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Implementation of a Surface Runoff Model with Horton and Dunne Mechanisms into the Regional Climate Model RegCM_NCC

SHI Xueli*[1] (史学丽), XIE Zhenghui[2] (谢正辉), LIU Yiming[1] (刘一鸣), and YANG Hongwei[2] (杨宏伟)

[1] *Laboratory for Climate Studies, National Climate Center, China Meteorological Administration, Beijing* 100081

[2] *State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics* (*LASG*) *Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing* 100029

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ABSTRACT

A surface runoff parameterization scheme that dynamically represents both Horton and Dunne runoff generation mechanisms within a model grid cell together with a consideration of the subgrid-scale soil heterogeneity, is implemented into the National Climate Center regional climate model (RegCM_NCC). The effects of the modified surface runoff scheme on RegCM_NCC performance are tested with an abnormal heavy rainfall process which occurred in summer 1998. Simulated results show that the model with the original surface runoff scheme (noted as CTL) basically captures the spatial pattern of precipitation, circulation and land surface variables, but generally overestimates rainfall compared to observations. The model with the new surface runoff scheme (noted as NRM) reasonably reproduces the distribution pattern of various variables and effectively diminishes the excessive precipitation in the CTL. The processes involved in the improvement of NRM-simulated rainfall may be as follows: with the new surface runoff scheme, simulated surface runoff is larger, soil moisture and evaporation (latent heat flux) are decreased, the available water into the atmosphere is decreased; correspondingly, the atmosphere is drier and rainfall is decreased through various processes. Therefore, the implementation of the new runoff scheme into the RegCM_NCC has a significant effect on results at not only the land surface, but also the overlying atmosphere.

Key words: surface runoff, regional climate model, precipitation, water vapor

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1. Introduction

Runoff plays an important role in water and energy balances between the land surface and the atmosphere. If runoff is not considered in a land surface model, soil moisture and evaporation in the model will increase with the hydrological budget (Yang et al., 1998). Koster and Milly (1997) noted that even a "perfect" description of canopy structure and stomatal behavior does not ensure realistic evaporation rates if the runoff formulation remains relatively crude or incompatible. Therefore, a reasonable calculation of runoff is very important for climate simulations.

Surface runoff is mainly generated by two mechanisms: infiltration excess (Horton) runoff and saturation excess (Dunne) runoff, which is related to the spatial variability of soil properties, antecedent soil moisture, topography and rainfall. For a large area (e.g., a model grid size of a regional climate model or a GCM), these runoff generation mechanisms commonly present at different portions of a grid cell simultaneously. Missing one of the two major runoff generation mechanisms or lacking consideration of spatial soil variability can result in significant bias in estimation of surface runoff, which can directly cause errors in soil moisture states and in the water and energy balance over each model grid cell. Therefore, a reasonable description of the runoff scheme in the model grid is essential. Liang and Xie (2001) developed a parameterization to represent the infiltration excess runoff mechanism in VIC-3L (Variable Infiltration Capacity land surface model) and combined it

*Corresponding author: SHI Xueli, shixl@cma.gov.cn

effectively with the original representation of the saturation excess runoff mechanism (Zhao, 1992). Further, they revised the surface runoff parameterization with the Philip infiltration formulation as the time compression analysis (TCA) that dynamically represents both the Horton and Dunne runoff generation mechanisms within a model grid cell (Xie et al., 2003). In this paper, the surface runoff parameterization with the Philip infiltration formulation as the TCA in the VIC-3L is implemented into the National Climate Center regional climate model (RegCM_NCC; Ding et al., 2000) based on the second generation regional climate model of the US National Center for Atmospheric Research (NCAR/RegCM2; Giorgi et al., 1993a,b). A preliminary evaluation of the performance with the new surface runoff scheme versus the original one in the RegCM_NCC and the differences between them are presented.

In section 2, the original surface runoff scheme in the Biosphere-Atmosphere Transfer Scheme (BATS; Dickinson et al., 1993), the new surface runoff scheme and the RegCM_NCC are briefly introduced. The design of the numerical experiments, the RegCM_NCC control simulations and comparison with observations, as well as results with the new surface runoff scheme are given in section 3. Finally, a summary and discussion is presented in section 4.

2. Model description

2.1 *Original runoff scheme in BATS*

The surface runoff paremeterization in BATS can be described with the following formula:

$$R_{\mathrm{s}} = \gamma G_{\mathrm{w}} \ , \tag{1}$$

where

$$G_{\mathrm{w}} = \max[0, P_0 + D_0 - E_{\mathrm{a}}] \tag{2}$$

and

$$\gamma = \min\left[1, \left(\frac{W_{\mathrm{u}} + W_{\mathrm{r}}}{2}\right)^n\right] \tag{3}$$

with

$$n = \begin{cases} 1 & T_{\mathrm{g}} < 273.16 \\ 4 & \text{otherwise} \ . \end{cases} \tag{4}$$

In Eqs. (1)–(4), γ is a coefficient related to the saturated and real soil water density; R_{s} is the surface runoff; G_{w} is the maximum of zero and the residual of precipitation (P_0), excess water dripping from canopy (D_0), and evaporation (E_{a}); W_{u} and W_{r} are soil water in the upper soil layer and root layer, respectively; and T_{g} is the ground temperature (Yang and Dickinson, 1996; Dickinson et al., 1993).

2.2 *The new surface runoff scheme with Horton and Dunne mechanisms*

The runoff generation mechanism formula used in this study is from the corresponding part used in the VIC land surface model (Liang and Xie, 2001, 2003), which is characterized by incorporating the two surface runoff generation mechanisms (Dunne and Horton) at the same time with some statistical approaches. For precipitation P at a time step, we can get y and all the terms of the equation $R_1(y) + R_2(y) + \Delta W = P$ by solving the equation. Here, $\Delta W = y - R_1(y)$, and the saturation excess runoff $R_1(y)$, infiltration excess runoff $R_2(y)$ can be obtained as follows:

(1) Saturation excess runoff $R_1(y)$, which is generated from saturated soil:

$$R_1(y) = \begin{cases} y - \dfrac{i_{\mathrm{m}}}{b+1}\left[\left(1-\dfrac{i_0}{i_{\mathrm{m}}}\right)^{b+1} - \left(1-\dfrac{i_0+y}{i_{\mathrm{m}}}\right)^{b+1}\right] \ , \\ \qquad 0 \leqslant y \leqslant i_{\mathrm{m}} - i_0 \ , \\ R_1(y)|_{y=i_{\mathrm{m}}-i_0} + y - (i_{\mathrm{m}} - i_0) \ , \\ \qquad i_{\mathrm{m}} - i_0 < y \leqslant P \ , \end{cases} \tag{5}$$

where i_{m} and i_0 represent, respectively, the maximum point soil moisture capacity and the point soil moisture capacity corresponding to the initial soil moisture; P is the amount of precipitation over a time step Δt; y is the vertical depth, representing the difference between precipitation and infiltration excess runoff over a time

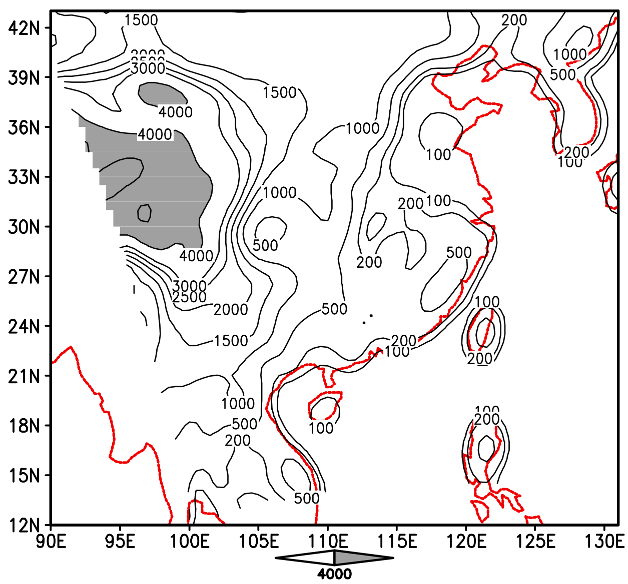

Fig. 1. Topography of the model domain (Units: m). Regions with height ⩾4000 m are shaded.

