ORIGINAL ARTICLE

Simulation and improvement of common land model on the bare soil of Loess Plateau underlying surface

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Abstract Climate model has become an irreplaceable tool for the study and prediction of climate changes. The land surface process, as one of the important parts of all climate models, must be considered so that the simulative ability of climate models could be improved. Using the common land model (CoLM) that is driven by the LOPEX experiment data, the characteristics of land surface processes of the Loess Plateau are simulated. Furthermore, based on the comparison of the field observation data with the simulated results, the simulative performance of CoLM in the Loess Plateau region is also examined. The results show that, CoLM can be used in the Loess Plateau, and it perfectly simulates net radiations and net short-wave radiations. However, the simulated land-surface temperature is slightly higher than actual measured value, while the simulated soil temperature values in lower layers (5, 10, 20, 40 cm) are relatively less and the variety phase of these also lag. Moreover, the simulated sensible heat flux is a little larger, while the simulated soil thermal conductivity value is obviously lower. By modifying the calculation plan of soil thermal conductivity, the simulated result has been greatly improved. As a whole, if CoLM is applied in the Loess Plateau of Northwestern China, the parameterization of soil thermal conductivity should be ameliorated, which can improve its simulative capacity in the Loess Plateau regions.

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Introduction

In recent years, a series of major global environmental and climatic anomaly issues, such as land desertification, persistent drought, global warming and water resource shortage, etc. have attracted unprecedented attention from governments and scientific communities worldwide, which have also become urgent issues of land–atmosphere interaction study. The request of the climate change study and climate prediction also boosts the land surface process model improvement. Consequently, climate model has become an irreplaceable tool for study and prediction of climate changes, while the land surface process model is a key research and development content that shall be considered by any climate model (Dickinson 1993; Bonan 1998). Therefore, it is an important way for improving the climate model that the characteristics of land surface processes of various underlying surfaces must be understood correctly. By studying the physical and biochemical processes of the interface between the various land underlying surfaces and atmosphere, the land surface model could be improved and developed, which must be very helpful for predicting the exchange of momentum, energy, material and radiation in the interface precisely, and for simulating the factors that are related to the climate change, such as land surface temperature and soil moisture and other factors of the atmospheric boundary layer.

Since the simple BUCKET model was developed by Manabe and Stouffer (1996) in the late 1960s, many land surface models have been developed. By better understanding of various parameterization schemes of land surface processes, the defects of these schemes would be found and improved, which would improve the climate model simulation and prediction capacity by a couple of the land surface process. The "Project of Intercomparison

of Land Parameterization Scheme" (PILPS) was eventually initiated in 1992 (Henderson 1993). The results of PILPS at various stages could show that all participation models have their own advantages and disadvantages (Wood et al. 1998; Liang et al. 1998; Lohmann et al. 1998). To integrate the advantages of all the land surface process models, the working panel of land surface models from NCAR-CCSM (Common Climatic System Model) proposed some development suggestions in February, 1992. Based on prototypes of LSM, BATS and IAP94, Dai et al. (2003) developed a new generation community land model (CLM). The standard of the model was completed in June, 1986 and its initial program was established in March, 1999. In June of 2004, the CLM3.0 (community land model 3.0) (NCAR) was published, and it was jointly maintained by Dai Yongjiu and E. Dickinson.

