ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 30, NO. 5, 2013, 1449–1460

Impact of Rain Snow Threshold Temperature on Snow Depth Simulation in Land Surface and Regional Atmospheric Models

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(Received 19 September 2012; revised 10 December 2012; accepted 31 December 2012)

ABSTRACT

This study investigates the impact of rain snow threshold (RST) temperatures on snow depth simulation using the Community Land Model (CLM) and the Weather Research and Forecasting model (WRF—coupled with the CLM and hereafter referred to as WRF_CLM), and the difference in impacts. Simulations were performed from 17 December 1994 to 30 May 1995 in the French Alps. Results showed that both the CLM and the WRF_CLM were able to represent a fair simulation of snow depth with actual terrain height and 2.5°C RST temperature. When six RST methods were applied to the simulation using WRF_CLM, the simulated snow depth was the closest to observations using 2.5°C RST temperature, followed by that with Pipes', USACE, Kienzle's, Dai's, and 0°C RST temperature methods. In the case of using CLM, simulated snow depth was the closest to the observation with Dai's method, followed by with USACE, Pipes', 2.5°C RST temperature, Kienzle's, and 0°C RST temperature method. The snow depth simulation using the WRF_CLM was comparatively sensitive to changes in RST temperatures, because the RST temperature was not only the factor to partition snow and rainfall. In addition, the simulated snow related to RST temperature could induce a significant feedback by influencing the meteorological variables forcing the land surface model in WRF_CLM. In comparison, the above variables did not change with changes in RST in CLM. Impacts of RST temperatures on snow depth simulation could also be influenced by the patterns of temperature and precipitation, spatial resolution, and input terrain heights.

Key words: snow simulation, RST temperature, WRF_CLM, CLM

Citation: Wen, L. J., N. Nagabhatla, S. H. Lü, and S.-Y. Wang, 2013: Impact of rain snow threshold temperature on snow depth simulation in land surface and regional atmospheric model. *Adv. Atmos. Sci.,* **30**(5), 1449–1460, doi: 10.1007/s00376-012-2192-7.

1. Introduction

Snow can modify regional and, possibly, remote hydroclimatic environments by changing the surface energy and water balance (Yeh et al., 1983; Walsh et al., 1985; Barnett et al., 1989; Yang et al., 1997; Essery et al., 1999). Accurate numerical modeling of snow is a potential way to not only understand local climate but

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also facilitate seasonal prediction. The separation of precipitation into snow and rain remains a key challenge in the snow simulation process. Many factors, such as thickness and temperature of the atmospheric boundary layer, position of the 0°C isotherm, cloud types, air mass, and humidity, determine the precipitation morphology (Kienzle, 2008). However, including all these factors for partitioning rain and snow in models will render complicated model physics, undermining the overall simulation efficiency of the model. In order to simplify the modeling process and improve the simulation efficiency, empirical studies have adopted climatologically parameterized values to determine the phase of precipitation. Rain snow threshold (RST) temperature is one such parameter, which is based on minimum air temperature, dew point temperature, or air temperature. The minimum air temperature was used in a rainfall–runoff model to determine the precipitation type in Australian Alpine region (Schreider et al., 1997). Marks and Winstral (2007) found that dew point temperature was more reliable than air temperature as a predictor of the precipitation phase in a mountain in Idaho, USA. However a study from Sweden (Feiccabrino and Lundberg, 2008) showed that air temperature is a better indicator than dew point temperature. And the RST air temperature has been reported to be the commonly used parameter (Motoyama, 1990; Yang et al., 1997; Gillies et al., 2012). Taking reference from the above examples, we employed RST air temperature for the current analysis. In our study, RST temperature referred to the air temperature. The RST temperature of 2.5°C was first determined by Auer (1974) based on nearly 1000 weather observations, which separated solid and liquid precipitations in equal probabilities. Auer (1974) also illustrated that 0°C (6.1°C) was the lowest (highest) temperature for rain (snow) to exist. Regional variations in RST temperature were also observed. For example, RST temperature was observed to be about 0°C at Hokkaido (northern region) and 2°C–3°C at Honshu (southern region) in central Japan (Motoyama, 1990). In other mountainous regions, RST temperatures varied with elevation (Lundquist et al., 2008).

Based on observations related to RST temperatures, climate models have adopted different parameterizations to categorize the precipitation phase. General circulation models typically employ a constant RST temperature; for instance, 2.2°C was applied as the RST temperature for the Biosphere–Atmosphere Transfer Scheme (BATS) (Dickinson et al., 1993; Yang et al., 1997). For lowland and lower Alpine regions of Switzerland, 0.5°C was considered as the optimal transitional temperature for partitioning snowfall and rainfall in the Hydrologiska Byråns Vattenbalansavdelning (HBV) runoff model, developed by the Swedish Meteorological and Hydrological Institute (Braun and Lang, 1986). In the tropical Andes Cordillera, a distinct RST temperature of −1.5°C was employed to distinguish snowfall and rainfall events in the Interactions between Soil, Biosphere, and Atmosphere (ISBA) model (Boone and Etchevers, 2001; Chevallier et al., 2004). The Community Atmospheric Model version 3.0 determined the percent of snowfall as a linear function of air temperature between 0°C and −5°C (Collins et al., 2004) and assumed that all precipitations occurred as snow (rain) when the temperature was less than −5°C (higher than 0°C). The Canadian University of British Columbia (UBC) Watershed Model (Pipes and Quick, 1977; Kienzle, 2008) applied a linear approach to depict a mixed precipitation of snow and rain, when the RST temperatures were regulated between 0.6°C and 3.6°C.

