Sensitivity of Numerical Simulations of Near-Surface Atmospheric Conditions to Snow Depth and Surface Albedo during an Ice Fog Event over Heber Valley

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(Manuscript received 7 March 2018, in final form 28 January 2019)

ABSTRACT

This study examines the sensitivity of numerical simulations of near-surface atmospheric conditions to the initial surface albedo and snow depth during an observed ice fog event in the Heber Valley of northern Utah. Numerical simulation results from the mesoscale community Weather Research and Forecasting (WRF) Model are compared with observations from the Mountain Terrain Atmospheric Modeling and Observations (MATERHORN) Program fog field program. It is found that near-surface cooling during the nighttime is significantly underestimated by the WRF Model, resulting in the failure of the model to reproduce the observed fog episode. Meanwhile, the model also overestimates the temperature during the daytime. Nevertheless, these errors could be reduced by increasing the initial surface albedo and snow depth, which act to cool the near-surface atmosphere by increasing the reflection of downward shortwave radiation and decreasing the heating effects from the soil layer. Overall results indicate the important effects of snow representation on the simulation of near-surface atmospheric conditions and highlight the need for snow measurements in the cold season for improved model physics parameterizations.

1. Introduction

Fog is a near-surface atmospheric phenomenon that has a significant influence on human activities such as transportation, aviation, and communication. The financial and human losses related to fog and low visibility are comparable to those from other weather events such as tornadoes or, in some situations, even hurricanes (Gultepe et al. 2007). Therefore, accurate fog prediction is of great importance, yet it remains a challenge, despite significant advances in numerical weather prediction (NWP; e.g., Golding 1993; Meyer and Rao 1999; Gultepe et al. 2016; Pu et al. 2016; Pu 2017). Zhou et al. (2012) evaluated the performance of low visibility/fog predictions over North America using the National Centers for Environmental Prediction (NCEP) operational forecast models. Results showed that the accuracy of visibility/fog forecasts from these models was poor in comparison to the accuracy of operational precipitation forecasts from the same models.

Previous studies with numerical models have been conducted to investigate the various factors that influence the accuracy of fog simulation and prediction. Musson-Genon (1987) indicated the importance of turbulence in fog formation and evolution. Bergot and Guedalia (1994) pointed out that the radiative balance of the surface layer is a key factor that affects the cooling rate of the surface and the likelihood of fog formation. Siebert et al. (1992) showed that surface vegetation strongly influences fog formation by changing the surface heat and moisture budget. Results from Steeneveld et al. (2015) showed that boundary layer formulation is critical for forecasting fog onset. Recent studies also found that inaccurate forecasts of near-surface atmospheric conditions are associated mostly with the failure of fog prediction in many cases (Pu et al. 2016; Chachere and Pu 2019). Despite these various factors that contribute to the inaccurate numerical prediction of fog events, different processes control the formation and evolution of various types of fog and thus make the forecast challenge for each kind of fog unique (Lin et al. 2017).
Among many types of fog events, ice fog is common and frequent in mountainous regions during the cold season. For instance, the Heber Valley in northern Utah has a frequent occurrence of ice fog (Hodges and Pu 2016). As with other types of fog, the presence of ice fog can be a hazard for ground or airborne traffic because of poor visibility and icing.

In general, ice fog forms through a complex interplay among surface radiative cooling, turbulent mixing in the surface layer, aerosol growth by deliquescence, activation of fog droplets related to the microphysical properties of crystals (Gultepe et al. 2017a,b), and mesoscale and microscale variations associated with changes in the landscape, etc. (e.g., snow cover). Because of the complexity of its formation, Gultepe et al. (2015) emphasized the difficulty of forecasting ice fog with numerical models because of limited surface in situ, ground-based remote sensing and satellite observations, and our limited understanding of ice microphysics.

Among many findings from these previous studies, surface radiative cooling, which is closely related to model performance in simulating near-surface atmospheric conditions, was noted as the main factor that determines the likelihood and timing of ice and radiation fog formation (e.g., Findlater 1985; Roach 1995; Dyknerke et al. 1999; Gultepe et al. 2007, 2016). Surface radiative cooling is closely related to the surface energy balance, which is composed of incoming and outgoing radiation and heat fluxes in the atmosphere, canopy, and soil. The complexities involved in the calculation of fluxes are substantial, especially in the case of radiation fog or ice fog. In numerical models, the parameterization of the surface energy balance is strongly related to the parameterizations of both the land surface and boundary layer. Specifically, near-surface meteorological conditions are critical in fog prediction over mountain valleys (Gultepe et al. 2014, 2016). However, numerical forecasts of near-surface atmospheric conditions (e.g., temperature and winds) are commonly erroneous (e.g., Liu et al. 2008a,b; Zhang et al. 2013; Zhang et al. 2015; Pu 2017).

