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Numerical Study of Impacts of Soil Moisture on the Diurnal and Seasonal Cycles of Sensible/Latent Heat Fluxes over Semi-arid Region

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ABSTRACT

The semi-arid regions, as climatic and ecosystem transitional zones, are the most vulnerable to global environmental change. Earlier researches indicate that the semi-arid regions are characterized by strong land-atmosphere coupling in which soil moisture is the crucial variable in land surface processes. In this paper, we investigate the sensitivity of the sensible/latent heat fluxes to soil moisture during the growing season based on the enhanced observations at Tongyu in the Jilin province of China, a reference site of international Coordinated Energy and Water Cycle Observations Project (CEOP) in the semi-arid regions, by using a sophisticated land surface model (NCAR_CLM3.0). Comparisons between the observed and simulated sensible/latent heat fluxes indicate that the soil moisture has obvious effects on the sensible/latent heat fluxes in terms of diurnal cycle and seasonal evolution. Better representation of the soil moisture could improve the model performance to a large degree. Therefore, for the purpose of simulating the land-atmosphere interaction and predicting the climate and water resource changes in semi-arid regions, it is necessary to enhance the description of the soil moisture distribution both in the way of observation and its treatment in land surface models.

Key words: semi-arid region, soil moisture, latent/sensible heat flux, diurnal cycle, seasonal evolution

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1. Introduction

The semi-arid regions of East Asia are located near the northern edge of the summer monsoon where the potential evaporation can exceed the annual average precipitation. The landscapes are characterized by dry climate, low vegetation cover, low nutrition content and low capacity of water conservation of the soil. These areas are most vulnerable to global environment change. It is a transitive zone between arid continental climate and humid monsoon climate, which is very sensitive to natural- and human-induced climate perturbations.

The variation of climate and water cycle in this area is highly correlated with the high variability of the Asia monsoon system. This leads to the high frequency of extreme events and climate disasters there. Both the observation and numerical modeling have shown that an aridification trend is occurring and will occur most significantly in the semi-arid regions under global warming (Fu and Wen, 2002; Ma and Fu, 2003). In recent years, studies focusing on the semi-arid region have been accepted by a series of international projects like CEOP (Coordinated Energy and Water Cycle Observation Project) and MAIRS (Fu et al., 2006).

In semi-arid regions, soil moisture plays a very important role in climate change. The variation of soil

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moisture changes the water supplied to plants by the soil and the moisture gradient between the land surface and atmosphere, which control the water exchange between that land surface and the atmosphere. Meanwhile, because of the impacts of soil moisture on land surface albedo and soil thermal/hydraulic properties, the water-energy balance is affected as well, causing the temperature gradient between the land surface and the atmosphere changes. In addition, the variation of the water and energy exchange between the land surface and the atmosphere can change the dynamic and thermal characteristics of the boundary layer, wind velocity and other characteristic variables, which determines the resistance to flux transfer between the land surface and atmosphere, and diurnal and seasonal cycles of water vapor and energy flux (Oleson et al., 2004; Sun, 2005). It is widely accepted that the variations of water vapor and energy and momentum fluxes between the land and the atmosphere, which are affected by soil moisture, have very important impacts on climate change (Chahine, 1992; Brubaker et al., 1993; Trenberth, 1999). It is believed that the impact of soil moisture on climate change is second only to SST, and even is more important than SST on the land (Shukla and Mintz, 1982). According to statistics, 65 percent of precipitation is from soil evaporation, and only 35 percent is from sea (Chahine, 1992). Percent contribution of local evaporation to precipitation is in the range between 20 to 40 percent when the spatial scale is larger than 1000 kilometers (Brubaker et al., 1993; Trenberth, 1999). Seasonal soil moisture anomalies have important impacts on seasonal climate variation (Namias, 1963). Dry soil can make future precipitation decrease and make temperature increase, while wet soil can make future precipitation increase and make temperature decrease (Rowntree and Bolton, 1983). Moreover, soil moisture has an important impact on mesoscale and microscale systems (Fast and McCorcle, 1991; Chang and Wetzel, 1991).

