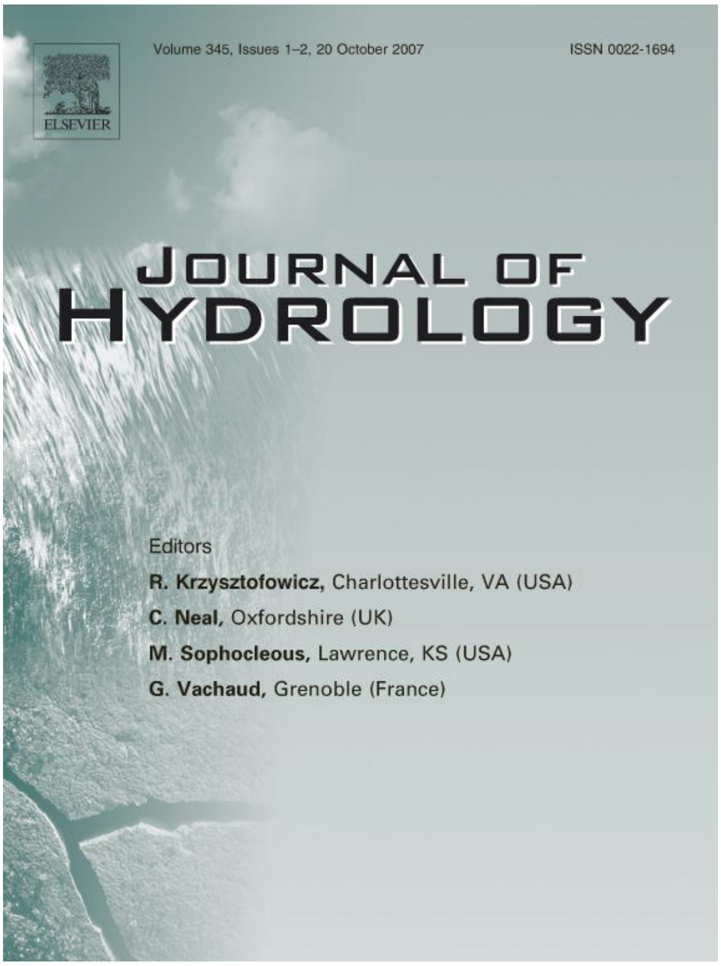
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Analysis and improvement of runoff generation in the land surface scheme CLASS and comparison with field measurements from China

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Summary The Canadian Land Surface Scheme (CLASS) is evaluated comprehensively using both site-specific data and observed hydrograph from the monsoon region of China. Two versions of CLASS, with and without hydrological modification allowing for interflow and baseflow, are used in this study. We modify standard CLASS for interflow generation using a field capacity threshold together with a spatial probability distribution function to represent sub-grid variability in soil field capacity. We also introduce a linear reservoir at the bottom of the third CLASS soil layer to model the baseflow. The 1998–99 HUBEX/GAME (HUaihe river Basin EXperiment/Monsoon Asian GEWEX Experiment) IOP (Intensive Observation Period) data set is used in this study. CLASS is driven by observed atmospheric forcing in a stand-alone mode. Both standard and modified versions of CLASS are first evaluated using the observed hydrograph at the outlet of the Shiguanhe sub-basin, part of the Huaihe River Basin in China, and soil moisture measurements at three sites over the sub-basin. The two versions are further validated for their ability to simulate net radiation, sensible and latent heat fluxes, ground heat flux, and soil temperature and moisture over four measurement sites with different land covers in the Huaihe River Basin. The total runoff in the Shiguanhe sub-basin simulated by the two versions is similar to each other, and is in close agreement with the observed value. The main difference between the two versions is in the partitioning of runoff components among the surface runoff,

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interflow and baseflow. Modified CLASS simulates better both peak flows and flood timing. The two versions of CLASS give similar results for the net radiation, sensible and latent heat fluxes, ground heat flux, and soil temperature and moisture, which compare well with observations over the study sites. Our modification of standard CLASS thus leads to an improvement in runoff and hydrograph simulation, while preserving its existing positive features.

Introduction

The land surface is the interface between the atmosphere and the underlying hydrological regime. The latter is mainly characterized by the surface heat fluxes, soil temperature and moisture, evaporation, infiltration, and runoff. The surface heat balance consists of the net radiation, sensible and latent heat fluxes and ground heat flux, while the water balance partitions the precipitation into evaporation, infiltration, surface runoff, interflow, and baseflow. These land surface processes have a major influence on the terrestrial water and energy budgets, and are as much a part of the climate system as atmospheric processes (Pielke, 2001).

Many studies have demonstrated the important role of land surface schemes (LSSs) in both numerical weather prediction models (e.g., Bouttier et al., 1993; Wen et al., 2000; Chen and Dudhia, 2001; Seuffert et al., 2002; Zhang et al. (2003); Jochum et al., 2004; Lin et al., 2005) and climate models (e.g., Nobre et al., 1991; Garratt, 1993; Milly and Dunne, 1994; Noilhan and Lacarrère (1995); Betts et al., 1996; Rosenzeig and Abramopoulos (1997); Arora and Boer (2002); Schmidt et al., 2006). Sensible and latent heat fluxes are two major feedbacks of a LSS to the atmosphere. These feedbacks are largely determined by the underlying soil moisture condition that controls the evaporation and evapotranspiration rates, which could be at its potential value or be limited by soil moisture supply. Although soils contain only a small fraction of the total available water in the world, soil moisture plays an important role in the surface water and energy balance. Much effort has been made towards the development of LSSs after the pioneering work of Manabe (1969). Deardorff (1978) proposed a simple parameterization of heat and moisture exchanges at the land surface for use in atmospheric models. In this ''force-restore'' approach, a vegetation layer is included that can interact both with the soil surface and the atmosphere. By the mid-1980s, results from many climate models indicated that systematic errors are associated with simple LSSs such as the force-restore method. The sensible and latent heat feedbacks from these LSSs to the atmosphere were particularly problematic. This motivated the development of the physically-based LSSs which treat explicitly the water and energy balance. A list of well-known LSSs can be found in Chen et al. (1997).

The Canadian Land Surface Scheme (CLASS; Verseghy, 1991; Verseghy et al., 1993) is a physically-based model that has been coupled to the Canadian Mesoscale Compressible Community (MC2; Benoit et al., 1997) model, the second and third-generation Canadian Atmospheric General Circulation Model (AGCM; McFarlane et al., 1992; Scinocca and McFarlane, 2004), and the Canadian Regional Climate Model (CRCM; Caya and Laprise, 1999). CLASS is also currently being coupled to the Canadian operational weather prediction model GEM (Global Environmental Multiscale; Coté et al., 1998). Over the past decade, CLASS has been tested and validated nationally and internationally in various experimental projects both in the stand-alone and coupled modes, with good results. However, these experimental sites are located in North America and Europe. There has been no published work on the use and validation of CLASS in the South Asian monsoon regions, which are often affected by flash floods. We will show in this study that CLASS simulates well the volume of total runoff, but fails to simulate a sub-basin hydrograph in the monsoon region of China. The simulated peak flows were particularly problematic. As we will see later, this is due to the partitioning of the runoff components among the surface runoff, interflow and baseflow. A comprehensive analysis of CLASS under different soil types, land covers, and climate conditions from different regions of the world is thus necessary. This has led to the objectives of our study, where we examine the runoff generation module of CLASS and evaluate multiple outputs of CLASS against multiple field measurements in an Asian monsoon region.

As mentioned above, CLASS has been coupled to the three Canadian weather and climate models and validated in many studies with good results. Therefore, our modification of CLASS should maximize the use of existing variables, preserve its positive features, and improve runoff and hydrograph simulation. We will give a detailed description of our newly modified version of CLASS, which consists of the use of a field capacity threshold together with a spatial probability distribution function to represent sub-gird variability in soil field capacity in interflow simulation. Such a function is used in Xinanjiang model (Zhao et al., 1980), Variable Infiltration Capacity (VIC; Liang et al., 1994, 1996) model, Hamburg Climate Model (Dümenil and Todini, 1992), and Interface Soil Biosphere Atmosphere (ISBA; Habets et al., 1999) model for calculating saturation excess runoff, and General Runoff Yield model (Wen et al., 1982) for generating infiltration excess runoff. The function is designed to take into account heterogeneity of land surface properties, and can give more realistic treatment of hydrological processes within a model grid cell. It is important to point out that in our modified version of CLASS, we will only use widely accepted procedures and openly accessible information for determining parameter values and model initialization. In this modification, not a single parameter is determined through optimization. Therefore, our results should provide a useful evaluation of CLASS as a LLS for coupling to weather and climate models. For such applications, an optimization procedure to determine parameter values would be unrealistic due to the large number of grid points in the domain. With 1998 summer data over China, we test both the original and modified versions of CLASS using the observed hydrograph at the outlet of the Shiguanhe sub-basin in the monsoon region of China, and soil moisture measurements at three sites over the sub-basin. We also evaluate the two versions of CLASS for their ability to simulate net radiation, sensible and latent fluxes, ground heat flux, surface temperature, and depth average soil moisture and temperature using the data collected from four different land cover sites over eight time periods in the summers of 1998 and 1999.

