Impacts of a Parameterization Deficiency on Offline and Coupled Land Surface Model Simulations

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ABSTRACT

Surface water and energy balance plays an important role in land surface models, especially in coupled land surface–atmospheric models due to the complicated interactions between land surfaces and the overlying atmosphere. The primary purpose of this paper is to demonstrate the significant negative impacts that a minor deficiency in the parameterization of canopy evaporation may have on offline and coupled land surface model simulations. In this research, using the offline NCAR Land Surface Model (LSM) and the locally coupled NCAR Single-column Community Climate Model (SCCM) as examples, intensive effort has been focused on the exploration of the mechanisms involved in the activation of unrealistically high canopy evaporation and thus unreasonable surface energy partitions because of a minor deficiency in the parameterization of canopy evaporation. The main causes responsible for exacerbating the impacts of the deficiency of the land surface model through the coupling of the two components are analyzed, along with possible impacts of land surface parameters in triggering the problems. Results from experimental runs show that, for a large number of randomly generated physically realistic land surface parameter sets, this model deficiency has caused the occurrences of negative canopy water with a significantly high frequency for both the offline NCAR LSM and the coupled NCAR SCCM, suggesting that land surface parameters are not the only important factors in triggering the problems associated with the model deficiency. In addition, the concurrence of intense solar radiation and enough precipitation is identified to be mainly responsible for exacerbating the negative impacts of the parameterization deficiency. Finally, a simple adjustment has been made in this study to effectively prevent the occurrences of negative canopy water storages, leading to significantly improved model performances.

1. Introduction

Land surface heat fluxes, including sensible heat and latent heat, are of particular significance in coupled land surface–atmospheric models in terms of transporting energy and water between the two systems. This emphasizes the importance of partitioning available energy between surface sensible and latent heat fluxes appropriately in land surface models to ensure a realistic distribution of precipitation between evapotranspiration and various surface water storages, while conserving the water and energy balances of the land surface at the same time. For a coupled land surface–atmospheric system, the distribution of surface water and energy is especially important as demonstrated by many numerical studies exploring the effects of varying soil moisture and resulting variations in surface energy fluxes on the global circulation and precipitation (e.g., Walker and Rowntree 1977; Shukla and Mintz 1982). However, the surface evapotranspiration rate, which couples the land surface water and energy balances, can easily be overestimated as addressed in many previous studies. According to Pan et al. (1989), the National Meteorological Center (NMC) medium-range forecast model with a simple bucket scheme considerably overestimates evapotranspiration over the Sahara Desert region compared to those models using a Penman–Monteith-based scheme. This has been further suggested by results from the Project for Intercomparison of Land Surface Parameterization Schemes (PILPS), where it has been found that some of the participating land surface models with a simple bucket-type scheme evaporate excessively at the expense of negative annually averaged sensible heat flux, which can also be partially attributed to their failure to conserve water and energy appropriately (Henderson-Sellers et al. 1995).

In order to achieve a successful surface energy partition, it is necessary to make distinctions between bare soil and vegetation because they interact quite differently with the atmosphere. Accordingly, in land surface

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models, vegetated surfaces and nonvegetated surfaces should be treated separately, and water and energy balances need to be conserved not only for the soil, but also for the canopy. It is not difficult to take this feature into account in land surface modeling. However, the water and energy balances of canopy deserve special care to be implemented appropriately, because canopy water storages are usually too limited to ensure potential canopy evaporation, especially under intense solar radiation. With measurements from the forest in the center of the Netherlands, Klaassen et al. (1998) noted that the common methods systematically overestimate canopy evaporation during rain, accompanied by an underestimation of the canopy water storage. This makes the constraint of maximum canopy evaporation necessary in land surface models to ensure realistic estimations of canopy evaporation and other related surface fluxes. However, in the National Center for Atmospheric Research (NCAR) Land Surface Model (NCAR LSM; Bonan 1996), no maximum canopy evaporation constraint has been applied to the canopy energy balance, and negative canopy water is allowed to avoid complexity in solving the energy balance for vegetation temperature. Consequently, the parameterization of canopy evaporation in this model relies on an underlying assumption that canopy water storage can be negative in model simulations, and this would not generate considerable negative impacts on the model performances. Unexpectedly, our study has shown that this simple assumption could significantly degrade the model simulations. As will be shown later in this paper, this minor deficiency in the parameterization of canopy evaporation has resulted in unrealistic jumps and dips in the modeled time series of surface latent heat and sensible heat fluxes. Although there are only a few such points in the offline case, the situation becomes much worse when the land surface model is running in a coupled environment, generating unstable time series of surface heat fluxes with rapid fluctuations during daytime when plenty of incoming solar energy is available.