The semi-arid regions of East Asia are in the continental middle latitudes, and some AGCM studies suggest that in the continental middle latitudes during summer, soil moisture has more impact on precipitation than over the oceans (Koster et al., 2000). The experiments based on a dozen AGCMs by GLACE show that there are some so-called “hot spots” on the Earth’s surface where soil moisture anomalies have a substantial impact on precipitation in boreal summer (June through August) due to the strong land-atmosphere coupling. The hot spots lie mainly in the transition zones between wet and dry climates. In wet climate regions, soil moisture is high, but evaporation is controlled not by soil moisture but by net radiation, and consequently the evaporation isn’t sensitive to soil moisture. In dry climate regions, evaporation is sensitive to soil moisture, but soil moisture is low. Therefore, the variation in soil moisture cannot have much effect on precipitation in wet and dry climate regions. In semi-arid climates, evaporation is sensitive to soil moisture, as is discussed in the paper, and is suitably high (Koster et al., 2004).

In Koster’s research, however, mechanisms and processes of land-atmosphere coupling are not investigated deeply. As we know, sensible heat flux (hereafter referred to as HS) and latent heat flux (hereafter referred to as LE) play an important role in exploring and understanding the mechanisms and processes of land-atmosphere interaction. Globally, approximately 60% of the solar radiation absorbed at the earth’s surface is released by HS and LE (Sellers, 1965). HS and LE influence the steady state of the atmosphere, and determine the mean profiles of the surface layer and the atmospheric boundary layer (Holtslag and Nieuwstadt, 1986; Beljaars and Holtslag, 1991). Moreover, HS and LE are the main mechanisms that contribute significantly to the energy enrichment of the lower tropospheric layers (Repapis et al., 1978; Cayan, 1992a,b; Doran et al., 1992; Lolis et al., 2004).

In recent years, more and more researchers have begun to realize that the diurnal cycle is one of the most fundamental atmospheric responses, alongside the variability of the global climate system, to the solar radiation forcing. It also plays an important role in regulating regional rainfall and circulation (Yang and Slingo, 2001). Model errors occurred in the first few days of integration are often indicators of the model’s systematic biases on the climate scale. The simulation of the amplitude and phase of the diurnal cycle provides an efficient way for testing the representation of the interactions between the surface, boundary layer, and the free atmosphere, and for verification of the physical parameterization in the models including land surface, planetary boundary layer and cloud processes (Yang et al., 2002).

Following the aforementioned considerations, in this study, we investigate the impacts of soil moisture on the diurnal and seasonal cycles of sensible/latent heat fluxes over the semi-arid region by using NCAR_CLM3.0 during the growing season (May to October) based on the enhanced long-term field observations.

2. Model and data description

The Community Land Model 3.0 (NCAR_CLM3.0) is a sophisticated land surface model, including biogeophysics, the carbon cycle, vegetation dynamics and river routing schemes. It is developed from the NCAR

