Impact of rain snow threshold (RST) temperature on snow depth simulation in land surface model and regional climate model

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Abstract

The study investigates the impact of rain snow threshold (RST) temperatures on snow depth simulation using Community Land Model (CLM) and Weather Research and Forecasting Model (WRF-recently coupled with CLM and hereafter referred as WRF_CLM). The difference of the impact between the above two models is also discussed. Simulations are performed from December 17 1994 to May 30 1995 in the Alps, France. Results show that newly coupled WRF_CLM model represents fair simulation of snow depth and near surface temperature with actual terrain height and 2.5°C RST temperature. When six RST methods are applied to the simulation using WRF_CLM, the simulated snow depth is the closest to the observation in the methods using 2.5 °C RST temperature, followed by with Pipes', USACE, Kienzle's, Dai's, 0°C RST temperature method. In the case of using CLM, simulated snow depth is the closest to the observation when using Dai's method, followed by with USACE, Pipes', 2.5 °C, Kienzle's and 0 °C RST temperature method. The snow depth simulation using regional atmosphere model WRF_CLM is comparatively sensitive to change in RST temperature. Because the RST temperature is not only the factor to partition snow and rainfall in WRF_CLM. In addition the simulated snow related to RST temperature can induce a significant feedback by influencing the meteorological variables forcing land surface model in WRF_CLM. In comparison, the above variables remain unvarying, in CLM with changing RST. The impact of RST temperature on snow depth simulation also can be influenced by pattern of temperature and precipitation, spatial resolution and input terrain height.

Key Words: Snow simulation; RST temperature; WRF_CLM; CLM

1. Introduction

Snow can modify regional and possibly the remote hydroclimatic environment by changing the surface energy and water balance (Barnett, et al., 1989;Essery, et al., 1999;Walsh, et al., 1985;Yang, et al., 1997;Yeh, et al., 1983). Accurate representation of snow based on numerical models is a potential way not only to understand local climate but also to facilitate seasonal prediction. The separation of precipitation from snow to rain remains a key challenge in the snow simulation process. Many factors determine the precipitation morphology, such as thickness and temperature of the atmospheric boundary layer, position of the 0 °C isotherm, cloud types, air mass and humidity (Kienzle, 2008). Including the above listed factors to partition rain and snow in models will render complicated model physics, hence undermining the overall simulation efficiency of the model.. In order to simplify the modeling process and to 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 based on minimum air temperature, the dew point temperature or air temperature. The minimum temperature is employed to determine the precipitation type in a rainfall-runoff model in Australia 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 for a mountain in Idaho, USA. According to the above reference, the dew point temperature is site independent and coherent to discriminate snow and rain. While a study from Sweden (Feiccabrino and Lundberg, 2008) shows that air temperature is a better indicator than dew point temperature. Commonly used parameter is the RST air temperature (Gillies, et al., 2012;Motoyama, 1990;Yang, et al., 1997) . Taking reference from the above example, the authors employ RST air temperature for the current analysis. RST temperature mentioned in our study refers to the air temperature. A RST temperature of 2.5 °C was first determined by Auer (1974) based on nearly 1000 weather observations, that separated solid and liquid precipitation equally in their probability. 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, in Japan, the observed RST temperature is about 0 °C at Hokkdaido (northern region) and 2-3 °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 the aforementioned observations for RST temperature, climate models have adopted different parameterization to categorize the precipitation phase. General circulation models typically employ a constant RST temperature; for instance 2.2 °C RST temperature was applied for the Biosphere–Atmosphere Transfer Scheme (BATS) (Dickinson, et al., 1993;Yang, et al., 1997). For lowland and lower Alpine regions of Switzerland, a RST temperature of 0.5 °C was considered as 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, snowfall and rainfall events had a distinct RST temperature of -1.5 °C employed in the model *viz*., Interactions between Soil, Biosphere, and Atmosphere (ISBA) (Boone and Etchevers, 2001;Chevallier, et al., 2004). In the Community Atmospheric Model Version 3.0 (Collins, et al., 2004), the percent of snowfall is determined by a linear function of air temperature between 0 and -5 °C, that is, all precipitation falls as snow (rain) when the temperature is less than -5 °C (higher than 0 °C). The Canadian University of British Columbia (UBC) Watershed Model (Kienzle, 2008;Pipes and Quick, 1977) applied a linear approach to depict a mix of snowfall and rainfall, when the RST temperatures was regulated as 0.6 and 3.6 °C.

Apparently, there has been wide ranging difference in RST temperatures used in different models, mostly influenced by local snow properties and universal numbers. Simulated snow and related energy budget are sensitive to the change in RST temperatures (Fassnacht and Soulis, 2002;Loth, et al., 1993). With 3 different RST temperature methods, The accumulated simulated snow depths and snow water equivalents were significantly different in the study by Loth, et al. (1993). Fassnacht and Soulis (2002) thought warmer RST temperature produced more snow and bigger latent heat flux and ground heat flux during melt period And surface heat flux However, up to now only few studies examined the impacts of different RST temperature methods on snow simulation. Even fewer delved into studying varied impacts in offline land surface models (forced with observed meteorological data, without considering the interaction between atmosphere and land surface) and regional atmosphere models coupled with land surface model (considering the interaction between atmosphere and land surface). Our study intends to address this research gaps with an objective to study the impact and sensitivity of RST temperature methods on snow simulation in the offline land surface model (Community Land Model version 3.5, CLM) and regional atmosphere model (Weather Research and Forecasting model version 3.2, recently coupled with CLM model *viz.,* WRF_CLM). Section 2 of this article describes six RST methods that are applied for the models to study impact comparison. Section 3 introduces the observation data and models, simultaneously providing a detailed insight about the model settings and the experiments. Section 4 illustrates the snow depth simulation from 1994 December 17 (snow appears) to 1995 May 30 (snow melts out). Six popular RST temperature methods are applied into offline land surface model CLM and regional atmosphere 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 interval on snow depth simulation is discussed. Other factors that possibly affects the RST temperature impact on snow simulation is addressed in conjunction. Discussion and conclusions are showed in the last section.

