

IMPROVEMENTS IN THE SURFACE AND BOUNDARY LAYER PROCESSES FOR THE INDIA-CENTRIC CLIMATE SIMULATIONS

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**CENTRE FOR ATMOSPHERIC SCIENCES
INDIAN INSTITUTE OF TECHNOLOGY DELHI
DECEMBER 2024**

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**Improvements in the Surface and Boundary Layer Processes for
the India-Centric Climate Simulations**

by

Prabhakar Namdev

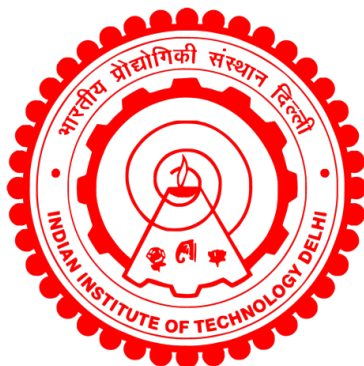
Centre for Atmospheric Sciences

Submitted

in fulfilment of the requirements of the degree of

DOCTOR OF PHILOSOPHY

to the



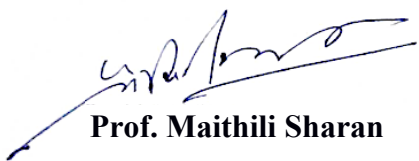
INDIAN INSTITUTE OF TECHNOLOGY DELHI

December 2024

*Dedicated to My
Grand Parents*

Certificate

This is to certify that the thesis entitled “*Improvements in the Surface and Boundary Layer Processes for the India-Centric Climate Simulations*” being submitted by **Mr. Prabhakar Namdev** 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 him. He has worked under our joint guidance and supervision and has fulfilled the requirements for the submission of the 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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December 2024



Prof. Saroj Kanta Mishra

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Acknowledgements

Firstly, I would like to express my sincere gratitude to my supervisors **Prof. Maithili Sharan** and **Prof. Saroj Kanta Mishra** for continuous support throughout my PhD thesis, for their patience, inspiration, and unparalleled expertise. Their relentless encouragement always helped me to resolve many difficult situations and complete this thesis. They have always given me the freedom to pursue my interests and provided me with insightful suggestions and support in developing independent thinking and research skills. Their constant motivation for scientific excellence has induced high ambitions within me. They have been the exceptional mentors, and I appreciate both our professional and personal conversations over the years. The knowledge and wisdom I have gained from them will forever guide me in education and life.

Besides my advisors, I also wish to extend my deep appreciation to my SRC members, Prof. A. D. Rao, Prof. Sarvesh Kumar Dubey, Prof. R. K. Sharma (Department of Mathematics), and Dr. Sandeep Sahany and Head Centre for Atmospheric Sciences (CAS) Prof. Somnath Baidya Roy for generously sharing their knowledge and time. I would also like to thank the entire CAS faculty for the training they provided during the course work and for suggestions during my pre-PhD synopsis as well as semester progress presentations.

I also wish to express my gratefulness to Dr. Piyush Srivastava (IIT Roorkee; India) and Dr. Gavendra Pandey (University of North Carolina at Chapel Hill; USA) for the scientific discussions as well as their help and suggestions.

I gratefully acknowledge the financial support received from IIT Delhi, UGC, and DST Centre of Excellence in Climate Modeling, IITD and all necessary logistics during my PhD tenure. IITD Super Computing Facility is gratefully acknowledged for providing the computing resources

for my PhD thesis. Data support received from the U. K. Met Office for the Cardington turbulent measurements, National Centre for Atmospheric Research (NCAR) for Cooperative Atmosphere-Surface Exchange Study-1999 (CASES-99) observations and CTCZ program for turbulence observations at BIT Ranchi (India) is gratefully acknowledged.

I take this opportunity to thank all of CAS and DST Centre of Excellence in Climate Modeling, IITD staff members for their help in various official and technical issues during my Ph.D. I would like to thank my colleagues and friends in the research group, Dr. Abhishek Anand, Dr. Popat Salunke, Dr. Raju Pathak, Dr. Ankur Dixit, Sweta Choubey, Shoobhangi Tyagi, Nisha, Saurabh Gaur, Pankaj Upadhyaya, Debi Prasad Bhuyan, Sundeep Barik, and Ashish Dwivedi for their active cooperation and support. I also thank my friends from our centre for their support, encouragement, and making my life enjoyable at IITD.