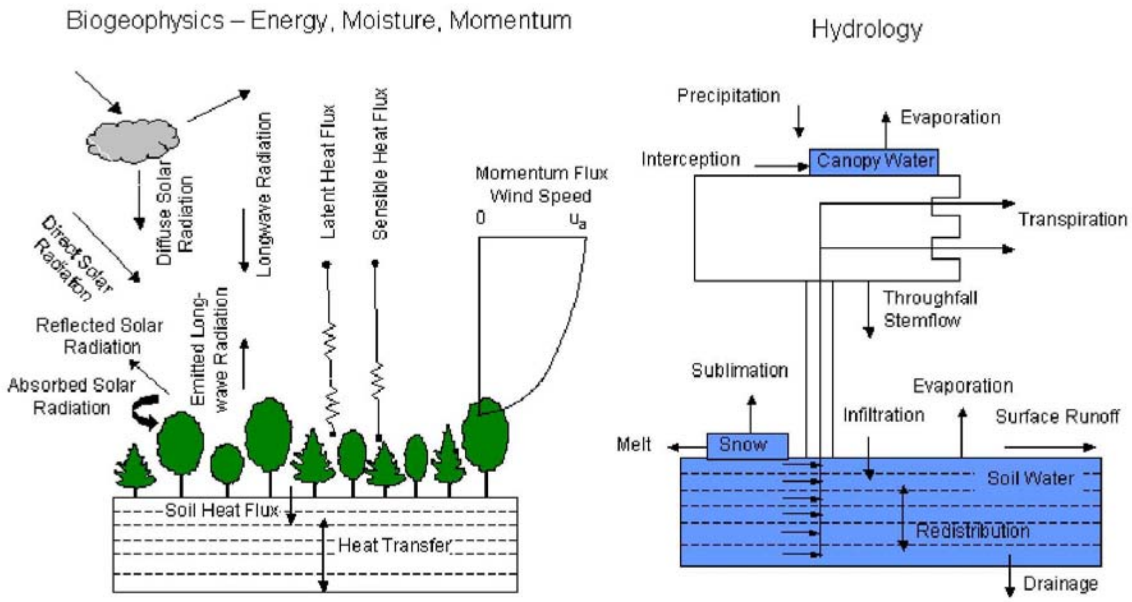

Fig. 1. Schematic map for land biogeophysical and hydrologic processes simulated by CLM3.0 (Oleson et al., 2004).

Land Surface Model (NCAR_CLM2.0), which combined the advantages of the Common Land Model (Dai et al., 2003) and the NCAR Land Surface Model (NCAR LSM) (Dickinson et al., 1993; Bonan, 1996, 1998; Oleson et al., 2004).

As shown in Fig. 1, the biogeophysics processes simulated include: vegetation composition, structure, and phenology; absorption, reflection, and transmittance of solar radiation; absorption and emission of longwave radiation; momentum, sensible heat (ground and canopy), and latent heat (ground evaporation, canopy evaporation, transpiration) fluxes; heat transfer in soil and snow including phase change; canopy hydrology (interception, throughfall, and drip); snow hydrology (snow accumulation and melt, compaction, water transfer between snow layers); soil hydrology (surface runoff, infiltration, sub-surface drainage, redistribution of water within the column); stomatal physiology and photosynthesis; lake temperature and fluxes; routing of runoff from rivers to ocean; volatile organic compounds (Oleson et al., 2004).

To drive the model and evaluate the model output, we use the long-term enhanced field observations at Tongyu station. Tongyu station is one of the CEOP reference sites invested and designed completely by Chinese scientists. Tongyu is located in Northeast China (44°25′N, 122°52′E) with an elevation of 184 m and has an annual mean precipitation of 404.3 mm which is normal for to the semi-arid regions under the continental semi-arid monsoonal climate. Two sites were built respectively in degraded grassland and cropland about 5 km away from each other (Liu et al., 2004).

The data used in the study is observed meteorological data and flux data (water vapor, heat and CO_2 flux) at 30 minute intervals over degraded grassland during the growing season (May to October) in 2003. The observed fields include surface energy budget, near surface gradient, land surface fluxes by eddy covariance (EC) technology, and soil wetness/temperature at different soil layers.

Guo et al. (2007) validated CLM3.0 at Tongyu based on the *in-situ* observation through the years 2003 and 2004, and found that the model could reasonably reproduce the basic characteristics of surface energy budget and the diurnal/seasonal cycles of surface heat fluxes compared with the observations. This lays a solid foundation for this study.

3. Experiment design

To investigate the impact of soil moisture on LE and HS during the growing season in semi-arid regions, we conducted two sets of experiments. In both experiments, the model is driven by meteorological forcing including surface air temperature, precipitation, wind velocity, air pressure, specific humidity, and short- and long-wave radiation. The integration covers a period from 13 May to 31 October 2003 with a time step of 30 minutes.