2. RST temperature methods

Six RST methods applied for the models to study impact comparison are listed in Table 1. The first method tests the RST temperature value as 2.5 °C based on about 1000 weather observations (Auer, 1974). Precipitation falls as snow (rain) if the temperature is cooler (warmer) than the threshold temperature. The second method employs 0 °C RST temperature referred from Noah Model (Koren, et al., 1999). The third method that applies threshold method as the linear function of air temperature was used in Canadian UBC Watershed Model (Pipes and Quick, 1977),

$$rp = \begin{cases} 0 & T \le 0.6 \\ T/3 - 0.2 & 0.6 < T < 3.6 \\ 1 & T \ge 3.6 \end{cases} \qquad (1),$$

Wherein, rp is the ratio of falling rain to precipitation, T is the air temperature (°C).

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

$$rp = \begin{cases} 0 & T \le 0 \\ -54.632 + 0.2(T + 273.16) & 0 < T < 2 \\ 0.4 & 2 < T < 2.5 \\ 1 & T \ge 2.5 \end{cases} \tag{2}$$

The fifth RST temperature method is parameterized from daily precipitation data of 113 climate stations in South-Western Alberta and South-Eastern British Columbia (Kienzle, 2008) and is a curvilinear function of temperature

$$rp = \begin{cases} \max(0,5\left(\frac{T-T_T}{1.4T_R}\right)^3 + 6.76\left(\frac{T-T_T}{1.4T_R}\right)^2 + 3.19\left(\frac{T-T_T}{1.4T_R}\right) + 0.5 & T \le T_T \\ \min(1,5\left(\frac{T-T_T}{1.4T_R}\right)^3 - 6.76\left(\frac{T-T_T}{1.4T_R}\right)^2 + 3.19\left(\frac{T-T_T}{1.4T_R}\right) + 0.5 & T \ge T_T \end{cases} \tag{3}$$

where, T_T (2.6 °C) is temperature to separate the rainfall and snow fall evenly; T_R is the temperature range where the rainfall and snowfall can exist together and is set as 13.3 °C. The sixth calculator is fitted from the 3-hourly synoptic weather reports over 15,000 land stations and many ships globally (Dai, 2008). Here, the rainfall percentage is a hyperbolic tangent function of temperature.

$$rp = 1 - a(\tanh(b(T - c)) - d)/100 \tag{4}$$

where, a, b, c and d are the annual parameters on land and equals -48.2292, 0.7205,1.1662 and 1.0223, respectively.

3. Data and models

The data (Essery, et al., 1999) used to force offline land surface model CLM and validate WRF_CLM model includes hourly records of air temperature, humidity, wind speed, shortwave radiation, long wave radiation and precipitation. The above data was retrieved from Centre d'Etudes de la Neige site at Col de Porte (45 °N, 6 °E, 1320 m) over short grass land (Figure 1) from December 17 1994 to May 30 1995. The observed data for temperature and humidity was collected at 2 m above ground and the wind speed was measured at 2.5 m. Snow depth was monitored at hourly basis using an anultrsonic sensor. Surface temperature and albedo were calculated using long wave and short wave radiation measurements. This data set has been employed to assess lot other models , such as Snow MPI, SSIB, BATS, ISBA, CROCUS, ESCIMO and more (Belair, et al., 2003;Essery and Etchevers, 2004;Fernández, 1998;Strasser, et al., 2002;Sun and Xue, 2001).

The aforementioned observed hourly interval atmospheric data is used to drive CLM and to evaluate the effect of different RST temperatures on the snow depth simulation in offline land surface models. The land surface model CLM is developed by NCAR and is used extensively for offline and coupled model simulations in varied landscapes globally. Oleson, et al. (2008) and Collins, et al. (2006) have introduced the model in detail. In the present study, the offline simulation period is performed from December 17 1994 (snow appeared) to the end of May in 1995 (all snow melted) with CLM model.

Further, the newly coupled regional atmosphere model WRF_CLM is applied to study the effect of RST temperature on snow simulation and on the interaction between the land surface and atmosphere. Details on the model can be referred from Subin, et al. (2011) . WRF model is a limited-area, non-hydrostatic, primitive-equation model with multiple options for various physical parameterization schemes (Skamarock and Klemp, 2008). The selected options for atmospheric physics referred in our study are listed in Table 2. The simulation period using WRF_CLM is in accordance with the study period using CLM. The simulated domain is centered at 46 °N, 9 °W with 20 km horizontal grid spacing (Figure 1). The grid point dimension is 60×60. The model is set to 30 vertical layers with the top layer at 200 hPa. The initial and lateral boundary conditions are provided by National Centers for Environmental Prediction (NCEP) reanalyzed data version II (Kanamitsu, et al., 2002) and the latter is updated every 6 hours.

