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Assessment of Meteorological Parameters on Air Pollution Variability in North-West Himalayas

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Abstract— ***Air quality in the Northwest Himalayas is affected by meteorological factors, seasonal variations, and elevation-stratified dynamics. This study analyzes the influence of temperature, humidity, mixing height and precipitation on major pollutants—PM2.5, PM10, SO_2, CO, O_3, and NO_2—using data from 2010 to 2024. Results show that PM10peaks in winter due to atmospheric stagnation and biomass burning, while monsoon rainfall reduces pollution through wet deposition whereas PM2.5 peaks in monsoon season due to formation of secondary aerosols in upper Himalayas. Temperature correlates negatively with pollutant levels, and wind speed and humidity show season- dependent effects.***

Elevation plays a critical role in air quality variation. Lower elevations (below 2,000m) record higher pollution levels due to anthropogenic activities and valley entrapment. In contrast, higher altitudes (above 3,500m) benefit from stronger winds and fewer emissions, enhancing dispersion. PM2.5 is particularly sensitive to humidity because of the precursor gas SO2 that further oxidizes to SO4 that contributes to PM2.5, aggravating pollution in valleys and upper elevations. Additionally, pollutant transport from the Indo-Gangetic Plain worsens air quality in the lower Himalayas during winter and post-monsoon.

These findings highlight the need for elevation-specific, seasonally adaptive air quality strategies. The study emphasizes regional cooperation and targeted policies to mitigate pollution and reduce associated health risks in the Himalayan region.

Keywords: Northwest Himalayas, Air Quality.

I. INTRODUCTION

Air pollution is a major global concern, responsible for over 7 million premature deaths annually. It has severe consequences for human health and the environment, particularly in South and East Asia, where it accounts for nearly 9 percent of all deaths [1], [2]. Particulate matter (PM10), consisting of airborne particles smaller than 10 µm, is a critical pollutant affecting air quality worldwide [3]. While most studies in India focus on metropolitan regions and the Indo-Gangetic Plain, recent research indicates increasing pollution levels in high altitude areas like the Northwest Himalayas [4], [5]

A. Motivation for the Study

The Himalayas, once considered a pristine environment, now experience pollution levels that exceed WHO safety standards during certain seasons. The complex terrain traps pollutants transported from the Indo-Gangetic Plain, leading to elevated PM concentrations [6]. Meteorological factors, including wind circulation, temperature inversions, and precipitation patterns, influence the accumulation and dispersion of pollutants [7], [8]. Understanding these factors is crucial for improving air quality predictions in mountainous regions.

B. Challenges in Monitoring Air Quality in the Himalayas

The unique topography of the Himalayas presents significant challenges in monitoring air quality. Limited ground-based observations and sparse monitoring networks hinder accurate pollution assessments. Additionally, extreme weather conditions and accessibility issues make continuous data collection difficult. The reliance on satellite data requires bias correction to improve accuracy in such complex terrains [9]. Suri and Azad (2024) further emphasize that inadequate rain gauge placement in the Himalayas leads to unreliable precipitation data, which in turn affects pollution transport modeling and weather forecasting [10]. Their work suggests improvements in observational strategies to enhance environmental monitoring in complex terrain.

C. Limitations of Existing Studies

Previous research has primarily focused on urban air pollution, often neglecting the impact of meteorological parameters on pollutant dynamics in high-altitude regions [11]. Studies by Jena, Azad, and Rajeevan (2016) highlight how climate change affects monsoon rainfall, which in turn influences pollution trends [12]. Additionally, Jena, Garg, and Azad (2020) assessed the accuracy of IMD rainfall data in detecting cloud burst events, emphasizing the challenges of extreme weather prediction in the Himalayas [13]. These studies underscore the need for improved monitoring techniques and predictive models to better understand pollution transport in high-altitude regions.

II. OBJECTIVE OF THE STUDY

This study aims to analyze the transport mechanisms of regional pollutants, evaluate their seasonal trends, and investigate the influence of meteorological parameters on air quality in the Himalayas. This research seeks to enhance the understanding of pollution dynamics in complex terrains.

III. METHODS AND MATERIALS

A. Study Area

The Northwest Himalayas, stretching across Jammu & Kashmir, Ladakh, Himachal Pradesh, and Uttarakhand, form one of India's most ecologically and geographically diverse regions [14]. Known for its majestic mountains, deep valleys, and pristine landscapes, this region extends approximately between

$$30°22'40'' - 37°06'N \quad \text{and} \quad 75°47'55'' - 80°06'E$$

with elevations ranging from 350 meters in the foothills to over 8,000 meters in the towering peaks.

Agro-Climatic Zones: The climate and topography of the Northwest Himalayas vary dramatically, creating four distinct agro-climatic zones [15]:

- **Low hills (1,000–2,000 m):** Experience temperatures between 5◦C and 38◦C, making them ideal for agriculture and human settlements.
- **High hills (2,000–3,500 m):** Receive heavy annual rain fall (around 280 cm), with temperatures ranging from 5◦C to 25◦C.
- **Alpine zones (above 3,500 m):** Characterized by frequent snowfall, temperatures as low as-10◦C, and an annual rainfall of 138 cm.
- **Cold desert regions (Ladakh & parts of Himachal Pradesh):** Among the harshest climates in India, these areas endure 3–5 meters of snow cover, with winter temperatures plunging to-40◦C.

Fig. 1. Geographical location of the study area within India, highlighted by a red bounding box, and its detailed regional division.

B. Air Quality and Meteorological Data

This study utilizes reanalysis data from **MERRA-2** [16], NASA's second-generation atmospheric reanalysis product. MERRA-2 employs **the Goddard Earth Observing System, version 5 (GEOS-5)** to assimilate various atmospheric and aerosol components, offering high-quality global datasets. The data used spans from 2010 to 2024 with a spatial resolution of 0.5◦ × 0.625◦ (latitude × longitude), using monthly aver ages. The analyzed parameters include both **air quality** and **meteorological variables**, as outlined below.

***Air Quality Parameters*:**

To evaluate air pollution levels, we considered multiple atmospheric components i.e. PM2.5, PM10, SO2, CO, O3, and NO2. While most of these values were directly obtained from MERRA-2, PM10 was computed using aerosol mass mixing ratios and standard air density. The total PM10 concentration was derived as follows:

$$\mathrm{PM}_{10} = \rho_{\mathrm{air}} \times 10^9 \times \sum_{i=1}^{n} w_i M_i$$

where:

- ρ_{air} is the standard air density (kg/m3),
- M_i represents the mass mixing ratio of each aerosol species (kg/kg),
- ω_i is the weighting factor for each species,
- $n = 5$, accounting for five aerosol components.

Meteorological Parameters:

Meteorological data were also analyzed to assess their influence on pollution dispersion. The key meteorological variables included:

- Temperature (T Celsius)
- Relative Humidity (RH)(%)
- Precipitation (P)(mm per month).
- Wind Speed (WS)(m/s).
- Mixing Height (MH)(m).
- Ventilation Index (V I)

$$VI = MH \times WS$$

Data Sources:

All datasets were sourced from MERRA-2, which has been validated through comparisons with ground-based measurements. The reliability and consistency of MERRA-2 make it a robust dataset for long-term air quality and climate studies.