Table 1. Integration experiments description.

Integration period	April–June	May–June	June
Control experiments (CTL)	CTL-Ini4	CTL-Ini5	CTL-Ini6
Experiments with new surface runoff model (NRM)	NRM-Ini4	NRM-Ini5	NRM-Ini6

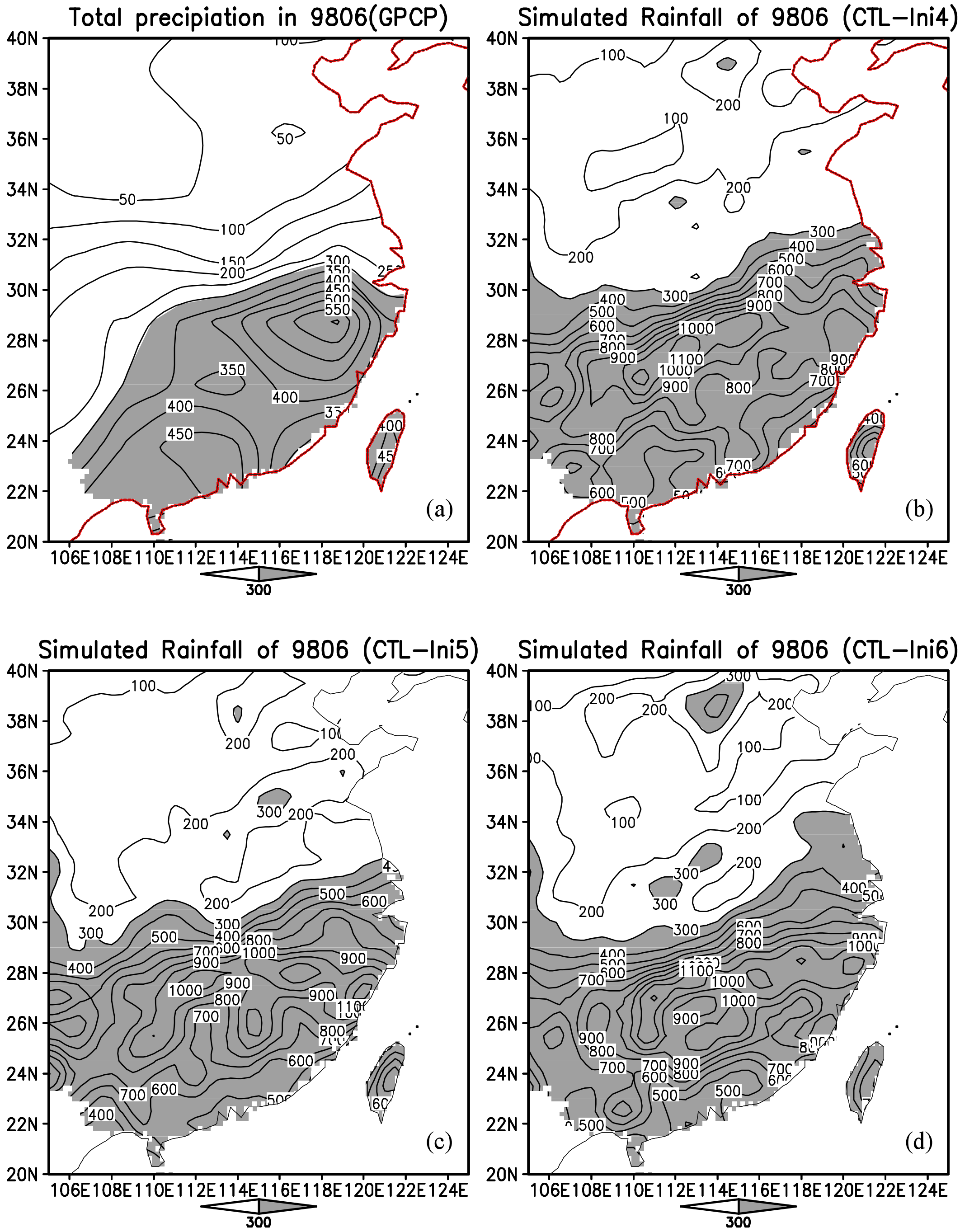

Fig. 2. Monthly precipitation in June 1998 (Units: mm). (a) GPCP data; (b)–(d) simulations of CTL-Ini4, CTL-Ini5, and CTL-Ini6, respectively. Rainfall amounts ⩾300 mm are shaded.

