URBANIZATION-DRIVEN CHANGES IN FOG OVER THE INDO-GANGETIC PLAIN: AN INVESTIGATION USING OBSERVATIONS AND WRF FRAMEWORK

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A Journey of a Thousand Miles Begins with a Single Step.

- Lao Tzu

Dedicated to my beloved parents

CERTIFICATE

This is to certify that the thesis titled **Urbanization-Driven Changes in Fog over the Indo-Gangetic Plain: An Investigation Using Observations and WRF Framework**, submitted by **Ms. Anie K Lal (2020ASZ8178)** to the Indian Institute of Technology, Delhi, for the award of the degree of **Doctor of Philosophy**, is a bonafide record of the research work done by her under our supervision and guidance. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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(Anie K Lal)

ABSTRACT

Wintertime fog occurring across the Indo-Gangetic Plain (IGP) exerts profound socio-economic impacts, particularly on transportation, aviation, and public safety. During the past few decades, the region has experienced rapid urban expansion accompanied by substantial modifications in Land Use and Land Cover (LULC), along with an increase in human-induced aerosol emissions. Despite these developments, the extent to which these factors influence the formation, intensity, and evolution of fog remains insufficiently understood. This thesis investigates the evolving characteristics of winter fog over the IGP, with a particular focus on urban regions, by integrating long-term observations with high-resolution numerical modelling to elucidate both large-scale trends and underlying physical mechanisms.

Using multi-decadal ground-based visibility records and satellite observations, the first part of the study examines spatial and temporal trends in fog occurrence across eight urban centers spanning the upper, middle, and lower IGP. The analysis reveals a paradoxical behavior over major cities, particularly Delhi, where overall fog frequency has increased while dense fog occurrences have declined markedly. Satellite data further identify extensive and expanding fog holes over established and emerging urban areas. The spatial extent of these fog holes exhibits a strong association with the expansion of urban built-up areas ($r = 0.94$). These findings suggest that urbanization-induced temperature and moisture modifications suppress conditions favorable for dense fog formation, despite an overall increase in fog-prone

environments across the IGP.

To investigate the physical drivers of these changes, the second part of the thesis employs high-resolution Weather Research and Forecasting (WRF) model simulations to assess the impact of LULC changes on the fog life cycle during a severe fog episode over the Delhi National Capital Region (NCR) in January 2021. Sensitivity experiments contrasting present-day and historical (2004) land-use conditions demonstrate that urban expansion accelerates fog dissipation by 1-2 hours. This early dissipation is linked to reduced near-surface soil moisture, altered surface energy fluxes, quantified by changes in the Bowen ratio and turbulent kinetic energy, and enhanced near-surface warming and drying. These processes contribute to the development of localized fog holes and highlight the role of surface-atmosphere interactions in modulating fog persistence.

The final part of the thesis advances this investigation by untangling the independent and combined effects of LULC changes and enhanced aerosol emissions using WRF-Chem. Simulations of dense fog episodes indicate that nighttime aerosol-radiation interactions delay fog onset by inducing surface warming and strengthening near-surface winds. In contrast, aerosol-cloud interactions prolong fog persistence by delaying its dissipation. LULC changes, however, generally accelerate fog dissipation through enhanced surface heating and increased turbulence. When these drivers act simultaneously, the aerosol-induced effects dominate, leading to an overall extension of fog duration. Both LULC and aerosol effects also modify the vertical structure of fog, promoting elevated fog layers and influencing fog-hole formation through spatial variability in liquid water path.

Overall, this thesis demonstrates that urbanization fundamentally reshapes fog characteristics over the IGP through coupled temperature, moisture, and aerosol-driven processes.

By combining long-term observations with process-based modelling, the study provides new insights into the mechanisms governing fog variability in rapidly urbanizing regions. It underscores the importance of incorporating changes in land-surface and aerosol effects to improve fog prediction, with broad implications for aviation safety.

