On simulation improvement of the Noah_LSM by coupling with a hydrological model using a double-excess runoff production scheme in the GRAPES_Meso model

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ABSTRACT: Land surface models play an important role in simulating mass, energy and momentum exchanges between the atmosphere and land surface in numerical weather prediction systems. The Noah land surface model (Noah_LSM) is adapted to describe the water and energy balance in the GRAPES_Meso model (V4.0). However, the Noah_LSM does not distinguish the infiltration-excess runoff and the saturation-excess runoff effects and does not simulate runoff routing, making its applicability limited in China. In this work, the Noah_LSM was improved by incorporating double-excess runoff production and routing schemes. The double-excess runoff production scheme is based on the depletion of water storage coupling with the Holtan method. The Muskingum model is used for routing. To evaluate the performance of the improved model, numerical simulations were carried out using the old and improved models to investigate the feedback of changes in the land surface hydrological model to numerical simulations for meteorology. The results demonstrate that the improved land surface hydrological model affects numerical simulations for meteorology in terms of the soil temperature, soil moisture, air temperature and wind speed as well as predicting rainfall events better in terms of the rainfall regime.

KEY WORDS: Noah land surface model; double-excess runoff production scheme; GRAPES_Meso model

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1. Introduction

A land surface model is designed to simulate land surface processes and the exchange of surface water and energy fluxes at the land–atmosphere interface. The variations of land water storage capacity and heat can retain evidence of weather and climate event anomalies. In return, anomalous conditions in land water and heat storage as filtered signals of noisy weather events can affect atmospheric predictability through their effects on surface energy and water fluxes (Jiang et al., 2009; Niu et al., 2011). In an atmospheric model, the land surface model controls the surface energy and water balance with feedback from sensible and latent heat fluxes (Roesci et al., 2001; Jiang et al., 2009). Many studies of the energy balance in land surface models have been conducted in the past and their findings have been applied to operational numerical prediction models. Fewer studies have been conducted on enhancing the hydrological processes in the land surface model within an atmospheric model other than the energy processes. The water balance directly determines the change of soil moisture and provides an important feedback to the atmospheric model that affects the simulation of the rainfall regime (Chen et al., 1996; Peterslilard et al., 1998; Bates and De Roo, 2000; Chen and Dudhia, 2001; Wang and Chen, 2013; Wang and Bao, 2015; Wang et al., 2016). Therefore, an accurate simulation of land surface water balance is critical for improving the performance of atmospheric models.

The Global/Regional Assimilation and Prediction System (GRAPES; Chen and Shen, 2006; Chen et al., 2008; Xue and Chen, 2008) is an operational numerical weather prediction system developed by China Meteorological Administration. Compared to the earlier GRAPES_Meso model V3.3, the GRAPES_Meso model V4.0 has been updated by adding the MRF PBL, LW schemes and other components. In addition, the resolutions of the models have been increased in both the vertical (31 levels to 50 levels) and horizontal (15–10 km) directions. The Noah land surface model (Noah_LSM) was used for simulating the land surface water and energy balances in the GRAPES_Meso model system (V4.0). However, the Noah_LSM does not sufficiently simulate every component of the hydrological cycle because it uses a simple parameterized scheme called the simple water balance (Entekhabi et al., 1999). This is an obvious limitation of the Noah_LSM for the simulation of hydrological processes (Wang and Chen, 2013). Saturation-excess and infiltration-excess runoff generation mechanisms are two classic mechanisms in hydrological modeling (Zhao, 1983; Li and Zhang, 2008). Previous studies have shown that the single saturation-excess runoff generation scheme is not suitable everywhere in China (Yao et al., 2012, 2014; Wang and Chen, 2013). In fact, humid, semi-humid, semi-arid and arid climate zones are distributed from south to north in China. The saturation-excess runoff production mechanism is usually dominant in humid zones, while the infiltration-excess runoff production mechanism and the saturation-excess runoff production mechanism, also called the double-excess runoff production scheme, coexist in arid, semi-arid and semi-humid zones (Zhao, 1983; Chen et al., 2013; Bao et al., 2016a, 2016b). Most of northern China belongs to the non-humid zones. Based on the
above analyses, it is necessary to introduce the double-excess runoff production scheme and routing scheme into the surface hydrological process of the Noah_LSM to make it more applicable in China. Therefore, this study was aimed at improving the modelling of the hydrological cycle in the Noah_LSM by (1) refining the runoff generation component through accounting for the spatial variation of runoff yield mechanisms within the grid cell for better representation of within-grid-cell runoff yield and (2) adding the flow routing model to simulate the whole land surface water cycle (Wang and Chen, 2013).