To tackle the difficulties in predicting mountain weather, the Mountain Terrain Atmospheric Modeling and Observations (MATERHORN) Program was conducted in northern Utah (Fernando et al. 2015). In particular, the MATERHORN-Fog field program, which was part of the MATERHORN field program, was conducted from 7 January to 1 February 2015 (with a total of 10 intensive observing periods) over the Heber Valley to understand the ice fog process (Gultepe et al. 2016). With the observations collected during the field program, Pu et al. (2016) evaluated the performance of the mesoscale community Weather Research and Forecasting (WRF) Model (Skamarock et al. 2008) in predicting near-surface atmospheric conditions that are closely related to ice fog occurrence over mountainous regions. They found that although synoptic flows could be well portrayed by real-time forecasts using the WRF Model, the model produced significant errors in simulating near-surface atmospheric conditions, thus also failing to predict all ice fog events over the Heber Valley during the MATERHORN-Fog program. More important, these errors in the near-surface atmosphere could be strongly associated with land-cover conditions such as snow on the ground.

In light of the outstanding problems around fog prediction and their association with inaccurate near-surface atmospheric conditions as well as the previous results from the MATERHORN-Fog program, it is our purpose to examine the effects of land surface parameters, especially albedo and snow depth, on the prediction of near-surface atmospheric conditions. In this study, a series of numerical simulations are conducted to elaborate the sensitivity of numerical simulations of surface radiative cooling and near-surface atmospheric conditions, both of which are important to fog simulation, to initial land surface conditions in terms of surface albedo and snow depth. Specifically, an observed radiation ice fog event during the MATERHORN-Fog experiment is chosen as a case study. The prediction of near-surface atmospheric conditions is emphasized for comparison with observations.

Section 2 briefly describes the fog case, the configuration of the WRF Model, and observations. Section 3 describes the key process of snow in the Noah land surface scheme, which is closely related to the sensitivity study and experimental design. The sensitivity of the simulations to initial surface albedo and snow depth is detailed in section 4. A discussion and concluding remarks are made in sections 5 and 6, respectively.

2. Description of fog episode, model, and observations

An ice fog event from 0735 to 1435 UTC 16 January 2015 during the MATERHORN-Fog project is selected. According to Gultepe et al. (2016), the ice fog was caused by radiative cooling with visibility values around 100 m in the early morning, and occurred in the Heber Valley (−111.46°E, 40.53°N; Fig. 1b).

An advanced research version of the WRF (ARW) Model (Skamarock et al. 2008), version 3.8.1, is employed for numerical simulations. Four-level, one-way nested domains (Fig. 1a) are used, with horizontal grid resolutions of 64, 16, 4, and 1 km, respectively. The innermost model domain focuses on Heber City, Utah, and the vicinity. A previous study (e.g., Wilson and Fovell 2016) indicated that the decrease in the height of the lowest model level (13 m in their study) had a positive influence on the simulation in the mountainous region during the
cold season. In this study, the WRF Model includes 47 vertical levels, with 10 vertical levels below 500 m and the lowest level at about 15 m above ground level (AGL). The physical parameterization schemes include the Kain–Fritsch cumulus scheme (Kain 2004; for the “d01 and d02” domains only, while the cumulus scheme is deactivated in the “d03 and d04” domains); the WSM6 microphysics scheme (Hong and Lim 2006); the Rapid Radiative Transfer Model (RRTM; Mlawer et al. 1997) for longwave radiation; the Dudhia scheme (Dudhia 1989) for shortwave radiation; and the Noah land surface model (Chen and Dudhia 2001). The planetary boundary layer (PBL) parameterization used in this study is MYNN2.5 (Nakanishi 2001), which originated from the well-known MYJ scheme (Mellor and Yamada 1982) with additional consideration of buoyancy effects on the pressure covariances and newly proposed parameterizations for the master length scale. In addition, Nakanishi and Niino (2006) stated that the MYNN scheme predicts vertical profiles of mean quantities such as temperature that are in good agreement with those obtained from a large-eddy simulation of a radiation fog; moreover, in regional prediction, it also reasonably reproduces the satellite-observed horizontal distribution of an advection fog. According to a series of real-time forecasting and previous simulations (see details in Pu et al. 2016), the WRF Model failed to predict the observed fog events in the Heber Valley during the entire MATERHORN-Fog period, although the synoptic flows were well portrayed by the WRF Model. The inaccurate fog prediction by the WRF Model can be (at least in part) attributed to uncertainties in near-surface atmospheric conditions, regardless of the configuration of different physical parameterizations including, for example, the microphysics, radiation and boundary layer schemes used in the model (Pu et al. 2016).

