Simulation Characteristics of Planetary Boundary Layer Parameterization Schemes over Xinjiang in Summer: A Postprint

Authors: Zhang Hailiang, Li Huoqing, Memeteli Memetimin, Memeteli Memetimin

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Abstract

Planetary Boundary Layer (PBL) parameterization schemes exert significant influence on the simulation and forecasting of weather, climate, and atmospheric environment. Through idealized single-point experiments in Urumqi based on a Single-Column Model (SCM), together with simulation verification and diagnostic analysis of a precipitation event in Xinjiang from August 15–18, 2019, this study investigates the response characteristics of meteorological elements such as atmospheric specific humidity and potential temperature simulated by six commonly used PBL parameterization schemes—YSU, ACM2, BOULAC, GBM, MYJ, and QNSE—to soil moisture variations. The results demonstrate that when soil moisture increases, the lower atmosphere simulated by different PBL parameterization schemes all exhibit significant features of increased specific humidity, decreased potential temperature, and reduced boundary layer height. In GBM and ACM2, the vertical water vapor transport efficiency is relatively low, resulting in lower atmospheric specific humidity, higher potential temperature, a larger turbulent eddy action range, and a tendency for precipitation under-forecasting. In QNSE and MYJ, the vertical water vapor transport efficiency is relatively high, leading to higher atmospheric specific humidity, lower potential temperature, a smaller turbulent eddy action range, and a tendency for precipitation over-forecasting. QNSE and MYJ simulate the maximum 2 m specific humidity; ACM2 simulates the minimum 2 m specific humidity; QNSE simulates the lowest 2 m temperature at night; MYJ simulates the highest 2 m temperature during daytime; QNSE and MYJ simulate the highest 10 m wind speed. These simulation characteristics are closely related to differences in vertical water vapor transport efficiency among the PBL schemes.

Full Text

Simulation Characteristics of Planetary Boundary Layer Parameterization Schemes in Xinjiang During Summer

ZHANG Hailiang, LI Huoqing, Ali Mamtimin
Institute of Desert Meteorology, China Meteorological Administration, Urumqi 830002, Xinjiang, China

Abstract

Planetary boundary layer (PBL) parameterization schemes have significant impacts on the simulation and prediction of weather, climate, and atmospheric environment. Based on idealized single-column model (SCM) experiments at Urumqi and simulation verification and diagnostic analysis of a precipitation event from August 15–18, 2019 in Xinjiang, this study investigates the response characteristics of atmospheric specific humidity and potential temperature to soil moisture changes under six PBL parameterization schemes: YSU, ACM2, BOULAC, GBM, MYJ, and QNSE. The results show that when soil moisture increases, the simulated atmospheric boundary layer under different PBL schemes exhibits significant characteristics of increasing specific humidity, decreasing potential temperature, and decreasing boundary layer height in the lower atmosphere. In GBM and ACM2 schemes, the vertical water vapor transport efficiency is low, atmospheric specific humidity is relatively low, potential temperature is high, eddy action range is large, and precipitation is under-forecast. In QNSE and MYJ schemes, the vertical water vapor transport efficiency is high, atmospheric specific humidity is high, potential temperature is low, eddy action range is small, and precipitation is over-forecast. The maximum 2 m specific humidity is achieved with QNSE and MYJ schemes; the highest 2 m temperature is with MYJ scheme; the minimum 2 m specific humidity is with ACM2 scheme; the lowest nighttime 2 m temperature is with QNSE scheme; and the highest daytime 10 m wind speed is with QNSE and MYJ schemes. These simulation characteristics are closely related to differences in vertical water vapor transport efficiency among different PBL parameterization schemes.

Keywords: WRF model; single-column model; planetary boundary layer parameterization; soil moisture

Introduction

The Weather Research and Forecasting (WRF) model, developed by the National Center for Atmospheric Research (NCAR), is a new-generation mesoscale regional numerical weather prediction system that integrates comprehensive physical process parameterization schemes and has been widely applied globally. PBL parameterization schemes significantly impact weather and climate simulations and forecasts by calculating subgrid-scale exchanges of heat, momentum, energy dissipation, and water vapor transport between the underlying surface and the atmosphere, thereby revising the WRF dynamical framework calculations. Cumulus convection parameterization schemes are also crucial for WRF simulations, closely related to water vapor condensation heating and mesoscale structural characteristics of thunderstorms. This study focuses specifically on the simulation characteristics of PBL parameterization schemes.