2. Brief description of the Noah_LSM

2.1. Hydrological scheme

In the Noah_LSM, the soil water content ($\theta$) in each soil layer is solved from the prognostic equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left( D z \frac{\partial \theta}{\partial z} \right) + \frac{\partial K}{\partial z} + F_\theta \tag{1}$$

where $K$ is the hydraulic conductivity, $\theta$ is the soil moisture content, $z$ is the soil depth, $F_\theta$ are the sources and sinks for soil water and $D$ is the soil water diffusivity. $D$ can be solved using the following equations:

$$D = K(\theta) (\partial \psi / \partial \theta) \tag{2}$$

$$K(\theta) = K_S \left( \theta / \theta_S \right)^{2b+1} \tag{3}$$

and

$$\psi(\theta) = \psi_S \left( \theta / \theta_S \right)^{b} \tag{4}$$

where $b$ is a curve-fitting parameter; $K_S$ is the saturated hydraulic conductivity, $\psi_S$ is the saturated soil water tension and $\theta_S$ is the saturated soil moisture content. All these variables are dependent on soil type.

Substitution of Equations (2)–(4) in Equation (1) gives:

$$d_1 \frac{\partial \theta}{\partial t} = -D \left( \frac{\partial \theta}{\partial z} \right)_{\zeta_1} - K_{\zeta_1} + P_d - R - E_{\text{dir}} - E_{\text{can}} \tag{5}$$

$$d_2 \frac{\partial \theta}{\partial t} = D \left( \frac{\partial \theta}{\partial z} \right)_{\zeta_2} - D \left( \frac{\partial \theta}{\partial z} \right)_{\zeta_2} + K_{\zeta_1} - K_{\zeta_2} + - E_{\text{dir}} \tag{6}$$

$$d_3 \frac{\partial \theta}{\partial t} = D \left( \frac{\partial \theta}{\partial z} \right)_{\zeta_3} - D \left( \frac{\partial \theta}{\partial z} \right)_{\zeta_3} + K_{\zeta_2} - K_{\zeta_3} + - E_{\text{can}} \tag{7}$$

$$d_4 \frac{\partial \theta}{\partial t} = D \left( \frac{\partial \theta}{\partial z} \right)_{\zeta_4} + K_{\zeta_3} - K_{\zeta_4} \tag{8}$$

where $\theta_0$ is the $n$th soil layer thickness, $t$ is the time, $P_d$ is the precipitation, $E_{\text{dir}}$ is the canopy transpiration in the $n$th soil layer, $K_{\text{can}}$ is the subsurface runoff or drainage and $R$ is the surface runoff. $R$ is calculated as:

$$R = P_d - I_{\text{max}} \tag{9}$$

$$I_{\text{max}} = P_d D \left\{ 1 - \exp \left( -k dt \sigma_i \right) \right\} \tag{10}$$

$$D_\text{can} = \sum_{i=1}^{n} \Delta Z_i (\theta_0 - \theta_i) \tag{11}$$

$$k dt = k dt_{\text{ref}} \frac{K_S}{K_{\text{ref}}} \tag{12}$$

and

$$\sigma_i = \sigma / 86400 \tag{13}$$

where $I_{\text{max}}$ is the maximum infiltration, $\Delta Z_i$ is the $i$th soil layer thickness, $\sigma_i$ is the model time step $\sigma$, $k dt_{\text{ref}} = 3.0$ and $K_{\text{ref}} = 2 \times 10^{-6} \text{m s}^{-1}$ (Wood et al., 1998).