IV. METHODOLOGY

The methodology analyzes the spatiotemporal trend over a given region. The key steps are:

a. Data Representation

The dataset consists of pollutant concentrations recorded at spatial coordinates (x_i,y_i) over time:

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$$D = \{(x_i, y_i, C_i(t_j)) \mid i = 1, 2, \ldots, N, j = 1, 2, \ldots, T\}$$

where $C_i(t_j)$ represents the pollutant concentration at location (x_i,y_i) at time t_j.

b. Trend Estimation via Linear Regression.

For each location, the time series Ci(t) is modeled as:

$$C_i(t) = \beta_{0,i} + \beta_{1,i} t + \epsilon_i$$

where $\beta_{1,i}$ represents the trend (slope). It is estimated using the least squares method:

$$\hat{\beta}_{1,i} = \frac{\sum_{j=1}^{T}(t_j - \bar{t})(C_i(t_j) - \bar{C}_i)}{\sum_{j=1}^{T}(t_j - \bar{t})^2}$$

c. Spatial Interpolation and Masking

Trend values are interpolated using cubic interpolation:

$$\hat{\beta}_1(x, y) = \sum_{i=1}^{N} w_i(x, y)\hat{\beta}_{1,i}$$

where $w_i(x,y)$ are interpolation weights. A masking function M(x,y) ensures analysis within the study region:

$$\hat{\beta}_1^{\text{masked}}(x, y) = M(x, y) \cdot \hat{\beta}_1(x, y)$$

d. Visualization

Regions with the highest and lowest trends are identified as:

$$(x_{\max}, y_{\max}) = \arg\max_{(x,y)} \hat{\beta}_1^{\text{masked}}(x, y)$$

This methodology provides a structured framework for analyzing air pollution trends across geographic regions.

V. RESULTS AND DISCUSSION

a. Seasonal Influence on Air Quality

Air quality is strongly influenced by meteorological factors, which either disperse pollutants or trap them, leading to periods of high pollution. Parameters such as wind speed, wind direction, temperature, humidity, mixing height, and ventilation coefficient play a crucial role in determining pollution levels across different seasons.

1) PM2.5 and PM10 Seasonal Trends: Influence of Dust and Meteorology:

The seasonal variation of PM2.5 and PM10 shows distinct patterns, with the highest concentrations observed in summer (PM2.5: 83.76 µg/m3) and a significant decline during the monsoon (50 µg/m3). This reduction is mainly due to rainfall effectively removing particulate matter from the atmosphere, a well-established phenomenon where PM10 is removed more efficiently than PM2.5. However, in winter, PM2.5 rises again, reaching 31.68 µg/m3, which aligns with stagnant weather conditions, biomass burning, and low mixing layer height, all of which contribute to pollutant accumulation.

During summer, dust storms from the Thar Desert significantly contribute to increased fugitive dust, especially with low moisture levels in the air, leading to higher resuspension of PM (40–50% in summer vs. less than 10% in winter). This supports the observed peak in PM10 levels during summer. Additionally, higher wind speeds in summer help disperse pollutants, but the extreme heat and stagnant air during heat waves can worsen ozone and particulate pollution.

2) Winter: Pollutant Accumulation Due to Stagnation and Biomass Burning:

Winter months experience the highest levels of PM2.5 (100–200 µg/m3), driven by a combination of low wind speeds, stable atmospheric conditions, and increased heating emissions. The mixing layer height is at its lowest during winter nights, allowing pollutants to accumulate. Additionally, biomass burning for heating contributes to 10-30% of PM pollution, with emissions peaking at night when atmospheric dispersion is weakest.

Furthermore, anticyclonic conditions, characterized by subsiding air, clear skies, and minimal precipitation, promote the accumulation of air pollutants. This leads to prolonged pollution episodes, especially during cold, stagnant weather. Conversely, when a cyclonic system approaches, pollutants are dispersed due to stronger winds and precipitation, leading to improved air quality.

A particularly important phenomenon affecting winter air quality is the Western Disturbance (WD). As a WD approaches, minimum temperatures rise, and precipitation occurs, leading to temporary air quality improvement. However, once the WD passes, temperatures drop, fog formation in creases, and cold waves spread southward, worsening pollution levels due to the suppression of vertical mixing.

3) Ventilation Coefficient and Mixing Height:

Key Factors in Dispersion: The ventilation coefficient—a product of the mixing height and transport wind speed—is an essential indicator of the atmosphere's ability to disperse pollutants. When the ventilation index falls below 6000 m2/s, with average wind speeds below 10 kmph, dispersion is unfavorable, leading to pollution buildup.

A strong negative correlation exists between PM concentrations and the mixing boundary layer depth, confirming that lower mixing heights in winter contribute to pollution accumulation, while higher mixing heights in summer aid in dispersion.

4) Monsoon:

Rainfall as a Natural Cleanser: During the monsoon, air pollution levels drop significantly as precipitation acts as an efficient removal mechanism. Rain scavenges particulate pollutants from the air, with PM10 removed more effectively than PM2.5 due to its larger particle size. However, humid conditions and overcast skies may slow down dispersion, occasionally leading to localized pollutant accumulation.

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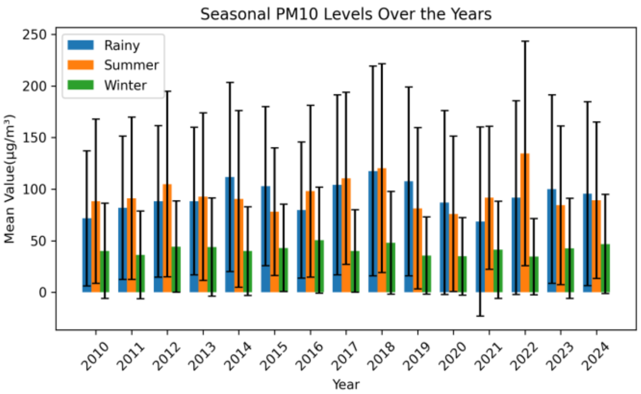
b. Trends Across Regions: Upper vs. Lower Himalayas

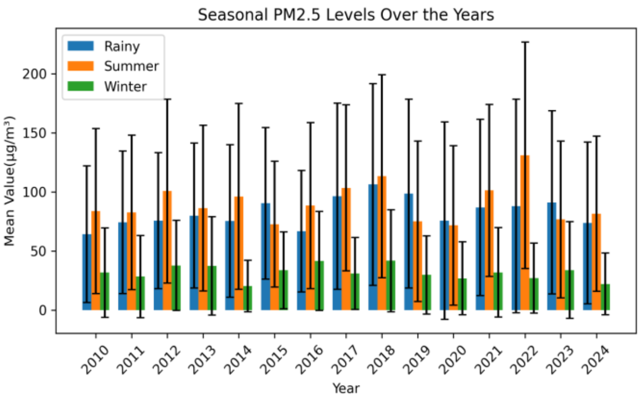
1) Yearly Variations in the Upper Himalayas:

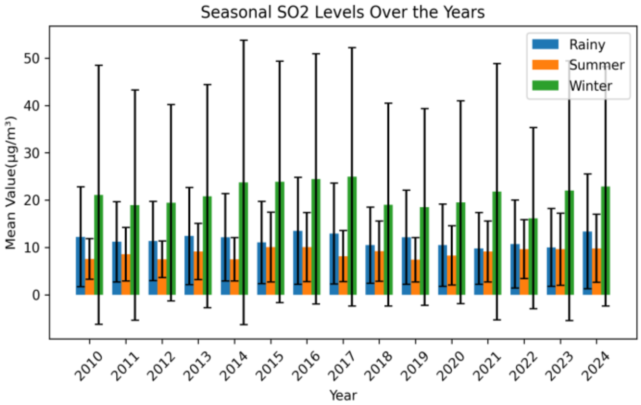
The intricate relationship between weather patterns and air quality in the Upper Himalayas is shaped by the region's unique geography and atmospheric conditions. Observations from Kishtwar, Leh highlight how meteorological factors such as wind speed, temperature, and precipitation influence pollutant dispersion, accumulation, and removal in these high-altitude environments.

