Postprint: Evaluation of Land Surface Temperature Simulations over Inner Mongolia by the NCAR/CLM Series Land Surface Models

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Abstract

Land surface temperature is an important geophysical variable that influences energy and material exchange between the land and atmosphere, playing an indispensable role in regulating the energy cycle of the global climate system. To investigate the simulation capability of the Community Land Model (CLM) from the National Center for Atmospheric Research (NCAR) for land surface temperature, offline simulations of land surface temperature in the Inner Mongolia region from 1981-2004 were conducted using atmospheric forcing fields from the National Centers for Environmental Prediction (NCEP) for 1948-2004 and NCAR land surface models CLM3.0, CLM3.5, CLM4.0, and CLM4.5, with results compared against observed ground temperature data. The results indicate that the NCAR/CLM series of land surface models can satisfactorily reproduce the spatiotemporal variation characteristics of land surface temperature in Inner Mongolia, demonstrating good consistency with station observations. Among these, CLM4.5 exhibits the best simulation capability in the Inner Mongolia region, with the highest correlation coefficient with observations and the smallest mean bias and root mean square error, primarily attributable to the improved roughness calculation in CLM4.5. Simulated land surface temperatures from different CLM versions are generally lower than observed values, with the mean bias between simulation results and observations reaching its minimum in winter and increasing in summer, particularly in the eastern region where the summer bias exceeds 3°C. This indicates that the simulation capability for maximum land surface temperature in the eastern and central regions is significantly lower than in the western region. The differences among various versions in the western region are less pronounced than in the eastern and central regions, which is related to the improved snow scheme and hydrological processes in CLM4.0 and CLM4.5. In summary, CLM4.0 and CLM4.5 demonstrate good applicability in the Inner Mongolia region, with simulated values consistently lower than measured land surface temperature, smaller bias in winter, increased bias in summer, and greater bias in the eastern region than in the central and western regions.

Full Text

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Simulation and comparative analysis of surface temperature over Inner Mongolia using four NCAR Community Land Models*

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Abstract: Surface temperature, as a geophysical variable characterizing soil hydrothermal conditions, is one of the important factors affecting energy and substance exchange between land and atmosphere [1-2], influencing global climate change through its impact on surface energy and water budgets [3]. Ye et al. [4] demonstrated that surface heating over the Tibetan Plateau significantly influences the summer atmospheric circulation in East Asia. Wu et al. [5-6] proposed that soil temperature feedback can substantially amplify temperature variability, contributing 30%–70% of the variance to summer climate interannual variability. Yang et al. [7-8] suggested that soil temperature memory varies with season, region, and depth, with spring soil temperature showing significant relationships with summer air temperature in arid/semi-arid regions of Northwest China. Therefore, obtaining accurate surface temperature is crucial for studying climate change, soil moisture, permafrost thawing, crop planting, and other related fields [9].

Long-term surface temperature observations from meteorological stations are discrete and lack spatial continuity; satellite-retrieved surface temperature can provide spatially continuous data but with relatively short time series. In recent years, simulating surface temperature through land surface models has become an effective approach for obtaining high spatiotemporal resolution surface temperature data. The land surface model used in this study is the Community Land Model (CLM) developed by the National Center for Atmospheric Research (NCAR). As one of the most sophisticated third-generation land surface models internationally, CLM serves as the land component of the Community Climate System Model (CCSM) and is widely applied in land surface process simulation and climate change research.

Since significant differences exist among different versions of the CLM series, these differences can largely represent variations in certain key land surface physical processes. By comparing simulation results from different versions, we can understand the impacts of these key process differences and deepen our understanding of critical land surface physical processes. Chen et al. [10-11] used CLM3.0 to simulate and compare shallow and deep soil temperatures over China, while Zhu et al. [12-13] conducted simulations and comparisons of global land surface conditions over the past 50 years using three CLM versions (CLM3.0, CLM3.5, and CLM4.0). However, the simulation capability of CLM4.5 has not yet been evaluated. Furthermore, assessment studies conducted at global and national scales have used relatively few validation stations. Given Inner Mongolia' s large east-west span and complex land surface types characterized by interlaced agriculture, pastoral areas, and forests, it is necessary to increase the number of surface observation points to enhance the representativeness of comparative evaluations.

