

# Improvement of land surface temperature simulation over the Tibetan Plateau and the associated impact on circulation in East Asia

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## Abstract

A new sensible-heat (*SH*) parameterization was used in the Weather Research and Forecasting model to improve the vertical heat transfer simulation in arid regions. With this new scheme, the simulated *SH* decreased, resulting in a 2 °C reduction of the cold bias in the land surface temperature over the Tibetan Plateau. The weakened *SH* led to anticyclonic circulation and cyclonical flow changes in the northern East China due to Rossby wave propagation. The summer-rainfall in East Asian is marginally improved. It is suggested that the *SH* simulation over the Plateau is a land–atmosphere coupling issue that is important to the dynamical downscaling in East Asian.

**Keywords:** Tibetan Plateau; land surface temperature; East Asian summer monsoon; WRF; CLM

Received: 8 July 2015  
Revised: 2 October 2015  
Accepted: 28 October 2015

## 1. Introduction

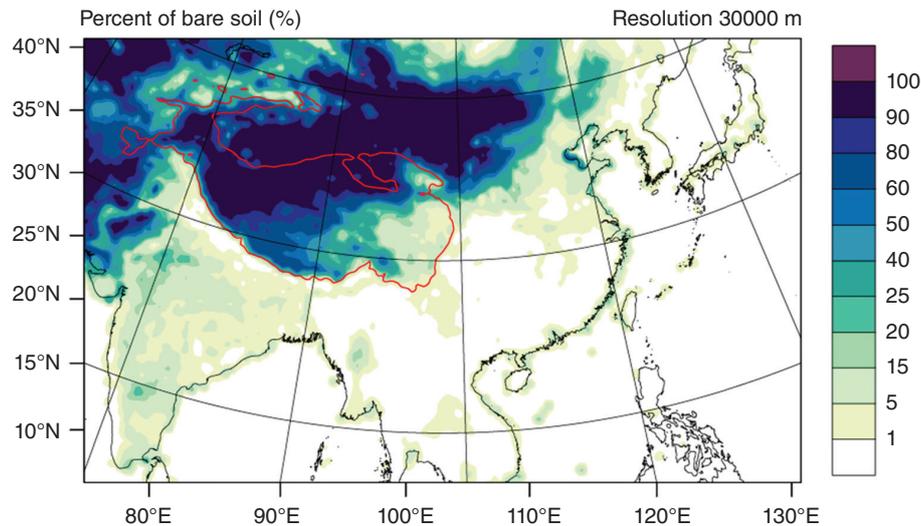
Owing to the unique geography of the Tibetan Plateau (TP) and land–atmosphere interaction characteristics, all of the global climate models underestimate surface air temperature in the TP, and most overestimate its precipitation (Hao *et al.*, 2013). Most of the reanalysis datasets also tend to underestimate temperature in the TP (You *et al.*, 2010; Wang and Zeng, 2012). Land surfaces form the lower boundary conditions of the atmosphere, which essentially dominate local energy and water transfer, and can affect local, regional, and global climate processes. Proper description of land surface processes in earth system models is a popular research topic.

Arid and semi-arid regions constitute approximately one-fourth of the total global land area, and account for approximately 40% of the land area in China (Hu and Zhang, 2001). They are mostly distributed in Northwest China and in the TP. Because vegetation coverage and rainfall are extremely rare in these regions, the land–atmosphere interaction process is dominated by heat transfer processes. However in the arid and semi-arid regions, surface temperature and energy are poorly simulated.

The unique solar radiation and energy transfer processes in the TP differ significantly from those in regions of lower altitude (Smith and Shi, 1992; Zhang *et al.*, 2014). The development of the turbulent transfer theory in recent years has allowed scientists to conduct numerous land surface parameterization field

experiments in arid and semi-arid regions (Zeng *et al.*, 1998; Yang *et al.*, 2008; Chen *et al.*, 2010). In such studies, the surface energy transfer process was investigated, and several new parameterization schemes of land surface models were developed (Zeng *et al.*, 2012; Wang *et al.*, 2014).

