Comparison of Soil Water and Heat Transfer Modeling Over the Tibetan Plateau Using Two Community Land Surface Model (CLM) Versions

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Abstract Soil water and heat transfer is one of the most important parts of water and energy partition between atmosphere and land surface, and it is more complicated over the cold regions. In this study, the observed soil moisture and temperature are selected from four sites over the Tibetan Plateau (TP) to evaluate the performances two versions of Community Land Model (CLM), that is, CLM4.5 and CLM5.0. In addition, soil temperature observations from 67 sites and soil moisture observations from Maqu and Naqu monitoring network over the TP were used to evaluate the performances of regional simulations. The results indicated that the simulated soil temperature generally coincided with that of the observed, while CLM5.0 outputs are closer to the observed soil temperature in the arid and semiarid regions compared to CLM4.5. Generally, CLM5.0 tended to overestimate soil moisture at most sites at four soil depths (5, 10, 20, and 40 cm) but got some improvements at Maqu site. The overestimation of soil moisture was mainly caused by the introduction of a dry surface layer-based (DSL) soil evaporation resistance parameterization in CLM5.0, which improves the soil evaporation simulation over the TP, especially in the semiarid region. Moreover, we tried to distinguish the factors that affect the soil water and heat transfer in the models. The results showed that soil property data play a main role in soil water and heat transfer modeling.

Plain Language Summary The CLM5.0 is the latest version of the Community Land Model (CLM). Here, we selected observed soil moisture and temperature data over the Tibetan Plateau (TP) to evaluate the performances of CLM4.5 and CLM5.0. The results showed that the simulated soil temperature generally coincided with that of the observed, while CLM5.0 outputs are closer to the observed soil temperature in the arid and semiarid regions. Moreover, the simulated soil moisture by CLM5.0 tended to reduce the bias of soil moisture at subhumid area and overestimated soil moisture at semiarid area. The overestimation of soil moisture was mainly caused by the introduction of a dry surface layer-based (DSL) soil evaporation resistance parameterization in CLM5.0, which improves the soil evaporation and surface total water storage simulation over the TP, especially in the semiarid region. Finally, we replaced the forcing data (ITP) and soil property data by using the observed data to investigate the possibly causes in soil water and heat transfer. Single-point simulations show that model bias was possibly influenced by the uncertainties of soil category data and atmospheric forcing data. The impact of soil property data is more important than that caused by the forcing data.

1. Introduction

The Tibetan Plateau (TP) has an average elevation of more than 4,000 m, and a complex terrain, often referred to as the “Third Pole,” has been proved to have a significant impact on the climate in China and even in East Asia through its thermal and dynamic forcing (Deng et al., 2019; Duan et al., 2012). Moreover, the TP is also known as the “Asian Water Tower” which performs as the sources of Yangtze River, Yellow River, Langcang-Mekong River, and so forth. (Cui et al., 2015; Zhang et al., 2018). With the global warming, climate changes in the TP and its substantial effects have aroused a rapidly growing attention (Gao et al., 2014; Tian et al., 2014). The warming rate of the TP is 1.5 times of that of the global warming...
(Liu & Chen, 2000), showing that the TP is one of the most sensitive areas to global climate change (Kuang & Jiao, 2016; Liu & Chen, 2000). Thus, the TP is considered as an amplifier of the global warming (Meng et al., 2018; Yang et al., 2006). The accelerated climate warming on the TP has caused many environment changes, such as rapid glacier retreat, snow melt, and the permafrost degradation (Cheng & Wu, 2007). As a result, the increased warming will lead to major changes in hydrology and water resources over the TP (Cuo et al., 2013).

Interactions between land surface and the atmosphere affect weather and climate through changes on water and energy cycles. Soil moisture is regarded as a key variable in hydrological modeling, weather, and short-term climate forecasting (Meng et al., 2018). The variation of soil moisture directly affects the water vapor fluxes and weather and climate consequently (Akhar et al., 2018; Bao et al., 2017; Teuling et al., 2007; Zeng et al., 2015). Meanwhile, soil moisture controls the energy partition and regulates the surface runoff and soil freezing and thaw status (Seneviratne et al., 2010).

Soil (include bare soil and soil under vegetation) has quite different hydraulic and thermal properties, resulting in different behaviors of heat and moisture transport (Luo et al., 2017). The coexistence of ice and liquid water in the frozen soil greatly changes the soil thermal and hydraulic thermal properties (Farouki, 1986; Lawrence & Slater, 2008; Lundin, 1990), which in turn affects the distribution of water and heat across the soil column (Zhang et al., 2008). As one of the key thermal properties in numerical model, soil thermal conductivity is used to determine soil temperature and heat flux (Gao, 2005; Gao et al., 2003). In cold region, the cold condition makes slow decomposition of soil organic carbon (SOC) and thus leads to accumulation of dense roots and high SOC contents in the topsoil layer (Chen et al., 2012). Compared with other part of China, the soil in TP has higher gravel content; the porosity, density, and soil hydro-thermal characteristics of gravel are different. The existence of gravel will change the soil structure to a large extent, which will have a nonnegligible influence on the hydro-thermal process of soil. During phase change, soil moisture coupled with heat transport, and soil temperature changes interact with soil water (Hansson et al., 2004; Swenson et al., 2012), which makes the mechanism of soil water and heat transport more complicated (Cuntz & Haverd, 2018).

