

SPATIO-TEMPORAL VARIATION OF OZONE OVER THE EASTERN AND WESTERN INDO-GANGETIC PLAIN

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Partial Fulfilment of the Requirements for the
Degree of
MASTER OF TECHNOLOGY
in
Environmental Engineering**

**Submitted by
Anubha Singh**

24/ENE/03

**Under the Supervision of
Dr. Lovleen Gupta**

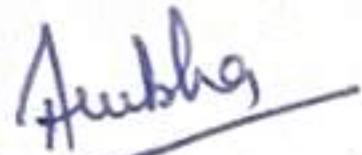


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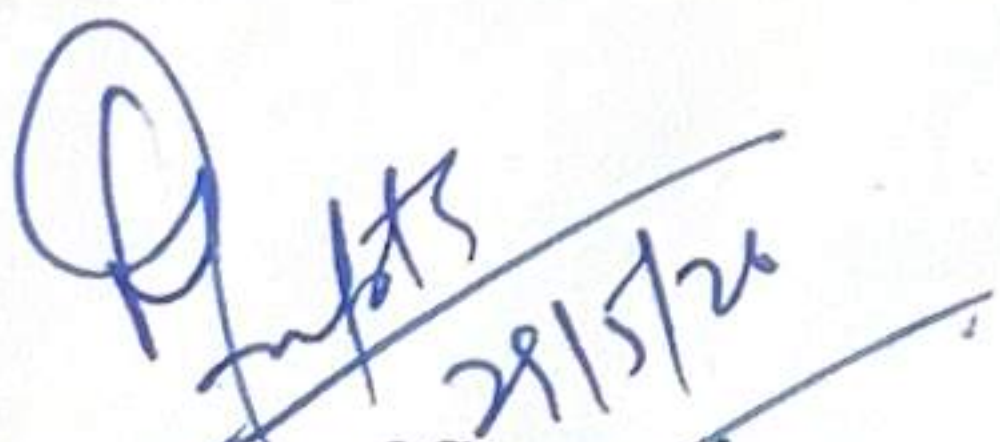
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I, Anubha Singh, Roll No. 24/ENE/03 hereby certify that the work which is being presented in the thesis entitled "**Spatio-Temporal Variation of O₃ Over the Eastern and Western Indo-Gangetic Plain**" in partial fulfilment of the requirements for the award of the Degree of Master of Technology, submitted in the Department of Environmental Science and Engineering, Delhi Technological University, is original and not copied from any source without proper citation. The matter presented in the thesis has not been submitted by me for the award of any other degree of this or any other Institute.


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This is to certify that the student has incorporated all the corrections suggested by the examiners in the thesis and the statement made by the candidate is correct to the best of our knowledge.


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CERTIFICATE BY THE SUPERVISOR

Certified that **Anubha Singh** (24/ENE/03) has carried out her research work presented in this thesis entitled **“Spatio-Temporal Variation of O₃ Over the Eastern and Western Indo-Gangetic Plain”** for the award of **Master of Technology** from the Department of Environmental Science and Engineering, Delhi Technological University, Delhi, under my supervision. The thesis embodies results of original work, and studies are carried out by the student herself, and the contents of the thesis do not form the basis for the award of any other degree to the candidate or to anybody else from this or any other University/Institution.

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SPATIO-TEMPORAL VARIATION OF O₃ OVER THE EASTERN AND WESTERN INDO-GANGETIC PLAIN

ABSTRACT

One of the most populated and polluted parts of India is the Indo Gangetic plain (IGP), where the systematic analysis of TCO trends on a sub-regional basis over a considerable period of time is still lacking. This study examines the spatio-temporal variation and long-term trends of the TCO over two contrasting ends of the IGP — the state of Punjab in the West and the state of West Bengal in the East — covering the period of 2004–2025 using satellite data from NASA's O₃ Monitoring Instrument (OMI) and ESA's Sentinel-5P TROPOMI, extracted using the Google Earth Engine (GEE). Within each state, a high-O₃ and a low-O₃ region were identified and studied separately to capture the intra-state variability. Trend analysis was performed out using the Mann-Kendall (MK) test and Sen's slope estimator using R, across monthly, seasonal, and annual time periods.

Results show that Punjab consistently recorded higher TCO values (annual mean O₃ of around 286 DU) than West Bengal (annual O₃ of around 270 DU), consistent with the north-to-south O₃ gradient observed over India. Both states show statistically significant increasing annual trends ($p < 0.05$ for all four regions). The pre-monsoon season (March–May) comes out as the period of peak O₃ loading in both regions, driven by improved photochemical activity and biomass burning. The lowest O₃ values appear during the post-monsoon period (October–December). Sen's slope values show an increase of about 0.42–0.50 DU/year across all regions. These findings highlight the need for region-specific air quality supervision, specifically ozone.

Keywords: Indo Gangetic Plain, TCO, Mann-Kendall, Sen's Slope, Google Earth Engine, O₃ Monitoring Instrument

LIST OF CONTENTS

Title	Page No.
Acknowledgement	ii
Candidate's Declaration	iii
Certificate by the Supervisor	iv
Abstract	v
List of Tables	vii
List of Figures	vii
List of Equations	vii
List of Abbreviations	vii
CHAPTER 1: INTRODUCTION	1-4
1.1 Background and Context	1
1.2 Problem Statement	3
1.3 Objectives of the Study	3
1.4 Significance of the Study	3
1.5 Structure of the Thesis	4
CHAPTER 2: BACKGROUND STUDY AND LITERATURE REVIEW	5-
2.1 O ₃ Trends Over India	5
2.2 Indo-Gangetic Plain as an O ₃ Hotspot	6
2.3 Satellite-Based O ₃ Monitoring	6
2.4 Statistical Methods for Trend Detection	7
2.4 Literature Review	7-11
CHAPTER 3: STUDY AREA	12-14
3.1 Overview of the Indo-Gangetic Plain	12
3.2 Punjab (Western IGP) and West Bengal (Eastern IGP)	
3.3 Rationale for Sub-Regional Delineation	14
CHAPTER 4: DATA AND METHODOLOGY	15-20
4.1 Satellite Data Sources	15
4.1.1 NASA O ₃ Monitoring Instrument (OMI)	15
4.1.2 ESA Sentinel-5P TROPOMI	15
4.2 Data Extraction Using Google Earth Engine	15
4.3 Seasonal Classification	19
4.4 Statistical Trend Analysis	19
4.4.1 Mann-Kendall Non-Parametric Test	19
4.4.2 Sen's Slope Estimator	19
4.4.3 Analysis Framework	20
CHAPTER 5: RESULTS AND DISCUSSION	21-32
5.1 Mean O ₃ Levels and Regional Comparison	21
5.2 Mann-Kendall Trend Analysis: Punjab	21
5.2.1 Punjab — High-O ₃ Region	21
5.2.2 Punjab — Southern Region	22
5.3 Mann-Kendall Trend Analysis: West Bengal	23
5.3.1 West Bengal — Northern Region	23
5.3.2 West Bengal — Southern Region	24
5.4 Annual Trend Visualisation	26
5.5 Seasonal O ₃ Patterns	27
5.6 Monthly O ₃ Patterns	28
5.7 Sen's Slope Comparison	31
5.8 Comparison of Eastern vs. Western IGP	31
CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS	33-35
1.1 Summary of Key Findings	33
1.2 Policy Implications	34
1.3 Limitations of the Study	34
1.4 Recommendations for Future Research	35
REFERENCES	36-38
ANNEXURES	39
CERTIFICATE OF THESIS SUBMISSION FOR EVALUATION	42
CERTIFICATE OF FINAL THESIS SUBMISSION	43
PLAGIARISM VERIFICATION	44
LIST OF CONFERENCE PROCEEDINGS	45

LIST OF TABLES

2. **Table 1:** Summary of Selected Literature on TCO Studies
3. **Table 2:** Description and Interpretation of Mann-Kendall Test and Sen's Slope Parameters
4. **Table 3:** Monthly, Seasonal and Annual TCO — Mann-Kendall Results for Punjab Northern Region (2004–2025)
5. **Table 4:** Monthly, Seasonal and Annual TCO — Mann-Kendall Results for Punjab Southern Region (2004–2025)
6. **Table 5:** Monthly, Seasonal and Annual TCO — Mann-Kendall Results for West Bengal Northern Region (2004–2025)
7. **Table 6:** Monthly, Seasonal and Annual TCO — Mann-Kendall Results for West Bengal Southern Region (2004–2025)

LIST OF FIGURES

1. **Fig. 1:** Study Area
2. **Fig. 2:** Google Earth Engine Interface
3. **Fig. 3:** Punjab Annual O₃ (DU) – 2018 to 2025
4. **Fig. 4:** West Bengal Annual O₃ (DU) – 2018 to 2025
5. **Fig. 5:** Annual Mean TCO (DU) over Punjab's High-O₃ and Low-O₃ Sub-Regions (2004–2025)
6. **Fig. 6:** Annual Mean TCO (DU) over West Bengal's High-O₃ and Low-O₃ Sub-Regions (2004–2025)
7. **Fig. 7:** Seasonal O₃ Comparison Across All Regions (Punjab) (2004–2025)
8. **Fig. 8:** Seasonal O₃ Comparison Across All Regions (West Bengal) (2004–2025)
9. **Fig. 9:** Monthly O₃ Profiles Across All Regions of Punjab (2004–2025)
10. **Fig. 10:** Monthly O₃ Profiles Across All Regions of West Bengal (2004–2025)

LIST OF EQUATIONS

1. **Equation 1:** MK test statistic (S)
2. **Equation 2:** Sen's slope (β)

LIST OF ABBREVIATIONS

1. **GEE:** Google Earth Engine
2. **MK Test:** Mann-Kendall Test

CHAPTER 1: INTRODUCTION

1.1 Background and Context

Ground-level and TCO is a critical atmospheric parameters that plays a dual role: protecting life from harmful Ultra Violet radiation in the stratosphere while acting as a harmful pollutant and a potent greenhouse gas in the troposphere. In urban and agricultural regions, O_3 forms through complex photochemical reactions involving precursor gases such as nitrogen oxides (NO_x) and volatile organic compounds (VOCs), both of which are produced in abundance by vehicular traffic, industrial operations, and agricultural burning. The dual nature of O_3 — protective aloft and damaging near the surface — makes it one of the most challenging pollutants to regulate and study.

O_3 is an important component of Earth's atmosphere as it protects us from harmful UV radiation from the Sun, but on the other hand it acts as a secondary pollutant and a greenhouse gas causing serious issues to human health, vegetation and the ecosystem (Monks et al., 2015; Budakoti, 2025; Dhanya et al., 2024). It is estimated that about 90% of the TCO is concentrated in the stratosphere, which absorbs the harmful radiation of the range 2000-3000 Å (Armstrong), and the remaining 10% is in the troposphere (Budakoti, 2025; Moncy et al., 2025). This aspect induces a necessity to study variability of O_3 in the atmosphere. O_3 is generated from chemical changes affected by light on atmospheric trace gases including the oxidation of carbon monoxide (CO) and methane (CH_4) and the combination of VOCs and nitrogen oxides (NO_x) in the presence of strong sunlight (Monks et al., 2015; Dhanya et al. 2024). The photochemical reactions that create O_3 are dependent on a number of meteorological factors (for example, temperature, sunlight intensity, UV radiation, wind speed, and relative humidity), each of which impact the efficiencies of the chemical reactions that produce O_3 (Londhe et al., 2008; Dhanya et al., 2024). Increased surface temperature leads to greater rates of photochemical reaction, while increased humidity increases the rate at which O_3 is removed from the atmosphere through photolytic reaction or reaction with hydroxyl radical ($\cdot OH$) (Londhe et al., 2008). Tropospheric O_3 plays a significant role in influencing the balance of total radiation of the Earth's surface and global warming through the effects of radiative forcing on regional climate systems and weather patterns (Budakoti, 2025; Moncy et al., 2025).

All of these characteristics make tropospheric O₃ an important parameter for air quality and climate change management. Research has shown that the variability of the amount of O₃ in a vertical column of air above the surface area (1 cm²) is a determinant of the changes in stratospheric O₃ on the lower levels (Budakoti, 2025; Gupta et al., 2023). Furthermore, changes to stratospheric O₃ occur as a result of changes within the photochemical formation of O₃ as well as during transportation via atmospheric transport patterns within large scale weather patterns, such as the Brewer Dobson Circulation, which transports O₃ from the mid-latitude regions of the tropics to the Northern Hemisphere (Weber et al., 2018, 2022; Budakoti, 2025). Since the implementation of the Montreal Protocol towards the end of 1990s, and a reduction of O₃ depleting substances (ODS) that contain halogens, an increase in the amount of stratospheric O₃ has been observed; and studies also indicate that there will continue to be an increase in the amount of O₃ over the long term (Weber et al., 2022; Budakoti, 2025).

The Indo Gangetic Plain (IGP) region of India is one of the regions with high surface and TCO concentration in the world. The IGP is spread across northern India and includes some of the highest emission rates, and population densities and intensification of agriculture in the world. A number of studies using satellite data (such as the O₃ Monitoring Instrument) have consistently reported higher concentrations of tropospheric O₃ in northern Indian areas, especially during the pre-monsoon season. The IGP is surrounded by the Himalayan Mountains to the North and the Vindhya and Aravalli Ranges to the south, creating a geographical configuration that is conducive to the build-up of pollutants and the formation of O₃.