A brief history highlighting the improvements and refinements made in CLASS over the years is summarized in Verseghy (2000). CLASS, together with 24 LSSs, has been involved since its inception in the Project for Intercomparison of Land-Surface Parameterization Schemes (PILPS; Henderson-Sellers et al., 1993; Henderson-Sellers et al., 1995). Results from stand-alone model runs in Phase 2 study of PILPS indicated that surface fluxes simulated by CLASS were among the closest to the observations at the Cabauw site in the Netherlands (Chen et al., 1997). However, CLASS overestimated evapotranspiration during the Hydrology-Atmosphere Pilot Experiment-Modelisation du Bilan Hydrique (HAPEX-MOBILHY; Shao and Henderson-Sellers, 1996). The overestimation was also found in the Red-Arkansas River Basin experiment (Liang et al., 1998) and at two agricultural sites in Québec, Canada (Wen et al., 1998). For the simulated runoff, Arora and Boer (2002) reported the globally-averaged CLASS runoff over land compares well with observation. However, CLASS partitions a larger fraction of total runoff into drainage (≈77%), while global estimates suggest it is surface runoff that is responsible for majority of the total runoff (≈77%; L'vovich, 1979). On a basin scale, Lohmann et al. (1998) noted that CLASS may give a more balanced division of surface runoff and drainage in certain regions of the world, but underestimates the total runoff for most of the year.

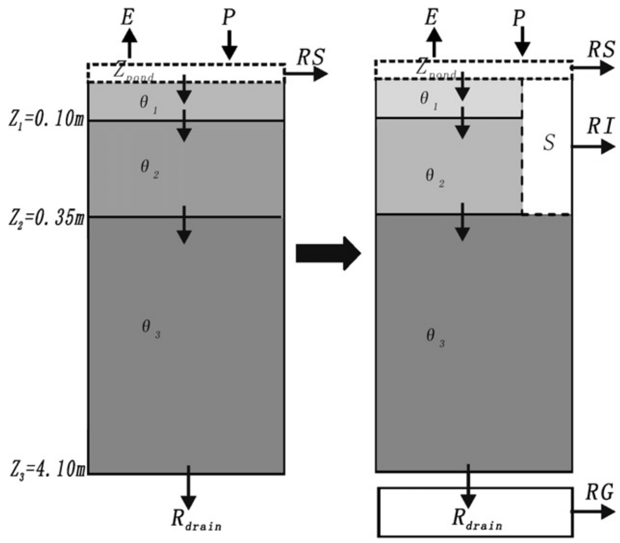
Modification of class

The original version of CLASS (v2.7; Verseghy, 1991; Verseghy et al., 1993) was developed at Environment Canada. We will refer to the original version as standard CLASS, which has been coupled to MC2 (Wen et al., 2000), the Canadian AGCM (Arora and Boer, 2002), and CRCM (MacKay et al., 2006). Standard CLASS has no interflow and a baseflow that is not appropriate for hydrograph simulations. Lin et al. (2002) modified this version through the use of a field capacity threshold to allow for interflow generation and the introduction of a reservoir at the bottom of the third CLASS soil layer for baseflow. The latter is similar to the parameterization of drainage introduced by Dümenil and Todini (1992), which uses a new reservoir parameter. Modifications of CLASS by Lin et al. (2002) were included in the coupled mesoscale atmospheric model MC2/CLASS (Wen et al., 2000) to simulate the July 1996 flash flood event in the Ha! Ha! River basin of the Saguenay region in eastern Québec, Canada. However, the use of the field capacity threshold alone in Lin et al. (2002) can simulate only interflow based on the grid mean soil moisture content. It cannot account for sub-grid variation of interflow, which is often important in coarse grid model applications. Also, the newly introduced reservoir parameter needs to be defined using either calibration procedures or some pre-determined value. We describe in this section further modifications to CLASS, that maximizes the use of existing variables, and preserves existing positive features of the model, and at the same time improves runoff and hydrograph simulation. We will refer to this modified version as modified CLASS.

Formulation of soil moisture and improved evaporation over bare soil

Standard CLASS is a one-dimensional column model, and is designed to represent the average characteristics of a grid cell. The cell can be further divided into a maximum of four sub-areas: bare soil, snow-covered, vegetation-covered, and both snow- and vegetation-covered. The soil column has three layers as shown in Fig. 1a, with physically-based calculations of heat and moisture transfer at the surface and across the layer interface. A composite vegetation layer is included, which can interact with both the surface soil layer and the atmosphere. The depth averaged temperature and moisture content are modeled for each of the three soil layers. At the bottom of the third layer, both the heat flux and the soil moisture suction gradient are assumed to be zero, consistent with field observations showing negligible temperature and moisture content variations over small time intervals. The soil moisture flux at the bottom of the third layer thus takes the value of the hydraulic conductivity. Standard CLASS drainage (baseflow) is taken to be the bottom soil moisture flux modified by a multiplicative parameter, which varies between 0 and 1 depending upon the soil type.

As shown in Fig. 1a, the thickness of the three soil layers in standard CLASS are 0.10, 0.25 and 3.75 m. The change in soil moisture content of a particular layer over a time step is entirely controlled by the change in moisture flux over the



(a) Standard CLASS (b) Modified CLASS

Figure 1 Schematic illustrations of soil structure and runoff components for the two versions of CLASS: (a) standard CLASS and (b) modified CLASS.

depth of that layer. Richard's equation for unsaturated flow is used for the simulation of this flux. At the ground surface, the moisture flux is determined by either the surface evaporation rate or the infiltration rate, depending upon the availability of precipitation. The Green and Ampt (1911) formula is applied to model the infiltration process. Surface ponding is allowed up to a maximum value when the infiltration capacity is exceeded.

Richard's equation is expressed as

$$F(z) = -k(z)\frac{d\psi(z)}{dz}\bigg|_z + k(z) \quad z \neq 0 \tag{1}$$

where z is the depth measured positive downward; $F(z)$ is the moisture flux. The unsaturated hydraulic conductivity $k(z)$, and unsaturated soil moisture suction $\psi(z)$, are given as in Clapp and Hornberger (1978) and can be expressed as

$$k(z) = k_{\mathrm{sat}}\left(\frac{\theta_i}{\theta_{i,p}}\right)^{(2b+3)} \tag{2}$$

$$\psi(z) = \psi_{\mathrm{sat}}\left(\frac{\theta_i}{\theta_{i,p}}\right)^{-b} \tag{3}$$

where k_{sat} and ψ_{sat} are the saturated hydraulic conductivity and soil moisture suction respectively; θ_i represents the soil moisture content of a layer i, and $\theta_{i,p}$ is the saturated soil moisture content; b is a soil clay parameter that reflects the presence of clay. Statistical relationships between b, θ_p, k_{sat}, ψ_{sat} and soil texture as derived in Cosby et al. (1984) are used in CLASS.

A commonly used form for calculating evaporation E over bare soil is

$$E = \rho_a C_E u_a \beta[\alpha q_{sat}(T_0) - q_a] \tag{4}$$

where ρ_a is the air density, C_E a bulk transfer coefficient for moisture vapor, u_a the wind speed, T_0 the soil surface temperature, $q_{\mathrm{sat}}(T_0)$ the saturated soil specific humidity at temperature T_0, and q_a specific humidity of the air near the surface. The two coefficients α and β are used to specify the moisture availability at the ground surface, and their values vary between 0 and 1.0. Usually, one of them is set to 1.0 so that the model is either of α-or β-type. There are many empirical α and β expressions proposed by different researchers (e.g., Lee and Pielke, 1992; Mihailovic and Kallos, 1997). The expression used over bare soil in standard CLASS is the one introduced by Philip (1957), where $\beta = 1$, and α is defined as

$$\alpha = \exp\left[-\frac{g\psi_0}{R_w T_0}\right] \tag{5}$$

where, g is the acceleration due to gravity, R_w the gas constant for moisture vapor, and ψ_0 the soil moisture suction at the surface (taken as positive). However, Philip's equation is known to overestimate evaporation (e.g., Lee and Pielke, 1992; Mihailovic et al., 1993; Kondo and Saigusa, 1994; Wen et al., 1998; Wu et al., 2000). To counter this in CLASS, Wen et al. (1998) replaced Philip's equation with a formulation proposed by Lee and Pielke (1992), which leads to lower evaporation over bare soil. This β-type formula has $\alpha = 1$ with

$$\beta = \begin{cases} \frac{1}{4}\left[1 - \cos\left(\frac{\theta_1}{\theta_{1,fc}}\pi\right)\right]^2 & \theta_1 < \theta_{\mathrm{fc}} \\ 1 & \theta_1 \geqslant \theta_{\mathrm{fc}} \end{cases} \tag{6}$$

where the soil moisture content (θ_1) and the field capacity ($\theta_{1,\mathrm{fc}}$) are taken from the first CLASS soil layer. A look-up table for defining $\theta_{1,\mathrm{fc}}$ using soil texture information is provided by Lee and Pielke (1992). Wen et al. (1998) suggested 70% of the saturated soil moisture content would be a good approximation for the field capacity, and noted that evaporation over bare soil can be further reduced with their alternate α-type formula, in which $\beta = 1$ and α is given by Eq. (6).