This study simulates surface temperature during land surface processes in Inner Mongolia using four different versions of the NCAR/CLM series (CLM3.0, CLM3.5, CLM4.0, and CLM4.5). We evaluate the simulation results from different NCAR/CLM versions using monthly 0 cm surface temperature observations from 113 stations in Inner Mongolia (1981-2004). The simulation performance and accuracy of the NCAR/CLM series are examined over the Inner Mongolia Plateau, which spans semi-humid, semi-arid, and arid regions, on a relatively long timescale. The aim is to systematically compare and analyze differences in results among the model versions, test their simulation capabilities in the Inner Mongolia region, and provide guidance and reference for future model improvements.

Keywords: NCEP; CLM; Surface temperature; Numerical simulation; Inner Mongolia

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1.1 Data Sources and Processing

The data used in this study include NCEP atmospheric forcing data and observation data from Inner Mongolia stations. Qian et al. [14-15] developed meteorological forcing data with 3-hour temporal resolution and T62 spatial resolution based on NCAR/NCEP global near-surface air temperature, pressure, wind speed, specific humidity, radiation, and precipitation data from 1948-2004. Research has shown that using NCEP atmospheric forcing to drive CLM3 yields good simulations of land surface hydrological variables. The meteorological station observation data used for surface temperature evaluation were provided by the Inner Mongolia Ecological and Agricultural Meteorology Center, containing monthly average surface temperature observations from 113 conventional manual stations across the autonomous region from 1981-2004. Excluded stations include: three stations with insufficient data periods (Huolinguole established in 2006, Hohhot South Suburb established in 1991, and Luanjingtan established in 1991), one relocated station (Toudaohu), and two stations located at national border edges that could not be used due to spatial resolution constraints (Erenhot and Manzhouli).

The NCAR/CLM was driven by NCEP atmospheric forcing data (1948-2004) and run for 112 years to generate an initial field before starting the CLM simulation with an integration time step of 1800 s. Results from 1981–2004 were used for analysis. The monthly average surface temperature data output from each NCAR/CLM version has a spatial resolution of 0.5°$×$0.5°, covering the entire Inner Mongolia region. When analyzing differences between model outputs and observations, the nearest grid point to each observation location was matched with the station data using a one-to-one correspondence method [16].

To quantitatively analyze differences in surface temperature outputs from different versions over Inner Mongolia, three characteristic statistical metrics were employed: mean bias, root mean square error (RMSE), and correlation coefficient.

1.2 Analysis of Differences Among CLM Versions

CLM3.0 was officially released in 2004, featuring one vegetation canopy layer, ten soil layers, and up to five snow layers (depending on snow depth) in the vertical dimension. It can simulate biogeophysical processes, biogeochemical processes, hydrological processes, and optional global dynamic vegetation processes. Each grid cell’ s underlying surface is divided into five sub-grid cover types: glacier, wetland, lake, vegetation, and urban, with vegetation in each grid further categorized into multiple plant functional types. Soil texture considers vertical variations in sand and clay content [17-18].

CLM3.5 was released in 2008, building upon CLM3.0 by adopting surface data based on MODIS observations [19], improving the canopy interception scheme [20], employing a TOPMODEL-based module for runoff simulation, adding a simple groundwater module [21], and introducing a new frozen soil parameterization scheme [22]. Compared with CLM3.0, this version features finer-resolution updated underlying surface data, resulting in significant improvements in soil moisture and temperature simulations [23].

CLM4.0 was released in 2010. Compared with CLM3.5, it primarily revised the numerical solution scheme for the Richards equation, replaced the resistance coefficient with a soil evaporation resistance function, improved soil boundary conditions to directly couple groundwater with soil water [24-25], and considered the effects of canopy litter and intra-canopy stability, as well as the influence of soil organic matter on water movement [26]. The snow scheme was also substantially improved [27], and these enhancements greatly improved the model’ s simulation of water and heat [28].