Initial and boundary conditions are derived from the analyses produced by the NCEP North American Mesoscale Forecast System (NAM). A 54-h simulation is made with initial time at 1800 UTC 14 January 2015. Specifically, results from 1500 UTC 15 January to 1500 UTC 16 January 2015 are emphasized because this period corresponds well to a complete diurnal cycle and is closely related to fog development and maintenance. The time of sunset and sunrise in the Heber Valley was about 0030 and 1500 UTC 16 January 2015, respectively.

The observational datasets used in this study include conventional surface observations from Automated Surface Observing System (ASOS; namely, surface mesonet) stations, surface temperature, surface sensible heat flux (SHF), surface latent heat flux (LHF), Monin–Obukhov length $L$, upward and downward surface radiation in terms of shortwave and longwave, and the vertical profile in terms of temperature, dewpoint, relative humidity, wind speed, and wind direction obtained during the MATERHORN-Fog field program (Gultepe et al. 2016).

3. Key snow process in the Noah land surface scheme and experiment design

As stated in previous studies, surface radiative cooling is the main mechanism that determines the likelihood and timing of radiation fog formation (e.g., Findlater 1985; Roach 1995; Duynkerke et al. 1999; Gultepe et al. 2007, 2016).
Simulation errors in surface radiative cooling might be closely related to the simulation of the surface energy balance, which depends mainly on soil heat flux, surface radiation balance, SHF, and LHF in the near-surface atmosphere. During the cold season, snow physical characteristics are important to the surface energy budget, which influences both the surface albedo and soil heat flux (e.g., Ek et al. 2003; van der Velde et al. 2009; Livneh et al. 2010; Wang et al. 2010) and therefore affects SHF and LHF accordingly.

Surface shortwave albedo is the ratio of reflected shortwave irradiance to the incoming shortwave irradiance incident upon a surface (Stroeve et al. 2005). Land surface albedo is one of the key parameters in weather models since it regulates the shortwave radiation absorbed by Earth’s surface (Wang et al. 2010). Snow and ice cover are important components of Earth’s energy balance because of their high reflectance in the visible bands compared to plain surfaces and their great seasonal variation. Snow albedo feedback amplifies the sensitivity of snow and ice to small changes in albedo (Stroeve et al. 2007). Snow effects are parameterized in the Noah land surface scheme. Specifically, snow density \( \rho_{\text{snow}} \) (kg m\(^{-3}\)) is defined as

\[
\rho_{\text{snow}} = \frac{\text{swe}}{d_{\text{snow}}},
\]

where swe is the snow water equivalent (kg m\(^{-2}\)) and \( d_{\text{snow}} \) is snow depth (m). The variation of \( d_{\text{snow}} \) and swe depends on the ablation (e.g., sublimation and melting) of snow. Snow thermal conductivity \( k_{\text{snow}} \) is calculated based on \( \rho_{\text{snow}} \), expressed as

\[
k_{\text{snow}} = 0.0763 \times 10^{2.25\rho_{\text{snow}}}.\]

Snow-cover fraction \( C_{\text{snow}} \) (dimensionless) is derived from

\[
R_{\text{snow}} = \frac{\text{swe}}{\text{swe}_{\text{max}}}
\]

and

\[
C_{\text{snow}} = 1.0 - \left( e^{-2.6 \times R_{\text{snow}}} - R_{\text{snow}} e^{-2.6} \right),
\]

where \( \text{swe}_{\text{max}} \) is the threshold of snow water equivalent that implies 100% snow cover, which is a predefined value based on the vegetation type (e.g., “VEGPARM.TBL” in the WRF Model).

Surface albedo can be derived from

\[
\alpha_{\text{max}} = \alpha_{\text{max.sat}} + 0.5(\alpha_{\text{max_CE}} - \alpha_{\text{max.sat}}) \quad \text{and} \quad (5)
\]

\[
\alpha_{\text{snow}} = \alpha_{\text{max}} A^a, \quad (6)
\]

where \( \alpha_{\text{max}} \) is the albedo value of freshly fallen snow, and \( \alpha_{\text{max.sat}} \) is the satellite-based annual maximum snow albedo (Robinson and Kukla 1985) derived from initial land surface conditions, with a value of about 0.45 in the vicinity of the observation site in the control (CTL) experiment (not shown). Albedo \( \alpha_{\text{max_CE}} = 0.85 \) is a maximum snow albedo based on the U.S. Army Corps of Engineers (1956; also see Fig. 3 of Livneh et al. 2010). Albedo \( \alpha_{\text{snow}} \) is the snow albedo, \( t \) is the number of days since the last snowfall, and \( A \) and \( B \) are equal to 0.94 and 0.58, respectively, during the snow accumulation phase and to 0.82 and 0.46, respectively, during the snow ablation phase (Livneh et al. 2010). Specifically, in this paper \( A = 0.94 \) and \( B = 0.58 \) are used and a light snowfall occurs during the simulation period (not shown), so that

\[
\alpha = \alpha_{\text{snow.free}} + C_{\text{snow}}(\alpha_{\text{snow}} - \alpha_{\text{snow.free}}), \quad (7)
\]

where \( \alpha \) is surface albedo after considering snow effects. Albedo \( \alpha_{\text{snow.free}} \) is the background surface albedo without the snow; its value depends on the land-cover conditions (e.g., vegetation type; see VEGPARM.TBL in the WRF Model). In the study case, it is equal to \( \sim 0.25 \) at the observation site from the model output.