Due to the harsh natural environment, there are few observation sites and data accumulations in the TP, especially for the soil moisture data (Bi et al., 2016; Chen et al., 2013). Since the 1990s, the reanalysis data and land surface model data have provided important data support for atmospheric scientific research. Zhang et al. (2018) used the data of the soil moisture monitoring network in Naqu, the semi-arid region of the central TP and Maqu, the humid area of the eastern TP, to evaluate the soil moisture (SM) products of the European Space Agency (ESA), ERA-Interim, Modern-Era Retrospective analysis for Research and Applications (MERRA), and GLDAS (Global Land Data Assimilation System) and find that GLDAS-NOAH has better applicability on the TP. Chen et al. (2013) analyzed soil moisture and temperature data from Naqu soil moisture observation network in the central TP and found that all four land surface model products in the GLDAS underestimated the surface soil moisture, while GLDAS-CLM and GLDAS-NOAH model data have more representative performances on the 10-40 cm soil layer. In addition, large number of efforts have been made recently to improve the parameterization of soil freezing–thawing (FT) process, which have improved the simulation of terrestrial cycles and surface energy balances in the cold regions (Bao et al., 2016; Cuo et al., 2015; Hu et al., 2017; Zheng & van der Velde, 2015). Current land surface models (LSMs) have been thoroughly used for a better simulation of soil moisture and temperature profiles (Chen et al., 2010; Zeng et al., 2012). Luo and Zhang (2008) found that the CoLM with Farouki’s scheme overestimated the thermal conductivity of alpine grassland on the TP. Chen et al. (2012) investigated soil based on 77 soil profiles at 34 station and found that higher SOC content contained in the topsoil of alpine grasslands than the underlying soil layers. A new parameterization scheme was proposed by Chen et al. (2012) to take the impacts of SOC into account and found that the soil porosity and thermal characteristics cannot ignore the impact of gravel.

The CLM5.0 is the latest version in CLM, and there are no previous studies to evaluate the performances of CLM5.0 over the TP. In this study, the comparison between the two CLM versions against in situ observations is made over the TP. We focused on the following questions: How is the performance of the two CLM versions in simulation soil moisture and temperature? What are the main factors that affect the
performance of CLM5.0 in simulating soil moisture? What are the main factors that influence the soil water and heat transfer?

2. Data and Method

2.1. Study Area

The Tibetan Plateau, which covers a total area of $2.5 \times 10^6$ km$^2$ and with an average elevation of more than 4,000 m above sea level. The observed data we used in this paper are mainly from four observational stations (the red point in Figure 1) with surface fluxes observations, 67 soil temperature observation sites (the black points in Figure 1), and two soil moisture monitoring network in Maqu and Naqu (Tables 2 and 3) over the TP. The climate at Maqu site is cold and damp, the vegetation there is typical alpine meadow, and the soil is silt-clay-loam. The mean annual temperature is 1.9°C, and the mean annual precipitation amount is 593 mm (during 1981–2010) (Luo et al., 2017). The second site Maduo is situated near Eling lake, Qinghai Province China, with a cold and semiarid climate. The vegetation in Maduo is also typical steppe, and the soil contains large amounts of gravel. The third site Naqu-BJ is located in the middle of the TP with a cold and subhumid climate, the mean annual temperature is −3.35°C, and the mean annual precipitation amount is about 420 mm. The vegetation there is a typical alpine meadow, and the soil is mainly sand with sparse gravel. The site Amdo belongs to semiarid climate, and the vegetation in Amdo is typical steppe. The differences between typical steppe and typical alpine meadow are mainly distinguished by its growth conditions. The growth condition of typical steppe is mainly in semiarid or subhumid environment, where the mean annual precipitation amount is greater than 200 mm and less than 600 mm. The growth condition of typical alpine meadow is mainly in subhumid or humid environment, with the mean annual precipitation amount is roughly 400 to 450 mm. According to the Aridity Index (AI) defined by the United Nations Environment Programme, we divided the TP into three climate zones: arid region, semiarid region, and subhumid region, respectively (Figure 1).

2.2. Data

2.2.1. The Single-Point Observed Data

The observed atmospheric forcing data at four sites (Maqu, Maduo, Naqu-BJ, and Amdo) over TP were used in forcing single-point offline experiments. The atmospheric forcing data include air temperature, specific humidity, wind and pressure near surface, and precipitation, downward shortwave radiation, downward longwave radiation, with half-hourly temporal resolution. The observed soil moisture and temperature data at four sites (Table 1) were used to evaluate the performance of the two CLM versions.

2.2.2. Soil Moisture and Temperature Monitoring Network

To verify the universality of two CLM version, the observed soil moisture from two multiscale soil moisture monitoring networks in a cold subhumid region in Naqu and a cold humid region (Yang et al., 2013) (Table 2) in Maqu (Su et al., 2011) (Table 3) were used to evaluated the performances of regional simulations. The observed soil temperature mainly from the 67 sites over the TP (Figure 1).

Table 1

| Station | Latitude | Longitude | Elevation (m) | Land cover       | Depth (cm) | Climate zone   |
|---------|----------|-----------|---------------|------------------|------------|----------------|
| 1 Maqu  | 33.9     | 102.17    | 3,471         | Alpine meadow    | 5, 10, 20, 40 | Humid zone     |
| 2 Maduo | 34.9     | 97.57     | 4,272         | Alpine grassland | 5, 10, 20, 40 | Semiarid zone  |
| 3 Naqu-BJ | 31.37   | 91.90     | 4,509         | Alpine meadow    | 5, 10, 20, 40 | Subhumid zone  |
| 4 Amdo  | 32.24    | 91.62     | 4,695         | Alpine grassland | 5, 10, 20, 4 | Semiarid zone  |
2.2.3. ITP Forcing Data

The regional atmospheric forcing data are the China Meteorological Forcing Data set developed by the Institute of Tibetan Plateau Research (ITP), Chinese Academy of Sciences. The ITP data cover the period of 1979–2016, with 0.1° × 0.1° spatial resolution and 3-hourly temporal resolution.