Without considering vegetation, the emissivity  $\varepsilon$  of bare soil in Community Land Model (CLM) is set to a constant at approximately 0.96. Therefore, in arid and semi-arid regions, the main factors affecting the calculation of the land–atmosphere energy balance are surface albedo  $\alpha$ , aerodynamic roughness length  $z_{0m}$ , thermal roughness length  $z_{0h}$ , soil heat capacity  $c_v$ , and soil thermal conductivity  $K_{soil}$ . After conducting more than 10 years of observation at three stations in alpine and desert areas including Gobi, Huang *et al.* (2005) assigned a surface albedo value of  $0.255 \pm 0.021$  to the Dunhuang area of Gobi. Zhou *et al.* (2012) assigned a momentum roughness length  $z_{0m}$  of  $0.61 \pm 0.02$  mm in Dunhuang, and an average thermal roughness length  $z_{0h}$  of approximately 0.05 mm during the daytime. Chen *et al.* (2009) used these parameters to evaluate the Biosphere–Atmosphere Transfer Scheme (BATS) and showed that the cold bias in land surface temperature (*LST*) simulation has been improved in the daytime, and its diurnal cycle has been accurately simulated. In addition, some studies have shown that vegetation degeneration in northwest arid areas not only affects local precipitation (Li and Xue, 2010) but also drive an anticyclone anomalies in the upper troposphere in the spring, and maintain to summer, at last affect the



**Figure 1.** Model domain and the distribution of bare soil in the Community Land Model. The red solid line area indicates elevation >3000 m.

precipitation in the northeast part of TP through “silk road” wave train (Zhou and Huang, 2010; Huang *et al.*, 2011).

Moreover, many studies have derived surface sub-layer turbulent heat transfer parameterization for incorporating  $z_{0h}$  in past decades (Sheppard, 1958; Brutsaert, 1982; Zeng and Dickinson, 1998; Kanda *et al.*, 2007; Yang *et al.*, 2008). However, some problems remain (Hogue *et al.*, 2005; Jiménez *et al.*, 2011; Decker *et al.*, 2012). Many land surface models such as Noah land surface model (Noah LSM) and CLM overestimate the  $SH$  and thus underestimate  $LST$  during the dry season in arid areas (Hogue *et al.*, 2005). Chen *et al.* (2010) evaluated the parameterization of  $z_{0h}$  when simulating  $LST$  with six different schemes of the Noah LSM. They found that original Noah significantly underestimated  $LST$  and overestimated  $SH$  in the daytime. The offline run with revised parameterization schemes can give better results of both  $LST$  and  $SH$  owing to better simulation of the diurnal variation in  $z_{0h}$ .

Recently, through both theoretical analyses and data-model comparison, Zeng *et al.* (2012) used *in situ* observation and offline experiments at several stations in arid and semi-arid regions, including the Arizona desert and the TP, to further revise the coefficients of  $z_{0h}$  both in Noah and CLM. They also set a constraint of minimum friction velocity and take a prescribed soil texture. This measure significantly reduced the underestimation of  $LST$  in the daytime. Their new scheme has been successfully applied to the National Centers for Environmental Prediction Global Forecast System (NCEP-GFS) assimilation (Zheng *et al.*, 2012). However, it is unknown whether these improvements can be effectively applied in the land–atmosphere coupled model. Simulation is then applied over East Asia. These analyses will be used to examine the extent to which the new  $SH$  parameterization improves  $LST$  simulation. Moreover, we discuss the impacts of

land–atmosphere interaction on diabatic heating and local and downstream circulation.