A variety of PBL parameterization schemes exist. Based on the closure forms of the atmospheric Reynolds-averaged equations, they can be classified as first-order closure, 1.5-order closure, or higher-order schemes. The closure equations employed include both momentum-form and spectral-form atmospheric equations. How to select appropriate boundary layer parameterization schemes to improve the forecasting skill of regional numerical models like WRF? Numerous studies have addressed this question. Banks et al. compared YSU and MYJ parameterization schemes in Athens simulations. Huang et al. compared five boundary layer schemes for simulating thermal and dynamic structures over northern US forest regions. Shin et al. evaluated seven boundary layer parameterization schemes based on the CASES-99 experiment using a single-column model (SCM). Cheng et al. investigated the role of boundary layer schemes in meteorological and air quality simulations over the Taiwan area. Xie et al. evaluated nonlocal and local boundary layer parameterization schemes in the WRF model. Zhang et al. assessed four PBL schemes in the WRF model over complex topographic areas. Wang et al. verified WRF model simulation capabilities for boundary layers in valley cities. Chen et al. evaluated the sensitivity of WRF model simulations in the Tianshan Mountains region. These studies provide valuable guidance for the application of PBL parameterization schemes, highlighting that different schemes exhibit distinct applicability characteristics across various regions.

As research progresses, increasing attention has been paid to understanding why different PBL parameterization schemes produce varying simulation results across different regions. To reveal the causes of these differences, Huang et al. conducted studies from dynamic and thermal perspectives. However, research focusing on the water vapor vertical transport simulation characteristics of PBL parameterization schemes remains relatively scarce. Water vapor content significantly influences atmospheric temperature and humidity characteristics as well as local secondary circulations, making it crucial for understanding differences in simulation characteristics among various PBL schemes. Meanwhile, due to Xinjiang' s critical geographical location in Central Asia, research on PBL parameterization scheme simulation characteristics specifically for the Xinjiang region is also limited.

Based on this, to reveal the causes of humidity differences among different PBL parameterization schemes in Xinjiang and to compare systematic biases in their simulation results over the region, this study employs a single-column model to investigate the response characteristics of atmospheric specific humidity and potential temperature to soil moisture under six PBL parameterization schemes: YSU, ACM2, BOULAC, GBM, MYJ, and QNSE. Through three-dimensional simulation verification and diagnostic analysis of a heavy precipitation event from August 15-18, 2019 in Xinjiang, we obtain verification characteristics and systematic bias features of forecast results for upper-air and surface meteorological elements, providing a scientific basis for the application of PBL parameterization schemes in the Xinjiang region.

1.1 Research Methods

The study employs doubly periodic lateral boundary conditions to run the single-column model. To decouple interference from other physical processes, only radiation, land surface, PBL, and surface layer parameterization schemes are activated. The potential temperature is configured to be higher in the upper layers and lower in the lower layers to maintain a stable atmospheric stratification. The single-column model is forced by varying soil volumetric water content to investigate the response characteristics of simulated atmospheric specific humidity and potential temperature to soil moisture changes under different PBL parameterization schemes. The experimental parameters are listed in Table 1.

The simulation characteristics of PBL parameterization schemes require verification against real weather cases for comprehensive application assessment. This study uses the WRF model with six PBL parameterization schemes to simulate and analyze a heavy precipitation event from August 15-18, 2019 in Xinjiang. Simulation results are verified using observational data from 14 sounding stations and 105 national surface meteorological stations in Xinjiang. The analysis yields forecast performance characteristics and systematic bias features of the six PBL parameterization schemes during summer in Xinjiang, which are closely related to the water vapor vertical transport capacity of each scheme. Verification metrics include mean bias (BIAS) and root mean square error (RMSE).

The simulation domain employs a two-way nested configuration (Fig. 1), with the outer domain covering Central Asia at a grid resolution of 9 km $\times$ 9 km, and the inner domain focusing on Xinjiang at a finer resolution of 3 km $\times$ 3 km.

1.2 Data Sources

Upper-air wind speed, temperature, and geopotential height data used in this study are obtained from 14 sounding stations and 105 national surface meteorological stations provided by the Xinjiang Meteorological Bureau. The background field data for the model are sourced from the NCEP Global Forecast System (GFS) gridded data at 0.25° $\times$ 0.25° resolution.

Results and Analysis

In real weather process simulations, complex nonlinear interactions exist between turbulent and diffusive processes in the atmospheric boundary layer and other physical processes. To decouple these interactions, single-column model simulations are commonly employed to conduct sensitivity experiments for physical parameterization scheme verification.