Snow can also significantly affect subsurface heat fluxes \( G \) from the soil layer:

\[
G = \frac{k_{\text{eff}}(T_{\text{sfc}} - T_{\text{soil_1st}})}{d_{\text{snow}} + d_{\text{soil_1st}}}, \quad (8)
\]

where \( k_{\text{eff}} \) is the thermal conductivity of a patchy snow-covered surface, namely, the combination of thermal conductivity from both the snowpack and the soil layer (Ek et al. 2003). Here \( T_{\text{sfc}} \) is surface temperature and subscript soil_1st indicates the variable in the first soil layer below the surface.

According to Eqs. (1)–(8), the physical characteristics of snow can evidently modulate the surface energy balance and affect the simulation of the near-surface atmosphere through changes in the surface albedo and ground heat flux \( G \). To investigate the sensitivity of numerical simulations of near-surface atmospheric conditions to initial land surface conditions in the cold season, the following three experiments are designed:

1) CTL is the default configuration of the WRF Model as described in section 2.
2) ALB is the same as CTL, but with the initial surface albedo [$\alpha$ in Eq. (7)] increased to be consistent with observations. In particular, $\alpha_{\text{max, sat}}$ in Eq. (5) is the only modified quantity that is equal to the maximum limit of $\alpha_{\text{max, CE}} = 0.85$. Consequently, $\alpha_{\text{max}}$ is increased and is equal to $\alpha_{\text{max, CE}} = 0.85$, leading to the increase in $\alpha_{\text{snow}}$ and $\alpha$ according to Eqs. (6) and (7). This experiment is designed to investigate the impact of the increased surface albedo that is induced by snow on the ground on near-surface atmospheric simulations.

3) ALB_SNOW is the same as ALB, but with the initial $d_{\text{snow}}$ and swe increased by 50% simultaneously [Eq. (1)] according to real-time visual observations. The reason why $d_{\text{snow}}$ and swe are increased by the same magnitude is that swe is determined from $d_{\text{snow}}$ under a specified assumption of the snow density ratio, as stated by Ek et al. (2003). Both swe and $d_{\text{snow}}$ are provided by the initial fields. The experiment is designed to further illustrate the effects of changes in ground heat flux associated with snow on the ground on the near-surface atmospheric simulations.

4. Sensitivity of simulated near-surface conditions to the initial snow depth and surface albedo

Figure 2 compares the surface albedo from different experiments with observations. It clearly shows that the surface albedo is mostly above 0.77 in the observations, whereas it is about 0.58–0.62 in the default WRF Model, suggesting that the WRF Model significantly underestimates the surface albedo, as well as the subsequent upwelling shortwave radiation energy during the daytime. With the increase in initial surface albedo in the ALB and ALB_SNOW experiments, the simulated surface albedo is improved. In addition, surface albedo is higher in ALB_SNOW than in ALB throughout the simulation because the increased snow water equivalent can consequently increase snow cover (Fig. 4d) according to Eqs. (3)–(7). Note that swe in the ALB and ALB_SNOW experiments is the same, because swe is bounded at an upper limit of the “SNUP” parameter in VEGPARAM.TBL in the WRF Model. Specifically, this parameter represents the threshold water equivalent snow depth (m) that implies 100% snow cover, depending on the vegetation type of the land surface (not shown). Moreover, the observed surface albedo is about 0.80 at 1500 UTC 15 January 2015, and it decreases to about 0.78 at 2000 UTC 15 January 2015 and then increases to above 0.80 near sunset at 0000 UTC 16 January 2015. The increase in observed albedo right before sunset might be caused by the low solar zenith angle, which enhances the reflection of sunlight from the snow surface. However, the simulated surface albedo in all experiments shows that the surface albedo decreases gradually with time and does not capture the detailed variations of the observed surface albedo. This is obvious because the parameterization of surface albedo in Eq. (7) does not depend on zenith angle, implying the need to improve the model’s representation of dynamic variations in surface albedo, especially with low solar zenith angle under snow-cover conditions.