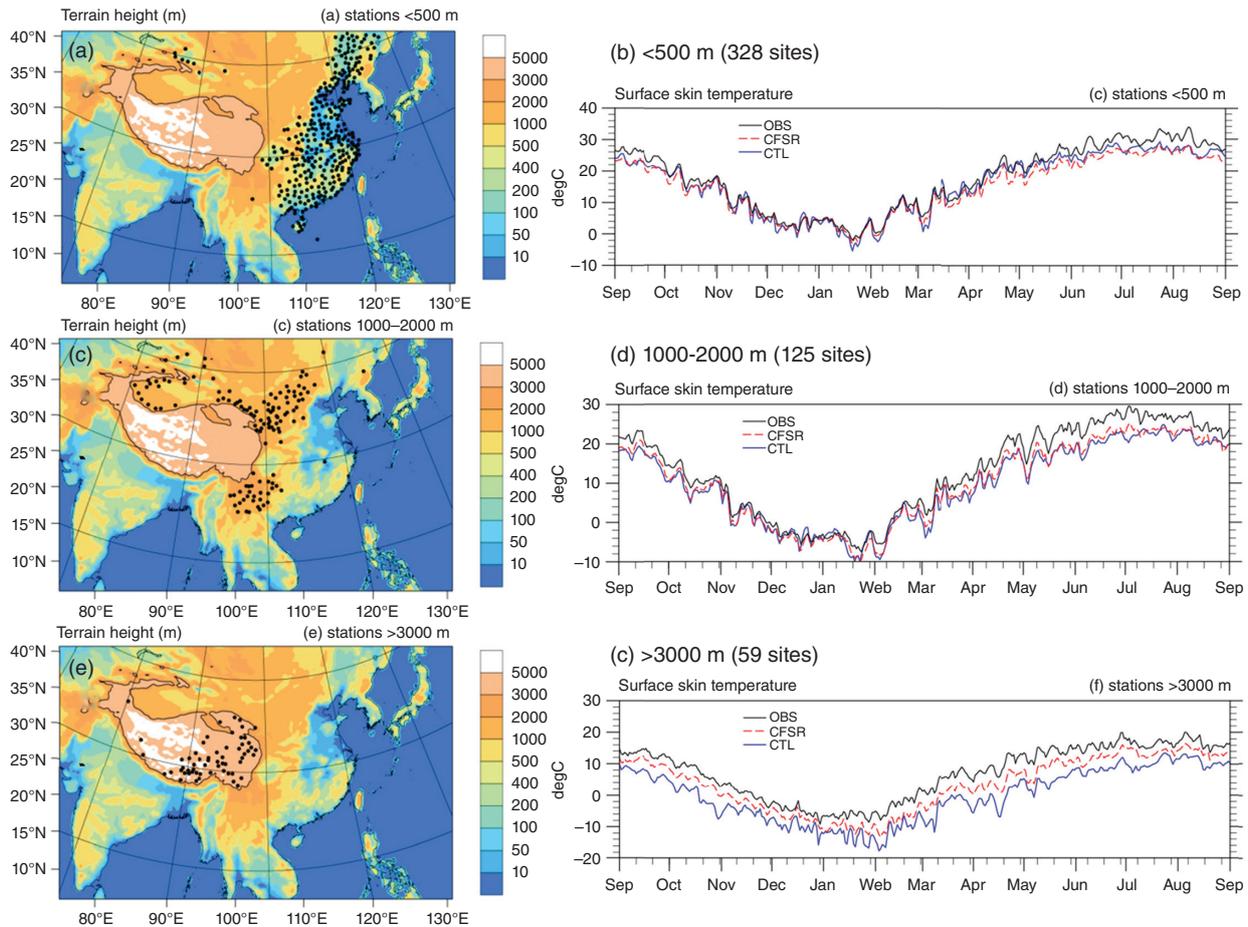
This study helps us deeply understand the attribution of the land surface process of large-scale topography. Moreover, the discovery of direct and indirect effects of the land surface heat transfer process from TP to the downstream regions can be applied to improve the climate prediction of East Asia effectively.