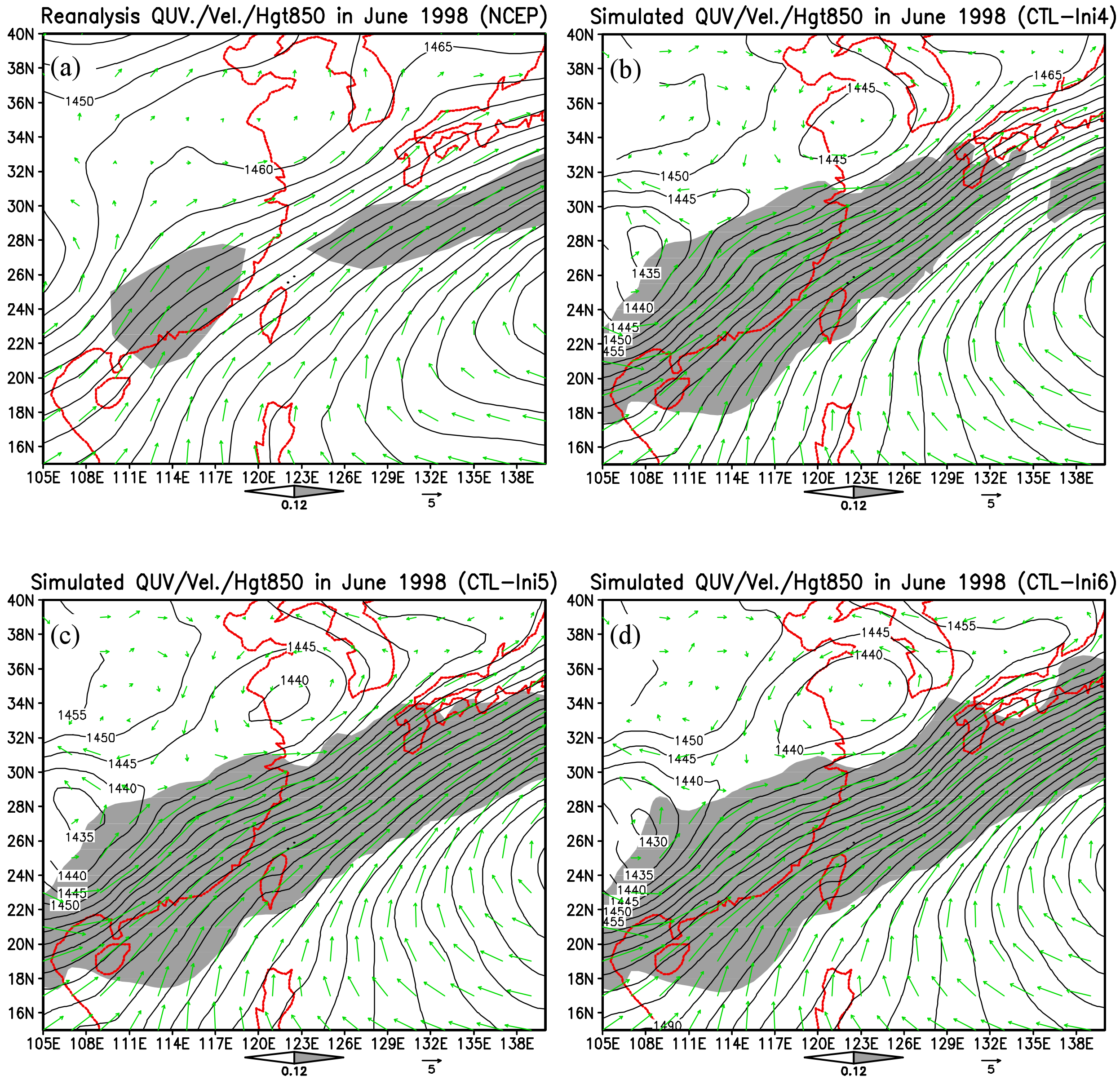

Fig. 3. Monthly mean moisture transport, wind vector, and geopotential height at 850 hPa in June 1998. Units of moisture transport, wind vector, and height are m g kg^{-1} s^{-1}, m s^{-1}, and m, respectively. (a) NCEP/NCAR reanalysis; (b)–(d) are simulations of CTL-Ini4, CTL-Ini5, and CTL-Ini6, respectively. Moisture transports $\geqslant$0.12 m g kg^{-1} s^{-1} are shaded.

step Δt for a study area; and b is the soil moisture capacity shape parameter, which is a measure of the spatial variability of the soil moisture capacity and defined as the maximum amount of water that can be stored in the upper layer of the soil column, which is a surrogate for spatial heterogeneity of soil properties (Liang and Xie, 2001).

(2) Infiltration excess runoff $R_2(y)$, which is generated due to subgrid-scale variability of soil infiltration rate:

$$R_2(y)=\begin{cases} P-R_1(y)-f_{\mathrm{k}}\Delta t\left[1-\left(1-\dfrac{P-R_1(y)}{f_{\mathrm{m}}\Delta t}\right)^{B+1}\right], \\ \qquad \dfrac{P-R_1(y)}{f_{\mathrm{m}}\Delta t}<1\,, \\ P-R_1(y)-f_{\mathrm{k}}\Delta t\,, \\ \qquad \dfrac{P-R_1(y)}{f_{\mathrm{m}}\Delta t}\geqslant 1\,, \end{cases} \tag{6}$$

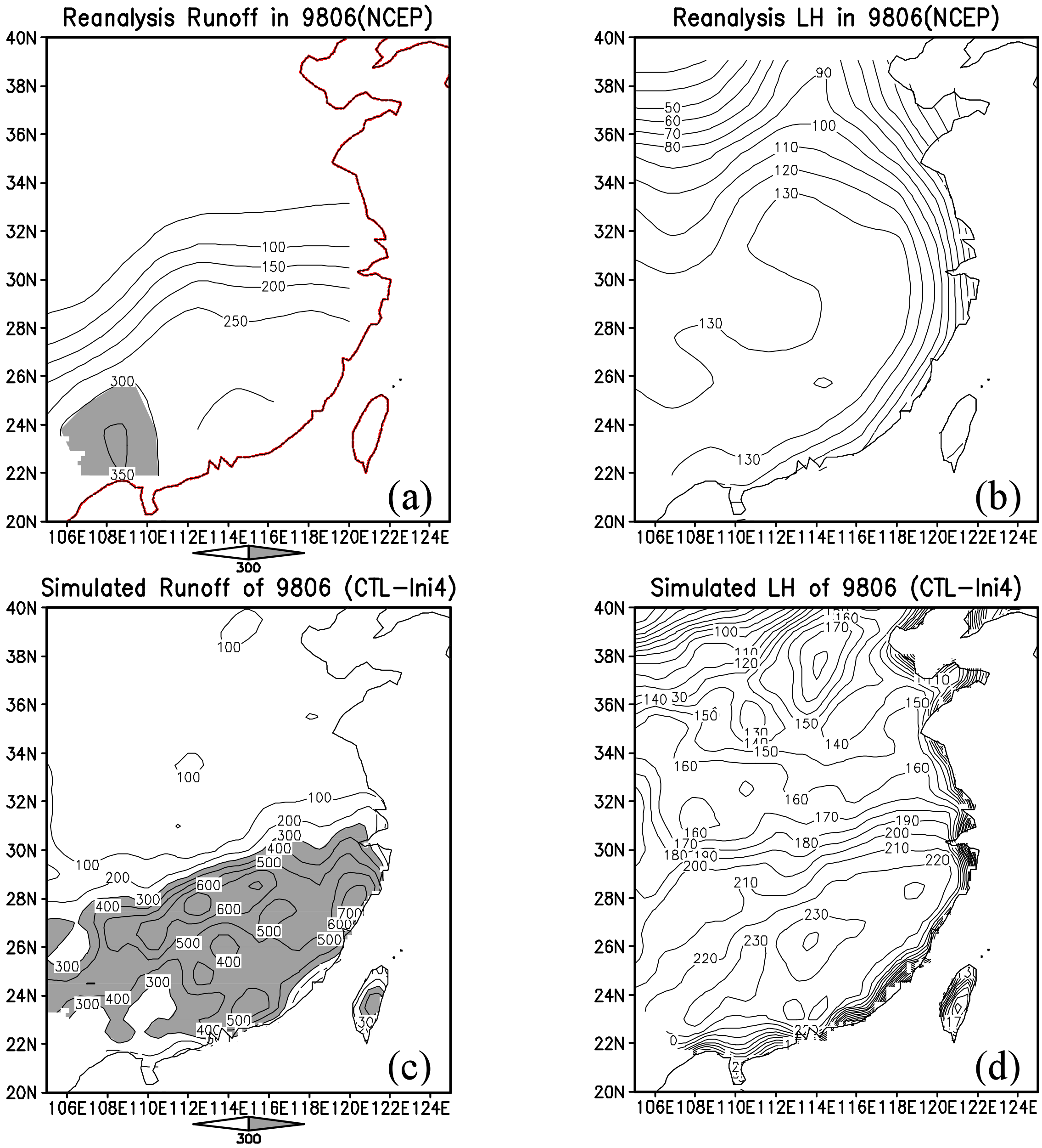

Fig. 4. Monthly surface runoff (left) and latent heat flux (right) in June 1998. (a) and (b): NCEP/NCAR reanalysis; (c) and (d): CTL-Ini4; (e) and (f): CTL-Ini5; (g) and (h): CTL-Ini6. Units of runoff and heat flux are mm and W m^{-2} respectively. Runoff amounts $\geqslant$300 mm are shaded.

where $f_{\rm k}$ is the average potential infiltration rate, which can be expressed as:

$$f_{\rm k}=\int_0^1 f_{\rm m}[1-(1-C)^{1/B}]dC=\frac{f_{\rm m}}{1+b}\,. \qquad (7)$$

Here, $f_{\rm m}$ is the maximum potential infiltration; C is the fraction of an area for which the potential infiltration rate is $\leqslant 1$; and B is the potential infiltration rate shape parameter, taken to be 1 in this study, as in Liang and Xie (2001).