Because of including the good characteristics of the land surface model (LSM), the biosphere–atmosphere transfer scheme (BATS) and the 1994 version Chinese Academy of Sciences Institute of Atmospheric Physics (IAP94), CoLM (common land model) is a relatively advanced land surface process model currently, which mainly consists of four parts: (1) the physical process of biological earth, which refers to the exchanges between land and atmosphere in energy, water and momentum; (2) the hydrological cycle, consisting of vegetation intercepted water, throughfall (drips off the vegetation), runoff, infiltration, soil water movement, and snow surface runoff, etc. These factors would directly or indirectly affect rainfall, temperature and runoff, which would be injected into main river systems globally through hydrologic modeling computation; (3) the biogeochemical process, which refers to the chemical exchanges between land and atmosphere, including commonly biological flux, carbon, dust, dry deposition, and other mass exchanges; (4) the dynamic vegetation, which refers to the dynamic description over the material or energy exchanges between vegetation and environment, and it also includes the growth conditions of vegetation under the climate or environment change. A large number of validation experiments, such as the experiments in the Russian Valdai prairie and in the Brazilian Amazon forest, etc. (Oleson et al. 2004), have been conducted to demonstrate that the CoLM had a better simulative capacity in different types of underlying surface in different climatic zones all over the world. However, could CoLM be used in China? In recent years, many Chinese meteorologists also conducted studies on the practicability of the CoLM model in different regions of China. Liu and Lin (2005) conducted the experiments to demonstrate the simulative capacity of the CoLM model in three different typical underlying land surfaces of East Asian, which includes highland sparse-vegetation underlying surface, forest and paddy fields. The experimental results showed that the surface temperature

simulated by CoLM in highland sparse-vegetation underlying surfaces was quite close to the actually measured values. Furthermore, CoLM could simulate the variation characteristics of soil temperature with the time and depth. However, the simulated amplitude of surface temperature was significantly smaller than the measured value. For the energy flux, all energy fluxes variation except the sensible heat flux could be simulated perfectly by CoLM and the simulated results agreed well with the observed values. Using the HUCEX data of 1998, Huang et al. (2004) tested the simulation capacity of CoLM. The results showed that CoLM could present a good simulative capacity not only on the various land–atmosphere energy fluxes, but also on the temporal and spatial distribution characteristics of soil temperature. However, there were still some defects of CoLM; for example, the simulated flux was not quite precise and the simulated soil temperature was lower than the actual value. Xin et al. (2006) conducted an off-line verification test to show whether the CoLM model could be used in typical arid zone and Qinghai-Tibetan plateau. According to the test results, the CoLM model presented a good simulative ability in the land surface process of irrigated farmland in an oasis of typical arid zone. In addition, the daily and seasonal variation trends of soil temperature in different layers could be precisely simulated as well. The test results also showed that when the CoLM model was applied in the simulation of energy balance component in the plateau region, it could simulate accurately the net radiation and sensible heat, but the simulated value of latent heat component was slightly larger than the actual value. Using the CoLM model, Wang and Shi (2007) simulated the land surface characteristics of the western part of Qinghai-Tibetan plateau. They found that the model presented a good applicability in simulating the land surface characteristics of the Tibetan Plateau. However, there is no relevant study concerning the practicability of the CoLM model in the Loess Plateau. The Loess Plateau has a complex land surface environment, the climate of which belongs to the transitional belt from the arid to humid climate. The above mentioned indicates that the land surface process of Loess Plateau is quite different from one in humid and pure arid region. Can CoLM be used to simulate accurately the characteristics of the land surface processes of the Loess Plateau? In the paper, based on the natural condition of the Loess Plateau, CoLM model was improved and then it could be applied to simulate land surface processes of the Loess Plateau.

Data source

In August, 2004, the pre-experiment of Loess Plateau land–atmosphere interaction (Loess Plateau Land Surface

Table 1 Underlying surface parameters and the model initiation

Underlying surface type		Soil texture (%)		Color index	Vegetation coverage (%)	Roughness of bare land surface (m)	Ratio of direct solar radiation and scattered radiation (%)	
Wasteland	1.0	Sand	22.7	3	0	0.01	Direct solar radiation	70
		Clay	1.75				Scattered radiation	30

Process Field Experiment, short for LOPEX) was conducted by the Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Science in Pingliang Thunder, Lightning and Hailstorm Experiment Station. During the period from July 15 to August 29, 2005, a large-scale land–atmosphere interaction experiment (LOPEX05) was formally conducted and then a supplementary experiment (LOPEX06) was started in April 2006. Please refer to related literatures (Li et al. 2008; Wei et al. 2005; Wen and Wei 2009) for the details of these experiments. The forced data in this paper are the observed data of Yuanxia station of LOPEX05. At that time the underlying surface of this station was a newly plowed bare land. All data, including the values, which were used to compare with the simulation results, has been processed by abnormal data deletion, WPL correction, etc.