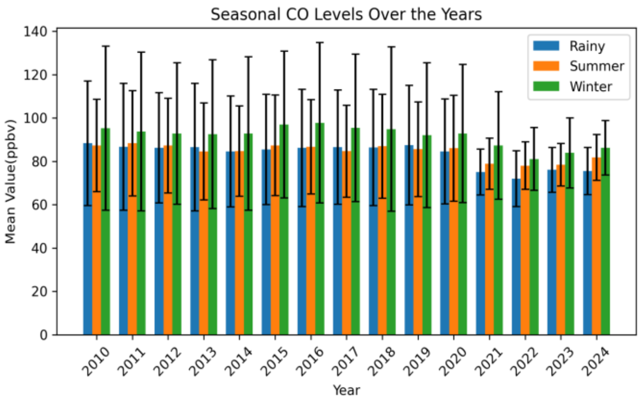
Wind speed plays a crucial role in maintaining air quality in the Upper Himalayas. Strong winds act as natural cleansers, diluting and dispersing pollutants such as PM10, O3, and SO2, preventing them from accumulating near the surface. This effect is particularly evident in open, high-altitude areas where air circulation remains relatively unhindered.

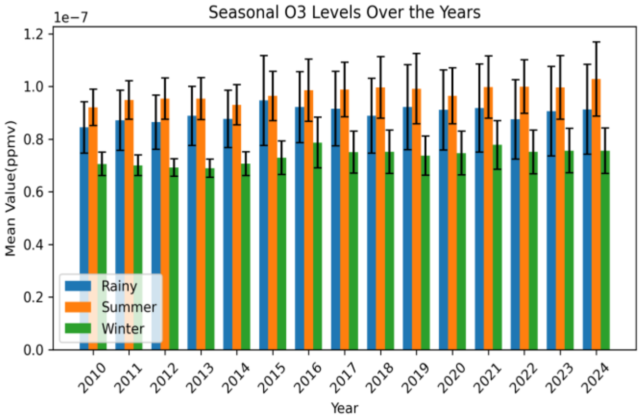
However, during periods of weak wind activity, pollutants tend to stagnate, especially in valleys where airflow is restricted by surrounding terrain. This stagnation can lead to localized pollution hotspots, where contaminants linger for extended periods until atmospheric conditions shift.

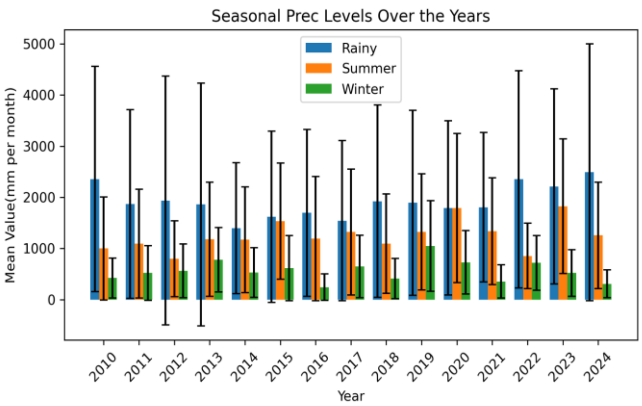












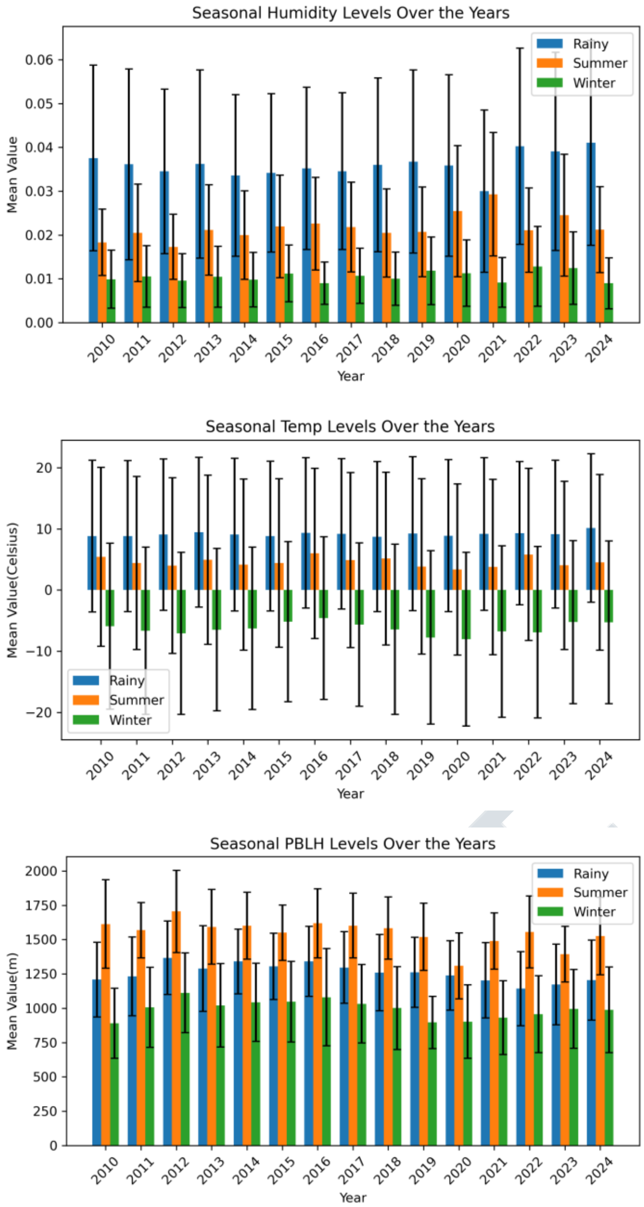
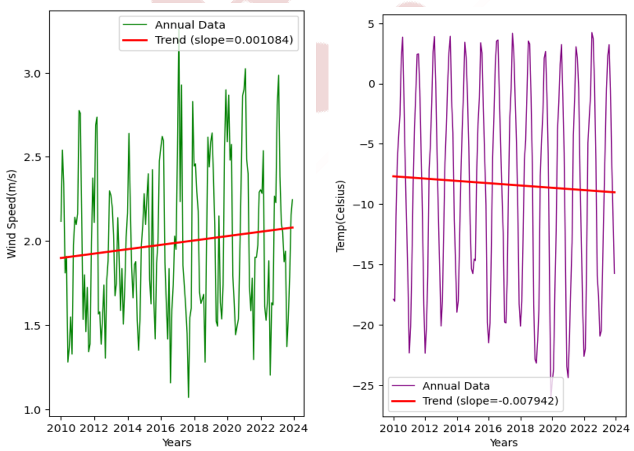


Fig. 2. Seasonal Variation of Air Quality and Meteorological Parameters in North-West Himalayas