New modification to CLASS

Standard CLASS simulates only the vertical movement of water and does not consider interflow in soil layers (Soulis et al., 2000; Lin et al., 2002); the latter is an important runoff component in forming a hydrograph. The total runoff in standard CLASS is only the sum of the drainage from the bottom of the soil column (baseflow) and the excess water from the surface when the ponding limit is reached. Such a simple runoff scheme can result in excessively wet soil layers after a precipitation event, which can in turn lead to an overestimation of evapotranspiration. Without interflow, the surface runoff can be overestimated for clay type soil with low hydraulic conductivity, resulting in excessive simulated peak flows in hydrographs; in contrary, the baseflow can be overestimated for sandy type soil with high hydraulic conductivity, resulting in insufficient simulated peak flows in hydrographs. This is especially true for heavy precipitation. Our analysis also shows that standard CLASS can overestimate baseflow if the initial value of soil moisture in the third layer is greater than field capacity. The problem with soil moisture initialization in simulating event-based runoff is more evident for sandy type soils.

Over the past several years, we have further improved the version of CLASS used in Lin et al. (2002); new features are described here. Fig. 1b shows the structure of modified CLASS, which has the same three soil layers as standard CLASS. The differences between the two versions are mainly in the treatment of runoff processes. Modified CLASS simulates three runoff components: surface runoff (RS), interflow (RI), and baseflow (RG); as mentioned already, only surface runoff and baseflow are considered in standard CLASS. Both versions of CLASS simulate surface runoff using the same formulation:

$$\mathrm{RS} = Z_{\mathrm{pond}} - Z_{\mathrm{pond\_max}} \tag{7}$$

where Z_{pond} and $Z_{\mathrm{pond\_max}}$ represent the current and maximum ponded water on the ground surface. The value of $Z_{\mathrm{pond\_max}}$ varies with vegetation types and is usually between 1 and 3 mm. The only exception is for forested regions, where it takes on the value of 10 mm.

We assume that interflow (RI) can only be generated from the first and second soil layers in modified CLASS:

$$\mathrm{RI} = \mathrm{RI}_1 + \mathrm{RI}_2 \tag{8}$$

where RI_1 and RI_2 are the interflow from the first and second soil layers. Many studies have shown that the interflow is the result of free water in soil layers. For a specific grid cell (or a hydrological catchment), we calculate CLASS free water using a spatial probability distribution function to represent sub-grid variability in soil field capacity. The function is designed to take into account heterogeneity of land surface properties, and can give more realistic treatment of hydrological processes within a model grid cell. Generally, there is no limitation to the size of the grid cell to which the function is applied (Dümenil and Todini, 1992). For a CLASS soil column, the free water (S_i) in the first two soil layers is illustrated in Fig. 2, and can be expressed as

$$S_i = \begin{cases} \theta_i - \theta_{i,\mathrm{fc}} & \text{if } \theta_i \geqslant \theta_{i,\mathrm{fc}}(1+a) \\ \theta_i - \theta_{i,\mathrm{fc}}\left[1 - \left[1 - \frac{\theta_i}{\theta_{i,\mathrm{fc}}(1+a)}\right]^{1+a}\right] & \text{if } \theta_i < \theta_{i,\mathrm{fc}}(1+a) \end{cases} \quad (i = 1,2) \tag{9}$$

where θ_i represents the soil moisture content of a particular layer i (i = 1,2), and the corresponding field capacity is $\theta_{i,\mathrm{fc}}$. The value of $\theta_{i,\mathrm{fc}}$ is assumed as being 70% of the saturated soil moisture content. The shape parameter a in Eq. (9) is constant for a given grid cell and should reflect the property of soil texture and surface geomorphology. Our sensitivity study indicates that for normal types of soil in the mountain and flat terrains, the values of a can be assigned to 0.3 and 0.2, respectively, which is close to the typical average value (a = 0.2) reported in Dümenil and Todini (1992). Interflow cannot be generated when $S_i < 0$ in Eq. (9).

During a CLASS time step, if the condition $S_i > 0$ is met, we assume only a portion of S_i will be removed from the first two soil layers to generate interflow. The latter of the two CLASS layers (RI_i) is expressed as

$$\mathrm{RI}_i = \chi\gamma S_i \Delta z_i \quad (i = 1,2) \tag{10}$$

where Δz_i (i = 1, 2) represents the thickness of CLASS layer 1 or 2. The geomorphologic parameter χ is a constant for both CLASS layers and should reflect the river network density of a simulation region and the surface slope. The value of χ is in between 0 and 1. Our sensitivity study shows that for a catchment with a moderate river network density and surface slope, the value of χ can be assigned to 0.25. The parameter γ is a measure of soil clay and relative moisture conditions, and is determined by a formula similar to Eq. (2):

$$\gamma = \left(\frac{\theta_i}{\theta_{i,p}}\right)^{(2b_i+3)} \tag{11}$$

Variations of γ to the changes of θ and b for a given soil type (θ_p) are illustrated in Fig. 3. For a given relative soil moisture content (θ/θ_p), the value of γ will increase with b being decreased. As discussed in Clapp and Hornberger (1978), the parameter b measures the soil clay condition; large values correspond to fine soil textures. A large value of γ will allow for more free water to be shed from the soil layers.

Our baseflow generation in modified CLASS involves the use of a linear reservoir at the bottom of the third soil layer. The reservoir stores the drainage (R_{drain}) of standard CLASS, and moderates the release of water as baseflow. The reservoir can thus circumvent the problem of baseflow overestimation caused by soil moisture initialization. The baseflow in modified CLASS is taken to be the reservoir outflow:

$$\mathrm{RG}(t) = \beta_G R_{\mathrm{drain}} \tag{12}$$

where the parameter $\beta_G(t)$ is the reservoir outflow coefficient:

$$\beta_G(t) = \frac{\theta_3(t-1)}{\theta_{3,p}} \tag{13}$$

Both the third layer soil moisture (θ_3) and drainage (R_{drain}) are updated at each time step of the model integration. The value of the outflow coefficient at the current time step $\beta_G(t)$ depends upon the relative soil moisture content from the previous time step, $\theta_3(t-1)$. The use of Eq. (13) for determining the outflow coefficient avoids calibration procedures. This is important as a large scale optimization to determine CLASS parameters for coupled land—atmosphere modeling is unrealistic due to the large number grid points in the domain.

Soil moisture initialization in weather and climate models and in hydrological modeling applications remains an important unsolved problem. At this stage, we have no objective method for obtaining accurate soil moisture for model initialization. Nevertheless, the results presented in this study indicate that Eqs. (12) and (13) give a reasonable baseflow (RG) in modified CLASS. If the actual soil moisture content is not known, all three CLASS soil layers can be initialized with field capacity or a value determined by antecedent condition.

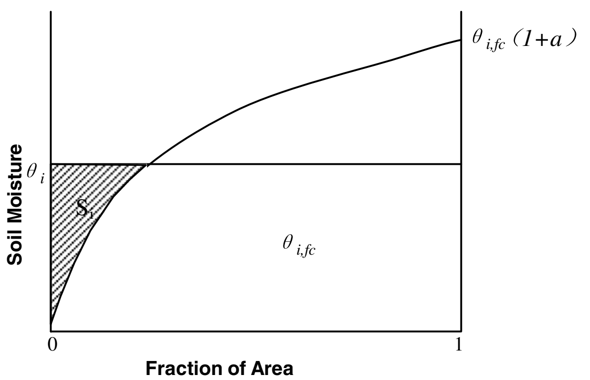


Figure 2 Schematic representation of the spatial probability distribution function to represent sub-grid variability in soil field capacity. $\theta_{i,fc}(1 + a)$ corresponds to the max value of soil field capacity over a grid cell.