Words cannot completely express my love and gratitude to my family members who have supported and encouraged me through this journey. I would like to thank my parents, as well as my brothers Sudhakar, Kaushalendra, and Ram Manohar, and my sisters Jagrati and Shraddha, and especially my wife Pooja, for their life-long support, everlasting love, and sacrifices, which sustained my interest in research and motivated me towards the successful completion of this study.

Finally, I thank the almighty God for the passion, strength, perseverance, and the resources to complete this study.

Prabhakar Namdev,
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Abstract

Over the years, notable contributions have been made by the researchers to improve the accuracy of various physical parameterizations based on recent scientific developments, increase in computing resources, and the availability of more reliable observational datasets. Researchers evaluated the performance of the existing numerical models and also attempted to improve their performance by increasing horizontal resolution, manual and semi-automatic tuning of parameters, modifications in the cloud and convective parametrizations for the India-centric climate simulations; however, challenges still persist. This thesis is focused on critically evaluating the existing surface and boundary layer parameterizations of global as well as regional scale numerical models, and attempts have also been made to update these schemes based on recent scientific advancements and existing mathematical inconsistencies to potentially improve their representation/performance for the India-centric climate simulations.

The surface layer parameterizations in various Numerical Weather Prediction (NWP) and General Circulation Models (GCMs) are based on the famous Monin–Obukhov similarity theory (MOST) and follows an iterative or bulk approach. The non-dimensional vertical gradients of wind and temperature are expressed in terms of stability correction functions for momentum (φ_m) and heat (φ_h), respectively. According to MOST, φ_m and φ_h are universal functions of the Monin–Obukhov stability parameter (ζ) and generally known as the similarity functions.

It is a well-known fact that different functional forms of similarity functions in surface layer parameterization may perform better over different locations as well as seasons. For this purpose, some of the well-established similarity functions under stable as well as convective conditions have been incorporated and evaluated in the surface layer parameterization of National Centre for Atmospheric Research Community Atmosphere Model version 5 (NCAR-CAM5) over

Indian land and associated different climatic zones. This suggests that the performance of different similarity functions is spatially and temporally dependent and these functions may judiciously be chosen for climate simulations. It is observed that different surface layer schemes have restrictions on the values of either ζ and bulk Richardson number (Ri_B) due to limited applicability of similarity functions under stable conditions. To address this issue a systematic mathematical analysis has been carried out to estimate the extent of applicability of various non-linear similarity functions in terms of ζ and Ri_B for computing surface turbulent fluxes under stable conditions. The mathematical analysis is carried out by exploiting the monotonicity in the observed behaviour of both transfer coefficients for momentum (C_D) and heat (C_H).

It is observed that φ_m and φ_h , based on the three sub-layer model proposed by Kader and Yaglom (1990), are the only functions that are able to produce C_D consistent with its observed non-monotonic behaviour under convective conditions over Indian land; however, these functions are not commonly used in numerical modeling frameworks. For the first time, the three sublayer model has been implemented and evaluated in the surface layer scheme of the Weather Research and Forecasting (WRF) Model over an Indian land site. Moreover, an updated surface layer module for the WRF modeling system with the provision of various similarity functions for the computation of surface fluxes under both stable and convective conditions is proposed in this thesis.

On the other hand, the planetary boundary layer (PBL) parameterization is used to describe the turbulence transport above the surface layer and its height (PBLH) varies significantly during a diurnal cycle in response to changes in the thermal stratification. The structure of the PBL becomes complex with the weakening of wind and the extent of stability. This thesis attempted to evaluate the performance of the two PBL schemes in NCAR-CAM5 model over Indian land and associated different climatic zones. Moreover, to improve the performance of a PBL scheme for the India-centric climate simulations, the existing single value of critical bulk Richardson number

(Ri_{cr}) in all stratification conditions has been replaced by a thermal stratification dependent Ri_{cr} in a PBL scheme of NCAR-CAM5. The modified scheme shows encouraging results in simulating PBLH and other considered variables including surface air temperature and precipitation over Indian land.

