** Areas such as Bhopal, Patna, and Roorkee, which show high percentage increases in PET, should be prioritized for adaptive water management and climate-resilient agriculture programs.
- **Update Irrigation Scheduling and Crop Calendars:** PET-based adjustments to sowing and harvesting periods, along with efficient irrigation systems like drip and sprinkler irrigation, should be adopted to match future climatic conditions.
- **Strengthen Rainwater Harvesting and Groundwater Recharge:** Increased atmospheric demand underscores the need for enhancing rainwater storage infrastructure, recharge wells, and watershed management.
- **Promote Climate-Resilient Agriculture:** Shift toward drought-tolerant crop varieties, short-duration crops, and climate-smart farming practices to minimize water use during high-PET periods.
- **Enhance Climate Monitoring and Early Warning Systems:** Development of PET-informed drought early warning systems can improve decision-making for agriculture, water utilities, and disaster preparedness.
- **Mitigation and Policy Advocacy:** The sharper PET increases under SSP5-8.5 highlight the importance of emission mitigation policies at both national and international levels to limit long-term climate impacts.

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ANNEXURE

Absolute Change in mean daily PET for different seasons under ssp245 and ssp585

Station	Summer		Monsoon		Post-Monsoon		Winter	
	ssp245	ssp585	ssp245	ssp585	ssp245	ssp585	ssp245	ssp585
Jammu	0.22	0.52	0.28	0.54	0.16	0.34	0.17	0.3
Guwahati	0.22	0.38	0.07	0.23	0.18	0.43	0.16	0.33
Patna	0.73	1.14	0.32	0.65	0.26	0.53	0.35	0.55
Bhopal	0.86	1.51	0.28	0.65	0.36	0.66	0.52	0.79
Jodhpur	0.41	0.71	0.33	0.66	0.36	0.57	0.32	0.47
Kakinada	0.21	0.48	0.19	0.39	0.2	0.38	0.15	0.38
Roorkee	0.48	0.91	0.25	0.56	0.38	0.65	0.49	0.71
Belgaum	0.39	0.64	0.2	0.34	0.22	0.38	0.44	0.67

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