2.1 Response Characteristics of Atmospheric Specific Humidity and Potential Temperature to Soil Moisture

When soil moisture increases, the strong turbulent mixing within the summer convective boundary layer enables soil moisture to rapidly influence the atmospheric boundary layer. Table 1 reveals the characteristics of atmospheric specific humidity response to soil moisture changes under different boundary layer parameterization schemes: when atmospheric water vapor content is unsaturated, soil volumetric water content exhibits a nonlinear positive correlation with lower-atmosphere specific humidity—the higher the soil volumetric water content, the greater the lower-atmosphere specific humidity, while upper-atmosphere specific humidity remains essentially unchanged. Figure 2 illustrates the response characteristics of atmospheric potential temperature to soil moisture changes under different boundary layer parameterization schemes: when atmospheric water vapor content is unsaturated, soil volumetric water content shows a nonlinear inverse relationship with lower-atmosphere potential temperature—the higher the soil volumetric water content, the lower the lower-atmosphere potential temperature, while upper-atmosphere potential temperature remains essentially constant. Combined analysis of Figs. 2 and 3 indicates that when atmospheric water vapor content is unsaturated and soil moisture continuously increases, the lower atmosphere exhibits significant characteristics of continuously increasing humidity, decreasing potential temperature, and decreasing eddy action height. This is primarily because, under the forcing of a moist underlying surface, increased soil moisture leads to higher boundary layer atmospheric humidity. The vaporization of liquid water absorbs substantial latent heat, causing continuous decrease in lower-atmosphere potential temperature, reducing the buoyancy component of boundary layer turbulent kinetic energy, shrinking the eddy action region, and lowering the action height.

The response magnitude of lower-atmosphere potential temperature and specific humidity to soil moisture varies when using different PBL parameterization schemes. Simulation results from the GBM scheme show that it produces the lowest lower-atmosphere specific humidity, highest atmospheric potential temperature, largest eddy action region, and highest eddy action height, with minimal soil moisture impact on atmospheric specific humidity, thus indicating the lowest vertical water vapor transport efficiency. The ACM2 scheme yields relatively low lower-atmosphere specific humidity, relatively low potential temperature, a relatively small eddy action region, and relatively low eddy action height, with greater soil moisture influence on atmospheric specific humidity, thus demonstrating higher vertical water vapor transport efficiency. In QNSE and MYJ schemes, soil moisture impacts on the atmosphere are similar to the BOULAC scheme, with vertical water vapor transport efficiency falling between that of GBM and ACM2 (Figs. 2 and 3).

2.2.1 Upper-Air Meteorological Element Forecast Performance Characteristics

Observational data from 14 sounding stations in Xinjiang during 00:00–12:00 UTC are selected for comparison with simulation results. The simulated atmosphere below 700 hPa is drier than observations. QNSE and MYJ produce the highest specific humidity, followed by BOULAC, while GBM and ACM2 yield the lowest specific humidity, with MYJ values falling between these groups. The synoptic case simulation results are basically consistent with single-column model simulations (Fig. 4). No significant patterns are observed in wind speed variations across pressure levels (Fig. 4). The simulated 500 hPa geopotential height is lower than other schemes. The 700–850 hPa layer shows the lowest geopotential height; at 500 hPa, simulated geopotential height is relatively high, while at 700–850 hPa it is relatively low. In summary: QNSE and MYJ exhibit the highest upward vertical water vapor transport efficiency, resulting in maximum specific humidity below 700 hPa and minimum potential temperature at 500 hPa. GBM and ACM2 show the lowest upward vertical water vapor transport efficiency, leading to negative specific humidity bias below 700 hPa, maximum potential temperature at 500 hPa, and highest geopotential height at 500 hPa. These results are essentially consistent with single-column model simulations.

2.2.2 Surface Meteorological Element Forecast Performance Characteristics

Simulation results are verified against surface observations from 105 national meteorological stations in Xinjiang. Simulated 2 m specific humidity shows negative bias, indicating drier conditions than observed. QNSE and MYJ produce the maximum specific humidity and lowest nighttime 2 m temperature, while ACM2 yields the minimum specific humidity and higher nighttime 2 m temperature. Simulated 2 m temperature is generally positively biased, suggesting overestimation compared to observations. At night, QNSE shows the lowest temperature with minimum root mean square error (RMSE), while MYJ shows higher temperature with larger RMSE. During daytime, MYJ produces the highest temperature, which may be related to its temperature calculation method. Simulated 10 m wind speed exhibits positive bias, indicating overestimation of surface wind speed. QNSE and MYJ produce the highest wind speeds with larger RMSE, while GBM and ACM2 yield lower wind speeds with smaller RMSE. In summary, QNSE and MYJ schemes with higher vertical water vapor transport efficiency produce maximum 2 m specific humidity, lowest nighttime 2 m temperature, and highest 10 m wind speed. GBM and ACM2 schemes with lower vertical water vapor transport efficiency produce minimum 2 m specific humidity, higher nighttime 2 m temperature, and lower 10 m wind speed with smaller RMSE. During daytime, MYJ produces the highest temperature, consistent with single-column ideal experiment results.