Table 2

| Station | Latitude/longitude (deg.) | Elevation (m) | Land cover | Depth (cm) | Soil texture |
|---------|---------------------------|---------------|------------|------------|--------------|
| CST_01  | 33.88/102.13              | 3,431         | Grass      | 5, 10, 20, 40, 80 | —            |
| CST_02  | 33.67/102.13              | 3,449         | Grass      | 5, 10, 20, 40, 80 | —            |
| CST_03  | 33.90/101.97              | 3,507         | Grass      | 5, 10, 20, 40, 80 | —            |
| CST_04  | 33.77/101.72              | 3,504         | Grass      | 5, 10, 20, 40, 80 | —            |
| CST_05  | 33.67/101.88              | 3,542         | Grass      | 5, 10, 20, 40, 80 | —            |
| NST_01  | 33.88/102.13              | 3,431         | Grass      | 5, 10, 20, 40, 80 | Silt loam    |
| NST_02  | 33.88/102.13              | 3,434         | Grass      | 5, 10         | Silt loam    |
| NST_03  | 33.77/102.13              | 3,513         | Grass      | 5, 10         | Silt loam    |
| NST_04  | 33.62/102.05              | 3,448         | Wetland grass | 5, 10        | Silt loam    |
| NST_05  | 33.63/102.05              | 3,476         | Grass      | 5, 10, 20, 40 | Silt loam    |
| NST_06  | 34.00/102.27              | 3,428         | Grass      | 5, 10, 20, 40 | Silt loam    |
| NST_07  | 33.98/102.35              | 3,430         | Grass      | 5, 10         | Silt loam    |
| NST_08  | 33.97/102.60              | 3,473         | Grass      | 5, 10         | Silt loam    |
| NST_09  | 33.90/102.55              | 3,434         | Grass      | 5, 10         | Sandy loam   |
| NST_10  | 33.85/102.57              | 3,412         | Grass      | 5, 10, 20, 40 | Silt loam    |
| NST_11  | 33.68/102.47              | 3,442         | Wetland grass | 5, 10        | Silt loam    |
| NST_12  | 34.02/101.93              | 3,519         | Grass      | 5, 10, 20, 40 | Silt loam    |
| NST_13  | 33.85/101.88              | 3,752         | Grass      | 5, 10         | Silt loam    |

Table 3

| Station | Latitude/longitude (deg.) | Elevation (m) | SOC (%) | Clay (%) | Silt (%) | Depth (cm) |
|---------|---------------------------|---------------|---------|----------|----------|------------|
| L01     | 31.946/91.721             | 4,637         | 2.0     | 3.5      | 34.5     | 5, 10, 20, 40 |
| L02     | 31.890/91.700             | 4,731         | 2.0     | 3.5      | 34.5     | 5, 10, 20, 40 |
| L03     | 31.843/91.706             | 4,799         | 2.0     | 3.5      | 34.5     | 5, 10, 20, 40 |
| L04     | 31.806/91.750             | 4,818         | 2.0     | 3.5      | 34.5     | 5, 10, 20, 40 |
| L05     | 31.754/91.783             | 4,723         | 2.0     | 3.5      | 34.5     | 5, 10, 20, 40 |
| L06     | 31.678/91.842             | 4,628         | 2.0     | 3.5      | 34.5     | 5, 10, 20, 40 |
| L07     | 31.662/91.795             | 4,574         | 2.0     | 3.5      | 34.5     | 5, 10, 20, 40 |
| L08     | 31.639/91.755             | 4,570         | 2.0     | 3.5      | 34.5     | 5, 10, 20, 40 |
| L09     | 31.614/91.740             | 4,552         | 2.0     | 3.5      | 34.5     | 5, 10, 20, 40 |
| L10     | 31.587/91.793             | 4,539         | 2.0     | 3.5      | 34.5     | 5, 10, 20, 40 |
| L11     | 31.546/91.985             | 4,574         | 2.0     | 3.5      | 34.5     | 5, 10, 20, 40 |
| L12     | 31.521/92.050             | 4,516         | 2.0     | 3.5      | 34.5     | 5, 10, 20, 40 |
| L13     | 31.332/92.041             | 4,470         | 2.0     | 3.5      | 34.5     | 5, 10, 20, 40 |
| L14     | 31.274/92.109             | 4,478         | 2.0     | 3.5      | 34.5     | 5, 10, 20, 40 |
| L15     | 31.172/92.197             | 4,548         | 2.0     | 3.5      | 34.5     | 5, 10, 20, 40 |
| L16     | 31.128/92.250             | 4,609         | 2.0     | 3.5      | 34.5     | 5, 10, 20, 40 |
| L17     | 31.107/92.309             | 4,690         | 2.0     | 3.5      | 34.5     | 5, 10, 20, 40 |
| L18     | 31.713/92.458             | 4,762         | 2.0     | 3.5      | 34.5     | 5, 10, 20, 40 |
| L19     | 31.683/92.405             | 4,612         | 2.0     | 3.5      | 34.5     | 5, 10, 20, 40 |
| L20     | 31.664/92.342             | 4,518         | 2.0     | 3.5      | 34.5     | 5, 10, 20, 40 |
| L21     | 31.541/92.206             | 4,769         | 2.0     | 3.5      | 34.5     | 5, 10, 20, 40 |
| L22     | 31.369/91.899             | 4,505         | 2.0     | 3.5      | 34.5     | 5, 10, 20, 40 |
| L23     | 31.301/91.848             | 4,574         | 2.0     | 3.5      | 34.5     | 5, 10, 20, 40 |
| L24     | 31.259/91.799             | 4,630         | 2.0     | 3.5      | 34.5     | 5, 10, 20, 40 |
| L25     | 31.175/91.760             | 4,633         | 2.0     | 3.5      | 34.5     | 5, 10, 20, 40 |
| L26     | 31.129/91.726             | 4,765         | 2.0     | 3.5      | 34.5     | 5, 10, 20, 40 |
| L27     | 31.089/91.688             | 4,736         | 2.0     | 3.5      | 34.5     | 5, 10, 20, 40 |
| L28     | 31.033/91.679             | 4,675         | 2.0     | 3.5      | 34.5     | 5, 10, 20, 40 |
2.3. Methods

2.3.1. Description of CLM Versions

CLM5.0 is the latest version of the Community Land Model (CLM) released by the National Center for Atmospheric Research (NCAR), which is an upgraded version of CLM4.5. Most of the main components of the model have been updated, with particularly significantly changes between CLM5.0 and CLM4.5 in soil and plant hydrology, snow density (see Table 4 for details), river modeling, carbon and nitrogen cycling and coupling, and crop modeling (Lawrence et al., 2019).

2.3.2. Model Setup

To investigate the performance of CLM5.0 and CLM4.5, a set of single-point simulations at four representative sites and a long-term regional simulation were conducted over the TP. In this study, we selected “T” compset, which contain CLM with a data atmosphere model and a stub ocean, and stub sea-ice models. The regional and single-point simulations ran the Satellite Phenology Model (CLMSP) by using ITP forcing data and observed forcing data, respectively. The single-point simulation of CLM5.0 and CLM4.5 at Maqu, Naqu-BJ, Maduo, and Amdo sites ran one and half year. The first half-year result was used for spin-up, and we only used the last one-year results for analysis.