## 2. Experiment design

### 2.1. Model and data

The Weather Research and Forecasting (WRF) model is currently the most widely used mesoscale model. Its latest WRFV3.6.1 (Skamarock *et al.*, 2008) coupled with CLM4 (Oleson *et al.*, 2013) was used in this study. The related physics includes MYNN surface layer and Mellor–Yamada Nakanishi and Niino Level 3 PBL. According to the model domain shown in Figure 1, the percentage of bare soil has gradually increased from Southeast China, with rich vegetation, to the Northwest China, which is sparsely vegetated. Particularly in the western plateau, most parts of the TP are sparsely vegetated.

We conducted two experiments: a control experiment (CTL) and a sensitivity experiment (SEN). Both used the same basic settings except that the new parameterization of  $SH$  was used in the SEN experiment. The central point of the model domain is (30°N, 103°E). The horizontal resolution was 30 km with 150 grid points from south to north and 240 grid points from west to east. Integration was from September 1, 2003, to August 31, 2010, and was continuous with the same initial condition at 00Z UTC. The forcing data used in this study were 6-hourly NCEP climate forecast system reanalysis (CFSR) products (Saha *et al.*, 2010). In addition, we used the daily site observation data of the Chinese Meteorological Administration (CMA) from 2003 to 2010;



**Figure 2.** (a), (c), (e) Site distribution and corresponding land surface temperature time series of observation (black line), Climate Forecast System Reanalysis data (red dashed line), and Weather Research and Forecasting simulation (blue line) for (b) 0–500 m, (d) 1000–2000 m, and (f) >3000 m recorded September to August for 1-year integration.

the *LST* observation of the Moderate Resolution Imaging Spectroradiometer (MODIS) which recorded four times daily; and the Tropical Rainfall Measuring Mission (TRMM)-3B42 dataset.

## 2.2. Evaluation of the WRF model

In the present study, we compare the CMA station data against the corresponding model location in the CTL (Figure 2). The sites used for comparison are distributed in three different regions: elevation below 500 m (328 sites), at 1000–2000 m (125 sites), and higher than 3000 m (59 sites). The percentage of bare soil is larger at the stations located at higher elevations. In Figure 2, the left-hand side shows the terrain height and locations of the CMA sites, and the right-hand side shows averaged *LST*. The values of the CTL were obtained from the grid point in closest proximity to the site location. Because each site's *LST* is based on actual terrain elevation and the model's elevation may not be the same, we adjusted the temperature by using temperature vertical lapse rate of  $\sim 6^\circ\text{C km}^{-1}$ . The results show that the cold bias of *LST* gradually increased with an increase in altitude. The cold bias was obviously greater for the sites in the TP, with a root-mean-square deviation (RMSD) of  $\sim 7.6^\circ\text{C}$  and elevation higher than 3000 m,

than that in the eastern plain, with an RMSD of  $\sim 2.4^\circ\text{C}$  and elevation below 500 m. The original CLM model underestimates the *LST* in arid and semi-arid regions.

