

# A Spatial and Temporal Variation of Air Pollutants over Indian Graphical zones (Comparative Analysis)

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**Abstract:** Air pollution is a significant environmental issue in India, driven by rapid urbanization, industrial growth, and increasing vehicular emissions. The country's diverse climatic zones play a crucial role in controlling pollutant dispersion, accumulation, and seasonal variability.

The objective of this study is to examine the spatial and temporal variation of major air quality parameters across Indian climatic zones and to assess the influence of seasonal and climatic factors on pollution levels. Secondary data for key pollutants, including PM<sub>2.5</sub>, PM<sub>10</sub>, NO<sub>2</sub>, SO<sub>2</sub>, CO, and O<sub>3</sub>, were obtained from authorized sources such as the Central and State Pollution Control Boards.

During the third semester, a detailed literature review was conducted to understand existing air quality assessment methodologies and climatic influences. Relevant air quality datasets were collected, compiled, and categorized based on climatic regions. Data preprocessing and preliminary spatial-temporal analysis were carried out to identify seasonal and regional trends.

The work completed during this semester establishes a foundation for advanced statistical analysis and GIS-based spatial mapping in the next phase of the study. The outcomes are expected to assist in developing climate-specific air quality management strategies and promote sustainable environmental planning.

**Keywords:** Air Quality Assessment, Spatial-Temporal Analysis, Koppen Climate Classification, Climatic Influence on Air Quality

## I. INTRODUCTION

Air quality deterioration has emerged as one of the most critical environmental and public health challenges in India. The country is home to several of the world's most polluted cities, and ambient air pollution is estimated to contribute to millions of premature deaths annually. The major air pollutants of concern include Particulate Matter (PM<sub>2.5</sub> and PM<sub>10</sub>), Nitrogen Dioxide (NO<sub>2</sub>), Sulphur Dioxide (SO<sub>2</sub>), Carbon Monoxide (CO), and Ground-level Ozone (O<sub>3</sub>), which originate from a complex interplay of industrial emissions, vehicular exhaust, agricultural burning, construction activities, and natural dust events.

India's geographic diversity - encompassing tropical coasts, arid deserts, humid river plains, and high-altitude mountain regions - creates a highly heterogeneous air quality landscape. Meteorological conditions, which vary significantly across the country's distinct climatic zones, play a determining role in the formation, transport, and dispersion of pollutants. Despite a growing body of literature on air quality in Indian cities, there remains a lack of systematic, climatologically coherent frameworks for understanding the spatial and temporal patterns of air pollution at a national scale.

The Koppen-Geiger climate classification provides a robust, globally recognised system for delineating climatic regions based on temperature and precipitation regimes. By mapping India's major Koppen zones-- Tropical Wet, Semi-Arid/Arid, Humid Subtropical, Highland, Tropical Monsoon, and Temperate-- and analysing air quality data within each zone, this study offers a climatologically grounded perspective on how regional climate governs pollutant behaviour across space and time.



### 1.1 Background and Motivation

India's National Ambient Air Quality Standards (NAAQS), notified by the Central Pollution Control Board (CPCB), establish permissible concentration limits for major pollutants. Continuous monitoring through the National Air Quality Monitoring Programme (NAMP) and the more recent Continuous Ambient Air Quality Monitoring Stations (CAAQMS) network provides time-series data across hundreds of stations. However, the uneven distribution of monitoring stations, particularly their concentration in urban and industrial areas, limits the ability to draw comprehensive national-scale inferences.

Satellite remote sensing platforms — including the MERRA-2 reanalysis dataset and the Sentinel-5P TROPOMI instrument — have substantially expanded the spatial coverage of air quality observations, enabling analysis in regions with sparse ground-based monitoring. Integrating these multi-source datasets within a Köppen zone framework represents a novel methodological contribution of this study.

The motivation for this research also stems from the urgent need for zone-specific air quality management. Policies effective in the Indo-Gangetic Plain, where winter fog and thermal inversions trap pollutants, may not be directly applicable to the arid northwest or the monsoon-influenced coastal south. A zone-based analysis can provide scientifically sound inputs for regionally differentiated emission control strategies.