To compare the impact of different RST temperature in offline and regional atmosphere models and the impact difference between the two kinds of models, we employ CLM and WRF_CLM models to do a couple of simulations. However, the simulation by WRF_CLM model with default settings as explained in the next section is not so satisfactory . The previous study (Jin and Wen, 2012) show that replacement of realistic terrain height could improve the snow simulation ability of the adopted model. The comparison of RST impact with WRF_CLM is based on the improvement in the model setting. To see the impact of RST temperature on snow simulation under different terrain height, we perform sensitivity runs with different RST temperatures and different terrain heights. The detail of CLM and WRF_CLM experiments are listed in Table 3.

4.Result

4.1 Validation of models

With default model setting (2.5 °C RST temperature), CLM model could capture the observed snow depth variation fairly well (Figure 2a). However it tends to underestimate the snow. In general it can be used for the snow study. The experiment is referred as CLM-2.5 hereafter (Table 3).

When using WRF_CLM model with default model setting (with input terrain height at about 20 km horizontal spatial resolution and 2.5 °C RST temperature), deep snow depth at the station is simulated compared with the observation value (Figure 3a). The simulation experiment is refereed as OH-2.5 in the rest of the script (Table 3). The maximum simulated snow depth is nearly 4 m while the observation value is only 1.9 m. The simulated temperature is always lower than the observation value (Figure 3c). The simulated precipitation is slightly high in general (Figure not shown). The inaccuracy in the experiment OH-2.5 may be attributed to incorrect input terrain height value for the station (1860 m in the model while the actual value is 1320 m). The higher terrain height cooling the surface atmosphere and lowering the saturated vapor pressure induces more precipitation and produces deep snow. The deep snow makes the atmosphere cooler with more precipitation, and causes further more snow. Thus a positive feedback loop forms. Owing to low temperature, the snow melts quite slow, hence preventing temperature rise. So simulated snow depth of 3 m still exist in mid-May (Figure 3 a) and the simulated 2 m height temperature is around 0 °C (Figure 3 c). While in actuality there is no observation value for snow and the observed maximum daily temperature is about 10 °C.

Both the fine spatial resolution and the coarse spatial resolution with the accurate topography could possibly improve the snow simulation (Jin and Wen, 2012). Hence, to save the machine time (storage) and improve the simulation ability of the model, the simulation based on OH-2.5 experiment, in which the terrain height of the observation site in the model is replaced with the real value, is repeated and called CH-2.5 (Table 3). From RMSD (root mean square deviation) and the bias in Table 4, it can be seen that the simulation of CH-2.5 has been improved significantly. The CH-2.5 experiment captures snow depth variation fairly well except that snow is a little underestimated and melts a little bit earlier (Figure 2b & Figure 3b). The simulated temperature is more realistic in CH-2.5 experiment (Figure 3d). In summary, CH-2.5 has better simulation than OH-2.5. The model has the ability for adoption in similar research assignments whilst the real terrain height value is adjusted well in the whole domain. So the study with WRF_CLM employs the real terrain height value in the following, except for some sensitivity analysis.

4.2 Impact of different RST temperature on snow simulation

The separation of precipitation into snow and rain in models can affect the simulation of water and energy balance notably. There are lots of RST temperature methods used in numeric models presently. What is the difference in impact of these popularly used RST temperature methods on snow simulation? To answer this question, six different RST temperature methods described in Section 2 are applied into offline land surface model CLM and regional atmosphere model WRF_CLM for the comparison. The corresponding experiments are listed in Table 3. The offline land surface model CLM with different RST temperature methods can all simulate the snow depth fairly well (Figure 2) as it employs observed forcing. The difference caused by RST temperature with CLM model reflects primarily on the magnitude of the simulated snow depth. All methods in general overestimate the snow depth except with Dai's method and 0°C threshold temperature using CLM. The average maximum snow depth is simulated using Kienzle's method, followed by CLM-2.5. The finest simulation is achieved with Dai's method (Table 4&Table 5). In CLM-0 the simulation was most unfit.

In the experiments using regional atmosphere model WRF_CLM with the actual terrain height, the simulated snow depth with all different RST temperatures（Figure 2）are underestimated and snow melts earlier. The above results are different from the offline CLM. The finest simulation ability is seen from CH-2.5 (Table 4 & Table 5), however snow disappears 20 days earlier. Following is simulation with Pipes', USACE and Kienzle's methods (Table 4& Table 5), although the values are quite close to each other. Correspondingly, the less snow simulated causes 33, 34, 34 days earlier melting, respectively.

The accuracy of simulation with offline land surface model CLM and regional atmosphere model WRF_CLM corresponds to different RST temperature. The simulated snow has different responses to different RST temperature with CLM and WRF_CLM models. This is possibly because RST temperature partitions precipitation in different forcing height in offline land surface model CLM and regional atmosphere model WRF_CLM. The forcing height to the land surface model is 2 m and 54 m in CLM and WRF_CLM, respectively. In addition, there are other factors that influence the simulation in regional atmosphere model WRF, (such as spatial resolution, input terrain height, system error for simulating temperature, precipitation, radiation and assumingly more).