Apparently, there has been a wide ranging difference between RST temperatures used in different models. Simulated snow and related energy budget were sensitive to the changes in RST temperatures (Loth et al., 1993; Fassnacht and Soulis, 2002) Loth et al. (1993) found significant differences between the simulated snow depths and snow water equivalents with three different RST temperature methods. Fassnacht and Soulis (2002) show that warmer RST temperatures produced more snow, larger latent heat flux and ground heat flux during the melt period, along with increased surface heat flux. However, up to now only few studies have examined the impacts of different RST temperature methods on snow simulation. Even fewer have delved into studying the impacts with offline land surface models (forced with observed meteorological data, without considering the interaction between atmosphere and land surface) and regional atmospheric models coupled with land surface models (considering the interaction between atmosphere and land surface). Our study intended to address this research gaps with an objective to study the impact and sensitivity of RST temperature methods to snow simulation using an offline land surface model (Community Land Model version 3.5, CLM) and a regional atmospheric model (Weather Research and Forecasting model version 3.2, WRF, which was recently coupled with the CLM—WRF_CLM). Section 2 of this article describes six RST methods applied to the models for comparing their impacts on snow depth simulation. Section 3 introduces the observation data and models, simultaneously providing a detailed insight into the model settings and experiments. Section 4 illustrates the snow depth simulation from 17 December 1994 (when snow started to appear) to 30 May 1995 (when snow melted out). Six popular RST temperature methods were applied to the offline land surface model CLM and regional atmospheric model WRF_CLM to demonstrate their impacts on snow depth simulation and study the feedback on the meteorological fields. In addition, sensitivity of RST temperatures (with same intervals) to snow depth simulation is discussed. Other factors that possibly affect how RST temperatures influence snow simulation are also addressed. The last section includes discussion of results and conclusions.

2. RST temperature methods

Six RST temperature methods were applied to the models to compare the impacts of RST methods on snow simulation in the study. The first method was based on about 1000 weather observations (Auer, 1974) and set the RST temperature as 2.5°C. Precipitation occurred as snow (rain) when the temperature was cooler (warmer) than the threshold temperature. The second method employed 0°C RST temperature, as was used in case of the Noah Model (Koren et al., 1999). In the third method, a linear function of air temperature was used in the Canadian UBC Watershed Model (Pipes and Quick, 1977; Kienzle, 2008):

$$r_{\rm p}=\begin{cases}0\,, & T\leqslant 0.6\\ \dfrac{T}{3}-0.2\,, & 0.6<T<3.6\\ 1\,, & T\geqslant 3.6\end{cases}\,, \tag{1}$$

where $r_{\rm p}$ is the ratio of falling rain to precipitation and T is the air temperature (°C).

The fourth method was similar to function (1), except the upper (lower) limit temperature and the slope, which is as follows (U.S. Army Corps of Engineers, 1956) :

$$r_{\rm p}=\begin{cases}0\,, & T\leqslant 0\\ -54.632+0.2(T+273.16)\,, & 0<T<2\\ 0.4\,, & 2<T<2.5\\ 1\,, & T\geqslant 2.5\end{cases}\,, \tag{2}$$

For short, the method is called USACE. The fifth RST temperature method was parameterized from daily precipitation data of 113 climate stations in South-Western Alberta and South-Eastern British Columbia (Kienzle, 2008) and used a curvilinear function of temperature:

$$r_{\rm p}=\begin{cases}\max\left(0,5\left(\dfrac{T-T_{\rm t}}{1.4T_{\rm R}}\right)^3+6.76\left(\dfrac{T-T_{\rm t}}{1.4T_{\rm R}}\right)^2+\right.\\ \left.3.19\left(\dfrac{T-T_{\rm t}}{1.4T_{\rm R}}\right)+0.5\right)\,, \quad T\leqslant T_{\rm t}\\ \min\left(1,5\left(\dfrac{T-T_{\rm t}}{1.4T_{\rm R}}\right)^3-6.76\left(\dfrac{T-T_{\rm t}}{1.4T_{\rm R}}\right)^2+\right.\\ \left.3.19\left(\dfrac{T-T_{\rm t}}{1.4T_{\rm R}}\right)+0.5\right)\,, \quad T\geqslant T_{\rm t}\end{cases}\,, \tag{3}$$

where $T_{\rm t}$(2.6°C) is the threshold temperature at which rainfall and snowfall were equal; $T_{\rm R}$ is the temperature range at which rainfall and snowfall could exist together, and it was set as 13.3°C. The sixth method was based on the three-hourly synoptic weather reports from over 15 000 land stations and many ships globally (Dai, 2008). Here, the percentage of rainfall was a hyperbolic tangent function of temperature:

$$r_{\rm p}=1-\frac{a\{\tanh[b(T-c)]-d\}}{100}\,, \tag{4}$$

where a, b, c, and d are the annual parameters for land and equal −48.2292, 0.7205, 1.1662, and 1.0223, respectively.

