

**INVESTIGATION OF THUNDERSTORM VARIABILITY
OVER NORTHWEST INDIA: A PRAGMATIC
APPROACH UTILIZING MULTI-DECADAL
OBSERVATIONS TO HIGH RESOLUTION URBAN
MODELING**

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**Investigation of Thunderstorm Variability over Northwest
India: A Pragmatic Approach Utilizing Multi-Decadal
Observations to High Resolution Urban Modeling**

by

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Submitted

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CERTIFICATE

This is to certify that the thesis entitled “**Investigation Of Thunderstorm Variability Over Northwest India: A Pragmatic Approach Utilizing Multi-Decadal Observations To High Resolution Urban Modeling**” being submitted by Mr. SHIBIN BALAKRISHNAN to the Indian Institute of Technology Delhi for the award of the degree of Doctor of Philosophy, is a record of original Bonafide research work carried out by him. He has worked under my guidance and supervision and has fulfilled the requirements for the submission of this thesis. The results presented in this thesis have not been submitted in part or full to any other University or Institute for the award of any degree or diploma.

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ABSTRACT

Severe weather events are the biggest natural disaster in the world, crippling infrastructure, crops and human lives. Asia, the most populated continent on this planet with dense population clusters experiences severe weather events through thunderstorms, torrential rains, lightning and violent wind gusts leading to vulnerable socio-economic conditions. India, faces the wrath of the severe weather events round the year with pre-monsoon season, specifically impacted by thunderstorms, lightning, strong gusty winds and associated destructions. The multi-scale factors controlling these events originate from the local boundary layer dynamics to the large multi-scale climate variability, significantly impacting the urban settlements and poses a grave challenge to the forecasters to issue a precise, timely and error-free forecast.

The current thesis is formulated to achieve better insights towards severe thunderstorms and its dynamics across northwest India, one of the major urban hotspots of the region. The thesis addresses investigation based the observational analysis of the climatology of thunderstorm days over northwest India. The observational study is followed by high resolution WRF modelling sensitivity studies to precisely demarcate the most suitable PBL schemes for thunderstorm simulations over north India. The study further dives into ultra- high kilometre scale modelling of thunderstorms, specifically targeting urban clusters of Delhi-NCR. The motive of this thesis is to address the gaps in high-resolution simulation of thunderstorms, its evolution, owing to natural and anthropogenic induced land surface modifications, investigation of diagnostic predictors of convection and long - term climatological trends.

The current thesis begins with the examination of thunderstorm occurrences over northwest India during the last five decades during pre-monsoon and post monsoon

season. Significant inter-decadal fluctuations in thunderstorm frequency and intensity were envisaged from the long - term observational analyses. The findings depict the large variability in the frequency and amplitude of thunderstorms over the region. The study further researched on the significance of the thunderstorm days over the region. The scientific outcome paved way to further probe the significance of multiple meteorological parameters in understanding the evolution of thunderstorms. The exhaustive observational information of thunderstorm days over the region laid the foundation for the observational ground work for further research.

The second section of the thesis explored the multiple stability indices over the region, to detect the thermodynamics signal during convection. The stability indices are researched during thunderstorm and non-thunderstorm days. The K Index (KI), Lifted Index (LI), Showalter Index (SI), Convective Available Potential Energy (CAPE) and Convective Inhibition (CIN) are among the stability indices utilized for this study. Multiple techniques like box plots and Empirical Cumulative Distribution Function (ECDF) were utilized to detect the role of multiple stability indices in precise detection of thunderstorms. The Colour Coded Correlation is employed to detect the improved detection of high performing and low performing stability indices in thunderstorm detection. The True Skill Statistics (TSS), used in the study, further explores the optimal threshold values as per each index's role for thunderstorm and non-thunderstorm days. This scientific metric is superior in generating area specific stability index threshold, rather than relying on conventional thunderstorm climatological threshold.

The thesis, after working through observational thunderstorm detection and progresses into high resolution modelling, simulating severe thunderstorm occurrences using Weather Research and Forecasting (WRF) model. Boundary Layer dynamics has a significant impact on storm onset and further intensification. To address this research

problem, the current study investigated the sensitivity experiments of PBL schemes through MYJ, YSU, BouLac, TEMF and Shin-Hong. The simulation exhibited MYJ scheme to be among the best in precise simulation of near-surface conditions and storm initiation. This study throws light on the crucial role in precise selection of boundary layer physics for thunderstorm simulation and improved predictability at regional scales. The physics of the upper atmosphere plays a vital role in thunderstorm evolution. Model derived upper - level variables are validated with Wyoming upper air sounding data. These results, exhibited the variability in simulation of upper - level meteorological parameters.