The difference of simulated snow depth between CH-2.5 and CH-0 is high when compared with that between CLM-2.5 and CLM-0 (Figure 2). Additionally, the simulated snow depth in regional atmosphere model WRF_CLM is more sensitive to RST temperatures than that in offline land surface model CLM. This is because not only RST temperature is a key factor to partition the snowfall and rainfall in regional atmosphere model WRF_CLM, but also simulated snow related to RST temperature can induce the big 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 is to the change in RST temperature, the sensitivity experiments with 1 °C RST temperature intervals are conducted using regional atmosphere model WRF_CLM and offline land surface model CLM. Such an analysis would help reflect the effect of RST temperature on snow simulation in addition to the energy and water interaction between land and the atmosphere.

4.3 Sensitivity of RST temperature on snow simulation

From the beginning of snow accumulation towards the end of its melting, the average observed snow depth is 0.87 m, whereas the average simulated snow depth in CLM-3, CLM-2, CLM-1 and CLM-0 are 1.22, 1.01, 0.89 and 0.48 m, respectively（Figure 4a). The snow depth in CLM-3, CLM-2 and CLM-1 is high as compared with the observation. The simulation in CLM-1 is the closest to observation perhaps because the actual RST temperature is around 1

°C. The long term observation in a meteorological station in Davos (1590m, 45 km north of Morteratsch) show mixed precipitation average between 0.75 and 1.5 °C with a standard deviation approximately ranging from 0.3 to 0.5 °C (Rohrer, 1989). The average 50% rain (snow) falls between 0.5 and 1 °C (L'Hote, et al., 2005). The simulated snow depth difference with offline land surface model CLM is relatively small between experiments with 1 °C interval from 3 to 1 °C RST temperature. The difference of average snow depth is only 0.21 (0.12) m between 3 and 2 (2 and 1) °C RST temperature. But the difference between experiments with 1 and 0 °C RST temperature can be as large as 0.41 m. The diverse discrepancies caused by the same RST temperature interval are possibly induced by the distribution of pattern of the observed temperature and precipitation forcing the offline land surface model CLM (Figure 5). Nearly 1/6th of the accumulated precipitation in the snow accumulation period falls between 0 and 1 °C and that almost equals to the sum of precipitation falling between 1 and 2 °C and between 2 and 3 °C. It is important to note that the simulated snow depth is not the same in the above experiments. However, the time of accumulation and end of ablation are closely simulated from the experiments as the forcing meteorological data is same.

Simulated snow depth with offline land surface model CLM and regional atmosphere model WRF_CLM is highest with maximum value of RST temperature that can partition major portion of precipitation as snow (Figure 4). In general the simulated snow depths in all experiments with WRF_CLM model are underestimated (Figure 4b). The average snow depth is roughly 0.68, 0.53, 0.14 and 0.05 m simulated with 3, 2, 1 and 0 °C RST temperature. The average simulated snow decreases about 93% from CH-0 to CH-3; and decreases nearly 61%

from CLM-3 to CLM-0. The simulated snow melting out time is also varied in above experiments employing WRF_CLM. The earliest ablation is at the beginning of April and the latest toward the beginning of May with WRF_CLM model. While all the simulations by CLM reflect melting out time during mid-May when using different RST temperatures .

The regional atmosphere model WRF_CLM is more sensitive to change of RST temperature than the offline land surface model CLM model owing to the feedback induced by different RST temperatures in the atmosphere model. The data forcing CLM does not change with the variation of RST temperature. While in experiments with the regional atmosphere model WRF_CLM,RST temperature not only decides the separation of snow and rain, but also the simulated snow related to RST temperature possibly alters the simulation of temperature, precipitation and energy balance in the atmosphere model. The simulated precipitation is almost same for WRF runs with different RST temperature, indicating that the precipitation is dominated by a large scale circulation in the simulated period and is not affected by change of land surface. The simulated 2 m height temperature by regional atmosphere model WRF_CLM with different RST temperatures is varied（Figure 6a）. The average 2 m height temperature in CH-3, CH-2, CH-1 and CH-0 for the simulated period is -0.2, 0.0, 1.0 and 1.7 °C, respectively. The difference can reach up to 1.9 °C. The simulated temperature in our study is nearly same with various snow depths before the melting out. The temperature difference gradually appears when there is no snow in the experiments with 0, 1, 2 °C RST temperature. Snow disappearance will result in the fast increase of air (Figure 6a) and surface (Figure 6b) temperature owing to the dramatic change of albedo (Figure 6c) and the energy budget, such as the change of latent heat flux (Figure 6d) and sensible heat flux (Figure 6e).

On April 10^{th} when there is no snow in CH-0 and snow still exists in other WRF_CLM runs, the albedo is about 0.4 and 0.8 in CH-0 and CH-3, respectively. Correspondingly, the simulated net radiation is 9.4 and 37 $w \cdot m^{-2}$ in CH-3 and CH-0, with same downward short wave radiation. In CH-0, more energy is utilized to heat the ground with small albedo. The sensible heat flux in CH-0 is 57.2 $w \cdot m^{-2}$ while in CH-3 it is -26.9 $w \cdot m^{-2}$. The sensible heat flux shifts from a negative to a positive value with snow disappearance, transferring the energy from atmosphere-to-snow to ground-to-atmosphere and simultaneously heating the atmosphere.