The study of TCO (TCO) combines both stratospheric and tropospheric O₃ and provides an important understanding on atmospheric O₃ budget, UV radiation reaching the Earth's surface, and the radiative forcing effects of O₃ on the climate system. TCO is typically measured in Dobson Units (DU), where 1 DU equals 0.01 mm thickness of O₃ at standard temperature and pressure. Long-term satellite observations of TCO offer continuous coverage (spatial and temporal) , making them invaluable for trend detection and regional comparisons.

1.2 Problem Statement

The number of studies conducted in the O₃ for the country is increasing but detailed comparison of the east and west end of IGP is still limited. Punjab (west), and West Bengal (east), are two different emission and agro-climatic environments in the same plain. Punjab is the centre of large scale burning of crop residues, high usage of pesticides and fertilizers and is also very close to the city of Delhi which is one of the most polluted cities in the world. In West Bengal,

the megacity of Kolkata, river delta agriculture, and a relatively humid sub-tropical climate with strong influence from the Bay of Bengal, dominate.

Comparing O₃ behavior across these two states can reveal important differences in O₃ formation mechanisms, seasonal drivers, and long-term trajectories. Moreover, the absence of long-term (>20 years) trend analyses at the sub-state level — distinguishing between high-O₃ and low-O₃ zones within each state — creates a critical gap in our understanding of intra-regional O₃ dynamics across the IGP. The present study addresses this gap.

1.3 Objectives of the Study

The specific objectives of this research are as follows:

1. To get the data for spatio temporal analysis of O₃ over study region.
2. To analyse long term trends of O₃ over the study location.
3. To analyse spatial variation monthly, seasonally, and annually.

1.4 Significance of the Study

This research contributes to the growing of satellite-based atmospheric studies over South Asia by providing a 22-year comparative analysis of TCO trends across two environmentally and climatologically distinct ends of the Indo Gangetic Plain. The findings have direct link to air quality policy, farming based health planning, and climate change assessments. By identifying seasonally and regionally specific trends, the study provides actionable insights for environmental managers and policymakers in one of the world's most air-pollution-challenged regions.

1.5 Structure of the Thesis

The thesis is divided into six chapters. Chapter one includes an overview of the background information, problem statement, objectives, and importance of the study. Background information and literature review are discussed in Chapter Two. The study area is discussed in Chapter Three. Data source and methodology are covered in chapter four. Results and discussion are included in chapter five using statistics and graphs. Conclusion and future recommendations are discussed in chapter six. The thesis ends with references.

CHAPTER 2: BACKGROUND STUDY AND LITERATURE REVIEW

2.1 O₃ Trends Over India

O₃ is found throughout the Earth's atmosphere, with about 90% concentrated in the stratosphere (15–50 km altitude) and the remaining 10% in the troposphere (0–15 km altitude). Stratospheric O₃ is important because it absorbs ultraviolet radiation (UV-B and UV-C) from the sun which is harmful to communities and human health. In contrast, tropospheric O₃ is a secondary pollutant, which is produced by photochemical reactions of NO_x and VOCs in sunlight, and is classified as a criteria air pollutant by the World Health Organisation (WHO) because of the harm it does to human health, to vegetation and to crop yields.

The TCO is measured as total O₃ in the atmosphere in the vertical column from the ground level to the highest level, and is expressed in Dobson Units (DU). The TCO suggests the stratospheric and tropospheric O₃ changes, therefore monitoring TCO is important for patterns of O₃ in the atmosphere.

Due to geography, the rapid growing economy and diverse land use pattern in India, O₃ environment is very diversified. O₃ long-term ground-based observations carried out by India Meteorological Department (IMD) and satellite O₃ observations e.g. by OMI instrument have shown the general increasing trend in tropospheric O₃ concentration over Indian subcontinent during last 20-30 years. The surface O₃ variation by season has been recorded at Lal et al (2000) station, which showed that the pre-monsoon season is the season of maximum production of O₃. The influence of the monsoon dynamics on O₃ variations has been discussed by Chakrabarty et al. (1998) which analysed long-term changing trends in column O₃ over India.

Recent studies, such as Kunchala et al. (2022) and Rathore et al. (2023), have used Mann-Kendall trend tests, confirming significant increasing trends in O₃ across different areas of India. Pathakoti et al. (2021) applied machine learning methods for spatiotemporal weather-related mapping of O₃ over India, showing hotspots matched up with urban and agricultural burning zones. These studies altogether establish the IGP as a primary area of concern for O₃ pollution.

2.2 Indo-Gangetic Plain as an O₃ Hotspot

The IGP area has been consistently found to be among the worst hot spots in terms of O₃ pollution in Asia. The IGP is especially vulnerable to the accumulation of O₃ because of several characteristics. Firstly, it is surrounded by different mountain ranges which limit the spread of pollution. Secondly, it supports some of the significantly large agricultural burning practices

including rice stub burning in October-November across Punjab and Haryana and wheat residue burning in May causing high emission of NO_x , CO and VOCs. Third, the rapid growth of the region's car fleet and industry throughout the year continually adds precursor gas emissions.

Ravindra et al. (2020) specifically studied Chandigarh — located in the IGP — and recorded trends in PM and O_3 concentrations over the years, highlighting the role of crop burning in raising autumn O_3 levels. Peshin et al. (2017) studied photochemical O_3 buildup in Delhi-NCR, proving how high NO_x and VOC concentrations combine with intense summer solar radiation to produce O_3 concentrations frequently exceeding national and WHO standards. The IGP's O_3 challenge is thus multidimensional: driven by agriculture, industry, and transport simultaneously.

2.3 Satellite-Based O_3 Monitoring

The satellite atmospheric measurements of O_3 monitoring have enabled the study of TCO at high spatial resolution, which is very valuable at high spatial resolution, especially over large geographic areas at high spatial resolution. The Total O_3 Mapping Spectrometer (TOMS) instrument at NASA provided O_3 data for the entire world between 1978 and 2005. This is continued by the O_3 Monitoring Instrument (OMI) instrument on the Aura satellite, which was launched in 2004, with improved spatial resolution (13×24 km at nadir) and spectral range, allowing the measurement of TCO, aerosols, NO_2 , SO_2 and other trace gases.

The Sentinel-5P satellite, developed by European Space Agency (ESA) launched in 2017 with the instrument (TROPOMI), offers spatial resolution (3.5×7 km) and frequent global monitoring, allowing detailed mapping of atmospheric structure at minor scales. The Google Earth Engine (GEE) platform has further access to these satellite datasets, enabling researchers to extract, process, and study time series over specific land areas with unique efficiency.

2.4 Statistical Methods for Trend Detection

Mann-Kendall (MK) non-parametric trend test was developed by Mann (1945) and further validated by Kendall (1975) is most commonly used test for trend detection in meteorological or atmospheric time series. It has merits of no data normality assumption, data resistant to outliers, and when suitably adjusted it could be applied to autocorrelated series (Hamed and Rao, 1998; Yue and Wang, 2004). S is the test statistic used to represent the difference in sign of all possible pairs of monitoring — a positive value for S indicates an upward trend, a negative value indicates a downward trend.

Sen's slope estimator (Sen, 1968) provides a strong, non-parametric approximation of the rate of change (slope) in a time series, computed as the median of all pair slopes. Unlike ordinary least squares regression, Sen's slope is not sensitive to exceptions or unusual distributions, making it useful for analyzing satellite-derived atmospheric data that may contain uncertain measurements or extreme events. The Mann-Kendall (MK) test and Sen's slope together provide both the significance and the magnitude of a detected trend.

2.6 Literature Review Table

Table 1: Summary of Selected Literature on TCO Studies.

S.No.	Reference	Study Area	Methodology	Key Findings
1	Moncy et al. (2025)	Indian metro cities	Remote sensing; geospatial analysis; MK test	Significant increasing trends in ground-level O ₃ in all major Indian metros
2	Alduwais et al. (2024)	Arabian Peninsula	Satellite data; meteorological correlation	Meteorological controls on surface O ₃ ; positive trend observed
3	Bhattarai et al. (2024)	Global	Climate-chemistry model; CMIP6 projections	Mid-21st century O ₃ changes linked to climate, land use and emission shifts
4	Gupta et al. (2024)	India	Trace gas distribution; satellite data	Spatial mapping of NO ₂ , CO and O ₃ distributions across India
5	Ganguly & Gupta (2024)	Global	Literature synthesis	O ₃ hole dynamics and greenhouse gas feedback on warming
6	Rathore et al. (2023)	India	OMI; long-term tropospheric O ₃ analysis	Increasing tropospheric O ₃ over India; post-monsoon maxima dominant
7	Kunchala et al. (2022)	India (pan-India)	Satellite + ground data; MK trend test	Spatiotemporal variability and increasing
8	Pathakoti et al. (2021)	India	Machine learning; spatiotemporal climatology	ML-assisted climatological classification of O ₃ patterns; seasonal drivers identified
9	WHO (2021)	Global	Meta-analysis; air quality guidelines review	Updated global air quality guidelines;
10	Ravindra et al. (2020)	Chandigarh (IGP)	Air quality station data; trend analysis	Seasonal variation and increasing trend in PM and O ₃ in Indo-Gangetic Plain

11	Peshin et al. (2017)	Delhi-NCR	Station data; photochemical analysis	Anthropogenic emissions driving O ₃ buildup; PM and NO _x major precursors
12	Fiore et al. (2002)	United States	OMI satellite data analysis	Background O ₃ levels and contributions from trans-boundary transport
13	Lal et al. (2000)	Urban India	Ground-based monitoring; surface O ₃ & precursors	Seasonal variation in surface O ₃ ; NO _x and VOC identified as key precursors

2.6.1 Satellite-Based Trend Analysis Over India

The spatiotemporal dynamics of O₃ over India obtained from the satellite observations and statistical trend analysis in the present study have been established by various recent studies, using trend analysis techniques similar to that followed in the present study and satellite data directly comparable. In a recent study, Kunchala et al. (2022) analyzed surface O₃ variability and trends over India by combining satellite observations with surface measurements, which are also analyzed in this study, using the Mann-Kendall trend test, the same non-parametric statistical technique employed in this study. The results presented here are contrasted with their results of significant increasing trends of O₃ over various regions of India, which gives a pan-India baseline to compare the sub-regional trends and results. On this basis, Rathore et al. (2023) went on to analyse long-term changes in tropospheric O₃ over the Indian region using OMI data, the main instrument used in this thesis, and concluded that the trend of tropospheric O₃ has been increasing with post-monsoon maximums as the major seasonal feature. The present study is confined to the TCO over the IGP and not to the column O₃ in the troposphere, however, the seasonal trends do support this: It is the minimum season for TCO (post-monsoon) when a statistically significant increase is recorded over West Bengal, consistent with the documentation of O₃ accumulation in the autumn season by Rathore et al. across India..

2.2 Machine Learning and Climatological Mapping

Using machine learning methods, Pathakoti et al. (2021) classified spatiotemporal climatological patterns of O₃ across Indian subcontinent, and found the O₃ hotspots were closely linked to urban centres and agricultural burning regions. The climatological maps suggest that the IGP and especially the northwest region of the country with the influence of Punjab has one of the highest concentration zones of O₃ in India, which is reflected in the significantly higher annual mean TCO values (~286 DU) found for Punjab in this study

compared to West Bengal (~270 DU). (Changes in tropospheric O₃ over India: Variability, long-term trends and climate forcing, 2023) The pre-monsoon seasonality found in the current work in all four sub-regions, with the photochemical and the biomass burning processes being prominent in this season, are consistent with the ones identified in Pathakoti et al. for the national scale, confirming that the four processes are robustly present at the sub-state scale in the IGP. (Lu et al., 2018, pp. 3101-3118).

2.3 Urban and Metropolitan O₃ Trends

Moncy et al. (2025) This study is of special interest to the present study because of two reasons: This study is of great interest to the present study in the following ways: First, the methodology used (satellite remote sensing with MK trend analysis) is similar to the analytical approach adopted in the sub-state regions of Punjab and West Bengal. Secondly, the results of Moncy et al. are similar to what we are seeing – namely, higher O₃ loading in the northern part of the Punjab, which is close to high-density urban industrial activity, as well as topographic trapping. Likewise, Gupta et al. (2024) used satellite data to present a spatio-temporal distribution of pollutant trace gases (including O₃) over India; their spatial maps concur with the north-south gradient in the O₃ results found in this study, with the north-western IGP (including the Punjab) exhibiting consistently higher concentrations of the trace gases

2.4 Global Health Guidelines and Policy Context

The Global Air Quality Guidelines (WHO, 2021) have been updated, and this work has relevance to the policy implications. The updated guidelines set new lower limits for exposure to O₃, reflecting the increasing evidence of human health impacts caused by higher levels of O₃ exposure on the respiratory and cardiovascular systems. This continuing trend of increasing TCOs, in this study was statistically significant at 0.42–0.50 DU/year across the four IGP sub-regions, needs to be viewed against this policy background. (Changes in tropospheric O₃ over India: Variability, long-term trends and climate forcing, 2023) The present study fulfills this need by providing 22-year sub-regional trend evidence for the IGP, which is highlighted in the WHO (2021) guidelines.