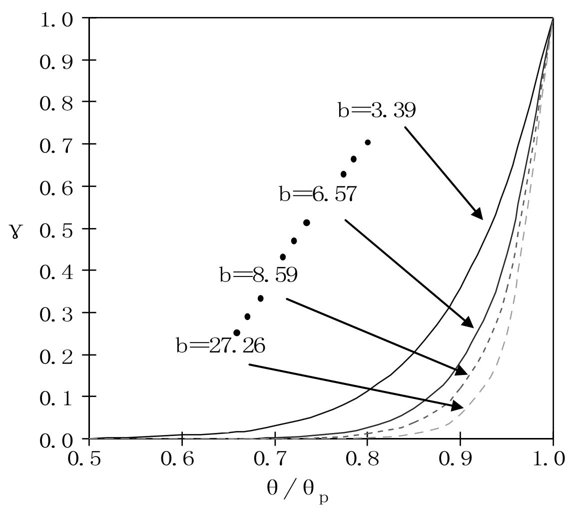


Figure 3 Illustration of variations of parameter γ to the changes of soil moisture θ and soil clay parameter b for a given soil type (θ_p).

The 1998–99 HUBEX/GAME IOP data and experimental design with CLASS

As part of the Global Energy and Water cycle EXperiment (GEWEX), the GEWEX Asian Monsoon Experiment (GAME) was implemented to better understand the role of the Asian monsoon in the global energy and water cycle. GAME was launched in 1996, with the Huaihe River Basin (270,000 km^2) in China being the study site for HUBEX (HUaihe river Basin EXperiment, China's contribution to GAME). The Intensive Observation Period (IOP) of HUBEX/GAME was carried out mainly over the Shiguanhe sub-basin (5930 km^2), part of the Huaihe River Basin, during the summers of 1998 and 1999. A comprehensive hydrometeorological data set is available from the IOPs that include the net radiation, sensible and latent heat fluxes, ground heat flux, surface temperature, soil temperature and moisture, and hydrographs at selected outlets. This data set will be used for testing the two versions of CLASS under different land cover conditions at both basin and point scales.

Huaihe River Basin and Shiguanhe sub-basin

The Huaihe River Basin (Fig. 4) is one of the seven major river basins in China. Climatologically, it lies in the warm semi-humid monsoon region, which is a transition zone between the climates of North and South China. The basin exhibits a diversified natural topography, land surface cover, soil texture, hydrology and climatology. Precipitation mainly occurs in the period from mid-May to mid-October. Anomalies of the Meiyu front during the rain season, which is in turn influenced by the South Asian monsoon, often cause basin wide flooding. The Shiguanhe sub-basin (Fig. 4) is located in the southern part of the Huaihe River Basin, and Jiangji is the sub-basin outlet. The sub-basin slopes from south to north with the elevation changing from 1500 to 1000 m over a horizontal extent of about 128 km. The northern part is characterized by hills, hillocks and river valley plain. The Shiguanhe River is an important tributary of the Huaihe River and originates from the northern slope of the Dabie Mountain in the south Huaihe River Basin. The river system has two major tributaries: Shihe River to the east and Guanhe River to the west, and they merge near the Jiangji outlet. The two tributaries are regulated by the Meishan and Nianyushan reservoirs over watershed areas of 1970 and 924 km^2 respectively, with corresponding travel distances of 88 and 89 km from reservoir outflow to the Jiangji outlet and an average travel time of almost 24 h.

1998–99 HUBEX/GAME IOP data

The IOP of HUBEX/GAME was carried out mainly over the Shiguanhe sub-basin during the summers of 1998 and 1999. The 1998 IOP was from May 1 to August 31; while the 1999 IOP was from June 24 to August 26. The 1998–99 IOP data are provided by the Bureau of Hydrology (BOH) of the Chinese Ministry of Water Resources (CMWR).

During the summer of 1998, 48 rain gauges covering the Shiguanhe sub-basin and a long-term flux monitoring station located at Shouxian were deployed. Stream flows at the Jiangji outlet were measured together with the soil moisture for the top 35 cm at three sites (Meishan, Nianyushan and Jiangji) over the sub-basin. The geographical locations of the 48 rain gauges, long-term flux monitoring station, three soil moisture sites, and Jiangji outlet are shown in Fig. 4. The Shouxian station is approximately 100 km from the Jiangji outlet. The rain gauges and long-term flux station provide atmospheric forcing for CLASS runoff and hydrograph simulations over the sub-basin. The three soil moisture sites give reference values for initializing CLASS

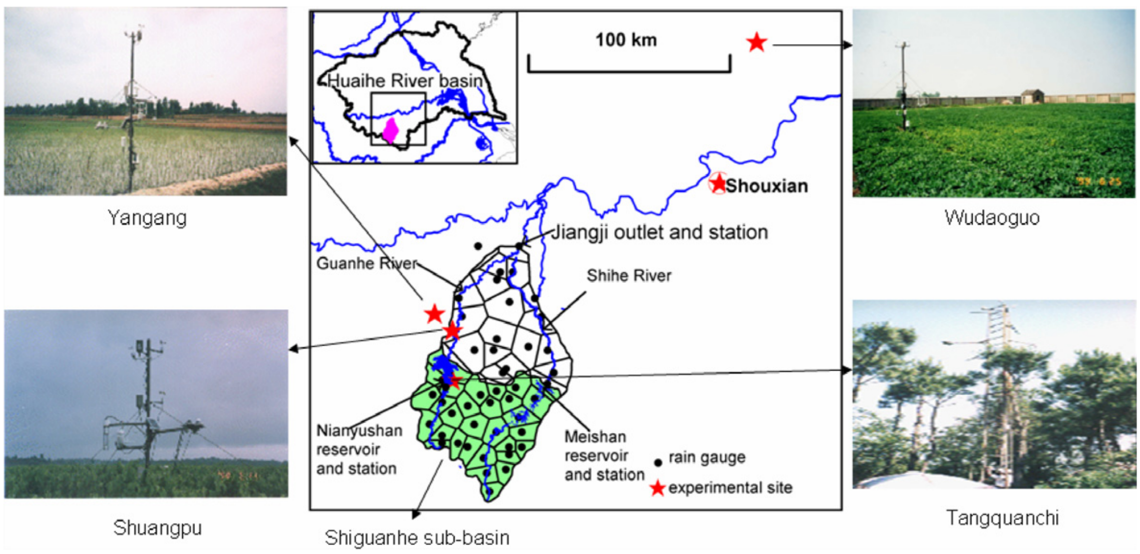


Figure 4 The center panel shows the Shiguanhe sub-basin (5930 km^2), and the side panels show four corresponding experimental sites: Tangquanchi, Yangang, Shangpu, and Wudaoguo. The Meishan and Nianyushan reservoirs and Jiangji outlet are also identified. The larger Huaihe River Basin (270,000 km^2) and the delineation of the Shiguanhe sub-basin using Theissen polygons, together with the 48 rain gauge locations are also shown. The four side panels show the different land cover at the sites. See text for further description.

Table 1 A summary of the four observational sites during the 1998–99 HUBEX/GAME IOPs

Site	Lon.	Lat.	Land cover	Soil type	Period of observation
Tangquanchi	115.36°E	31.70°N	Evergreen needleleaf pine tree	Luvisols	May 25–29, 1998 August 22–27, 1998 October 30–November 3, 1998
Yangang	115.30°E	31.99°N	Paddy field	Anthrosols	May 18–24, 1998 August 8–15, 1998
Shangpu	115.39°E	31.91°N	Mulberry	Luvisols	May 10–18, 1998 August 17–21, 1998
Wudaoguo	117.00°E	33.20°N	Bean	Dark semi-hydromorphic soils	June 24–August 26, 1999

and data for validating CLASS simulated soil moisture. The Jiangji outlet hydrograph is used for CLASS validation.

Additional site-specific data are also available from the two IOPs including net radiation, sensible and latent heat fluxes, ground heat flux, surface temperature, soil temperature and moisture. These data can be used to further evaluate CLASS point scale simulations. During the 1998 IOP, a portable automated meteorological station of Kyoto University (KU-AWS) was deployed at three sites (Tangquanchi, Yangang, and Shangpu) with different land covers. The station was installed at a fourth site (Wudaoguo) during the 1999 IOP. All three of the 1998 sites are located in the Shiguanhe sub-basin, and the 1999 site to the north of the Huaihe River (Fig. 4). The detailed information on the four sites is given in Table 1, and photographs showing the different land cover are included in Fig. 4. There are eight periods of observation over the two IOPs, lasting from a few days to more than two months (Table 1). At each of the four sites, the observed incoming short-wave and outgoing long wave radiation, precipitation rate, near surface air temperature, wind speed and direction, humidity, and atmospheric pressure are used to drive CLASS. Precipitation was measured every hour, while the remaining meteorological variables and soil temperature were monitored at time intervals of 2–10 min. Soil temperature measurements were made at three depths: 1, 10, and 20 cm. Soil moisture was measured at only one site (Wudaoguo) using time domain reflectrometry (TDR) over the depths of 0–15, 15–30, 30–45, 45–60 cm, with once daily measurement on average.