2.3 *The regional climate model (RegCM_NCC)*

The model used in this study is the regional climate model RegCM_NCC developed by the National Climate Center of China, which is based on the NCAR/RegCM2 and established by assembling parameterization schemes of various physical processes (e.g., the land surface process, the cumulus convection, radiative transfer, the planetary boundary layer, and so on) (Ding et al., 2006a). The RegCM_NCC is designed to simulate/predict the summer precipitation

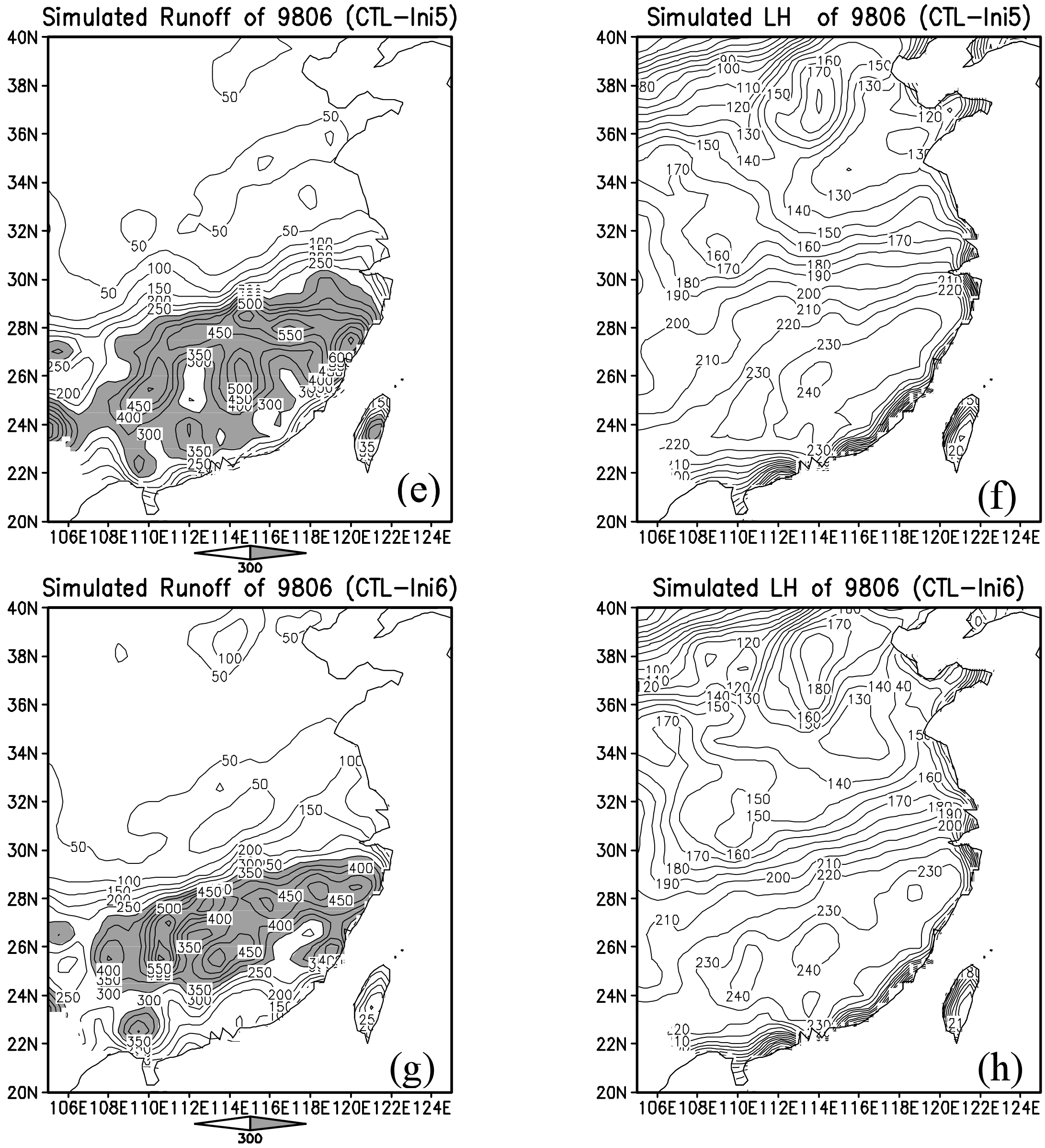

Fig. 4. Continued.

throughout China, and results have shown that the model can reasonably reproduce the precipitation and circulation patterns (e.g., Shi et al., 2001; Ding et al., 2006b). However, one of the weaknesses of the model is that it generally overestimates rainfall comparing to observation at the land, which is actually a common weakness of the regional climate models (e.g., Kato et al., 1999; Lee and Suh, 2000).

2.4 *Implementation of the surface runoff model into the RegCM_NCC*

The surface runoff scheme described in section 2.2 is implemented into the regional climate model RegCM_NCC by replacing the original surface runoff scheme in BATS coupled with the regional climate model. For each time step, the surface runoff scheme obtains results from regional climate model, such as precipitation and upper layer soil moisture, as inputs to the scheme, and calculates the surface runoff as the output, which is finally transferred to the land surface model BATS in the regional climate model RegCM_NCC. The land surface model BATS calculates the related variables according to the updated runoff (such as soil moisture, temperature and evaporation), and finally calculates the sensible and latent heat flux to provide the energy and water to the overlying atmosphere. This procedure loops during the model integration.