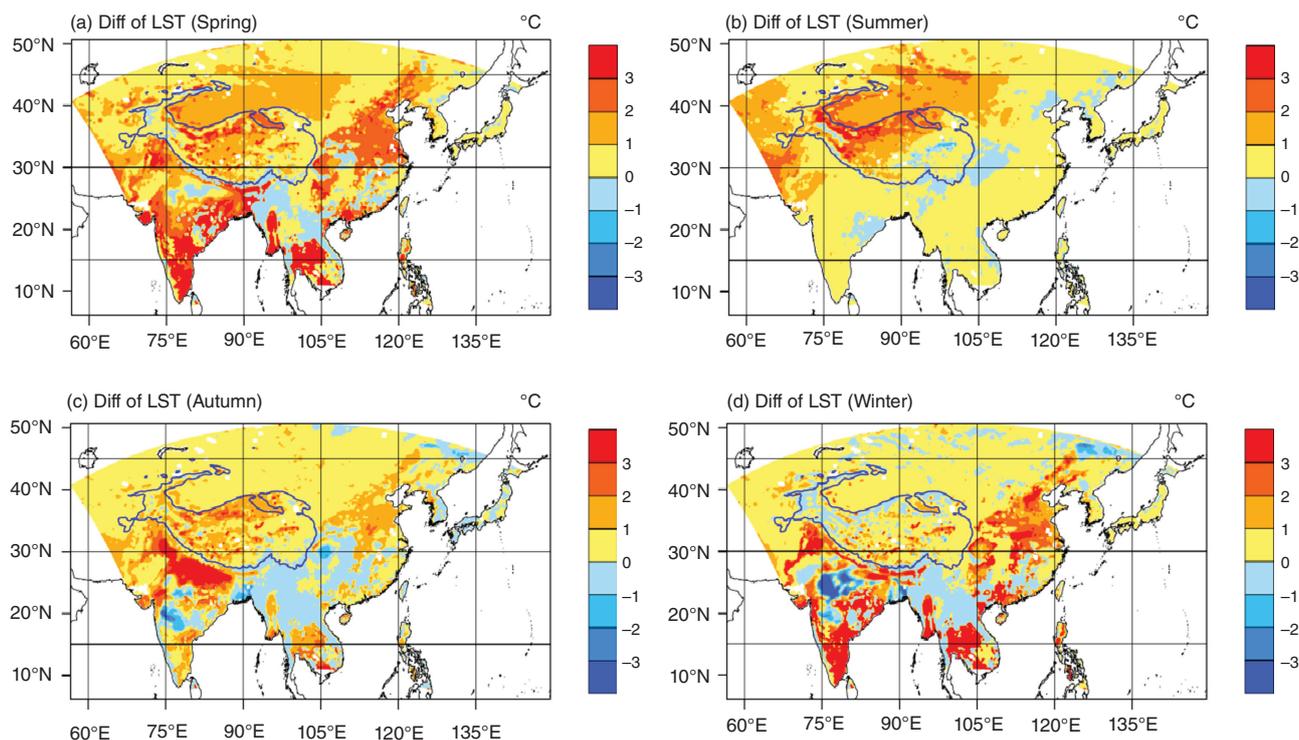
## 2.3. Model configuration with new scheme

Zeng and Dickinson (1998) previously reported a relationship between  $z_{0h}$  and  $z_{0m}$ . Recently, they revised the constants “a” and “b” from 0.13/0.45 to 0.36/0.5 and constrained the minimum friction velocity  $u_{*min}$  to 0.07 m in bare soil (Zeng *et al.*, 2012). The three parameters used in the *SH* of non-vegetated surfaces are  $z_{0h}$ ,  $z_{0m}$ , and minimum friction velocity  $u_{*min}$ :

$$\ln\left(\frac{z_{0m}}{z_{0h}}\right) = a\left(\frac{u_* z_{0m}}{\nu}\right)^b \quad (1)$$

$$u_{*min} = 0.07 \frac{\rho_0}{\rho} \left(\frac{z_{0m}}{z_{0g}}\right)^{0.18} \quad (2)$$

where  $\nu = 1.5 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$  refers to the molecular viscosity. The air density at sea level  $\rho_0$  is  $1.22 \text{ kg m}^{-3}$ , and the roughness length of bare soil is 0.01 m. It is shown that the underestimation of *LST* is significantly improved in the daytime (Zeng *et al.*, 2012; Wang *et al.*, 2014).



**Figure 3.** Differences in seasonal mean land surface temperature determined by subtracting the results of the control experiment from those of the sensitivity experiment (2003–2010): (a) spring, (b) summer, (c) autumn, and (d) winter.