Figure 2 shows the bias between the observed and simulated soil moisture averaged from 0 to 20 cm after eleven-point smoothing in the control run and contrast run. It is notable that the bias increases rapidly with

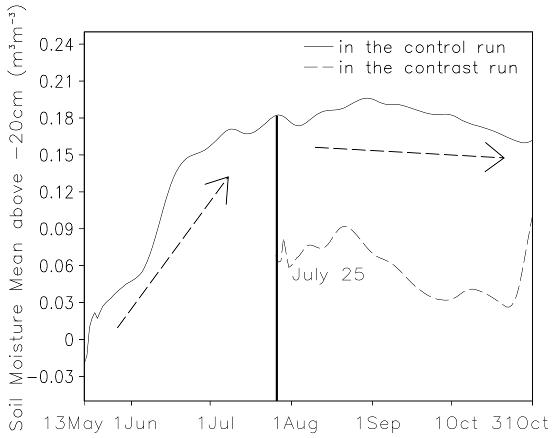

Fig. 2. The difference between the observed and simulated soil moisture averaged from 0 to 20 cm after eleven-point smoothing in the control run and in contrast run from 13 May to 31 October 2003.

time at the beginning stage of the simulation until late July. After that time, the bias doesn't really vary with time. It seems that the model anticipates a lower soil moisture than the observation, and it takes about two and half months for the model to reach equilibrium.

The soil moisture spin up/down is very important in the land surface modeling and the spin-up time of soil moisture is relatively longer than other variables, which depends heavily on applied forcing. The soil is divided into 10 levels from 0 to 3.4 m in the NCAR_CLM3.0. The depths of the observed soil moisture are 0.05, 0.1 and 0.2 m, respectively, which are not corresponding to the exact depths of the soil levels in the model. The maximum depth of observed soil moisture is less than the maximum soil depth in the model. In the paper, according to the observed multi-year averaged soil moisture profile, the interpolation is performed in order to obtain the initial conditions of soil moisture. Therefore, bigger errors may exist between the actual and the interpolated soil moisture in the deeper soil layers than in the shallow layers. Considering the simulation time is less than six months, the soil moisture error in the deep levels is assumed not to have an evident impact on the land-atmosphere interaction.

In this study, the NCAR_CLM3.0 is driven by the observed meteorological forcing. As mentioned above, the time length of spin-up is closely related to the applied forcing. Therefore, given the observed soil moisture at shallow layers, intensified observed meteorological forcing and actual surface condition information (vegetation type, soil color, soil type, etc.), which are already in a quasi-equilibrium state, the spin-up process would be much shorter in this case.

To take the aforementioned feature into consideration, we designed a contrast run accordingly. The differences between two experiments are as follows: in the control run, the simulation integrates from 13 May to 31 October 2003, using observed soil moisture and temperature on 13 May 2003 as initial condition. In the contrast run, the experiment design remains unchanged, but a restart is conducted on 25 July, simply with observed soil moisture as updated "initial values". Then, we make a comparison of the simulated latent/sensible heat flux in two experiments against the observed counterparts from 1 August to 31 October 2003 in terms of diurnal cycle and seasonal evolution.

4. Results and analysis

Figure 3 is the scatter map between simulated and observed daily average HS during the time from 1 August to 31 October 2003. In the control run, the correlation coefficient (hereafter referred to as R) between the observed and the simulated HS is 0.638, the daily root mean squared error (hereafter referred to as DRMS) is 24.9 W m^{-2}, and in the contrast run, R is 0.713, DRMS is 18.9 W m^{-2}. Figure 4 is the same as Fig. 3 but for LE. In the control run, R between the observed and the simulated LE is 0.72, DRMS is 33.1 W m^{-2}; while in the contrast run, R is 0.80 and DRMS is 28.7 W m^{-2}.

Based on these results, we could get a general idea that the soil moisture has a significant impact on the overall simulation of LE and HS. When the observed soil moisture is used to replace the simulated one as the initial condition, the model shows an obvious improvement in terms of R and DRMS between the observed and the simulated LE/HS.