The primary purpose of this paper is to demonstrate the importance of appropriately parameterizing canopy evaporation to maintain canopy water and energy balances in land surface models, especially in coupled land surface–atmospheric models, and to explore the mechanisms, primarily in terms of land surface–atmospheric coupling and land-surface parameters, which are likely to be responsible for the nonignorable negative impacts of a minor deficiency in the parameterization of canopy evaporation on land surface model simulations. In section 2, the land surface model and the locally coupled single-column model used in this research are introduced, and the data used to force and evaluate the models are briefly described. Then, in section 3, model simulations with the default land surface parameter set and those with an optimal parameter set from offline LSM calibrations are compared, for both offline and coupled cases. The model deficiency in the parameterization of canopy evaporation and its implications are presented in section 4. Sources and mechanisms responsible for the significant negative impacts of the parameterization deficiency are explored in section 5. To illustrate the importance of an appropriate parameterization of canopy evaporation, especially in a coupled environment, results from some experiments with randomly generated land-surface parameter sets will also be summarized to demonstrate the high frequency of the occurrence of the problem. A description of the simple adjustment made in this research to improve the model performances is presented in section 6, followed by a summary and related conclusions in section 7.

2. Models and data

a. The NCAR LSM

The land surface model used in this research is the NCAR LSM (hereinafter referred to as LSM), which is a one-dimensional, time-dependent model dealing with the multiple interactions between land surfaces and the atmosphere in terms of exchanging momentum, energy, water, and CO_2 fluxes (Bonan 1996). The model allows for multiple surface types in a single grid cell, accounting for ecological differences among different vegetation types and optical, thermal, and hydraulic differences among different soil types. The atmospheric forcing terms of the model include incident direct and diffuse solar radiation, incident longwave radiation, convective and large-scale precipitation, specific humidity, temperature, pressure, wind, and reference height. When driven by these forcing terms, which can be generated by an atmospheric model or specified from observations, the land surface model calculates diffuse and direct surface albedos, zonal and meridional momentum fluxes, constituent fluxes (H_2O and CO_2), surface-emitted longwave radiation, surface sensible and latent heat fluxes, soil and vegetation temperatures, and soil moisture contents. For details of the model physics, interested readers are referred to Bonan (1996), where a comprehensive description about the model is presented. In this paper, however, only the canopy energy balance of vegetated surfaces will be reillustrated briefly, because it is directly related to the parameterization deficiency analyzed in this study. In the LSM, at each time step, the vegetation temperature T_v is solved from the canopy energy balance equation as follows:

$$S_v = L_v(T_v) + H_v(T_v) + E_v^{va}(T_v) + E_v^{tr}(T_v), \quad (1)$$

where S_v, L_v, H_v, E_v^{va}, and E_v^{tr} are the net solar radiation absorbed by vegetation, the net longwave radiation flux to the atmosphere, the sensible heat flux, and the latent heat fluxes of evaporation from wet canopy and transpiration from dry canopy, respectively, all in units of W m^{-2}.

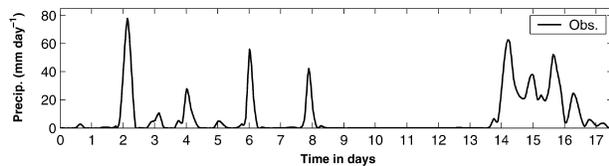The LSM has been used in many ecological, hydrological, and atmospheric studies. For example, Bonan

FIG. 1. Observed precipitation (mm day^{-1}), starting from 0530 UTC 18 Jul 1995.

et al. (1997) and Lynch et al. (1999) compared the LSM-simulated surface fluxes to the observations for the boreal forest sites in Canada and the tundra ecosystems in Alaska, respectively; Lynch et al. (2001) used a reduced form model to investigate the sensitivity of the LSM to climate changes. Other LSM-related studies include Bonan (1995a) and Craig et al. (1998), where the LSM was used to investigate the land–atmosphere CO_2 exchanges; Bonan (1995b), where the sensitivity of a GCM simulation to the inclusion of inland water surfaces was explored; and Bonan (1997-1999), where the effects of land use and the impacts of deforestation on the climate of the United States were studied, respectively.

