Numerical Simulation of Near-Surface Atmospheric Conditions during a Radiation Fog over the Complex Terrain

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Abstract. Numerical simulation of near-surface atmosphere during a radiation fog episode over the complex terrain is conducted. Results indicate that, the simulation of near-surface atmospheric wind, temperature, and humidity are very sensitive to land surface and boundary layer parameterization schemes. Simulation impacts of land surface and boundary layer scheme are manifested mainly in near-surface thermodynamic and dynamic quantities, respectively. The NOAH land surface scheme evidently overestimates the near-surface temperature, while underestimates the near-surface dew point and humidity during the fog formation period. The MYNN boundary layer scheme outperforms in near-surface wind simulation than other schemes. Combination of RUC land surface scheme and MYNN boundary layer scheme best simulates and reproduces the near-surface atmospheric conditions. Inter-comparison on the dynamic and thermodynamic of near-surface atmosphere among the experiments indicates that the simulation discrepancies are mainly in near-surface atmospheric stability, which could be the key factor in affecting the simulation performances. In particular, during the fog period, near-surface atmosphere is dominated by stable stratification, and the vertical velocity is relatively weak; before and after the fog period, the near-surface atmospheric stability is unstable.

Keywords. Near-surface atmosphere; WRF model; land surface and boundary layer schemes; radiation fog.

1. Introduction

Fog is a weather phenomenon in which a large number of water vapor condensates in the near-surface atmosphere (about 100 meters above the ground), leading to the horizontal visibility less than 1 km and cause severe natural hazards that are comparable to tornadoes, typhoons and other severe convective weather [1].

Since the formation, evolution and dissipation of fog is the result of complex interactions of dynamic and thermodynamic processes in the near-surface atmosphere [2], therefore, the parameterization of atmospheric boundary layer and land surface processes are the key factors that influence the fog simulation. Numerical simulation of a fog episode over the relative flat terrain showed that, the local convergence of water vapor in the lower atmosphere is important to fog formation [3]. Simulation sensitivity studies also found that different parameterization schemes have different impacts on the simulation performances of the dynamic and thermodynamic processes in the near-surface atmosphere, especially when the underlying land surface has large heterogeneity. For instance, simulation discrepancies of near-surface wind and temperature are distinct among different
boundary layer schemes [4].

Above studies have definitely suggested the respective role of land surface and boundary layer parameterizations on near-surface atmospheric conditions. However, boundary layer and land surface are coupled and interact together in nature; the variation of land surface has significant impacts on boundary layer structures, or vice versa. Therefore, basic research on the interactions between boundary layer and land surface, as well as the corresponding role and impact on the simulation of near-surface atmosphere, especially over the complex terrain, is essential to improve our understanding on the fog evolution. This study will investigate the model simulation performance during a radiation fog episode over complex terrain in northwestern China, with different configuration of land surface and boundary layer schemes. Two issues will be focused: (1) what is the simulation sensitivity of near-surface atmosphere to different configuration of land surface and boundary layer parameterizations; (2) what are the kinematic and thermodynamic structures of near-surface atmosphere during the radiation fog episode?

The next section describes the fog episode. The model, data, experiment design and methods are given in Section 3. Section 4 presents the simulation results regarding the validation of simulation results and the diagnosis of thermodynamic and kinematic structures in near-surface atmosphere. The discussion and concluding remarks will be made in Section 5.

2. Description of Fog Episode

Radiation fog is commonly occurred in mountainous regions, its evolution is directly related to thermodynamic and kinematic progresses in near-surface atmosphere. Studies [1, 5, 6] have consistently found that although numerical models could well simulate the synoptic flows, the inaccurate predictions of near-surface atmosphere are still significant and are mostly associated with the prediction performance of fog in many cases. A radiation fog event from 1830 UTC 23 Jul 2014 to 2345 UTC 23 Jul 2014, with minimum visibility around 50 m (figure 1a), happened in northwestern China (figure 1b) that is nearby the Tibetan Plateau, is selected and analyzed the model performance on near-surface atmosphere simulation in this study. According to the synoptic background analysis (not shown), the occurrence of this fog event is mainly related to the anticyclone ridge accompanied with a pocket of warm air at 700 hPa and the uniform distribution of sea level pressure at near-surface.