3. Data and models

The data (Essery et al., 1999) used to force the offline land surface model CLM and validate the WRF_CLM model included hourly records of air temperature, humidity, wind speed, shortwave radiation, long wave radiation, and precipitation from 17 December 1994 to 30 May 1995, which were retrieved from the Centre d'Etudes de la Neige situated at Col de Porte (45°N, 6°E, 1320 m) over a short grassland (Fig. 1). The observed data for temperature and humi-

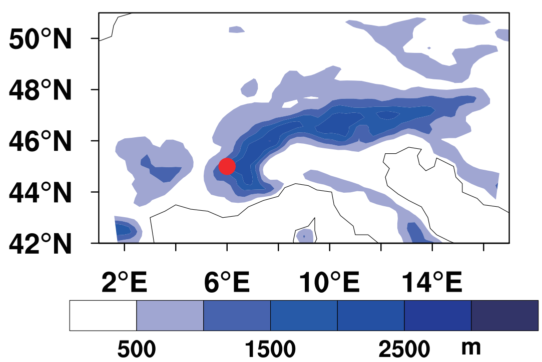

Fig. 1. Topography of the simulated domain and the observation site (red circle).

Table 1. Parameterization schemes used in the simulation.

Physics Options	Parameterization Schemes
Microphysics	Morrison double-moment scheme (Morrison et al., 2005)
Cumulus parameterization	Kain-Fritsch scheme (Kain, 2004)
Shortwave radiation	Dudhia scheme (Dudhia, 1989)
Longwave radiation	Rapid Radiative Transfer Model (RRTM) scheme (Mlawer et al., 1997)
Land surface	CLM3.5 (Oleson et al., 2008)
Planetary boundary layer	Yonsei University (YSU) scheme (Noh et al., 2003)

dity were collected at 2 m above ground and the wind speed was measured at 2.5 m. Snow depth was monitored on an hourly basis using an ultrasonic sensor. Surface temperature and albedo were calculated using long and shortwave radiation measurements. This data set has also been reported to be employed in case of various other models, such as Chameleon Surface Model (CHASM), Simplified Simple Biosphere Model (SSIB), BATS, ISBA, Energy balance Snow Cover Integrated Model (ESCIMO), and others (Fernández, 1998; Sun and Xue, 2001; Strasser et al., 2002; Belair et al., 2003; Essery and Etchevers, 2004).

The aforementioned observed hourly interval atmospheric data were used to drive CLM and evaluate the effects of different RST temperatures on the snow depth simulation in offline land surface and regional atmospheric models. The land surface model CLM was developed by the National Center for Atmospheric Research (NCAR) and was used extensively for offline and coupled model simulations in varied landscapes globally. Oleson and Coauthors (2008) and Collins et al (2006) described the model in detail. In the present study, the offline simulation was performed during the period from 17 December 1994 (when snow started to appeared) to the end of May in 1995 (when all snow melted) using the CLM model.

Further, the newly coupled regional atmospheric model WRF_CLM was applied to study the effects of RST temperatures on snow simulation and on the interaction between land surface and atmosphere. Details on the model can be obtained from the study of Subin et al. (2011). The WRF model is a limited-area, nonhydrostatic, primitive-equation model with multiple options for various physical parameterization schemes (Skamarock and Klemp, 2008). The options selected for atmospheric physics in our work are listed in Table 1. The period of simulations using the WRF_CLM was in accordance with the period of study using the CLM. The simulated domain was centered at 46°N, 9°W, with 20 km horizontal grid spacing (Fig. 1). The grid point dimension was 60×60. The model had 30 vertical layers. The initial and lateral boundary conditions were provided by National Centers for Environmental Prediction (NCEP) reanalysis data version II (Kanamitsu et al., 2002), which are updated every six hours.

To compare the impacts of different RST temperatures using offline and regional atmospheric models, we employed two models (CLM and WRF_CLM) to perform a couple of simulations. However, simulation by the WRF_CLM with default settings was not so satisfactory. As explained in the next section, replacement of model defaulted terrain height with the real value can improve the snow simulation ability in WRF_CLM. So the comparison of RST impact with WRF_CLM is based on the replacement. To evaluate the impacts of RST temperatures on snow simulation under different terrain heights, we performed sensitivity runs with different RST temperatures and different terrain heights. The details of CLM and WRF_CLM experiments are listed in Table 2.

4. Results

4.1 *Validation of models*

With default model settings (with 2.5°C RST temperature), the CLM could capture the observed snow depth variation fairly well (Fig. 2a). However, it tended to underestimate the snow depth. In general, it can be used for the snow study. Hereafter, the experiment will be referred to as CLM-2.5 (Table 2).

The simulation, using the WRF_CLM model with default model settings (with the input terrain height at about 20-km horizontal spatial resolution and 2.5°C RST temperature), will be referred to as OH-2.5 in the rest of the script (Table 2). The maximum simulated snow depth was nearly 4 m in OH-2.5 (Fig. 3a), while the observation value was only 1.9 m. The simulated temperature was always lower than the observation value (Fig. 3c) and the simulated precipitation was slightly high in general (figure not shown). The inaccuracy in the results of experiment OH-2.5 may be attributed to incorrect input value of the terrain height for the station (1860 m was used in the model, whereas the actual value was 1320 m). Use of higher terrain heights led to a cooling of the surface atmosphere and lowering of the saturated vapor pressure, inducing more precipitation and increasing snow depth. This snow accumulation made the atmosphere even cooler,

Table 2. Details of the Model experiments.

