IMPACTS OF CLIMATE CHANGE ON THE FIRE WEATHER IN INDIAN FORESTS

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Impacts of climate change on the fire weather in Indian forests

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Certificate

This is to certify that the thesis entitled **" Impacts of climate change on the fire weather in Indian forests"** being submitted by **Anasuya Barik** to the Indian Institute of Technology Delhi for the award of the degree of **DOCTOR OF PHILOSOPHY** is a record of original bonafide research carried out by her. Anasuya has worked under my guidance and supervision and has fulfilled the requirements for the submission of this thesis. The results contained in this thesis have not been submitted part or full to any other University or Institute for the award of any degree or diploma.

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Abstract

Forest fires are influenced by changing climatic conditions. The changing climate and its impact on fire frequencies have led to increased interest within the research community in investigating climate-fire interactions at both global and regional scales. India experiences a large number of forest fires. This thesis presents a detailed analysis of the forest fire patterns across India, the influence of meteorological conditions, and the projected impact of climate change on fire weather regimes by the end-century over forests in India. For this study, Indian forests were classified into five zones: Himalayan, Northeast, Central India, Deccan, and Western Ghat. This classification was based on the climate and forest types of these zones. A comprehensive analysis of MODIS active fire data from 2003 to 2021 shows spatial heterogeneity in fire activity across India's forest zones. The highest fire occurrence is observed in the Northeast (NE) zone, with concentrations up to 250 fires per year in some of the 25km grids. Temporal analysis reveals a clear seasonality, with fires occurring mainly in the pre-monsoon months with high temperatures and low humidity.

Next, the Canadian Forest Fire Danger Rating System Fire Weather Index (CFFDRS-FWI) system was evaluated under Indian climatic conditions. It was found that with a spin-up period of about 365 days, the algorithm produced stable values of FWI over the Indian forest zones. Further analysis shows that high FWI is an essential requirement for fire occurrence. This makes FWI a good metric for estimating fire danger. After this, a Fire Danger Rating System (FDRS) was developed and tailored to each forest zone. This FDRS was based on the simulated FWI from the CFFDRS, ERA5 reanalysis data as meteorological input to CFFDRS and MODIS active fire

observations from 2003 to 2021 for validation. An ensemble of methods using logistic regression, FWI percentiles, fire occurrence percentages, and k-means clustering was employed to classify FWI values into five fire danger categories. Machine learning techniques were introduced to reduce the subjective decisions in these methods. This increased the efficiency of the FDRS to detect fire probability by 30-50%.

To drive this CFFDRS and compute baseline and future FWI, a high-resolution dynamically downscaled climate projection DSCESM was used for a baseline (2006-2015) and an end-century (2091-2100) period. DSCESM dataset is a 10-km gridded hydrometeorological dataset over India developed by dynamic downscaling of the bias-corrected Community Earth System Model (CESMv1) climate projections under RCP8.5 scenario using the state-of-the-art Weather Research and Forecasting (WRF) model. It is archived in the World Data Center for Climate (WDCC) portal at three temporal resolutions (daily, monthly, and monthly climatology) for current (2006–2015), mid-century (2041–2050) and end-century (2091–2100) periods. All the DSCESM variables were extensively evaluated against reanalysis data and station observations for the period 2006–2015. Variables such as 2-m air temperature, total accumulated precipitation, wind speed, and relative humidity were used as input for the CFFDRS algorithm.

To assess the impact of climate change on the Fire Weather Index (FWI) across Indian forest zones, this study compared various aspects of baseline and future FWI, fire weather danger, Seasonal Severity Ratings (SSR), and seasonal characteristics of fire danger. Results indicated substantial variability in both baseline and projected fire weather danger across different zones and within forest zones. Climate change is anticipated to significantly impact fire weather, with days exceeding the Very High FWI threshold projected to increase by 30-40 days by the end of the century, despite only a 5% rise in annual FWI values. In dry forests, severe fire weather days could increase by up to 60% by the century's end due to rising temperatures. In contrast, humid forests may experience a reduction of up to 40% in severe fire weather days, attributed to an expected increase in precipitation by the century's end. The fire season is also expected to extend by 3–61 days throughout India. SSR analysis suggests a peak in fire disturbances during the pre-monsoon months (March–April–May), affecting about 55% of India's forest area, while the post-monsoon season (September–October–November) is likely to show minimal impact. Forests at highest risk of fire disturbances by century's end include moist deciduous and evergreen forests in the northern Western Ghats (WG), mixed dry deciduous forests in central and southern Central India (CEN), Pine and Sal forests in the Himalayas (HIM), and scrub forests in the Deccan (DEC) zone.