The last section of the thesis utilized advanced Urban Canopy Modelling experiments to examine the urban morphology and its impact on thunderstorms. Simulations were performed to investigate the role of urban surfaces in altering the local convection using WRF with ingestion of UCM. The study further researched on the ingestion of high-resolution Urban Fraction data from Sentinel product. The study performed control run (WRF UCM with default MODIS LULC 21 Class product) and experimental run (WRF UCM with default MODIS LULC 21 Class product with Sentinel Urban Fraction data). The scientific findings demonstrated the more precise position of urban cores improves timing and severity of thunderstorms owing to the high heat capacity, impermeable surfaces and enhanced sensible heat fluxes and localized convergence. The results further demonstrate the urban clusters as not just passive backdrops, albeit active participants in the regional storm dynamics.

सार

खराब मौसम की घटनाएं दुनिया की सबसे बड़ी प्राकृतिक आपदाएं हैं, जो बुनियादी ढांचे, फसलों और इंसानी जिंदगियों को बुरी तरह प्रभावित करती हैं। एशिया, जो घनी आबादी वाला महाद्वीप है, वहां आंधी-तूफान, मूसलाधार बारिश, बिजली गिरने और तेज हवाओं जैसी खराब मौसम की घटनाओं का असर होता है, जिससे सामाजिक-आर्थिक हालात मुश्किल हो जाते हैं। भारत को साल भर खराब मौसम की घटनाओं का सामना करना पड़ता है, खासकर मॉनसून से पहले के मौसम में आंधी-तूफान, बिजली गिरने, तेज हवाओं और उनसे होने वाली तबाही का असर होता है। इन घटनाओं को नियंत्रित करने वाले कई स्तर के कारक स्थानीय बाउंड्री लेयर की गतिविधियों से लेकर बड़े पैमाने पर जलवायु में बदलाव तक होते हैं, जो शहरी बस्तियों को काफी प्रभावित करते हैं और मौसम की भविष्यवाणी करने वालों के लिए सटीक, समय पर और बिना गलती वाली भविष्यवाणी करना एक बड़ी चुनौती बन जाता है। यह थीसिस उत्तर-पश्चिम भारत में गंभीर आंधी-तूफान और उनकी गतिविधियों के बारे में बेहतर जानकारी हासिल करने के लिए तैयार की गई है; यह क्षेत्र शहरी हॉटस्पॉट में से एक है। यह थीसिस उत्तर-पश्चिम भारत में आंधी-तूफान वाले दिनों की जलवायु संबंधी जानकारी के अवलोकन-आधारित विश्लेषण पर केंद्रित है। अवलोकन-आधारित अध्ययन के बाद, उत्तर भारत में आंधी-तूफान के सिमुलेशन के लिए सबसे उपयुक्त PBL स्कीम की पहचान करने के लिए हाई-रिज़ॉल्यूशन WRF मॉडलिंग संवेदनशीलता अध्ययन किए गए। अध्ययन में आगे आंधी-तूफान की अल्ट्रा-हाई किलोमीटर-स्केल मॉडलिंग पर भी ध्यान दिया गया, जिसमें खास तौर पर दिल्ली-NCR के शहरी इलाकों को शामिल किया गया। इस थीसिस का मकसद आंधी-तूफान के हाई-रिज़ॉल्यूशन सिमुलेशन और उनके विकास में मौजूद कमियों को दूर करना है; इसमें प्राकृतिक और इंसानी गतिविधियों से ज़मीन की सतह में हुए बदलावों, कन्वेक्शन (संवहन) के डायग्नोस्टिक