2.5 Future O₃ Projections and Climate Feedbacks

Bhattarai et al. (2024) have employed climate-chemistry models and projections from the Coupled Model Intercomparison Project (CMIP6) to investigate the future evolution of global O₃ air quality through the mid-21st century, concluding that the changes in climate, land use and emissions will all contribute to substantial changes in O₃ air quality. The increase in O₃

levels in the South Asian region continues under BAsUs can be seen as a projection on which the trends observed in this thesis are forward-looking. The Sen's values of 0.42 to 0.50 DU per year obtained here when extrapolated to future decades suggest an increase of 8-10 DU in IGP TCO by mid-century as Bhattarai et al. imply this increase will lead to higher UV exposure, crop damage and radiative forcing. (Skeie et al., 2020) Ganguly and

Gupta (2024) also explored the interplay between the accumulation of greenhouse gases and the occurrence of O₃ holes in the context of global warming, as well as feedbacks that increase the rate of photochemical O₃ formation with increasing surface temperatures. This is consistent with the positive feedback between warming and O₃ in the present study, which was found in both Punjab and West Bengal, indicating that the warming-O₃ positive feedback that was identified by Ganguly and Gupta may already be detectable at the sub-regional IGP scale. (Changes in tropospheric O₃ over India: Variability, long-term trends and climate forcing, 2023)

2.6 Meteorological Controls and Regional Comparisons

In their study, Alduwais et al. (2024) observed the spatiotemporal variability of surface O₃ over the Arabian Peninsula and identified meteorological conditions that are key drivers of O₃ formation, such as solar radiation, temperature, and wind patterns, which align with the photochemical drivers discussed in the present thesis. Geographically this study is not part of the IGP, but methodologically relevant because it has shown the application of satellite trend analysis together with meteorological correlation, in a semi-arid, high-emission environment. The results showing the primary O₃ enhancing meteorological variables for this study, such as elevated temperature and solar radiation, is directly analogous to pre-monsoon peak O₃ loading in March to May in the state of Punjab with temperature above 40°C, corroborating the pre-monsoon high O₃ loading with the above mentioned photochemical mechanisms in the study area. (Ojha et al., 2022, pp. 11645-11656)

CHAPTER 3: STUDY AREA

3.1 Study Location

The Indo-Gangetic Plain is considered one of the largest alluvial plains in the world, covering nearly 2,400 km from western Pakistan to eastern Bangladesh, comprising river valleys and drainage areas of the Indus, Ganga, and Brahmaputra rivers. Approximately 400 million people live in this plain, making it one of the most populous regions in the world. Punjab is situated in the northwestern Indo-Gangetic Plain lying between 29° N–32° N latitudes and 73°E – 76°E longitudes.

Agriculturally, the IGP supports two major cropping seasons — the Kharif (summer) and Rabi (winter) — and is India's primary food production zone for wheat, rice, and other staples. The combination of dense population, intensive agriculture, rapid industrialization, and growing urban sprawl makes the IGP a region of exceptional environmental concern, particularly for air quality.

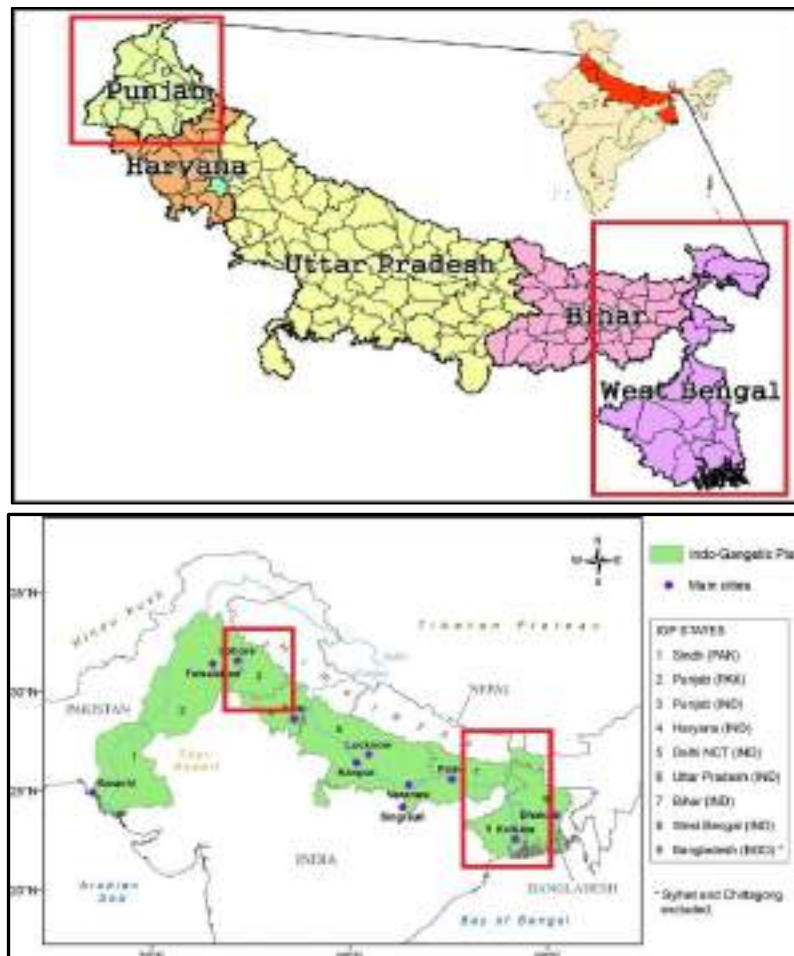


Fig. 1: Study Area.

3.2 Punjab (Western IGP) and West Bengal (Eastern IGP)

Punjab is bounded to its northeast by Himachal Pradesh, to its south by Haryana and Rajasthan states and lies on the western side of Pakistan. The state experiences a semi-arid to sub-humid continental climate, with very hot summers from March to May where temperature goes up beyond 45°C, moderate monsoon with an annual precipitation of 400–700 mm from June to September and very cold winters from January to February with temperature falling to below 5°C.

Punjab is one of India's most productive states, often described as the "breadbasket of India," with a most common wheat-rice cropping rotation system. This double cropping system requires rapid field preparation between harvests, which has resulted in the widespread and controversial practice of crop residue burning — especially paddy stubble burning during October–November after the Kharif harvest. These burning events create a huge amount of smoke containing particulate matter (PM_{2.5}, PM₁₀), CO, NO_x, CH₄, and VOCs, significantly contributing to regional air pollution and O₃ formation. Punjab's closeness to Delhi-NCR further amplifies its air quality challenges, as pollutant transport between the regions is well-documented.

The present study describes two regions based on the observed gradient of TCO values derived from satellite data. The northern region generally goes along with the central and northern districts of Punjab, including Amritsar, Gurdaspur, and Hoshiarpur, where topographic features and emission density create higher O₃ concentrations. The southern region broadly cover the southern and southwestern districts, including Bathinda and Fazilka, seen as relatively lower emissions and a drier landscape.

West Bengal is located in the eastern IGP, between 21°N–27°N and 85°E–89°E. It is located by Bangladesh (east), the Bay of Bengal (south), Odisha and Jharkhand (west), and Bihar and Sikkim (north). The state experiences a humid sub-tropical climate with most in control monsoon season (June–October) receiving 1,400–2,000 mm of annual rainfall, significantly more than Punjab. Temperatures are milder but more humid, with maximum summer temperatures of 35–42°C and minimum winter temperatures of 10–15°C in the plains.

The economy of West Bengal is diversified, with the intensive cultivation of rice in the Gangetic delta and a respectable industrial base in the belt of Hooghly-Durgapur and the megacity Kolkata with more than 15 million people. In contrast to Punjab, the burning of crop residues is not a major issue in the state, and its air quality problem is mainly due to vehicular

emissions, industrial effluents from the Hooghly corridor and transboundary pollution from neighbouring Bangladesh. The impact of the Bay of Bengal on the wind system and monsoonal circulation plays a prominent role in the seasonality of atmospheric O₃.

The southern region in West Bengal are broadly coinciding with the districts of Malda, Murshidabad, and Bardhaman, which are influenced by (1) the concentration of industrial emissions from the Durgapur–Asansol industrial corridor and (2) agricultural operations in the region. The southern region is the coastal and southern districts (South 24 Parganas, North 24 Parganas), where the marine breezes from the Bay of Bengal blow clean and dilute pollutants from neighbouring areas.

3.3 Rationale for Sub-Regional Delineation

The rationale behind the definition of high and low O₃ sub-regions for each state instead of working with mean concentrations calculated at the state level lies in the fact that there are significant variations of O₃ concentrations across the states because of differences in emission rates, topography, land use type, meteorological exposure, and urbanization. Separate consideration of the two sub-regions allows for a better representation of the intra-state variations and a more detailed analysis of spatial patterns of O₃ across the IGP area.

CHAPTER 4: DATA AND METHODOLOGY

4.1 Data Sources

TCO data for this study were obtained from two satellite instruments:

4.1.1 NASA O₃ Monitoring Instrument (OMI)

The O₃ Monitoring Instrument (OMI) is an imaging spectrometer carried onboard NASA's Aura satellite, which was launched on 15 July 2004. OMI performs measurements of solar backscatter in the ultraviolet and visible wavelength range of 270-500 nm. Spatial resolution of OMI is 13x24 km, and daily global coverage is nearly complete. TCO (TCO) is retrieved based on the TOMS algorithm (Collection 3), measured in Dobson Units (DU). OMI data are freely available from the NASA GES DISC archive and have been compared to ground-based measurements obtained by Brewer and Dobson spectrophotometers with $\pm 1-2\%$ accuracy.

4.1.2 ESA Sentinel-5P TROPOMI

The Tropospheric Monitoring Instrument (TROPOMI), carried on board the European Space Agency (ESA) satellite Sentinel-5P, which was launched into orbit on 13 October 2017, gives TCO (TCO) measurements at higher spatial resolution (3.5×7 km). TROPOMI follows the DOAS (Differential Optical Absorption Spectroscopy) method of TCO retrieval and provides near real-time global coverage. Beginning from 2017, the TROPOMI data joined the OMI data, both of which were available on Google Earth Engine. The merging of OMI (2004-2025) and TROPOMI (2017-2025) gives an uninterrupted 22-year data for this analysis.

4.2 Data Extraction Using Google Earth Engine

For obtaining monthly mean values of TCO for each of the four sub-regions (high-O₃ Punjab, low-O₃ Punjab, high-O₃ West Bengal, low-O₃ West Bengal), Google Earth Engine (GEE) was employed, which is a cloud-based geospatial data analysis platform that allows accessing vast amounts of geospatial data directly (e.g., NASA satellite images and ESA satellite images). In the current case study, the GEE APIs in Python and JavaScript were useful in (a) downloading the satellite imagery data from 2004 January till 2025 December; (b) creating choropleth maps for the areas in the four sub-regions; (c) determining the mean TCO values per month in each of the regions from the application of the reduce region function using mean reduction; and (4) exporting the output time-series to a CSV format.

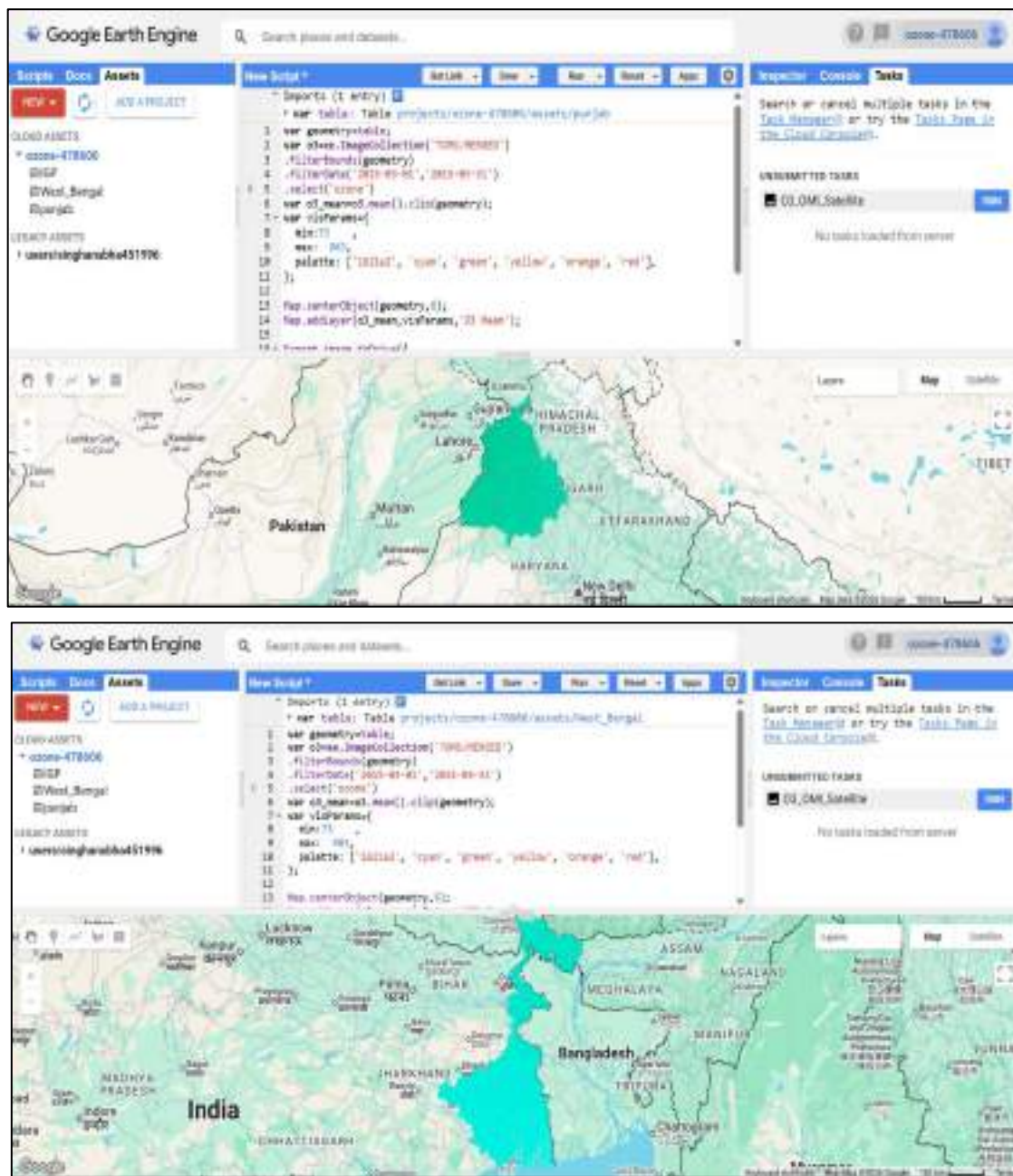


Fig. 2: Google Earth Engine Interface.