b. The NCAR SCCM

In order to explore the impact of the deficiency in implementing the parameterization of canopy evaporation in the LSM in a coupled mode, the locally coupled NCAR Single-column Community Climate Model (NCAR-SCCM, hereinafter referred to as SCCM), was also used in this research. It is a single-grid column model developed from the global climate model NCAR Community Climate Model (CCM3). The physical parameterizations in the SCCM, such as those of radiation, clouds, deep and shallow convection, large-scale condensation, and boundary layer processes, are the same as those in CCM3. More details about the physical parameterizations of CCM3 are given by Kiehl et al. (1996). The SCCM is chosen not only because the land surface model coupled to it is also the LSM, but also because single-column model applications can avoid huge computational expense and the difficulty of separating the effects of specific parameterizations from those of other complicated interdependent processes (Xu and Arakawa 1992; Randall et al. 1996). The SCCM, however, lacks the horizontal feedbacks available in the more complicated three-dimensional CCM3, making it necessary to prescribe the horizontal advective tendencies from observations or analysis data. Interested readers are referred to Hack et al. (1999) and Randall and Cripe (1999) for more information about specifying the effects of neighboring columns in the SCCM. Although several problems have arisen from the use of the SCCM in terms of simulating precipitation, temperature, and moisture fields (Hack and Pedretti 2000; Xie and Zhang 2000), the SCCM provides a unique locally coupled environment for this research in investigating the im-
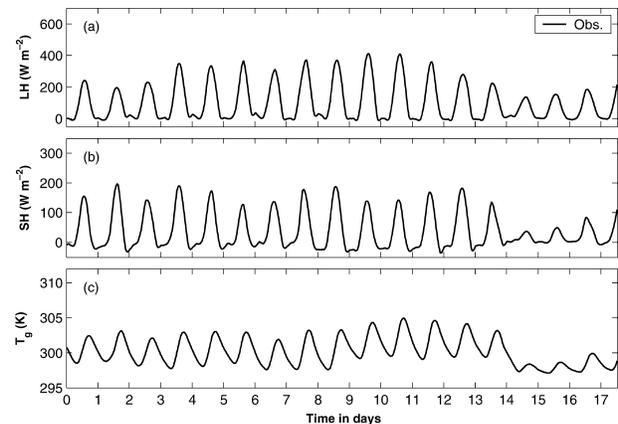

FIG. 2. Observations for (a) surface latent heat flux (W m^{-2}), (b) surface sensible heat flux (W m^{-2}), and (c) ground temperature (K).

pacts of the coupling of the land surface and the atmosphere on the implementation of the parameterization of canopy evaporation in the LSM.

c. Data

In this research, both the offline LSM and the locally coupled SCCM were driven and evaluated with the Atmospheric Radiation Measurement Program (ARM) July 1995 Intensive Operational Periods (IOP) dataset attached to the SCCM package available from www.cgd.ucar.edu/cms/sccm/sccm.html. This IOP dataset extends for 17.5 days from 0530 UTC 18 July 1995 [0030 local time (LT)] to 1730 UTC 4 August 1995 (1230 LT) and experiences various summer weather conditions, including several intensive precipitation periods (Fig. 1). As shown in Fig. 1, most of the major rainfall events occurred during midnight to early morning (days 2, 3, 4, 6, and 8), except that, at the end of this period, the longest event lasted continuously for 2–3 days. Also worth mentioning is the fact that all the variables available in the 1995 IOP dataset were interpolated at 20-min intervals based on the original 3-h observations using the cubic interpolation method;[1] therefore, the time series of all the forcing and evaluating terms are perfectly smooth, including horizontal advective tendencies of temperature, specific humidity, and wind speeds. Shown in Fig. 2 are the smooth time series of surface latent heat flux (W m^{-2}), sensible heat flux (W m^{-2}), and ground temperature (K), on which the model performance evaluations will be based. The feature of smoothness of the observational data is of particular importance in evaluating the impacts of the minor parameterization deficiency in canopy evaporation on model simulations in both offline and coupled modes, because generally relatively smooth outputs are

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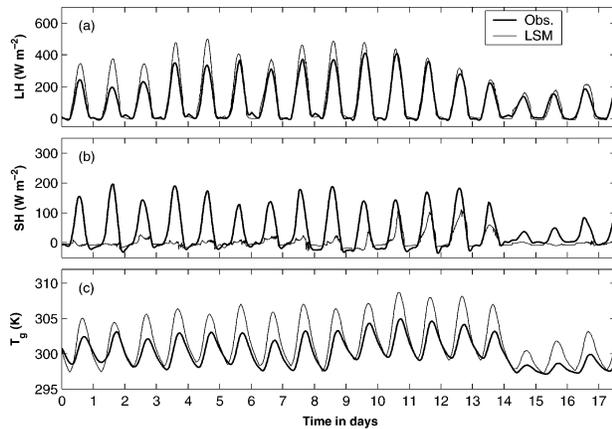[1] Done by John Pedretti (pedretti@ucar.edu) as indicated in the NetCDF data file.

FIG. 3. Comparisons of the offline LSM simulations (light solid line) with the default land surface parameter set $\{\theta_{def}\}$ to the observations (bold solid line) for (a) latent heat flux (W m^{-2}), (b) sensible heat flux (W m^{-2}), and (c) ground temperature (K).

FIG. 4. Same as in Fig. 3 but for the coupled SCCM.

expected if the models are driven with smooth input data, which happens to be not true for the cases in this research as shown in the following sections.

