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Role of land surface parameterizations on modeling cold-pooling events and low-level jets

Thara V. Prabha [a,b,]*, Gerrit Hoogenboom [a,c], Tatiana G. Smirnova [d,e]

[a] Department of Biological and Agricultural Engineering, The University of Georgia, Griffin, GA 30223-1797, USA
[b] Indian Institute of Tropical Meteorology (IITM), Dr. Homi Bhabha Road, Pashan, Pune-8, India
[c] AgWeatherNet, Washington State University, Prosser, WA 99350, USA
[d] NOAA Earth System Research Laboratory, Global Systems Division, Boulder, CO, USA
[e] Cooperative Institute for Research in Environmental Sciences (CIRES), Boulder, CO, USA

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ABSTRACT

Land surface parameterization schemes play a significant role in the accuracy of meso-local scale numerical models by accounting for the exchange of energy and water between the soil and the atmosphere. The role of land surface processes during large-scale cold-pooling events was studied with two land surface schemes (LSMs) in the Advanced Research Weather Forecasting model (ARW). Model evaluation was complex due to the surface and boundary layer interactions at different temporal and spatial scales as revealed by a scale dependent variance analysis. Wavelet analysis was used for the first time to analyze the model errors with specific focus on land surface processes. The ARW model was also evaluated for the formation of a low-level jet (LLJ). It is shown that vertical resolution in the model boundary layer played a significant role in determining the characteristics of LLJ, which influenced the lower boundary layer structure and moisture distribution. The results showed that the simulated low-level jet over southern Georgia was sensitive to the land surface parameterization and led to a significant difference in the boundary layer exchange. The jet shear played a crucial role in the maintenance of turbulence and weak shear caused excessive radiative cooling leading to unrealistic cold pools in the model. The results are important for regional downscaling as the excessive cold pools that are simulated in the model can go unnoticed.

1. Introduction

Land surface processes play an important role in the accuracy of near surface temperature, moisture and wind fields by partitioning the energy and water exchange at the surface. Land surface models (LSMs) are used to derive the boundary conditions (Bhumralkar, 1975; Deardorff, 1978; McCumber and Pielke, 1981; Pan and Mahrt, 1987) for temperature and moisture at the surface boundary. The surface temperature and moisture are further used in the surface layer model to estimate surface fluxes using the exchange coefficients of momentum, heat and water vapor provided by the surface layer scheme. The surface fluxes couple the boundary layer in the exchange of momentum, heat and mass with the surface. Other physical parameterizations such as cloud and radiation influence the available energy and turbulent fluxes and, thus, alter the energy balance (Ek et al., 2003) at the surface.

High-resolution numerical modeling is becoming more practical for many environmental applications such as air quality and agricultural decision-making such as frost prediction (Prabha and Hoogenboom, 2008), severe weather prediction, downscaling of regional climate, etc. Model physics inter-comparisons and verification studies provide valuable insights into the representation of physical processes in the models and isolate problems that adversely affect the forecast outcome

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* Corresponding author. Indian Institute of Tropical Meteorology (IITM), Dr. Homi Bhabha Road, Pashan, Pune-8, India.
E-mail address: prabha.thara@gmail.com (T.V. Prabha).

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(Cuxart et al., 2006). In this respect, observations that have not been incorporated in the reanalysis data such as those available from the Georgia Automated Environmental Monitoring Network (AEMN; www.Georgiaweather.net) are invaluable. Cold pools over Georgia are sometimes observed in association with cold air damming (CAD) along the Appalachian Mountains (Bell and Bosart, 1988), conditions where cloudiness, evaporative cooling of falling precipitation and radiative cooling may be important in their formation. Typically a 'U' shaped pressure ridge extends over to central Georgia in association with the cold dome (Bell and Bosart, 1988). A low-level jet is also associated with CAD events which sustain the cold pool by cold air advection to the region. Another type of cold pool can form due to radiative cooling under extended periods of high pressure conditions with clear skies. These events sometimes result in surface freezing conditions over a large area that is a few hundred × hundred kilometers wide and are of high significance for frost prediction in the region. The main goal of this study was to investigate the role of land surface parameterization of the ARW model during a cold-pooling event and to evaluate the formation of a low-level jet associated with the cold pools.