4.1 *Impacts of soil moisture on diurnal cycle of land surface heat fluxes*

Taking advantage of the enhanced observations, we are able to have a detailed view of the behaviors of the HS/LE diurnal cycle. As indicated in Fig. 5, the observed HS in September is larger than that in August and October, corresponding to the growing period of the crop at Tongyu. Generally speaking, the two experiments can accurately replicate the basic pattern of HS evolution. For example, R between the diurnal cycles of the observed and simulated HS during August, September and October in two experiments are 0.995, 0.990; 0.997, 0.995; 0.991, 0.992, respectively, passing the confidence level of 99.9%. However, the diurnal ranges of the simulated HS are overestimated compared to the observation in the control run, especially in the daytime. Compared with the control run, the biases of the diurnal ranges between the observed

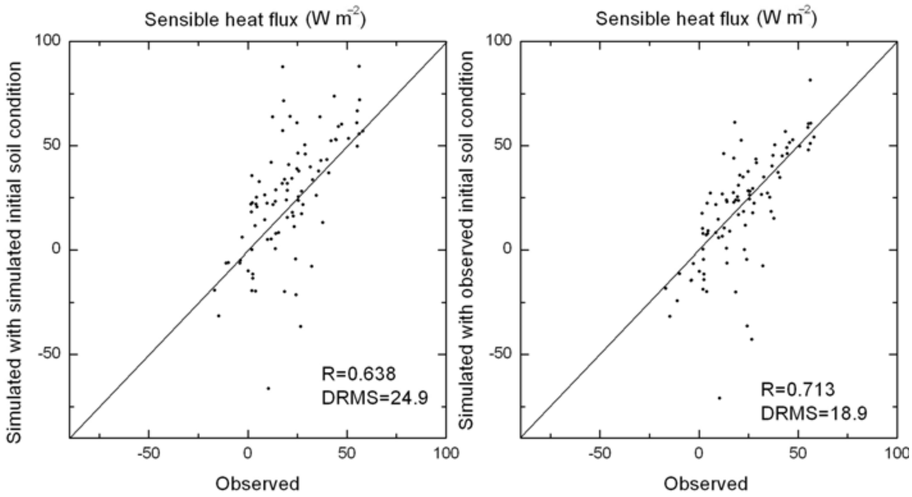

Fig. 3. Scatter map of the observed and simulated daily average sensible heat flux during the time from 1 August to 31 October 2003 (R: correlation coefficient; DRMS: Daily Root Mean Squared Error): (a) for control run; (b) for contrast run.

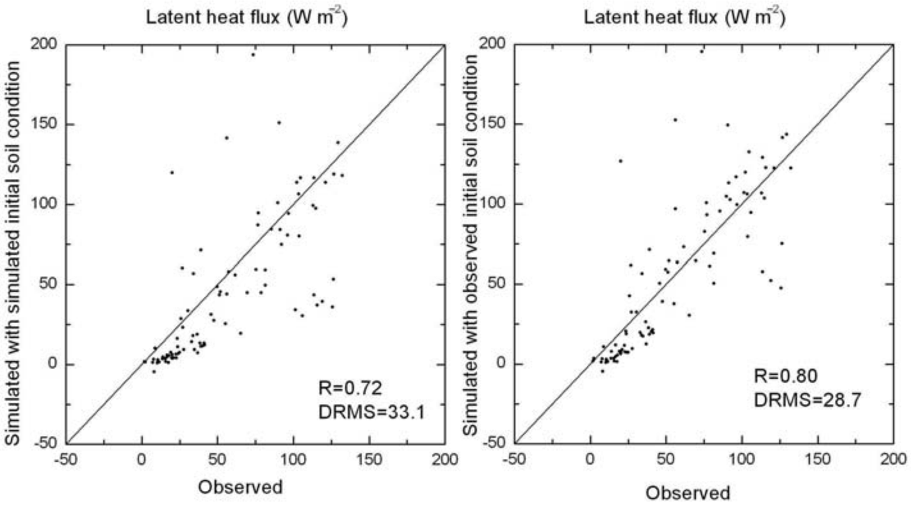

Fig. 4. Same as Fig. 3 but for LE.

and simulated HS are much smaller in the contrast run except for those in October. Specifically, the biases between the simulated and observed HS during the daytime in the contrast run are smaller by 66.8%, 22.4% and 0.3% in the three months respectively. At the same time, the improvement in the contrast run decays with time, which reflects the decline of the impact of the initial soil moisture of the simulated HS. For instance, the improvement almost doesn't occur in October. As described above, the contrast run can better represent both the diurnal evolution and the diurnal ranges of HS compared to those in the control run.