Name	Model	Terrain height (m)	RST temperature
OH-3	WRF_CLM	1860 (defaulted)	3°C
OH-2.5	WRF_CLM	1860 (defaulted)	2.5°C (defaulted)
OH-2	WRF_CLM	1860 (defaulted)	2°C
OH-1	WRF_CLM	1860 (defaulted)	1°C
OH-0	WRF_CLM	1860 (defaulted)	0°C
CH-3	WRF_CLM	1320	3°C
CH-2.5	WRF_CLM	1320	2.5°C (defaulted)
CH-2	WRF_CLM	1320	2°C
CH-1	WRF_CLM	1320	1°C
CH-0	WRF_CLM	1320	0°C
CH-Dai's	WRF_CLM	1320	Dai's (Dai, 2008)
CH-Kienzle's	WRF_CLM	1320	Kienzle's (Kienzle, 2008)
CH-Pipes'	WRF_CLM	1320	Pipes' (Pipes and Quick, 1977)
CH-USACE	WRF_CLM	1320	USACE (U.S. Army Corps of Engineers, 1956)
CLM-3	CLM	1320	3°C
CLM-2.5	CLM	1320	2.5°C (defaulted)
CLM-2	CLM	1320	2°C
CLM-1	CLM	1320	1°C
CLM-0	CLM	1320	0°C
CLM-Dai's	CLM	1320	Dai's (Dai, 2008)
CLM-Kienzle's	CLM	1320	Kienzle's (Kienzle, 2008)
CLM-Pipes'	CLM	1320	Pipes' (Pipes and Quick, 1977)
CLM-USACE	CLM	1320	USACE (U.S. Army Corps of Engineers, 1956)

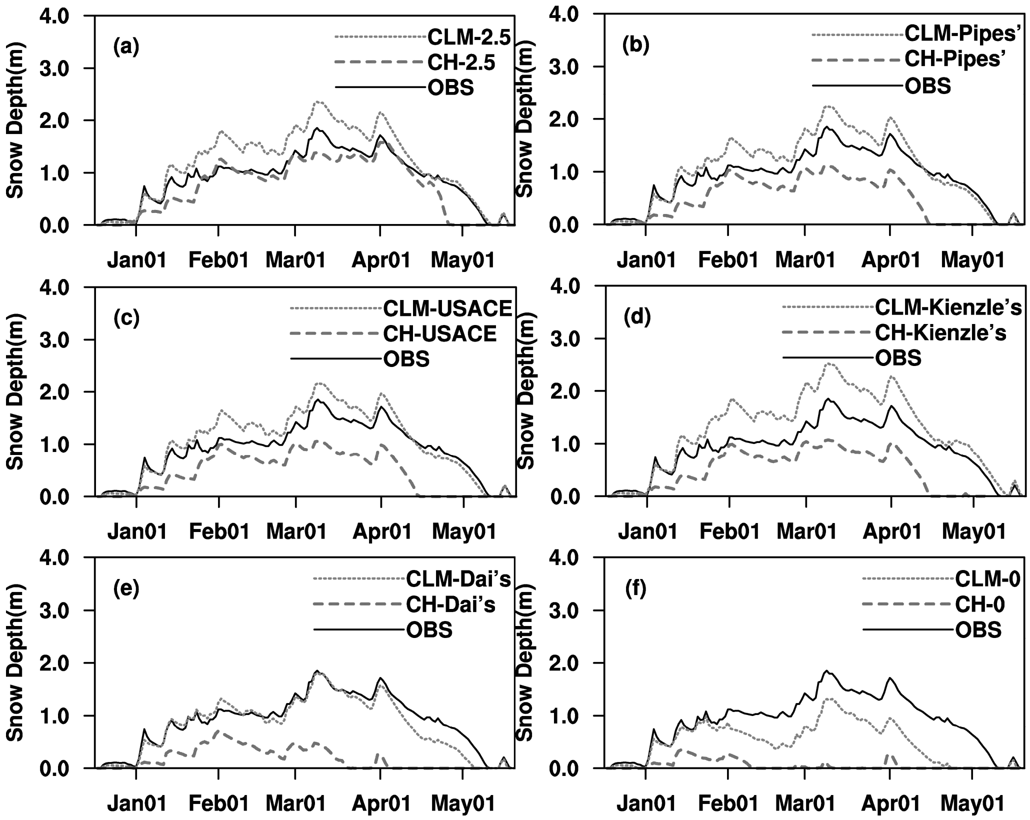

Fig. 2. Observed and simulated snow depths with different RST temperature methods by CLM and WRF_CLM.