4.3 Seasonal Classification

Seasonal classification follows the Indian Meteorological Department (IMD) convention, which divides the year into four meteorological seasons:

- **Winter:** January–February — characterised by low temperatures, temperature inversions, and reduced solar radiation.
- **Pre-Monsoon:** March–May — hot and dry with intense solar radiation and elevated photochemical O₃ production.
- **Monsoon:** June–September — wet season with increased humidity, cloud cover, and decreased solar radiation.
- **Post-Monsoon:** October–December — season with decreasing temperatures and crop residue burning in Punjab.

4.4 Statistical Trend Analysis

4.4.1 Mann-Kendall Non-Parametric Test

The Mann-Kendall (MK) test was applied to monthly, seasonal, and annual time series for all regions. The MK test statistic S is computed as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i) \quad \dots\dots\dots \text{eq.1}$$

A data quality filtering process was conducted to exclude any pixels identified as clouds with x_i and x_j representing consecutive data points, while $\text{sgn}()$ stands for the sign function, which yields +1, 0, or -1. The standardized test statistic Z assumes a standard normal distribution under the assumption of non-trend, while a positive Z implies a rising trend, and a negative Z implies a declining trend. Significance was checked at a 95% confidence level ($p < 0.05$). Analysis was done using the "trend" and "Kendall" packages on R software (Version 4.3.1).

4.4.2 Sen's Slope Estimator

Quality control filters for the data were used to eliminate those pixels marked for clouds. The Sen's slope (β) was estimated as the median of all slopes between pairs of observations in the series:

$$\beta = \text{Median} [(x_j - x_i) / (j - i)] \text{ for all } i < j \quad \dots\dots\dots \text{eq.2}$$

This is an extremely robust estimator that is not sensitive to outliers and does not assume any particular distribution. The values for Sen's slope are given in units of DU/year, which reflect the rate of change of the TCO per year.

4.4.3 Analysis Framework

Trend analysis was carried out independently on: (1) the 12 months of the year (monthly analysis); (2) the four IMD seasons (seasonal analysis); and (3) the annual average (annual analysis). The use of multiple time scales makes it possible to determine the exact periods of time during which trends in TCO levels are evident and statistically significant.

Table 2: Description and Interpretation of Mann-Kendall Test and Sen's Slope Parameters.

Parameter	Symbol	Units/Range	Interpretation
Kendall Tau	τ	-1 to +1	$\tau > 0$: upward trend; $\tau < 0$: downward trend; $ \tau $ closer to 1 = stronger trend
p-value	p	0 to 1	$p \leq 0.05$: significant at 95% CI; $p \leq 0.01$: significant at 99% CI
z-score	Z	Dimensionless	$Z > 0$: increasing trend; $Z < 0$: decreasing trend
Sen's Slope	β	DU year ⁻¹	$\beta > 0$: O3 increasing; 95% CI provided for annual estimates

MK = Mann-Kendall; DU = Dobson Units; CI = Confidence Interval.

CHAPTER 5: RESULTS AND DISCUSSION

5.1 Mean O₃ Levels and Regional Comparison

The results reveal a consistent positive (increasing) trend in TCO across both states and both regions over the study period, though with considerable variation in statistical significance across months and seasons. The mean value of TCO during a year for Punjab, which is a northern region, is 287 DU, while that for Punjab as a southern region is 284 DU. The mean value of TCO in a year in the case of West Bengal, which is a northern region, is around 272 DU, while for West Bengal as a southern region, the value is 268 DU.

In the pre-monsoon period (March-May), the maximum mean values of TCO are recorded in all regions, up to a maximum value of ~322 DU in Punjab's northern region for the year 2024. Such high values during the pre-monsoon period are a result of strong solar insolation, increased surface temperature, and increased NO_x and VOCs owing to the burning of crops in Punjab and increased vehicular density, which promote O₃ formation through the photochemical reaction process. The post-monsoon period (October-December) marks the minimum TCO values in all regions.

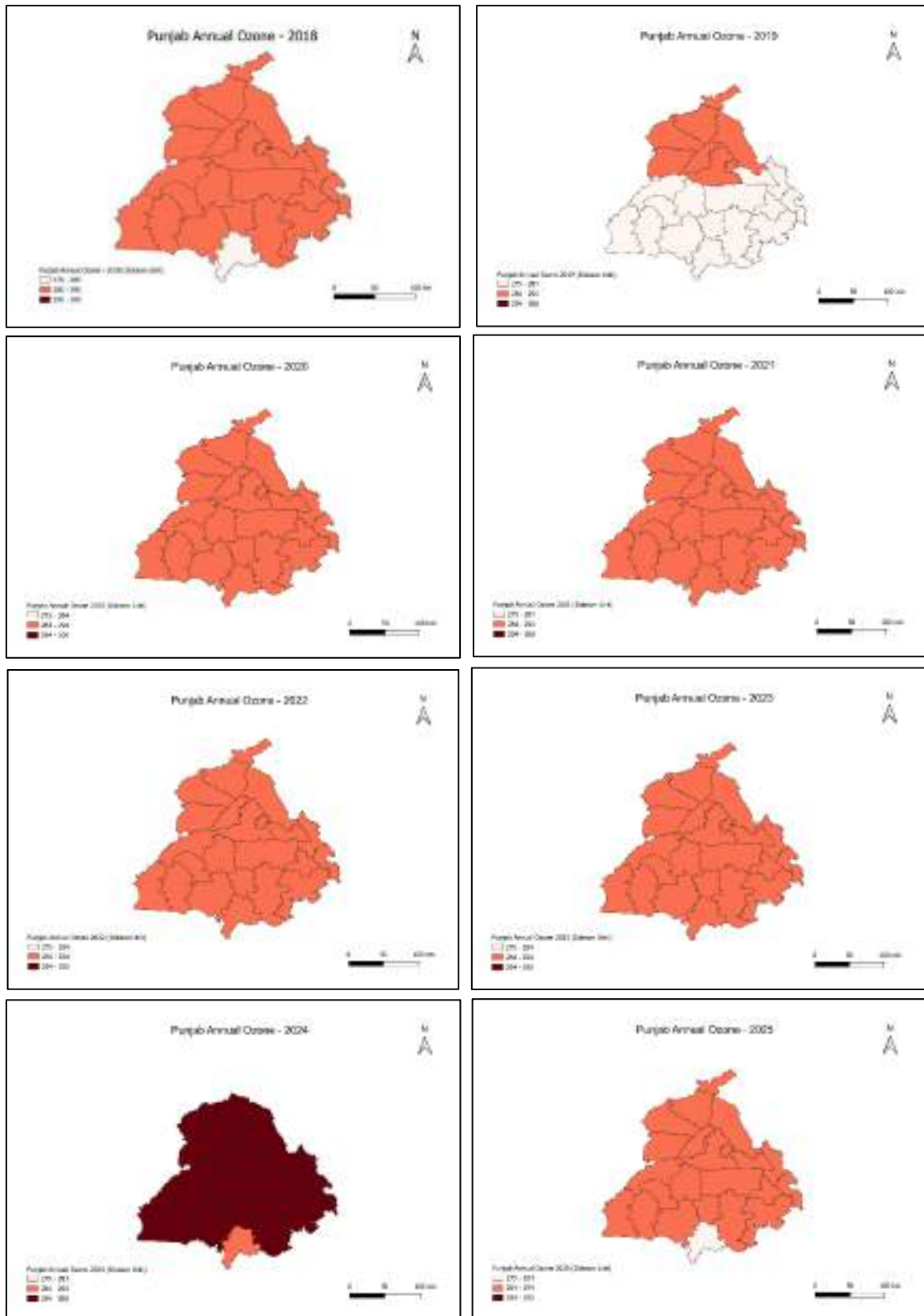


Fig. 3: Punjab Annual O₃ (DU) – 2018 to 2025.

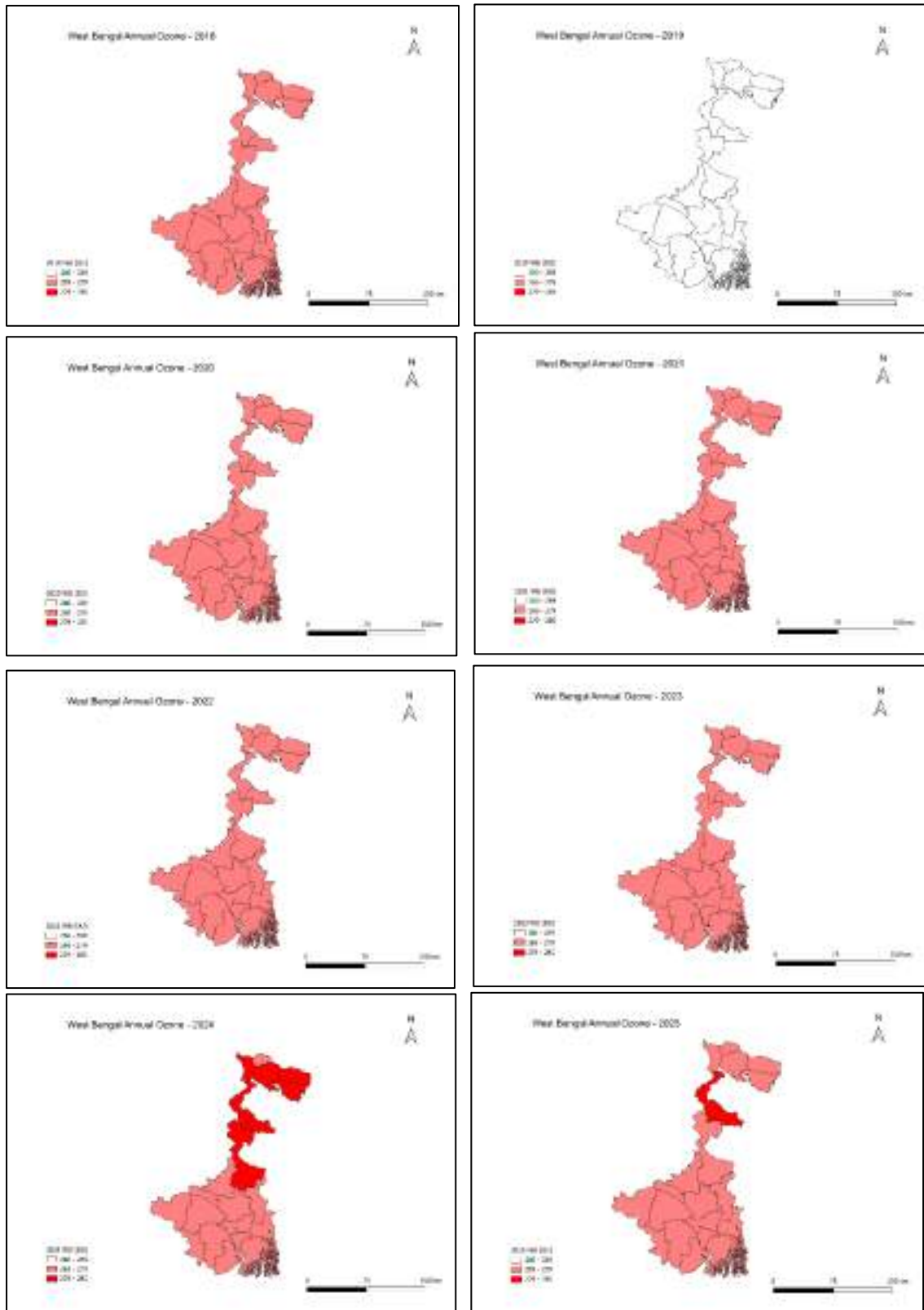


Fig. 4: West Bengal Annual O₃ (DU) – 2018 to 2025.