3. Model, Data, and Experiment Design

The WRF (ARW) model version 3.6.1 was used, with four one-way nested domains (figure 1a). The horizontal grid resolutions are 27, 9, 3, and 1 km, respectively. The terrain height of interest domain is shown in figure 1b. There are 46 vertical terrain-following levels. The physical schemes are [4] the Betts-Miller-Janjić cumulus scheme (only for “d01 and d02”); the Purdue Lin microphysics scheme; the longwave and shortwave radiation schemes are Rapid Radiative Transfer Model. The NOAH and RUC land surface models, and YSU, MYNN3rd, MYJ, and QNSE-EDMF boundary layer schemes are selected, to quantitatively the sensitivity of near-surface atmosphere simulation to different land surface and boundary layer schemes. The above physics schemes have a long history of development are widely used in weather and climate simulation over the research region [7, 8]. Five experiments are designed in this study (table 1).

The Final Analysis Data of Global Forecast System (FNL) is used as initial and boundary conditions for WRF model. The whole integration time is 42 h, the initial integration time is 1200 UTC 22 Jul 2014, the first 12 hours are regarded as the spin-up period and are not analyzed in this study. Results from 0000 UTC 23 Jul 2014 to 0600 UTC 24 Jul 2014 are focused because it is closely related to the evolution of fog.
Figure 1. The (a) configuration of the simulation domain and (b) terrain height in the innermost domain. The black dot is the observational site.

Table 1. Configuration of the numerical sensitivity simulation experiments.

| Experiment name | Land surface scheme | Boundary layer scheme |
|-----------------|---------------------|-----------------------|
| NOAH - YSU      | NOAH                | YSU                   |
| RUC - YSU       | RUC                 | YSU                   |
| RUC - MYNN      | RUC                 | MYNN 3rd              |
| RUC - MYJ       | RUC                 | MYJ                   |
| RUC - QNSE      | RUC                 | QNSE-EDMF             |

The observational datasets used in this study include the in-situ near-surface observations such as temperature, wind speed and wind direction, relative humidity, dew point, and visibility at 2 m above ground level (AGL). The conventional data that is used to do synoptic background analysis comes from China Meteorological Administration (CMA).

4. Simulation Results

4.1. Evaluation of Simulation Results among Different Experiments

Figures 2b-2d compares the simulation performance of near-surface wind speed, relative humidity and temperature against the observations, with different configurations of land surface and boundary layer schemes. Results show that, the simulations can well reflect the actual evolution process of temperature and relative humidity during the fog event, however, they tend to overestimate the observed temperature while underestimate the observed relative humidity in the whole simulation. The simulation performances are best in RUC-MYNN, followed by RUC-YSU and NOAH-YSU, the simulation performances of RUC-MYJ and RUC-QNSE are similar as RUC-MYNN (not shown). The observed wind speeds are weak but have strong volatility. Simulation results show that, NOAH-YSU and RUC-YSU obviously overestimate the near-surface wind during the attenuation of the fog, while RUC-YSU overestimates the near-surface wind before the fog.

Table 2 compares the root mean square error (RMSE) of meteorological quantities in different experiments. Results show that, the RMSE of NOAH-YSU is largest. Comparison of the simulation results among different experiments show that, simulations of wind speed are worse than that of temperature and humidity, the RMSE of wind speed in NOAH-YSU and RUC-YSU are larger than other experiments. The simulation performances of RUC-MYJ and RUC-QNSE are similar as RUC-MYNN, which have better simulation performances than NOAH-YSU and RUC-YSU.

Overall, the simulation performances are best in RUC-MYNN, followed by RUC-YSU,
NOAH-MYNN and NOAH-YSU. RUC-MYNN could well portray the evolution of relative humidity and temperature, suggesting that the near-surface atmosphere simulations during this fog episode are best with the configuration of RUC and MYNN schemes. In other words, the simulation of temperature and relative humidity in near-surface is more sensitive to land surface scheme; the simulation improvement of near-surface wind depends mainly on boundary layer scheme.

Table 2. Root mean square error (RMSE) of temperature (TC), relative humidity (RH) and wind speed (WSD) in near-surface in different experiment.

|        | RUC-YSU | NOAH-YSU | RUC-MYJ | RUC-MYNN | RUC-QNSE |
|--------|---------|-----------|---------|----------|----------|
| TC     | 3.31    | 5.30      | 2.18    | 2.22     | 2.05     |
| RH     | 12.32   | 35.46     | 6.58    | 5.11     | 3.64     |
| WSD    | 1.48    | 1.42      | 0.92    | 0.98     | 0.99     |

Figure 2. (a) The observed horizontal visibility during the fog episode. Comparison of near-surface (b) temperature, (c) relative humidity, and (d) wind speed between the simulations and the observations.