Numerical experiment design

The CoLM model is driven by the atmospheric boundary parameters, which included solar short-wave radiation (W m^{-2}), atmospheric long-wave radiation (W m^{-2}), precipitation rate (mm s^{-1}), atmosphere temperature (K), wind volume in the eastward direction u_x (m s^{-1}), wind volume in the northward direction u_y (m s^{-1}), atmospheric pressure (Pa) and specific humidity (Kg Kg^{-1}) at reference height. The reference height is set at 2 m, and the observation height of wind velocity is 3 m. The underlying surface type was wasteland, and it was different with the default type of the model, which indicated that the wasteland and farmland should be half to half. The sand and clay contents of the soil, based on the observation value, were 22.7 and 1.75%, respectively, while, based on the model requirement, their values should be 43 and 18%, respectively. The principles that direct radiation took up 70% were adopted, and scattered radiation took up 30%. In the meantime, visible light occupied 50% and near infrared light occupied 50%. Therefore, the total solar radiation could be divided into four parts, i.e., direct visible light radiation, scattered visible light radiation, direct near infrared radiation and scattered near infrared radiation (Oleson et al. 2004). The underlying surface parameters used in the model and the initiation of the model are shown in Table 1. Eighteen (18) days were selected for simulation

between August 12 and 29, 2005. Most of the days in the study period were cloudy, with only a few days of sun and rain, which was quite beneficial for the overall examination of the simulative ability of the model under various weather conditions. The time step for the simulation time was 30 min and the variation trends of the forced quantities were input for the model, which are shown in Fig. 1.

In the land surface process model, the simulation of soil temperature is a key factor. The soil temperature calculation is closely related to the energy and mass exchanges between land surface and atmosphere, which would further affect the simulation of the atmosphere model (Zhou et al. 2004). In CoLM, soil was divided into 10 layers, i.e. the depths of 0.71, 2.79, 6.23, 11.89, 21.22, 36.61, 61.98, 103.80, 172.76 and 286.46 cm, while the observation data were recorded at the depths of 5, 10, 20 and 40 cm, respectively. Consequently, comparisons between 6.23, 11.89, 21.22 and 36.61 cm depth in the model and 5, 10, 20 and 40 cm depth from the observed data were made. Due to limitation of the observation data, the soil temperature and moisture initial values at the third, fourth, fifth and sixth layers in the CoLM model were measured, while the soil temperature values at other layers were set at 288 K and the soil moisture values at the first and second layers were same as that in the third layer, and the soil moisture content in other layers were same as that in the sixth layer. Therefore, the formula, which converts the measured soil moisture content to soil moisture required by the model, is as followed:

$$\omega = \theta \times \Delta z \qquad (1)$$

where ω is the soil moisture (kg m^{-2}), θ is the soil moisture (kg m^{-3}), while Δz is the thickness of different soil layers (m). Soil temperature and soil moisture values at various layers were input for the model, which are listed in Table 2.