The presence of nocturnal low-level jets (LLJs) with super geostrophic winds contributes to regional horizontal transport and down mixing as flow acceleration happens above the temperature inversion. However, the representation of LLJs and their formation and maintenance are closely related to land surface heterogeneities and associated processes (Wu and Raman, 1998; Zhong et al., 2007), keeping in mind that there are several other physical and dynamical mechanisms responsible for the formation of LLJs such as inertial oscillation winds, baroclinically induced flows, etc (Baas et al., 2009) . Observational studies (Smedman et al., 1993, 1995,; Banta et al., 2002, 2003) have emphasized the fact that LLJs often contribute to enhancement of vertical mixing and represent upside down boundary layers, where turbulence is generated just below the jet axis. However, during the decay of the jet, turbulence is often intermittent and non-stationary and models often fail under such situations (Bosveld et al., 2008). The turbulence might also get detached from the surface and the boundary layer might be too thin, sometimes so thin that it is not resolved in the numerical model. In such situations where the surface atmosphere exchange is cut off due to the weak wind stable conditions, surface fluxes are based on a poor approximation (Mahrt, 2008) as the non-stationary weak turbulence is not represented well by the Monin Obukhov similarity theory (Sorbjan, 2006). The influence of surface emissivity and longwave radiative cooling takes predominance, which leads to cooler surface layers and cold biases (Edwards 2009; Steeneveld et al., 2010). The main objective of this study was to investigate similar problems during the cold-pooling events over Georgia, focusing on the model surface layer parameters and their error analysis and relationship with the characteristics of a low-level jet.

2. Materials and methods

2.1. WRF model configuration

The ARW V2.2 model has three options for the land surface parameterization, namely Noah, RUC LSMs with moisture, and the Slab model without moisture. In this study, the Noah and RUC land surface models were used for a 30-day period during the month of December 2006 over the state of Georgia. The Slab model was not used in this study. All physical parameterizations (boundary layer, surface layer, radiation, cloud microphycics, etc.), except for LSM numerical options, were kept the same for both simulations. The Yonsei University (YSU) Planetary Boundary Layer (PBL) scheme is a non-local scheme that accounts for the counter gradient fluxes and is the next generation Medium Range Forecast Model (MRF) PBL (Hong and Pan 1996) scheme. The WSM3 microphysics, Kain Fritsch cumulus parameterization, Rapid Radiative Transfer Model (RRTM) for longwave, and Mesoscale Model 5 (MM5) shortwave parameterizations were set the same for the two runs of the Noah and RUC land surface models that were made in this study. The details of these physics options in WRF are described in the technical manual (see http://www.mmm.ucar.edu/wrf/users/docs/arw_v2.pdf). Two sets of simulations are thus conducted with the two land surface schemes. The boundary and initial conditions for both the runs are kept the same. Both LSM cases were initialized with North American Regional Reanalysis (NARR) data on December 1 at 000 UTC. NARR data are available at a 32-km spatial resolution. Model runs were carried out with two, two-way interactive nested domains with spatial resolutions at 9 km and 3 km for continuous 30 days. There are 184 × 226 grid points in the horizontal. Forty vertical pressure levels were considered with finer resolution in the boundary layer. There are 15 vertical levels below 1.6 km and the lowest level is at approximately 7 m above the surface. Two coarse resolution simulations with 11 vertical levels below 1.6 km were also conducted to check the sensitivity of boundary layer characteristics to vertical resolution of the model for both LSMs. The outer domain incorporated Georgia and parts of all neighboring states while the inner 3-km domain was mainly over Georgia only. The boundary of the outer domain was updated with NARR data every 3 h. The sea surface temperature was also updated accordingly at the same interval. The topography of domain 2 is presented in Fig. 1. The small valleys in the region east and southeast of the Appalachian Mountains were resolved in the 3-km resolution.

A comparison of the two land surface models used in this study is shown in Table 1. The Noah LSM (Chen and Dudhia, 2001a,b; Ek et al., 2003; Tewari et al., 2005) is derived from the Oregon State University land surface model (Chen et al., 1996; Chen and Dudhia, 2001a). The Noah LSM has four layers of soil temperature and moisture. Another land surface developed by Smirnova et al. (1997) and implemented in WRF is from the Rapid Update Cycle (RUC) model and has undergone significant testing and verification (Smirnova et al., 2000) in the RUC framework. The RUC LSM has six layers. However, there was a need for verification against Noah in the WRF model framework. A modified version of RUC LSM was used in the present study. Modifications were made for the drag coefficient, which was derived from the surface layer scheme. In addition, the vegetation transpiration parameter was modified to have a reduced effect than was present in the ARWV 2.2 and these changes were later made available with more recent versions of ARW.