4.2. Comparison of Near-Surface Atmospheric Structures

Comparison results of figures 2b-2d and table 1 indicate that, the simulation performances are best in RUC-MYNN, followed by RUC-YSU, NOAH-MYNN and NOAH-YSU. RUC-MYNN could well portray the evolution of relative humidity and temperature, suggesting that the near-surface atmosphere simulations during this fog episode are best with the configuration of RUC land surface scheme and MYNN boundary layer scheme. In other words, the simulation performances of near-surface atmosphere are sensitive to both land surface and PBL schemes. Specifically, the simulation of near-surface temperature and relative humidity is more sensitive to land surface scheme; the simulation improvement of near-surface wind depends mainly on boundary layer scheme.

Figure 3 compares the height-latitude cross section of potential temperature and relative humidity among different experiment before, during and after the fog. Results of all experiments consistently show that, before the fog, the near-surface atmosphere is unstable, the humidity is relatively low, and distributes mainly in the upper layer. The near-surface atmosphere gradually becomes stable near and during the fog, with the largest relative humidity. After the fog, the unstable near-surface atmosphere is destroyed and becomes unstable, with evident decrease of relative humidity. The corresponding
vertical velocity also indicates that (not shown), before the fog, the vertical velocity in the near-surface atmosphere is strong, suggesting that the turbulence activity is strong. Near and during the fog, the vertical movement becomes weaker and even near calm. After the fog, the vertical movement of the near-surface atmosphere becomes stronger again. Inter-comparisons among all experiments indicate that, NOAH land surface scheme simulates lower relative humidity and stronger instability in the near-surface atmosphere; RUC-MYNN simulates more stable near-surface atmosphere, with weaker vertical velocity than RUC-YSU. The RUC-MYNN experiment could produce more humid and stable atmosphere that are conducive to the fog formation.

Figure 3. Height-latitude cross section (black line in figure 1) of relative humidity (contours, unit: %) and potential temperature (shaded, unit: K) (a), (d), (g) before, (b), (e), (h) during and (c), (f), (i) after the fog episode in (a)-(c) NOAH-YSU, (d)-(f) RUC-YSU, and (g)-(i) RUC-MYNN.

To further understand the kinematic and thermodynamic structures of near-surface atmosphere, the relative humidity and temperature at 2 m AGL, and wind vectors at 10 m AGL are compared and analyzed in figure 4. Results show that, the near-surface temperature and wind decrease near and during the fog and increase after the fog. In particular, near-surface temperature and wind are weakest during fog, the simulated northwest near-surface wind brings abundant water vapor to the research area, which produce conducive conditions for fog formation. After the fog, near-surface wind and temperature increase rapidly, leading to the rapid decrease of near-surface relative humidity, thus are conducive to the attenuation of the fog episode. Inter-comparisons among the experiments indicate that, NOAH land surface scheme simulates higher temperature, lower relative humidity, and more disordered wind vectors, compared to RUC scheme. Although the near-surface wind and temperature in RUC-YSU and RUC-MYNN are similar, however, MYNN boundary layer scheme produces larger near-surface relative humidity than YSU scheme. Therefore, RUC-MYNN produces most favorable near-surface atmospheric structures that are conducive to the fog formation, and it is likely that the better simulation of near-surface atmospheric stability could be a crucial factor that influences the near-surface atmosphere simulation, as well as the fog evolution.
5. Conclusion

Numerical simulations of a radiation fog over the complex terrain in Northwestern China are conducted. It is found that the simulations of temperature and relative humidity in near-surface are more sensitive to land surface schemes, NOAH-YSU obviously overestimates the near-surface temperature while underestimates the near-surface relative humidity. Although the simulations of near-surface wind are worse than the simulations of temperature and humidity, they could be improved by boundary layer schemes. Overall evaluation indicates that RUC land surface scheme, combined with MYNN, MYJ or QNSE scheme could achieve the best simulation results, suggesting that reasonable configuration of land surface and boundary layer schemes are important to near-surface atmosphere simulation over the complex terrain.

Further diagnosis on the near-surface structures indicate that, the near-surface atmosphere is unstable and relative dry before and after the fog while is stable and much moist during the fog. RUC and MYNN schemes produce more stable and humid near-surface atmosphere than NOAH scheme during the fog, better simulation of near-surface atmospheric stability is crucial to near-surface atmosphere simulations, thus are important for the simulation of fog evolution.

Figure 4. Near-surface relative humidity (shaded, unit: %), temperature (contours, unit: K), and wind vectors (vectors, unit: m s⁻¹) (a), (d), (g) before, (b), (e), (h) during and (c), (f), (i) after the fog episode in (a)-(c) NOAH-YSU, (d)-(f) RUC-YSU, and (g)-(i) RUC-MYNN.
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