4.4 Sensitivity of RST temperature on snow simulation under different terrain height

With original input terrain height from model, the difference of average snow depth between OH-3 and OH-0 is about 0.31 m (Figure 7a). This difference is comparatively low compared with the difference (0.63 m) between CH-3 and CH-0 (Figure 4b). The reason for this immense difference is accredited to the relatively low temperature simulated by WRF_CLM model with the original input terrain height (Figure 7b). The temperate is averaged about -4.1 °C both in OH-3 and OH-0. The false original terrain height makes the temperature nearly below 0 °C during the simulated period. Therefore, with 0 and 3 °C RST temperature practically comparable separation of the precipitation into rain or snow takes place. Conversely, after changing the input terrain height to the actual value, the simulated average 2 m height temperature is 1.7 and -0.2 °C in CH-0 and CH-3, respectively (Figure 6a). Referring to the above experiments, one can possibly conclude that the impact of RST temperature on snow depth simulation is perhaps affected by other model parameters except the terrain height.

5. Discussion and conclusion

In this study, two major objectives are addressed. First is to validate the snow simulation ability of the recently coupled regional atmosphere model WRF_CLM. Second, to illustrate the impact of different RST temperature methods on snow depth simulation based on offline land surface model CLM (forced by observation, not considering the interaction between atmosphere and land surface) and the regional atmosphere model WRF_CLM (considering the interaction between atmosphere and land surface). In addition the difference in impact between the above two models is also deliberated. The results reflect that regional atmosphere model WRF_CLM demonstrates good simulation capacity for snow depth and near surface temperature with actual terrain height and default 2.5 °C RST temperature. Snow depth simulated based on the offline land surface model CLM using Dai's method is the closest to the observation. This is followed by with USACE, Pipes', 2.5 °C, Kienzle's, 0 °C RST temperature method. While simulated snow depth based on WRF_CLM with 2.5 °C RST temperature is the closest to the observation, followed by with Pipes', USACE, Kienzle's, Dai's, 0 °C RST temperature method. The difference in performance of the above two models can be explained based on factors in regional atmosphere model WRF that affects the simulation such as these including spatial resolution, input terrain height, system error for the simulation of temperature, precipitation, radiation, and more. In case of the offline land surface model CLM, the forcing data is fed with observed values. The difference of snow simulation with the same interval of RST temperature by regional atmosphere model

WRF_CLM is much higher than that by offline land surface model CLM. That is because RST temperature not only decides the partition of snowfall and rainfall, but also the simulated snow related to RST temperature can also induce the significant feedback by changing the forcing meteorological variables in regional atmosphere model WRF_CLM. Reversely the forcing data is always the same for different RST temperatures in offline land surface model CLM. The pattern of temperature and precipitation along with other factors influencing the temperature simulation can influence the effect of RST temperature on snow simulation in regional atmosphere model WRF_CLM. Therefore, realistic treatment of model parameters, such as terrain height and spatial resolution is highly recommended. In addition, representation of precipitation phase with suitable RST temperature is vital for snow simulation in the models considering the interaction between atmosphere and land surface, such as the regional atmosphere model WRF_CLM.

In addition to the above , the impact of different RST temperature methods on the snow depth simulation and impact difference between offline land surface model and regional atmosphere model also are tested with data from Boreal Ecosystem Atmosphere Study (Shewchuk, 1997) and Valdai, Russia (Schlosser, et al., 1997). It is noted that e accuracy rate of simulated results is not consistent for different sites with different RST temperature methods. However a broad conclusion can be drawn stating that simulated results with the regional atmosphere model is more sensitive to the change of RST temperature than with the offline land surface model. Other factors (pattern of temperature and precipitation, spatial resolution and input terrain height) have a considerable affect on simulation sensitivity of the regional atmosphere model to the change of RST temperature.

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Table 1 RST temperature methods

RST temperature method	Function
2.5 °C RST temperature (Auer, 1974)	$rp = \begin{cases} 0 & T < 2.5 \\ 1 & T \geq 2.5 \end{cases}$ rp: percentage of rainfall; T:air temperature
0 °C RST temperature (Koren, et al., 1999)	$rp = \begin{cases} 0 & T < 0 \\ 1 & T \geq 0 \end{cases}$
Pipes' (Pipes and Quick, 1977)	$rp = \begin{cases} 0 & T \leq 0.6 \\ T/3 - 0.2 & 0.6 < T < 3.6 \\ 1 & T \geq 3.6 \end{cases}$
USACE (U.S. Army Corps of Engineers, 1956)	$rp = \begin{cases} 0 & T \leq 0 \\ -54.632 + 0.2(T + 273.16) & 0 < T < 2 \\ 0.4 & 2 < T < 2.5 \\ 1 & T \geq 2.5 \end{cases}$
Kienzle's (Kienzle, 2008)	$rp = \begin{cases} \max(0,5\left(\frac{T-T_T}{1.4T_R}\right)^3 + 6.76\left(\frac{T-T_T}{1.4T_R}\right)^2 + 3.19\left(\frac{T-T_T}{1.4T_R}\right) + 0.5 & T \leq T_T \\ \min(1,5\left(\frac{T-T_T}{1.4T_R}\right)^3 - 6.76\left(\frac{T-T_T}{1.4T_R}\right)^2 + 3.19\left(\frac{T-T_T}{1.4T_R}\right) + 0.5 & T \geq T_T \end{cases}$ T_T :2.6 °C; T_R: 13.3 °C
Dai's (Dai, 2008)	$rp = 1 - a(\tanh(b(T - c)) - d)/100$ a: -48.2292; b: 0.7205; c: 1.1662 and d:1.0223