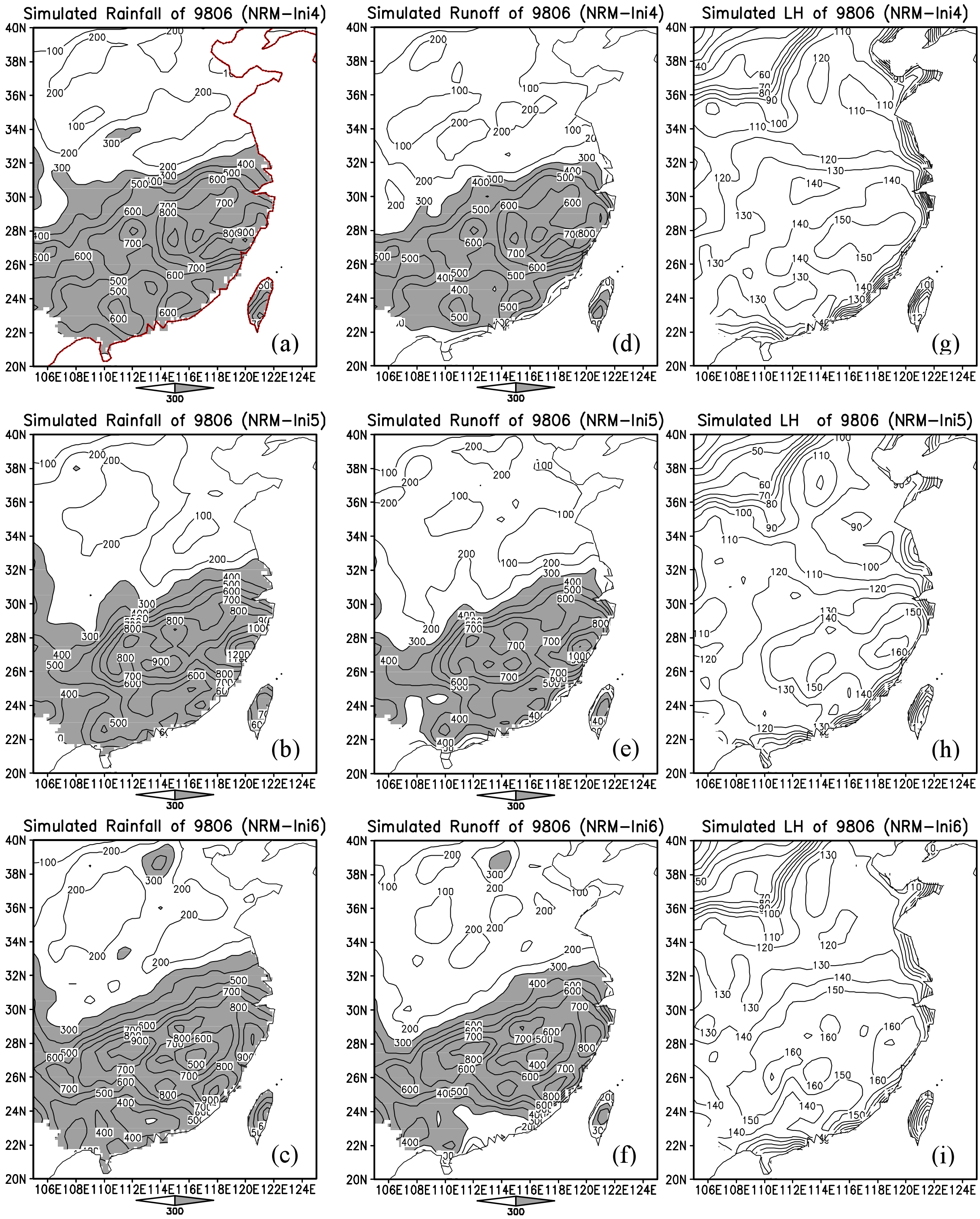

Fig. 5. NRM-simulated precipitation (left), surface runoff (middle) and latent heat flux (right) in June 1998. (a), (d) and (g): NRM-Ini4; (b), (e) and (h): NRM-Ini5; (c), (f) and (i): NRM-Ini6. Units of precipitation and runoff are mm, and heat flux are W m^{-2}. Precipitation and runoff ⩾300 mm are shaded.

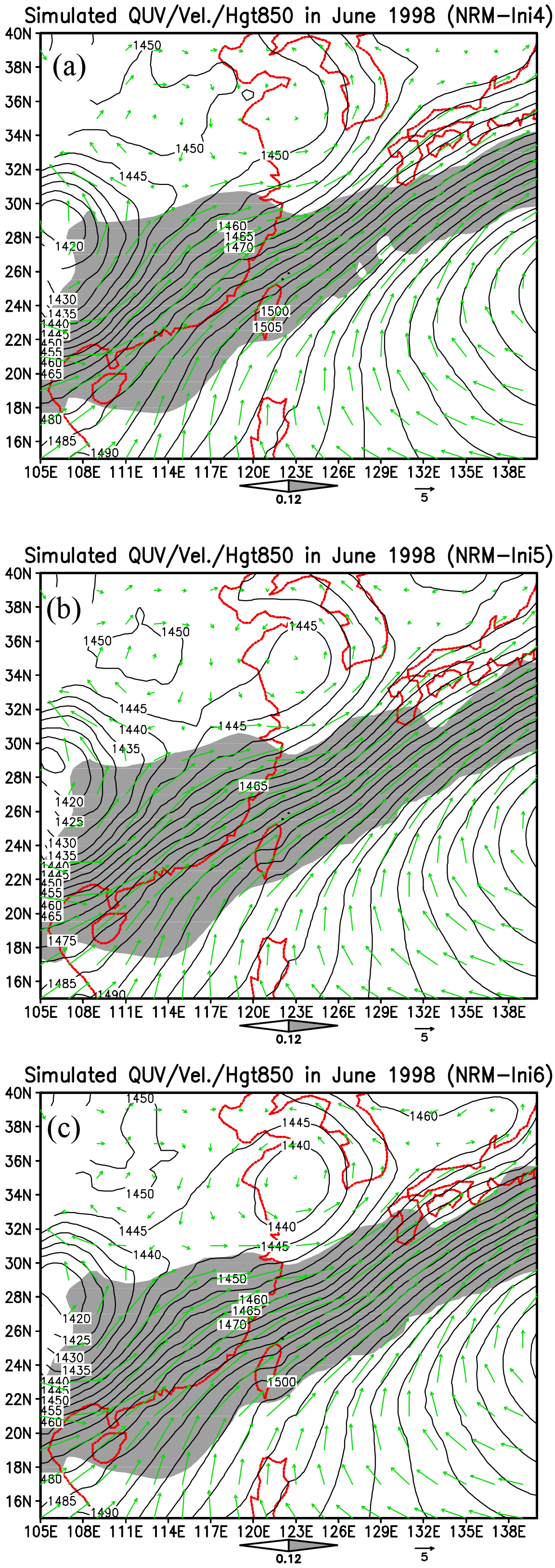

Fig. 6. As in Fig. 3, but for NRM results.

3. Numerical experiment design and results

3.1 *Numerical experiment design*

An abnormal heavy rainfall process in the Yangtze River basin (YRB) in the summer of 1998 was chosen for the simulation. The large-scale data are from the NCAR/NCEP reanalysis with 6-hour intervals (Kalnay et al., 1996). There are 65 and 85 grid points respectively in the longitudinal and latitudinal directions, with a 60-km resolution. The model domain is around (12°–48°N, 90°–145°E) (Fig. 1), in which the eastern part of the Tibetan Plateau (with the maximum height being (5000 m) is included.

The physical process schemes used in the experiments include the revised mass flux scheme (Liu and Ding, 2001) for convective precipitation, the Holtslag scheme (Holtslag et al., 1990) for the planetary boundary layer, the radiation transfer scheme (Kiehl et al., 1996) used in the NCAR Community climate Model Version 3, and BATS (Dickinson et al., 1993) for the land surface process. The Reynolds weekly optimum interpolation (OI) sea surface temperature (SST) data with a $1^\circ \times 1^\circ$ spatial resolution generated by the US NOAA-CIRES Climate Diagnostics Center are also applied (Reynolds et al., 2002). The Global Precipitation Climatology Project (GPCP) version 2 data (Adler et al., 2003) is used for the precipitation comparison.

Two sets of simulations were conducted to investigate the impacts of the implementation of the surface runoff scheme into the regional climate model. The first ran the RegCM_NCC with the original surface runoff scheme in BATS, called the control experiments (noted as CTL), and the second ran the RegCM_NCC with the new surface runoff model in BATS and all the other configurations as the same as those in the CTL (noted as NRM). Additionally, in order to test the impacts of the integration period on the model results, three experiments with different initial times were conducted for each set of simulations. Table 1 lists detailed information of these experiments and the corresponding notes. In all of the experiments, the earliest initial date is 1 April (noted as Ini4). Next, is 1 May (noted as Ini5), and then 1 June (noted as Ini6). The following analysis is mainly focused on the climate features in June 1998.

3.2 *CTL simulations*

The abnormal severe and persistent rainfall along the YRB and broad regions of South China experienced during June of 1998 have been studied using regional climate modeling by, for example, Lee et al. (2004), Liu and Ding (2002) and Wang et al. (2003).