संक्षेप,

इंडो-गैंगेटिक प्लेन (IGP) पर सर्दियों का कोहरा गहरा सोशियो-इकोनॉमिक असर डालता है, खासकर ट्रांसपोर्टेशन, एविएशन और पब्लिक सेफ्टी पर। हाल के दशकों में, इस इलाके में तेज़ी से शहरीकरण के साथ-साथ ज़मीन के इस्तेमाल और ज़मीन के कवर (LULC) में बड़े पैमाने पर बदलाव हुए हैं और इंसानों द्वारा एयरोसोल एमिशन भी बढ़ा है, फिर भी कोहरे के होने, उसकी तेज़ी और लाइफ साइकिल पर उनके असर को पूरी तरह से समझा नहीं गया है। यह थीसिस IGP पर सर्दियों के कोहरे की बदलती खासियतों की जांच करती है, जिसमें खास तौर पर शहरी इलाकों पर फोकस किया गया है, और इसमें लंबे समय के ऑब्ज़र्वेशन को हाई-रिज़ॉल्यूशन न्यूमेरिकल मॉडलिंग के साथ मिलाकर बड़े पैमाने के ट्रेंड और अंदरूनी फिजिकल मैकेनिज्म को साफ किया गया है।

कई दशकों के ग्राउंड-बेस्ड विजिबिलिटी रिकॉर्ड और सैटेलाइट ऑब्ज़र्वेशन का इस्तेमाल करते हुए, स्टडी का पहला हिस्सा ऊपरी, बीच और निचले IGP में फैले आठ शहरी सेंटर में कोहरे के होने के जगह और समय के ट्रेंड की जांच करता है। एनालिसिस से बड़े शहरों, खासकर दिल्ली में एक उलटा व्यवहार पता चलता है, जहां कुल मिलाकर कोहरे की फ्रीक्वेंसी बढ़ी है जबकि घने कोहरे के होने में काफी कमी आई है। सैटेलाइट डेटा से पता चलता है कि बसे हुए और उभरते शहरी इलाकों में बड़े और फैलते हुए फॉग होल हैं, जिनमें फॉग होल का फैलाव शहरी और बनी हुई ज़मीन के बढ़ने से बहुत ज़्यादा जुड़ा हुआ है ($r = 0.94$)। इन नतीजों से पता चलता है कि शहरीकरण से होने वाले थर्मल और नमी में बदलाव, IGP में कोहरे वाले माहौल में कुल मिलाकर बढ़ोतरी के बावजूद, घने कोहरे के बनने के लिए सही हालात को दबा देते हैं।

इन बदलावों के फिजिकल कारणों की जांच करने के लिए, थीसिस के दूसरे हिस्से में जनवरी 2021 में दिल्ली नेशनल कैपिटल रीजन (NCR) में बहुत ज़्यादा कोहरे के दौरान LULC बदलावों के कोहरे की लाइफ साइकिल पर पड़ने वाले असर का अंदाज़ा लगाने के लिए हाई-रिज़ॉल्यूशन वेदर रिसर्च एंड फोरकास्टिंग (WRF) मॉडल सिमुलेशन का इस्तेमाल किया गया है। आज के और पुराने (2004) लैंड-यूज़ के हालात के

बीच सेंसिटिविटी एक्सपेरिमेंट से पता चलता है कि शहरी फैलाव कोहरे के छंटने को 1–2 घंटे तेज़ कर देता है। यह जल्दी खत्म होना, सतह के पास मिट्टी की नमी में कमी, सतह की एनर्जी के फ्लक्स में बदलाव, जिसे बोवेन रेश्यो और टर्बुलेंट काइनेटिक एनर्जी में बदलाव से मापा जाता है, और सतह के पास गर्मी और सूखने में बढ़ोतरी से जुड़ा है। ये प्रोसेस लोकल फॉग होल बनाने में मदद करते हैं और फॉग के बने रहने में सतह-एटमॉस्फियर इंटरैक्शन की मुख्य भूमिका को दिखाते हैं।

थीसिस का आखिरी हिस्सा LULC बदलावों और बढ़े हुए एरोसोल एमिशन के अलग-अलग और मिले-जुले असर को WRF मॉडल के साथ केमिस्ट्री (WRF-Chem) का इस्तेमाल करके अलग करके इस एनालिसिस को आगे बढ़ाता है। तीन घने फॉग इवेंट्स के सिमुलेशन से पता चलता है कि रात के समय एरोसोल-रेडिएशन इंटरैक्शन सतह की गर्मी बढ़ाकर और सतह के पास हवा की स्पीड बढ़ाकर फॉग शुरू होने में देरी करते हैं, जबकि LULC बदलाव बढ़े हुए टर्बुलेंस और सतह की गर्मी से फॉग को दबाते हैं। जब एक साथ काम करते हैं, तो एरोसोल इफेक्ट हावी होते हैं, जिससे फॉग का कुल समय बढ़ जाता है। मैच्योर और डिसिपेशन फेज़ के दौरान, एरोसोल-क्लाउड इंटरैक्शन बहुत ज़रूरी हो जाते हैं, जो वर्टिकल फॉग स्ट्रक्चर को बदलते हैं और सिर्फ़ शहरी ज़मीन के कवर के बजाय लिक्विड पानी के रास्ते में जगह के बदलावों के ज़रिए फॉग होल बनने पर असर डालते हैं।

