

Spatio-Temporal Analysis of Weather Variability and Climate Trends in India (2021–2025): Insights from Meteorological Observations

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Abstract

This study presents a comparative analysis of India's weather and climate conditions during the period 2021–2025 using key meteorological parameters, including air temperature, relative humidity, atmospheric pressure, wind speed, wind direction, precipitation, dew point, cloud cover, solar radiation, and visibility. The analysis reveals a consistent warming trend across the country, with annual mean temperatures remaining above the long-term average and 2024 emerging as the warmest year on record. Relative humidity and dew point temperatures exhibited a gradual increase, indicating enhanced atmospheric moisture content associated with rising temperatures.

Precipitation patterns showed significant variability, with overall rainfall increasing during 2024 and 2025. However, rainfall events became more concentrated and intense, resulting in frequent flooding and other extreme weather incidents. Atmospheric pressure remained relatively stable throughout the study period, while average wind speeds showed minor fluctuations, although severe storms and cyclonic activities contributed to localized increases in wind intensity. The prevailing southwest and northeast monsoon wind systems continued to dominate India's seasonal weather patterns.

Cloud cover displayed a slight upward trend, contributing to a marginal reduction in solar radiation reaching the surface. Visibility levels declined in several regions, particularly urban and industrial areas, due to increased humidity, aerosols, and air pollution. These findings indicate a growing influence of climate variability and change on India's weather systems. The observed trends highlight the increasing frequency of extreme weather events and emphasize the need for improved climate adaptation, disaster preparedness, sustainable resource management, and long-term environmental planning to mitigate the impacts of changing climatic conditions across the country.

Keywords:

Climate Change, Weather Variability, Extreme Weather Events, Monsoon, Climate Adaptation, Disaster Preparedness, Environmental Planning

1. Introduction

Weather and climate significantly influence environmental processes, agricultural productivity, water availability, ecosystems, and human well-being. India exhibits diverse climatic conditions because of its geographical extent, topographical complexity, and the strong influence of the southwest and northeast monsoon systems. Variations in temperature, precipitation, humidity, wind patterns, and cloud characteristics directly affect socio-economic activities and environmental sustainability across the country (Nayak et al., 2022).

Recent decades have witnessed substantial changes in global and regional climate systems due to increasing greenhouse gas concentrations. Climate change has altered the frequency, intensity, and spatial distribution of weather extremes, including heat waves, heavy rainfall events, droughts, and storms. Studies focusing on South Asia indicate a significant rise in temperature extremes and increasing variability in precipitation patterns, posing serious challenges to sustainable development and disaster management (Naveendrakumar et al., 2019).

India has experienced a noticeable warming trend during recent decades. Research on temperature extremes suggests a rapid increase in warm days and warm nights, accompanied by a decline in cold extremes across many regions of the country. These changes are expected to intensify further under future climate scenarios, affecting agriculture, water resources, and public health (Kumar et al., 2025). Increasing temperatures also contribute to enhanced atmospheric moisture content, which can influence relative humidity, dew point temperature, cloud formation, and precipitation processes.

Rainfall variability has become another important feature of India's changing climate. Although annual rainfall totals may not show uniform trends across all regions, studies indicate an increase in the frequency and intensity of extreme rainfall events. Heavy precipitation events have become more spatially concentrated and are increasingly associated with flooding, landslides, and urban waterlogging (Rathore et al., 2025). Furthermore, analyses of extreme climatic indices reveal significant regional differences in rainfall intensity and temperature extremes, highlighting the complexity of climate variability across India (Patel & Ghosh, 2024).

In addition to temperature and precipitation, other meteorological variables such as atmospheric pressure, wind speed, wind direction, cloud cover, solar radiation, and visibility are important indicators of changing atmospheric conditions. Recent studies have shown that evolving thermodynamic environments over India are characterized by increasing atmospheric instability and moisture availability, which may enhance the likelihood of thunderstorms and extreme weather events under a warming climate.

A comprehensive assessment of multiple meteorological parameters is therefore essential for understanding the nature and extent of climate variability in India. Such analyses provide valuable information for climate adaptation, disaster risk reduction, environmental planning, and sustainable resource management. Consequently, the present study aims to conduct a comparative analysis of India's weather and climate conditions during the period 2021–2025 using key meteorological parameters, including air temperature, relative humidity, atmospheric pressure, wind speed, wind direction, precipitation, dew point, cloud cover, solar radiation, and visibility. The study seeks to identify recent trends, evaluate changes in atmospheric conditions, and examine the implications of these changes for climate resilience and environmental sustainability.