Figure 6 is same as Fig. 5 but for LE. The observed LE drops sharply from August to October due to the simulation period being at the end of the growing season of the crop, which can be reproduced well in the control and contrast run. In August, September and October, R between the diurnal cycles of observed and simulated LE in two experiments are 0.992, 0.991; 0.983, 0.981; 0.902, 0.913, respectively, passing the confidence level of 99.9%. However, the simulated diurnal ranges of LE in the control run are less than that in the observed. The biases between the observed and simulated amplitude of LE in the daytime are larger than those at night. In the daytime, the biases between simulated and observed LE are reduced by 13.3%, 24.0% and 5% in August, September, and October, respectively, in the contrast run. Particularly, in September, the improvement of LE simulation in the contrast run is more significant than other months, while the simulation shows almost no change

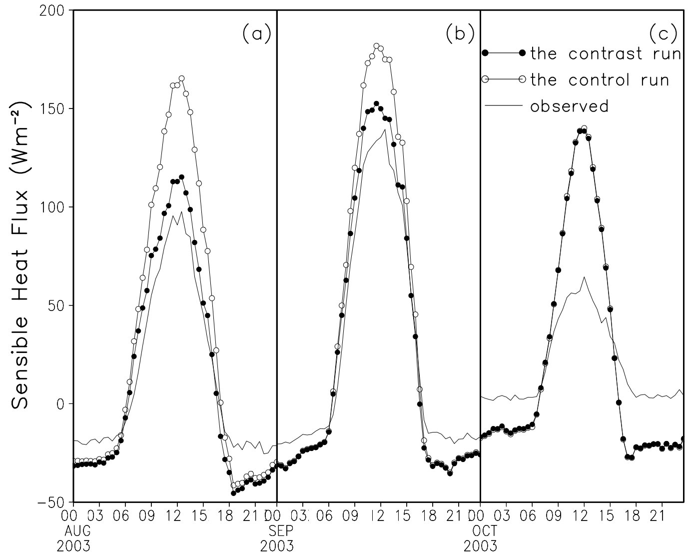

Fig. 5. Diurnal cycles of HS of the observation and simulations in two experiments in (a) August, (b) September, and (c) October 2003.

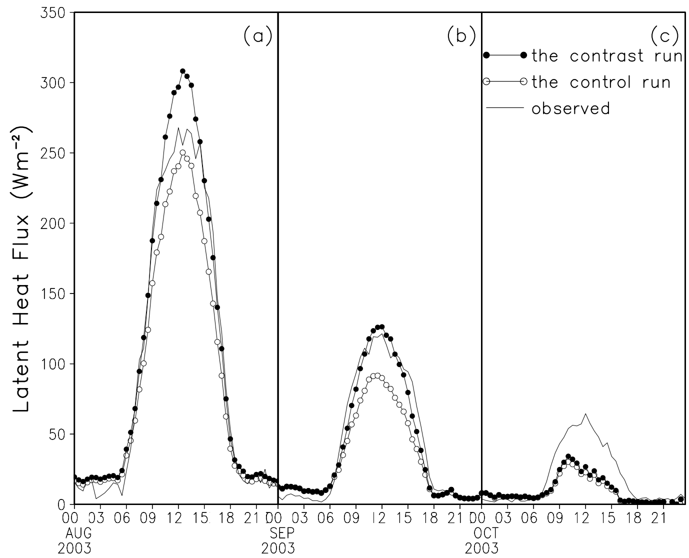

Fig. 6. Same as Fig. 5 but for LE.

in October. Similar to the case of HS, the advantages of the contrast run over the control run decay with the time for LE. Overall, the simulation of HS is improved greatly compare to that of LE in the contrast run.