### 3. Results

#### 3.1. LST simulation

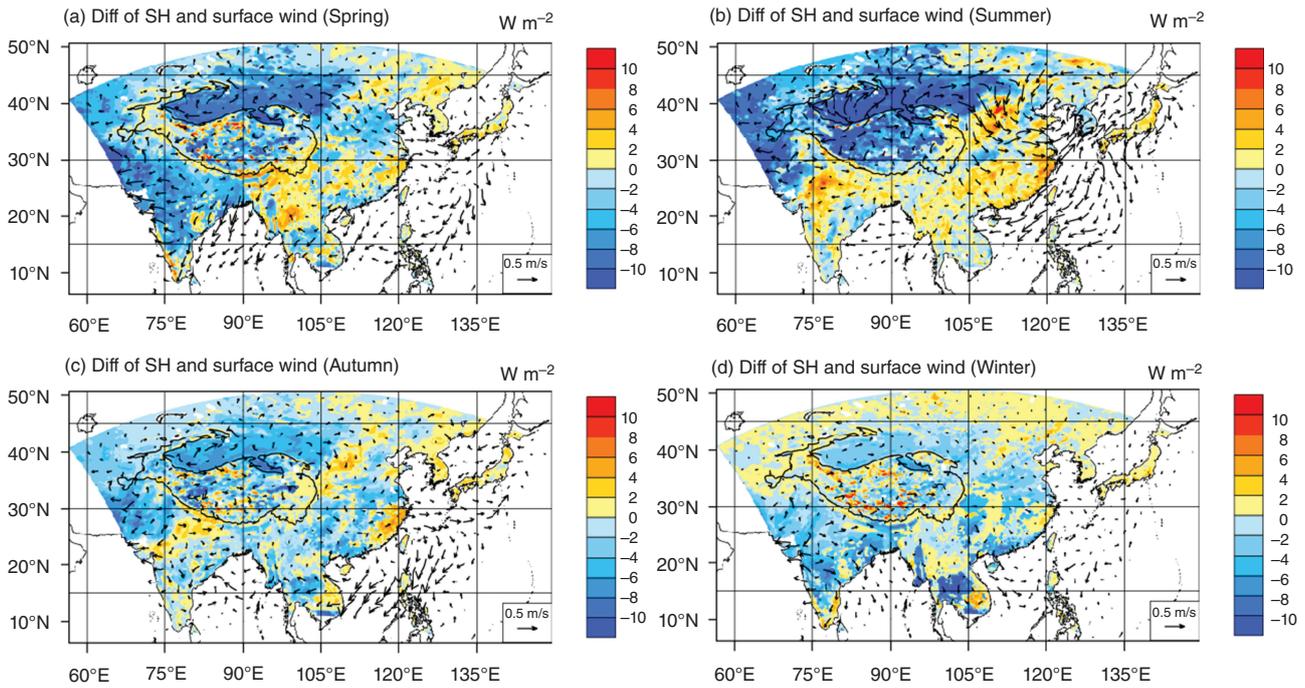
When a two-way feedback of land–atmosphere interaction was considered, the *LST* showed an obvious improvement in all of the arid and semi-arid regions, particularly in the TP and the Taklamakan Desert, but showed variations among seasons. The TP has the largest impacts in summer because the thermal forcing in the weak wind plays a more important role than the heating in strong wind in other seasons (Wu *et al.*, 2007). The surface sensible heating over the Plateau pumps moisture from oceans so contributes the formation and variation of the Asian monsoon (Wu *et al.*, 2012a, 2012b; Liu *et al.*, 2102). The maximum *LST* increase, 3 °C, occurred in summer over the western TP; otherwise, the *LST* increase in the Taklamakan Desert was smaller than that in the TP. The changes in other regions indicate responses to the interaction in arid regions (Figure 3).

Figure 4 shows the differences in *SH* between SEN and CTL. The *SH* decreased in arid and semi-arid regions when using the new scheme. Of the four seasons, the *SH* decrease was most obvious in summer. Moreover, the surface wind changed with the *SH*; wind divergence was noted near the TP. The impact on East Asia was strong in summer. The cyclonic wind deviation was located in Northeast China, although the anti-cyclonic wind deviation occurred in the South China. Because thermal forcing had the strongest impacts on circulation in summer, the following analyses and discussions focus on summer.