Experimental design with CLASS

CLASS point simulations are carried out over the four sites (Tangquanchi, Yangang, Shangpu, and Wudaoguo) with photographs shown in Fig. 4. A half hour time step is used. Being a physically-based model, CLASS parameters can be determined either from measurements or from the literature, or a combination. In this study, all but one CLASS parameters are determined using the look-up table in Verseghy (1991) and Verseghy et al. (1993) based upon observed site soil and vegetation information, thus ensuring compatibility between our results and other modeling studies using CLASS. The only exception is the new hydrological parameter a that we introduced to calculate interflow in modified CLASS. As discussed earlier, this shape parameter a is constant for a given grid cell and represents sub-grid variability in soil field capacity. Our sensitivity study indicates that for normal soil characteristic of mountain and flat terrain, appropriate values of a are 0.3 and 0.2, respectively. Table 2 lists the CLASS soil, vegetation and hydrological parameters used at the four sites.

Tests of CLASS runoff simulation are conducted over the Shiguanhe sub-basin, covered by 48 rain gauges with the outlet located at Jiangji (Fig. 4); 48 Theissen polygons are used to delineate coverage by the gauges as shown in the figure. The runoff of 25 of the 48 polygons drains directly into the two reservoirs in the upper sub-basin and these 25 polygons are colored green in Fig. 4. The Jiangji outlet hydrograph can thus be decomposed into three major components: outflows from two reservoirs, and runoff generated at the lower sub-basin from the remaining 23 contributing polygons. These 23 polygons cover an area of 3036 km^2 and lie downstream of the two reservoirs, and hence their runoff calculation is not influenced by the reservoirs. Both standard and modified versions of CLASS are used to generate runoff over each of these 23 polygons. The University of Maryland 1-km Global Land Cover Classification data (http://glcf.umiacs.umd.edu/data/landcover/) together with the look-up table in Verseghy (1991) and Verseghy et al. (1993), and the China regional soil type classification database developed by the Institute of Soil Science, Chinese Academy of Sciences (http://www.soil.csdb.cn/stdc.htm) are used to determine the CLASS vegetation and soil parameters for the 23 polygons. The determination of the new hydrological parameter a has been addressed earlier. The soil moisture measured at Meishan, Nianyushan and Jiangji are used to initialize CLASS. The initial temperature of the canopy and first soil layer takes the values of the measured air temperature. The meteorological driving fields for CLASS comes from two observational sources: rain gauges covering each of the 23 contributing polygons and the long-term flux monitoring station located at Shouxian. The topography database from the GTOPO30 global digital elevation model (DEM) of the US Geological Survey with a horizontal resolution of 1 km (http://edcdaac.usgs.gov/gtopo30/gtopo30.asp) is used to set up the flow routing network over the sub-basin. The Clark unit hydrograph (CUH; Clark, 1945) and the Muskingum-Cunge (MC) channel routing method (Cunge, 1969) are used for flow routing to obtain hydrographs at the Jiangji outlet. We will henceforth refer to the ensemble of the three hydrological modules (CLASS runoff generation, CUH, MC method) as the CLASS hydrological modeling system. Prior to the current study, we have calibrated the parameters of both CUH and MC method with historical rainfall–runoff data for the sub-basin. We will thus not discuss the details of the calibration in this study and will focus instead on the validation of results. This methodology is sim-

Table 2 A description of the CLASS soil, vegetation, and hydrological parameters, and their numerical values used at the four observational sites

Parameter	Soil layer	Tangquanchi	Yangang	Shangpu	Wudaoguo
Vegetation					
Max leaf area index	Surface	5	6.5	4	5
Vegetation roughness (m)	Surface	1.5	0.08	0.27	0.15
Min leaf area index	Surface	4	0	0	0
Visible albedo	Surface	0.03	0.06	0.06	0.06
Near-infrared albedo	Surface	0.19	0.36	0.3	0.35
Canopy mass (kg/m)	Surface	25	2	2.5	3
Rooting depth (m)		1.5	1.2	0.8	0.6
Soil					
Empirical parameter (b)	1	5.77	5.77	8.95	8.16
	2	4.98	5.77	10.54	8.16
	3	4.18	7.36	8.95	7.36
Saturated soil moisture content	1	0.405	0.8	0.449	0.455
	2	0.398	0.423	0.455	0.461
	3	0.386	0.436	0.455	0.455
Saturated soil suction (m)	1	0.101	0	0.289	0.336
	2	0.0865	0.158	0.336	0.391
	3	0.0639	0.214	0.336	0.336
Saturated hydraulic conductivity	1	9.76E−06	2.00E−06	2.85E−06	2.39E−06
	2	8.65E−02	5.76E−06	2.39E−06	2.00E−06
	3	1.66E−05	4.05E−06	2.39E−06	2.39E−06
Soil color	Surface	4	4	2	5
Drainage	Bottom	0.5	0.5	0.5	0.5
Hydrology					
Empirical parameter (a)	1	0.30	0.20	0.20	0.20
	2	0.30	0.20	0.20	0.20

ilar to that used in Lin et al. (2006) for the simulation of flood events in the Huaihe River Basin. A four-month continuous simulation using the CLASS hydrological modeling system is performed over the Shiguanhe sub-basin. A half hour time step is used for both runoff generation and flow routing in the simulation.

Results

Evaluation of CLASS basin scale simulations

With the 1998 IOP data, we evaluate CLASS simulated runoff and hydrographs and soil moisture using the observed hydrograph at the Jiangji outlet of the Shiguanhe sub-basin and the soil moisture at three sites (Meishan, Nianyushan and Jiangji) over the sub-basin. As mentioned in the objective of this study, our goal is to evaluate multiple outputs of CLASS against multiple field measurements, which in this case are the hydrograph and soil moisture.

A widely used procedure for evaluating simulated hydrographs is the Nash—Sutcliffe model efficiency coefficient (r^2; Nash and Sutcliffe, 1970):

$$r^2 = 1 - \frac{\sum_{t=1}^{T}(Q_o^t - Q_m^t)^2}{\sum_{t=1}^{T}(Q_o^t - \overline{Q}_o)^2} \qquad (14)$$

where, Q_o^t and Q_m^t are the observed and simulated discharge at time step (t), respectively, and $\overline{Q}_o$ represents the time averaged observed discharge. The mean bias error (MBE) and the square of the correlation coefficient (R^2) are used as quantitative measures for evaluating simulated soil moisture.

As discussed in the last section, the CLASS hydrological modeling system is applied over each of the 23 contributing polygons of the Shiguanhe sub-basin. Over each of these polygons, the same observed atmospheric data are used to drive the two versions of CLASS. The simulation period is from May 1 (0:00 GMT) to August 31 (24:00 GMT) of 1998. The first 19 days is treated as model spin-up; and the model evaluation period is from May 20 (GMT) to August 31 (GMT). CLASS simulated stream flow and soil moisture are saved every half hour for the model evaluation period, and will be compared with observations.

Simulated hydrographs

Fig. 5 shows the observed and CLASS simulated hydrographs at the Jiangji outlet. We first examine the simulated total runoff with the two versions of CLASS. The total observed runoff during the evaluation period is 1.122 billion m^3. The corresponding values for standard and modified CLASS are 1.173 and 1.198 billion m^3, giving relative errors of 4.5% and 6.8%, respectively. The runoff ratio (runoff/precipitation) of standard and modified CLASS is 0.31 and 0.32, respectively, very close to the observed value of 0.30. The two versions of CLASS thus simulate well the volume of total runoff. Up to now, we have seen almost no difference in the

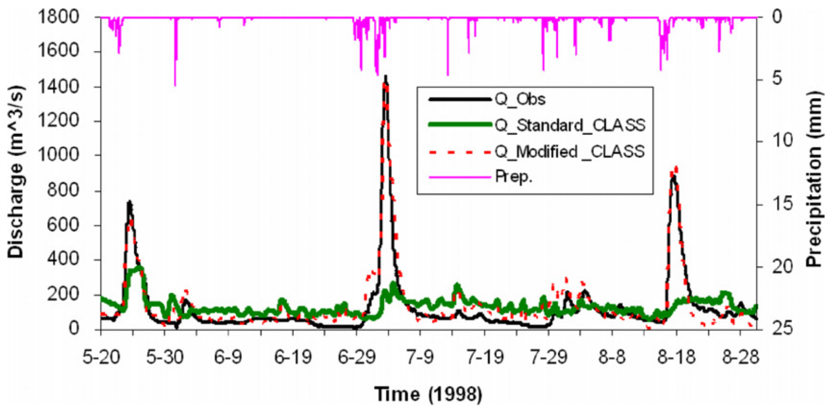


Figure 5 Comparison of model and observed hydrographs at the Jiangji outlet of the Shiguanhe sub-basin during the 1998 IOP. The observed hydrograph is shown in black. The simulated hydrographs with standard and modified CLASS are shown as the green and dotted red curves respectively. The area mean precipitation is shown as the pink vertical bar at the top of the figure.

simulated total runoff between the two versions of CLASS. The situation is however different for simulated hydrographs.

