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

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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 Urumqi single-point idealized experiments based on the Single-Column Model (SCM) and simulation verification and diagnostic analysis of a precipitation event in Xinjiang from August 15–18, 2019, this study investigates the 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) in response to soil moisture variations. The results indicate that when soil moisture increases, the lower atmosphere simulated by different PBL parameterization schemes all exhibit significant characteristics 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, atmospheric specific humidity is lower, potential temperature is higher, the turbulent eddy range is larger, and precipitation is biased toward missed forecasts. In QNSE and MYJ, the vertical water vapor transport efficiency is relatively high, atmospheric specific humidity is higher, potential temperature is lower, the turbulent eddy range is smaller, and precipitation is biased toward false alarms. 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

Preamble

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

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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. This study employs idealized single-column model (SCM) experiments at Urumqi and three-dimensional WRF simulations of a heavy precipitation event from 15–18 August 2019 in Xinjiang to investigate 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. Results demonstrate that as soil moisture increases, all schemes simulate notable increases in specific humidity, decreases in potential temperature, and reductions in boundary layer height. However, substantial differences emerge among the schemes. The GBM and ACM2 schemes exhibit low vertical water vapor transport efficiency, yielding lower atmospheric specific humidity, higher potential temperature, larger eddy action ranges, and precipitation underprediction. In contrast, the QNSE and MYJ schemes show high vertical water vapor transport efficiency, producing higher specific humidity, lower potential temperature, smaller eddy action ranges, and precipitation overprediction. The QNSE and MYJ schemes generate the maximum 2 m specific humidity, while ACM2 produces the minimum. The MYJ scheme yields the highest daytime temperature, whereas QNSE produces the lowest nighttime temperature. The QNSE and MYJ schemes also produce the highest 10 m wind speeds. These simulation characteristics are closely related to differences in vertical water vapor transport efficiency among the PBL parameterization schemes.

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

1.1 Research Methods

Idealized single-column model (SCM) experiments with double-periodic lateral boundary conditions were conducted to isolate the effects of PBL parameterizations. Only radiation, land surface, PBL, and surface layer schemes were activated, with potential temperature initialized to decrease with height to maintain atmospheric stability. The SCM was forced by varying soil volumetric water content to investigate how atmospheric specific humidity and potential temperature respond to soil moisture changes under different PBL schemes. The experimental configuration is detailed in Table 1 .

To comprehensively evaluate the simulation characteristics of PBL parameterizations, a real weather case study was necessary. The Weather Research and Forecasting (WRF) model was employed to simulate a heavy precipitation event in Xinjiang from 15-18 August 2019. Six PBL parameterization schemes were tested: YSU, ACM2, BOULAC, GBM, MYJ, and QNSE. Simulation results were verified against observations from 14 sounding stations and 105 national surface meteorological stations across Xinjiang. Verification metrics included mean bias (BIAS) and root mean square error (RMSE). Due to the influence of atmospheric advection and coupling with other physical parameterizations in real weather simulations, the characteristic trends of PBL schemes may not be as pronounced as in idealized experiments.

The simulation employed a two-way nested domain configuration (Figure 1 [Figure 1: see original paper]), with the outer domain covering Central Asia at 9 km horizontal resolution and the inner domain focused on Xinjiang at 3 km resolution. The model utilized 51 vertical levels, with background fields derived from the NCEP Global Forecast System (GFS) 0.25°$×$0.25° grid data.

1.2 Data Sources

Upper-air wind speed, temperature, and geopotential height observations were obtained from 14 sounding stations in Xinjiang. Surface meteorological data were collected from 105 national surface weather stations. The model background fields were derived from NCEP GFS gridded data at 0.25°$×$0.25° resolution.

2 Results and Analysis

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

Using the SCM with only PBL parameterizations activated and other physical schemes deactivated, the response of atmospheric conditions to soil moisture changes was investigated. During summer, strong turbulent mixing in the convective boundary layer allows soil moisture to rapidly influence atmospheric conditions. Table 1 presents the initial parameter configurations for the idealized experiments.

When atmospheric water vapor is unsaturated, soil volumetric water content exhibits a nonlinear inverse relationship with lower-atmosphere potential temperature: higher soil moisture leads to lower potential temperature in the lower atmosphere, while upper-atmosphere potential temperature remains essentially unchanged. As shown in Figures 2 [Figure 2: see original paper] and 3 [Figure 3: see original paper], increasing soil moisture consistently produces three significant characteristics across all schemes: continuous increase in lower-atmosphere humidity, continuous decrease in potential temperature, and continuous reduction in turbulent eddy height. This occurs because increased soil moisture enhances boundary layer humidity, and liquid water vaporization absorbs substantial latent heat, reducing lower-atmosphere potential temperature and decreasing the buoyancy component of turbulent kinetic energy, which consequently shrinks the eddy action region and lowers its height.

However, the degree of response varies significantly among different PBL parameterizations. The GBM scheme simulates the lowest lower-atmosphere specific humidity, highest potential temperature, largest eddy action region, and highest eddy action height, indicating minimal soil moisture impact on atmospheric humidity and thus the lowest water vapor transport efficiency. The ACM2 scheme produces relatively low specific humidity, moderately low potential temperature, a smaller eddy region, and lower eddy height, suggesting greater soil moisture impact and higher water vapor transport efficiency than GBM. The BOULAC scheme exhibits characteristics intermediate between GBM and ACM2. The QNSE and MYJ schemes demonstrate the highest water vapor transport efficiency, producing the highest specific humidity and lowest potential temperature in the lower atmosphere.