Table 2 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)

Table 3 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)

Table 4 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
	2m height temperature (°C)	6.1	3.2
	Precipitation(mm)	11.4	10.7
Bias	Snow depth(m)	1.5	-0.2
	2m height temperature (°C)	5.4	2.1
	Precipitation(mm)	0.9	-1

Table 5 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 6 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

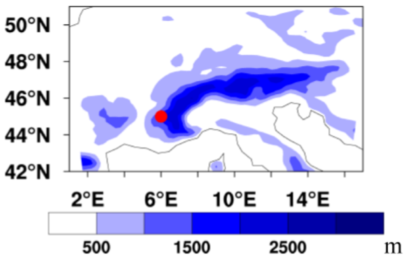
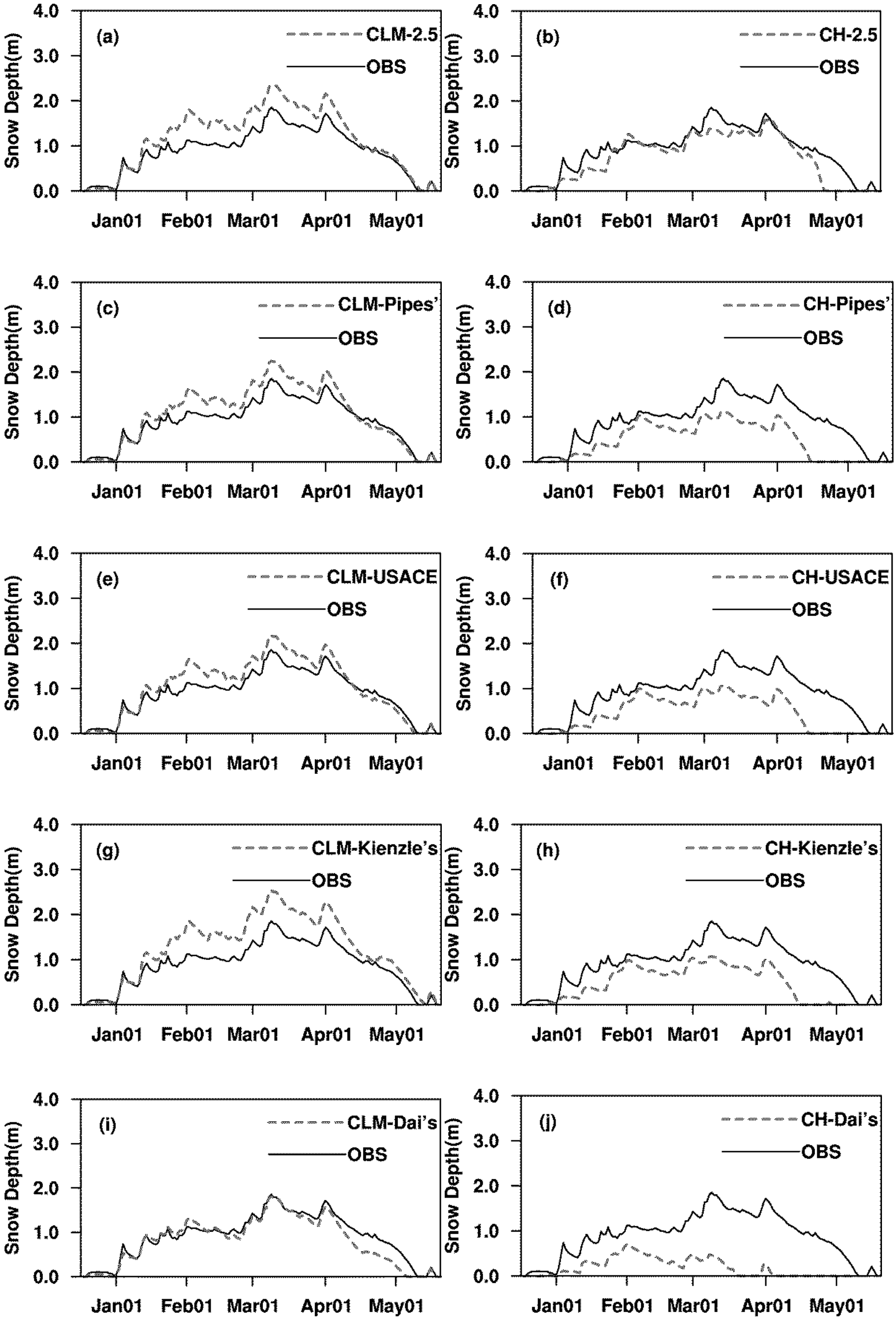


Figure 1 Topography of the simulated domain and the observation site (red circle)