3. Experiment with LSM and SCCM

With the a priori prescribed land surface parameter set (hereinafter referred to as the default parameter set $\{\theta_{def}\}$), neither the LSM nor the SCCM can satisfactorily reproduce the observed surface latent heat flux (LH), sensible heat flux (SH), and ground temperature (T_g). In this case, for both of the models, the initial volumetric soil moisture contents are set to 0.3, and the soil temperatures are initialized with the observed ground temperature. For the offline case (Fig. 3), although the model reproduces the latent heat flux fairly well with a slight overestimation, it systematically underestimates the sensible heat flux and overestimates the ground temperature. The root-mean-square (rms) errors of these three variables (LH, SH, and T_g) are 48 W m^{-2}, 64 W m^{-2}, and 2.1 K, respectively. For the locally coupled case (Fig. 4), a similar trend can be noticed, except that the SCCM estimates the sensible heat flux better but more greatly overestimates the latent heat flux compared to the offline LSM. In this case, the rms errors for LH, SH, and T_g are 94 W m^{-2}, 52 W m^{-2}, and 3.2 K, respectively. These results suggest that the land surface model may have an energy partition problem that deserves an effort of model calibration, which has been used in many studies to improve performances of hydrological or land surface models (e.g., Bastidas et al. 1999; Gupta et al. 1998, 1999; Sorooshian et al. 1993; Yapo et al. 1997). In this research, the automatic multiobjective optimization algorithm (MOCOM-UA; Yapo et al. 1997) was used to calibrate the LSM in an offline mode with 32 land surface parameters, including the initial soil moisture contents of the first four soil layers (Appendix, Table A1). Over the automatic calibration
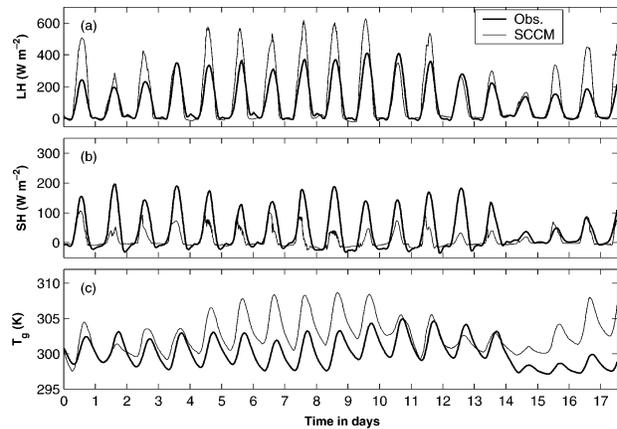
process, reasonable upper- and lower-parameter boundaries and appropriate interparameter constraints were applied to the varying parameters to ensure that the optimized parameters are biologically and hydrologically realistic and to preserve the appropriate relationships among the parameters. For example, vegetation displacement heights and roughness lengths should be less than vegetation heights, and soil water contents must not be higher than porosity. In this calibration experiment, we were attempting to match the simulations of the three calibration variables (LH, SH, and T_g) to their corresponding observations so that minimum rms errors for these variables can be achieved. The readers are referred to Yapo et al. (1997) for details about how the optimization algorithm works. One of the optimal parameter sets from the offline calibration (hereinafter referred to as the optimal parameter set $\{\theta_{opt}\}$, also given in Table 1), for which the rms errors of LH, SH, and T_g are 24 W m^{-2}, 24 W m^{-2}, and 0.57 K, respectively, was then applied to LSM and SCCM simulations. The resulting rms errors of LH, SH, and T_g by applying $\{\theta_{opt}\}$ to the SCCM are 105 W m^{-2}, 48 W m^{-2}, and 5.9 K, respectively. With $\{\theta_{opt}\}$, although the rms errors of LH, SH, and T_g for the offline case have been greatly reduced compared to the default case, the simulations by the coupled SCCM do not improve much, indicating that optimal parameter sets from offline calibrations do not necessarily apply well to the coupled model due to the complicated two-way feedbacks within the coupled environment. In addition, the high temperature errors in the coupled case can also be partially attributed to the basic limitations of a single-column model, such as the absence of large-scale feedbacks (Hack and Pedretti 2000). The time series of the three simulated variables (LH, SH, and T_g) for the offline and coupled cases are shown in Figs. 5 and 6, respectively.