5.2 Mann-Kendall Trend Analysis: Punjab

5.2.1 Punjab — Northern Region

Northern Region (PUNJAB)					
Time Period	Mean (DU)	τ	p-value	z	Sen's slope
January	278.0	0.177	0.259	1.128	0.466
February	282.9	0.247	0.114	1.579	1.121
March	286.3	0.195	0.215	1.241	0.572
April	287.3	0.343	0.028*	2.201	0.617
May	284.7	0.208	0.185	1.326	0.468
June	279.5	0.130	0.413	0.818	0.155
July	273.6	0.226	0.150	1.439	0.254
August	269.0	0.186	0.236	1.184	0.151
September	268.1	0.143	0.367	0.902	0.135
October	263.1	0.186	0.236	1.184	0.343
November	260.1	0.238	0.128	1.523	0.293
December	263.4	0.307	0.048*	1.974	1.035
Winter	280.5	0.203	0.195	1.297	0.707
Pre-Monsoon	286.1	0.316	0.042*	2.030	0.671
Monsoon	272.6	0.212	0.176	1.354	0.171
Post-Monsoon	262.2	0.316	0.042*	2.030	0.559
Annual	287.1	0.446	0.004**	2.876	0.419

Table 1: The Mann-Kendall trend analysis results for Punjab's northern region at monthly, seasonal, and annual levels are shown in Table 1 below. At the monthly level, increasing trends are statistically significant for April ($\tau = 0.343$, $p = 0.028$) and December ($\tau = 0.307$, $p = 0.048$). For the seasonal levels, the pre-monsoon and post-monsoon periods have statistical significance ($p = 0.042$). At the annual level, an extremely significant increasing trend is observed ($\tau = 0.446$, $p = 0.004$) with Sen's slope = 0.419 DU/year.

Table 3: Monthly, Seasonal and Annual TCO — Mann-Kendall Results for Punjab Northern Region (2004–2025).

5.2.2 Punjab — Southern Region

The results from the southern zone of Punjab are also generally in agreement (Table 2), with April having the highest positive correlation ($\tau = 0.343$, $p = 0.028$) among all the months, and the pre-monsoon season having the highest positive trend ($\tau = 0.368$, $p = 0.018$) amongst all the seasons. The trend for the entire year is also highly significant ($\tau = 0.446$, $p = 0.004$, Sen's slope = 0.431 DU/year). December has almost reached significance levels ($p = 0.055$).

Table 4: Monthly, Seasonal and Annual TCO — Mann-Kendall Results for Punjab Southern Region (2004–2025).

Southern Region (PUNJAB)					
Time Period	Mean (DU)	τ	p-value	z	Sen's slope
January	272.4	0.126	0.430	0.790	0.335
February	277.4	0.247	0.114	1.579	1.126
March	282.1	0.247	0.114	1.579	0.609
April	284.9	0.343	0.028*	2.201	0.748
May	283.0	0.243	0.121	1.552	0.424
June	278.4	0.165	0.297	1.044	0.120
July	272.4	0.260	0.096	1.664	0.279
August	267.5	0.143	0.367	0.902	0.134
September	267.1	0.160	0.310	1.015	0.129
October	261.5	0.221	0.159	1.410	0.282
November	257.2	0.203	0.195	1.297	0.341
December	259.1	0.299	0.055	1.918	0.903
Winter	274.9	0.221	0.159	1.410	0.738
Pre-Monsoon	283.3	0.368	0.018*	2.369	0.630
Monsoon	271.4	0.212	0.176	1.354	0.179
Post-Monsoon	259.3	0.299	0.055	1.918	0.513
Annual	284.3	0.446	0.004**	2.876	0.431

5.3 Mann-Kendall Trend Analysis: West Bengal

5.3.1 West Bengal — Northern Region

The northern area of West Bengal shows more interesting trends than Punjab (Table 3). In terms of months, there are statistically significant upward trends in February ($p = 0.028$), April ($p = 0.037$), July ($p = 0.042$), August ($p = 0.024$), October ($p = 0.018$), and December ($p = 0.048$). It is interesting to note that October shows the highest value of tau for the month ($\tau = 0.398$),

indicating a strong and persistent upward trend in O_3 after the monsoon season. There are significant trends in all four IMD seasons, while the annual trend is statistically significant ($p = 0.015$) with Sen's slope of 0.501 DU/year.

Table 5: Monthly, Seasonal and Annual TCO — Mann-Kendall Results for West Bengal Northern Region (2004–2025).

Northern Region (WEST BENGAL)					
Time Period	Mean (DU)	τ	p-value	z	Sen's slope
January	251.1	0.152	0.338	0.959	0.552
February	258.3	0.342	0.028*	2.199	1.279
March	268.9	0.238	0.128	1.523	0.648
April	278.6	0.325	0.037*	2.087	0.478
May	277.6	0.290	0.063	1.861	0.291
June	271.3	0.212	0.176	1.354	0.311
July	262.7	0.316	0.042*	2.030	0.494
August	261.1	0.351	0.024*	2.256	0.435
September	259.1	0.247	0.114	1.579	0.267
October	254.6	0.398	0.018*	2.369	0.477
November	246.8	0.174	0.271	1.100	0.286
December	245.2	0.307	0.048*	1.974	0.680
Winter	254.7	0.351	0.024*	2.256	0.907
Pre-Monsoon	275.1	0.359	0.021*	2.312	0.512
Monsoon	263.6	0.307	0.048*	1.974	0.397

Post-Monsoon	248.9	0.342	0.028*	2.199	0.452
Annual	272.4	0.377	0.015*	2.425	0.501

5.3.2 West Bengal — Southern Region

The southern region of West Bengal (Table 4) exhibits the strongest overall trend signal among all four sub-regions. April is highly significant ($\tau = 0.403$, $p = 0.009$), and October ($p = 0.013$) and August ($p = 0.021$) also show strong monthly trends. At the seasonal level, all four seasons are significant, and the annual trend is highly significant ($\tau = 0.420$, $p = 0.007$, Sen's slope = 0.469 DU/year). The winter Sen's slope for this region (0.837 DU/year) is particularly noteworthy, reflecting rapidly intensifying wintertime O₃ accumulation likely linked to increasing urban and industrial emissions in the Kolkata metropolitan area.

Table 6: Monthly, Seasonal and Annual TCO — Mann-Kendall Results for West Bengal Southern Region (2004–2025).

Southern Region (WEST BENGAL)					
Time Period	Mean (DU)	τ	p-value	z	Sen's slope
January	244.1	0.273	0.080	1.748	0.650
February	250.9	0.351	0.024*	2.256	0.961
March	261.9	0.247	0.114	1.579	0.536
April	272.7	0.403	0.009**	2.594	0.589
May	274.9	0.281	0.071	1.805	0.375
June	268.8	0.247	0.114	1.579	0.375
July	261.8	0.316	0.042*	2.030	0.506
August	259.9	0.359	0.021*	2.312	0.470
September	257.8	0.247	0.114	1.579	0.375
October	254.4	0.385	0.013*	2.481	0.515
November	245.2	0.182	0.247	1.157	0.187
December	240.3	0.238	0.128	1.523	0.500
Winter	247.5	0.359	0.021*	2.312	0.837
Pre-Monsoon	269.8	0.377	0.015*	2.425	0.629
Monsoon	262.1	0.325	0.037*	2.087	0.422
Post-Monsoon	246.6	0.316	0.042*	2.030	0.512
Annual	268.1	0.420	0.007**	2.707	0.469

* $p < 0.05$ (statistically significant); ** $p < 0.01$ (highly significant). τ = Kendall tau.

5.4 Annual Trend Visualisation

The annual time series of TCO values in Figures 5 and 6 show clearly rising trends for the past 22 years in both regions with linear fit lines. In addition, the rate of increase is steeper after 2015. It is important to note that 2024 is the highest annual O₃ year for three of the four regions studied.

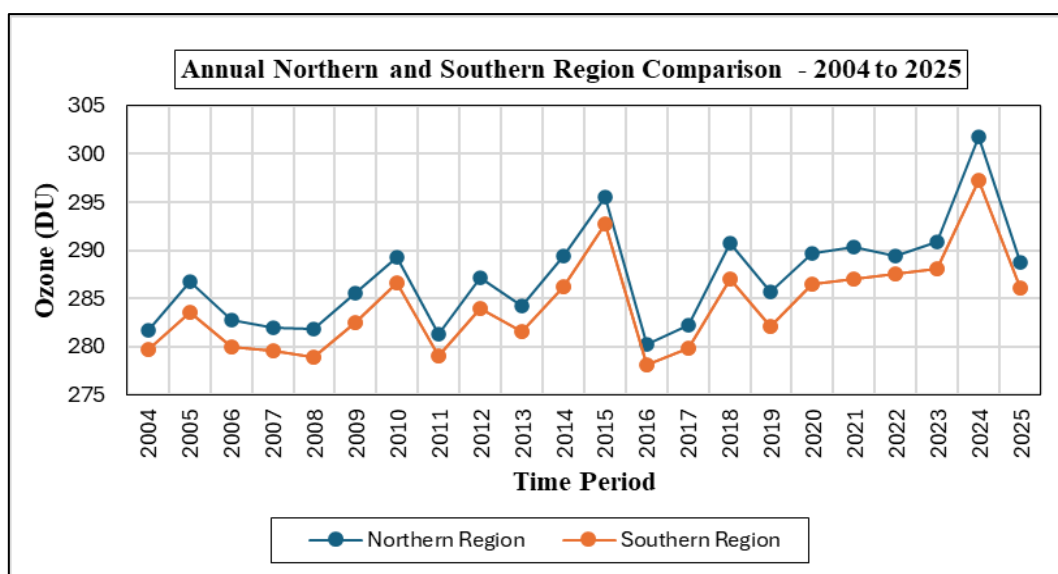


Fig. 5: Annual Mean TCO (DU) over Punjab's High-O₃ and Low-O₃ Sub-Regions (2004–2025).

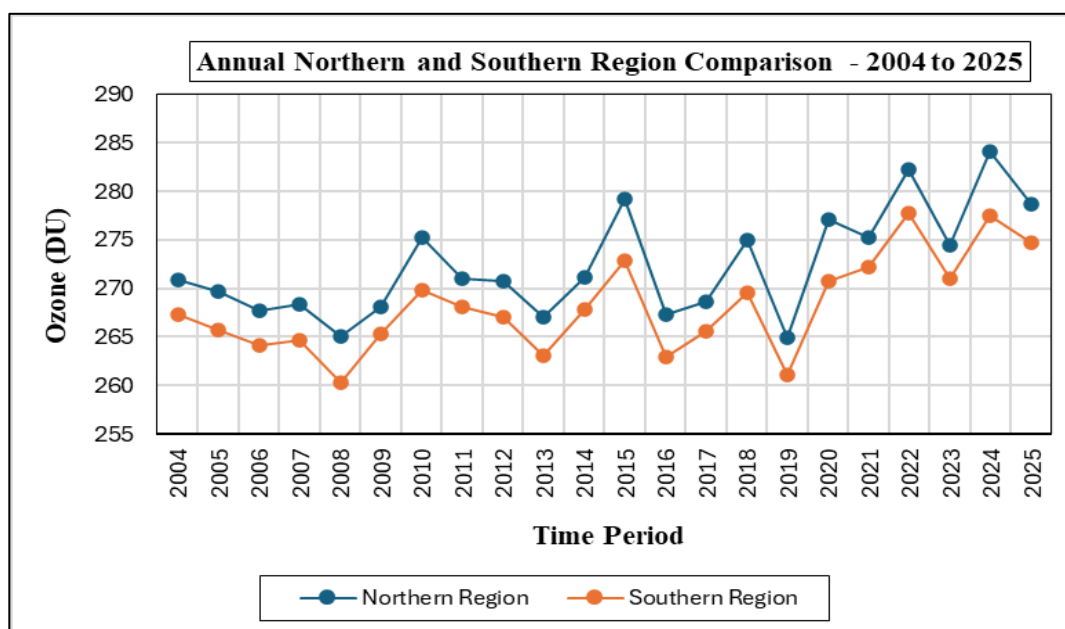


Fig. 6: Annual Mean TCO (DU) over West Bengal's High-O₃ and Low-O₃ Sub-Regions (2004–2025).

5.5 Seasonal O₃ Patterns

Figure 7 shows the comparative graph of seasonal means of TCO in both the States. For Punjab, pre-monsoon always has the maximum O₃ loading followed by monsoon, winter and post-monsoon. The ordering in the region of West Bengal is pre-monsoon > monsoon > winter > post-monsoon. The pre-monsoon dominance in both states is an indication of the influence of intense solar radiation, high temperatures (based on >40°C) and biomass burning emissions, which prevail during March-May favourable for photochemical O₃ formation.

Lower O₃ values during monsoon season is related to smaller amounts of precursor emissions, but also is related to weaker solar radiation intensity, to wet deposition removing O₃ and precursor gases, and to stronger vertical mixing of the O₃ and its precursors throughout the

troposphere. The seasonality minimum is also observed in this part of the study period, in both states, but the post-monsoon is remarkable for an increasing trend for the season, especially in West Bengal, which could be linked to shift in the monsoon withdrawal patterns and growing fall agricultural burning..