(a)
CLM-2.5
OBS
(b)
CH-2.5
OBS
(c)
CLM-Pipes'
OBS
(d)
CH-Pipes'
OBS
(e)
CLM-USACE
OBS
(f)
CH-USACE
OBS
(g)
CLM-Kienzle's
OBS
(h)
CH-Kienzle's
OBS
(i)
CLM-Dai's
OBS
(j)
CH-Dai's
OBS
Snow Depth(m)
0.0
1.0
2.0
3.0
4.0
Jan01
Feb01
Mar01
Apr01
May01

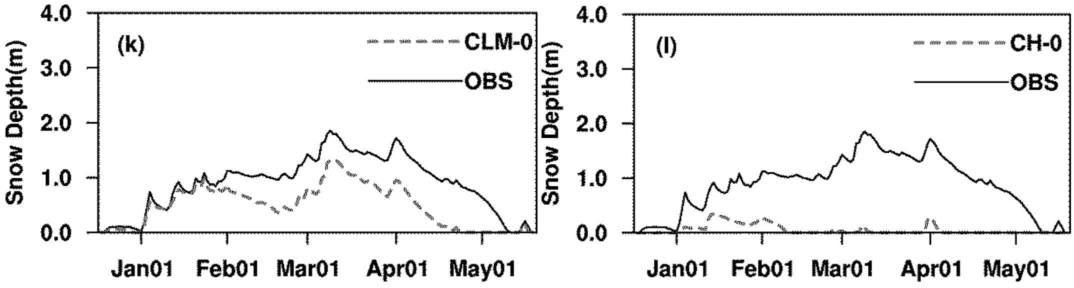


Figure 2 Observed and simulated snow depth with different RST temperature methods by CLM and WRF_CLM

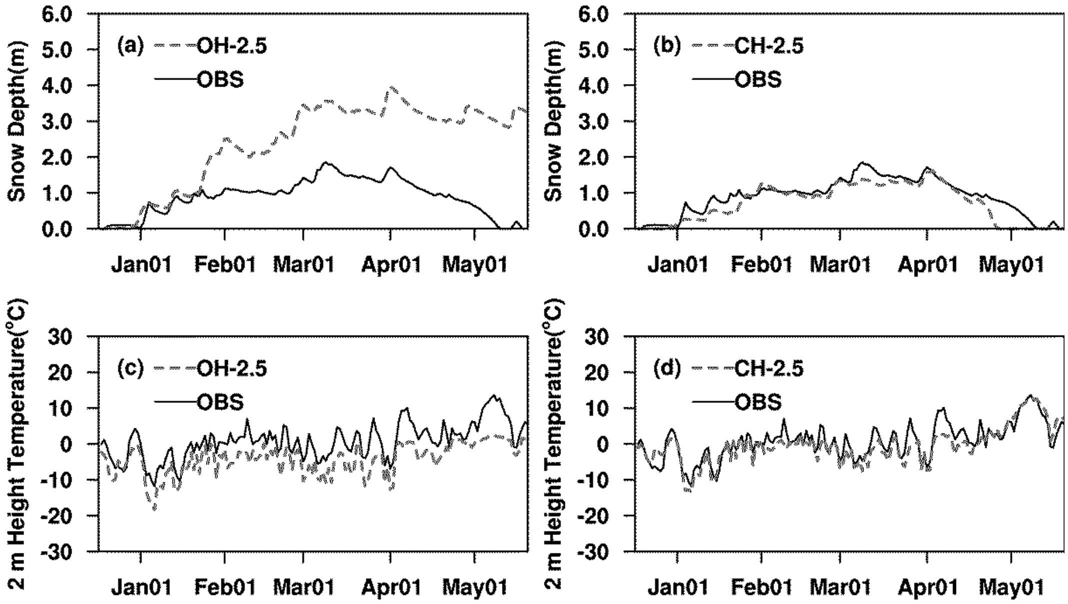


Figure 3 Observed and simulated snow depth and 2 m height air temperature with 2.5 °C RST temperature and default/changed terrain height.

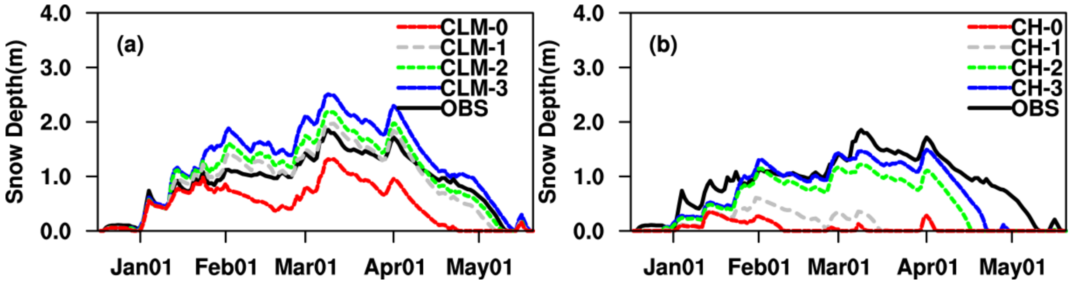


Figure 4 Observed and simulated snow depth with 3, 2, 1 and 0 °C RST temperature by CLM and WRF_CLM