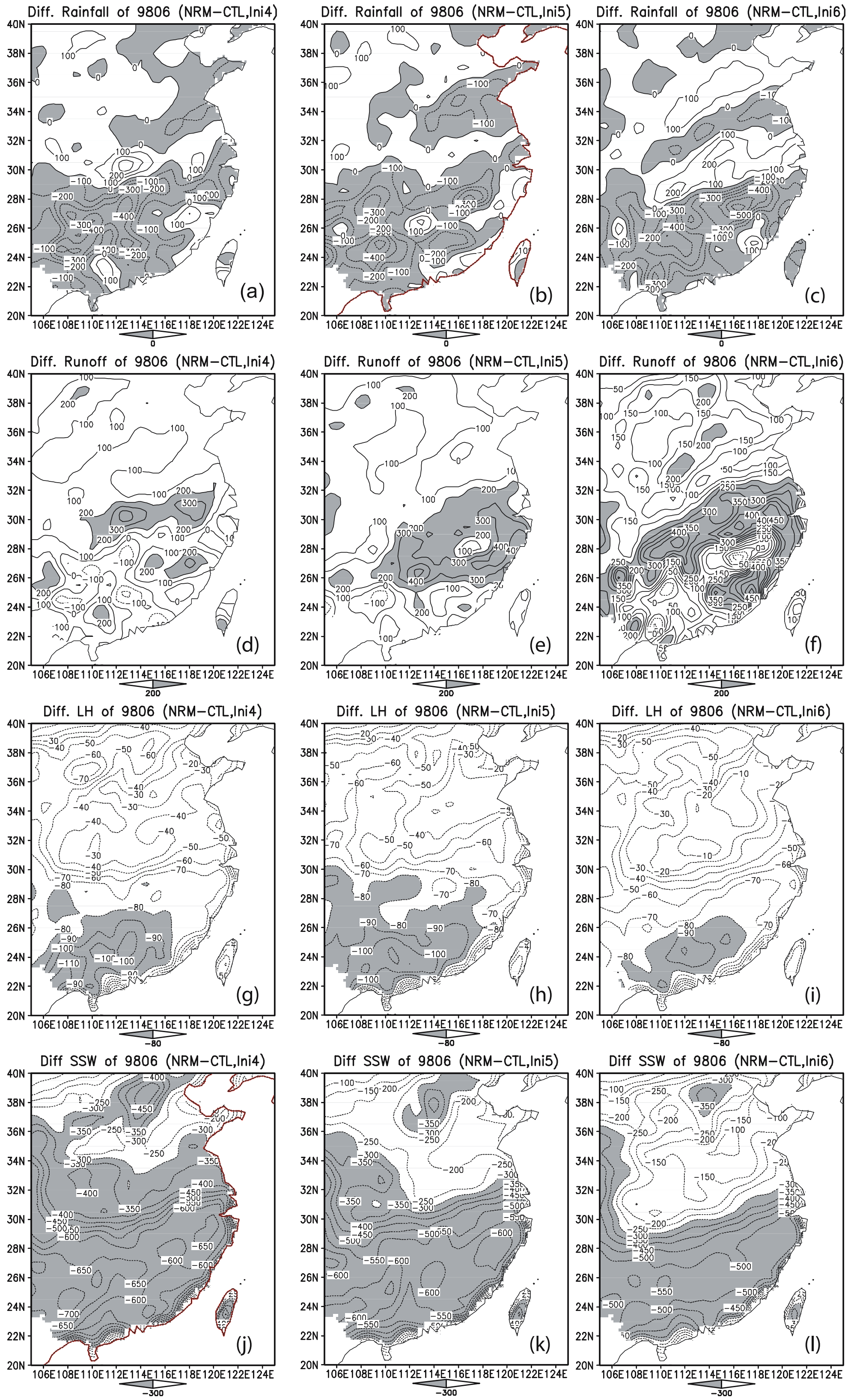

Fig. 7. Differences between NRM and CTL in June 1998. (a), (b), and (c): precipitation (mm) of Ini4, Ini5, and Ini6; (d), (e), and (f): surface runoff (mm); (g), (h), and (i): latent heat flux (W m^{-2}); (j), (k), and (l): soil moisture (mm). Shaded areas denote, respectively, precipitation differences $\leqslant$0 mm, surface runoff differences $\geqslant$200 mm, latent heat flux differences $\leqslant -80$ W m^{-2}, and soil moisture differences $\leqslant -300$ mm.

The observed rain belt during June 1998 was located in the broad regions from the mid-lower reaches of the YRB and South China (Fig. 2a). In the CTL runs with a different initial date, the location of the major rain belt generally reproduced consistently with the major rainfall centers at the broad regions along and south of the YRB, but the simulated rainfall amount was mostly much larger than observations (Figs. 2b–d). Among them, the largest rainfall appears in the CTL-Ini6, with the maximum mounting to 1200 mm, followed by the CTL-Ini4 being 1100 mm, and the least (but still larger than observed) in the CTL-Ini5. In terms of the location of the maximum precipitation south of the lower reaches of the YRB, the CTL-Ini5 seems to be the best (Fig. 2c).

At 850 hPa, the observed circulation pattern is a cyclonic (anticyclonic) circulation in the regions north (south) of the YRB, with the maximum water vapor transport located in the regions south of the lower reaches of the YRB and part of the western North Pacific (Fig. 3a). The CTL experiments also reproduced reasonably the cyclonic (anticyclonic) flow in the north (south) of the model domain, and the simulated moisture transport was too strong along and south of the YRB in the experiments (Figs. 3b–d).

The surface runoff is more highly correlated with precipitation (Dickinson et al., 2003), so the runoff pattern should be similar with precipitation. Actually, the accumulated runoff of NCEP/NCAR is larger in the regions along and south of the mid-lower reaches of the YRB in June 1998 (Fig. 4a). The simulated monthly surface runoff for the CTL is also characterized as wet in the south part and relatively dry in the north part of the model domain separated by the YRB (Figs. 4c, 4e and 4g). The similar distribution pattern between observation and CTL shows a certain capability of the model. The spatial pattern of the larger (smaller) value of the latent heat flux in the south (north) part in the NCEP/NCAR reanalysis (Fig. 4b) is also generally captured in the CTL (Figs. 4d, 4f and 4h), and the simulated ones are mostly larger than the reanalysis data. The dense contour lines along the coastal lines appear (Figs. 4b, 4d, 4f, and 4h) in both the reanalysis and CTL runs since the latent heat over the ocean is larger than that on land.

Therefore, the regional climate model RegCM_NCC with the original surface runoff scheme can basically reproduce the monthly rain belt and circulation pattern in June 1998, and generally overestimates precipitation and moisture transport at 850 hPa.

3.3 *NRM simulations*

Figure 5 shows that the simulation results by the regional climate model RegCM_NCC with the new surface runoff scheme described in section 2.2 are generally similar to those of CTL and the NCEP/NCAR reanalysis, with the centers of heavy rainfall (Figs. 5a–c), surface runoff (Figs. 5d–f), as well as those of the latent heat flux (Figs. 5g–i) located at the south part of the model domain (i.e., the YRB and South China). However, the simulated surface runoff in NRM is larger than that in CTL. The NRM simulations of the location of the rainfall centers in the provinces of Hunan and Anhui are more realistic than those in the CTL, especially in the Ini5 experiments.

The simulated monthly mean water vapor transport by NRM in the lower troposphere is generally consistent with that in CTL and the NCEP/NCAR reanalysis (Fig. 6). The results of the three sets of experiments with a different initial date are mostly the same, but the water vapor belt west of 120°E is broader in Ini4 (Fig. 6a) than in Ini5 and Ini6 (Figs. 6b–c).