Emissivity is an important factor that contributes to the calculation of upward longwave radiation $L\uparrow$, since $L\uparrow = \varepsilon \sigma T_{\text{sfc}}^4$, where $\sigma = 5.67 \times 10^{-8}$ is the Stefan–Boltzmann constant, $\varepsilon$ is surface emissivity, and $T_{\text{sfc}}$ denotes surface temperature. Figure 3 shows the surface emissivity in all experiments. The values of surface emissivity become larger in ALB and ALB_SNOW than those in CTRL and gradually approach the observed emissivity, which is greater than 0.96 (not shown in Fig. 3). In addition, the corresponding results for the accumulated melted snow, snow water equivalent, snow depth, and snow cover (Fig. 4) indicate that the increase in initial surface albedo can result in a decrease in the efficiency of snowmelt. This is mainly because of the effective reflection of shortwave radiation (Fig. 5), which results in the slow decrease in snow water equivalent, snow depth, and snow cover with integration time.

To analyze the effects of the modified snow depth and surface albedo on the simulation of the surface energy balance and near-surface atmospheric stability, Fig. 5 compares the observed surface radiation balance and surface temperature with these values from the different simulation experiments. The downward longwave and
shortwave radiation are essentially the same in the different experiments. However, all experiments tend to underestimate the downward longwave radiation (Fig. 5a) and overestimate the downward shortwave radiation (Fig. 5c) during the daytime, respectively, perhaps because of the lack of overlying cloud during the daytime in the model simulations, this might relate to the lack of cloud parameterization or uncertainties in ice microphysics. Meanwhile, the downward longwave radiation (Fig. 5a) is also underestimated by the different experiments during the fog event from 0735 to 1435 UTC 16 January 2015. These errors could be attributed to the failure of the model simulations to reproduce fog; thus the radiative effects of the fog were absent. The failure to reproduce fog during the nighttime could be closely related to several factors, for instance, the huge warm biases in temperature and dry biases in humidity in the near-surface atmosphere (Fig. 9). These near-surface forecast errors could also link with the lack of a macroscale cloud parameterization (e.g., Hughes et al. 2015; Boutle et al. 2016) and land surface parameterization regarding ground heat fluxes (Fig. 8). Uncertainties in ice microphysical parameterization could be another related factor since current microphysics parameterizations, such as the Milbrandt and Yau scheme (Milbrandt and Yau 2005a,b), Morrison scheme (Morrison et al. 2005; Morrison and Milbrandt 2011), and Thompson scheme (Thompson et al. 2004, 2008), do not fully consider the nucleation process for ice fog parameterization in the near-surface atmosphere, leading to the underestimation of the ice crystal number concentration $N_i$ in ice fog conditions (Gultepe et al. 2015, 2016).

Meanwhile, a great discrepancy among the different experiments is present mainly in the upward longwave and shortwave radiation. Specifically, CTL underestimates the maximum upward shortwave radiation (Fig. 5d),
while ALB and ALB_SNOW produce good simulations because of the improved surface albedo (as shown Fig. 2). Moreover, CTL also overestimates the maximum upward longwave radiation during the daytime, while ALB and ALB_SNOW produce better simulations. During the night before the fog event, however, the upward longwave radiation is overestimated by CTL but is improved with ALB and ALB_SNOW. Since upward longwave radiation is expressed as surface temperature multiplied by surface emissivity (Stull 1988), the improved (colder) surface temperatures in ALB and ALB_SNOW are directly responsible for the improved (lower) upwelling longwave radiation (Fig. 5f) relative to CTL.

In addition, the observed upward longwave radiation increases continuously during the fog event, which could be due to the increased downward longwave radiation in reality (Fig. 5a), which acts to warm the surface (Fig. 5f), leading to an increase in surface temperature and upward longwave radiation. However, none of the experiments capture such features and produce weaker upward longwave radiation compared to observations. This could be attributed to the failure to reproduce fog during this period, so that the heating effects of downwelling longwave radiation on the land surface are absent in the model. Moreover, compared to the simulations, the upwelling longwave radiation is stronger in the observations with lower surface temperature, suggesting
the stronger surface emissivity in the observations, as is clearly shown in Fig. 3.

Understanding the uncertainty of heating effects from the soil layer, atmosphere, surface emissivity, and their interactions is essential to the accurate simulation of near-surface atmospheric conditions. Figure 5e indicates that CTL tends to overestimate surface net radiation during the daytime. The overall effects of increasing surface albedo (ALB and ALB_SNOW) tend to decrease surface net radiation during the daytime. Moreover, Fig. 5f shows that the surface temperature simulation improves continuously in ALB and ALB_SNOW, mainly because the deeper snow leads to weaker heating from the land surface (Fig. 9). However, the trend of observed temperature variations is not well reproduced by either of the experiments, implying that the snow variations associated with its freezing and thawing might also not be well simulated by the model (see discussion in next section).