A unique feature of this thesis is that it covers the aspects of numerical modeling, mathematical analysis as well as data analysis. The modifications are made in the existing surface and boundary parameterizations of NCAR-CAM5 as well as WRF Models. For the first time, the thermal stratification dependent Ri_{cr} has been implemented and evaluated in a PBL scheme of NCAR-CAM5 model for improved simulations. The schemes that have been modified in this thesis are evaluated against the observational datasets from the India Meteorological Department (IMD), reanalysis datasets including ERA-Interim, ERA5, and ERA5-Land, and turbulence measurements from two different sites: (i) Ranchi (India), and (ii) CASES-99. The proposed updated surface layer module for the WRF modeling system could enhance its potential applicability for the community.

सार

पिछले कुछ वर्षों में, हाल के वैज्ञानिक विकासों, कंप्यूटिंग संसाधनों में वृद्धि और अधिक विश्वसनीय अवलोकन डेटासेट की उपलब्धता के आधार पर विभिन्न भौतिक पैरामीट्रिज़ेशनो की सटीकता में सुधार करने के लिए शोधकर्ताओं द्वारा उल्लेखनीय योगदान दिया गया है। शोधकर्ताओं ने मौजूदा संख्यात्मक मॉडलों के प्रदर्शन का मूल्यांकन किया और भारत-केंद्रित जलवायु सिमुलेशन के लिए क्षेत्रीय रिज़ॉल्यूशन, मापदंडों की मैनुअल और अर्ध-स्वचालित ट्यूनिंग, क्लाउड और संवहन पैरामीट्रिज़ेशन के प्रदर्शन में सुधार करने का भी प्रयास किया; हालाँकि, चुनौतियाँ अभी भी बनी हुई हैं। यह थीसिस वैश्विक और साथ ही क्षेत्रीय पैमाने के संख्यात्मक मॉडलों की मौजूदा सतह और सीमा परत पैरामीट्रिज़ेशनो का गंभीर रूप से मूल्यांकन करने पर केंद्रित है, और संभावित रूप से उनके प्रतिनिधित्व/प्रदर्शन में सुधार के लिए हाल की वैज्ञानिक प्रगति और मौजूदा गणितीय विसंगतियों के आधार पर इन योजनाओं को भारत-केंद्रित जलवायु सिमुलेशन के लिए अद्यतन करने का भी प्रयास किया गया है।

विभिन्न संख्यात्मक मौसम पूर्वानुमान (NWP) और जनरल सर्कुलेशन मॉडल (GCM) में सतह परत पैरामीट्रिज़ेशन प्रसिद्ध मोनिन-ओबुखोव समानता सिद्धांत (MOST) पर आधारित हैं और एक पुनरावृत्त या बल्क दृष्टिकोण का पालन करते हैं। हवा और तापमान के गैर-आयामी ऊर्ध्वाधर ग्रेडियेंट क्रमशः गति (ϕ_m) और ताप (ϕ_h) के लिए स्थिरता सुधार कार्यों के संदर्भ में व्यक्त किए जाते हैं। MOST के अनुसार, ϕ_m और ϕ_h मोनिन-ओबुखोव स्थिरता पैरामीटर (τ) के सार्वभौमिक फलन हैं और आम तौर पर समानता फलनो के रूप में जाने जाते हैं।

यह एक सर्वविदित तथ्य है कि सतह परत पैरामीट्रिज़ेशन में समानता फलनो के विभिन्न कार्यात्मक रूप विभिन्न स्थानों के साथ-साथ मौसमों में भी बेहतर प्रदर्शन कर सकते हैं। इस उद्देश्य के लिए, स्थिर और साथ ही संवहन स्थितियों के तहत कुछ अच्छी तरह से स्थापित समानता फलनो को भारतीय भूमि और