Fig. 5 shows a good agreement between the observed and simulated hydrograph with modified CLASS, but with much less satisfactory agreement for standard CLASS. The Nash—Sutcliffe coefficient for modified CLASS reaches a statistically significant value of $r^2 = 0.91$. Both peak flow and its timing are well simulated for all three flood events during the evaluation period. The relative errors for the May 24 and August 18 peak flows are −11.9% and 7.3%, respectively. For the largest flood event, the observed and simulated July 3 peak flows are 1482 and 1475 m^3/s, respectively, with the same peak time at 12:00 GMT, indicating a very good flood peak simulation. A successful simulation of flood peaks is essential in accessing the performance of a hydrological model. The simulated discharge for low flow periods also compares well with observations; this is important for applications in water resources management. The results with standard CLASS are much less favorable (Fig. 5). Its simulated discharge for the three flood peaks (May 24, July 3 and August 18) only reach 356, 240 and 207 m^3/s, with relative errors of −51.6%, −83.8% and −76.6%. The simulated peak timing is also delayed by 1—7 days. Furthermore, the simulated discharge for low flow periods is significantly higher than the observations for most of the time. The overall model performance as measured by the Nash—Sutcliffe coefficient of $r^2 = 0.15$ over the evaluation period is poor. From Fig. 5, we also note the simulated discharge at the beginning of the evaluation period (May 20) is more than twice the observed value, after a 19-day model spin-up period. In contrast, the simulated value with modified CLASS is much closer to the observations (Fig. 5).

A close examination of the simulated runoff components (surface runoff, RS; interflow, RI; and baseflow, RG) would help to understand the differences between the hydrographs of standard and modified CLASS. Recall standard CLASS does not generate interflow and thus has RI = 0, while modified CLASS simulates all three runoff components (New modification to CLASS section). Over the evaluation period, the relative magnitudes of these components are RS:RI:RG = 1:0:11.5 for standard CLASS, and 1:17:2 for modified CLASS. Thus, the largest runoff component for modified CLASS is interflow, while it is the baseflow for standard CLASS. The discharge overestimation during low flow periods is associated with the large baseflow in standard CLASS. This can also lead to an underestimation of peak flow and delayed peak timing. The introduction of the new interflow component in modified CLASS circumvents the problem of too large a baseflow, and gives a more reasonable partitioning of the simulated total runoff. The success of our interflow modification to standard CLASS is thus clearly demonstrated in the analysis of simulated hydrographs with the two versions of CLASS.

Soil moisture simulation at Meishan, Nianyushan and Jiangji

Soil moisture and runoff are closely connected in balancing surface water in LLSs. Soil moisture plays a key role in controlling the rates of surface feedbacks of a LLS to the atmosphere. Fig. 6 shows soil moisture by volume for the three sites and the sub-basin average for the two versions of CLASS and observations over the evaluation period. The soil moisture is averaged over the depth of 0—35 cm, and the observed sub-basin average is assumed to be the mean value of the three sites. In general, both standard and modified versions of CLASS reproduce well the observations, with little difference between them. The good performance of standard CLASS in simulating soil moisture had been reported in our pervious study (Wen et al. (1998)). Such a feature is also well preserved in modified CLASS, which is important in simulating hydrographs and surface fluxes. Fig. 6 shows the measured soil moisture having higher frequency of variation than both simulations. This frequent soil moisture variation in close to the surface layer is often found in field observations. There could be many factors contributing to this variation. It would be unrealistic to expect any LLS to be able to precisely simulate the soil moisture variation close to the surface layer. We have also compared the third layer CLASS soil moisture between the two versions. The mean value over the entire evaluation period is below the model field capacity, which is taken to be 70% of the saturated soil moisture content. Standard CLASS is about 9% wetter than the modified version. This

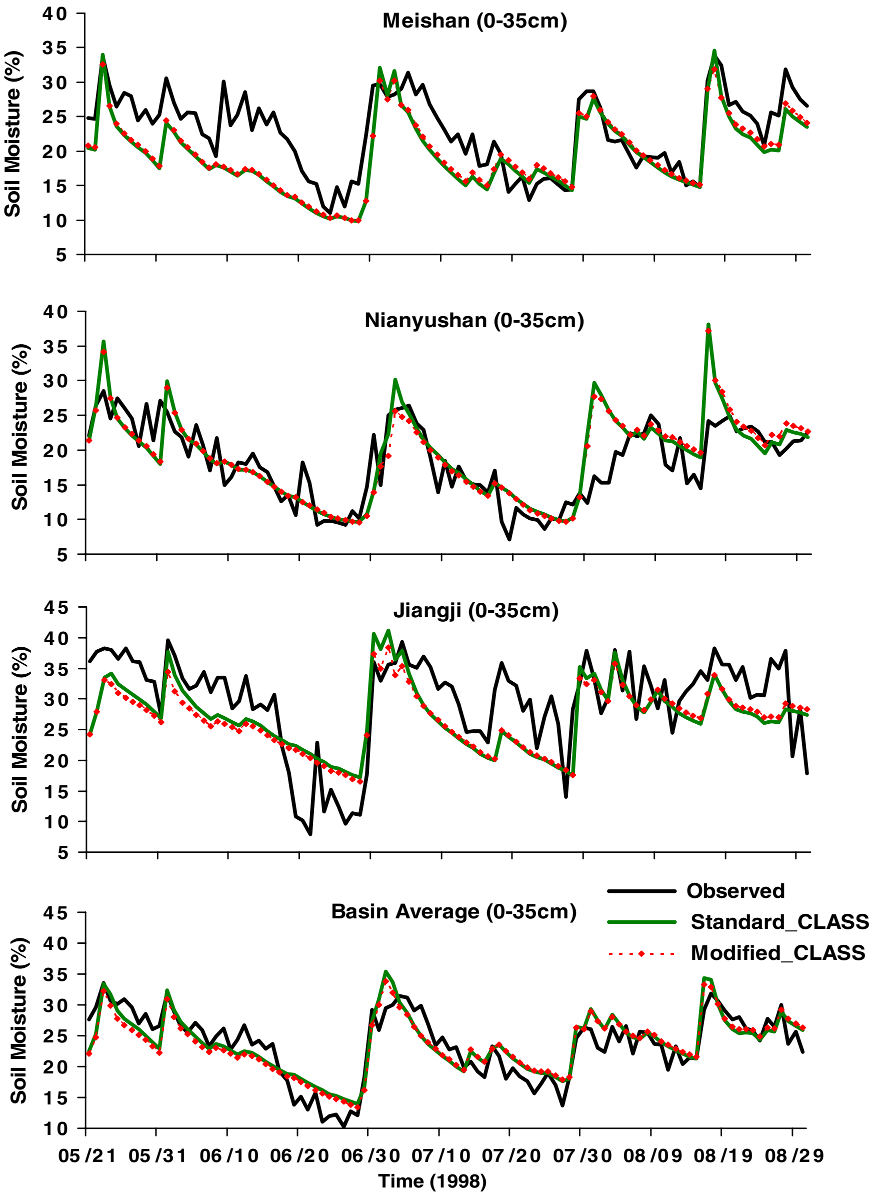


Figure 6 A comparison of the soil moisture content simulated by standard CLASS (green) and modified CLASS (dashed red line with diamonds) with observed values (black) over the three measurement sites (Meishan, Nianyushan, and Jiangji) and the sub-basin average.

is due to the interflow modification introduced in the first two soil layers and the use of the linear reservoir at the bottom of the third soil layer in modified CLASS.

Table 3 shows the statistics for the three sites and the sub-basin average over the depth of 0–35 cm. Both versions of CLASS underestimate slightly the soil moisture at

Table 3 Comparison of soil moisture simulated by the two versions of CLASS with observations over three sites (Meishan, Nianyushan, and Jiangji), and the sub-basin average over the depth of 0–35 cm

	Meishan		Nianyushan		Jiangji		Sub-basin average	
	SCLASS	MCLASS	SCLASS	MCLASS	SCLASS	MCLASS	SCLASS	MCLASS
MBE (%)	−3.4	−3.1	0.9	0.8	−2.5	−2.9	0.3	0.0
R^2	0.64	0.64	0.61	0.63	0.47	0.52	0.77	0.77

SCLASS and MCLASS denote the standard and modified versions of CLASS, respectively.

Meishan and Jiangji, and overestimate the value at Nianyushan; the result is marginally better and dryer for modified CLASS. The values of MBE for the two versions of CLASS are within ±4% for the three sties and the sub-basin average. The R^2 values are acceptable, which are generally greater than 0.5. Better MBE and R^2 scores are found for the sub-basin average having almost bias free results for both versions of CLASS. This is most likely due to smoothing over the individual sites.