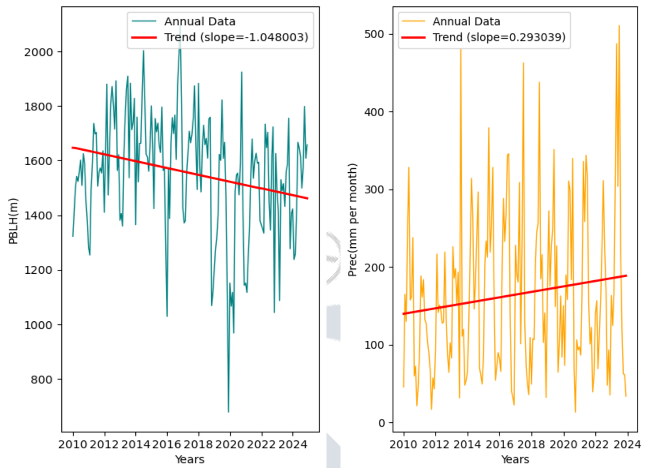


Fig. 3. Time series plot for Meteorological data of location at Lat.: 34.5 and Lon.: 77.5 (Leh, Kashmir, India) with trend line.

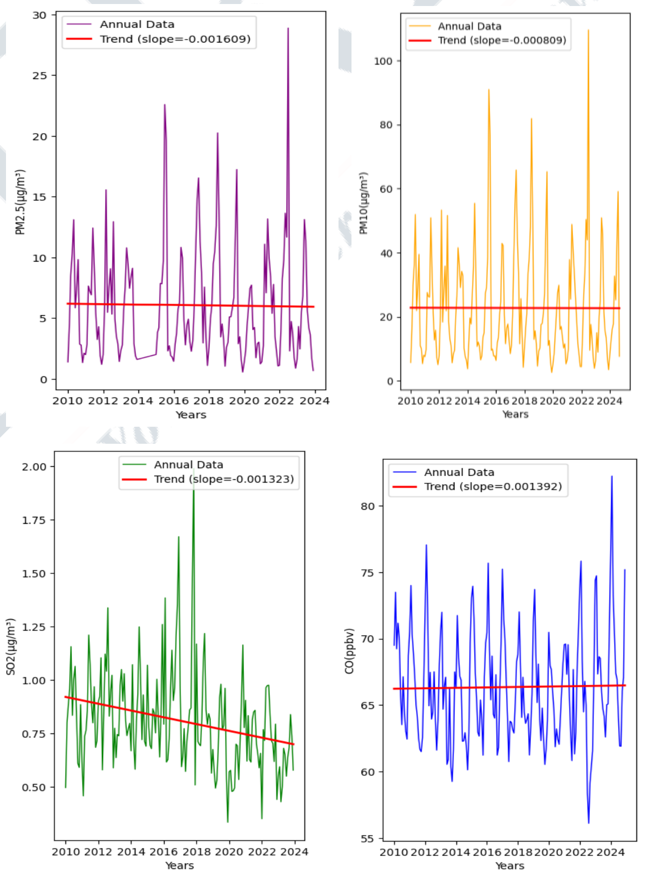


Fig. 4: Time series plot for Air quality of location at Lat.: 34.5 and Lon: 77.5 (Leh, Kashmir, India) with trend line.

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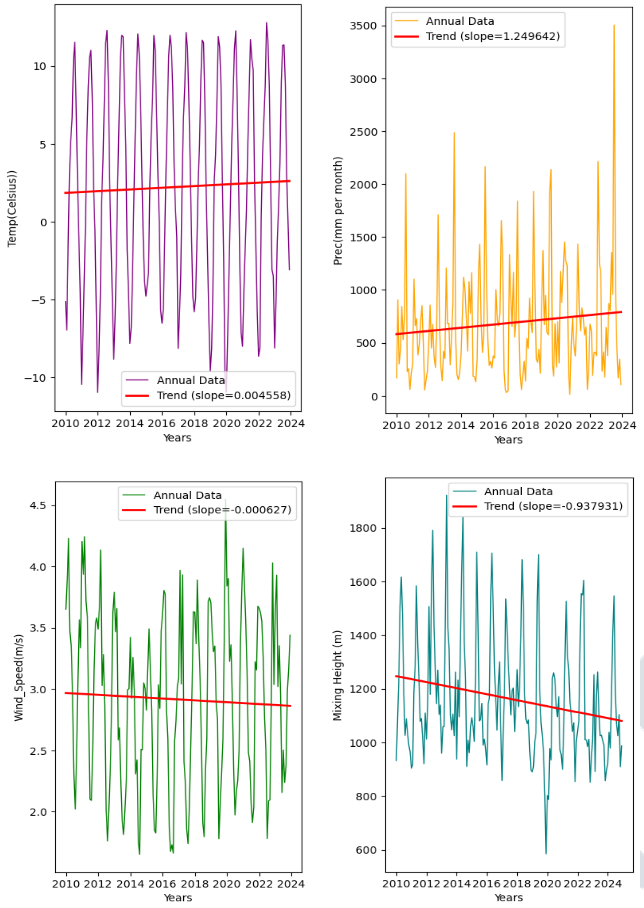
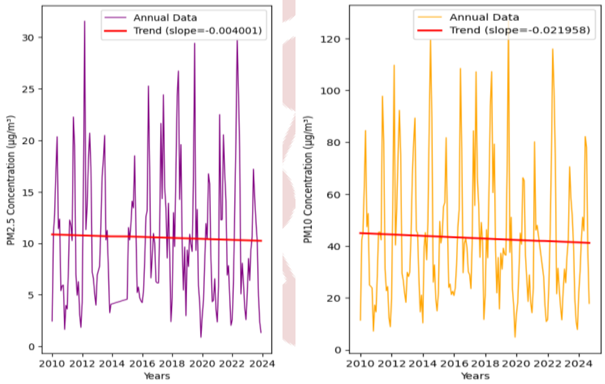


Fig 5. Time series plot for Meteorological data of location at Lat.: 33.5 and Lon.: 75.625 (Kishtwar, Kashmir, India) with trend line.



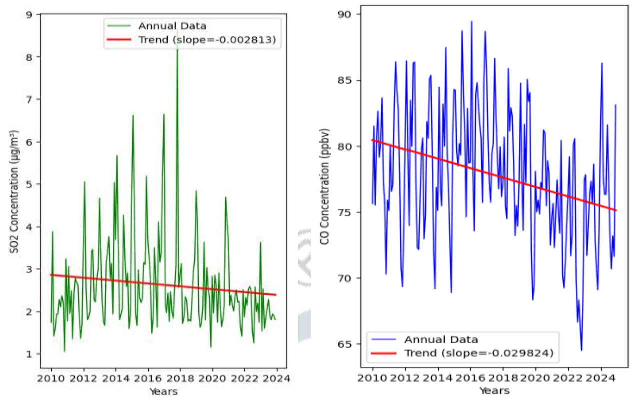


Fig. 6: Time series plot for Air quality of location at Lat: 34.5 and Lon.: 77.5 (Leh, Kashmir, India) with trend line.

Temperature fluctuations further influence **pollutant mixing and dispersion**. The data suggests a slight upward trend in temperature over time (0.004558), aligning with global warming trends that have begun to affect high-altitude regions. Lower temperatures generally contribute to **unstable atmospheric conditions**, promoting vertical mixing that enhances pollutant dilution. However, during winter months, **temperature inversion events**—where a warm layer of air traps colder air below—can prevent pollutants from rising, **leading to a temporary build-up of PM10 and SO2 near the surface.** This phenomenon is particularly common in the Himalayan valleys, where the trapped pollutants create hazy conditions until external weather disturbances clear them away.