CESM1.2.0 incorporates CLM4.5 as its land component, which improved vegetation radiation processes and related parameters [29-30], enhanced hydrological processes in permafrost regions [31], added an optional hydrological process VIC [32], and introduced new snow partial parameterization processes to improve the simulation of seasonal snow depth and snow cover percentage [33].

Since few evaluation studies using the NCAR/CLM land surface model have been conducted in China, and the impacts of differences among various

NCAR/CLM versions on simulated surface temperature remain unclear, it is necessary to conduct numerical simulation and evaluation using this version in the study region.

1.3 Overview of the Study Area

Inner Mongolia serves as an important ecological barrier in northern China, covering 12.3% of the country' s land area. The region is vast, with relatively sparse meteorological station observations. The Greater Khingan Mountains-Yinshan-Helan Mountains constitute the marginal zone of the East Asian monsoon, where precipitation gradually decreases and annual mean temperature increases from east to west, transitioning from semi-humid to semi-arid to arid conditions. To reasonably evaluate surface temperature across Inner Mongolia' s diverse climate zones, the region was divided into three areas—eastern, central, and western—according to the "Notice on Using Unified Standard Meteorological Forecast Regional Terminology" (Nei Qi Ke Han [2008] No. 34). The eastern region includes Hulunbuir, Hinggan League, Tongliao, and Chifeng; the central region includes Xilingol, Ulanqab, and Hohhot; and the western region includes Baotou, Ordos, Bayannur, Wuhai, and Alxa. The geographical locations of each league city are shown in Figure 1 [Figure 1: see original paper] [34].

2.1 Spatial Distribution Characteristics and Statistical Analysis of Surface Temperature Climatology

Cold bias refers to simulated surface temperature being lower than observations, while warm bias is the opposite. The spatial distributions of average surface temperature from station observations and simulations by different CLM versions for 1981–2004 were plotted (Figure 2 [Figure 2: see original paper]).

The spatial distribution of average surface temperature from 1981–2004 shows that simulations from CLM3.0, CLM3.5, CLM4.0, and CLM4.5 exhibit good consistency with station observations, successfully reproducing the characteristic spatial pattern of gradually increasing surface temperature from northeast to west across Inner Mongolia (Figure 2). The distribution is primarily zonal, with large temperature differences between east and west. Northern Hulunbuir represents a low-value region for multi-year average surface temperature, with minimum values below -2 ℃; Alxa League is a high-value region, with central average maximum temperatures exceeding 12 ℃. Surface temperatures are also relatively high in parts of the Xiliao River Basin such as Chifeng and Tongliao, second only to the Alxa Plateau region. Central region surface temperatures are around 4 ℃. Simulated surface temperatures from all model versions are relatively close to observations, particularly in the western region.

Compared with station observation data, all models show cold biases across the autonomous region, with these biases being larger in the eastern region than in the western region. Chen et al. [10] found that CLM3.0 produced warm biases in the Hetao region and areas to its east, while showing cold biases in most other regions, which is consistent with our results. In Inner Mongolia, cold biases are relatively small in the Hetao region and areas to its east, exhibiting a decreasing trend from east to west. In northern Hulunbuir, all CLM versions simulate low-value areas with surface temperatures below -4 ℃; however, as this region lies in the heart of the Greater Khingan Mountains without observation data, the reliability of the simulation results cannot be determined. In the Xiliao River Basin area, all model versions show a tendency to underestimate surface temperature, with CLM4.0 and CLM4.5 performing relatively better. In the Ordos Plateau, all model versions significantly underestimate surface temperature, though CLM4.0 and CLM4.5 show improvements in simulating the southern Ordos Plateau. In southern Alxa Right Banner, all model versions underestimate surface temperature, particularly CLM3.5 which underestimates by more than 6 ℃; this improves in CLM4.0 and CLM4.5 but still shows an underestimation of about 2 ℃. For western desert areas, simulation results agree well with observations. Zhu [13] indicated that CLM4.0 has relatively smaller systematic biases compared with the previous two versions, and that results from all models are extremely close in shallow layers, which is consistent with our findings. The spatial distribution patterns of surface temperature simulated by different versions are similar, with CLM4.0 and CLM4.5 demonstrating better simulation capabilities.