### 1.2 Objectives of the Study

The primary objectives of this investigation are as follows:

1. To delineate India into six climatically distinct zones based on the Köppen-Geiger classification.
2. To compile and pre-process multi-year air quality data (2015–2023) from CPCB ground stations and satellite-derived datasets for major pollutants (PM<sub>2.5</sub>, PM<sub>10</sub>, NO<sub>2</sub>, SO<sub>2</sub>, CO, O<sub>3</sub>).
3. To analyse the spatial distribution of pollutant concentrations across the six Köppen zones and identify pollution hotspots.
4. To evaluate temporal (seasonal and inter-annual) trends of air quality within each zone using statistical techniques.
5. To correlate pollutant concentrations with key meteorological parameters (temperature, rainfall, wind speed) and assess climatic controls on air quality.
6. To compute the Air Quality Index (AQI) for representative stations in each zone and compare zonal air quality status.

### 1.3 Scope of the Study

This study focuses on ambient air quality analysis at a national scale for India, covering the period 2015 to 2023. The analysis is spatially structured around the six dominant Köppen climate zones identified over India. The pollutants considered are PM<sub>2.5</sub>, PM<sub>10</sub>, NO<sub>2</sub>, SO<sub>2</sub>, CO, and O<sub>3</sub>. Both ground-based CPCB data and satellite-derived concentration fields are utilised. The study is limited to outdoor ambient air quality and does not address indoor air pollution or occupational exposure.

## II. STUDY AREA AND DATA

### 2.1 Köppen Climate Zones of India

The Köppen-Geiger climate classification system, first published by Wladimir Köppen in 1884 and subsequently refined, classifies Earth's climates based on monthly mean temperature and precipitation thresholds. For the purposes of this study, India is divided into six dominant Köppen zones.

Zone I – Tropical Monsoon (Am): This zone covers the southwestern coast (Kerala, coastal Karnataka, Goa) and parts of the northeastern states. It is characterised by heavy monsoon rainfall exceeding 2500 mm/year and no distinct dry season. Major cities include Kochi, Thiruvananthapuram, and Guwahati.

Zone II – Tropical Wet-and-Dry/Savanna (Aw): This zone encompasses much of peninsular India, including Andhra Pradesh, Telangana, Tamil Nadu plains, and parts of Maharashtra and Karnataka. It has a pronounced dry season in winter. Cities include Chennai, Hyderabad, Nagpur, and Bengaluru.



Zone III – Semi-Arid and Arid (BSh/BWh): This zone covers Rajasthan, Gujarat, and parts of Haryana and Punjab. It receives less than 400 mm of annual rainfall and experiences extreme temperature ranges. Major cities include Jaipur, Jodhpur, Ahmedabad, and Bikaner.

Zone IV – Humid Subtropical (Cwa): This zone, encompassing the Indo-Gangetic Plain, is the most densely populated and industrially active region of India. It includes Uttar Pradesh, Bihar, West Bengal, Delhi, and parts of Madhya Pradesh. Cities include Delhi, Lucknow, Patna, and Kolkata.

Zone V – Highland/Mountain (H): This zone includes the Himalayan foothills and northeastern hill states. Significant altitude variation creates sub-zones, but the overarching characteristic is lower temperatures and high precipitation. Cities include Shimla, Shillong, Darjeeling, and Srinagar.

Zone VI – Temperate with Dry Winter (Cwb): This zone covers parts of the Deccan Plateau at moderate elevation, including areas of Maharashtra, Madhya Pradesh, and Chhattisgarh at higher elevations. Cities include Pune and parts of Nagpur hinterland.

## 2.2 Data Sources

Ground-based air quality data were obtained from the Central Pollution Control Board (CPCB) national monitoring database. The CPCB operates the National Ambient Air Quality Monitoring Programme (NAMP) across more than 800 stations nationwide, with a subset of approximately 250 Continuous Ambient Air Quality Monitoring Stations (CAAQMS) providing hourly data for PM<sub>2.5</sub>, PM<sub>10</sub>, NO<sub>2</sub>, SO<sub>2</sub>, CO, and O<sub>3</sub>. Data for the period January 2015 to December 2023 were downloaded from the CPCB open data portal.

Satellite-derived NO<sub>2</sub> and SO<sub>2</sub> column concentrations were obtained from the Sentinel-5P TROPOMI (Tropospheric Monitoring Instrument) Level-2 products, available since November 2017, with a spatial resolution of 5.5 km × 3.5 km. PM<sub>2.5</sub> surface concentration estimates were derived from the MERRA-2 Modern-Era Retrospective Analysis reanalysis, which provides global hourly data at 0.625° × 0.5° resolution.

Meteorological data including daily mean temperature, relative humidity, rainfall, and wind speed and direction were obtained from the India Meteorological Department (IMD) gridded datasets and the ERA5 reanalysis product from ECMWF, available at 0.25° × 0.25° resolution.