संबंधित विभिन्न जलवायु क्षेत्रों में बेहतर सिमुलेशन के लिए नेशनल सेंटर फॉर एटमॉस्फेरिक रिसर्च कम्प्यूनिटी एटमॉस्फियर मॉडल संस्करण 5 (NCAR-CAM5) के सतह परत पैरामीट्रिज़ेशन में शामिल और मूल्यांकन किया गया है। इससे पता चलता है कि विभिन्न समानता फलनों का प्रदर्शन स्थानिक और अस्थायी रूप से निर्भर है और इन फलनों को जलवायु सिमुलेशन के लिए विवेकपूर्ण ढंग से चुना जा सकता है। यह देखा गया है कि विभिन्न सतह परत योजनाओं में स्थिर परिस्थितियों में समानता फलनों की सीमित प्रयोज्यता के कारण τ और बल्क रिचर्डसन संख्या (Ri_b) के मूल्यों पर प्रतिबंध है। इस मुद्दे को हल करने के लिए स्थिर परिस्थितियों में सतह टर्बुलेंट प्रवाह की गणना के लिए τ और Ri_b के संदर्भ में विभिन्न गैर-रेखीय समानता फलनों की प्रयोज्यता की सीमा का अनुमान लगाने के लिए एक व्यवस्थित गणितीय विश्लेषण किया गया है। गणितीय विश्लेषण संवेग (C_D) और ताप (C_H) दोनों स्थानांतरण गुणांकों के देखे गए व्यवहार में मोनोटोनिसिटी के आधार पर किया जाता है।

यह देखा गया है कि कादर और याग्लोम (1990) द्वारा प्रस्तावित तीन उप-परत मॉडल के आधार पर ϕ_m और ϕ_h , एकमात्र फलन हैं जो भारतीय भूमि पर संवहन स्थितियों के तहत अपने देखे गए गैर-मोनोटोनिक व्यवहार के अनुरूप C_D का उत्पादन करने में सक्षम हैं; हालाँकि, इन फलनों का उपयोग आमतौर पर संख्यात्मक मॉडलिंग ढाँचे में नहीं किया जाता है। पहली बार, भारतीय भूमि पर मौसम अनुसंधान और पूर्वानुमान (WRF) मॉडल की सतह परत पैरामीट्रिज़ेशन में तीन सबलेयर मॉडल को शामिल और मूल्यांकन किया गया है। इसके अलावा, स्थिर और संवहन दोनों स्थितियों के तहत सतह के प्रवाह की गणना के लिए विभिन्न समानता फलनों के प्रावधान के साथ डब्ल्यूआरएफ मॉडलिंग प्रणाली के लिए एक अद्यतन सतह परत मॉड्यूल इस थीसिस में प्रस्तावित है।

दूसरी ओर, सीमा परत (PBL) पैरामीटराइज़ेशन का उपयोग सतह परत के ऊपर टर्बुलेंट परिवहन का वर्णन करने के लिए किया जाता है और थर्मल स्तरीकरण में परिवर्तन के जवाब में दैनिक चक्र के दौरान इसकी ऊंचाई (PBLH) काफी भिन्न होती है। पीबीएल की संरचना हवा के कमजोर होने और स्थिरता की सीमा के साथ जटिल हो जाती है। इस थीसिस में भारतीय भूमि और संबंधित विभिन्न जलवायु क्षेत्रों में NCAR-

CAM5 मॉडल में दो PBL पैरामीट्रिज़ेशनो के प्रदर्शन का मूल्यांकन किया गया। इसके अलावा, भारत-केंद्रित जलवायु सिमुलेशन के लिए पीबीएल योजना के प्रदर्शन में सुधार करने के लिए, सभी स्तरीकरण स्थितियों में क्रिटिकल बल्क रिचर्डसन नंबर (Ri_{cr}) के मौजूदा एकल मूल्य को NCAR-CAM5 की पीबीएल योजना में थर्मल स्तरीकरण पर निर्भर Ri_{cr} द्वारा प्रतिस्थापित किया गया है। संशोधित योजना पीबीएलएच और भारतीय भूमि पर सतही हवा के तापमान और वर्षा सहित अन्य विचारित चर के अनुकरण में उत्साहजनक परिणाम दिखाती है।