2.2 Verification of Real Weather Process Simulation

2.2.1 Upper-Air Meteorological Element Forecast Performance Simulation results were compared against observations from 14 Xinjiang sounding stations for the period 00:00–12:00 UTC. Below 700 hPa, all simulations exhibit a dry bias compared to observations (Figure 4 [Figure 4: see original paper]). The QNSE and MYJ schemes simulate the highest specific humidity at 700 hPa, followed by MYJ, while GBM produces the lowest, with ACM2 being the second lowest. The BOULAC scheme yields values between these extremes. These results are consistent with the SCM experiments.

At 500 hPa, QNSE and MYJ simulate lower geopotential heights than other schemes, while GBM produces higher heights and ACM2 lower heights. The BOULAC scheme falls between these. Simulated wind speed variations show no significant pattern across schemes. In summary, QNSE and MYJ exhibit the highest specific humidity below 700–850 hPa and the lowest geopotential height below 500 hPa, while GBM shows the lowest specific humidity and highest geopotential height. These patterns align well with SCM results.

2.2.2 Surface Meteorological Element Forecast Performance Surface forecasts were verified against data from 105 national surface stations across Xinjiang. The QNSE and MYJ schemes produce the highest 2 m specific humidity, while ACM2 generates the lowest, with BOULAC intermediate (Figure 5 [Figure 5: see original paper]). For 2 m temperature, MYJ simulates the highest daytime temperatures, whereas QNSE produces the lowest nighttime temperatures, consistent with SCM results. The QNSE and MYJ schemes generate the highest 10 m wind speeds, while BOULAC produces the lowest. RMSE analysis indicates that schemes with higher water vapor transport efficiency (QNSE, MYJ) exhibit smaller specific humidity errors, while lower-efficiency schemes (ACM2, GBM) show larger errors. Temperature errors follow similar patterns, with QNSE showing the lowest nighttime temperature errors and MYJ the highest daytime temperature errors, consistent with their respective vertical transport characteristics.

2.2.3 Precipitation Forecast Performance Twenty-four-hour accumulated precipitation forecasts were evaluated against observations across Xinjiang. Forecast hits, misses, false alarms, and correct negatives were accumulated to calculate Threat Scores (TS) and precipitation bias (BIAS) for different precipitation thresholds. For precipitation $ $0.01 mm, QNSE and MYJ achieve the highest TS scores but exhibit positive BIAS (tendency toward false alarms), while GBM shows the lowest TS score with negative BIAS (tendency toward misses). This indicates that QNSE and MYJ, with their high water vapor transport efficiency, can transport more moisture into the atmosphere, leading to precipitation overprediction, whereas GBM' s low efficiency results in underprediction. These differences are particularly pronounced for precipitation thresholds $ $12.1 mm (Figure 6 [Figure 6: see original paper]).

2.3 Systematic Bias Characteristics of PBL Parameterization Schemes

PBL parameterization schemes exhibit systematic biases in water vapor, momentum, and heat transport. Hourly systematic biases were computed by averaging all grid points across the simulation domain. Figure 7 [Figure 7: see original paper] reveals that QNSE and MYJ produce maximum positive specific humidity bias, while ACM2 generates minimum bias. For temperature, QNSE shows the lowest nighttime temperature bias, while MYJ exhibits the highest daytime temperature bias. For wind speed, QNSE and MYJ produce the highest wind speed biases, while BOULAC produces the lowest. These systematic biases are closely related to differences in vertical water vapor transport efficiency among the PBL schemes.

2.4 Application of PBL Parameterization Scheme Simulation Characteristics

The NCEP GFS background field exhibits uncertain moisture biases (either dry or wet). In Xinjiang, the GFS background field tends to be dry in the lower troposphere with warm potential temperature biases, leading to precipitation underprediction. Based on the revealed differences in vertical water vapor transport efficiency among PBL schemes, we recommend: for dry background fields in Xinjiang, use high-efficiency schemes (QNSE, MYJ) to enhance moisture transport from the land surface to the atmosphere; for wet background fields, use low-efficiency schemes (GBM, ACM2) to reduce moisture transport.

3 Conclusions

This study reveals the following key findings:

1) As soil moisture increases, all PBL parameterization schemes simulate significant increases in boundary layer specific humidity, decreases in potential temperature, and reductions in boundary layer height. However, substantial differences exist in vertical water vapor transport efficiency. The GBM and ACM2 schemes exhibit low efficiency, resulting in lower atmospheric humidity, higher temperature, elevated boundary layer height, and precipitation underprediction. The QNSE and MYJ schemes demonstrate high efficiency, producing higher humidity, lower temperature, reduced boundary layer height, and precipitation overprediction.

2) Systematic bias characteristics vary significantly among schemes: QNSE and MYJ produce maximum specific humidity bias, while ACM2 produces minimum; QNSE yields the lowest nighttime temperature, while MYJ produces the highest daytime temperature; QNSE and MYJ generate the highest wind speeds. These biases are intimately connected to differences in vertical water vapor transport efficiency.

3) For the Xinjiang region, when using dry background fields (such as NCEP GFS), high-efficiency PBL schemes (QNSE, MYJ) should be employed to enhance land-atmosphere moisture transport. Conversely, for wet background fields, low-efficiency schemes (GBM, ACM2) are recommended to reduce moisture transport.

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