As shown by the statistical characteristics in Table 1 , all CLM versions demonstrate good simulation capabilities for surface temperature variation trends in most areas of the study region across the eastern, central, and western areas, with differences among versions not being particularly significant.

Table 1 Surface temperature correlation coefficient, mean deviation, and root mean square error of CLM simulation and station observation in different regions of Inner Mongolia

[Table content would be preserved here]

** indicates passing the 99.9% confidence test.

Correlation coefficients exceed 0.995 and all pass the 99.9% confidence test. Differences in correlation coefficients among the four model versions are minimal. In the eastern region, the lowest correlation coefficient is 0.9956, with an extremely small difference from the highest value of 0.9981. Differences are even smaller in the central and western regions, indicating that all CLM versions have slightly weaker capability in simulating surface temperature trends in the eastern region compared with the central and western regions.

In terms of mean deviation, notable differences exist among versions. In the eastern region, CLM4.5 has the smallest mean deviation at -1.87 ℃, while CLM3.0 shows the largest deviation at -3.15 ℃, demonstrating that CLM4.5 provides more ideal simulation biases for the eastern region. In the central region, CLM4.5 also has the smallest deviation at -0.07 ℃, significantly lower than CLM3.5' s -1.05 ℃. In the western region, CLM4.5 again has the lowest deviation, significantly smaller than that of CLM3.5. These results indicate that CLM4.5 has the smallest biases overall, with simulation deviations in the central and western regions being smaller than in the eastern region.

Regarding root mean square error (RMSE), CLM4.0 has the smallest RMSE in the eastern region at 2.57, comparable to CLM4.5, and both are significantly smaller than CLM3.0's RMSE. In the central region, differences in RMSE among versions are not obvious, with CLM4.5 and CLM4.0 having the smallest values at 1.70 and 1.73, respectively. In the western region, differences in RMSE among versions are similarly insignificant, with CLM4.0 and CLM4.5 performing best, outperforming both CLM3.0 and CLM3.5.

Considering all three statistical metrics comprehensively, CLM4.5 performs significantly better than CLM3.0 and CLM3.5 in the central and western regions, with relatively small differences from CLM4.0, achieving the best results in terms of correlation coefficient, mean deviation, and RMSE. In the eastern region, CLM4.0 performs best with the highest correlation coefficient and lowest RMSE, though its bias is slightly worse than CLM4.5. CLM4.0 and CLM4.5 show consistent performance across the three sub-regions, both demonstrating higher simulation capabilities in the central and western regions than in the eastern region, where biases and RMSE are slightly larger. All versions exhibit cold biases, with smaller deviations and RMSE in the central and western regions.

2.2 Seasonal Cycle of Surface Temperature Simulated by CLM Models and Observations

By analyzing the seasonal variation of monthly average surface temperature in the three sub-regions (eastern, central, and western) of Inner Mongolia from 1981–2004 [Figure 3: see original paper], it can be seen that all CLM versions can reasonably reproduce the seasonal cycle of surface temperature, with relatively close magnitudes, particularly during November–January of the following year. Surface temperature reaches its minimum in January across all three sub-regions, falling below -18 ℃ in the eastern and central regions and below -10 ℃ in the western region. July sees the maximum temperatures, exceeding 26 ℃ in the eastern and central regions and 29 ℃ in the western region.

Simulation results from different CLM versions show consistent variation trends across the eastern, central, and western regions. As seen from the mean deviations between simulated and observed monthly average surface temperature from different CLM versions (Figure 4 [Figure 4: see original paper]), simulated surface temperatures from all versions are generally lower than observed values. Deviations reach their minimum in winter and increase in summer, particularly in the eastern region where summer differences range from 3–8 ℃, larger than in other regions. This indicates that the simulation capability for maximum surface temperature in the eastern and central regions is significantly lower than in the western region. CLM4.0 and CLM4.5 simulation results are noticeably better than those from CLM3.0 and CLM3.5, with values closer to observations. However, differences among versions in the western region are not as pronounced as in the eastern and central regions, which is related to improvements in snow and hydrological processes in CLM4.0 and CLM4.5. All CLM versions show high consistency in temporal variation trends and describe the months with lowest ground temperature well, though their capability to simulate maximum surface temperature needs further improvement.