The total surface evaporation $E$ is defined as $E = E_{\text{dir}} + E_{\text{can}} + E_{\text{can}}$, where $E_{\text{dir}}$ is direct evaporation, $E_{\text{can}}$ is the wet canopy evaporation and $E_{\text{can}}$ is the canopy evapotranspiration. They are determined by:

$$E_{\text{dir}} = (1 - \lambda) \beta P_{\text{can}}$$

$$\beta = \frac{\theta_{\text{can}} - \theta_{\text{can}}}{\theta_{\text{can}} - \theta_{\text{can}}} \tag{14}$$

$$E_{\text{can}} = \lambda E_{\text{can}} \left( \frac{W_S}{S} \right)^n$$

$$\frac{\partial W_S}{\partial t} = \lambda P - D - E_{\text{can}} \tag{15}$$

$$E_{\text{can}} = \lambda E_{\text{can}} \left( 1 - \left( \frac{W_S}{S} \right)^n \right) \tag{16}$$

where $\theta_{\text{can}}$ is the field capacity, $\theta_{\text{can}}$ is the wetting point, $\lambda$ is the percentage of vegetation fraction, $E_{\text{can}}$ is the potential evaporation, $W_S$ is the intercepted canopy water content, $S$ is the maximum canopy capacity, $P$ is the total rainfall and $B_s$ is a function of the canopy resistance.

2.2. Thermodynamic scheme

The soil temperature $T$ in the Noah_LSM is determined using the following diffusion equations:

$$C(\theta) \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left\{ H(\theta) \frac{\partial T}{\partial z} \right\} \tag{17}$$

$$H(\theta) = \begin{cases} 420 \times \exp \left\{ - (2.7 + P_t) \right\}, & 0 \leq P_t \leq 5.1 \\ 0.1744, & \text{other} \end{cases}$$

and

$$P_t = \log \left\{ \psi_S \left( \theta_S / \theta_S \right)^{b} \right\} \tag{18}$$

where $C(\theta)$ is the heat capacity as a function of $\theta$, $\psi_S$ is the saturated soil water tension and $H(\theta)$ is the thermal conductivity as a function of $\theta$ (Pan and Mahrt, 1987).

3. Improvement of the hydrological scheme in the Noah_LSM

During the rainfall-runoff process, the saturated area varies over time and space. At the beginning of the rainfall event, the saturated area is smaller; however, as precipitation continues, the saturated area also increases. In the saturated area, all precipitation plus surface, subsurface and groundwater runoff is called excess-saturated runoff. The runoff in the unsaturated area is called excess-infiltrated overland flow.

The infiltration curve of a grid cell can be estimated through a hydrological method or an infiltration model. Frequently used models include the Horton, Philip and Holton equations. Because of the simplicity and effectiveness of the Holton method, this method was adopted in the present research:

$$f = a \left( F_p - \theta \right)^p + fc \tag{19}$$

where $F_p$ is the water holding capacity of the soil and is equal to the value of the mean tension water capacity ($W_M$) and $a$ and $n$ are parameters, $\theta$ is the soil water content and $fc$ is the steady infiltration rate.

If $PE = P - E > 0$, runoff occurs; otherwise, no runoff occurs. Let $R$ be the amount of runoff calculated through the improved Noah_LSM model (Wang and Chen, 2013). Then, the runoff generation area is $FR = R/PE$ and the unsaturated area is $1 - f/F$. 
To calculate the runoff generated from an unsaturated area, the following equation is used, which is a parabolic equation that represents the area distribution of the infiltration rate in the unsaturated area, defined as:

$$\delta = 1 - \left(1 - \frac{f}{f_{mm}}\right)E_f$$

(20)

where $\delta$ is the area in which the infiltration rate is less than $f$ and $E_f$ is a parameter. $f_{mm} = (1 + E_f f_m)$ is the average maximum value of $f$. The actual infiltration $f$ can be calculated using Equation (19). $i_r$ is the amount of runoff generated from the unsaturated area:

if $PE \geq f_{mm}$ then

$$i_r = (PE - f_{mm}) \left(1 - f \right)$$

(21)

if $PE < f_{mm}$ then

$$i_r = \left[PE - f_{mm} E_f + 1 \left(1 - \left(1 - \frac{PE}{f_{mm}}\right)E_{f+1}\right)\right] \left(1 - f \right)$$

(22)

The details about the routing module can be found in Wang and Chen (2013), Wang et al. (2016) and Ye et al. (2013).