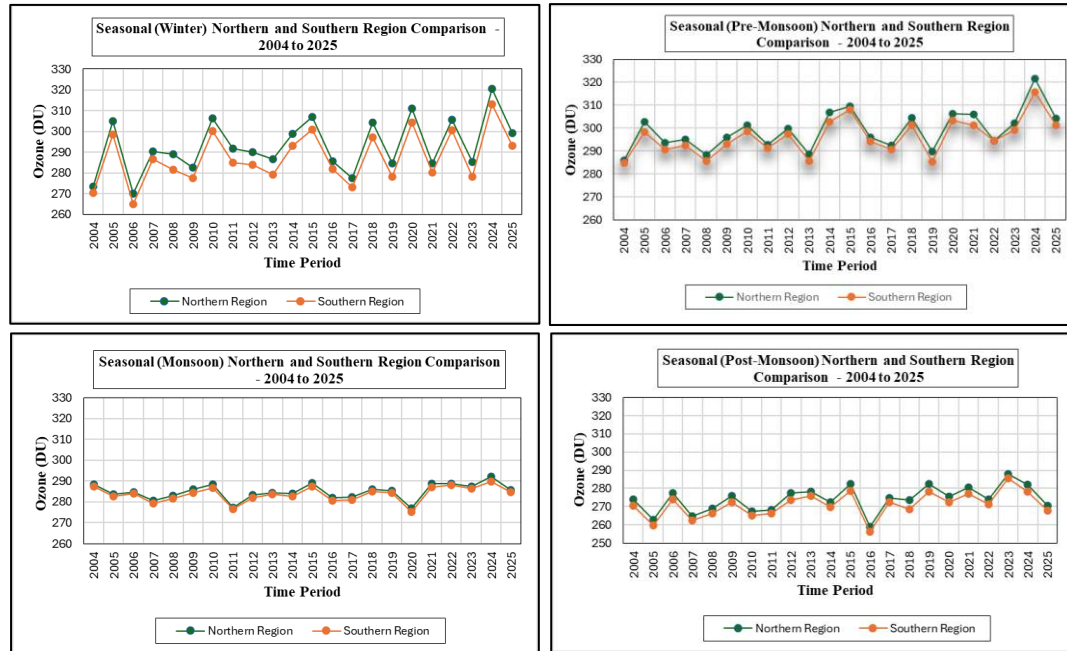


Fig. 7: Seasonal O₃ Comparison Across All Regions (Punjab) (2004–2025)

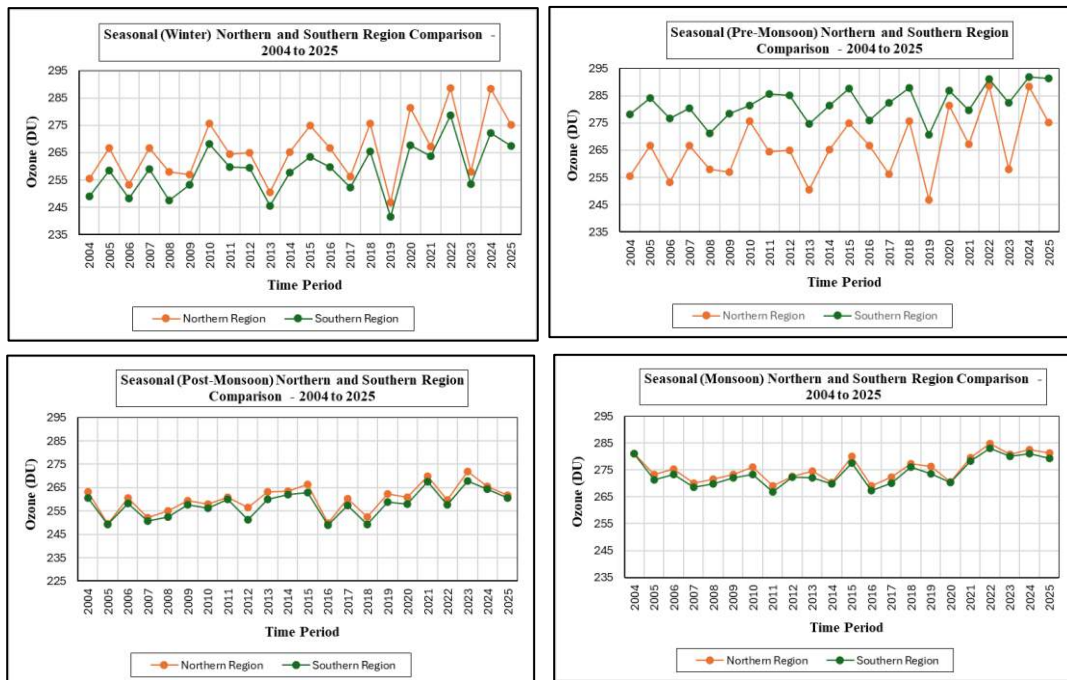


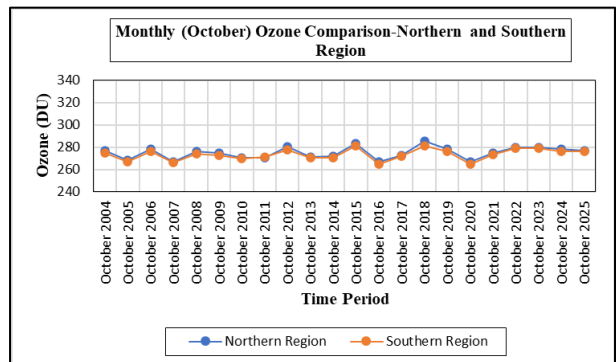
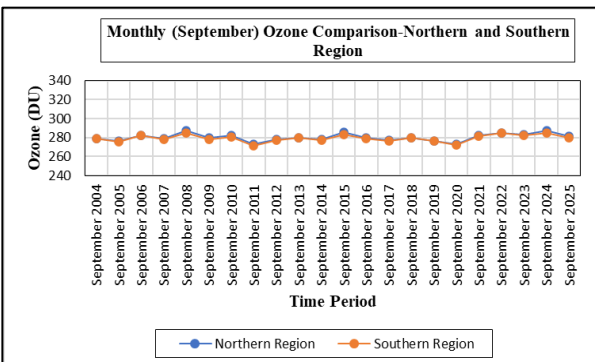
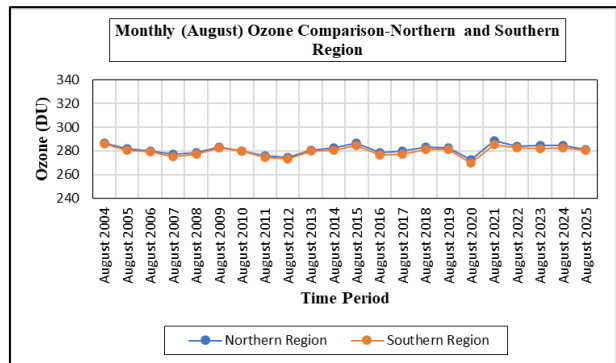
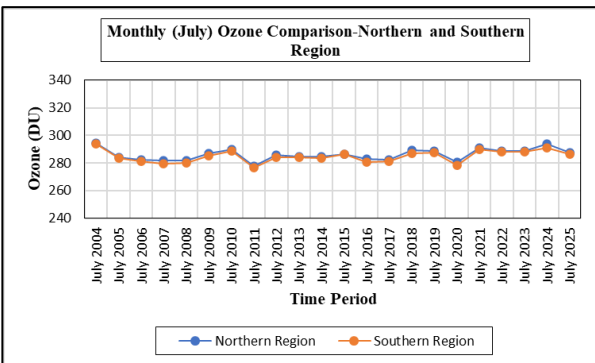
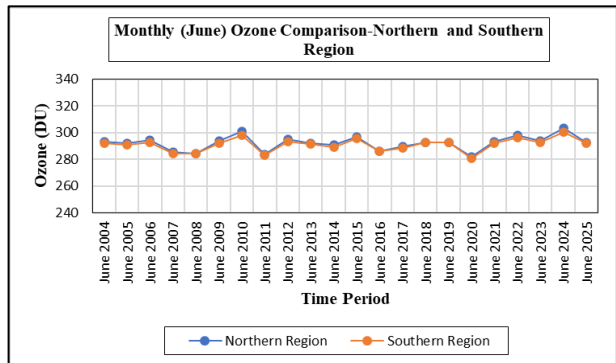
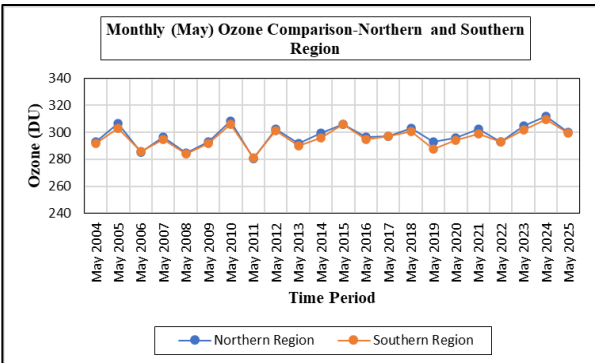
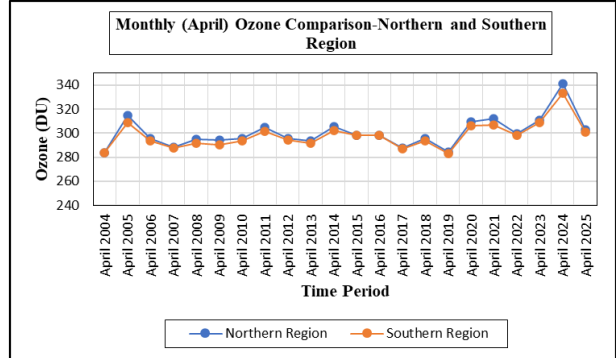
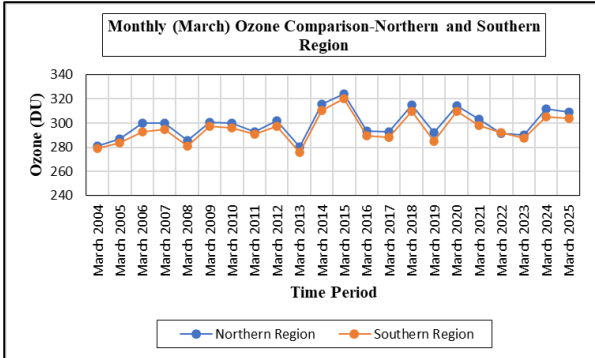
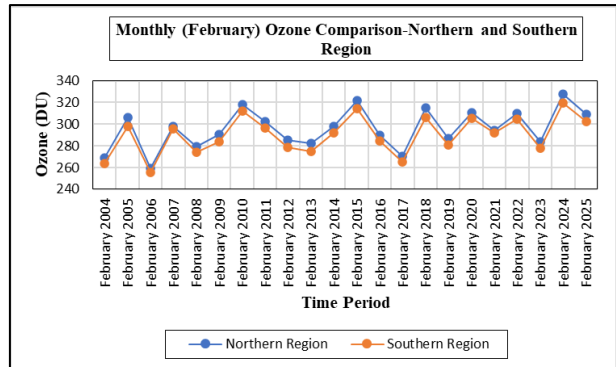
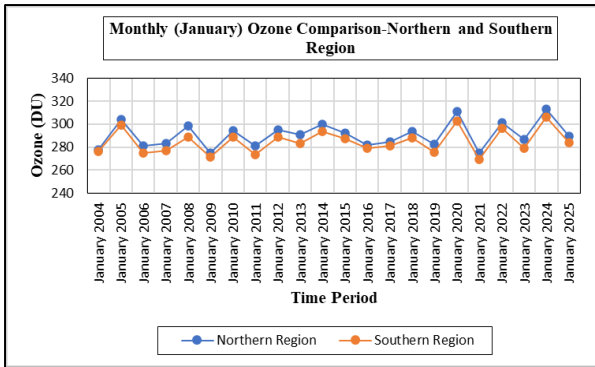
Fig. 8: Seasonal O₃ Comparison Across All Regions (West Bengal) (2004–2025).

5.6 Monthly O₃ Patterns

Overall Punjab Pattern: The Northern Region persistently maintains higher TCO than the Southern Region throughout the year, but the **difference is smallest during the monsoon** and

largest during the pre-monsoon, suggesting that large-scale dynamical processes (stratospheric transport, Brewer-Dobson Circulation) dominate in spring while monsoonal convection suppresses spatial differentiation in summer.

Overall West Bengal Pattern: In contrast to a Northern – Southern pattern in Punjab, West Bengal displays a weaker and less persistent pattern, with line crossovers observed over months. TCO is at its yearly lowest level in all four regions in November when the monsoon recedes, the photochemical O₃ production decreases and solar angles are lowered.