2.3.3. Designs of Sensitivity Experiments by CLM4.5

To distinguish the influence of atmospheric forcing data and soil property data on the CLM4.5 simulations, a set of single-point offline experiments (SP0, SP1, and SP2) at the Maqu, Maduo, and Naqu-BJ sites was conducted. Details of the numerical experiment designs are described in Table 5. According to the actual situation of the three sites, the plant function type (PFT) at Maqu sites was modified to grass, and the vegetation height was changed to 0.2 m; the PFT at Maduo sites was modified to grass, the PFT and lake percent at Maduo is 54% and 46%, respectively, the vegetation height was changed to 0.05 m; the PFT at Naqu-BJ is bare soil and grass, the proportion of bare soil and grass was modified to 20% and 80%, respectively, and the vegetation height was changed to 0.1 m.

2.3.4. Analytical Method

The land surface model simulations and observations data were processed to daily averaged value. The soil is layered into 15 layers in CLM4.5 and 25 layers in CLM5.0. The top 10 layers in CLM4.5 is 0–1.75 cm, 1.75–4.51 cm, 4.51–9.06 cm, 9.06–16.55 cm, 16.55–28.91 cm, 28.91–49.29 cm, 49.29–82.89 cm, 82.89–138.28 cm, 138.28–229.61 cm, and 229.61–380.19 cm, respectively. The calculation of soil temperature and moisture is located in the middle of each layer, corresponding to the soil depth is 0.71, 2.79, 6.23, 11.89, 21.22, 36.61, 61.98, 103.80, 172.76, and 286.46 cm, respectively. Four-layer soil moisture and temperature observations from four sites are used to compare with CLM4.5. Observations at 5 cm were compared against CLM4.5 at 6.23 cm, observations at 10 cm were compared against CLM4.5 at 11.89 cm, observations at 20 cm were compared against CLM4.5 at 21.22 cm, and observations at 40 cm were compared against CLM4.5 at 36.61 cm. The top 10 layers in CLM5.0 is 0–2, 2–6, 6–12, 12–20, 20–32, 32–48, 48–68, 68–92, 92–120, 120–152 cm, respectively. The calculation of soil temperature and moisture is located in the middle of each layer, corresponding to the soil depth is 1, 4, 9, 16, 26, 40, 58, 80, 106, and 136 cm, respectively. Observations at 5 cm were compared against CLM5.0 at 4 cm, observations at 10 cm were compared against CLM5.0 at 9 cm, observations at 20 cm were compared against CLM5.0 at 16 cm, and observations at 40 cm were compared against CLM5.0 at 40 cm.

| Table 4 |
| List of Updates May Influence Soil Water and Heat Transfer Modeling in CLM4.5 and CLM5.0 (Lawrence et al., 2019) |
| Component | CLM4.5 | CLM5.0 |
| --- | --- | --- |
| Hydrology | Hydraulic properties for frozen soil | Dry surface layer for ground evaporation |
| | Determined by liquid water only; Surface water store replaces wetland land unit | Spatially variable soil depth (0.4 to 8.5 m) |
| Snow | Surface energy fluxes calculated separately for snow-covered and snow-free portions of each land unit | Adaptive time-stepping solution of Richard’s equation |
| | Surface energy | Separate liquid and ice canopy water stores and radiative treatment, snow unloading due to temperature and wind |
| | | Wind and T effects on fresh snow density |

| Table 5 |
| Designs of Single-Point Experiments by CLM |
| Soil property data sets | Atmospheric forcing | Parameterization scheme |
| --- | --- | --- |
| SP0 | CLM default | ITP data set | CLM default |
| SP1 | CLM default | Observation | CLM default |
| SP2 | Observation | ITP data set | CLM default |
The simulation results from models were compared with the observed data on the basis of three statistical measures: bias (Bias), root mean square error (RMSE), correlation coefficient (Corr).

3. Results

3.1. Single-Point Simulation Results

Figure 2 compares the observed soil moisture to the simulated soil moisture by two CLM versions in four soil depths (5, 10, 20, and 40 cm) at four sites (Maqu, Naqu-BJ, Maduo, and Amdo). In the shallow layer (5 cm) at Maqu site, there was a slightly overestimation for soil liquid water content in both CLM versions, while the lowest Bias and highest Corr are identified in CLM4.5 (Table 6). In other layers, the CLM5.0 simulated soil moisture generally coincided with the observations. Compared to CLM4.5, the CLM5.0 simulated a shorter freezing time, which is closer to observations. In addition, CLM5.0 effectively reduced the dry biases at these four layers, especially during nonfreezing period. Compared to CLM4.5, the mean Bias of CLM5.0 significantly decreased. The Corr between the simulated and observed soil moisture has a significant improvement in CLM5.0. For example, the mean Corr between the CLM4.5 and CLM5.0 simulations and the observations of these four depths were 0.841 and 0.867, respectively. The annual mean precipitation amount in Maqu site is higher than other sites, which caused the soil in Maqu site is wetter.

Figure 2. Model simulations from CLM4.5 and CLM5.0 versus observations of daily soil moisture (unit: m$^3$ m$^{-3}$) at Maqu, Naqu, Maduo, and Amdo sites.
In CLM5.0 experiment at Naqu-BJ site, there was a significantly overestimation of the soil liquid water content at the four depths in the whole year. In CLM4.5 experiment, soil moisture generally coincided with that of the observed. It is seen that soil liquid water in CLM4.5 is closer to observations from Table 6. The mean Bias and mean RMSE between CLM5.0 simulations and observations are higher than CLM4.5, while the mean Corr is lower.

At the Maduo and Amdo sites, the CLM5.0 simulated soil moisture overestimated the observed at four layers, while the performance of CLM4.5 is better than CLM5.0 (Table 6). At the Maduo site, the CLM5.0 simulations overestimated soil liquid water at 20 and 40 cm. Compared to CLM4.5, CLM5.0 effectively decreased dry biases in 5 cm layer. At the Amdo site, the simulations overestimated soil liquid water during the freezing period at the top soil depths (5 and 10 cm), and overestimated soil liquid water in the whole year at the bottom soil depths (20 and 40 cm). Compared to CLM5.0, the mean Bias of CLM4.5 at these four depths decreased significantly, and the mean Corr increased (Table 6).