As clearly shown in Fig. 5, with the selected optimal parameter set $\{\theta_{opt}\}$, the simulated surface heat fluxes and ground temperature for the offline LSM match the
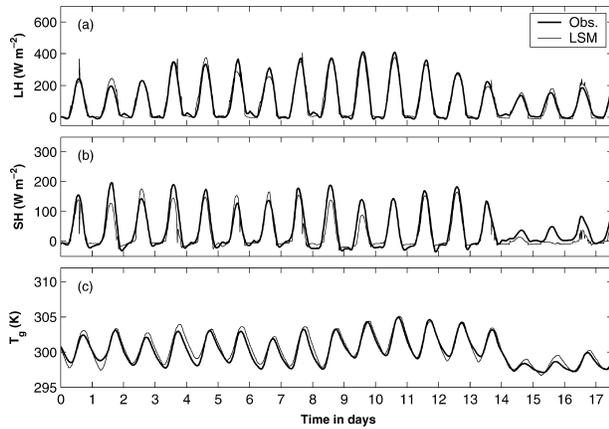
FIG. 5. Comparisons of the offline LSM simulations (light solid line) with the optimal land surface parameter set $\{\theta_{opt}\}$ to the observations (bold solid line) for (a) latent heat flux (W m^{-2}), (b) sensible heat flux (W m^{-2}), and (c) ground temperature (K).

FIG. 7. (a), (b), (c) Same as in Fig. 5, but are shown only for the first 4-day period for clarity. (d) The observed precipitation (mm day^{-1}) for the first 4-day period.

observations much better compared to the control run with the default parameter set $\{\theta_{def}\}$, indicating the success of parameter optimization. However, at some time steps, the land surface model seems to have a problem in partitioning available energy between latent heat and sensible heat fluxes, resulting in unexpected sudden increases in latent heat flux and corresponding sudden decreases in sensible heat flux. When the same optimal parameter set is applied to the coupled SCCM, the situation becomes even much worse, and the modeled surface fluxes fluctuate tremendously between continuous time steps, varying from more than 600 to almost 300 W m^{-2} for latent heat flux and from more than 200 W m^{-2} to less than zero for sensible heat flux over a single time step of 20 min (Fig. 6). These problems can be noticed more clearly in Figs. 7a,b for the off-line case and Figs. 8a,b for the coupled case, where only the fluxes of the first 4 days are shown for clarity. There are also some slight fluctuations in the simulated time series with the default parameter set $\{\theta_{def}\}$, although they cannot be detected easily from Figs. 3 and 4. While
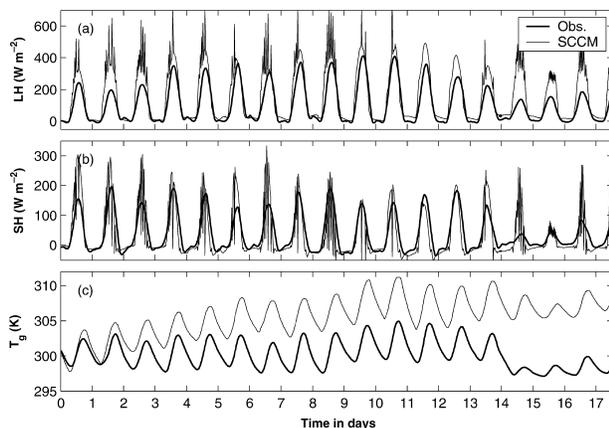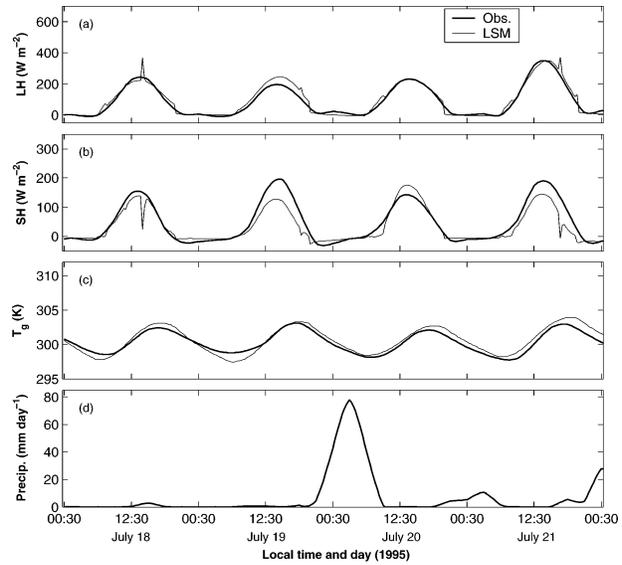
the models were driven with completely smooth data, relatively smooth surface fluxes were expected at least for the offline LSM simulations. For the coupled simulations, although there may be some uncertainties or instabilities in the atmosphere, the modeled surface fluxes with severe fluctuations are definitely unrealistic, indicating again the energy-partitioning problem within the land surface model.