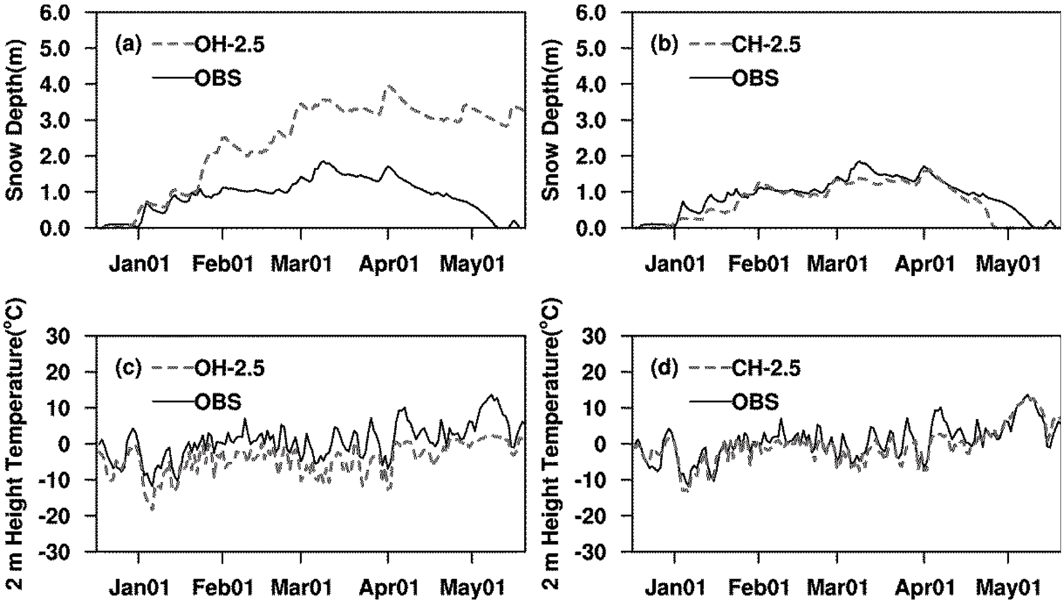

Fig. 3. Observed and simulated snow depths and 2-m-height air temperature with 2.5°C RST temperature and default/changed terrain height.

causing more precipitation and further snow accumulation. Thus, a positive feedback loop was formed. Owing to a low temperature, the snow melted quite slowly, thereby preventing a rise in temperature. As a consequence, a simulated snow depth of 3 m still existed in mid-May (Fig. 3a) and the simulated 2-m height temperature was around 0°C (Fig. 3c). However, there was no observation value for snow and the observed maximum daily temperature was about 10°C.

Application of the accurate topography could possibly improve the snow simulation (Jin and Wen, 2012). Hence, the simulation called CH-2.5 was performed, that is almost same with the OH-2.5 experiment, but we replaced the terrain height of the observation site in the model with the real value. From the root mean square deviation (RMSD) values and the bias in Table 3, it can be seen that the simulation of CH-2.5 was improved significantly. The CH-2.5 experiment captured snow depth variation fairly well, except that snow was a little underestimated and melted a little bit earlier (Figs. 2b and 3b). The simulated temperature was more realistic in the CH-2.5 experiment (Fig. 3d). In summary, the CH-2.5 experiment showed better simulation than the OH-2.5 one. The model was found to be suitable for adoption in similar research assignments if the real terrain height value could be adjusted well across the whole domain. Therefore, henceforth the study with WRF_CLM was performed with the real terrain height value, except for some sensitivity analyses.

4.2 *Impact of different RST temperatures on snow simulation*

The separation of precipitation into snow and rain in models was found to affect the simulation of water and energy balance notably. Presently, lots of RST temperature methods are used in numerical models. To find the differences in the impacts of these popularly used RST temperature methods on snow simulation, six different RST temperature methods (described in section 2) were applied to the offline

Table 3. RMSD and Bias (°C) between the observation and simulation in CH-2.5 and OH-2.5.

		OH-2.5	CH-2.5
RMSD	Snow depth (m)	1.8	0.3
	2 m height temperature (°C)	6.1	3.2
	Precipitation (mm)	11.4	10.7
Bias	Snow depth (m)	1.5	−0.2
	2 m height temperature (°C)	5.4	2.1
	Precipitation (mm)	0.9	−1.0

land surface model CLM and the regional atmospheric model WRF_CLM for comparison. The corresponding experiments are listed in Table 2. The offline land surface model CLM with all these different RST temperature methods could simulate the snow depth fairly well (Fig. 2), as it employed observed forcing. The difference caused by RST temperature with the CLM model reflects primarily on the magnitude of the simulated snow depth. All methods in general overestimated the snow depth, except Dai's method and 0°C threshold temperature when using the CLM model. The average maximum snow depth was simulated using Kienzle's method, followed by CLM-2.5. The finest simulation was achieved with Dai's method (Tables 4 and 5) and the worst was in case of CLM-0.

In the experiments using the regional atmospheric model WRF_CLM with the actual terrain height, the simulated snow depth with all different RST temperatures (Fig. 2) were underestimated and snow melted earlier. These results were different from those obtained using the offline CLM. The finest simulation was obtained in CH-2.5 experiment (Tables 4 and5); however, snow disappeared 20 days earlier. This was followed by simulations with Pipes', USACE, and Kienzle's methods (Tables 4 and 5), although the values were quite close to each other; simulation of less snow caused its melting 33, 34, 34 days earlier, respectively.

The accuracy of simulation with the offline land surface model CLM and regional atmospheric model WRF_CLM varied with the change of the RST temperature. The simulated snow had different responses to different RST temperatures with CLM and WRF_CLM models. This is possibly because RST temperatures partitioned precipitation in different forcing heights in offline land surface model CLM and regional atmospheric model WRF_CLM. The forcing heights in the land surface model were 2 m and 54 m in CLM and WRF_CLM, respectively. In addition, certain other factors influenced the simulation in regional atmospheric model WRF (such as spatial resolution, input terrain height, system error for simulating temperature, precipitation, radiation, and assumingly more).