Results

Figure 2 shows the comparisons between simulated soil temperature and measured values at the depths of 5, 10, 20 and 40 cm. It is obvious that the trends of the simulated soil temperature and the measured values at all layers are basically the same. However, there is a large gap between
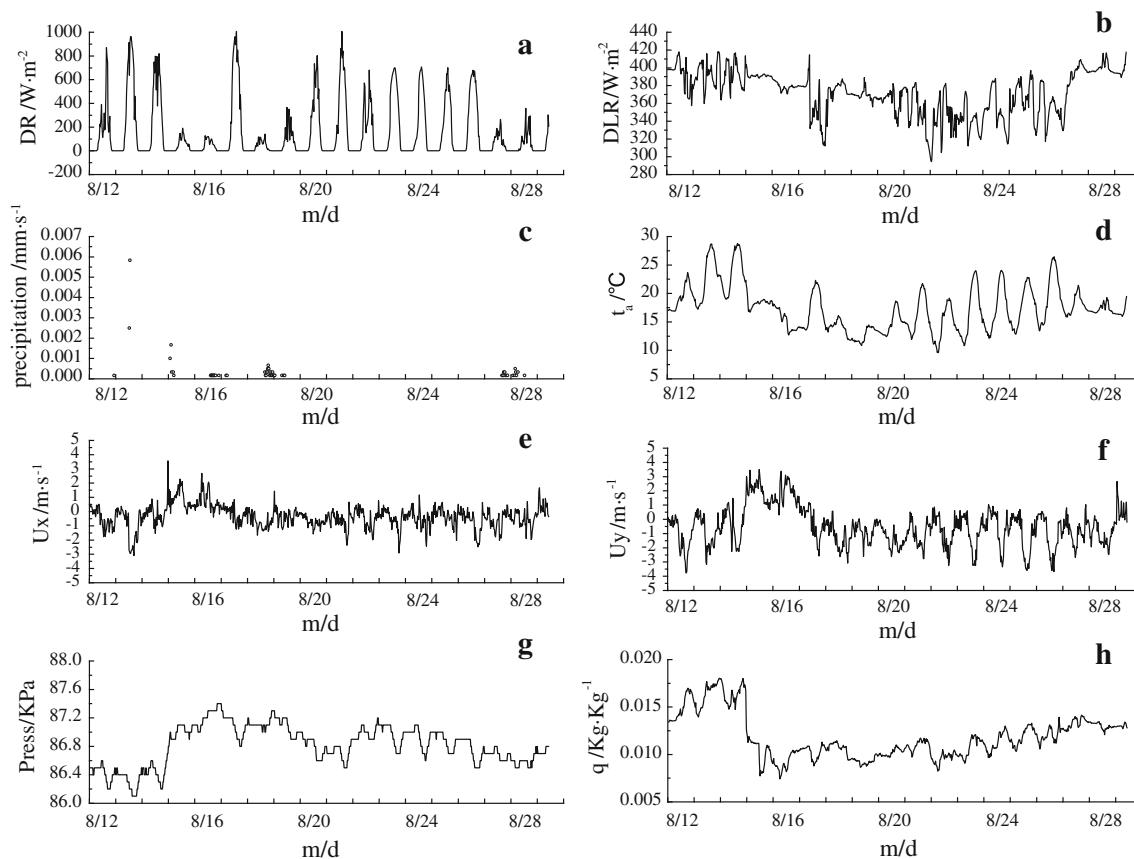
Fig. 1 Forced quantities of the model at Yuanxia station from August 12 to 29, 2005. **a** Downward short radiation; **b** downward long-wave radiation; **c** precipitation rate; **d** air temperature; **e** wind velocity of u_x direction; **f** wind velocity of u_y direction; **g** atmosphere pressure; **h** specific humidity

Table 2 Soil temperature and soil moisture at different layers

Layers	Depth (z) (cm)	Thickness ($\triangle z$) (cm)	Node depth (z_h) (cm)	Temperature (T) (K)	Moisture (w) (kg m^{-2})
1	1.75	1.75	0.71	288	1.8
2	4.51	2.76	2.79	288	3.4
3	9.06	4.55	6.23	291.76	4.41
4	16.56	7.50	11.89	293.33	6.955
5	28.91	12.35	21.22	294	14.83
6	49.3	20.39	36.61	293.69	32.55
7	82.89	33.59	61.98	288	78.59
8	138.28	55.39	103.80	288	154.37
9	229.61	91.33	172.76	288	210.7
10	343.31	113.70	286.46	288	326

the simulated value and the measured value. Actually, the simulated values are generally smaller than the measured values. The maximum difference between simulated value and measured value at 5 cm is 6 k. Furthermore, the amplitude of simulated temperature is also much smaller than that of the measured temperature. It can also be seen from the Fig. 2 that the variation of the simulated soil temperature lags behind the measured value change. Since