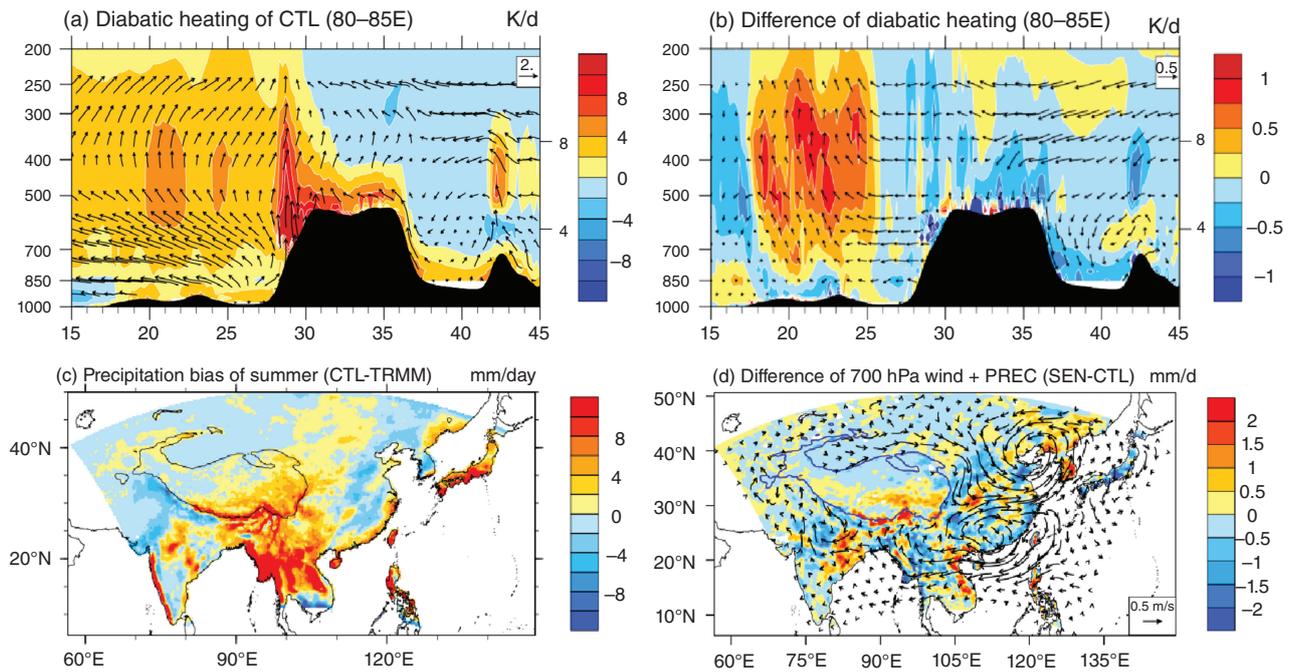
#### 3.2. Impact on the circulation and the East Asia climate in summer

To determine the causes of the cyclonic deviation of surface wind in summer, we analyzed the thermal heating effects of the TP on the atmospheric circulation. In summer, the cumulus convection is strong at the south slope and southern edge of the plateau; the maximum diabatic heating is  $10 \text{ K day}^{-1}$  at the south slope (Figure 5(a)). The updraft airflow is located at both sides of the TP due to the *SH* air pump effect (Wu *et al.*, 2007). The flow on the south slope is considerably stronger owing to moisture physics feedback. However, the pumping effect was weakened after the application of the new scheme. The upward movement and the diabatic heating also became weaker on both north and south of the TP (Figure 5(b)).