प्रेडिक्टर्स की जांच और लंबे समय के जलवायु संबंधी रुझानों पर ध्यान दिया गया है। यह थीसिस उत्तर-पश्चिम भारत में पिछले पांच दशकों के दौरान मॉनसून से पहले और मॉनसून के बाद के मौसम में आंधी-तूफान की घटनाओं की जांच से शुरू होती है। लंबे समय के अवलोकन-आधारित विश्लेषणों से आंधी-तूफान की आवृत्ति और तीव्रता में दशक-दर-दशक बड़े उतार-चढ़ाव देखे गए। नतीजों से इस क्षेत्र में आंधी-तूफान की आवृत्ति और तीव्रता में भारी बदलाव का पता चलता है। अध्ययन में आगे इस क्षेत्र में आंधी-तूफान वाले दिनों के महत्व पर भी शोध किया गया। वैज्ञानिक नतीजों ने आंधी-तूफान के विकास को समझने में कई मौसम संबंधी पैमानों के महत्व की और जांच करने का रास्ता साफ किया। इस क्षेत्र में आंधी-तूफान वाले दिनों की विस्तृत अवलोकन-आधारित जानकारी ने आगे के शोध के लिए ज़मीनी काम की नींव रखी। थीसिस के दूसरे हिस्से में कन्वेक्शन के दौरान थर्मोडायनामिक्स सिग्नल का पता लगाने के लिए इस क्षेत्र में कई स्टेबिलिटी इंडेक्स (स्थिरता सूचकांक) की जांच की गई। आंधी-तूफान वाले और बिना आंधी-तूफान वाले दिनों के दौरान स्टेबिलिटी इंडेक्स पर शोध किया गया। इस स्टडी में K इंडेक्स (KI), लिफ्टेड इंडेक्स (LI), शोवाल्टर इंडेक्स (SI), कन्वेक्टिव अवेलेबल पोटेंशियल एनर्जी (CAPE) और कन्वेक्टिव इनहिबिशन (CIN) जैसे स्टेबिलिटी इंडेक्स का इस्तेमाल किया गया है। थंडरस्टॉर्म का सटीक पता लगाने में अलग-अलग स्टेबिलिटी इंडेक्स की भूमिका को समझने के लिए बॉक्स प्लॉट और एम्पिरिकल क्यूमुलेटिव डिस्ट्रीब्यूशन फंक्शन (ECDF) जैसी कई तकनीकों का इस्तेमाल किया गया। थंडरस्टॉर्म का पता लगाने में बेहतर और कम असरदार स्टेबिलिटी इंडेक्स की पहचान करने के लिए कलर-कोडेड कोरिलेशन का इस्तेमाल किया गया। स्टडी में इस्तेमाल किए गए 'टू स्किल स्टैटिस्टिक्स' (TSS) से थंडरस्टॉर्म वाले और बिना थंडरस्टॉर्म वाले दिनों के लिए हर इंडेक्स की भूमिका के हिसाब से सबसे सही थ्रेशोल्ड वैल्यू का पता लगाया गया। यह साइंटिफिक मेट्रिक, पारंपरिक थंडरस्टॉर्म क्लाइमेटोलॉजिकल थ्रेशोल्ड पर निर्भर रहने के बजाय, किसी खास इलाके के लिए स्टेबिलिटी इंडेक्स थ्रेशोल्ड बनाने में ज़्यादा बेहतर है।

यह थीसिस, ऑब्जर्वेशनल थंडरस्टॉर्म डिटेक्शन पर काम करने के बाद, हाई-रिज़ॉल्यूशन मॉडलिंग की ओर बढ़ती है और वेदर रिसर्च एंड फोरकास्टिंग (WRF) मॉडल का इस्तेमाल करके गंभीर थंडरस्टॉर्म की घटनाओं का सिमुलेशन करती है। बाउंड्री लेयर डायनामिक्स का तूफ़ान शुरू होने और उसके और तेज़ होने पर काफ़ी असर पड़ता है। इस रिसर्च प्रॉब्लम को समझने के लिए, मौजूदा स्टडी में MYJ, YSU, BouLac, TEMF और Shin-Hong के ज़रिए PBL स्कीम के सेंसिटिविटी एक्सपेरिमेंट की जांच की गई। सिमुलेशन से पता चला कि सतह के पास की स्थितियों और तूफ़ान की शुरुआत का सटीक सिमुलेशन करने में MYJ स्कीम सबसे अच्छी स्कीम में से एक है। यह स्टडी थंडरस्टॉर्म सिमुलेशन के लिए बाउंड्री लेयर फ़िज़िक्स को सही ढंग से चुनने और क्षेत्रीय स्तर पर बेहतर भविष्यवाणी करने में इसकी अहम भूमिका पर रोशनी डालती है। थंडरस्टॉर्म के बनने में ऊपरी वायुमंडल की फ़िज़िक्स अहम भूमिका निभाती है। मॉडल से मिले ऊपरी-स्तर के वेरिफ़ाईड को व्योमिंग अपर एयर साउंडिंग डेटा से वेरिफ़ाई किया गया। इन नतीजों से ऊपरी-स्तर के मौसम संबंधी पैरामीटर्स के सिमुलेशन में अंतर का पता चला।