This research represents one of the first efforts to quantify climate change effects on forest fire hazards in India. The high-resolution analysis shows intricate patterns of the relationship between weather variables and fire occurrences, which are different from those suggested by coarser-resolution global studies. This study counters the conventional view that fire regimes will intensify homogenously with rising temperatures. Precipitation and humidity are likely to moderate the impact of temperature increases under changing climate, particularly in humid zones. Such findings highlight the importance of considering changes in monsoon dynamics alongside temperature changes for fire-climate interaction studies. This study also has significant policy implications and can be valuable in targeted efforts towards regional fire hazards under evolving climate conditions.

सारांश

वनाग्नियाँ परिवर्तित होते जलवायु परिस्थितियों से प्रभावित होती हैं। जलवायु परिवर्तन तथा इसके कारण आग की आवृत्तियों में हो रहे बदलावों ने वैश्विक एवं क्षेत्रीय स्तर पर आग-जलवायु अंतःक्रियाओं के अध्ययन में शोध समुदाय की रुचि बढ़ाई है। भारत में प्रतिवर्ष बड़ी संख्या में वनाग्नियाँ घटित होती हैं। यह शोध प्रबंध भारत में वनाग्नि प्रवृत्तियों, मौसमीय परिस्थितियों के प्रभाव, तथा भविष्य में जलवायु परिवर्तन के कारण आग के मौसम पर संभावित प्रभावों का विश्लेषण प्रस्तुत करता है। इस अध्ययन में भारतीय वनों को उनके जलवायु एवं वन प्रकारों के आधार पर पाँच क्षेत्रों — हिमालय, उत्तर-पूर्व, मध्य भारत, दक्कन तथा पश्चिमी घाट — में वर्गीकृत किया गया है।

2003 से 2021 तक के MODIS सक्रिय अग्नि डेटा का विश्लेषण भारत के वन क्षेत्रों में आग की स्थानिक विषमता को दर्शाता है। सर्वाधिक अग्नि घटनाएँ उत्तर-पूर्व (NE) क्षेत्र में पाई गईं, जहाँ कुछ 25-किमी ग्रिड में प्रतिवर्ष 250 तक आग की घटनाएँ दर्ज हुईं। कालानुक्रमिक विश्लेषण में पूर्व मानसून महीनों में उच्च तापमान एवं कम आर्द्रता के साथ आग की मौसमी प्रवृत्ति स्पष्ट रूप से परिलक्षित होती है।

अगले चरण में, Canadian Forest Fire Danger Rating System Fire Weather Index (CFFDRS-FWI) प्रणाली का भारतीय परिस्थितियों में परीक्षण किया गया। पाया गया कि लगभग 365 दिन के स्पिन-अप काल के साथ, यह एल्गोरिद्म भारतीय वन क्षेत्रों में स्थिर FWI मान प्रदान करता है। उच्च FWI मान को आग की घटनाओं के लिए अनिवार्य पाया गया, जिससे यह FWI को आग के खतरे के आकलन का उपयुक्त संकेतक बनाता है। इसके पश्चात, CFFDRS सिम्युलेटेड FWI, ERA5 पुनःविश्लेषण डेटा तथा MODIS आग प्रेक्षणों (2003–2021) पर आधारित, प्रत्येक वन क्षेत्र के अनुरूप एक Fire Danger Rating System (FDRS) विकसित किया गया। लॉजिस्टिक रिग्रेशन, FWI परसेंटाइल, आग की घटना प्रतिशत एवं k-means क्लस्टरिंग जैसी तकनीकों के संयोजन से FWI को पाँच श्रेणियों में वर्गीकृत किया गया। मशीन लर्निंग तकनीकों को शामिल कर इन विधियों में व्यक्तिपरक निर्णयों को कम किया गया, जिससे FDRS की भविष्यवाणी क्षमता में 30–50% तक सुधार हुआ। इस प्रणाली को चलाने तथा वर्तमान एवं भविष्य की FWI की गणना के लिए उच्च-रिज़ॉल्यूशन, डायनामिकली डाउनस्केल्ड जलवायु प्रक्षेपण DSCESM का उपयोग किया गया। यह डेटा सेट 10-किमी ग्रिड आकार में CESMv1 जलवायु प्रक्षेपणों को RCP8.5 परिदृश्य के अंतर्गत WRF मॉडल द्वारा डाउनस्केल कर विकसित किया गया है। यह World Data Center for Climate (WDCC) पोर्टल