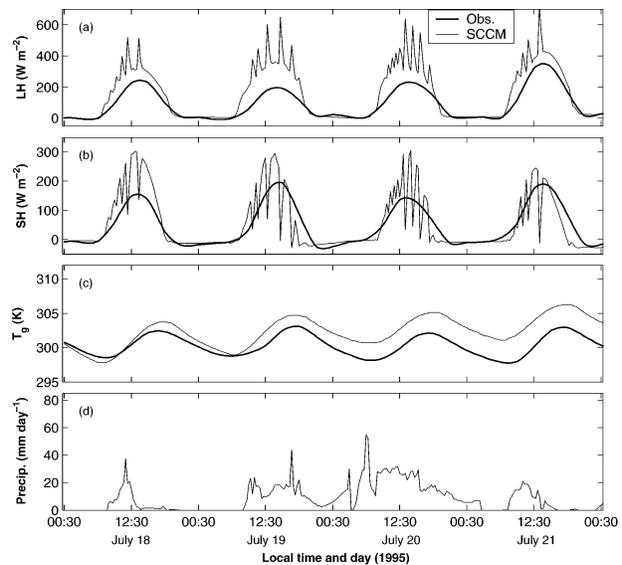FIG. 6. Same as in Fig. 5 but for the coupled SCCM.

FIG. 8. (a), (b), (c) Same as in Fig. 6, but are shown only for the first 4-day period for clarity. (d) The precipitation (mm day^{-1}) for the first 4-day period simulated by the SCCM with the selected optimal parameter set $\{\theta_{opt}\}$.

4. The parameterization deficiency and its implications

In reality, it is commonly known that a canopy cannot evaporate more than its current water storage, that is, the amount of water intercepted from precipitation or dew. On the other hand, canopy evaporation estimated by a numerical model can easily be higher than available canopy water, which makes it necessary to constrain estimated canopy evaporation to be no more than available canopy water. However, in the LSM, in order to avoid the complexity in solving the canopy energy balance for vegetation temperatures, there has been no constraint of maximum canopy evaporation applied, and the canopy water storage is allowed to be negative (Bonan 1996). Underlying this is a simple assumption that canopy water storage in a simulation can be less than zero, and considerable negative impacts on the model simulation are not expected. According to the diagnosis, it is this minor deficiency in implementing the parameterization of canopy evaporation that has led to unrealistic, high canopy evaporation, and thus inappropriate surface energy partitions. In the original land surface model, at each time step, the energy balance is conducted first to solve for vegetation temperature and corresponding surface fluxes, including the latent heat flux (evaporation) that is then used in the canopy water balance to obtain the remaining canopy water after evaporation. The wet fraction of canopy of the next time step is then decided from this remaining canopy water and is used to calculate canopy evaporation of the next time step by solving the energy balance. As the model simulation evolves with time, it happens that, at some specific time steps when plenty of solar energy is available, the computed canopy evaporation by solving the energy balance becomes unrealistically high, resulting in large decreases in the sensible heat flux by more than 100 W m^{-2} over 20 min. Consequently, the canopy water storage becomes negative by the water balance, leading to zero wet canopy fraction and thus no canopy evaporation during the next time step, with any intercepted precipitation or dew water filling the gap of negative canopy water to conserve water in the system. As a result, to balance available energy, the sensible heat flux increases significantly from the previous very low value to a very high value, sometimes by more than 200 W m^{-2}, and vegetation temperature also increases greatly due to water stresses. However, once the canopy water storage becomes positive again after several time steps by intercepting precipitation, if any, canopy wet fraction becomes positive, resulting in unrealistically high canopy evaporation again. This, combined with transpiration and ground evaporation which are relatively smooth, generates the ''seesaw'' pattern of surface fluxes modeled by the coupled SCCM as shown in Figs. 6 and 8. In this research, much effort has been focused on the interesting fact demonstrated by Figs. 3–8 that the energy-partitioning problem appears to be most se-

rious when the land surface model is running in the coupled mode with the specific optimal parameter set $\{\theta_{opt}\}$. This suggests that both land surface parameters and the coupling of the two systems—the land surface and the overlying atmosphere—could greatly influence the model performances in terms of reproducing observed surface heat fluxes and state variables such as ground temperature.

5. Explore mechanisms and sources for the problem

a. Why is canopy evaporation easily overestimated?

The simulations show that, for some time steps with a positive wet canopy fraction (f_{wet}), canopy evaporation can easily be overestimated, especially for the coupled cases. As shown in Eq. (1), the canopy energy balance is maintained by partitioning the absorbed solar energy (S_v) into various energy components, including net longwave radiation (L_v), sensible heat (H_v), canopy evaporation (E_v^{va}), and canopy transpiration (E_v^{tr}). Although these four energy components all increase monotonically with vegetation temperature, their sensitivities to a unit change in vegetation temperature differ from one to another. The value H_v is a linear function of vegetation temperature T_v with a slope usually less than 1; the net longwave radiation (L_v) is a function of $(T_v)^4$, but the very small Stefan–Boltzmann's constant (5.67 $\times$ 10^{-8}) will cancel the power effect so that L_v does not increase greatly with T_v; canopy evaporation and transpiration (E_v^{va} and E_v^{tr}) depend on the saturation vapor pressure evaluated at the vegetation temperature [$e_*(T_v)$], which increases exponentially with T_v and tends to result in high canopy evapotranspiration at high vegetation temperatures. In addition, the increase in the saturation vapor pressure per unit increase in vegetation temperature $\partial[e_*(T_v)]/\partial T_v$ also increases exponentially with T_v. However, as transpiration from the wetted part of the canopy is suppressed by evaporation processes, vegetation conductances for transpiration (c_l^w), usually on the order of 10^{-2}, are much smaller than vegetation conductances for evaporation (c_e^w, usually on the order of 10^{-1}) for wetted canopies. As a result, for a wetted canopy under intense solar radiation, the model-estimated potential canopy evaporation would tend to be much higher than the actual evaporation rate, resulting in negative canopy water storages.