Table 1. Latitude and longitude of the stations.

| Station name | Latitude (° N) | Longitude (° E) |
|--------------|----------------|-----------------|
| Dingxi       | 35.55          | 104.33          |
| Huining      | 35.41          | 105.05          |
| Huajialing   | 35.23          | 105.00          |

4. Experiments and analysis

4.1. River gauge stations

In this study, the double-excess runoff production scheme was incorporated into the Noah_LSM to make it more applicable in semi-humid, semi-arid and arid regions and to overcome the limitation of the single excess-saturated runoff production scheme. Therefore, observations were used at several stations in a typical semi-arid region to evaluate the performance of the improved Noah_LSM. Dingxi station is located in the Western Loess Plateau, a typical semi-arid region. Observations of soil moisture and soil temperature were used to evaluate the model. The observations of 2 m air temperature (T2m) and 10 m wind speed (W10m) at Dingxi and its two neighbouring sites, Huajialing and Huining stations, were also used to evaluate the model (Table 1).

4.2. Experimental design

To compare the performance of the old and improved models, a numerical experiment was conducted to simulate precipitation from 1 May to 31 October 2013. The forecast was initiated at 0000:0000 UTC every day with a forecast validity period of 48 h. National Centers for Environmental Prediction (NCEP) forecasts with a spatial resolution of $1^\circ \times 1^\circ$ were applied for the initial fields and lateral boundaries in this experiment. The GRAPES_Meso model (V4.0) has a $0.1^\circ \times 0.1^\circ$ horizontal resolution.

Soil moisture is directly affected by improvement in land surface hydrological processes, especially for the soil moisture of the upper levels (0–10 cm soil depth and 10–40 cm soil depth below the ground in the GRAPES_Meso model (V4.0)). Soil moisture, T2m, W10m and precipitation were selected for...
Figure 3. Comparison of modelled and observed soil temperature in the first soil layer at Dingxi station. (a) 24–25 July 2013; (b) 6–7 August 2013.

Figure 4. Time series of the simulated and observed 2 m air temperature and accumulated rain at (a) Dingxi station, (b) Huining station and (c) Huajialing station. 24–25 July 2013.
Figure 5. Time series of the simulated and observed 2m air temperature and accumulated rain at (a) Dingxi station, (b) Huining station and (c) Huajialing station. 23–24 August 2013.

4.3. Analysis

4.3.1. Soil moisture and temperature

Compared with the old model, the simulated soil moisture in the improved model is changed in both the vertical and horizontal directions, especially in the upper levels (0–10 cm depth and 10–40 cm depth; see Equations (5) and (17)). Observed soil moisture is only available at depths of 0–10 and 10–40 cm at Dingxi station from 24 July to 6 August 2013, so only the tendency of soil moisture from 24 to 25 July and from 5 to 6 August when rainfall events occurred can be compared.

Figure 1 shows the simulated and observed time series of soil moisture at a depth of 0–10 and 10–40 cm alongside the precipitation at Dingxi station. Due to the addition of the double-excess runoff production scheme, the soil moisture content in the first soil layer simulated by the improved model is more sensitive to precipitation than the old model (Figures 1(a) and 2(a)).
Improvement of Noah_LSM by coupling with a double-excess scheme

Figure 6. Time series of the simulated and observed 10 m wind speed and accumulated rain at (a) Dingxi station, (b) Huining station and (c) Huajialing station. 24–25 July 2013.

In addition, because of the soil water exchange between the first and second soil layers, the soil water content in the second soil layer simulated by the improved model shows better agreement with observation (Figures 1(b) and 2(b)). In general, Figures 1 and 2 indicate that the improved model performs better for reproducing the varying tendency of the soil moisture than the old model. Furthermore, the results of the improved model also show better agreement with the soil temperature observations than the old model (Figure 3). The soil moisture changes can impact the simulation of the T2m, W10m and other variables with feedback to the atmospheric model in the land surface model (Chen et al., 1996; Peterslidan et al., 1998; Chen and Duddia, 2001).

4.3.2. Temperature at 2 m and wind speed at 10 m

The GRAPES output contains T2m, which is determined from the surface temperature, heat flux and other variables. In this study, the Noah_LSM is improved by a hydrological model using the double-excess runoff production and routing schemes. Compared to the old hydrological model (Equation (10)) in the Noah_LSM, the improved equations (Equations (21) and (22)) appropriately yield less (or more) thermal conductivity $H_t(\theta)$ for moister soil (in Equation (18)) and thus less (or more) soil temperature $T$ (Equation (17)), which in turn leads to a more (less) amplified diurnal signal in T2m and W10m.
Figure 7. Time series of the simulated and observed 10 m wind speed and accumulated rain at (a) Dingxi station, (b) Huining station and (c) Huajialing station. 23–24 August 2013.