2.2.3 Precipitation Forecast Performance Characteristics

Observational data of 24-hour accumulated precipitation in Xinjiang are used to verify simulation results. For each simulation time, the numbers of precipitation forecast hits, misses, false alarms, and missed events for different magnitude categories are accumulated, and Threat Score (TS) and precipitation bias (BIAS) are calculated for different 24-hour precipitation magnitudes. For the rain/no-rain forecast threshold of $ $0.01 mm, QNSE and MYJ produce the highest BIAS scores, indicating over-forecasting tendency, while GBM and ACM2 yield the lowest BIAS scores, showing under-forecasting tendency. For precipitation magnitudes $ $12.1 mm, QNSE and MYJ achieve the highest TS scores, related to their high vertical water vapor transport efficiency that can deliver more moisture to the atmosphere and produce maximum 2 m specific humidity. GBM and ACM2 with lower vertical water vapor transport efficiency produce smaller 2 m specific humidity and lower precipitation forecast BIAS scores, reflecting relatively less atmospheric water vapor content in their simulations. Significant differences exist in precipitation TS scores among various PBL schemes (Fig. 6). As shown, QNSE and MYJ produce higher precipitation TS scores across different precipitation levels, particularly for magnitudes $ $12.1 mm, where they achieve the highest TS scores, attributable to their high vertical water vapor transport efficiency. In summary: QNSE and MYJ simulations with higher water vapor vertical transport efficiency produce the highest precipitation forecast BIAS scores with over-forecasting tendency, while GBM and ACM2 simulations with lower water vapor vertical transport efficiency yield the lowest precipitation forecast BIAS scores with under-forecasting tendency.

2.3 Systematic Bias Characteristics of PBL Parameterization Scheme Simulations

The water vapor bias in GFS background fields from the National Centers for Environmental Prediction (NCEP) is uncertain (either dry or wet). The new GFS background field used in this study shows dry bias in lower-level water vapor, warm bias in potential temperature, and under-forecasting bias in precipitation compared to observations. Based on the revealed differences in vertical water vapor transport capacity among different PBL parameterization schemes, for dry background fields in the Xinjiang region, PBL schemes with higher vertical water vapor transport efficiency such as QNSE and MYJ should be used to enhance water vapor transport from the land surface to the atmosphere. For wet background fields, PBL schemes with lower vertical water vapor transport efficiency such as GBM and ACM2 should be employed to reduce water vapor transport from the land surface to the atmosphere.

Systematic biases exist in 2 m specific humidity simulated by different PBL schemes (Fig. 7), with QNSE and MYJ producing the maximum 2 m specific humidity and ACM2 producing the minimum. Systematic biases are also observed in 2 m temperature (Fig. 7); at night, QNSE yields the lowest 2 m temperature while differences among other schemes are not significant. Systematic biases in 10 m wind speed are present as well (Fig. 7), with QNSE and MYJ producing the highest 10 m wind speeds and GBM and ACM2 producing the lowest. These systematic biases are closely related to differences in vertical water vapor transport efficiency among different boundary layer parameterization schemes.

2.4 Application of PBL Parameterization Scheme Simulation Characteristics

Based on the revealed differences in vertical water vapor transport capacity among different PBL parameterization schemes, for dry background fields in the Xinjiang region, PBL schemes with higher vertical water vapor transport efficiency such as QNSE and MYJ should be used to enhance water vapor transport from the land surface to the atmosphere. For wet background fields, PBL schemes with lower vertical water vapor transport efficiency such as GBM and ACM2 should be employed to reduce water vapor transport from the land surface to the atmosphere.

Conclusions

1. When soil moisture increases, the atmospheric boundary layer simulated by different PBL parameterization schemes exhibits significant characteristics of increasing specific humidity, decreasing potential temperature, and decreasing boundary layer height. However, vertical water vapor transport efficiency differs among PBL schemes. GBM and ACM2 schemes with lower vertical water vapor transport efficiency simulate lower specific humidity, higher potential temperature, and higher boundary layer height in the lower atmosphere, with precipitation forecasts tending toward under-forecasting. QNSE and MYJ schemes with higher vertical water vapor transport efficiency simulate higher specific humidity, lower potential temperature, and lower boundary layer height, with precipitation forecasts tending toward over-forecasting.
2. QNSE and MYJ schemes produce the maximum 2 m specific humidity. QNSE yields the lowest nighttime 2 m temperature, while MYJ produces the highest daytime 2 m temperature. QNSE and MYJ schemes generate the highest 10 m wind speeds. These systematic biases are closely related to differences in vertical water vapor transport efficiency among different boundary layer parameterization schemes.
3. In the Xinjiang region, for dry background fields, PBL parameterization schemes with higher vertical water vapor transport efficiency such as QNSE and MYJ should be used to enhance water vapor transport from the land surface to the atmosphere. For wet background fields, PBL schemes with lower vertical water vapor transport efficiency such as GBM and ACM2 should be employed to reduce water vapor transport from the land surface to the atmosphere.

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Note: Figure translations are in progress. See original paper for figures.