Figure 3 compares the observed soil temperature with the CLM5.0 and CLM4.5 simulations at four soil depths (5, 10, 20, and 40 cm) at Maqu station, Naqu, Maduo, and Amdo sites. The simulated soil temperature can well coincide with that of the observed. Compared to the CLM4.5, the CLM5.0 simulations show a significant improvement during the freezing period. During the freezing period, the CLM5.0 version effectively decreased cold bias at Maqu site. The mean Bias of soil temperature simulated by CLM5.0 and CLM4.5 was roughly 1 and 2°C at Maqu site (Table 7), respectively. In the Naqu site in the subhumid zone, the simulated soil temperature by two CLM versions can be well coincided with that of the observed. The mean Bias and RMSE between the simulated and observed soil temperature decreased with the soil depth, and the mean Corr increased respectively (Table 8). For example, the mean Bias at these four depths (5, 10, 20, and 40 cm) were −0.709, −0.463, −0.179, and −0.054°C, respectively. Compared to CLM4.5, CLM5.0 effectively decreased cold biases in the thawing period and increased the warm biases in the completely freezing period at Maduo site and decreased cold biases during the freezing period at Amdo site.

### 3.2. Regional Simulation Results

#### 3.2.1. Soil Temperature

From the above results, a potential suggestion of soil moisture simulations in different climate zone regions seems to be different for two CLM versions. The locations of soil temperature observation sites were shown in Figure 1. We divided these sites into three types according to the climate zones division (Figure 1) over the TP and calculated the average value for each type of sites. The observed soil temperature we used was from 1980 to 2014, and we calculated the mean annual cycle from long-term daily data. On average, at these four depths, more substantial improvements occurred in CLM 5.0 version, in which the mean Bias was reduced approximately 0.3°C compared to CLM4.5 simulations; RSME was reduced from 0.98, 1.19, 1.66, and 1.06°C to 0.56, 0.69, 1.06, and 0.59°C, and Corr increased slightly respectively (Table 8). In subhumid area, the simulated Bias was smaller than that for the other climate zones throughout the whole year. Overall, the CLM5.0 improved the simulated soil temperature effectively and reduced the cold biases in arid and semiarid area.
Figure 3. Same as Figure 2, but for soil temperature (unit: °C).

Table 7
Same as Table 6, but for Soil Temperature (Unit: °C)

| Variables | CLM4.5 | CLM5.0 |
|-----------|--------|--------|
|           | Maqu   | Maduo  | Naqu  | Amdo  | Maqu   | Maduo  | Naqu  | Amdo  |
| Bias      |        |        |       |       |        |        |       |       |
| 5 cm      | -1.565 | 2.205  | -0.709| -0.557| -0.706 | 0.317  | 1.872 | -0.397|
| 10 cm     | -1.736 | 2.273  | -0.463| -0.843| -0.855 | 0.653  | 1.612 | -0.118|
| 20 cm     | -2.066 | 1.920  | -0.179| -0.679| -1.203 | 0.611  | 1.317 | -0.973|
| 40 cm     | -2.562 | 2.605  | -0.054| -0.704| -1.585 | 1.117  | 0.981 | -0.098|
| RMSE      |        |        |       |       |        |        |       |       |
| 5 cm      | 3.496  | 3.120  | 2.422 | 2.019 | 2.460  | 2.455  | 2.944 | 2.069 |
| 10 cm     | 3.423  | 3.299  | 2.527 | 2.022 | 2.512  | 2.946  | 2.926 | 2.047 |
| 20 cm     | 3.389  | 3.611  | 2.817 | 2.198 | 2.673  | 3.659  | 2.974 | 2.129 |
| 40 cm     | 3.452  | 4.085  | 3.416 | 2.638 | 3.448  | 3.316  | 3.547 | 2.831 |
| Corr      |        |        |       |       |        |        |       |       |
| 5 cm      | 0.944  | 0.963  | 0.962 | 0.973 | 0.960  | 0.970  | 0.962 | 0.973 |
| 10 cm     | 0.966  | 0.970  | 0.974 | 0.983 | 0.974  | 0.978  | 0.973 | 0.985 |
| 20 cm     | 0.968  | 0.975  | 0.981 | 0.979 | 0.973  | 0.980  | 0.978 | 0.983 |
| 40 cm     | 0.960  | 0.976  | 0.984 | 0.970 | 0.961  | 0.960  | 0.981 | 0.982 |
In order to reduce the influence of site average and the mean annual cycle, we selected three types of soil temperature observation sites from arid, semiarid, subhumid area, respectively, and calculated the decade mean value. Figure 4 displays the simulated and observed daily soil temperature at 10 cm in the three climate zones in four decades. In the arid area, the CLM4.5 tended to underestimate soil temperature in these four decades throughout the whole year. The simulated Biases tended to increase when observed soil temperature more than 1°C, and the Biases in 2010–2014 are larger than in other decades. Compared to CLM4.5, CLM5.0 simulations were closer to observations. In the semiarid area, the CLM4.5 and CLM5.0 simulations tended to underestimate soil temperature. Compared to CLM4.5, CLM5.0 indicated some improvements throughout the whole year. In the subhumid area, the CLM4.5 and CLM5.0 simulations were better than in other climate zones.

### Table 8

| Climate zone | Bias CLM4.5 | Bias CLM5.0 | RMSE CLM4.5 | RMSE CLM5.0 | Corr CLM4.5 | Corr CLM5.0 |
|--------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Arid 5 cm    | −0.6876     | −0.0211     | 0.6917      | 0.6209      | 0.9995      | 0.9997      |
| 10 cm        | −0.4697     | 0.1911      | 0.6266      | 0.3445      | 0.9995      | 0.9996      |
| 20 cm        | −0.3099     | 0.3394      | 1.3559      | 0.8276      | 0.9979      | 0.9996      |
| 40 cm        | 0.0485      | 0.7024      | 1.3094      | 0.8803      | 0.9990      | 0.9994      |
| Semiarid 5 cm| −0.8130     | −0.4558     | 0.9751      | 0.5696      | 0.9991      | 0.9993      |
| 10 cm        | −0.7394     | −0.4288     | 1.1922      | 0.6926      | 0.9981      | 0.9988      |
| 20 cm        | −0.6172     | −0.3451     | 1.6635      | 1.0617      | 0.9947      | 0.9967      |
| 40 cm        | −0.8312     | −0.5839     | 1.0649      | 0.5959      | 0.9986      | 0.9993      |
| Subhumid 5 cm| 0.1781      | 0.7914      | 0.3615      | 0.7994      | 0.9993      | 0.9989      |
| 10 cm        | 0.1219      | 0.6973      | 0.3597      | 0.6973      | 0.9997      | 0.9989      |
| 20 cm        | 0.1271      | 0.6727      | 0.6703      | 0.6728      | 0.9988      | 0.9997      |
| 40 cm        | −0.0585     | 0.4844      | 0.4417      | 0.5294      | 0.9998      | 0.9993      |