Precipitation acts as a natural cleansing mechanism, significantly influencing air quality. **Rainfall effectively removes pollutants from the atmosphere**, leading to a noticeable drop in aerosol concentrations, especially for PM10 and SO2. However, in winter, heavy snowfall presents a contrasting effect. Instead of washing pollutants away immediately, snow can temporarily trap contaminants near the surface, delaying their removal until the snow melts. This can result in short term pollution accumulation despite ongoing precipitation. The relationship between temperature and precipitation follows a broader climatic trend, where higher temperatures enhance evaporation, potentially increasing precipitation levels. However, the unique microclimatic variations of the Upper Himalayas can alter this relationship, making localized precipitation patterns more complex.

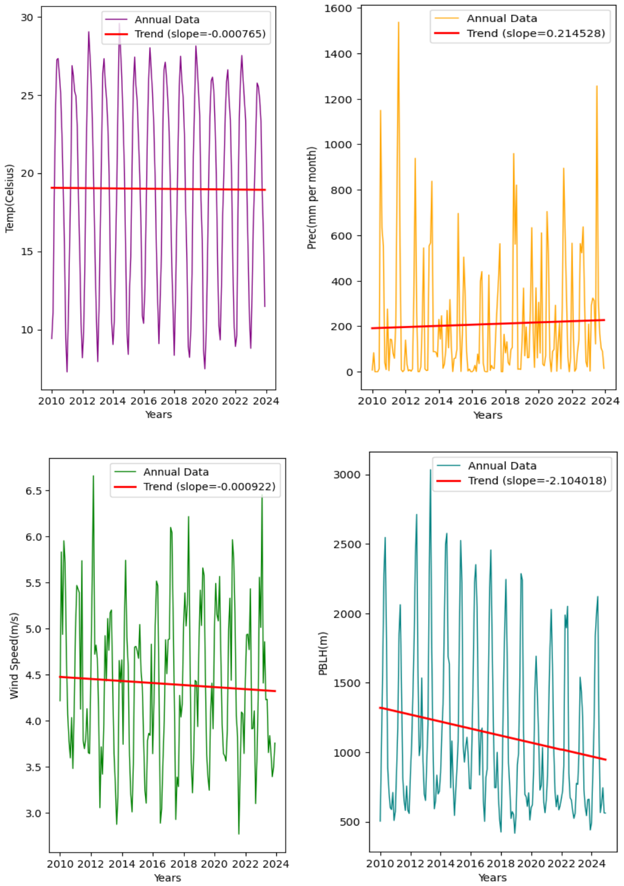


Fig. 7: Time series plot for Meteorological data of location at Lat.:30.5 and Lon.:76.875 (Basi, Punjab, India) with trend line.

The air quality dynamics of the **Upper Himalayas** are governed by a fine balance between **wind activity, atmospheric stability, and precipitation patterns.** While strong winds and atmospheric instability promote pollutant dispersion, **temperature inversions and snowfall can temporarily trap pollutants, leading to episodic air quality fluctuations.** These interactions underscore the need for continuous monitoring to understand how climatic shifts may impact pollution levels in this ecologically sensitive region.

2) Yearly Variations in the Lower Himalayas:

The PBLH in the Lower Himalayas remains relatively lower, restricting pollutant dispersion and leading to increased surface-level pollution accumulation. In contrast, the Upper Himalayas experience a higher PBLH, which allows for better air circulation and pollutant dilution.

Air pollution in the Lower Himalayas is significantly higher, particularly for PM2.5 and PM10. This is largely due to increased human activities such as transportation, biomass burning, and industrial emissions. The Upper Himalayas, with lower population density and industrialization, experience much lower pollutant levels, although long-range transport of pollutants occasionally affects the region. Precipitation plays a crucial role in pollutant removal. The Lower Himalayas receive more frequent rainfall, which aids in washing out pollutants, whereas the Upper Himalayas, with extended dry periods, experience prolonged pollution retention. Sulfur dioxide (SO2) concentrations are also higher in the Lower Himalayas due to emissions from vehicles and industries, while the Upper Himalayas maintain relatively lower levels.

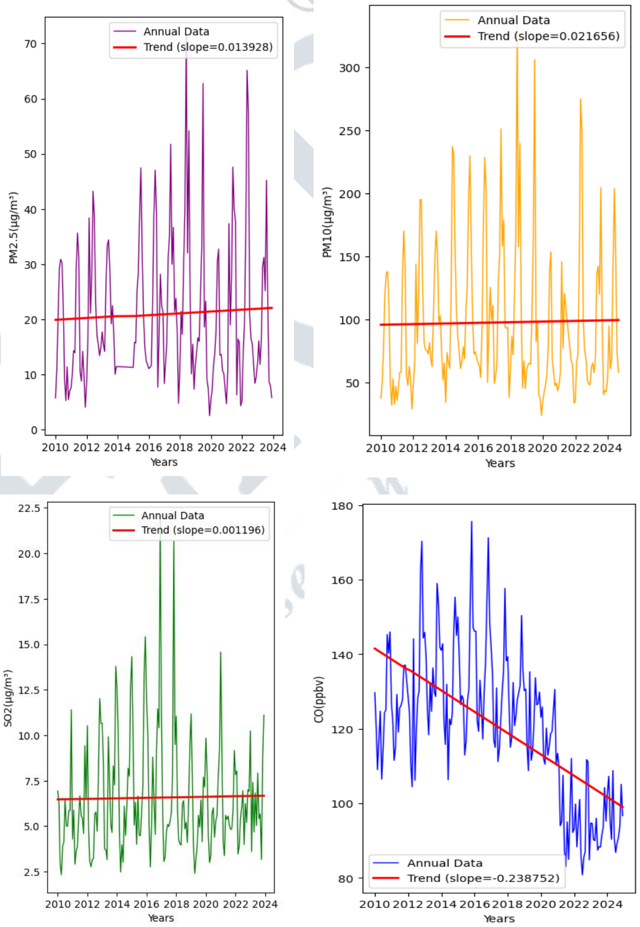


Fig. 8. Time series plot for Air Quality of location at Lat.: 30.5 and Lon.: 76.875 (Basi, Punjab, India) with trend line.

Temperature and wind patterns further differentiate these regions. During colder months, pollutants remain trapped closer to the surface in the Lower Himalayas, leading to deteriorating air quality. Additionally, lower wind speeds limit pollutant dispersion. In contrast, the Upper Himalayas benefit from stronger winds that facilitate pollutant removal.

Carbon monoxide (CO) levels follow a similar trend, being elevated in the Lower Himalayas due to combustion-related emissions, while the Upper Himalayas, with minimal human activity, sustain lower concentrations, except when pollutants are transported from lower elevations.

The Lower Himalayas experience higher pollution levels due to local emissions and unfavorable meteorological conditions. In contrast, the Upper Himalayas benefit from natural factors such as higher wind speeds, greater

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precipitation variability, and an elevated PBLH, which help maintain cleaner air. These differences highlight the influence of geography, climate, and human activities on air quality across the Himalayan range.

c. Spatial Analysis

Air quality varies significantly across different seasons due to shifts in temperature, wind patterns, and atmospheric conditions. Each season presents unique challenges, shaping pollution levels and their impact on the environment.