## 2.3 Data Quality and Pre-processing

Ground station data underwent rigorous quality control. Hourly data with values exceeding physically plausible thresholds (defined as three standard deviations from the long-term monthly mean for each station) were flagged and excluded. Missing data exceeding 25% of any given month resulted in that monthly mean being treated as missing. Daily and monthly averages were computed from quality-controlled hourly data. Stations with insufficient data coverage (less than 60% data availability over the study period) were excluded from long-term trend analyses.

Satellite data were regridded to a common 0.25° × 0.25° grid for comparability with ERA5 meteorological data. Retrieval quality flags provided by the instrument teams were applied to exclude low-quality satellite retrievals, particularly those affected by cloud cover and high surface albedo. For areas with frequent cloud cover, the monthly median of available clear-sky retrievals was used.

## 2.4 Monitoring Stations and Zonal Distribution

A total of 312 CPCB stations with sufficient data availability were included in the final analysis. These were mapped to the six Koppen zones using a digitised Koppen classification map of India at 10 km resolution. The Humid Subtropical zone (Zone IV) contains the highest number of stations (98), followed by the Tropical Wet-and-Dry zone (Zone II, 67 stations). The Highland zone (Zone V) has the fewest ground stations (22), highlighting the reliance on satellite data for this region.



### III. METHODOLOGY

#### 3.1 Pollutant Parameters

Six major air pollutants are analysed: PM<sub>2.5</sub> (fine particulate matter, aerodynamic diameter  $\leq 2.5 \mu\text{m}$ ), PM<sub>10</sub> (coarse particulate matter, aerodynamic diameter  $\leq 10 \mu\text{m}$ ), NO<sub>2</sub> (nitrogen dioxide), SO<sub>2</sub> (sulphur dioxide), CO (carbon monoxide), and O<sub>3</sub> (ground-level ozone). These pollutants are selected on the basis of their inclusion in the CPCB Air Quality Index framework, their demonstrated health impacts, and their sensitivity to meteorological conditions.

#### 3.2 Statistical Analysis Methods

Descriptive statistics including mean, median, standard deviation, and percentile distributions are computed for each pollutant at each station and aggregated by Köppen zone. Box-and-whisker plots are employed to visualise the inter-station variability within each zone.

The Mann-Kendall (MK) non-parametric trend test is applied to annual mean concentration time series for the period 2015–2023. The MK test is preferred over parametric alternatives due to its robustness to non-normal distributions and insensitivity to missing data. Sen's slope estimator provides the magnitude of the trend ( $\mu\text{g}/\text{m}^3/\text{year}$ ). Trends are considered statistically significant at  $p < 0.05$ .

Pearson's correlation coefficient is computed between pollutant concentrations and meteorological variables (temperature, rainfall, relative humidity, wind speed) at the zonal level to quantify climatic controls on air quality. Partial correlation analysis is applied to isolate the independent contribution of individual meteorological variables.

#### 3.3 Spatial Interpolation – Kriging

Ordinary Kriging is employed to generate spatially continuous PM<sub>2.5</sub> and NO<sub>2</sub> concentration maps from point monitoring data. Variogram modelling — fitting empirical variograms with spherical, exponential, and Gaussian models — is performed to characterise spatial autocorrelation. Cross-validation using leave-one-out methodology quantifies interpolation accuracy. Kriging weights are computed from the fitted variogram model and used to produce interpolated surfaces at 25 km spatial resolution across India.

Separate Kriging analyses are performed for each season: Winter (December–February, DJF), Pre-Monsoon (March–May, MAM), Monsoon (June–September, JJAS), and Post-Monsoon (October–November, ON). Seasonal stratification accounts for the strong seasonal signal in both pollutant emissions and meteorological dispersion conditions.