there is no observation data of surface temperature, it is not possible to conduct a comparison between the simulated values of surface temperature and the measured values. The surface upward long-wave radiation can be used to show the soil surface temperature to some extent, and as shown in Fig. 3b, the simulated value of land surface upward long-wave radiation is slightly larger than the measured value, which means that the simulated soil surface
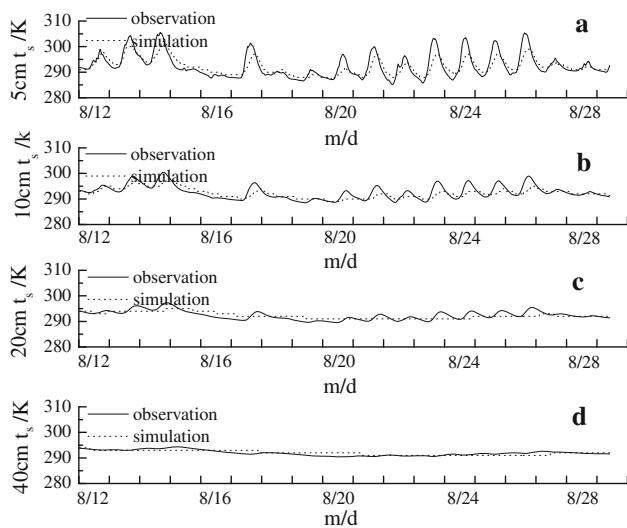
Fig. 2 Comparison of simulated and measured soil temperature values at the depths of **a** 5 cm, **b** 10 cm, **c** 20 cm and **d** 40 cm
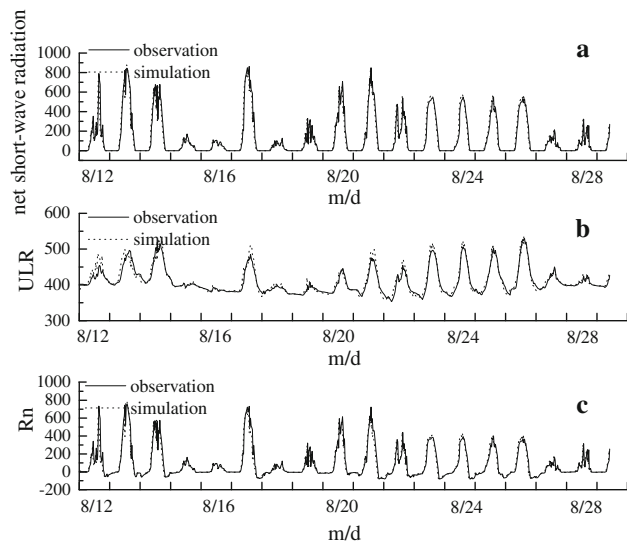

Fig. 3 Comparison of simulated and observed radiation flux **a** net short-wave radiation; **b** upward long-wave radiation; **c** net radiation. All are with W m^{-2} as the unit
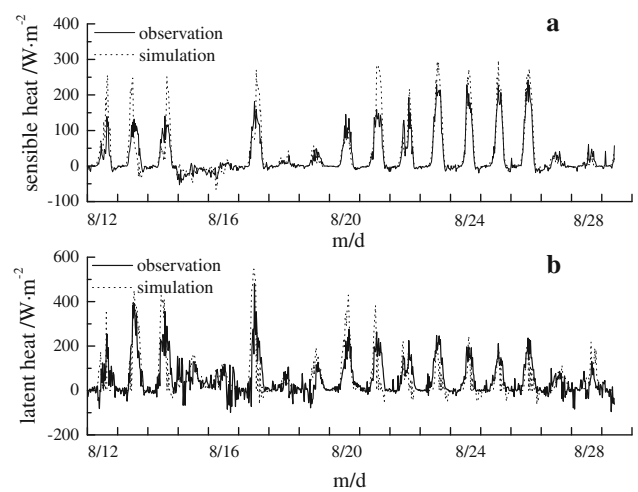

Fig. 4 Comparison of simulated **a** sensible heat flux and **b** latent heat flux with their observation values

Figure 3 shows the comparison between simulated and measured values of (a) net short-wave radiation, (b) upward long-wave radiation and (c) net radiation. It can be seen that the model can be used to simulate radiation components over the Loess Plateau. Moreover, the simulated net short-wave radiation, i.e. the short-wave radiation absorbed by surface soil, is consistent with the observed value, which indicates that the parameterization of surface albedo in the model is applicable to the situation of Loess Plateau regions. Otherwise, the simulated surface upward long-wave radiation value is slightly larger than the measured value.