Shown in Fig. 9 are the four energy components as functions of vegetation temperature for both typical wetted canopies (Fig. 9a, f_{wet} = 0.50) and dry stressed canopies (Fig. 9b, f_{wet} = 0.0), for the case where the optimal parameter set $\{\theta_{opt}\}$ is applied to the coupled model SCCM. In Figs. 9a,b, the lines of evaporation and transpiration become flat when vegetation temperature is greater than 323 K, because in the model saturation vapor pressures are calculated using Lowe's polynomials (Bonan 1996) that are assumed to be only
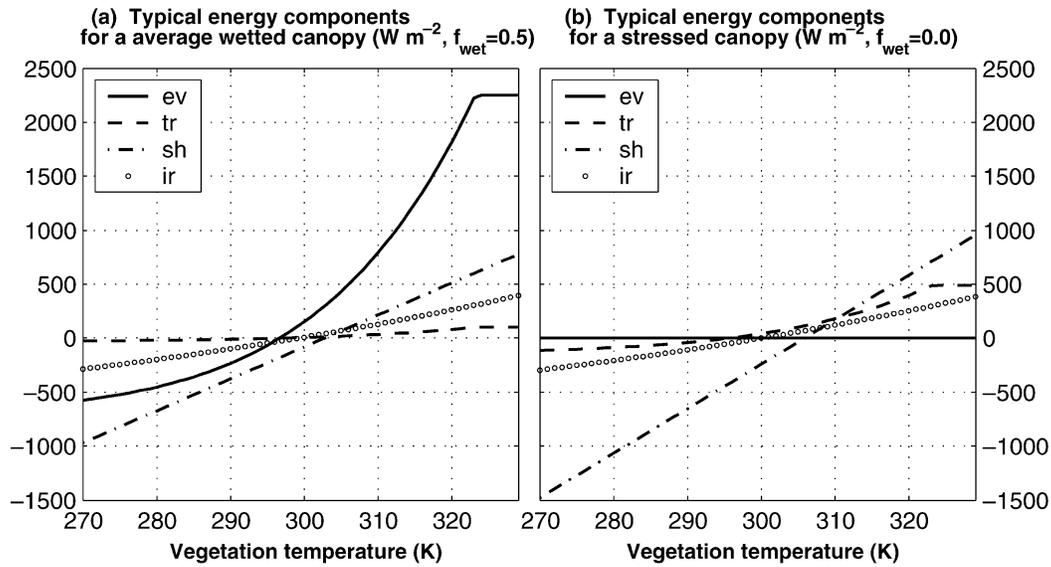
FIG. 9. Typical canopy energy components (W m^{-2}) for the coupled cases, including evaporation (ev), transpiration (tr), sensible heat (sh), and net longwave radiation (ir) as functions of vegetation temperature, for (a) a typical wetted canopy ($f_{wet} = 0.5$), and (b) a typical dry, stressed canopy ($f_{wet} = 0.0$).

valid for $223.15 \text{ K} \leq T \leq 323.15 \text{ K}$. As indicated by Fig. 9a, for an average wetted canopy ($f_{wet} = 0.50$), evaporation is most sensitive to a unit change in T_v, followed by sensible heat, net longwave radiation, and transpiration. In addition, $\partial(E_v^{va})/\partial T_v$ also increases with increasing vegetation temperature, further contributing to the overestimation of canopy evaporation at high vegetation temperatures. According to Fig. 9a, the evaporation component (E_v^{va}) increases tremendously with vegetation temperature $\{[\partial(E_v^{va})]/\partial T_v \geq 70 \text{ W m}^{-2}\}$ and dominates all of the other three components (H_v, L_v, and E_v^{tr}) when vegetation temperature is above 300 K. As a result, to balance the plenty of net energy absorbed from intense solar radiation, high latent heat flux of canopy evaporation will be generated, at the expense of other energy fluxes, which would be too low to be realistic. For example, in the case of the optimal parameter set $\{\theta_{opt}\}$, if the absorbed solar energy is 500 W m^{-2}, then more than 80% of the energy (400 W m^{-2}) is used to evaporate water at an amount much larger than the actual available canopy water, resulting in a relatively low vegetation temperature of 305 K. If the incoming solar radiation is more intensive and the absorbed solar energy is more than 500 W m^{-2}, the situation would be even much worse because the differences between evaporation and other energy components keep increasing when the vegetation temperature increases. In the case of dry canopies, the wet fraction of canopy is zero ($f_{wet} = 0$) so that the vegetation conductance for evaporation c_e^w is zero and there will be no evaporation. On the other hand, the vegetation conductance for transpiration c_l^w will be increased compared to the wetted canopy case, but may still be less than a typical value of c_e^w for a wetted canopy. Consequently, the absorbed en-