**Figure 4.** Model simulations versus observations of daily soil temperature (unit: °C) at 10 cm (a) CLM4.5 in the arid region, (b) CLM4.5 in the semiarid region, (c) CLM4.5 in the subhumid region, (d) CLM5.0 in the arid region, (e) CLM5.0 in the semiarid region, and (f) CLM5.0 in the subhumid region in four decades.
3.2.2. Soil Moisture

To verify the universality of simulations, the observed soil moisture from Maqu and Naqu network were used to evaluate the performance of regional simulations. Figure 5 shows the model simulations from CLM4.5 and CLM5.0 versus observations of daily soil moisture at 5 and 10 cm in the Maqu and Naqu network. It can be seen from Figure 5 that CLM4.5 and CLM5.0 simulations can reflect the seasonal variations of observations. At Maqu network, the model tended to underestimate soil moisture during the thawing period, and the CLM4.5 and CLM5.0 simulated soil moisture generally coincided with that of the observations during the freezing period. Compared to CLM4.5, the CLM5.0 effectively reduced the dry biases during the thawing period. On average, at these two depths, more substantial improvements in CLM5.0, in which the mean Biases reduced from $-0.07$, $-0.10$ to $-0.02$, $-0.06$, and the RMSE reduced from $0.08$, $0.10$ to $0.05$, $0.07$, respectively (Table 9). At Naqu network, the CLM5.0 effectively reduced the dry biases during the thawing period and increased the wet biases during the freezing period at these two depths. Compared to CLM5.0, CLM4.5 reduced the mean Bias and RMSE, and the Corr was increased. Overall, the CLM5.0 improved the soil moisture simulations during the thawing period in Maqu and Naqu network and increased the wet biases during the freezing period in Naqu network.

**Table 9**

| Network | Bias   | RMSE   | Corr   |
|---------|--------|--------|--------|
|         | CLM4.5 | CLM5.0 | CLM4.5 | CLM5.0 | CLM4.5 | CLM5.0 |
| Maqu    |        |        |        |
| 5 cm    | $-0.068$ | $-0.024$ | $0.082$ | $0.049$ | $0.957$ | $0.931$ |
| 10 cm   | $-0.095$ | $-0.036$ | $0.103$ | $0.067$ | $0.950$ | $0.936$ |
| Naqu    |        |        |        |
| 5 cm    | $-0.017$ | $0.039$ | $0.049$ | $0.056$ | $0.962$ | $0.839$ |
| 10 cm   | $-0.009$ | $0.042$ | $0.024$ | $0.044$ | $0.966$ | $0.893$ |
4. Differences of Soil Water and Heat Transfer Modeling Between Two Model Versions

4.1. Parameterization Scheme in CLM Models

4.1.1. Dry Surface Layer Soil Evaporation Resistance Parameterization for Ground Evaporation Estimation

Above all, the performance of CLM5.0 in simulating soil temperature is better than CLM4.5. For soil moisture, the CLM5.0 produced great improvement in the humid area and overestimated soil moisture in subhumid and semiarid area, which also resulted in the biases of surface flux. The overestimation of soil moisture was mainly caused by the introduction of a dry surface layer-based soil evaporation resistance parameterization (Swenson & Lawrence, 2014). The CLM4.5 shows a bias in evapotranspiration and total water storage in semiarid region, with the seasonal cycle amplitude of total water storage is too low, while evapotranspiration is too strong (Swenson & Lawrence, 2014). Soil evaporation is controlled by the rate of diffusion of water vapor through a dry surface layer (DSL). Based on the introduction of DSL, soil resistance expression reduced biases of evapotranspiration and increased total water storage, which led to the overestimation for soil moisture in the semiarid region.

The soil evaporation in CLM4.5 is

\[
E_{\text{soil}} = -\rho_{\text{atm}} \frac{\beta_{\text{soil}} (q_{\text{atm}} - q_{\text{soil}})}{r_{\text{aw}}} \tag{1}
\]

where \(q_{\text{atm}}\) is the atmospheric specific humidity (kg kg\(^{-1}\)), \(q_{\text{soil}}\), \(q_{\text{snow}}\), and \(q_{\text{h2osfc}}\) are the specific humidity (kg kg\(^{-1}\)) of the soil, snow, and surface water, respectively, \(r_{\text{aw}}\) is the aerodynamic resistance to water vapor transfer (s m\(^{-1}\)).
Then Equation 1 can be

\[ E_{\text{sol}} = -\rho_{\text{atm}} \frac{(q_{\text{atm}} - q_{\text{soil}})}{r_{\text{aw}} + r_{\beta}} \]  

(2)

\( r_{\text{aw}} \) is the soil resistance to water vapor transfer (s m\(^{-1}\)).

The dry surface layer (DSL) is parameterized as a function of the top soil layer moisture (Swenson & Lawrence, 2014):

\[ DSL = \begin{cases} \Delta z & \theta_{\text{d0}} < \theta_{\text{top}} \\ \Delta z \frac{\theta_{\text{d0}} - \theta_{\text{top}}}{\theta_{\text{top}} - \theta_{\text{air}}} & \theta_{\text{top}} \geq \theta_{\text{d0}} \end{cases} \]  

(3)

where \( \Delta z \) is the length scale of the maximum DSL thickness (m), \( \theta_{\text{d0}} \) is the moisture value at which the DSL initiates, \( \theta_{\text{top}} \) is the soil moisture value of the top model soil layer, and \( \theta_{\text{air}} \) is the “air-dry” soil moisture value (Dingman, 2002). After the dry surface layer thickness has been determined, the soil resistance to evaporation follows from

\[ R_{\text{sol}} = \frac{DSL}{D_v \tau} \]  

(4)

where \( D_v \) is the molecular diffusivity of water vapor in air (m\(^2\) s\(^{-1}\)) and \( \tau \) describes the tortuosity of the vapor flow paths through the soil matrix (Deol et al., 2012).