The heat energy fluxes play an important role in land–atmosphere interaction; therefore, it is one of the most common methods, which compares the simulated and observed values of the sensible and latent heat flux, to examine the simulation ability of the land surface model. Figure 4 shows the comparisons between the model-simulated and observed values: (a) sensible heat flux and (b) latent heat flux. It can be seen from Fig. 4a that the daily trend of simulated sensible heat fluxes is quite close to that of the observed values, but the simulated values are larger than the observed values. The daily trend of simulated latent heat fluxes also presents a good correspondence to that of the observed values, but there is a magnitude difference as shown in Fig. 4b. During the experiment, there was a lot of rainfall, which might cause the observation errors of the heat flux. Moreover, the simulated errors are an inevitable part. Nevertheless, based on the simulated results of both the sensible heat flux and the latent heat flux, the CoLM model still simulated the rainfall process very well. Besides the observation errors, the lower simulated soil thermal conductivity, which means that the simulated soil thermal flux is also lower and it leads to the smaller downward heat transmission, is another main reason of the higher simulated values of sensible heat flux.
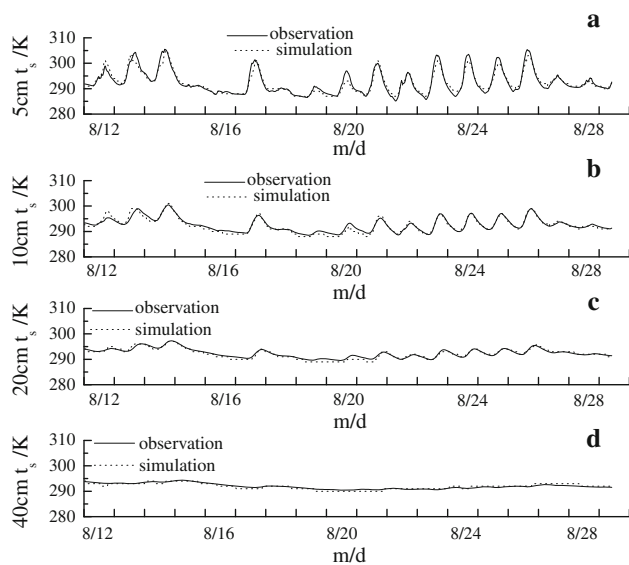
temperature is slightly larger than the measured surface temperature. By contrast, the simulated soil temperatures at the upper layers (5, 10, 20, 40 cm) are much smaller than the measured values, which indicates that the soil thermal conductivity of the model is smaller than the actual value. In CoLM, because of no observation data, a soil thermal conductivity parameterization scheme is constructed based on the assumption, where the soil thermal conductivity, the thermal conductivity of dry soil and the soil porosity are calculated by the empirical formulas. All of the abovementioned could lead to the calculation error.

Fig. 5 Comparison of simulated soil temperature values and the observed values after altering the soil thermal conductivity (**a** 5 cm; **b** 10 cm; **c** 20 cm; **d** 40 cm)

Fig. 6 Comparison of simulated **a** sensible heat flux and **b** latent heat flux with observed values after altering the soil heat conductivity

As has been mentioned above, the smaller simulated soil thermal conductivity has become a main reason because the simulated soil temperature is lower than the observation, the result of simulation lags behind the observation and the simulated sensible heat flux is higher than the actual value. Actually, the soil thermal conductivity of Yuanxia station can be calculated using the observation soil temperature and soil thermal flux.