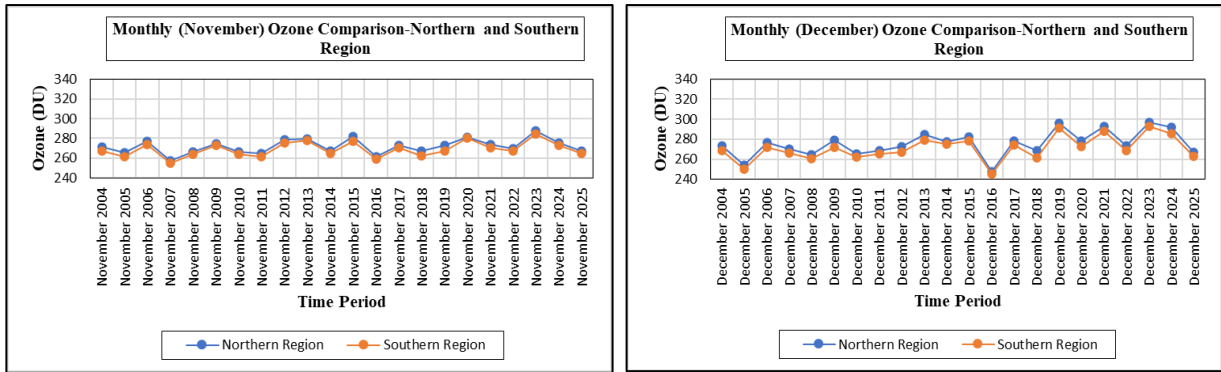
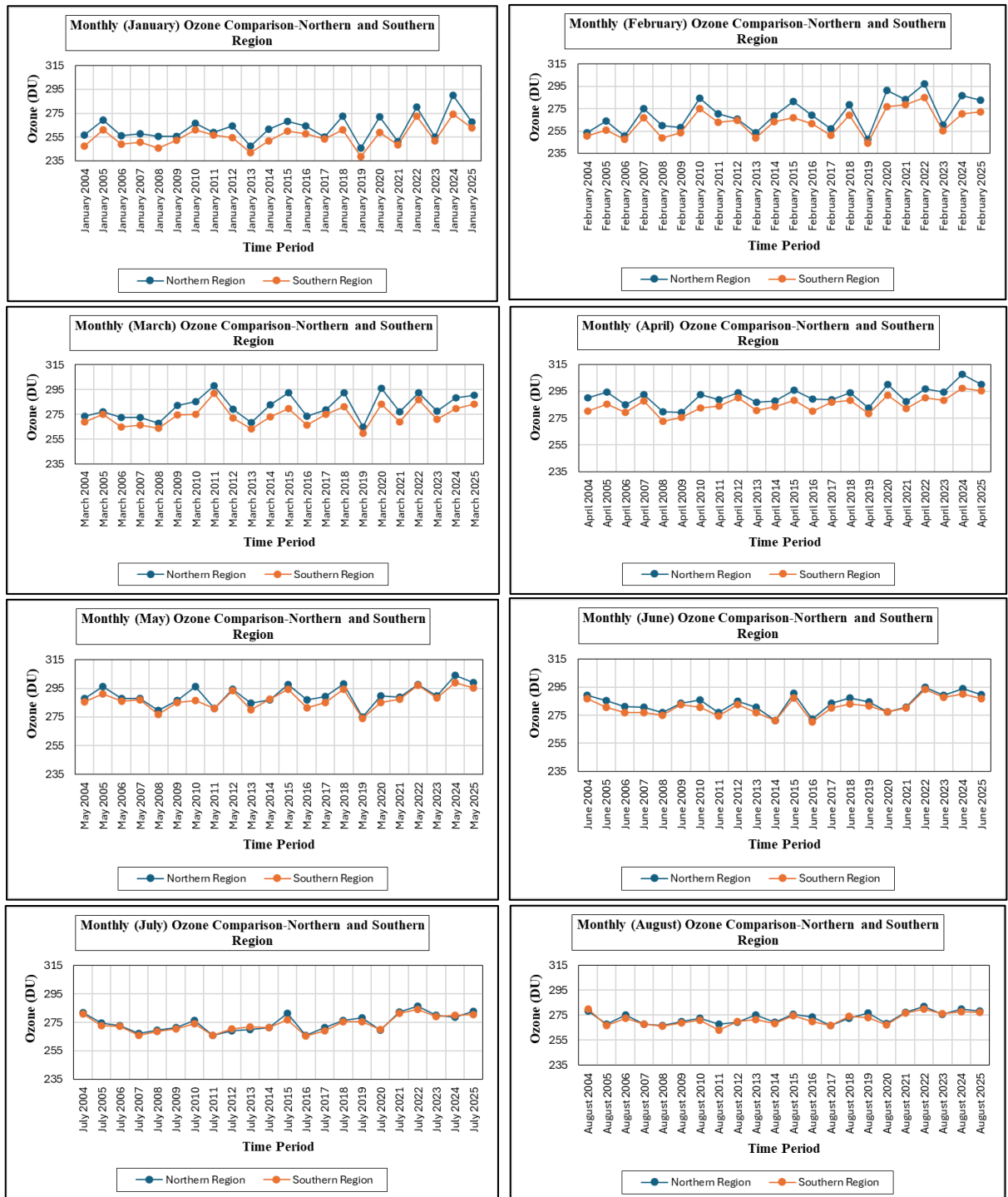


Fig. 9: Monthly O₃ Profiles Across All Regions of Punjab (2004–2025)



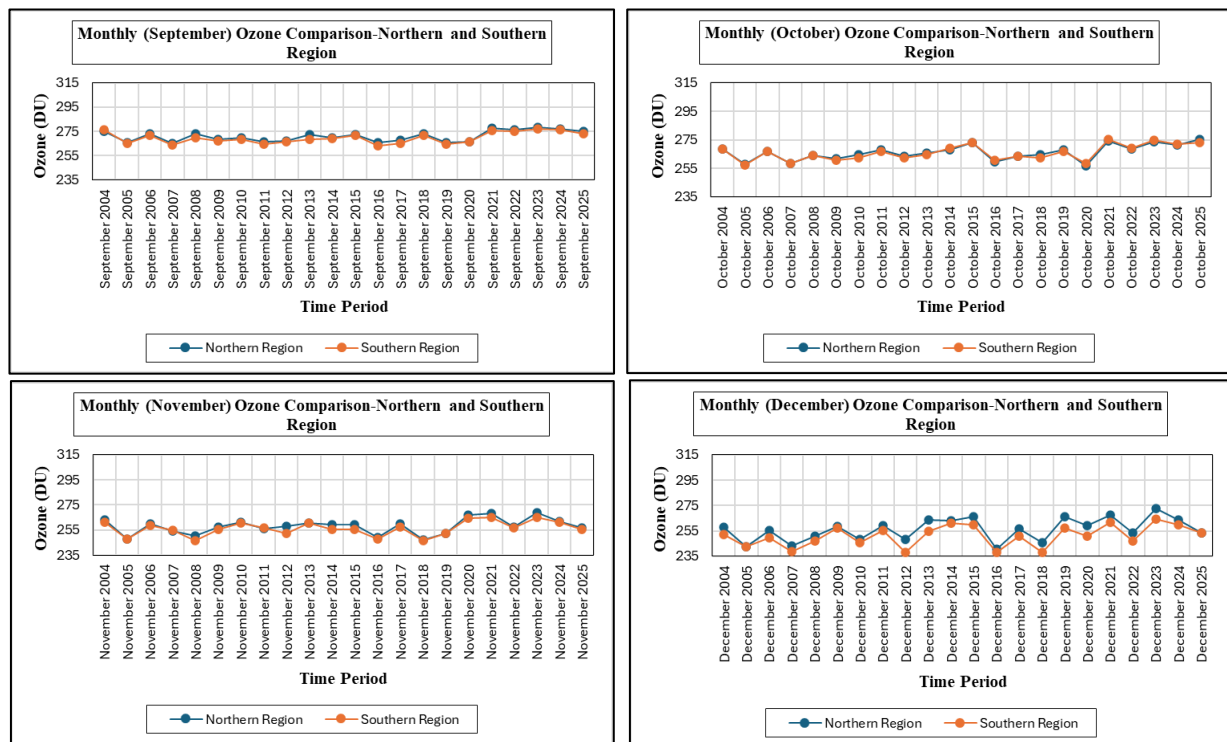


Fig. 10: Monthly O₃ Profiles Across All Regions of West Bengal (2004–2025).

5.7 Sen's Slope Comparison

Tables 3, 4, 5 and 6 are visualised comparative tables for annual and seasonal time period for all regions with regards to Sen's slope values. The annual change of the slopes of the Annual Sen varies by region and ranges between 0.419 DU/year in the north of Punjab and 0.501 DU/year in north of West Bengal. The highest Sen's slope has been observed for this winter period in West Bengal (0.907 DU/year for high; 0.837 DU/year for low) while for the pre-monsoon period, the highest slope has been observed in Punjab (0.671 DU/year for high; 0.630 DU/year for low) at the seasonal scale. Across the different regions, the monsoon season always exhibits the lowest Sen's slope value, which can be attributed to the suppression of O₃ accumulation caused by wet deposition and cloud coverage during the rainy season.

These slope values of approximately 0.42–0.50 DU/year for the annual trend, if sustained over the coming decades, imply an increase of 8–10 DU in TCO over the IGP by mid-21st century — a change with substantial implications for UV exposure, human health, crop damage, and radiative forcing over this densely populated region.

5.8 Comparison of Eastern vs. Western IGP

The disparity between Punjab and West Bengal on various analytical planes highlights crucial disparities in the behaviour of O₃ in the IGP region. With respect to TCO concentrations, Punjab has an annual average TCO concentration that is roughly 15 DU more than that of West Bengal.

This disparity is mainly due to Punjab's high latitude, proximity to the Delhi-NCR pollution zone, and agricultural and industrial activity in Punjab. In particular, the trend significance behaviour for the two states is noteworthy. Whereas Punjab shows significant seasonal trends exclusively in pre-monsoon and post-monsoon periods, West Bengal displays significant trends in all four seasons. This indicates that, besides the increase in O₃ loading, the trends in West Bengal are also seasonally consistent owing to emissions from multiple sources such as urban, industrial, and agricultural activities. Punjab, on the other hand, has trends that seem to be influenced by spring photochemical O₃ formation and autumn burning of crops.

In particular, the contrast in the behaviour of winter trend slopes stands out. The winter months of West Bengal demonstrate highly significant trends, with slopes in the range of 0.84–0.91 DU/year (among the most significant in the entire study), compared to the winter trends of Punjab, which remain below the threshold for statistical significance. It would be reasonable to assume that O₃ formation during winter in West Bengal undergoes a much faster and more pronounced rise due to changes in boundary layer dynamics, more frequent foggy periods preventing vertical gas exchange, and increased industrial emissions in the Kolkata region.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary of Key Findings

The present study provided a detailed examination of the variations in TCO concentration across the eastern and western parts of the Indo-Gangetic Plain region, namely West Bengal and Punjab, over 22 years (2004–2025), through the application of satellite data collected by the OMI and Sentinel-5P TROPOMI sensors. The main conclusions can be stated as follows:

1. The higher value of TCO (>286 DU/year) as compared to West Bengal (>270 DU/year) in Punjab region during all seasons and months have been observed and explained the identified pattern of north south gradient of O_3 over IGP region. This is believed to be due to latitudinal differences in background O_3 levels from the stratosphere, high emissions areas and topographic trapping effect.
2. Pre-Monsoon (spring months of March-May) represents the maximum O_3 levels as a result of strong photochemistry, higher surface temperature and active biomass burning emissions from both regions. The post-monsoon season (October-December) represents minimum O_3 levels in both areas.
3. There is a statistically significant increasing trend ($p < 0.05$) in all four subregions, with the value of Sen's slope varying from 0.419 to 0.501 DU/year. The presence of a statistically significant increasing trend in four different subregions for 22 consecutive years is considered sufficient proof of a systematic multi-decadal increase in the TCO level in the IGP.
4. There are statistically significant increasing trends in all four IMD seasons in West Bengal, but Punjab has only statistically significant seasonal trends during the pre-monsoon and post-monsoon periods. Such disparity indicates the presence of an overall year-long O_3 threat in West Bengal from various emission sources.
5. However, monthly assessment shows that the month of April is the significant month in Punjab consistently in both sub regions. But West Bengal has some months during which it is possible to see statistically significant trends: February, April, July, August, October, and December. Three of the four sub-regions had their highest annual mean TCO in 2024, which was an exceptional year. The overall post-2015 upwards trend in TCO is similar to that seen in much of the South Asian literature.

6.2 Policy Implications

The findings continue to stress the urgent need for regionally specific O₃ abatement measures in the IGP. As total-column O₃ moves further toward a positive trend above one of the most populated and agriculturally important parts of the planet, there are a number of policy implications:

1. The rise in the concentration of O₃ before the onset of the monsoon season in both areas due to agricultural fires and photochemistry requires a more stringent regulation of the ban on crop residue burning in Punjab. To better understand the possibility of changes in farming systems or climate in Punjab during 2024 when the event of high level of O₃ occurred for the first time.
2. It is necessary to consider the alarming rates of change in O₃ concentrations in winter in West Bengal, especially Sen's slopes of 1 DU/year in West Bengal. It would be essential to implement measures to control emissions in Kolkata, including tighter control on vehicles' exhaust gases, increasing metro rail transport facilities to lower vehicular emissions, and regulating industry NO_x emissions in the Hooghly corridor.
3. The universal significance of annual trends ($p < 0.01$ in three of four study regions) underlines the necessity for an O₃ monitoring and regulation policy for the entire IGP, which will have to transcend state boundaries.

6.3 Limitations of the Study

The satellite TCO value contains both the stratospheric and tropospheric components, and separation of the tropospheric component requires more data from other instruments like those from the OMI tropospheric column data or MOPITT data. Secondly, the boundaries used in the definition of the two sub-regions were arbitrarily defined using the observed O₃ spatial gradient and are not definitive in any way, and thus subjective in nature. Thirdly, the study lacks ground truth data, for example, CPCB monitor and Brewer spectrophotometer measurements, for validation of the satellite-derived values. Lastly, the autocorrelation factor was not corrected for in some months, and this may influence the significance of the MK test result.