कुल मिलाकर, यह थीसिस दिखाती है कि शहरीकरण, थर्मल, नमी और एरोसोल से चलने वाले प्रोसेस के ज़रिए IGP पर फॉग की खासियतों को पूरी तरह से बदल देता है। लंबे समय के ऑब्ज़र्वेशन को प्रोसेस-बेस्ड मॉडलिंग के साथ मिलाकर, यह स्टडी तेज़ी से शहर बन रहे इलाकों में फॉग में बदलाव को कंट्रोल करने वाले मैकेनिज़्म के बारे में नई जानकारी देती है। यह बेहतर फॉग प्रेडिक्शन के लिए ज़मीन की सतह में बदलाव और एरोसोल के असर को शामिल करने के महत्व पर ज़ोर देता है, जिसका एविएशन सेफ्टी और शहरी क्लाइमेट रेजिलिएंस पर बड़े असर पड़ता है।

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List of Abbreviations

ACI	Aerosol-Cloud Interaction
AO	Arctic Oscillation
AOD	Aerosol Optical Depth
ARI	Aerosol-Radiation Interaction
ARW	Advanced Research WRF
AWiFS	Advanced Wide Field Sensor
BC	Black carbon
Ca^{2+}	Calcium
CAAQM	Continuous Ambient Air Quality Monitoring
CAM	Community Atmosphere Model
CAT	Category
CB-4	Carbon Bond mechanism, version 4
CBL	Cloud Base Lowering
CBMZ	Carbon Bond Mechanism Z
CCN	Cloud Condensation Nuclei
CER	Cloud Effective Radius
$CH_3SO_3^-$	Methane sulfonate
Cl^-	Chloride

CO	Carbon monoxide
CO_3^{2-}	Carbonate
CORR	Correlation Coefficient
CPCB	Central Pollution Control Board
CTP	Cloud Top Pressure
DJF	December-January-February
DPCC	Delhi Pollution Control Committee
ECMWF	European Centre for Medium-Range Weather Forecasts
EDGARv5.0	Emission Database for Global Atmospheric Research version 5
FAO	Food and Agriculture Organization
FB	Fractional Bias
FINNv1.5	Fire Inventory from NCAR version 1.5
GIS	Geographical Information System
GOCART	GOddard Chemistry Aerosol Radiation and Transport
HSPCB	Haryana State Pollution Control Board
HWP	Huber Weight Parameter
ICAO	International Civil Aviation Organization
ICBC	Initial Conditions and Boundary Conditions
IGI	Indira Gandhi International
IGP	Indo-Gangetic Plain
IITM	Indian Institute of Tropical Meteorology
IMD	India Meteorological Department
IOA	Index of Agreement
ISD	Integrated Surface Database

KPP	Kinetic Pre-Processor
LAI	Leaf Area Index
LES	Large Eddy Simulation
LSM	Land Surface Model
LULC	Land Use and Land Cover
LWP	Liquid Water Path
MADE	Modal Aerosol Dynamics Model for Europe
MAM	Modal Aerosol Model
MB	Mean Bias
MEGAN	Model of Emissions of Gases and Aerosol from Nature
METAR	Meteorological Terminal Air Report
MODIS	Moderate Resolution Imaging Spectroradiometer
MOSAIC	Model for Simulating Aerosol Interactions and Chemistry
MOZART	Model for Ozone and Related chemical Tracers
MYNN	Mellor-Yamada-Nakanishi-Niino
Na^+	Sodium
NBL	Nocturnal Boundary Layer
NCEI	National Centres for Environmental Information
NCR	National Capital Region
NCT	National Capital Territory
NH_3	Ammonia
NH_4^+	Ammonium
NMHC9	Non-Methane Hydrocarbon mechanism (9-species version)
NMVOCs	Non-methane volatile organic compounds