Therefore, the spatial pattern of the NRM is mostly similar to that of CTL and the observation or NCAR/NCEP reanalysis data. The distinct feature is the increase of the surface runoff and the decrease of rainfall and latent heat flux in June 1998, and hence the observed heavy rainfall center is better captured by NRM than by CTL.

3.4 *Further analysis*

To understand the modifications with the implementation of the new runoff scheme into the regional climate model RegCM_NCC, the differences between NRM and CTL are analyzed.

The precipitation differences between NRM and CTL are mostly negative within the model domain, especially in the areas south of the YRB, as well as some parts of the regions around the Huaihe River basin (Figs. 7a–c). Since the rainfall in CTL is generally overestimated compared with the observations, the reduction of rainfall in NRM decreased the bias with the observation, and hence the simulated precipitation in NRM are closer to the observations, even if the rainfall amount is still somewhat overestimated (c.f. Fig. 3a and Fig. 5). The simulated monthly surface runoff by NRM is generally larger than that by CTL (Figs. 7d–f), with the largest positive differences between them as high as 300–400 mm in NRM-Ini6 (Fig. 7f). The latent heat flux difference is generally negative in the model domain, with the largest decrease appearing in South China and regions south of the mid-lower reaches of the YRB (Figs. 7g–i). Similarly, soil moisture is also decreased when applying the new surface runoff scheme (Figs. 7j–l).

At 850 hPa, the differences between NRM and CTL show a cyclonic circulation in the broad regions around

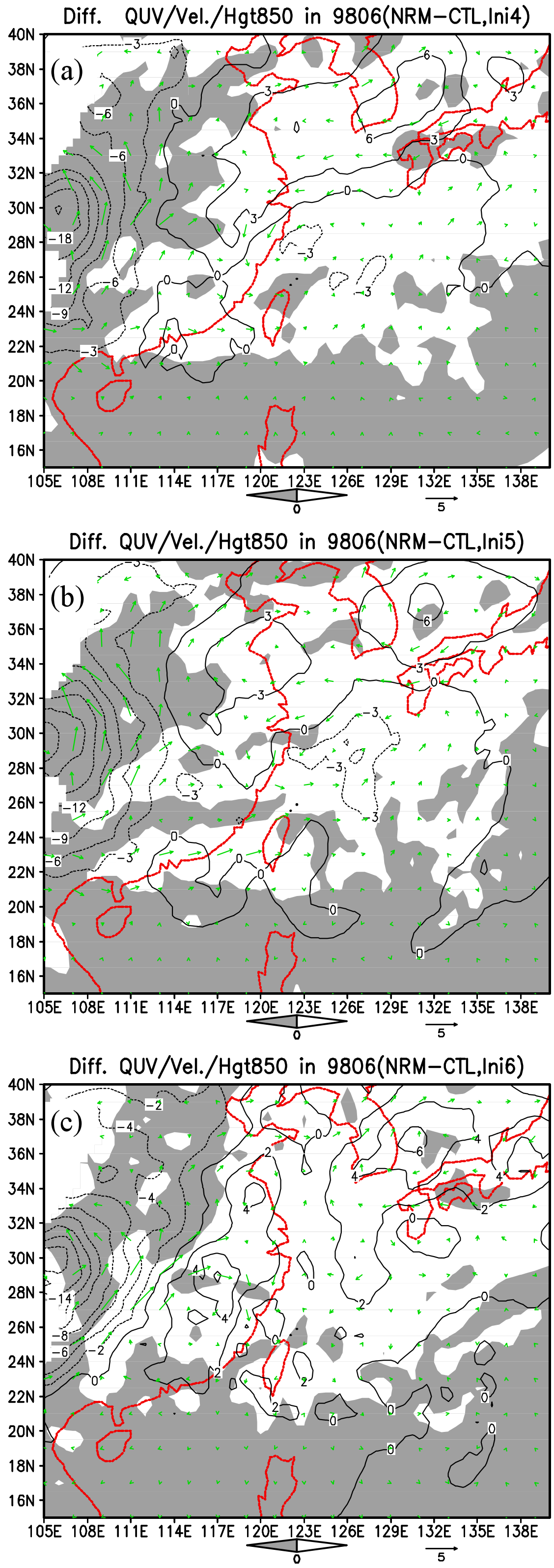

Fig. 8. As in Fig. 3, but for differences between NRM and CTL. Moisture transports $\leqslant 0$ m g kg^{-1} s^{-1} are shaded.

the western North Pacific and less water vapor transport in the regions to the south and west of the rainfall regions in all three experiments with different initial dates (Fig. 8). In June 1998, the anticyclonic circulation controls (subtropical high) the western North Pacific, and therefore the appearance of the cyclonic anomaly is not favorable for the development or maintenance of the subtropical high. This might be one of the reasons behind the rainfall decrease.

According to the observation data from the Huaihe River Basin Experiment (HUBEX), the mean rainfall during June 1998 for the Bengbu basin of Anhui Province (with an area of 121330 km^2) was 120.9 mm. The streamflow was 1610 m^3 s^{-1} (Liu et al., 2006), and hence the average runoff depth for the area is about 34 mm according to the equation $R = Q \times \Delta t / 1000A$, where Q is streamflow, Δt is time, and A is area. Therefore, the actual ration of runoff and precipitation in the Bengbu basin is around 0.29. We estimated the RegCM_NCC simulated area mean runoff, precipitation and the ratio between them around Bengbu (30°–33°N, 115°–117°E). The monthly mean ratio of runoff and precipitation of NRM-Ini4, NRM-Ini5, and NRM-Ini6 is 0.39, 0.31, and 0.35, respectively. That of CTL-Ini4, CTL-Ini5, and CTL-Ini6 is 0.16, 0.13, and 0.14, respectively. Therefore, the ratios of runoff and rainfall by CTL are much less than the observation and those by NRM seem to be somewhat larger than the observation. Table 2 lists the regional mean differences between NRM and CTL, which shows that the differences for surface runoff are 8.4, 9, and 8.4 mm for the three cases in Ini4, Ini5 and Ini6 respectively. The differences for soil moisture are −18, −16, and −12.8 mm in the Ini4, Ini5 and Ini6 experiments. The sensible heat flux differences are 49.1, 54.4, and 36 W m^{-2}, and those of latent heat flux are −62.7, −68.9, and −48.7 W m^{-2}. The precipitation differences are −1.6, −1, and −2 mm in the Ini4, Ini5, and Ini6 experiments. Among the three experiments, it seems that there is no obvious relationship between the integration period and the differences between NRM and CTL.

The regional mean atmospheric water vapor in June around Bengbu by NRM is mostly less than that by CTL (Fig. 9), with large negative centers between NRM and CTL appearing at, respectively, the beginning and the end of June. Similar to the comparison between observed and RegCM_NCC simulated rainfall, the atmospheric water vapor transport is much more excessive in CTL compared with the NCAR/NCEP reanalysis data; the NRM effectively diminished the bias in CTL.