इस थीसिस की एक अनूठी विशेषता यह है कि इसमें संख्यात्मक मॉडलिंग, गणितीय विश्लेषण के साथ-साथ डेटा विश्लेषण के पहलुओं को भी शामिल किया गया है। संशोधन NCAR-CAM5 के साथ-साथ WRF मॉडल की मौजूदा सतह और सीमा परत पैरामीट्रिज़ेशनो में किए गए हैं। पहली बार, बेहतर सिमुलेशन के लिए NCAR-CAM5 मॉडल की PBL योजना में थर्मल स्तरीकरण पर निर्भर Ri_{cr} को लागू और मूल्यांकन किया गया है। इस थीसिस में जिन योजनाओं को संशोधित किया गया है, उनका मूल्यांकन भारत मौसम विज्ञान विभाग (IMD) के अवलोकन संबंधी डेटासेट, ERA-Interim, ERA5 और ERA5-Land सहित पुनर्विश्लेषण डेटासेट और दो अलग-अलग साइटों: (i) रांची (भारत), और (ii) CASES-99 से टर्बुलेंस माप के आधार पर किया गया है। WRF मॉडलिंग प्रणाली के लिए प्रस्तावित अद्यतन सतह परत मॉड्यूल समुदाय के लिए इसकी संभावित प्रयोज्यता को बढ़ा सकता है।

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List of Acronyms

ASL	Atmospheric Surface Layer
ABL	Atmospheric Boundary Layer
BATS	Biosphere-Atmosphere Transfer Scheme
BD	Businger-Dyer
CASES-99	Cooperative Atmosphere Surface Exchange Study-1999
CAM	Community Atmosphere Model
CC	Correlation Coefficient
CCM	Community Climate Model
CCSM	Community Climate System Model
C_D	Transfer Coefficient for Momentum
C_H	Transfer Coefficient for Heat
CESM	Community Earth System Model
CL	Convective Layer
CLDTOT	Total Cloud Fraction
CLM	Community Land Model
CLUBB	Cloud Layers Unified by Binormals
CMIP5	Coupled Model Intercomparison Project Phase 5
DCS	Dynamic Convective Sublayer
DCS-FCS	Dynamic Convective-Free Convective Transition
DJF	December January February
DNS	Dynamic Sublayer
DNS-DCS	Dynamic-Dynamic Convective Transition
FCS	Free Convective Sublayer
GCM	General Circulation Model
GPCP	Global Precipitation Climatology Project
HB	Holtzlag and Boville PBL scheme
IAP94	Institute of Atmospheric Physics, Chinese Academy of Sciences land model
ICCM	India-Centric Climate Model
IOA	Index of Agreement

IMD	India Meteorological Department
JJA	June July August
LHF	Latent Heat Flux
LLJs	Low-level Jets
LU/LC	Land Use and Land Cover
MAM	March April May
MAE	Mean Absolute Error
MB	Mean Bias
MM5	Fifth generation Pennsylvania State University-National Center for Atmospheric Research Mesoscale Model
MODIS	Moderate Resolution Imaging Spectroradiometer
MOST	Monin-Obukhov Similarity Theory
MPI	Model Performance Index
MSE	Mean Square Error
NCAR-CAM5	National Centre for Atmospheric Research Community Atmosphere Model version 5
NCAR-LSM	National Centre for Atmospheric Research Land Surface Model
NOAA	National Oceanic and Atmospheric Administration
NWP	Numerical Weather Prediction
PBL	Planetary Boundary Layer
PBLH	Planetary Boundary Layer Height
PC	Pattern Correlation
PRECT	Total Precipitation
Q1000	Specific Humidity at 1000 hPa
RegCM	Regional Climate Model
RMSE	Root Mean Square Error
SBL	Stable Boundary Layer
SHEBA	Surface Heat Budget of the Arctic Ocean
SHF	Sensible Heat Flux
SON	September October November
SST	Sea Surface Temperature
TKE	Turbulent Kinetic Energy
TRMM	Tropical Rainfall Measuring Mission

T_s	Surface Temperature
T_{2m}	2-m Temperature
U₁₀	10-m Wind Speed
UBL	Unstable Boundary Layer
UW	University of Washington Moist Turbulence Scheme
WRF	Weather Research and Forecasting Model
YSU	Yonsei University PBL Scheme