During winter, pollution levels peak due to a combination of low temperatures and reduced atmospheric mixing. The planetary boundary layer remains shallow, trapping pollutants close to the surface. As a result, CO, PM2.5, and PM10 concentrations rise sharply, especially in the northern and central regions. Limited rainfall and weak winds further contribute to stagnant air, preventing the dispersion of pollutants.

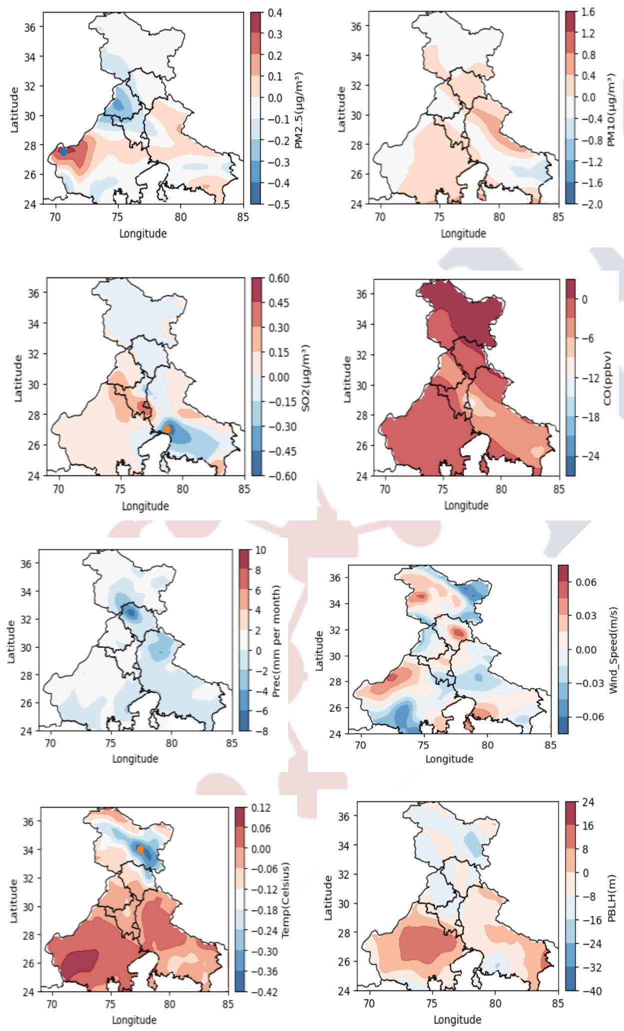

Fig. 9: Spatial plots for Air quality and Meteorological parameters during Winter Season.

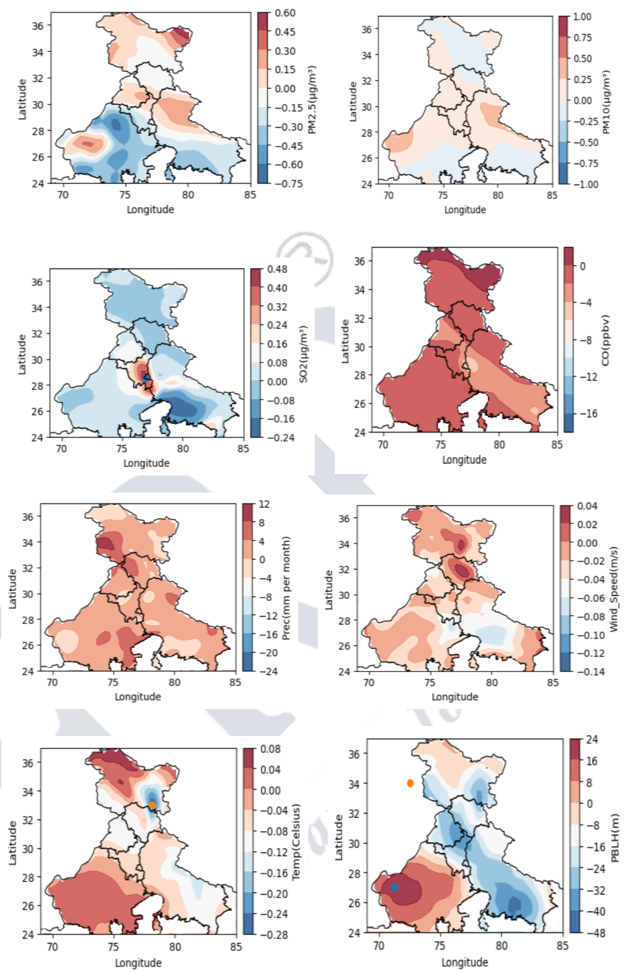

Fig. 10: Spatial plots for Air quality and Meteorological parameters during Summer Season.

SO levels also see a noticeable increase, likely due to industrial and heating-related emissions. Compared to other seasons, winter is the most challenging for air quality, with prolonged pollution episodes caused by stable atmospheric conditions.

In summer, air quality improves in some areas but remains a concern in others. CO levels remain elevated in the northern and southern regions, as reduced rainfall and weaker atmospheric cleansing allow emissions to persist longer. The planetary boundary layer height is higher in the west but lower in the east, leading to uneven pollutant dispersion. PM2.5 and PM10 concentrations show distinct spatial variations, with hotspots in the north and southwest, where dust and industrial activities contribute to particulate pollution. The limited summer rainfall does little to cleanse the air, unlike the rainy season, which benefits from frequent washouts. However, stronger winds in some areas help in pollutant dispersion, reducing localized pollution buildup.

The rainy season offers the cleanest air, because of consistent rainfall that effectively removes pollutants from the atmosphere. CO, PM2.5, and PM10 levels drop significantly as precipitation washes out fine and coarse particles. The planetary boundary layer tends to be lower, but the effect of pollutant trapping is countered by rain-driven removal. SO concentrations decline, except in regions with heavy industrial emissions, where localized pollution can persist. The cooling effect of rain lowers temperatures, reducing the intensity of photochemical reactions that contribute to secondary pollution formation.

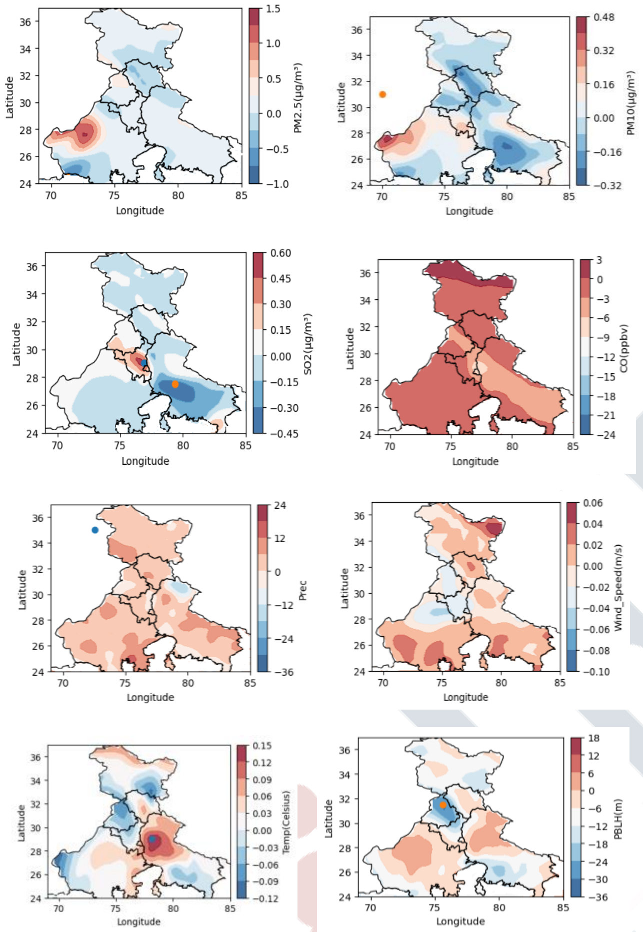

Fig. 11: Spatial plots for Air quality and Meteorological parameters during Rainy Season.