पर दैनिक, मासिक तथा मासिक औसत स्तर पर वर्तमान (2006–2015), मध्य-शती (2041–2050) एवं शताब्दी-अंत (2091–2100) कालखंडों के लिए उपलब्ध है। 2006–2015 की अवधि में DSCESM चरमानों का पुनःविश्लेषण तथा प्रेक्षण डेटा के साथ गहन परीक्षण किया गया।

वन क्षेत्रों में जलवायु परिवर्तन के FWI पर प्रभाव का आकलन करने हेतु आधारभूत एवं भविष्य FWI, आग मौसम खतरा, Seasonal Severity Ratings (SSR), तथा आग मौसम की मौसमी प्रवृत्तियों की तुलना की गई। परिणामों से स्पष्ट होता है कि अलग-अलग क्षेत्रों एवं वन क्षेत्रों के भीतर आग मौसम खतरे में पर्याप्त अंतर है। शताब्दी-अंत तक, अत्यंत उच्च FWI वाले दिनों की संख्या में 30–40 दिन की वृद्धि संभावित है, जबकि वार्षिक FWI में मात्र 5% की वृद्धि अनुमानित है। शुष्क वनों में, तीव्र आग मौसम वाले दिनों में तापमान वृद्धि के कारण 60% तक वृद्धि हो सकती है। दूसरी ओर, आर्द्र वनों में वर्षा वृद्धि के कारण 40% तक की कमी संभव है। पूरे भारत में आग का मौसम 3–61 दिन तक बढ़ सकता है। SSR विश्लेषण से पूर्व-मानसून महीनों (मार्च-अप्रैल-मई) में सर्वाधिक (~55%) वन क्षेत्र प्रभावित होने की संभावना है, जबकि उत्तर-मानसून (सितंबर-अक्टूबर-नवंबर) में प्रभाव न्यूनतम होगा। सर्वाधिक जोखिम वाले वन क्षेत्र शताब्दी-अंत तक उत्तरी पश्चिमी घाट के नम पतझड़ी एवं सदाबहार वन, मध्य एवं दक्षिणी मध्य भारत के मिश्रित शुष्क पतझड़ी वन, हिमालय के चीड़ एवं साल वन तथा दक्कन के स्क्रब वन हो सकते हैं।

यह अध्ययन भारत में वनाग्नि जोखिमों पर जलवायु परिवर्तन के प्रभाव का मात्रात्मक आकलन करने का प्रथम प्रयास है। उच्च-रिज़ॉल्यूशन विश्लेषण से यह स्पष्ट हुआ कि मौसमीय कारकों एवं आग की घटनाओं के बीच संबंध वैश्विक स्तर पर प्राप्त निष्कर्षों से भिन्न हैं। यह अध्ययन पारंपरिक धारणा का खंडन करता है कि तापमान वृद्धि के साथ आग की घटनाएँ समान रूप से बढ़ेंगी। आर्द्रता एवं वर्षा तापमान वृद्धि के प्रभाव को विशेषकर आर्द्र क्षेत्रों में संतुलित कर सकती हैं। यह परिणाम मानसूनी प्रवृत्तियों के परिवर्तनों को तापमान के साथ मिलाकर विचार करने की आवश्यकता को रेखांकित करता है। यह शोध नीति निर्माण में भी उपयोगी हो सकता है एवं क्षेत्रीय स्तर पर आग के खतरों के प्रबंधन हेतु महत्त्वपूर्ण दिशा-निर्देश प्रदान कर सकता है।

Contents

List of Publications Based on This Thesis

Journal articles

Barik, A., & Baidya Roy, S. (2023). Climate change strongly affects future fire weather danger in Indian forests. Communications Earth & Environment, 4(1), 452.