Therefore, the RegCM_NCC with the new surface runoff scheme produces more surface runoff in June 1998 (see Fig. 4). Correspondingly, the simulated ra-

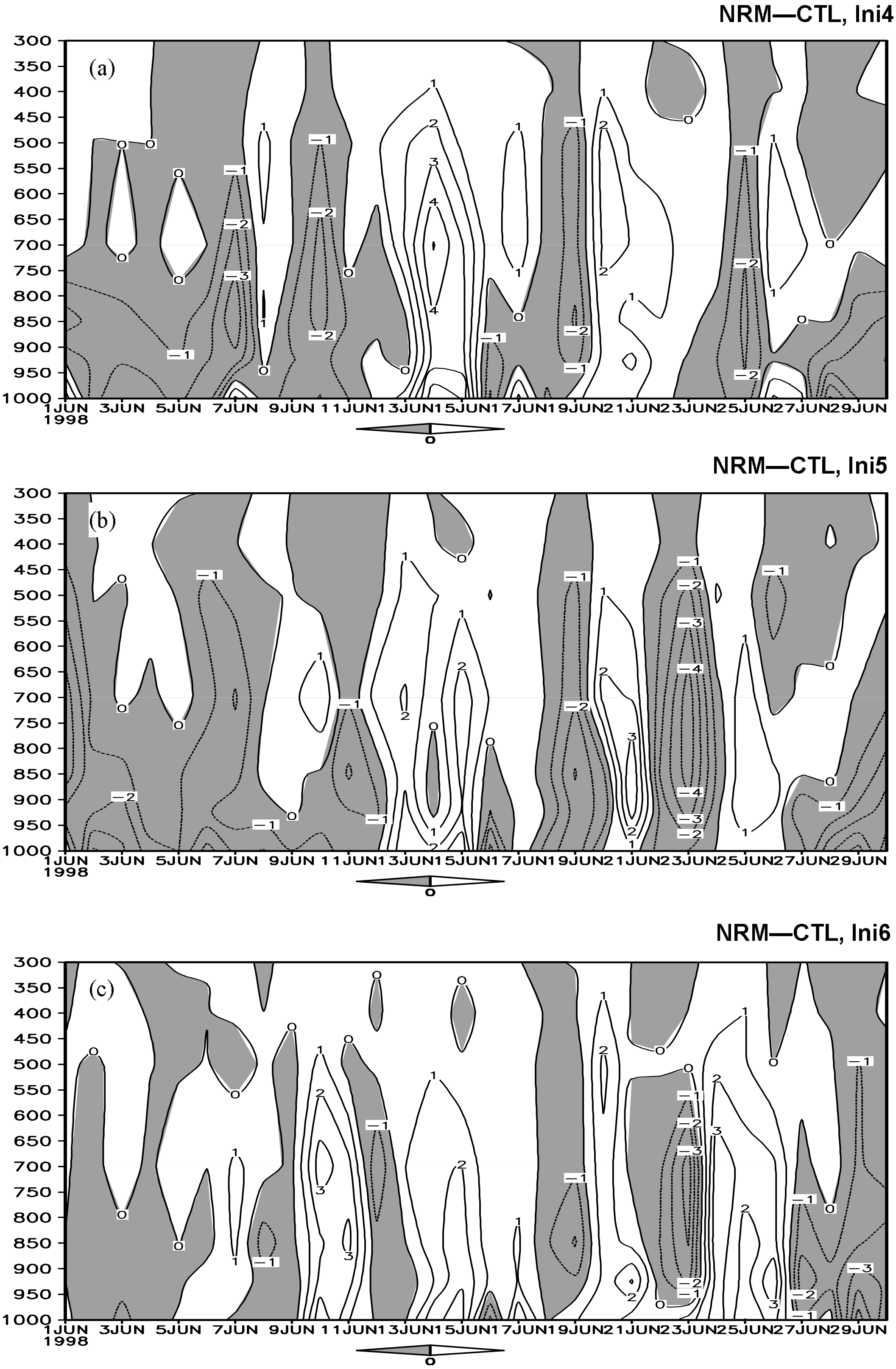

Fig. 9. Vertical atmospheric moisture differences between NRM and CTL in June 1998 over the region (30°–33°N, 115°–117°E). (Units: kg kg^{-1}). (a)–(c) are differences for Ini4, Ini5, and Ini6. Moisture differences $\leqslant 0$ kg kg^{-1} are shaded.

Table 2. Regional mean differences between NRM and CTL.

	Ini4	Ini5	Ini6
Surface Runoff	8.4	9	8.4
Rainfall	−1.6	−1	−2
Soil Moisture	−18	−16	−12.8
Sensible Heat Flux	49.1	54.4	36
Latent Heat Flux	−62.7	−68.9	−48.7

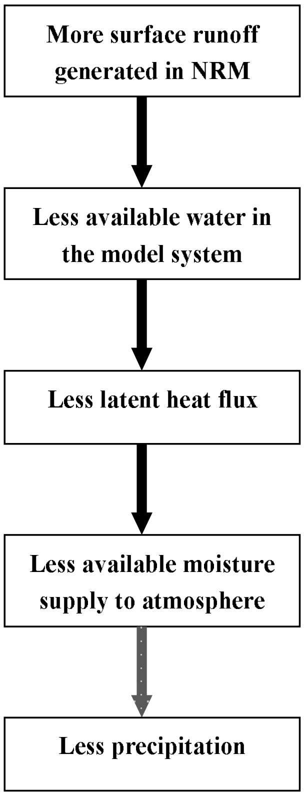

Fig. 10. Schematic figure of the possible processes involved in the surface runoff scheme's effects on simulated precipitation.

tion of runoff and precipitation is larger, and the model-simulated water partitioning into evaporation (latent heat flux) and moisture is decreased (see Table 2 and Fig. 7); the water vapor into the atmosphere is also decreased. The atmosphere system also experiences some changes (such as the weakness of the subtropical high of the western North Pacific) (Figs. 8 and 9), which will lead to the decrease of excessive precipitation. These are the conceptual figures shown in Fig. 10 that partly explain the possible processes involved in the NRM effects on the RegCM_NCC performance. Therefore, the surface runoff description has an important role in the model hydrological and energy system.

4. Summary and discussion

A dynamical surface runoff model with Dunne and Horton generation mechanisms was implemented into the regional climate model RegCM_NCC, and the model performances have been discussed. Indications are:

(1) The regional climate model RegCM_NCC with the Dunne and Horton generation mechanisms (NRM) can reasonably reproduce the climate features of June 1998, and the overestimation of precipitation in the CTL is effectively decreased in the NRM, with the implementation improving precipitation simulation.

(2) The improvement of rainfall simulation with the new surface runoff scheme seems to be due to the following processes: as the simulated surface runoff is increased, the evaporation (or latent heat flux) and soil moisture is decreased; correspondingly, the water supply into the overlying atmosphere is less, and the overestimated rainfall in CTL is effectively decreased in NRM via some processes. The results from this study imply that the surface runoff scheme modification has important effects on the model results for not only the surface hydrology and energy partitioning, but also for atmosphere components. But how the changes occur remains unanswered and requires further study. In addition, more cases like ensemble runs, or other cases in different years, are necessary to test the surface runoff scheme on the model performance.

(3) The surface runoff is only one part of the model hydrology; some other problems are not yet resolved. For example, according to Zeng et al. (2000a,b, 2003), the heterogeneity has significant effects on the model performance. Wu et al. (2005) adjusted the RegCM2 runoff scheme suitable for both loosened and compact soils with the heterogeneous surface runoff algorithm and found that the model could reasonably simulate precipitation distribution during the rainstorms in 1998. However, the subgrid heterogeneity in this paper is only presented by a constant, which actually should vary with the different grids. The groundwater is also an import part in the hydrological cycle; Liang et al. (2003) studied the effects on the land-surface model, but not regional climate models. The coupling of groundwater and the regional climate model will be discussed in another paper.

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