The soil moisture biases between CLM4.5 and CLM5.0 mainly caused by the improvement of soil evaporation. In this study, regional offline simulations over the TP using CLM4.5 and CLM5.0 were conducted to validate the simulation of soil evaporation and soil moisture. Figure 6 shows time series of soil evaporation and soil moisture over the TP and the arid, semiarid, and subhumid area. In these four regions, the CLM4.5
simulated soil evaporation is roughly twice as large as that of the CLM5.0 simulated. In addition, the simulation biases in the semiarid area were larger than in other regions. Compared to the CLM4.5, the CLM5.0 simulated soil moisture tended to increase in these four regions, and the simulation biases are the biggest in the semiarid area.

Figure 7 shows maps of the annual mean of ground evaporation and annual mean soil moisture in summer from 1980 to 2016 over the TP. The climatology of CLM4.5 and CLM5.0 ground evaporation simulations (Figures 7a and 7b) shows similar pattern with two models decrease from the central to the northwest and southwest of the TP, with the maximum in the semiarid area and the minimum in the desert in the north of the TP. As shown in Figures 7d and 7e, both CLM4.5 and CLM5.0 soil moisture simulations show the similar pattern in two models decreasing from the southeast to the northwest of the TP, and the CLM4.5 simulations are smaller than CLM5.0. Compared to the CLM4.5 simulated, the CLM5.0 simulated ground evaporation tended to decrease over the whole TP, with the maximum in the semiarid area, which lead to the increase of soil moisture over the TP. However, the maximum of ground evaporation is in the semiarid area of the TP, while the maximum of soil moisture is in the border between the arid and the semiarid areas.

Figure 8. Biases of soil moisture at 10 cm (unit: m$^3$ m$^{-3}$) between new parameterizations for fresh density and the original code in CLM5.0 model in summer from 1980 to 2016 over the TP.

Figure 9. Model simulations from SP0, SP1, and SP2 versus observations of daily soil moisture (unit: m$^3$·m$^{-3}$) at different depths (5, 10, and 20 cm) in Maqu, Maduo, and Naqu sites.
4.1.2. New Parameterization on Fresh Snow Density

New parameterizations, including the fresh snow density, which added the temperature effects and wind effects (Kampenhout et al., 2017). In the CLM4.5 code, the bulk density of newly fallen snow (kg m$^{-3}$) is parametrized following Anderson (1976),

$$\rho_{sno} = 50 + 1.7(T - T_f + 15)^{1.5} \begin{cases} 
50 + 1.7(T_f)^{1.5} & T_f > T_f + 2 \\
T_f - 15 < T \leq T_f + 2 & T \leq T_f - 15
\end{cases}$$

(5)

where $\rho_{sno}$ is the bulk density of newly fallen snow, $T$ is the atmospheric temperature (K), and $T_f$ is the freezing temperature (K).

In the CLM5.0 code, the bulk density of newly fallen snow is parameterized by a temperature-dependent and a wind-dependent term:

$$\rho_{sno} = \rho_T + \rho_w.$$  

(6)

The temperature dependent term is given by (Kampenhout et al., 2017)
Snow density increases due to wind-driven compaction according to Kampenhout et al. (2017):

\[
\rho_{\text{sno}} = \begin{cases} 
50 + 1.7(17)^{1.5} & T_f > T_f + 2 \\
50 + 1.7(T - T_f + 15)^{1.5} & T_f - 15 < T \leq T_f + 2 \\
-3.8382(T - T_f) - 0.0333(T - T_f)^2 & T \leq T_f - 15 
\end{cases}
\]  

(7)

Snow thermal conductivity is calculated following Jordan (1991):

\[
\lambda = \lambda_{\text{air}} + (7.75 \times 10^{15} \rho_{\text{sno}} + 1.105 \times 10^{-6} \rho_{\text{sno}}^2) (\lambda_{\text{ice}} - \lambda_{\text{air}}) 
\]

(9)

where \( \lambda_{\text{air}} = 0.023 W m^{-1} K^{-1} \) and \( \lambda_{\text{ice}} = 2.29 W m^{-1} K^{-1} \) are the thermal conductivity of air and ice, respectively.

The soil moisture biases between CLM4.5 and CLM5.0 may be caused by the new parameterizations for fresh snow density (updated temperature effects and wind effects). In this study, we replaced the new...
parameterizations for fresh snow density (Equation 7) by the CLM4.5 fresh snow density parameterizations (Equation 5) in the CLM5.0 model. Figure 8 shows the soil moisture biases between new parameterizations (Equation 7) for fresh density and the original code (Equation 5) in CLM5.0 model in summer from 1980 to 2016 over the TP. In CLM5.0, the soil moisture tended to decrease when we used the new parameterizations for fresh snow density. As a result, the overestimated of CLM5.0 soil moisture is mainly caused by the dry surface layer for ground evaporation.

4.2 Influence of Soil Property Data and Forcing Data

4.2.1 Single-Point Simulations

Atmospheric forcing data are important for land surface model simulation of land surface processes (Guo et al., 2017). Figure 9 shows the time series of the simulated soil moisture from different single-point experiments and observations at Maqu, Maduo, and Naqu-BJ sites, respectively. Comparing the simulation between SP0 and SP1, atmospheric forcing data mainly affect the simulation of soil moisture during the thawing period, which underestimated the soil moisture value in the thawing period at Maqu and Naqu sites. Soil category data, which represent the underlying property, are crucial for land surface model (LSM) simulation of surface hydrology (Yang et al., 2018). At Maqu and Maduo site, compared to SP0, soil moisture simulated by SP2 get greatly improved. The differences of the simulated soil moisture between ITP forcing data and observed atmospheric forcing data are relatively small. Figure 10 shows the simulated soil temperature from different single-point experiments versus observations at Maqu, Maduo, and Naqu-BJ sites, respectively. Compared to SP0, soil temperature simulated by SP2 is greatly improved.