Barik, A., Sahoo, S. K., Kumari, S., & Baidya Roy, S. (2024). High-resolution climate projection dataset over India using dynamical downscaling. Geoscience Data Journal, 11(4), 921-935.

Barik, A., & Baidya Roy, S. Modelling Fire Weather Hazard and Risk in Fragmented Tropical Forests: A Machine Learning Approach. npj Natural Hazards (under review)

Datasets

Barik, A., Sahoo, S. K., Kumari, S., & Baidya Roy, S. (2021). 10 km gridded hydrometeorological dataset developed by dynamical downscaling of the bias-corrected CMIP5 CESM RCP8. 5 projections over India for current (2006-2015) and future (2091-2100) periods using WRF, World Data Center for Climate (WDCC) at DKRZ.

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List of abbreviations

BMJ	Betts Miller Janjic
BUI	Buildup Index
C3S	Copernicus Climate Change Service
CDS	Climate Data Store
CEN	Central India
CESM	Community Earth System Model
CFFDRS	Canadian Forest Fire Weather Rating System
CISL	Computational and Information Systems Laboratory
CMIP	Coupled Model Intercomparison Project
CORDEX-SA	Coordinated Regional Climate Downscaling Experiment-South Asia
CRU TS	Climate Research Unit Time Series
CSI	Critical Success Index
CSR	Critical Success Rate
DC	Drought Code
DEC	Deccan
DMC	Duff Moisture Code
DSCESM	Downscaled CESM
DSR	Daily Severity Rating
ERA5	Fifth generation ECMWF reanalysis
ETM+	Enhanced Thematic Mapper Plus
FAST 3.0	Forest Fire Alert System v3.0
FAR	False Alarm Ratio
FDRS	Fire Danger Rating System
FFMC	Fine Fuel Moisture Code
FIRMS	Fire Information for Resource Management System
FPR	False Positive Rate
FRP	Fire Radiative Power
FSI	Forest Survey of India
FWI	Fire Weather Index
GCM	General Circulation Model

GPCC	Global Precipitation Climatology Centre
GPCP	Global Precipitation Climatology Project
GSOD	Global Summary of the Day
HIM	Himalayas
IGBP	International Geosphere-Biosphere Programme
IMDAA	Indian Monsoon Data Assimilation and Analysis
IPCC AR6	Intergovernmental Panel on Climate Change Sixth Assessment Report
IRS	India Remote Sensing
ISI	Initial Spread Index
KBDI	Keetch-Byram Drought Index
KDE	Kernel Density Estimation
KF	Kain–Fritsch
LISS	Linear Imaging Self-Scanning Sensor
LULC	Land Use and Land Cover
MM5	Fifth-Generation Penn State/NCAR Mesoscale Model
MODIS	Moderate Resolution Imaging Spectroradiometer
MPAS	Model for Prediction Across Scales
MSS	Multispectral Scanner
MYJ	Mellor-Yamada-Janjic
NCAR	National Center for Atmospheric Research
NE	North East
NOAH-MP	Noah Multi-parameterization
OLR	Outgoing Longwave Radiation
ORNL-DAAC	Oak Ridge National Laboratory Distributed Active Archive Center
PBL	Planetary Boundary Layer
PDF	Probability Density Function
PET	Potential Evapotranspiration
PI	Percentile Index
RCM	Regional Climate Models
RCP	Representative Concentration Pathways
RMSE	Root Mean Square Error

ROC	Receiver Operating Characteristic curve
RRTM	Rapid Radiative Transfer Model
SSR	Seasonal Severity Rating
T2m	2m Temperature
TH	Tropical thorn
TM	Thematic Mapper
TOA	Top Of Atmosphere
TPR	True Positive Rate
TS	Time Series
WDCC	World Data Center for Climate
WG	Western Ghats
WRF	Weather Research and Forecasting
YSU	Yonsei University Scheme