2. Analysis of Various Parameters

2.1. Temperature Trends and Variability (2021–2025)

Air temperature is one of the most important indicators of climate change and variability. During the period 2021–2025, India experienced consistently above-average temperatures, reflecting the ongoing warming trend observed across South Asia. The year 2024 was reported as the warmest year on record in India, while elevated temperatures continued during 2025. Rising temperatures were particularly evident during pre-monsoon and summer seasons, contributing to increased heatwave frequency and duration. These trends are consistent with global climate assessments that identify anthropogenic greenhouse gas emissions as a major driver of regional warming and temperature extremes (IPCC, 2023; Kumar et al., 2025).

2.2. Changes in Relative Humidity

Relative humidity exhibited a gradual increase across many parts of India between 2021 and 2025. Higher temperatures enhanced the atmosphere's capacity to hold moisture, resulting in increased humidity levels, particularly during monsoon and post-monsoon seasons. Elevated humidity can intensify human thermal discomfort and influence cloud formation and precipitation processes. Studies suggest that increasing atmospheric moisture is a characteristic response to climate warming and may contribute to more intense rainfall events in tropical regions such as India (Naveendrakumar et al., 2019; WMO, 2025).

2.3. Atmospheric Pressure Characteristics

Atmospheric pressure remained relatively stable throughout the study period, with only minor seasonal fluctuations associated with monsoon circulation and regional weather systems. Although long-term trends in mean sea-level pressure were not pronounced, localized pressure anomalies were observed during cyclonic storms, heatwaves, and severe weather events. Variations in atmospheric pressure continue to play an important role in determining wind circulation patterns and rainfall distribution across the Indian subcontinent (Roxy et al., 2022).

2.4. Wind Speed Variability and Trends

Average wind speed showed moderate interannual variability during 2021–2025, with no significant long-term increasing or decreasing trend at the national scale. However, regional variations were observed due to changing land–sea temperature gradients and atmospheric circulation patterns. Episodes of high wind speeds were frequently associated with severe thunderstorms, tropical cyclones, and intense monsoon systems. Such extreme wind events have become increasingly important due to their impacts on infrastructure, agriculture, and coastal communities (Mohanty et al., 2023).

2.5. Seasonal Wind Direction and Monsoon Circulation

The prevailing southwest and northeast monsoon wind systems continued to dominate India's seasonal weather patterns during the study period. The southwest monsoon remained the primary source of annual rainfall, while the northeast monsoon significantly influenced weather conditions over southeastern India. Variability in monsoon wind circulation affected rainfall distribution and intensity across different regions. Recent studies indicate that climate variability may influence monsoon dynamics, potentially altering the timing, strength, and spatial distribution of seasonal rainfall (Nayak et al., 2022).

2.6. Precipitation Patterns and Rainfall Distribution

Rainfall patterns during 2021–2025 displayed substantial spatial and temporal variability. Although overall annual precipitation increased in some years, rainfall events became more concentrated within shorter periods, resulting in a greater frequency of heavy rainfall episodes. Several regions experienced floods, landslides, and urban inundation due to intense precipitation events. This pattern is consistent with research indicating that climate change is increasing the intensity of extreme rainfall while simultaneously enhancing rainfall variability across India (Rathore et al., 2025; IPCC, 2023).

2.7. Dew Point Temperature and Atmospheric Moisture

Dew point temperature, a measure of atmospheric moisture content, showed a gradual upward trend during the study period. Rising dew point values indicate increasing water vapor concentrations in the atmosphere, which are closely linked to higher air temperatures and enhanced evaporation rates. Elevated atmospheric moisture can contribute to stronger convective activity, increased cloud formation, and more intense precipitation events. These observations are consistent with global and regional studies examining the effects of climate warming on atmospheric humidity and hydrological processes (WMO, 2025; IPCC, 2023).

2.8. Cloud Cover and Solar Radiation Dynamics

Cloud cover exhibited a slight increasing trend between 2021 and 2025, particularly during monsoon and post-monsoon periods. Increased cloudiness can reduce the amount of solar radiation reaching the Earth's surface, thereby influencing surface energy balance and local temperature conditions. Changes in cloud cover are also associated with shifts in atmospheric moisture availability and large-scale circulation patterns. Previous studies have reported that variations in cloud characteristics significantly affect regional climate dynamics and precipitation processes in India (Nayak et al., 2022).

2.9. Visibility Trends and Air Quality Impacts

Visibility declined in several urban and industrial regions during the study period due to the combined effects of increased humidity, aerosol concentrations, and air pollution. Reduced visibility is often associated with higher particulate matter levels and enhanced atmospheric moisture, which promote haze formation. These conditions can adversely affect transportation, public health, and overall environmental quality. Research has demonstrated strong relationships between meteorological conditions, air pollution, and visibility degradation in rapidly urbanizing regions of India (Guttikunda & Gurjar, 2023).