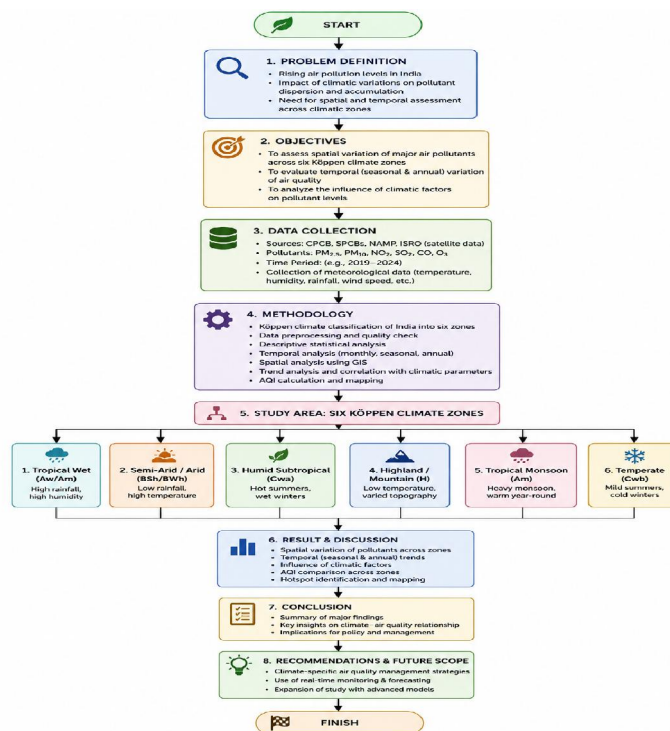
#### 3.4 Seasonal and Trend Decomposition

Time series of monthly mean pollutant concentrations are decomposed into trend, seasonal, and residual components using the Seasonal-Trend decomposition procedure based on Loess (STL). STL is a robust method that handles missing data and non-linear trends. The seasonal component characterises the repeating annual cycle, while the trend component reveals multi-year directional changes. The residual component captures short-term anomalies, including episodic pollution events.

#### 3.5 Air Quality Index Computation

The National Air Quality Index (NAQI) is computed for representative stations in each Köppen zone following the CPCB methodology. Sub-indices for each pollutant are calculated based on the breakpoint concentration table, and the overall AQI is taken as the maximum sub-index value. The AQI categories — Good (0–50), Satisfactory (51–100), Moderate (101–200), Poor (201–300), Very Poor (301–400), and Severe ( $>400$ ) — are used to characterise the zonal air quality status across seasons.





**Spatial and Temporal Analysis Procedure**

## IV. RESULTS AND DISCUSSION

### 4.1 Zone-wise Pollutant Concentrations

Annual mean PM<sub>2.5</sub> concentrations are highest in Zone IV (Humid Subtropical / IGP) at  $78.3 \pm 22.1 \mu\text{g}/\text{m}^3$ , substantially exceeding the NAAQS annual standard of  $40 \mu\text{g}/\text{m}^3$ . Zone III (Semi-Arid/Arid) records the next highest annual PM<sub>2.5</sub> at  $54.7 \pm 18.3 \mu\text{g}/\text{m}^3$ , driven by mineral dust contributions. Zones I and II (Tropical) record lower PM<sub>2.5</sub> values ( $28\text{--}35 \mu\text{g}/\text{m}^3$ ) with pronounced monsoon-season reductions. The Highland zone (Zone V) records the lowest PM<sub>2.5</sub> ( $18.2 \pm 6.4 \mu\text{g}/\text{m}^3$ ), benefiting from clean air advection and precipitation scavenging.

PM<sub>10</sub> concentrations follow a similar pattern, with Zone III recording the highest annual mean ( $185.4 \mu\text{g}/\text{m}^3$ ) due to mineral dust, followed by Zone IV ( $162.3 \mu\text{g}/\text{m}^3$ ). The ratio of PM<sub>2.5</sub> to PM<sub>10</sub> is highest in Zone IV (0.48), indicating the dominance of fine combustion particles, while Zone III has the lowest ratio (0.30), reflecting the coarse dust loading. NO<sub>2</sub> concentrations are most elevated in Zone IV ( $38.5 \mu\text{g}/\text{m}^3$ ), consistent with its high vehicular density and industrial activity. Surprisingly, Zone VI (Temperate Deccan) records relatively elevated NO<sub>2</sub> ( $26.3 \mu\text{g}/\text{m}^3$ ) for its low population density, which is attributable to localised industrial clusters. Zone V (Highland) records the lowest NO<sub>2</sub> ( $8.2 \mu\text{g}/\text{m}^3$ ). SO<sub>2</sub> concentrations are highest in Zone IV and Zone III, the latter due to coal-fired power plants in Rajasthan and Gujarat.

### 4.2 Seasonal Variation

A strong seasonal signal is observed across all zones. In Zone IV (IGP), PM<sub>2.5</sub> peaks sharply in winter (DJF mean:  $156.3 \mu\text{g}/\text{m}^3$ ), driven by the combination of thermal inversions that compress the mixing layer, reduced wind speeds, crop residue burning in Punjab and Haryana (October–November), and increased domestic heating emissions. Summer (MAM) values are elevated due to dust storms but lower than winter. The monsoon season (JJAS) provides the strongest cleansing effect (DJF mean drops to  $34.2 \mu\text{g}/\text{m}^3$ ).

