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

Prabhakar Namdev

(2017ASZ8468)

CENTRE FOR ATMOSPHERIC SCIENCES

INDIAN INSTITUTE OF TECHNOLOGY DELHI

November 2024

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.