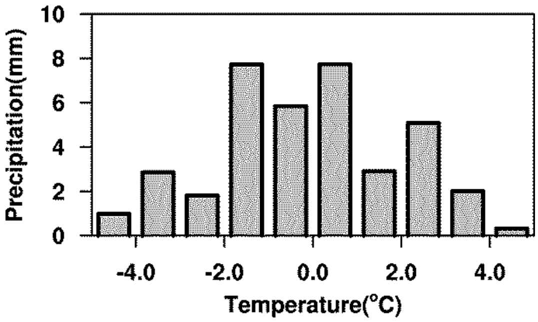


Figure 5 Distribution of observed precipitation and temperature

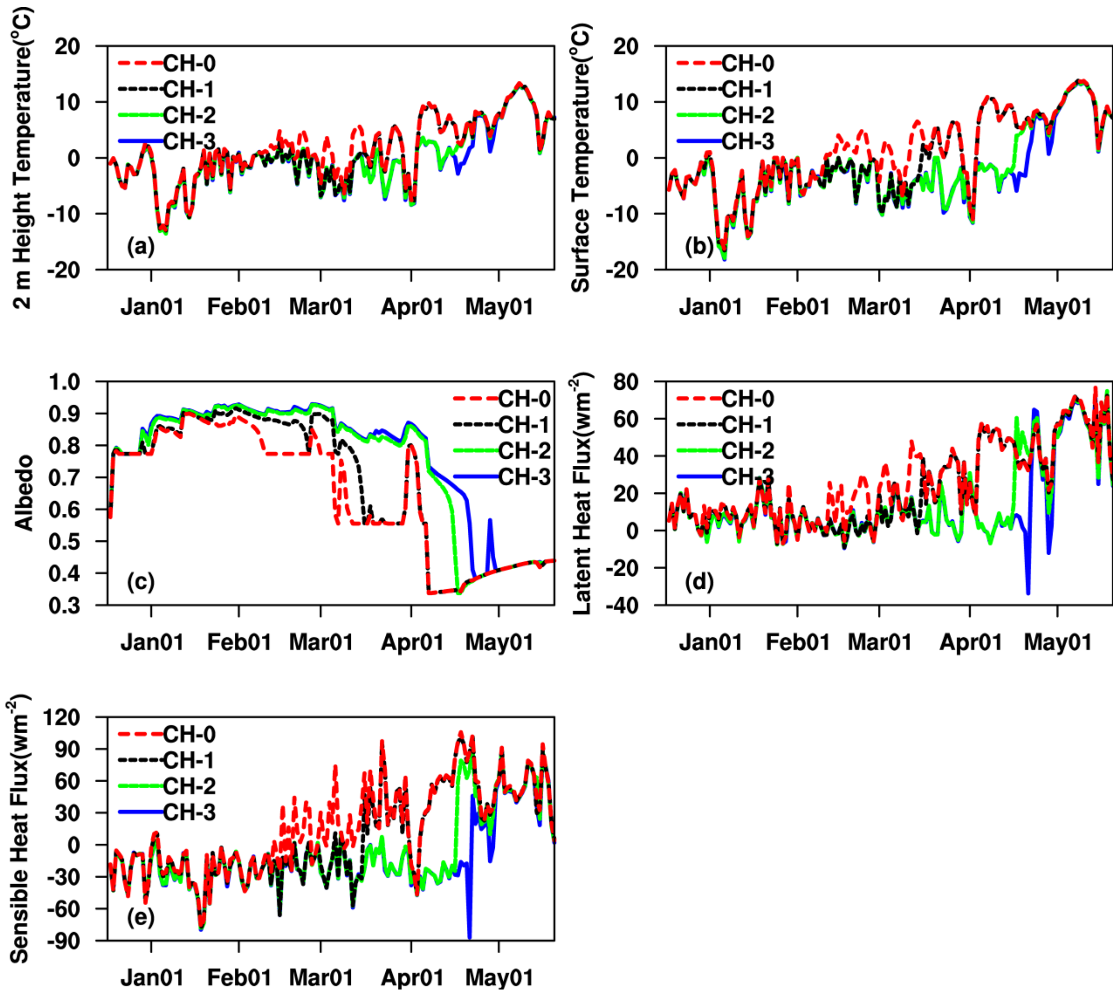


Figure 6 Simulated results by WRF_CLM with 3, 2, 1 and 0°C RST temperature

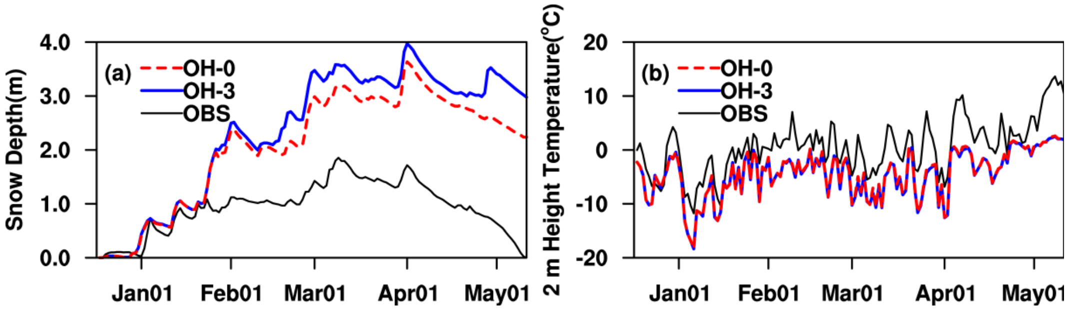


Figure 7 Simulated snow depth with 3/0 °C RST temperature and default terrain height by WRF_CLM