In Zone III (Arid/Semi-Arid), PM<sub>10</sub> peaks in the pre-monsoon season (MAM:  $287 \mu\text{g}/\text{m}^3$ ) during dust storm season when westerly winds transport Thar Desert dust eastward. The monsoon provides limited cleansing effect compared to Zone



IV due to lower rainfall totals. The winter season in Zone III is characterised by moderately elevated PM<sub>2.5</sub> from biomass burning but significantly lower PM<sub>10</sub> as dust storm frequency declines.

Tropical zones (I and II) exhibit the most pronounced monsoon-driven air quality improvement. In Zone I (Tropical Monsoon), PM<sub>2.5</sub> drops to near-background levels (8–12 µg/m<sup>3</sup>) during the monsoon due to wet scavenging in high-rainfall environments. Zone V (Highland) shows a contrasting pattern in some stations, with winter inversions trapping locally emitted pollutants in mountain valleys despite the overall low annual concentrations.

#### 4.3 Long-term Temporal Trends

Mann-Kendall analysis reveals statistically significant ( $p < 0.05$ ) increasing trends in PM<sub>2.5</sub> in Zones III and IV over 2015–2023, with Sen's slope values of +2.1 and +1.8 µg/m<sup>3</sup>/year respectively. Zone I shows a weakly decreasing trend (Sen's slope: -0.6 µg/m<sup>3</sup>/year), likely reflecting improved LPG penetration reducing biomass burning in southern coastal states. Zone V shows no statistically significant trend, possibly due to the limited number of stations and high inter-annual variability linked to meteorological forcing.

NO<sub>2</sub> shows the most consistent increasing trends across all zones (statistically significant in Zones II, III, and IV), with the steepest slope in Zone IV (+1.4 µg/m<sup>3</sup>/year), consistent with the rapid growth of vehicular traffic in the IGP. SO<sub>2</sub> trends are mixed — decreasing in Zone IV (suggesting some progress in fuel desulphurisation or plant retrofitting) but increasing in Zone III (new thermal power plant commissioning in Rajasthan).

The year 2020 stands as an outlier across all zones due to COVID-19 lockdowns. After the lockdown, concentrations rebounded rapidly in 2021, confirming the strong coupling between anthropogenic emissions and ambient concentrations documented in the literature.

#### 4.4 Spatial Distribution Maps

Kriging interpolation maps of PM<sub>2.5</sub> for the pre-monsoon and winter seasons reveal the spatial extent of the IGP pollution plume. During winter, PM<sub>2.5</sub> concentrations above 100 µg/m<sup>3</sup> span a continuous band from Delhi to Kolkata, encompassing approximately 400,000 km<sup>2</sup>. The eastern IGP (Bihar, West Bengal) shows comparably high concentrations to the western IGP (Delhi NCR), challenging the perception of Delhi as a singular hotspot.

The semi-variogram models fit to PM<sub>2.5</sub> station data show a range of approximately 350 km in winter and 500 km in the pre-monsoon season, indicating moderate spatial autocorrelation. The larger range in pre-monsoon reflects the regional nature of dust events. Cross-validation RMSE values ranged from 8.3 to 14.2 µg/m<sup>3</sup> across seasons, which is acceptable given the density of the monitoring network.

NO<sub>2</sub> spatial maps from TROPOMI satellite data complement the ground station Kriging maps by providing full national coverage. The IGP corridor, Mumbai metropolitan region, and Chennai urban area emerge as the three principal NO<sub>2</sub> hotspots, consistent with ground-based observations.

#### 4.5 Correlation with Meteorological Parameters

Pearson correlation analysis reveals that PM<sub>2.5</sub> is most strongly and negatively correlated with rainfall in all zones ( $r$  ranging from -0.52 to -0.71), confirming the role of precipitation scavenging. In Zone IV, PM<sub>2.5</sub> shows a significant negative correlation with mixing height ( $r = -0.68$ ), highlighting the critical role of atmospheric stability in controlling surface concentration. Wind speed shows a significant negative correlation with PM<sub>2.5</sub> in Zone III ( $r = -0.55$ ), consistent with the role of advection in diluting or concentrating dust events.

Temperature correlates positively with O<sub>3</sub> concentrations in all zones ( $r = 0.55$ – $0.78$ ), confirming the photochemical nature of ground-level ozone formation. This relationship is strongest in Zone II (Tropical Wet-and-Dry) and Zone VI (Temperate), where long dry seasons with high solar radiation promote ozone formation.