![Figure 12](image-url). Same as Figure 11, but for soil temperature (unit: °C).
at Maqu and Maduo site. At Naqu site, soil temperature simulated by SP1 is more coincidence with the observation.

4.2.2. Regional Simulations
The soil water and heat transfer are one of the important processes for the exchange of moisture and energy between land and atmosphere. Improving the accuracy of soil water and heat transfer modeling is an urgent need to improve the effects of land surface processes and climate simulations. The particle size of the soil is the basic physical properties of the soil, which has an influence on the soil water and heat properties. In this study, we used BNU (Beijing Normal University) soil property data replaced the CLM default soil property data to investigate soil water and heat transfer processes in four season.

Figures 11 and 12 show comparisons and differences of the simulated soil moisture and temperature by using CLM4.5 default and BNU soil property data in four seasons. By replacing the soil property data, the simulated soil moisture tended to increase in most region over the TP in summer and autumn and decrease in southwest over the TP in winter. Simulated soil temperature tended to decrease over the TP in four season by replacing the soil property data. It can be seen that soil water and heat transfer in land surface model were also influenced by soil property data.

5. Conclusion and Discussion
In this study, offline simulations at regional and single-point scales over the TP using CLM4.5 and CLM5.0 were conducted to validate the performances of the simulated soil moisture and temperature. Compared to the observed data (at Maqu, Naqu, Maduo, and Amdo sites), the RMSE of the CLM4.5 and CLM5.0 simulated soil temperature is within 4 and 3°C approximately, respectively. The RMSE of CLM4.5 and CLM5.0 regional simulations in the arid area at these four depth is within 1.36 and 0.88, and within 1.66 and 1.06°C in the semiarid area, and within 0.67 and 0.80°C in the subhumid area. Overall, the simulated soil temperature was generally coincided with that of the observed, and the CLM5.0 simulated soil temperature indicated some improvements in the arid and semiarid area compared to CLM4.5. The soil moisture deficiencies in CLM4.5 and CLM5.0 simulations mainly show that the content of soil liquid water has relatively large biases at Maqu, Naqu, Maduo, and Amdo sites. Compared to the CLM4.5 simulated, the CLM5.0 tended to decrease the biases during the freezing and thawing periods at Maqu site and overestimated soil moisture at Naqu, Maduo, and Amdo sites. In the Naqu and Maqu network, the CLM5.0 improved the soil moisture simulations during the thawing period and increased the wet bias during the freezing period in Naqu network.

The overestimation of soil moisture was mainly caused by the introduction of a dry surface layer-based soil evaporation resistance parameterization in the semiarid area. The CLM5.0 simulated soil evaporation tended to decrease in the arid, semiarid, and subhumid areas over the whole TP, with the maximum in the semiarid area, which led to the increase of soil moisture over the TP. New parameterizations for fresh snow density (updated temperature effects and wind effects) tended to overestimate the fresh snow density in southwest on the TP (picture omitted). The updated fresh snow density is not a mainly cause to influence the soil moisture. According to a set of single-point experiments conducted at Maqu, Naqu, and Maduo site, illustrating that the part biases of soil water and heat transfer are due to the forcing data and soil property data. The impact of soil property data is more important than forcing data. By replacing the CLM default soil property data by BNU data, simulated soil moisture tended to increase in most regions over the TP in summer and autumn.

Soil temperature can reflect the thermal state of the soil and directly affects the exchange of surface energy as the upward longwave radiation and sensible and ground heat fluxes depend on it (Mahanama et al., 2008; Zheng & van der Velde, 2015). To investigate the differences of soil heat transfer between two CLM versions, offline simulations of surface energy at single-point were conducted (picture omitted). At Maqu site, the mean Bias of the CLM5.0 simulated net radiation, sensible heat flux, and latent heat flux are smaller than CLM4.5 simulations, which caused the smaller mean Bias of soil temperature simulations. At Maduo site, the mean Bias of the simulated latent heat flux using CLM4.5 and CLM5.0 are 22.33 and 18.13 W m$^{-2}$, respectively. The overestimation of latent heat in CLM4.5 during thawing periods caused the increase of cold biases. The mean Bias of surface energy simulated by CLM5.0 at Naqu site is higher than that by CLM4.5, while soil temperature simulated by CLM4.5 are closer to the observations. The differences of the simulated
surface energy between two CLM versions were mainly caused by the differences of soil heat transfer in two models.

CLM5.0 improves the simulated soil evaporation by replacing CLM's existing empirical soil resistance parameterization with a more mechanistic one. Compared to CLM4.5, CLM5.0 overestimated the observed soil moisture in semiarid and arid regions. The performances of current CLM5.0 version have been improved in simulating the basic characteristics of soil moisture and temperature. Large biases of the simulated soil moisture still remain in cold period in cold regions on the TP. Next, we need to explore new soil parameterization, especially for the freezing–thawing processes over the TP. For example, soil property is a very basic and important parameter to affect water and energy transfer. So it could be an important step to involve a more realistic soil property data on the TP in CLM. In addition, the constant freezing point to determine occurring of phase change in the model is a fixed value, which may influence the condition of the frozen soil and the related soil temperature and moisture changes. Actually, Yang et al. (2018) found it will be more reasonable to use of virtual temperature instead of constant freezing point to determine occurring of phase change. More tests and improvements will be done in the future to increase the simulation of water and energy transfer on the TP.

Data Availability Statement

The China Meteorological Forcing Data Set and Maqu and Naqu observation network are provided by Institute of Tibetan Plateau Research, Chinese Academy of Sciences (http://www.tpedatabase.cn/portal/index.jsp). Observation data at Naqu-BJ and Amdo are provided by Naqu Alpine Climate Environment Observation and Research Station of the Northwest Institute of Eco-Environmental Resources, Chinese Academy of Sciences (http://naqu.casnw.net/). Maqu and Maduo observation data are from the Zoige Plateau Wetland Ecosystem Research Station of the Northwest Institute of Eco-Environmental Resources, Chinese Academy of Sciences (http://tpwrr.nieer.cas.cn/). Soil temperature over the TP is provided by China Meteorological Administration (http://data.cma.cn/). We also would like to thank CESM provider. The CESM1.2 and CESM2.1 are freely available online (http://www.cesm.ucar.edu/models/).

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