Figure 6 compares the surface SHFs, surface LHFs, and near-surface stability parameter $\zeta = z/L$ between the observations and the simulations with different experiments. Results show that the different experiments are comparable with each other, especially for the simulation of SHFs and $\zeta$. Specifically, the stronger SHFs (Fig. 6a) in the observations are much underestimated by all experiments during the daytime. During the nighttime, the observed SHFs are very weak and have negative values most of the time but become positive and significant during the fog event after 1000 UTC 16 January 2015. This could be related to the increased surface temperature caused by the increased downwelling longwave radiation, as well as the heating effects from the subsurface soil layer during the fog event. The simulations of SHF during the nighttime are very similar in the different experiments, producing much stronger negative SHFs and not capturing the positive SHFs in the later phase of the fog event. Results for LHFs (Fig. 6b) show that the increase in surface albedo can reduce LHFs during the daytime. Figure 6c indicates that the observed $\zeta$ is negative during the daytime and becomes positive from sunset to 0735 UTC 16 January 2015, indicating that the near-surface atmosphere is unstable and becomes stable after sunset. However, the observed $\zeta$ goes to zero and even becomes gradually negative during the fog event from 0735 to 1435 UTC 16 January 2015, suggesting that the observed near-surface atmosphere is stable in the early phase of the fog event but unstable in the later phase. Specifically, the observed unstable near-surface atmosphere during the later phase also corresponds well with the rapid increase in surface temperature (Fig. 5f) and the positive SHFs (Fig. 6a). Simulation results show that the simulated
stability in the near-surface atmosphere is comparable among the different experiments. The unstable near-surface atmosphere near sunset (from 2000 to 0030 UTC 16 January 2015) is wrongly simulated by all experiments as stable conditions. Meanwhile, although all simulations capture the stable near-surface atmospheric conditions in the early phase of the fog event and are similar to observations, they continue to produce a stable near-surface atmosphere in the later phase and are the opposite of observations. The incorrect near-surface stratification in the model during the later phase of the fog event could also be related to the failure to reproduce fog, which leads to weakening of the heating effects of downwelling longwave radiation on the land surface. This is similar to a recent study regarding the transition from stable to unstable stratification during a fog event (Boutle et al. 2018). In addition, the increase in initial surface albedo and snow depth cannot fix the unrealistic near-surface atmospheric stratification, indicating that uncertainty in near-surface atmospheric simulation is still a great challenge for numerical models (Mahrt et al. 1998; Mahrt 1999).

To investigate how changes in land surface conditions connect to the near-surface and subsurface, Fig. 7 compares the air temperature, dewpoint, relative humidity (RH) at 2 m AGL and surface wind speeds at 10 m AGL between the observations and the different simulations. It shows that increasing surface albedo can improve the daytime temperature simulation because the increased upward shortwave radiation tends to cool the surface during the daytime. The daytime temperature can be further improved by increasing the initial snow depth because of the larger surface albedo in ALB_SNOW than in ALB (Fig. 2). During the nighttime, the simulated air temperature is best in ALB_SNOW, followed by ALB and CTL, because of the improvement in the surface temperature simulation as shown in Fig. 5f. Results also show that although the simulated air temperature improves in the ALB and ALB_SNOW experiments, the significant surface cooling during the nighttime from 0030 UTC 16 January to 0735 UTC 16 January 2015 is still not well captured by the simulation. Compared to the air temperature simulation, the dewpoint at 2 m AGL is better reflected by all experiments, especially during the nighttime from 0030 to 0735 UTC 16 January 2015. The RH at 2 m AGL indicates that the simulation of RH can be improved by increasing initial surface albedo and snow depth, especially at night, which is closely related to the improvement in the temperature and humidity simulation in the lower atmosphere (as shown in Figs. 9a,b). The near-surface wind simulations are not changed, implying that increasing the initial surface albedo and snow depth does not change near-surface winds. Figure 8 compares...
the ground heat flux among the different experiments. Results show that increasing snow depth (see Fig. 3) can evidently decrease the heating effects from the soil layer, which is important to surface temperature simulation during the nighttime.

Figure 9 compares the vertical profile of temperature, RH, and wind speed between the observations and the different simulations valid at 2200 UTC 15 January, 0715 UTC 16 January, and 1116 UTC 16 January 2015, corresponding to the daytime before the fog onset, the nighttime close to the fog onset, and the nighttime during the fog event, respectively. It is apparent that simulations in the different experiments are the same during the nighttime and show little difference during the daytime, indicating that the increase in the initial surface albedo and snow depth has marginal effects on the vertical structure of near-surface atmospheric conditions, which could also be inferred from the comparable results with downward shortwave and longwave radiation in the different experiments (Figs. 5a,c).