NO_2	Nitrogen dioxide
NO_3^-	Nitrate
NO_x	Nitrogen oxide (NO and NO_2)
NWP	Numerical Weather Prediction
O_3	Ozone
OC	Organic carbon
PAR	Photosynthetically Active Radiation
PBL	Planetary Boundary Layer
PM_{10}	Particulate Matter with aerodynamic diameter 10 μm
$PM_{2.5}$	Particulate Matter with aerodynamic diameter 2.5 μm
PPFD	Photosynthetic Photon Flux Density
QGIS	Quantam Geographical Information System
RACM	Regional Atmospheric Chemistry Mechanism
RACM-MIM	Regional Atmospheric Chemistry Mechanism Mainz Isoprene Mechanism
RADM	Regional Acid Deposition Model
RMSE	Root Mean Square Error
RRTMG	Rapid Radiative Transfer Model for General Circulation Model
RSI	Regime Shift Index
RSPCB	Rajasthan State Pollution Control Board
SAPRC-99	Statewide Air Pollution Research Center mechanism, 1999 version
SO_2	Sulfur dioxide
SSA	Single Scattering Albedo
STARS	Sequential T-test Analysis of Regime Shifts

STL	Stratus Cloud Lowering
SULF	Sulfate aerosol
SYNOP	Surface Synoptic Observations
TKE	Turbulent Kinetic Energy
UCI	Urban Clear Islands
UCM	Urban Canopy Model
UDI	Urban Dry Island
UHI	Urban Heat Island
UPPCB	Uttar Pradesh Pollution Control Board
VOCs	Volatile Organic Compounds
WACCM	Whole Atmosphere Community Climate Model
WD	Western Disturbance
WiFEX	Winter Fog EXperiment
WMO	World Meteorological Organization
WPS	WRF Preprocessing System
WRF	Weather Research Forecasting model
WRF-Chem	Weather Research Forecasting model coupled with Chemistry
WSM3	WRF Single-Moment 3-class
WSM6	WRF Single-Moment 6-class

List of Symbols

$B(\eta)$	Terrain-following vertical weighting function (dimensionless)
BR	Bowen ratio (ratio of sensible to latent heat flux)
DD	Dewpoint depression, defined as $T - T_d$ (K)
EM	Biogenic emission rate ($\mu g\,m^{-2}\,h^{-1}$)
LHF	Latent heat flux ($W\,m^{-2}$)
LWC	Liquid water content ($g\,m^{-3}$)
RH	Relative humidity (%)
SHF	Sensible heat flux ($W\,m^{-2}$)
Z	Geopotential height (m)
η	Terrain-following hydrostatic pressure vertical coordinate (dimensionless)
η_c	Specified critical value of η where the coordinate transitions to pure pressure (dimensionless)
γ_{CE}	Canopy environment activity factor (dimensionless)
γ_{LAI}	Leaf area index activity factor (dimensionless)
γ_P	Light-dependent photosynthetic photon flux density activity factor (dimensionless)
γ_{SM}	Soil moisture activity factor (dimensionless)

γ_T	Temperature response activity factor (dimensionless)
γ_{age}	Leaf age activity factor (dimensionless)
$\hat{r}_{dk}$	Brownian diffusivity-related resistance for size bin k ($\mathrm{s\,m^{-1}}$)
$\hat{v}_{Gk}$	Polydisperse gravitational settling velocity for size bin k ($\mathrm{m\,s^{-1}}$)
ρ	Canopy loss and production factor (dimensionless)
θ	Potential temperature (K)
ε	Emission factor ($\mu\mathrm{g\,m^{-2}\,h^{-1}}$)
p_0	Reference sea-level pressure (Pa)
p_d	Hydrostatic pressure of dry air (Pa)
p_s	Hydrostatic surface pressure (Pa)
p_t	Top-level pressure of the model domain (Pa)
q	Water vapor mixing ratio ($\mathrm{kg\,kg^{-1}}$)
r_a	Aerodynamic resistance ($\mathrm{s\,m^{-1}}$)
r_s	Surface resistance ($\mathrm{s\,m^{-1}}$)
u	Zonal wind component ($\mathrm{m\,s^{-1}}$)
v	Meridional wind component ($\mathrm{m\,s^{-1}}$)
v_d	Dry deposition velocity ($\mathrm{m\,s^{-1}}$)
v_g	Gravitational settling velocity ($\mathrm{m\,s^{-1}}$)