CLASS point scale simulation

We have used the data from the 1998–99 IOPs, net radiation, sensible and latent fluxes, ground heat flux, soil temperature and moisture at four sites with different land covers (Tangquanchi, Yangang, Shangpu, Wudaoguo) over the Huaihe River Basin, to further evaluate CLASS point scale simulations. The geographical locations of the four sites with photographs are shown in Fig. 4. The 1998–99

Table 4 A summary of the comparison statistics of simulated CLASS variables over the four observational sites and different periods of the 1998–99 IOPs

Variable	Tangquanchi		Yangang		Shuangpu		Wudaoguo	
Period	5.25–29/98	8.22–27/98	10.30–11.3/98	5.18–24/98	8.8–15/98	5.10–18/98	8.17–21/98	6.24–8.26/99
R_{net} (W/m^2),	−25.6	−14.7	−24.0	−2.5	−27.1	12.0	−15.4	−27.1
net	*−25.6*	*−14.7*	*−24.0*	*−2.5*	*−27.1*	*12.0*	*−15.4*	*−28.0*
radiation	0.998	0.998	0.995	0.99	0.995	0.99	0.99	0.999
	0.998	*0.998*	*0.995*	*0.99*	*0.995*	*0.99*	*0.99*	*0.999*
Q_H (W/m^2),	−26.9	−8.7	−40.6	−1.3	22.3	2.1	19.0	19.8
sensible	*−26.9*	*−8.7*	*−40.6*	*−1.3*	*22.3*	*2.1*	*19.0*	*23.2*
heat flux	0.96	0.97	0.94	0.47	0.71	0.78	0.89	0.86
	0.96	*0.97*	*0.94*	*0.47*	*0.71*	*0.78*	*0.89*	*0.86*
Q_E (W/m^2),	−2.7	3.1	19.7	−20.9	−33.3	7.1	−35.0	−47.2
latent heat	*−2.7*	*3.1*	*19.7*	−20.9	−33.3	*7.4*	−35.0	−51.6
flux	0.94	0.97	0.66	0.58	0.90	0.98	0.94	0.99
	0.94	*0.97*	*0.66*	*0.58*	*0.90*	*0.98*	*0.94*	*0.98*
$G(0)$ (W/m^2),	4.1	−8.6	−2.1	−4.7	−6.1	2.8	0.66	0.6
ground heat	*4.1*	−8.6	−2.0	−4.7	−6.1	*2.5*	*0.66*	*0.5*
flux	0.65	0.63	0.66	0.77	0.65	0.88	0.82	0.92
	0.65	*0.68*	*0.66*	*0.77*	*0.85*	*0.87*	*0.82*	*0.92*
$T_{surface}$ (°C),	−1.0	−0.2	−1.4	1.2	1.0	1.3	1.0	0.4
surface	*−1.0*	*−0.2*	*−1.4*	*1.2*	*1.0*	*1.3*	*1.0*	*0.7*
temperature	0.97	0.93	0.91	0.97	0.74	0.83	0.72	0.87
	0.97	*0.93*	*0.91*	*0.97*	*0.74*	*0.83*	*0.72*	*0.88*
T_{layer1} (°C),	−0.2	−0.9	−0.6	−1.2	−0.3	−1.9	−0.5	0.6
layer 1 soil	*−0.2*	*−0.9*	*−0.6*	*−1.2*	−0.3	−1.9	−0.4	*0.8*
temperature	0.97	0.99	0.91	0.84	0.69	0.84	0.94	0.88
	0.97	*0.99*	*0.91*	*0.84*	*0.69*	*0.84*	*0.94*	*0.90*
T_{layer2} (°C),	−0.1	0.0	−1.2	−1.1	0.8	−2.3	−0.8	0.7
layer 2 soil	*−0.1*	*0.0*	−1.2	−1.0	*0.8*	−2.3	−0.8	*0.9*
temperature	0.78	0.69	0.32	0.56	0.85	0.99	0.95	0.54
	0.78	*0.69*	*0.32*	*0.56*	*0.85*	*0.99*	*0.94*	*0.59*
$S_{0-35\ cm}$ (%),	–	–	–	–	–	–	–	1.7
0–35 cm Soil	–	–	–	–	–	–	–	*0.9*
moisture	–	–	–	–	–	–	–	0.87
	–	–	–	–	–	–	–	*0.86*
$S_{0-60\ cm}$(%),	–	–	–	–	–	–	–	−1.9
0–60 cm	–	–	–	–	–	–	–	−2.5
soil moisture	–	–	–	–	–	–	–	0.84
	–	–	–	–	–	–	–	*0.84*

Within each box, the first two rows show the mean bias error (MBE) and the last two rows show the square of the correlation coefficient (R^2), with results for standard CLASS shown using normal font and modified CLASS in italics; missing values indicate observations are not available. All statistics but soil moisture correspond to the mean diurnal cycle of simulated variables.

IOPs covered eight time periods at these sites (Table 1), which results in a total of 16 standard-alone runs with the two versions of CLASS. For each of eight time periods at each site, the same observed atmospheric forcing data are used to drive the two versions of CLASS, and their multiple outputs are saved every half hour. The mean diurnal cycle of CLASS net radiation, sensible and latent fluxes, ground heat flux, and soil temperature are calculated, and will be

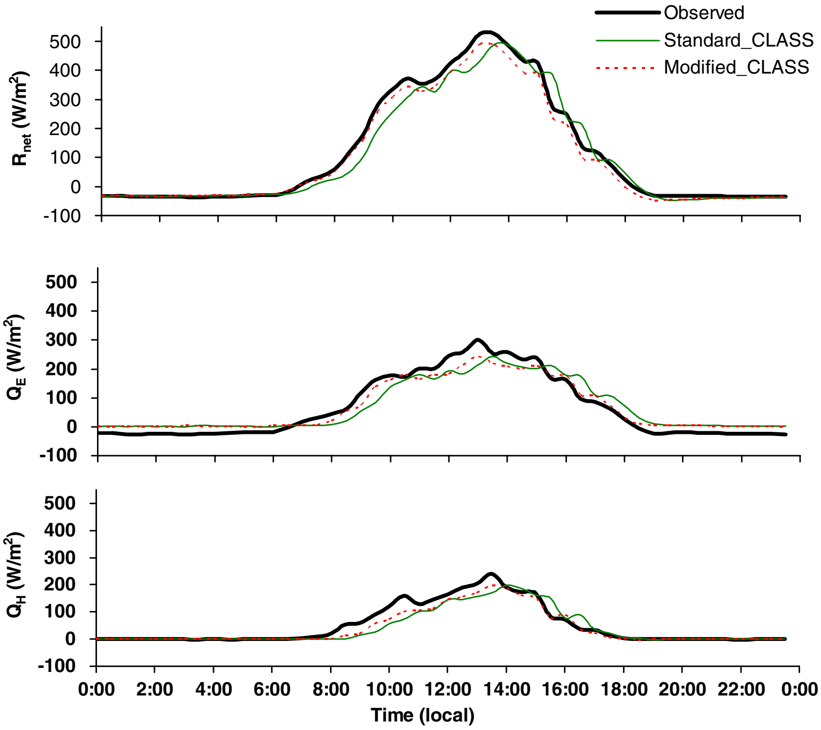


Figure 7 Comparison of observed and simulated mean diurnal cycle of net radiation and latent and sensible heat fluxes (R_{net},Q_E, Q_H) for the period August 22—27, 1998 at the Tangquanchi site using the two versions of CLASS.

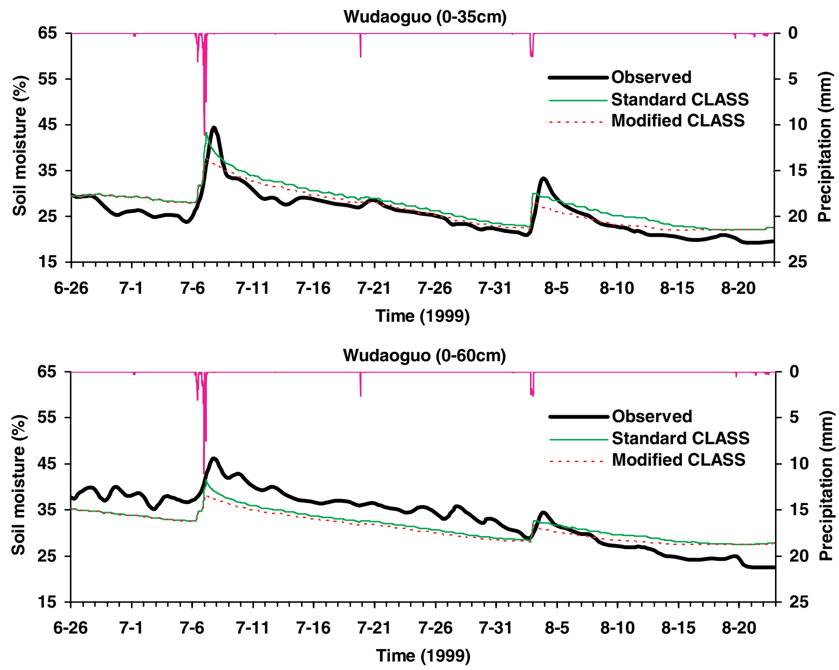


Figure 8 A comparison of the soil moisture content simulated by standard CLASS (thin green line) and modified CLASS (dashed red line) with observed values (black) for the site Wudaoguo. The comparison is done for two depths (0—35 and 0—60 cm) of the soil column. The gauged precipitation is shown as the pink vertical bar at the top of the figure.

used for model verification. MBE and R^2 are again used as quantitative measures for evaluating CLASS results. Table 4 gives the summary of the comparison statistics of simulated CLASS variables over the four sites and eight different periods of the 1998–99 IOPs.