Wind patterns, influenced by monsoonal shifts, aid in pollutant dispersion, though temporary stagnation in some areas can lead to short-lived pollution spikes. Overall, winter experiences the worst air quality, with high pollution levels due to atmospheric stagnation. Summer sees moderate pollution, with better dispersion but still notable buildup in certain regions. The rainy season provides the best air quality, as frequent showers and cooler temperatures help cleanse the atmosphere. These seasonal variations highlight the need for tailored pollution control measures, considering both natural and human-made influences on air quality.

VI. IMPACT OF THE INDO-GANGETIC PLAIN ON HIMALAYAN ENVIRONMENTAL DYNAMICS

A. Transport Analysis of Air Pollutants to the Himalayan Region

Pollutant transport from the Indo-Gangetic Plain (IGP) to the Himalayan region varies with the seasons, shaped by changes in wind patterns, precipitation, and temperature. These factors determine how pollutants move and accumulate, significantly impacting air quality in both regions.

During the monsoon season, high levels of PM in north west India, including Punjab, Haryana, and Delhi, get carried toward the Himalayas. Due to lower planetary boundary layer heights (PBLH), pollutants tend to settle in mountain valleys. SO2 and CO emissions from the IGP also follow this northward path, driven by wind circulation. However, heavy rainfall in the Himalayan region helps wash pollutants out of the atmosphere, reducing their impact. Cooler mountain temperatures further contribute to pollutant trapping in valleys.

In summer, strong northward winds push pollutants from the IGP toward the northwestern Himalayas. PM concentrations remain high, while SO2 from Uttar Pradesh and Bihar moves toward the mountains. CO levels peak across the IGP and warm temperatures enhance vertical mixing, dispersing pollutants more effectively. Rainfall in the northwestern Himalayas also helps lower pollution levels.

Winter brings a different challenge. With weaker winds and pollutants in Delhi, Punjab, and Uttar Pradesh accumulate near the surface, creating hazardous air quality. SO transport remains limited due to sluggish wind movement, while CO pollution spreads eastward. The lack of rain allows pollutants to build up, and cold temperatures cause atmospheric inversions, trapping them close to the ground.

These seasonal shifts highlight the intricate link between pollution sources in the IGP and air quality in the Himalayas. Understanding these patterns is essential for addressing cross border pollution and its environmental consequences.

The Indo-Gangetic Plain (IGP) plays a crucial role in research concerning the Himalayan region due to its significant environmental, climatic, and geological interactions. As a densely populated and highly industrialized region, the IGP is a major source of pollutant emissions. These pollutants are often transported to the Himalayas, influencing regional air quality and atmospheric composition. Studies have indicated that aerosols originating from the IGP can contribute to enhanced high-rainfall events near the Himalayan foothills during the monsoon season [17].

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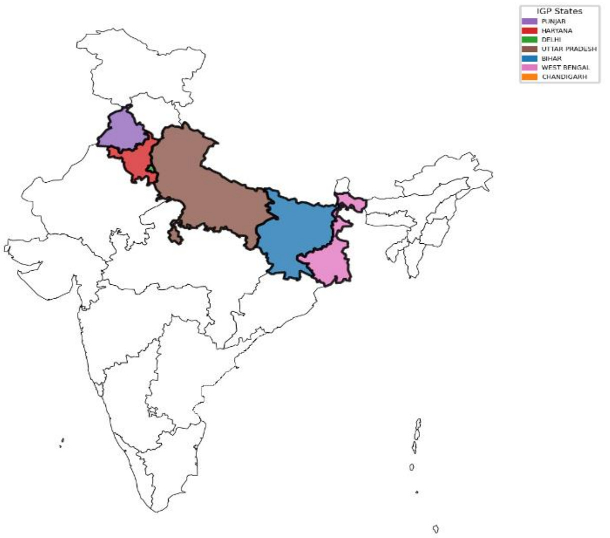


Fig. 12.: The picture depicts the Indo-Gangetic Plain

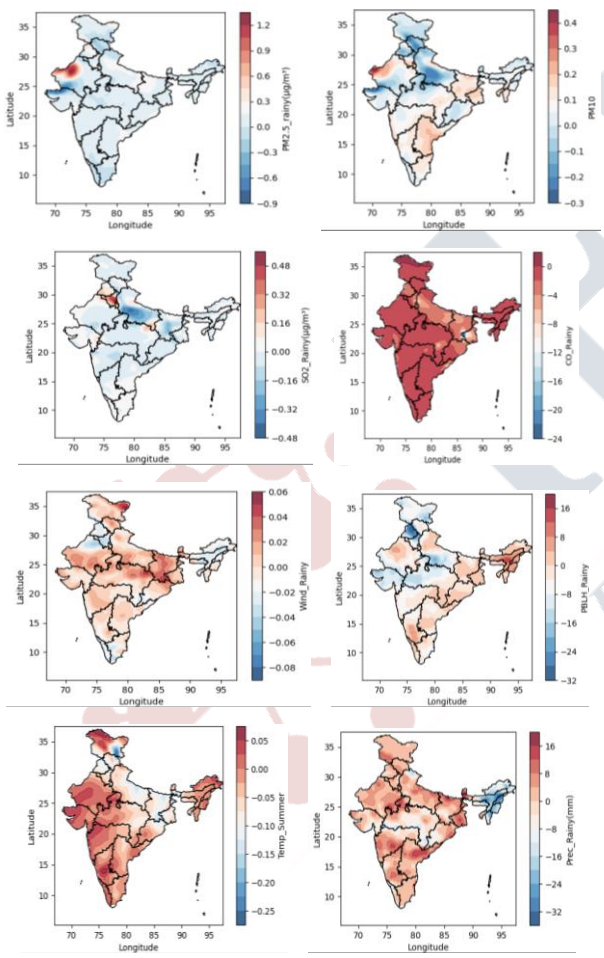


Fig. 13: Transport Analysis of Air Pollutants to the Himalayan Region during Summer season