शोध प्रबंध के अंतिम भाग में शहरी संरचना और गरज-चमक पर इसके प्रभाव का अध्ययन करने के लिए उन्नत शहरी आवरण मॉडलिंग प्रयोगों का उपयोग किया गया। शहरी सतहों की भूमिका का पता लगाने के लिए, यूसीएम के समावेश के साथ डब्ल्यूआरएफ का उपयोग करते हुए, स्थानीय संवहन में परिवर्तन का अध्ययन किया गया। अध्ययन में सेंटिनल उत्पाद से उच्च-रिज़ॉल्यूशन शहरी अंश डेटा के समावेश पर भी शोध किया गया। अध्ययन में एक नियंत्रण रन (डिफ़ॉल्ट MODIS LULC 21 क्लास उत्पाद के साथ डब्ल्यूआरएफ यूसीएम) और एक प्रायोगिक रन (सेंटिनल शहरी अंश डेटा के साथ डिफ़ॉल्ट MODIS LULC 21 क्लास उत्पाद के साथ डब्ल्यूआरएफ यूसीएम) किया गया। वैज्ञानिक निष्कर्षों से पता चला कि शहरी केंद्रों की अधिक सटीक स्थिति, उच्च ताप क्षमता, अभेद्य सतहों, बढ़ी हुई संवेदी ऊष्मा प्रवाह और स्थानीय

अभिसरण के कारण गरज-चमक के समय और तीव्रता में सुधार करती है। परिणाम यह भी दर्शाते हैं कि शहरी समूह केवल निष्क्रिय पृष्ठभूमि नहीं हैं, बल्कि क्षेत्रीय तूफान गतिशीलता में सक्रिय भागीदार हैं।

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LIST OF ABBREVIATIONS

ABL	: Atmospheric Boundary Layer
ADSI	: Accidental Deaths & Suicides in India
AI	: Artificial Intelligence
AVHRR	: Advanced Very High-Resolution Radiometer
AWS	: Automatic Weather Station
BEM	: Building Energy Model
BEP	: Building Effect Parameterization
BMJ	: Betts-Miller-Janjic
BT	: Brightness Temperature
CAPE	: Convective Available Potential Energy
CAT	: Clear Air Turbulence
CCN	: Cloud Condensation Nuclei
CG	: Cloud to Ground
CIN	: Convective Inhibition
CRI	: Climate Risk Index
CTH	: Cloud Top Height
CV	: Coefficient of Variation
DWR	: Doppler Weather Radar
ECDF	: Empirical Cumulative Distribution Function
ECMWF	: European Center for Medium Range Weather Forecast
EL	: Equilibrium Level
ENTLN	: Earth Networks Total Lightning Network
ESA	: European Space Agency
FB	: Fractional Bias
GIS	: Geographic Information Systems
GOES	: Geostationary Operational Environmental Satellite
HDI	: Human Development Index
IC	: Intra- Cloud
IDW	: Inverse Distance Weightage

IGBP	: International Geosphere- Biosphere Program
IGP	: Indo Gangetic Plain
INSAT	: Indian National Satellite System
IOA	: Index of Agreement
IQR	: Inter Quartile Range
IR	: Infra-Red
ISM	: Indian Summer Monsoon
KI	: K Index
LCL	: Lifting Condensation Level
LCZ	: Local Climate Zone
LFC	: Level of Free Convection
LI	: Lifted Index
LLJ	: Low Level Jet
LSM	: Land Surface Model
LULC	: Land Use Land Cover
MAE	: Mean Absolute Error
MB	: Mean Bias
MCAPE	: Maximum Convective Available Potential Energy
MCDA	: Multi Criteria Decision Analysis
METAR	: Meteorological Aerodrome Report
MYJ	: Mellor-Yamada-Janjic
MYNN	: Mellor-Yamada Nakanishi Niino
NCAR	: National Center for Atmospheric Research
NCEP	: National Center for Environment Prediction
NCR	: National Capital Region
NDMA	: National Disaster Management Authority
NDVI	: Normalized Difference Vegetation Index
NLDN	: National Lightning Detection Network
NMHS	: National Meteorological and Hydrological Services
NOAA	: National Oceanic and Atmospheric Administration

NTSD	: Non-Thunderstorm Day
NWP	: Numerical Weather Prediction
PBLH	: Planetary Boundary Layer Height
QGIS	: Quantum Geographical Information System
QNSE	: Quasi Normal Scale Elevation
RBC	: Rank Biserial Correlation
RMSE	: Root Mean Square Error
SFD	: Safdarjung
SI	: Showalter Index
SL	: Surface Layer
SLUCM	: Single Layer Urban Canopy Model
SST	: Sea Surface Temperature
SYNOP	: Synoptic Observations
TEB	: Town Energy Balance
TEMF	: Total Energy Mass Flux
TKE	: Turbulent Kinetic Energy
TSD	: Thunderstorm Day
TSS	: True Skill Statistics
UA	: Urban Agglomeration
UCF	: Urban Canopy Fraction
UCL	: Urban Canopy Layer
UCM	: Urban Canopy Model
UCP	: Urban Canopy Parameters
UHI	: Urban Heat Island
UTC	: Coordinated Universal Time
WD	: Western Disturbance
WHO	: World Health Organization
WMO	: World Meteorological Organization
WRF	: Weather Research and Forecasting
YSU	: Yonsei University