At 2200 UTC 15 January 2015 (daytime; Figs. 9a–c), the simulated near-surface atmosphere below 300 m is warmer and drier, with larger temperature and smaller RH than observed values. Above 300 m, the simulated temperature and RH are smaller and larger than observations, respectively, indicating that the simulated upper atmosphere is colder and moister than observations. Also, all experiments underestimate the wind speed at all vertical levels. At 0715 UTC 16 January 2015 (nighttime; Figs. 9d–f), close to the fog onset, the observed temperature and RH in the near-surface atmosphere continue to decrease and increase, respectively. The simulated near-surface atmosphere, however, is still warmer and drier than observations, and this unrealistic warm and dry near-surface atmosphere in the different experiments extends to a higher level from the surface to 600 m AGL, compared to 2200 UTC 15 January 2015 (daytime; Figs. 9a–c). The simulated wind speeds in the different experiments are stronger than observations, especially at levels above 300 m, and are much different when compared with 2200 UTC 15 January 2015 (daytime; Figs. 9a–c). At 1116 UTC 16 January 2015 (nighttime; Figs. 9j–l), during the fog event, the patterns of temperature and RH are similar to those at 0715 UTC 16 January 2015 (nighttime; Figs. 9d–f); specifically, the simulations are similar and tend to underestimate vertical wind, especially at levels above 400 m.

Figure 9 indicates that the simulation errors of the near-surface atmosphere in the nighttime are larger and extend to a higher vertical level than those in the daytime, suggesting that the great uncertainty in the simulation of the near-surface atmosphere is more obvious during the nighttime than during the daytime. In addition, the observed temperature, especially at the lower levels, decreases gradually during the nighttime, while the simulated temperature does not decrease accordingly, implying that the underestimation of the cooling of the near-surface atmosphere cannot be fixed by increasing the initial surface albedo or snow depth. To further compare the coupling effects of the land surface and near-surface atmosphere in each experiment, Figs. 9d, 9h, and 9l show the vertical profiles of temperature from the surface (0 m) to 50 m. Results indicate that the simulated near-surface temperature at each time is best in the ALB_SNOW experiment (closest to observation), followed by the ALB and CTL experiments. Namely, the increase in the initial surface albedo or snow depth could remedy the simulation error of the near-surface atmosphere in the default WRF Model. However, it is also found that in all experiments, the simulated temperature at the lowest model level still significantly differ from the surface temperature and the diagnostic temperature at 2 m, implying the need for further improvement in land-atmospheric coupling and parameterizations of surface processes.

5. Discussion

This work is a natural extension of the previous work of Pu et al. (2016), in which a WRF real-time forecast was conducted to provide NWP guidance during the MATERHORN-Fog field campaign. Results from Pu et al. (2016) showed that the WRF Model simulation has great uncertainty in representing near-surface and lower boundary layer atmospheric conditions over mountainous regions in the cold season. They also speculated that uncertainty in the surface land cover (e.g., snow or ice on the ground) affects surface albedo, and unawareness of this factor can cause forecast errors. This study further investigates the sensitivity of numerical simulations...
of near-surface atmospheric conditions in the cold season to the initial surface albedo and snow depth. It is found that the WRF Model overestimates the daytime temperatures and has less ability to accurately reflect surface cooling effects during the nighttime from 0030 to 0735 UTC 16 January 2015, which is closely related to the fog event. In particular, surface cooling effects are much underestimated by the WRF Model.

Compared to the CTL experiment, the ALB and ALB_SNOW experiments tend to increase surface albedo and surface emissivity but decrease the efficiency of snowmelt, leading to the larger surface albedo, surface emissivity and snow depth during the whole integration.

Fig. 9. Comparison of the vertical profiles of (a),(e),(i) relative humidity (%), (b),(f),(j) temperature (°C), and (c),(g),(k) wind speed (m s⁻¹) from 50 to 500 m and (d),(h),(l) temperature (°C) from the surface (0 m) to 50 m between observations and simulations valid at (top) 2200 UTC 15 Jan 2015, (middle) 0715 UTC 16 Jan 2015, and (bottom) 1116 UTC 16 Jan 2015.
Obviously, all these changes in snow properties could affect the near-surface atmospheric conditions because of their influences on surface energy balance during the cold season. As described in section 3, the Noah scheme considers snowpack aging in order to parameterize snow albedo, as well as the subsequent surface albedo. During the cold season, the transformation from snow to ice or from ice to snow can significantly change surface albedo. According to Fig. 5f, the observed surface temperature decreases significantly from −3° to −17°C from the daytime (e.g., 1800 UTC 15 January 2015) to the nighttime (e.g., 0600 UTC 16 January 2015), corresponding to the continuous increase in surface albedo from 1800 UTC 15 January 2015 to near sunset. This indicates the need to improve the model’s representation of dynamic variations in surface albedo, especially with low solar zenith angle when snow is present. Since snow cover, snow water equivalent, snow depth, surface emissivity, and ground heat flux are all related to snow properties that were not directly measured during the MATERHORN-Fog field campaign, results here also highlight the need for and importance of snow measurements in the cold season to validate model results and improve model performance.