4.2 *Impacts of soil moisture on seasonal evolution of land surface heat fluxes*

The time from August to October is the second half of the growing period. Thus, as indicated in Fig. 7 and Fig. 8, the monthly average of observed HS increases at first and then decreases with the time, while the observed LE decreases continuously from August

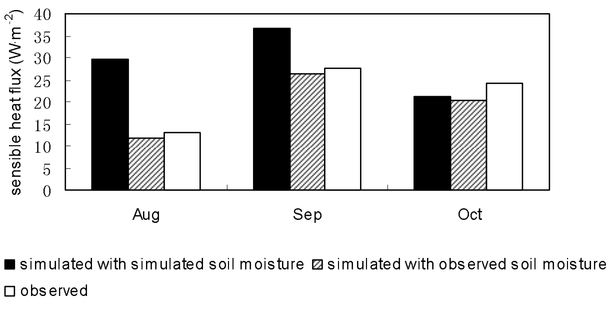

Fig. 7. Seasonal evolution of the observed and simulated HS in August, September, and October, 2003.

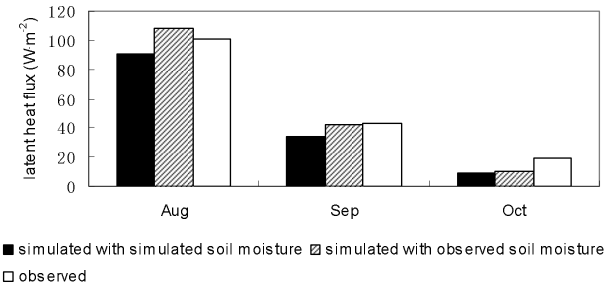

Fig. 8. Same as Fig. 7 but for LE.

to October, which can be reflected well in two experiments. However, the control run failed to reflect the seasonal evolution of HS.

Figure 7 shows the comparison of the monthly average of simulated and observed HS for August, September and October. The monthly average of the observation, and simulated HS in the contrast and control experiments are 12.98 W m^{-2}, 11.79 W m^{-2}, 29.61 W m^{-2} in August, 27.58 W m^{-2}, 26.48 W m^{-2}, 36.63 W m^{-2} in September, and 24.26 W m^{-2}, 20.44 W m^{-2}, 21.29 W m^{-2} in October respectively. Compared with the control run, the biases between simulated and observed HS for three month are dramatically reduced by 25.6% in the contrast run.

Figure 8 is the same as Fig. 7 but for LE. The monthly averaged observation and simulated LE in the contrast and control experiments are 100.52 W m^{-2}, 107.75 W m^{-2}, 90.64 W m^{-2} in August, 43.10 W m^{-2}, 41.97 W m^{-2}, 33.99 W m^{-2} in September, and 19.19 W m^{-2}, 9.70 W m^{-2} , 9.02 W m^{-2} in October, respectively. Compared with the control run, the biases for the three months are reduced by 15.8% on average in the contrast run, which is lower than the case for HS.

Based on the aforementioned analysis, the two experiments can simulate accurately the monthly average of LE/HS during the time from August to October. Both HS and LE are sensitive to the soil moisture in terms of monthly evolution. The simulations from the contrast experiment are obviously better than those from the control experiment, except the LE in October, which may be due to the decay of the impact of soil moisture on the surface fluxes.

5. Conclusions

In this paper, we present an analysis of the sensitivity of HS/LE to soil moisture from the viewpoint of land-atmosphere coupling in the semi-arid region during the growing season. In general, the simulations of HS/LE are much improved in the contrast experiment by updating the initial conditions of the soil moisture. For the diurnal cycle of HS/LE, both the range and the daytime peak are better simulated in the contrast run. At the same time, the improvements decay with time. For the seasonal evolution of HS/LE, the contrast experiment is capable of better representing the basic characteristics of the temporal evolutions of HS and LE than the control experiment. Compared with the control run, the biases between the observations and the simulations for the three months are reduced by 25.6% for HS and 15.8% for LE on average.

From this study, the high sensitivity of land surface heat fluxes to soil moisture at different time scales is revealed, which further supports the previous studies that the soil moisture plays a very important role in land-atmosphere interaction in the semi-arid region. Therefore, in order to better simulate the land-atmosphere interaction and predict the climate and water resource changes in semi-arid regions, it is necessary to better describe the soil moisture distribution, both in the way of observation and its treatment in land surface models.

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