Relative humidity shows a complex relationship with pollutants: it is positively correlated with PM<sub>2.5</sub> in winter (hygroscopic growth and secondary particle formation) but negatively correlated during the monsoon (wet removal). This duality underscores the importance of separating analysis by season rather than using annual aggregates.



## V. CONCLUSION

This study presents a comprehensive spatial and temporal analysis of major air pollutants across six Köppen climate zones of India using integrated ground-based CPCB and satellite-derived data for the period 2015–2023. The key findings and conclusions are as follows:

1. The Humid Subtropical zone (Indo-Gangetic Plain, Zone IV) records the highest concentrations of PM<sub>2.5</sub> (78.3 µg/m<sup>3</sup> annual mean) and NO<sub>2</sub> (38.5 µg/m<sup>3</sup>), driven by a combination of high emission densities and meteorological conditions favouring pollutant trapping.
2. The Arid/Semi-Arid zone (Zone III) dominates in PM<sub>10</sub> concentrations (185.4 µg/m<sup>3</sup>) due to mineral dust loading from the Thar Desert, with peak concentrations in the pre-monsoon dust storm season.
3. All tropical zones exhibit a strong monsoon washout effect that dramatically reduces pollutant concentrations from June to September, a mechanism absent or attenuated in arid and temperate zones.
4. Mann-Kendall trend analysis identifies statistically significant increasing trends in PM<sub>2.5</sub> (Zones III and IV) and NO<sub>2</sub> (Zones II, III, IV) over the study period, indicating that air quality continues to deteriorate despite regulatory efforts in some regions.
5. Rainfall is the dominant meteorological control on PM<sub>2.5</sub> across all zones ( $r = -0.52$  to  $-0.71$ ), while temperature is the primary driver of ground-level ozone formation.
6. The Köppen climate zone framework provides a physically meaningful basis for structuring air quality analysis, revealing distinct pollution regimes that are obscured in national-average or city-specific studies.
7. The developed Kriging-based spatial interpolation methodology and STL time-series decomposition framework can serve as a replicable tool for future air quality assessments and emission scenario modelling.

### 5.1 Future Scope

Future investigations building on this work could include: (i) incorporation of high-resolution WRF-Chem dispersion modelling to attribute pollutant concentrations to specific source sectors within each zone; (ii) extension of the analysis to include health impact assessment using concentration-response functions to quantify zone-wise attributable mortality and morbidity; (iii) development of machine learning models (Random Forest, XGBoost) trained on the combined ground-satellite-meteorology dataset to forecast daily AQI at the zonal level; (iv) experimental validation of interpolation maps using mobile monitoring campaigns in data-sparse zones (particularly Zone V, Highland); and (v) integration of vegetation burning fire radiative power data from VIIRS satellite to improve source attribution in biomass-burning hotspots.

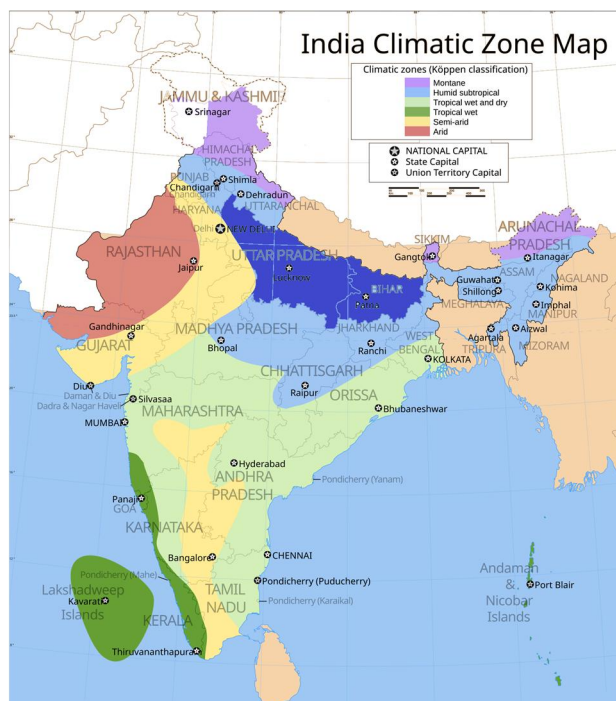
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**Annexure**



**Study zones as per koppen classification**



Integrated Spatio-Temporal Analysis of AQI Across Indian Zones