The formula of soil thermal conductivity is:

$$G = -\lambda \frac{\partial T}{\partial Z} \tag{2}$$

where G is the soil heat flux (W m^{-2}), λ is the soil thermal conductivity (W m^{-1} k^{-1}), while $\frac{\partial T}{\partial Z}$ is the gradient of the soil temperature (°C m^{-1}). Then it can be transformed to obtain the soil thermal conductivity λ:

$$\lambda = -G/(\partial T/\partial Z) \tag{3}$$

where G is the soil heat flux of the soil layer at the depth of 5 cm, and T is the soil temperature. Both of them are obtained through direct observation, $(\partial T/\partial Z)$ is the soil temperature gradients between the soil layer at the depth of 5 and 10 cm.

Based on the parameterization scheme of the CoLM model, the soil thermal conductivity at Yuanxia station in all layers is 0.216 (w m^{-1} k^{-1}), while the soil thermal conductivity, which is calculated based on formulae (2) and (3) using observed data, is 1.2 (w m^{-1} k^{-1}). After replacing the model soil thermal conductivity calculation scheme by the above scheme, the same simulation was conducted again at Yuanxia station. Even if the soil
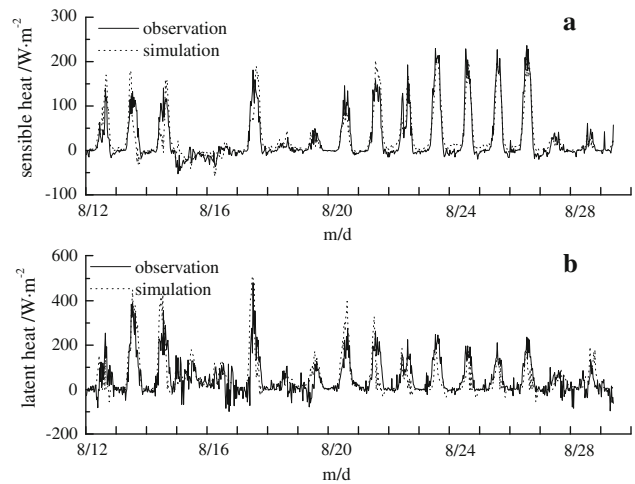
thermal conductivity was modified, the simulated results of various radiation components were very consistent with the results without modification. Detailed analysis would not be listed here any further. Figure 5 shows that after the soil thermal conductivity scheme was changed, the comparison between the simulated soil temperature values and the observed values at the depths of 5, 10, 20 and 40 cm. Comparing with Fig. 2, the simulated soil temperature has been greatly improved, and the simulated results and the observed values are very consistent and the phenomenon that the simulated values lag behind the observed values is not presented any further. The simulated values of sensible heat flux are also greatly improved, as shown in Fig. 6. The results show that the simulated values are much smaller, and are closer to the observed ones. However, the variation of simulated latent heat flux is not obvious.

Conclusions

In this study, using the LOPEX experiment data, the CoLM land surface processes model was adopted to simulate the characteristics of land surface processes in the Loess Plateau, and at the same time the practicability of the CoLM model in the Loess Plateau was tested as well. The following conclusions are finally drawn:

1. The CoLM land surface model has presented a good simulative ability of net radiation and net short-wave radiation, but the simulated soil surface temperature is slightly higher than the measured surface temperature, while the simulated soil temperature values on the lower layers are significantly lower, at the same time the simulated soil temperature variation lag behind the observation data change. In addition, the simulated

sensible heat flux is larger than the observed value. The abovementioned is related to the fact that the simulated soil thermal conductivity is smaller. The simulated soil thermal conductivity in various layers in the CoLM model is 0.216 (W m^{-1} k^{-1}), while the soil thermal conductivity, which is calculated by the observed data, is 1.2 (W m^{-1} k^{-1}).

2. Through modifying the calculating scheme of soil thermal conductivity, the simulative effect concerning soil temperature and sensible heat flux in all layers has been largely improved.

Soil thermal conductivity is closely related with factors such as soil texture and soil moisture; therefore, different soil layers have different thermal conductivities. To fully improve the simulation capacity of CoLM, it is necessary to improve the parameterization of soil thermal conductivity.

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