The difference in simulated snow depths between CH-2.5 and CH-0 was higher than that between CLM-2.5 and CLM-0 (Fig. 2). Additionally, the simulated snow depth in regional atmospheric model WRF_CLM was more sensitive to RST temperatures than that in offline land surface model CLM. This was because not only RST temperature was a key factor for partitioning the snowfall and rainfall in regional atmospheric model WRF_CLM, but also simulated snow related to RST temperature could induce the large feedback by changing the forcing meteorological variables, that is reversely always the same for different RST temperatures in offline land surface model CLM. In order to explain how sensitive the simulated snow was to the change in RST temperatures, sensitivity experiments were conducted with intervals of 1°C RST temperature, using the regional atmospheric model WRF_CLM and offline land surface model CLM. Such an analysis would help reflect the effect of RST temperatures on snow simulation, in addition to the energy and water interaction between land and the atmosphere.

4.3 *Sensitivity of RST temperatures to snow simulation*

From the beginning of snow accumulation toward the end of its melting, the average observed snow depth was 0.87 m, whereas the average simulated snow depth in CLM-3, CLM-2, CLM-1, and CLM-0 were 1.22, 1.01, 0.89, and 0.48 m, respectively (Fig. 4a). Snow depths simulations of CLM-3, CLM-2, and CLM-1 were high as compared with the observation. The simulation in CLM-1 was the closest to the observed values perhaps because the actual RST temperature was around 1°C. Long-term observations of a meteorological station in Davos (1590 m, 45 km north of Morter-

Table 4. RMSD (°C) between the observed and simulated snow depth with different RST temperature methods by CLM and WRF_CLM.

	2.5	Pipes'	USACE	Kienzle's	Dai's	0
CLM	0.34	0.25	0.23	0.42	0.18	0.49
WRF_CLM	0.25	0.49	0.52	0.53	0.87	0.98

Table 5. Bias (°C) between the observed and simulated snow depth with different RST temperature methods by CLM and WRF_CLM.

	2.5	Pipes'	USACE	Kienzle's	Dai's	0
CLM	0.25	0.16	0.13	0.34	−0.09	−0.40
WRF_CLM	−0.17	−0.41	−0.44	−0.46	−0.75	−0.84

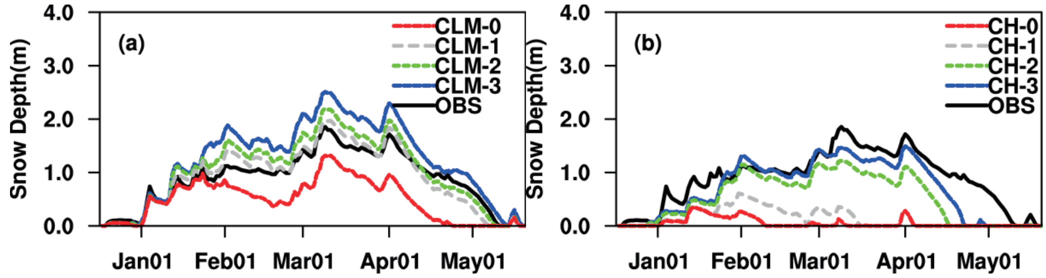

Fig. 4. Observed and simulated snow depths with 3°C, 2°C, 1°C, and 0°C RST temperatures by CLM and WRF_CLM.

atsch) showed mixed precipitation most appeared between 0.75°C and 1.5°C, with a standard deviation of approximately 0.3°C–0.5°C (Rohrer, 1989). On average, 50% rain (snow) fall occurred between 0.5°C and 1°C (L'Hote et al., 2005). The difference in snow depths simulated with offline land surface model CLM was relatively small between experiments with a 1°C interval in the RST temperature range from 3°C to 1°C. The difference in average snow depths was only 0.21 (0.12) m between RST temperatures 3°C and 2°C (2°C and 1°C). However, the difference between experiments with 1°C and 0°C RST temperatures could be as large as 0.41 m. Discrepancies in the results of experiments using the same RST temperature intervals were possibly induced by the different distribution patterns of the observed temperature and precipitation forcing the offline land surface model CLM (Fig. 5). Nearly one-sixth of the accumulated precipitation in the snow accumulation period occurred between 0°C and 1°C, which almost equaled the sum of precipitation falling between 1°C and 2°C and between 2°C and 3°C. It is important to note that the simulated snow depths were not the same in the above experiments. However, their simulated time of accumulation and end of ablation data were closely related, as the forcing meteorological data were same.

The highest value of simulated snow depth with

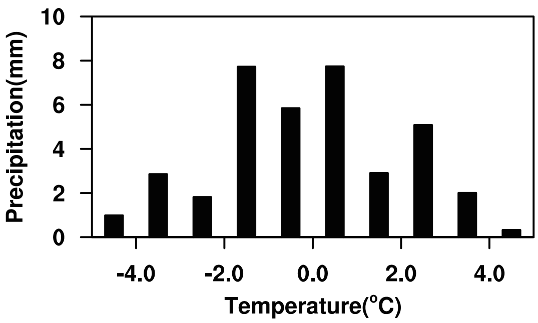

Fig. 5. Distribution of observed precipitation and temperature.

the offline land surface model CLM and regional atmospheric model WRF_CLM was obtained with the maximum value of RST temperature when the major portion of precipitation consisted of snow (Fig. 4). In general, the simulated snow depths in all experiments with WRF_CLM model were underestimated (Fig. 4b). The average simulated snow depths were approximately 0.68, 0.53, 0.14, and 0.05 m at RST temperature 3°C, 2°C, 1°C, and 0°C. The average simulated snow decreased by about 93% from CH-0 to CH-3, and by nearly 61% from CLM-3 to CLM-0. The simulated snow melting out time for the experiments employing the WRF_CLM also varied. Using the WRF_CLM, the earliest ablation was observed at the beginning of April and the latest toward the beginning of May. On the other hand, all the simulations by the CLM (using different RST temperatures) reflected melting out of snow during mid-May.