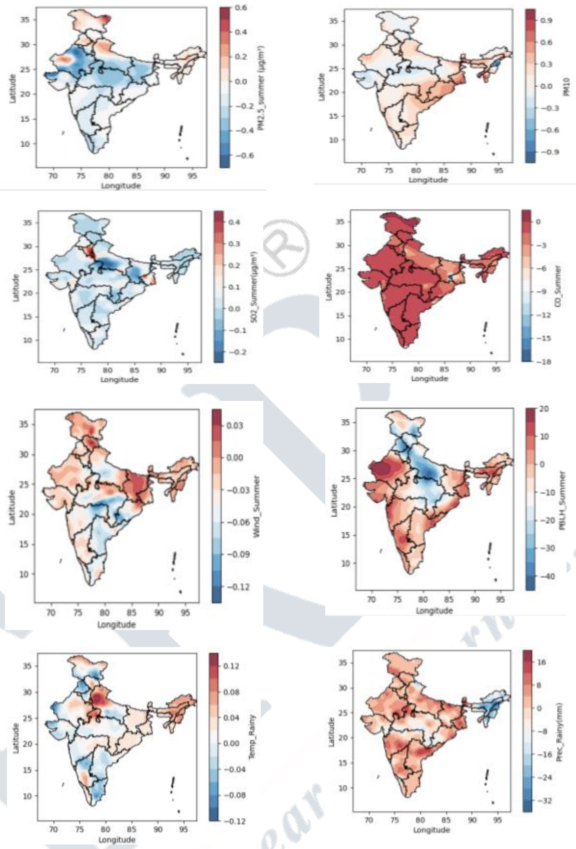
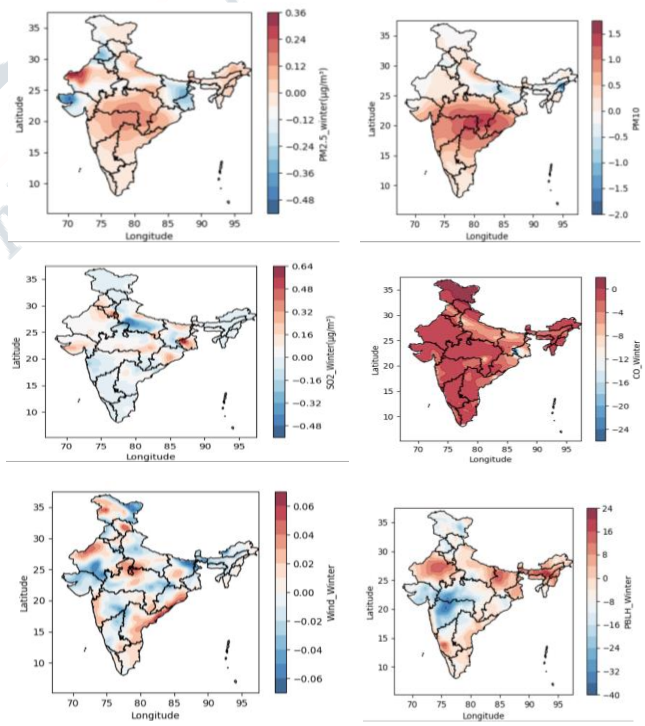


Fig.14: Transport Analysis of Air Pollutants to the Himalayan Region during Rainy season



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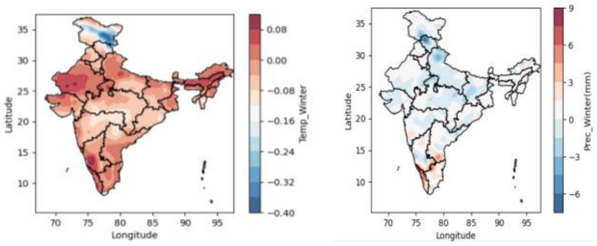

Fig.15: Transport Analysis of Air Pollutants to the Himalayan Region during Winter season

VII. CONCLUSION

This study highlights the complex relationship between meteorological parameters and air pollution in the Northwest Himalayas. Seasonal variations significantly influence pollutant concentrations, with winter witnessing severe pollution due to atmospheric stagnation, biomass burning, and temperature inversions, while the monsoon season offers a natural cleansing effect through wet deposition. Wind speed, humidity, and temperature also play key roles, shaping how pollutants disperse or accumulate across different elevations.

Elevation-based differences are striking—lower regions experience higher pollution levels due to human activities and topographical entrapment, whereas higher altitudes benefit from stronger winds and reduced emissions. Additionally, pollutants from the Indo-Gangetic Plain contribute to poor air quality in the lower Himalayas, particularly during winter and post-monsoon months.

These insights highlight the growing need for location specific and seasonally adaptive air quality management strategies. Protecting the fragile Himalayan ecosystem calls for a multi-faceted approach—stronger policies, collaborative regional efforts, and continuous air quality monitoring. By addressing these challenges, we can move toward a cleaner, healthier environment for the millions who depend on these mountain landscapes.

Table I Seasonal Variation of Pollutant Transport from IGP to The Himalayas

Factor	Rainy Season	Summer Season	Winter Season
PM2.5 Transport	High in NW India (Pun jab, Haryana, Delhi); settles in Himalayan valleys due to lower PBLH.	High in IGP; transported northward towards NWH.	High in IGP (Delhi, Pun jab, UP); limited dispersion due to low PBLH.
SO2 Transport	High over IGP; transported northward due to wind circulation.	High in UP & Bihar; transported northwest to wards NWH.	High in Delhi, UP, West Bengal; limited transport due to low wind speeds.
CO Transport	High in Central & North India; transported towards the Himalayan region.	Highest in IGP; moves northward due to strong summer winds.	Hotspots in IGP and Central India; transported eastward due to wind patterns.
Wind Influence	Winds push pollutants towards northern mountains.	Strong northward winds from IGP to NWH, aiding transport.	Low wind speeds in North India, trapping pollutants in IGP.
Precipitation Impact	High precipitation in Himalayas, causing wet deposition and pollution reduction.	High rainfall in NWH, reducing pollutant levels in those areas.	Low precipitation in North India, allowing pollutants to accumulate.
Temperature Effect	Cool temperatures in mountains trap pollutants.	Higher temperatures in IGP promote vertical mixing.	Cold temperatures in North India create inversions, trapping pollutants near the surface.

Table II Seasonal Variations in Weather Conditions and Air Quality, Highlighting Differences Between Plain Areas and Elevated Zones.

Season	Weather Conditions	Impact on Air Quality	Influence of Elevation
Winter (Nov–Feb)	Low temperatures, reduced PBLH, weak winds, frequent inversions	High PM2.5, NO2, CO levels due to poor dispersion	In valleys, pollutants accumulate due to cold air trapping, while higher elevations experience stronger winds that enhance dispersion.
Summer (Mar–June)	High temperatures, increased PBLH, strong winds, occasional dust storms	Higher PM10 levels in plains due to dust; lower PM2.5 due to enhanced mixing	In lowlands, dust storms increase PM10 levels, while in elevated regions, stronger winds improve dispersion, keeping pollutant levels lower.

Season	Weather Conditions	Impact on Air Quality	Influence of Elevation
Monsoon (July–Sep)	High humidity, strong winds, heavy rainfall	Wet deposition reduces PM2.5 and other pollutants	Rainfall effectively cleanses pollutants in both plains and mountains, but in higher elevations, orographic lifting can enhance precipitation, leading to better air cleansing.
Post-Monsoon (Oct–Nov)	Low wind speeds, temperature drop, crop residue burning effects	Elevated PM2.5 and CO due to biomass burning; declining PBLH traps pollutants.	In plains, pollution is worsened by agricultural burning, while in mountains, lower temperatures and weak winds cause pollutant stagnation, but stronger valley winds occasionally disperse them.

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Code and Data Availability

The authors can provide data and code on request.

Author Contributions

Muskan conducted the analysis, generated all the results, and drafted the initial manuscript. S.A. reviewed the manuscript, made necessary corrections, and ensured its finalization.

Conflict of Interest

The authors declare no competing interests.

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