To assess the performance of the improved and old models, comparisons were conducted with surface observations of T2m and W10m at Dingxi, Huining and Huajialing stations (Table 1). As shown in Figure 4, the observed 24 h accumulated precipitation from 24 to 25 July 2013 is 1.7, 8.2, 3.7 mm in Dingxi, Huining and Huajialing stations, respectively. As shown in Figure 5, the 24 h accumulated precipitation from 23 to 24 August 2013 is 15.7, 0 and 34.7 mm at the three sites, respectively. In general, there is good agreement between the observations and the improved model simulations (Figures 4–7). For light rain, the T2m simulated by the improved model is better than the old model (Figure 4). The W10m simulated by the models reached the same result (Figure 6). For heavy rain, the T2m values simulated by the improved and old models are significantly different in daytime than at night time because of the much higher net short-wave radiation in the daytime (Figures 5(a) and (c)). Although the observed accumulated precipitation is 0 mm at Huining station, the observed accumulated precipitation in 24 h is heavy rain at the Dingxi and Huajialing stations. The observed T2m and W10m at Huining station are influenced by the soil water exchange in the horizontal direction, so the improved model agrees better with observations (Figures 5(b) and 7(b)).

4.3.3. Precipitation

In this study, 2513 stations were chosen for verification of the forecasted precipitation. Five rainfall thresholds were...
used (≥100 mm, 50–100, 25–50, 10–25 and 0.1–10 mm, i.e. extremely heavy rain, torrential rain, heavy rain, moderate rain and light rain). The scoring regions included the following: all of China (73–135°E, 15–55°N), northeastern China (120–135°E, 40–53°N), the Xinjiang part of China (73–92°E, 15–50°N), the eastern part of northwest China (92–110°E, 35–45°N), northern China (110–123°E, 35–45°N), the central and southern parts of the Qinghai Tibet Plateau (79–100°E, 23–35°N), southwestern China (100–110°E, 21–35°N), the middle and lower reaches of the Yangtze River (110–123°E, 25–35°N) and southern China (105–123°E, 18–25°N). Table 2 shows the Threat Score (TS) of the 0–24 h precipitation forecast beginning at 0000:0000 UTC from 1 May to 31 October 2013, for the entire territory of China and the previously listed eight regions. The TS does not increase significantly. As shown in Figures 1, 4 and 5, the precipitation prediction was slightly improved for heavy rain (Figure 5(c)), moderate rain (Figure 5(a)) and light rain (Figures 1, 4(a), (c) and 5(b)) in Dingxi station, Huining station and Huajialing station which are in semi-arid and semi-humid regions.

5. Summary

The Noah land surface model (Noah_LSM) is improved by incorporating a hydrological model using the double-excess runoff production scheme and routing scheme, which considers both saturation-excess runoff and infiltration-excess runoff, realizing the simulation of a complete hydrological cycle in the GRAPEs_Meso model (V4.0). The Muskingum module is used for routing. To evaluate and verify the performance of the improved model, the predictive capabilities of the old and improved models were tested throughout China by conducting simulations and further investigating the feedback of changes in the land surface hydrological model to the climate model. The results for the temporal distribution of the 10 cm depth soil moisture in Dingxi station show that the improved model performs better for soil moisture simulation than the old model. It should also be noted that in the coupled atmosphere–land surface system the results of precipitation heavily depend on soil moisture simulations obtained from the numerical weather prediction model. The results also show that the improved land surface hydrological model has a marked impact on the results of simulated meteorological variables such as soil temperature, 2 m air temperature and 10 m wind speed, which generally lead to better results. The threat score results from all of China and the eight regions in the 24 h forecast time show that the threat scores are slightly higher for heavy rain, moderate rain and light rain in Xinjiang, China, eastern northwest China and northern China, and the improved model predicts the rainfall regime better. These results indicate that the improved model with coupling of the double-excess runoff production scheme and routing scheme in the Noah_LSM could affect the precipitation simulation. The soil moisture could also provide important feedback to the precipitation simulation of the numerical weather prediction model, suggesting that the improvement in the GRAPEs_Meso model (V4.0) Noah_LSM is effective and valid in this study, which highlights the important connection between land surface hydrology and meteorology. In future studies the improved model should be validated for more case studies in more regions, and more subtle simulations and analyses should be included on evaluating land surface–atmospheric interactions.

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