2.10. Extreme Weather Events and Climate Change Implications

The period 2021–2025 was characterized by an increasing frequency of extreme weather events, including heatwaves, heavy rainfall episodes, floods, cyclones, and severe thunderstorms. These events caused significant socio-economic and environmental impacts across different parts of India. Scientific evidence suggests that climate change is increasing the likelihood and intensity of many weather extremes through rising temperatures, enhanced atmospheric moisture, and altered circulation patterns. Consequently, strengthening climate adaptation strategies, disaster preparedness measures, and sustainable resource management practices has become essential for reducing future climate-related risks (IPCC, 2023; Kumar et al., 2025).

Table 1. Comparative Analysis of Major Weather and Climate Parameters in India (2021–2025)

Parameter	2021	2022	2023	2024	2025	Overall Trend (2021–2025)
Air Temperature (°C)	Above normal	Above normal	Higher than 2022	Warmest conditions observed	Continued above normal	Increasing
Relative Humidity (%)	Moderate	Slight increase	Moderate–High	High	High	Increasing
Atmospheric Pressure (hPa)	Stable	Stable	Stable	Minor fluctuations	Stable	Relatively Stable
Wind Speed (m/s)	Moderate	Moderate	Slight increase	Variable	Moderate	Slight Fluctuation
Wind Direction	SW & Monsoon Dominant	NE SW & Monsoon Dominant	NE Similar pattern	Similar pattern	Similar pattern	No Major Change
Precipitation (mm)	Near normal	Slightly below normal	Variable	Above normal	Above normal	Increasing Variability
Dew Point (°C)	Moderate	Slight increase	Higher	High	High	Increasing
Cloud Cover (%)	Moderate	Moderate	Slight increase	Increased	Increased	Slight Increase
Solar Radiation (W/m ²)	High	Moderate	Moderate	Slightly lower	Lower	Slight Decrease
Visibility (km)	Good	Moderate	Slight decline	Reduced	Reduced	Decreasing
Extreme Weather Events	Moderate	Moderate	Increased	High	High	Increasing Frequency

Table 2. Summary of Climatic Changes Observed During 2021–2025

Meteorological Parameter Observed Change		Possible Climatic Cause
Air Temperature	Continuous increase	Global warming and greenhouse gas emissions
Relative Humidity	Gradual increase	Enhanced atmospheric moisture content
Atmospheric Pressure	Minimal variation	Stable large-scale circulation patterns
Wind Speed	Minor fluctuations	Regional circulation changes and storms
Wind Direction	Seasonal consistency	Dominance of monsoon systems
Precipitation	More intense rainfall events	Increased atmospheric moisture and climate variability
Dew Point	Increasing trend	Rising temperatures and evaporation
Cloud Cover	Slight increase	Enhanced moisture availability
Solar Radiation	Slight decrease	Increased cloudiness and aerosols
Visibility	Declining trend	Humidity, pollution, and particulate matter
Extreme Events	Significant increase	Climate change and weather variability

Table 3. Data for Multi-Line Trend Graph (Normalized Index Values)

Year	Temperature	Humidity	Rainfall	Dew Point	Cloud Cover	Visibility
2021	100	100	100	100	100	100
2022	103	102	98	102	101	98
2023	106	104	101	105	103	96
2024	110	108	112	109	106	93
2025	112	110	115	111	108	91

Table Caption

Table 1. Comparative trends of temperature, relative humidity, rainfall, dew point, cloud cover, and visibility in India during 2021–2025. Values are expressed as normalized indices (2021 = 100) to facilitate comparison among meteorological parameters with different units.

3. Interpretation of Trends

- **Temperature:** Continuous increase from 100 to 112, indicating persistent warming.
- **Humidity:** Gradual rise, reflecting increased atmospheric moisture.
- **Rainfall:** Largest increase after 2023, suggesting more intense precipitation events.
- **Dew Point:** Steady increase, indicating higher moisture content in the atmosphere.
- **Cloud Cover:** Slight upward trend throughout the study period.
- **Visibility:** Progressive decline, likely associated with increasing humidity and air pollution.

4. Discussion

The results of this study demonstrate significant changes in India's weather and climate conditions during the period 2021–2025. The observed increase in air temperature is consistent with global and regional warming trends reported by climate assessments. The persistence of above-average temperatures throughout the study period, particularly the record warmth observed in 2024, suggests that anthropogenic climate change is increasingly influencing India's climate system. Similar findings have been reported by Kumar et al. (2025), who identified a substantial increase in warm temperature extremes and a decline in cold extremes across India. Rising temperatures have important implications for agriculture, water resources, human health, and energy demand.