As discussed earlier, standard CLASS has been tested and validated national and internationally in various experimental projects both in stand-alone and coupled modes, with good results. Existing positive features of standard CLASS must be preserved in the modified version. As shown in Table 4, the two versions of CLASS give similar results in simulating net radiation, sensible and latent heat fluxes, ground heat flux, surface temperature, and soil temperature and moisture (first and second CLASS layers) over the four sites. There is also good overall agreement with observations. Our study confirms many previous results of the good performance of standard CLASS in simulating surface fluxes and soil temperature and moisture; and demonstrates the new interflow modification to standard CLASS has little effect on these variables. Our modifications thus improve only CLASS runoff and hydrograph simulations, which have been demonstrated earlier. Results of CLASS point simulations are summarized in the next section.

Simulated surface fluxes and soil temperature

Net radiation (R_{net}) is the difference between the incoming and outgoing radiation, which gives a measure of the amount of energy actually added to or lost from the land surface. This energy is used in changing the phase of water through the latent heat flux (Q_E), air temperature through the sensible heat flux (Q_H), and in supplying the subsurface ground heat flux ($G(0)$):

$$R_{net} = Q_E + Q_H + G(0) \quad (15)$$

Correct simulation of R_{net} is thus the first step towards the successful simulation of the three radiation flux components (Q_E, Q_H, and $G(0)$). Fig. 7 shows an example of comparison of mean diurnal cycle of net radiation and latent and sensible heat fluxes simulated by the two versions of CLASS with observed values for Tangquanchi over the period August 22–27, 1998. The mean diurnal cycle of net radiation is well simulated by both versions; and R^2 reached a very high value exceeding 0.99. In general, the two versions of CLASS performs best over the mulberry site Shangpu as seen from the MBE and R^2 values in Table 4. At this site, the August 17–21, 1998 run has an almost bias free result with $R^2 = 0.99$. The worst value of MBE = -28 W/m^2 is obtained at the bean site Wudaoguo for the June 24–26, 1999 period. The net radiation is underestimated by CLASS by 2.5–28 W/m^2 in three out of the four sites as indicated by the MBE values in Table 4. However, such error margins are statistically insignificant as the average value of observed R_{net} can be of order several hundred W/m^2.

The mean diurnal cycle of sensible and latent fluxes are reasonably well simulated by CLASS over the four sites for the 15 runs as seen from the MBE and R^2 values in Table 4. CLASS has the best performance at the pine tree site Tangquanchi (Fig. 7) and the mulberry site Shangpu. For the former, the August 22–27, 1998 run has MBE = -8.7, 3.1 W/ m^2 for Q_H and Q_E, respectively, with corresponding values of $R^2 = 0.97$, 0.97. The results of the May 18–24, 1998 run at the paddy-field site Yangang are less satisfactory, with $R^2 = 0.47$, 0.58 for Q_H and Q_E, respectively. A likely explanation for the poor performance at this site is the lack of irrigation information for the paddy field. We are thus unable to provide CLASS with complete information for simulating the water balance. Q_H and Q_E are almost equally overestimated and underestimated in the 16 runs, but the error margins are small. The worst value of MBE = -51.6 W/m^2 for Q_E is found at the bean site Wudaoguo for the June 24–26, 1999 run; this is not surprising as the net radiation was also underestimated at this site. The simulated mean diurnal cycle of ground heat flux is also satisfactory for the four sites for the eight periods. As listed in Table 4, the values of MBE vary from -8.6 W/m^2 to 4.1 W/m^2, and R^2 from 0.63 to 0.92.

During the 1998–99 IOPs, the surface temperature was measured, as was the soil temperature at three depths (1, 10, and 20 cm) over the four sites. We average the measurements at the depths of 1 cm and 10 cm for comparison with the simulated soil temperature for the first CLASS soil layer. The observed temperature at the depth of 20 cm is used to evaluate the simulated value from the second CLASS soil layer. In general, the mean diurnal cycle of surface, first and second layer temperatures are all reasonably well simulated by CLASS over the four sites for all 16 runs as seen by the values of MBE and R^2 in Table 4. Typical errors for the simulated temperatures are ±2 °C over the 16 runs. An exception is the October 30–November 3, 1998 run at the pine tree site Tangquanchi, where $R^2 = 0.32$ for the second layer temperature, although the corresponding value of MBE = -1.2 °C is quite acceptable. CLASS performed best in simulating the first layer soil temperature (top 10 cm) as revealed by the values of MBE and R^2 in Table 4.

Soil moisture simulation at Wudaoguo

Soil moisture measurements were made only at the bean site Wudaoguo for the period from June 24 to August 26, 1999, at depths of 0–15, 15–30, 30–45, 45–60 cm. The measurements are used to evaluate the depth average soil moisture of the three CLASS soil layers in the simulation (0–35 cm and 0–60 cm). The results are shown in Table 4 and Fig. 8. The observed precipitation is also shown in the figure. In general, the two versions of CLASS simulate well the soil moisture as seen from the high R^2 values, with small difference between the two versions. For standard CLASS, the values of MBE are 1.7% and -1.9% by volume for the depths 0–35 and 0–60 cm, respectively; the corresponding values for modified CLASS are 0.9% and -2.5%. Although, the differences are small, modified CLASS tends to be dryer than the standard version. As shown in Fig. 8, this difference becomes more pronounced during heavy precipitation. This is because free water in the first two soil layers of modified CLASS is converted to interflow, and is shed from the soil column.

Conclusions

We have modified version 2.7 of the Canadian Land Surface Scheme (CLASS) and performed a comprehensive analysis using both site-specific data and observed hydrograph from the monsoon region of China. Two versions of CLASS were evaluated: ''standard'' (version 2.7) and our ''modified'' version. Standard CLASS has been coupled as the land surface scheme to three Canadian weather and climate models, and the results have been published in many studies. Standard CLASS has no interflow and a baseflow that is not appropriate for hydrograph simulation. We modify standard CLASS for interflow generation using a field capacity threshold together with a spatial probability distribution function to represent sub-grid variability in soil field capacity. Such a function can give a more realistic description of hydrological processes within a model grid, and has been adopted in several commonly used rainfall—runoff models and coupled AGCM/LSS modeling systems. We also introduce a linear reservoir at the bottom of the third CLASS soil layer to model the baseflow. We have given a detailed description of our newly modified version of CLASS, including parameter values in this study. It is important to point out that, we only use widely accepted procedures and openly accessible information for determining parameter values and model initialization. In our modified version of CLASS, not a single parameter is determined through optimization. Our study period corresponds to the IOP of HUBEX/GAME of the summers 1998 and 1999 over the Huaihe River Basin in China. CLASS simulations are done in a stand-alone mode and driven by observed atmospheric forcing.

Using the 1998 IOP data, the two versions of CLASS are first evaluated by comparing the simulated and observed hydrograph at the Jiangji outlet of the Shiguanhe sub-basin, part of the Huaihe River Basin, and soil moisture measurements at three sites (Meishan, Nianyushan and Jiangji) over the sub-basin. Since it is difficult to obtain measurements of surface runoff, interflow and baseflow at a basin scale through field surveys, an evaluation of the simulated hydrograph is an appropriate measure of the skill of a rainfall—runoff model. We also examine CLASS simulated net radiation, sensible and latent fluxes, ground heat flux, and soil temperature and moisture using data collected from the 1998—99 IOPs over four sites with different land covers in the Huaihe River Basin.

The total runoff simulated by the two versions of CLASS is similar to each other, which is in close agreement with the observed value. The major difference between the two versions is in the partitioning of runoff components among the surface runoff, interflow and baseflow. Standard CLASS does not allow for interflow, while modified CLASS simulates all three components. This in turn leads to improved simulation of peak flows and flood timing with modified CLASS, as seen from the high value of the Nash—Sutcliffe coefficient (0.91) of modified CLASS. The two versions of CLASS give similar results for the net radiation, sensible and latent heat fluxes, ground heat flux, and soil temperature and moisture over measurement sites, which compare well with observations. This shows standard CLASS already works well for these variables. Our modification of standard CLASS thus leads to an improvement in runoff and hydrograph simulation, while preserving its existing positive features. This contributes to making CLASS an effective land surface scheme for weather and climate models.

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