The regional atmospheric model WRF_CLM was more sensitive to the changes in RST temperatures than the offline land surface model CLM, owing to the feedback induced by different RST temperatures in the atmospheric model. The data forcing CLM did not change with variations in RST temperatures. In contrast, in experiments with the regional atmospheric model WRF_CLM, RST temperatures not only decided the separation of snow and rain, but also the simulated snow related to RST temperature possibly altered the simulation of temperature, precipitation, and energy balance in the atmospheric model. The simulated precipitation was almost same for the WRF runs with different RST temperatures, indicating that the precipitation was dominated by a large-scale circulation in the simulated period and not affected by a change in land surface. The simulated 2-m height temperatures obtained using the regional atmospheric model WRF_CLM with different RST temperatures also varied (Fig. 6a). The average 2-m height temperatures in CH-3, CH-2, CH-1, and CH-0 for the simulated period were −0.2°C, 0.0°C, 1.0°C, and 1.7°C, respectively. The difference could reach up to 1.9°C.

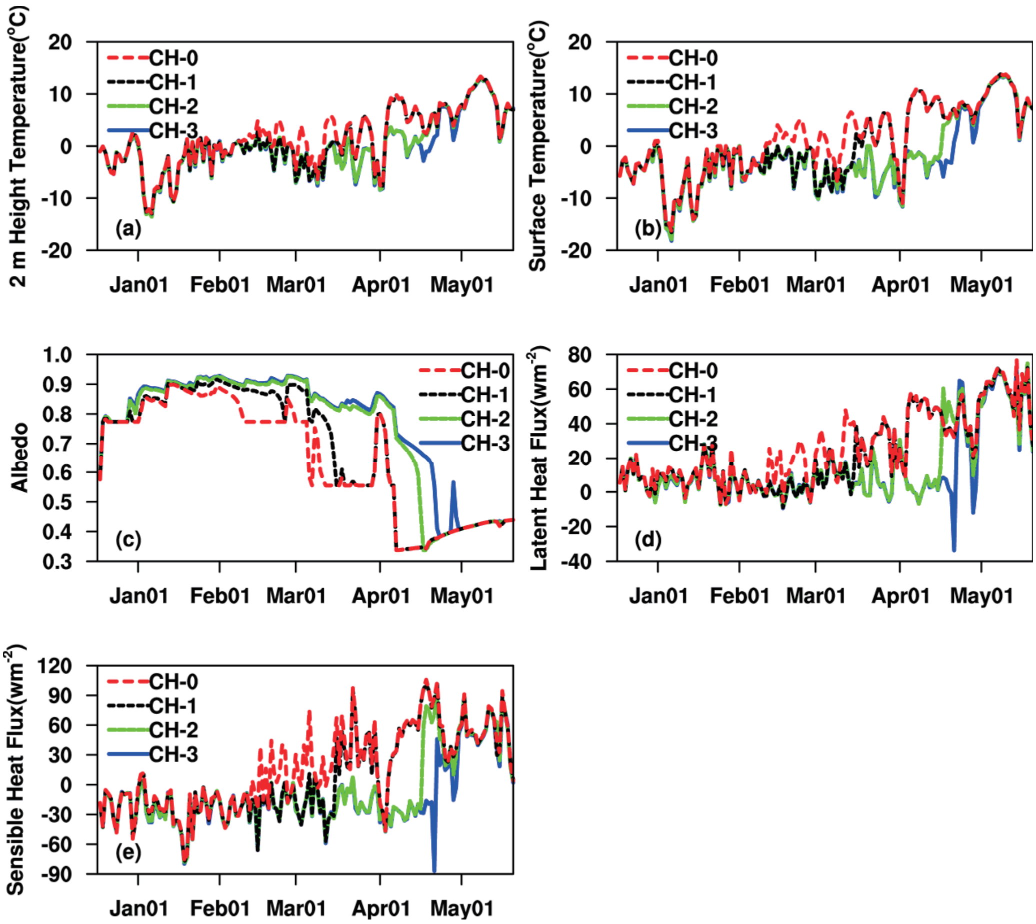

Fig. 6. Simulated results by WRF_CLM with 3°C, 2°C, 1°C, and 0°C RST temperatures.

However, before the snow melted out, the simulated temperature in our study did not change with changes in snow depths. The temperature difference gradually appeared when there was no snow in the experiments with 0°C, 1°C, and 2°C RST temperatures. Disappearance of snow results in a rapid increase of air (Fig. 6a) and surface (Fig. 6b) temperatures owing to dramatic changes in albedo (Fig, 6c) and the energy budget, such as the changes of latent heat flux Fig. 6d) and sensible heat flux (Fig, 6e). On April 10, when there was no snow in CH-0 but snow still existed in other WRF_CLM runs, the albedo was about 0.4 and 0.8 in CH-0 and CH-3, respectively. Correspondingly, the simulated net radiation was 9.4 and 37 W m^{-2} in CH-3 and CH-0, with the same downward shortwave radiation. In CH-0, more energy was utilized to heat the ground with a low albedo. The sensible heat flux in CH-0 was 57.2 W m^{-2} while in CH-3 it was -26.9 W m^{-2}. The sensible heat flux shifted from a negative to a positive value with the disappearance of snow, transferring the energy from atmosphere-to-snow to ground-to-atmosphere and simultaneously heating the atmosphere.