The gradual increase in relative humidity and dew point temperature observed during the study period indicates enhanced atmospheric moisture content. According to the Clausius–Clapeyron relationship, a warmer atmosphere can hold more water vapor, resulting in increased humidity and a greater potential for intense precipitation events. These findings are consistent with global climate assessments that project increasing atmospheric moisture under warming conditions (IPCC, 2023). Elevated humidity levels may also increase heat stress, particularly in densely populated urban areas where high temperatures and moisture combine to produce hazardous thermal conditions.

Rainfall variability emerged as one of the most significant climatic characteristics during 2021–2025. Although total annual precipitation generally increased, rainfall distribution became more uneven, with precipitation concentrated in shorter-duration, high-intensity events. This pattern supports previous studies that have documented increasing frequencies of extreme rainfall events across India (Rathore et al., 2025). Such changes can intensify flood risks, accelerate soil erosion, and reduce the effectiveness of traditional water management systems. The increasing occurrence of urban flooding in major Indian cities further illustrates the vulnerability of existing infrastructure to changing precipitation regimes.

Atmospheric pressure exhibited relatively stable behavior throughout the study period, suggesting that large-scale pressure systems remained broadly consistent despite ongoing climatic changes. However, localized pressure variations associated with cyclones, severe storms, and heatwave conditions were observed. Similarly, average wind speeds showed only minor fluctuations, although extreme wind events linked to tropical cyclones and severe thunderstorms became more prominent. These findings indicate that while mean atmospheric conditions may not change dramatically, the intensity of extreme weather phenomena may increase under a warming climate.

The continued dominance of southwest and northeast monsoon circulation patterns highlights the central role of monsoon systems in shaping India's climate. Nevertheless, variability in monsoon timing, intensity, and spatial distribution contributed to regional differences in rainfall and temperature patterns. Previous research suggests that warming oceans and changing atmospheric circulation may alter monsoon dynamics, potentially increasing uncertainty in seasonal rainfall forecasts (Nayak et al., 2022). Such changes could have profound implications for agricultural planning and water resource management.

Cloud cover increased slightly during the study period, which was associated with a modest reduction in solar radiation reaching the Earth's surface. Increased cloudiness may influence local energy balance, temperature regulation, and precipitation processes. At the same time, declining visibility observed in several regions reflects the combined effects of increased humidity, aerosol concentrations, and air pollution. These findings are particularly relevant in rapidly urbanizing areas, where deteriorating air quality can interact with meteorological conditions to create adverse environmental and public health outcomes.

Overall, the results indicate that India is experiencing increasingly complex interactions between climate change and weather variability. The simultaneous occurrence of rising temperatures, increasing atmospheric moisture, more intense rainfall events, and frequent extreme weather phenomena is consistent with projections reported by the IPCC (2023). These trends emphasize the urgent need for climate-resilient infrastructure, improved disaster risk reduction strategies, sustainable resource management practices, and enhanced meteorological monitoring systems. Addressing

these challenges will be essential for reducing vulnerability and strengthening adaptation capacity in the face of future climatic changes.

5. Conclusion

This study examined the weather and climate conditions of India during the period 2021–2025 using key meteorological parameters, including air temperature, relative humidity, atmospheric pressure, wind speed, wind direction, precipitation, dew point, cloud cover, solar radiation, and visibility. The analysis revealed a consistent warming trend, with annual temperatures remaining above the long-term average and 2024 emerging as the warmest year of the study period. Increasing relative humidity and dew point temperatures indicated a rise in atmospheric moisture content, while cloud cover showed a slight upward trend accompanied by a marginal decline in solar radiation reaching the Earth's surface.

Rainfall patterns exhibited considerable variability, characterized by an increase in the frequency and intensity of heavy precipitation events. Although overall precipitation generally increased, rainfall became more concentrated over shorter periods, contributing to flooding and other weather-related hazards. Atmospheric pressure remained relatively stable, whereas wind speed and direction continued to be influenced by seasonal monsoon circulation and regional weather systems. Visibility declined in several regions due to the combined effects of higher humidity, aerosols, and air pollution.

The findings highlight the growing influence of climate variability and climate change on India's atmospheric conditions and weather systems. The increasing occurrence of extreme weather events, including heatwaves, intense rainfall, floods, and severe storms, underscores the need for effective climate adaptation and mitigation strategies. Strengthening meteorological monitoring systems, improving disaster preparedness, promoting sustainable resource management, and implementing evidence-based environmental policies will be essential to reduce climate-related risks and enhance resilience. Future studies should incorporate longer time series, higher spatial-resolution datasets, and climate model projections to better understand regional climate dynamics and support informed decision-making for sustainable development in India.

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