A statistical classification of monthly mean deviations between simulated and observed values from different CLM versions across years (Table 2) reveals that in the eastern region, CLM3.0 simulation results are lower than observations by more than 5 ℃ for 82 months, indicating large biases, while other versions show better performance. In the central region, approximately 60% of months have simulated values 1–5 ℃ lower than observations; CLM3.0 and CLM3.5 simulations are 1–5 ℃ lower than observations for over 50% of months, while CLM4.0 and CLM4.5 perform slightly better. In the western region, about 50% of simulation results from all versions are 1–5 ℃ lower than observations, with results close to observations, differing by -1 to 1 ℃.

2.3 Comparison of Monthly Average Surface Temperature Time Series with Observations

Figure 5 [Figure 5: see original paper] compares the monthly average surface temperature time series simulated by CLM3.0, CLM3.5, CLM4.0, and CLM4.5 with observed values. It can be seen that simulation results from different CLM versions can successfully reproduce the temporal variation characteristics of surface temperature in the eastern, central, and western regions of Inner Mongolia, with good agreement in monthly values across the 24-year period.

Overall, all CLM versions can reasonably reproduce the seasonal cycle characteristics of surface temperature in Inner Mongolia’ s eastern, central, and western regions, with better performance in winter than in summer. This is primarily manifested by significantly smaller biases in winter simulations compared with summer across all versions. It should be noted that all CLM simulation results are lower than observed values, representing an underestimation of surface temperature, with greater underestimation in the eastern region than in the central and western regions.

3 Conclusions and Discussion

This study utilizes four versions of the CLM model to simulate the spatiotemporal variations of surface temperature in Inner Mongolia from 1981–2004, comparing the results with meteorological station observations. The simulation capabilities and differences of different NCAR/CLM versions in simulating surface temperature data across eastern, central, and western Inner Mongolia are investigated, and their applicability and accuracy in various regions of Inner Mongolia are discussed. The conclusions are as follows:

(1) NCAR land surface models of different versions can all reasonably reproduce the spatiotemporal variation characteristics of surface temperature

across various regions of Inner Mongolia. Among them, CLM4.5 performs best, with the smallest mean bias and RMSE and higher correlation coefficients. CLM4.0 and CLM4.5 produce similar simulation results and demonstrate good applicability in the Inner Mongolia region. The primary reasons are that CLM4.0 and CLM4.5 have improved land surface hydrological processes, snow schemes, and radiation processes. CLM3.5 uses MODIS underlying surface data from 2001, but the simulation analysis period is 1981-2004; affected by interannual variations in underlying surface types and data accuracy, CLM3.5 performs relatively poorly. In contrast, CLM4.0 and CLM4.5 employ higher-accuracy underlying surface data, effectively improving simulation results.

(2) Simulated values from all CLM versions are lower than measured surface temperatures, exhibiting cold biases. Biases are smaller in winter and larger in summer, with greater biases in the eastern region than in the central and western regions. The main reasons are twofold: 1) The biogeophysical process descriptions in CLM need further improvement, and there are issues related to unreasonable underlying surfaces in the land surface model; 2) Meteorological station observations are primarily conducted in bare land sections, which differ from natural conditions, with observed maximum temperatures being higher than those under natural conditions, while model simulations represent surface temperature under natural conditions, thus resulting in significant cold biases. CLM4.5 has improved parameterization in this regard, making its results closer to observations.

Due to the vast area of Inner Mongolia and the limited number of meteorological observation stations, there remain aspects needing improvement in this study. First, regarding the matching of different data scales in the validation process, station observations can only represent conditions at the observation point itself, with limited representativeness of the surrounding area, while the model data have a spatial resolution of 0.5°, representing the average state of the grid cell. In areas with dense observations, the average of all observation points within the grid cell coverage is used to represent the grid point state, whereas in sparsely observed areas, at most one station represents the grid cell, making biases inevitable. Second, the representativeness of the model' s underlying surface needs improvement, as the underlying surface varies each year, but the model runs from 1948-2004 using underlying surface data from a single year, inadequately considering changes in factors such as vegetation cover that affect surface temperature. This represents a focus for future research.

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