4.4 *Sensitivity of RST temperatures on snow simulation under different terrain heights*

With original input terrain height from model, the difference in average snow depths between OH-3 and OH-0 was about 0.31 m (Fig. 7a), which was low compared with the difference (0.63 m) between CH-3 and CH-0 (Fig. 4b). This reason for this immense difference could be attributed to the relatively low temperature simulated by WRF_CLM model with the original input terrain height (Fig. 7b), which was on average about -4.1°C in both OH-3 and OH-0. The false original terrain height made the temperature fall below 0°C during the simulated period. Therefore, with 0°C and 3°C RST temperatures, practically comparable separation of the precipitation into rain or snow took place. Conversely, after changing the input terrain height to the actual value, the simulated average 2-m height temperatures were 1.7°C and -0.2°C in CH-0 and CH-3, respectively (Fig. 6a). Referring to the above experiments, one can possibly conclude that

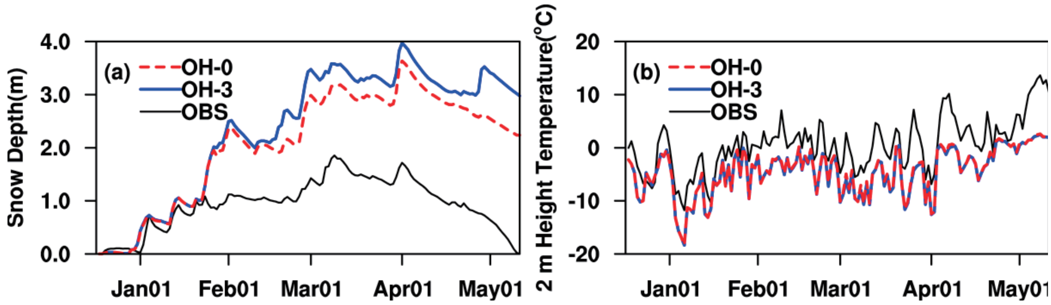

Fig. 7. Simulated snow depth with 3/0°C RST temperature and default terrain height by WRF_CLM.

the impact of RST temperatures on snow depth simulation was perhaps affected by other model parameters in addition to the terrain height.

5. Discussions and conclusions

In this study, two major objectives were addressed. The first was to validate the snow simulation ability of the recently coupled regional atmospheric model WRF_CLM and the second was to illustrate the impact of different RST temperature methods on snow depth simulation based on the offline land surface model CLM (forced by observation, not considering the interaction between atmosphere and land surface) and the regional atmospheric model WRF_CLM (considering the interaction between atmosphere and land surface). In addition, the difference in impacts estimated by the above two models was also deliberated. As the results reflected, both the CLM and the WRF_CLM demonstrated good simulation capacity for snow depth with the actual terrain height and the default 2.5°C RST temperature. Snow depth simulated by the offline land surface model CLM using Dai's method was the closest to the observation, followed by that with USACE, Pipes', 2.5°C RST temperature, Kienzle's, and 0°C RST temperature methods. The snow depth simulated by the WRF_CLM with 2.5°C RST temperature was the closest to the observation, followed by that with Pipes', USACE, Kienzle's, Dai's, and 0°C RST temperature methods. The difference in performance of the above two models could be explained based on factors such as spatial resolution, input terrain height, system error for the simulation of temperature, precipitation, radiation, and more, which affected simulation of the regional atmospheric model WRF. In case of the offline land surface model CLM, the forcing data were fed with observed values. The difference in snow depth simulations with the same intervals of RST temperature by the regional atmospheric model WRF_CLM was much higher than that by the offline land surface model CLM, not only because the RST temperature decided the partition of snowfall and rainfall, but also because the simulated snow related to RST temperature could induce a significant feedback by changing the forcing meteorological variables in the regional atmospheric model WRF_CLM. Reversely, the forcing data were always the same for different RST temperatures in the offline land surface model CLM. The pattern of temperature and precipitation, along with other factors influencing the temperature simulation, could influence the effect of RST temperatures on snow simulation in the regional atmospheric model WRF_CLM. Therefore, a realistic treatment of model parameters, such as terrain height and spatial resolution, is highly recommended. In addition, representation of precipitation phase with suitable RST temperatures is vital for snow simulation in the models (such as the regional atmospheric model WRF_CLM), considering the interaction between atmosphere and land surface.

In addition, the impact of different RST temperature methods on the snow depth simulation and difference between the impacts estimated by land surface and regional atmospheric models were also tested with data from the Boreal Ecosystem Atmosphere Study (Shewchuk, 1997) and Valdai, Russia (Schlosser et al., 1997). It was noted that the accuracy rate of simulated results was not consistent for different sites with different RST temperature methods. However, a broad conclusion can be drawn stating that simulated results with the regional atmospheric model were more sensitive to the changes in RST temperatures than those with the offline land surface model. Other factors (pattern of temperature and precipitation, spatial resolution, and input terrain heights) were shown to have considerable effects on simulation sensitivity of the regional atmospheric model, in addition to the changes of RST temperatures.

Acknowledgements. The study is under the auspices of the National Natural Science Foundation of China (Grant No. 41275014) and the National Basic Research

Program of China (973 Program) Project (Grant No. 2010CB950503). We acknowledge the support for using the computing resources at Supercomputing Center of Cold and Arid Region Environment and Engineering Research Institute of Chinese Academy of Sciences.

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