6.4 Recommendations for Future Research

Taking into account the results and limitations of the current study, the following recommendations for future research work may be outlined as follows, Cross-validation between CPCB ground-based O₃ measurements and satellite-based Brewer/Dobson spectrophotometers for improved trend assessment. Meteorology-based attribution analysis using ERA5 and MERRA reanalysis and WRF-Chem & GEOS-Chem chemical transport models to determine the relative contribution of meteorology, emissions, and chemistry in the observed trends. Differentiation between tropospheric and stratospheric contributions using OMI tropospheric column O₃ product. Investigating the contribution from different emission source types by incorporating EDGAR/CAMS emission inventories for specific regions and years analyzed. Extending the analysis regionally for the entire Indian Gangetic Plains (IGP: Bihar, UP, and Haryana).

REFERENCES

1. World Health Organization (WHO). (2021). WHO Global Air Quality Guidelines. Geneva: World Health Organization. <https://www.who.int/publications/i/item/9789240034228>
2. Fiore, A.M., et al. (2002). Background O₃ over the United States in summer: Origin, trend, and contribution to pollution episodes. *Journal of Geophysical Research*, 107(D15). <https://doi.org/10.1029/2001JD000982>
3. Lal, S., Naja, M., and Subbaraya, B.H. (2000). Seasonal variations in surface O₃ and its precursors over an urban site in India. *Atmospheric Environment*, 34(17), 2713–2724.
4. Ganguly, S., and Gupta, A.K. (2024). Global warming due to generation of greenhouse gases producing O₃ holes. *Science & Culture*, 90, 107–113.
5. Bhattacharai, H., et al. (2024). Impacts of changes in climate, land use, and emissions on global O₃ air quality by mid-21st century. *Science of the Total Environment*, 906, 167759.
6. Kunchala, R.K., et al. (2022). Understanding the spatiotemporal variability and trends of surface O₃ over India. *Environmental Science and Pollution Research*, 29(4), 6219–6236.
7. Chakrabarty, D.K., et al. (1998). Long-term trend of O₃ column over the Indian region. *Journal of Geophysical Research Atmospheres*, 103(D15), 19245–19251.
8. Rathore, A., Gopikrishnan, G.S., and Kuttippurath, J. (2023). Changes in tropospheric O₃ over India: variability, long-term trends and climate forcing. *Atmospheric Environment*, 309, 119959.
9. Pathakoti, M., et al. (2021). Assessment of spatio-temporal climatological trends of O₃ over the Indian region using machine learning. *Spatial Statistics*, 43, 100513.
10. Moncy, R.G., Mathew, A., and Shekar, P.R. (2025). Spatio-temporal variation and trend analysis of ground-level O₃ in major Indian metropolitan cities: A geospatial approach. *Remote Sensing Applications: Society and Environment*, 37, 101395.
11. Peshin, S.K., et al. (2017). Spatio-temporal variation of air pollutants and the impact of anthropogenic effects on the photochemical buildup of O₃ across Delhi-NCR. *Sustainable Cities and Society*, 35, 740–751.
12. Gupta, K., Saha, A., and Sen Gupta, B. (2024). Spatio-temporal distribution of pollutant trace gases in India. *Geology, Ecology, and Landscapes*, 8(3), 306–326.
13. Ravindra, K., Singh, T., Pandey, V., and Mor, S. (2020). Air pollution trend in Chandigarh city situated in Indo-Gangetic Plains. *Science of the Total Environment*, 729, 138717.
14. India Meteorological Department (IMD). Seasonal Classification. Government of India, Ministry of Earth Sciences, New Delhi.
15. Mann, H.B. (1945). Nonparametric tests against trend. *Econometrica*, 13(3), 245–259.
16. Kendall, M.G. (1975). Rank Correlation Methods (4th ed.). Charles Griffin, London.

17. Sen, P.K. (1968). Estimates of the regression coefficient based on Kendall's tau. *Journal of the American Statistical Association*, 63(324), 1379–1389.
18. Yue, S., and Wang, C. (2004). The Mann-Kendall test modified by effective sample size to detect trend in serially correlated hydrological series. *Water Resources Management*, 18(3), 201–218.
19. Hamed, K.H., and Rao, A.R. (1998). A modified Mann-Kendall trend test for autocorrelated data. *Journal of Hydrology*, 204(1–4), 182–196.
20. Alduwais, A.K., et al. (2024). Spatiotemporal variability of surface O₃ and associated meteorological conditions over the Arabian Peninsula. *Atmospheric Pollution Research*, 15(9), 102210.
21. Akimoto, H. (2003). Global air quality and pollution. *Science*, 302(5651), 1716–1719.
22. Cooper, O.R., et al. (2014). Global distribution and trends of tropospheric O₃: An observation-based review. *Elementa: Science of the Anthropocene*, 2, 29.
23. Levelt, P.F., et al. (2006). The O₃ Monitoring Instrument. *IEEE Transactions on Geoscience and Remote Sensing*, 44(5), 1093–1101.
24. Veefkind, J.P., et al. (2012). TROPOMI on the ESA Sentinel-5 Precursor: A GMES mission for global observations of the atmospheric composition for climate, air quality and O₃ layer applications. *Remote Sensing of Environment*, 120, 70–83.
25. Gorelick, N., et al. (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment*, 202, 18–27.
26. Monks, P.S., et al. (2015). Tropospheric O₃ and its precursors from the urban to the global scale from air quality to short-lived climate forcer. *Atmospheric Chemistry and Physics*, 15(15), 8889–8973.
27. Seinfeld, J.H., and Pandis, S.N. (2016). *Atmospheric Chemistry and Physics: From Air Pollution to Climate Change* (3rd ed.). John Wiley & Sons, New York.
28. Kumar, R., et al. (2010). O₃ distribution and budget over the Indo-Gangetic Plain. *Journal of Geophysical Research: Atmospheres*, 115(D24), D24305.
29. Nair, P.R., et al. (2002). Spatial and temporal variations of total O₃ over the Indian region using TOMS data. *Annales Geophysicae*, 20, 1447–1456.
30. Saraf, N., and Beig, G. (2004). Long-term trends in tropospheric O₃ over the Indian tropical region. *Geophysical Research Letters*, 31(5), L05101.
31. Sharma, A.R., et al. (2010). A review of sub-daily and daily surface O₃ variations and trend over India. *Atmospheric Environment*, 44(32), 3872–3882.
32. Beig, G., et al. (2007). Surface O₃ and NO_x in the tropical Indian region. *Journal of Atmospheric Chemistry*, 57(2), 111–128.
33. Yadav, R., et al. (2016). Factors influencing O₃ concentrations over the Indo-Gangetic Plain, India. *Atmospheric Research*, 177, 1–10.

34. Ghude, S.D., et al. (2016). Premature mortality in India due to PM_{2.5} and O₃ exposure. *Geophysical Research Letters*, 43(9), 4650–4658.
35. Mittal, M.L., Sharma, C., and Singh, R. (2009). Estimates of emissions from coal fired thermal power plants in India. *Proceedings of the International Emission Inventory Conference*, pp. 1–22.
36. Rajput, P., et al. (2014). Chemical characteristics of fine particulate matter and their role in light extinction in the rural atmosphere. *Science of the Total Environment*, 490, 266–275.
37. Intergovernmental Panel on Climate Change (IPCC). (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the IPCC*. Cambridge University Press.
38. Badarinath, K.V.S., et al. (2009). Analysis of aerosol optical depth and precipitable water vapor over Hyderabad, India. *International Journal of Remote Sensing*, 30(3), 643–658.
39. Padhy, S., et al. (2019). Surface O₃ over the Bay of Bengal and its association with boundary layer dynamics and marine aerosols. *Atmospheric Environment*, 213, 529–539.
40. Rao, C.V.K., Murthy, B.S., and Latha, R. (2012). Surface layer meteorology and turbulent characteristics over tropical urban station. *Boundary Layer Meteorology*, 145(1), 41–58.
41. Singh, A., et al. (2018). Surface O₃ over the Arabian Sea and West Coast of India: Impact of continental outflow. *Chemosphere*, 191, 993–1002.
42. Dey, S., and Di Girolamo, L. (2011). A decade of change in aerosol properties over the Indian subcontinent. *Geophysical Research Letters*, 38(14), L14811.
43. Talukdar, S., et al. (2019). Assessment of O₃ variations and their association with meteorological parameters over Kolkata, India. *Atmospheric Environment*, 214, 116827.
44. Central Pollution Control Board (CPCB). (2022). *National Clean Air Programme — Status Report*.
45. Ministry of Environment, Forest and Climate Change, Government of India, New Delhi.

ANNEXURES

1. Code used for extracting O3 data from AURA/OMI on Google Earth Engine

```
var geometry=table;
var O3=ee.ImageCollection("TOMS/MERGED")
.filterBounds(geometry)
.filterDate('2015-03-01','2015-03-31')
.select('O3')
var O3_mean=O3.mean().clip(geometry);
var visParams={
  min:73
  ,
  max: 983,
  palette: ['1621a2', 'cyan', 'green', 'yellow', 'orange', 'red'],
};
```

```
Map.centerObject(geometry,6);
Map.addLayer(O3_mean,visParams,'O3 Mean');
```

```
Export.image.toDrive({
  image: O3_mean,
  description: 'O3_OMI_Satellite',
  scale: 1000,
  region: geometry,
  fileFormat: 'GeoTIFF'
});
```

2. Code used for extracting O3 data from Sentinel 5P/TROPOMI on Google Earth Engine.

```
var geometry=District_shape_West_Bengal;
var O3=ee.ImageCollection("COPERNICUS/S5P/OFFL/L3_O3")
.filterBounds(geometry)
.filterDate('2019-01-01','2019-06-30')
.select('O3_column_number_density')
var O3_mean=O3.mean().clip(geometry);
var visParams={
  min:0.025
  ,
  max: 0.3048,
  palette: ['black', 'blue', 'purple', 'cyan', 'green', 'yellow', 'red']
};
Map.centerObject(geometry,6);
Map.addLayer(O3_mean,visParams,'O3 Mean');
Export.image.toDrive({
  image: O3_mean,
```

```

description: 'O3_Sentinel5P',
scale: 1000,
region: geometry,
maxPixels: 1e13,
fileFormat: 'GeoTIFF'
});

```

3. Code used for Mann-Kendall trend analysis and Sen's Slope estimation of O₃ data on R Studio

```

df <- read_excel("C:\\Users\\mohit\\Downloads\\WB_Jhargram_O3_2019_2024.xlsx")

install.packages("readxl")
install.packages("Kendall")
install.packages("ggplot2")
install.packages("trend")

library(readxl)
library(Kendall)
library(ggplot2)
library(trend)

y_min <- 240.0
y_max <- 345.0
y_interval <- 10.0
df$Date <- factor(df$Date, levels = unique(df$Date))
p <- ggplot(df, aes(x = Date, y = O3, group = 1)) +
  geom_line(color = "blue", linewidth = 0.5) +
  geom_point(color = "green", size = 1, alpha = 0.7) +
  scale_y_continuous(
    limits = c(y_min, y_max),
    breaks = seq(y_min, y_max, by = y_interval)
  ) +

  labs(x = "Time Period",
       y = "O3 Concentration (Dobson Unit)",
       title = "Higher O3 Region (Punjab) December 2004-2025"
  ) +
  theme_minimal() +
  theme(
    plot.background = element_rect(fill = "white", color = NA),
    panel.background = element_rect(fill = "white", color = NA),
    plot.title = element_text(hjust = 0.5),
    axis.text.x = element_text(size = 4)
  )

```

```
print(p)
ggsave(
  filename = "Higher December 2004-2025.jpg",
  plot     = p,
  device   = "jpeg",
  width    = 10,
  height   = 4,
  units    = "in",
  dpi      = 600,
  bg       = "white"
)
mk_test <- MannKendall(df$O3)
print("Mann-Kendall Test Results:")
print(mk_test)
sen_test <- sens.slope(df$O3)
print("Sen's Slope Test:")
print(sen_test)
```



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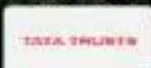
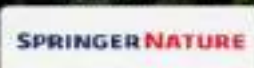
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Dear Dr. Singh,

On behalf of the Organizing Committee, I am pleased to inform you that your abstract titled "Spatio-Temporal Variation in Snowmelt over Western Indo-Gangetic Plain (2004-2023) for the Himalayan foothills" has been accepted for presentation at the International Conference on Climate and Disaster Resilient Himalayas (ICCDRH-2026).

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Dear **Amisha Singh, Lovleen Gupta,**

We are delighted to inform you that your abstract, titled **"Spatio-Temporal Variation of High Ozone Region of Western and Eastern Indo-Gangetic Plain Regions (2004 to 2025)"** has received approval from the Scientific Review Committee. It has been selected for an **Oral/Poster** Presentation at the forthcoming **Asia Pacific SDG & Sustainability Summit 2026**, a flagship international conference and awards forum organized by the Environment and Social Development Association (ESDA), Delhi, in collaboration with esteemed institutions including Dr. Bhabu Rao Ambedkar College, University of Delhi, Villa College, Maldives and Tribhuvan University, Kathmandu, Nepal. The summit is scheduled to be held from **June 20-22, 2026, in hybrid mode** at the prestigious India Habitat Centre, New Delhi (India).

Your contribution to our conference is greatly appreciated, and we look forward to your participation. The Technical Schedule of the conference will be in due course of time.

You are requested to please register yourself as soon as possible to confirm your participation.

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