Increasing the surface albedo results in increases in the upward shortwave radiation during the daytime, leading to improvement in the simulation of surface temperature during the daytime. Increasing the initial snow depth inhibits the heating effects from the soil layer, resulting in the decrease of surface temperature during the nighttime. Therefore, the simulation of surface temperature and upward longwave radiation during the nighttime from 0030 to 0735 UTC 16 January 2015, which is closely related to the near-surface cooling during the nighttime, is improved. The simulation results above also indicate a significant underestimation of the downward longwave fluxes that are present for most of the simulations, suggesting that the inaccurate simulations of daytime cloud and nighttime fog might be related to the huge biases in the temperature and humidity structure of the atmosphere. The lack of a macroscale cloud parameterization and the uncertainties in ice microphysical parameterization could also influence the simulation performance in the near-surface atmosphere during this fog event.

Overall, the limitations in the numerical simulations could be attributed to a variety of error sources across scales (time and space), model grid resolution, coupling effects between the land surface and near-surface atmosphere, uncertainty in the physics schemes, and lack of observations of snow and surface properties.

6. Concluding remarks

This study illustrates the sensitivity of the simulation of near-surface atmospheric conditions during an ice fog event in the Heber Valley to the initial surface albedo and snow depth. Comparison of results from the WRF Model with observations from the MATERHORN-Fog field campaign shows that the WRF Model has great simulation uncertainty in terms of representing and predicting atmospheric conditions in the near-surface and lower boundary layers over mountainous regions in the cold season. Specifically, near-surface cooling during the nighttime is much underestimated by the WRF Model; in addition, the WRF Model overestimates the temperature during the daytime. These issues could be improved by increasing the initial surface albedo (e.g., satellite-based annual maximum snow albedo) and snow depth based on observations, which act to cool the near-surface atmosphere by increasing the reflection of downward shortwave radiation and decreasing the heating effects from the soil layer.

Outcomes from this study also highlight the great uncertainty of snow effects in the cold season on the simulation of ice fog conditions in the near-surface atmosphere, although some of the analyses are speculative because of the lack of observations of snow cover, snow water equivalent, snow depth, surface emissivity, and ground heat flux. The outcomes from this study highlight that a well-planned field project with observations of snow properties and near-surface atmospheric conditions in the cold season is important and imperative to validate model results and ultimately improve the performance of physics parameterization processes.

Note that near-surface atmospheric simulations in the cold season are also closely related to the uncertainty of other processes, as detailed by Gultepe et al. (2016). Observation results from their study indicated some processes that should also be important in the simulation of near-surface atmospheric conditions in the cold season. For instance, local effects such as upslope advection were observed to affect near-surface atmospheric conditions, and an increase in aerosol count was also observed when visibility was reduced to less than 5 km. Furthermore, the measured ice crystal number concentration \( N_i \) in the near-surface atmosphere was as high as 100 cm\(^{-3}\) during periods of saturation with respect to ice, which changes with increasing ice water content rather than behaving as a constant, as is usually assumed in numerical models.

Additional sensitivity studies with the same episode were conducted with different boundary layer and microphysics schemes. Results (not shown) are the same as those of CTL in this study, implying that improvements
in land surface processes during the cold season (e.g., surface albedo and snow depth) are needed in conjunction with other physical processes (e.g., boundary layer and microphysics schemes, etc.). Meanwhile, there are also recent developments in improving fog simulations with very fine-resolution numerical simulations at the large-eddy scales. For instance, Vosper et al. (2013) noted that moving the lowest model level from 5 m to 2 and 1 m could lead to obvious differences in stable PBL simulations over complex terrain. Their results imply that vertical resolution is important in the coupling between the land surface and atmosphere and might be a critical factor influencing the simulation performance of the near-surface atmosphere in this fog episode. Thus, the influences of large-eddy simulations and the use of very high vertical resolution in the lower atmosphere on fog simulation should be explored in future work. Moreover, Pu et al. (2013), Massey et al. (2014), and Zhang et al. (2015) indicated that assimilation of surface observations is an effective way to improve forecasts of near-surface conditions. Future work should also concentrate on data assimilation methods to improve the simulation of the near-surface atmosphere.

Acknowledgments. This study was supported by the MATERHORN Program, funded by the Office of Naval Research Award N00014-11-1-0709. The MATERHORN-Fog team, Dr. Ismail Gultepe from Environment and Climate Change Canada, and Drs. Eric Pardyjak and Sebastian Hoch from the University of Utah are greatly appreciated. Computer support from the University of Utah’s Center for High-Performance Computing (CHPC) is acknowledged. The authors were also supported by NSF Award AGS-1243027 and ONR Grant N000141612491. Review comments from three anonymous reviewers were helpful for improving an early version of the paper.

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