The new scheme also affects the summer circulation and rainfall in East China. Figure 5(c) shows a comparison of CTL precipitation and TRMM observation, and Figure 5(d) shows the difference in precipitation and 700 hPa wind between SEN and CTL. The East Asia Summer Monsoon rain belt is underestimated by approximately  $4 \text{ mm day}^{-1}$  in East–Central China and is overestimated at the same rate in the eastern TP and the southeastern coast of China (Figure 5(c)). The new scheme improves the precipitation in most parts of East Asia. The underestimated rainfall in Northeast and East–Central China showed marginal improvement, as did the rainfall overestimated in the eastern TP, the Hetao region in Mongolia, and the southeast coast of China in summer. This result occurred because the new scheme obviously reduces the *SH* in the western and



**Figure 4.** Comparison of seasonal mean surface sensible heat (shading, units:  $\text{W m}^{-2}$ ) and surface wind (vector, units:  $\text{m s}^{-1}$ ), determined by subtracting the results of the control experiment from those of the sensitivity experiment (2003–2010): (a) spring, (b) summer, (c) autumn, and (d) winter.



**Figure 5.** Diabatic heating, wind, and precipitation in summer: (a)  $80^{\circ}$ – $85^{\circ}\text{E}$  mean diabatic heating and wind in the control experiment (CTL); (b)  $80^{\circ}$ – $85^{\circ}\text{E}$  mean difference of diabatic heating and wind determined by subtracting the results of CTL from those of the sensitivity experiment (SEN); (c) precipitation bias of CTL and the Tropical Rainfall Measuring Mission (TRMM); (d) difference in precipitation and 700 hPa wind (SEN minus CTL).

central TP, where the ground surface is dominated by bare soil. Thus, the *SH* air pump effect of the TP is weakened, and the diabatic heating and the updraft air-flow are reduced in both north and south sides of the TP. The weakened surface heating resulted in divergence and anticyclonic circulation close to the surface near the TP and cyclonical flow change in the northern

part of East China due to Rossby wave propagation. The southeasterly (westerly) winds of the cyclone led to convergence over Northeast (East–Central) China and contributed to the *in situ* rainfall increase. A compensatory anticyclone developed in South China, and its northwestern flow reduced the rainfall along the southeast coast.

In summary, the new *SH* scheme shows improvement in *LST* simulations in the TP and precipitation simulations in parts of East China in the summer monsoon season. On the other hand, soil moisture (Hong *et al.*, 2009; Moufouma-Okia and Rowell, 2010; Jaeger and Seneviratne, 2011) also play a role in the simulation in the regional models.

#### 4. Summary

This study investigated the influence of a new *SH* parameterization scheme for bare soil in the land–atmosphere coupling system of WRF. The results show that the overestimation of the *SH* and underestimation of *LST* over arid and semi-arid regions are improved by using the new scheme. The new scheme significantly improves the *LST* simulation over most of the western and central TP. The average cold bias of the *LST* was reduced by approximately 2 °C in the TP. The decrease in *SH* affects the vertical circulation near the TP. The *SH* air pump effect in the TP and the updraft motion of airflow around the plateau were also weakened. The diabatic heating over both the southern and northern slopes of the TP was also reduced.

Moreover, the decrease in *SH* affects the circulation and precipitation in East Asia. The new scheme led to divergence with the development of an anticyclone over the TP and a cyclone and anticyclone over Northeast and South China, respectively. The rain belt simulations were thus improved. The cyclonic circulation in Northeast China led to more precipitation in Northeastern and Central China. The anticyclonic circulation in South China decreased the overestimated rainfall in the southeastern coast. It is suggested that the *SH* simulation over the Plateau is a land–atmosphere coupled issue that is important to climate dynamical downscaling, as well as the climate prediction and weather forecasting in East Asian. The influence of the new scheme on global climate models deserves future investigation.

#### Acknowledgements

This work is supported by the National Natural Science Foundation of China (Grant No. 91437219) and the Third Tibetan Plateau Scientific Experiment (Grant No. GYHY201406001).

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