ergy will be partitioned into sensible heat, net longwave radiation, and canopy transpiration without considerable differences between one another. As can be noted from Fig. 9b, if the absorbed solar energy is 500 W m^{-2}, each of the three energy components, except for canopy evaporation, will be around 160 W m^{-2} with a resulting vegetation temperature about 310 K. In practice, these two cases always occur in continuous time steps when plenty of solar energy is available, resulting in sudden increases or decreases in surface fluxes and vegetation temperature.

b. Influences of land surface parameters

Land surface parameters, especially those related to vegetation, play an important role in regulating canopy evaporation and transpiration via changing the elements in canopy energy balance [Eq. (1)]. Although the land surface parameters interact with each other and it is difficult to separate the effects of a particular parameter from those of the others, partial effects of the parameters can be obtained by investigating the calculations of the components in the canopy energy balance equation. As demonstrated by the earlier analysis in section 5a, canopy evaporation depends on both the vegetation conductance for evaporation c_e^w, which determines how fast canopy evaporation changes with vegetation temperature, and the absorbed solar radiation by vegetation S_v, which determines the balanced vegetation temperature, thus the amount of canopy evaporation at balance. Accordingly, land surface parameters can influence the estimation of canopy evaporation via regulating these two variables. As indicated in Bonan (1996), c_e^w is proportional to the wet fraction of vegetation f_{wet} and the total

leaf and stem indices ($L + S$), with the latter set to be constant in the case of this research. The wet fraction of vegetation f_{wet}, however, can vary between 0.0 and 1.0, through its dependence on a variable parameter "$ch2op$"—the maximum water that can be held by the canopy per unit leaf and stem area (Table 1, parameter 9): the smaller the parameter "$ch2op$," the larger the wet fraction f_{wet} and the larger the vegetation conductance c_e^w, thus the higher the estimated evaporation. In addition, c_e^w is also inversely proportional to the leaf boundary layer resistance $\overline{r}_b$, which depends on several other parameters, including top of canopy, momentum roughness length of canopy, displacement height of canopy, and leaf dimension. The calculation of $\overline{r}_b$ is complicated, and the readers are referred to Bonan (1996) for a detailed description. However, if the integrated effect of these parameters is to decrease the parameter $\overline{r}_b$, then c_e^w will be increased, further enhancing the probability of overestimating canopy evaporation, and vice versa. The other important factor S_v, the absorbed solar radiation by canopy, can be changed directly by leaf reflectances and transmittances in visible (VIS) and near infrared (NIR) regions, which are also variable parameters in this study (Table A1, parameters 4–7). For example, for a given amount of incoming solar radiation, if the leaf reflectances and transmittances are decreased, the total absorbed solar energy by the canopy will be increased, resulting in increased vegetation temperature and thus increased potential canopy evaporation. In addition, other land surface parameters, including both vegetation and soil parameters, such as soil hydraulic and thermal conductivities, will also influence the estimation of canopy evaporation by regulating soil moisture contents and soil temperatures and various atmospheric forcing terms to the land surface model via complicated interactions between land surfaces and the atmosphere. In summary, land-surface parameters can amplify or mitigate the impacts of the deficiency in the parameterization of canopy evaporation in the LSM, thus potentially playing a role in regulating canopy evaporation.

The fact that the negative impacts of the parameterization deficiency became more significant when applying the optimal parameter set $\{\theta_{\text{opt}}\}$ to the models can be partially explained by comparing the two parameter sets $\{\theta_{\text{opt}}\}$ and $\{\theta_{\text{def}}\}$. In the case of $\{\theta_{\text{opt}}\}$, "$ch2op$," which specifies the maximum canopy storage, is 0.04 mm and is much smaller than in the default case ($ch2op$ = 0.1 mm). This may increase canopy wet fraction f_{wet} and thus the estimated canopy evaporation. In addition, for the optimal parameter set $\{\theta_{\text{opt}}\}$, the leaf reflectances in VIS and NIR and the leaf transmittances in VIS and NIR have also been reduced from the default values (0.11, 0.58, 0.07, and 0.25) to 0.09, 0.44, 0.06, and 0.16, respectively. These decreases in leaf reflectance and transmittances could result in increased net solar radiation absorbed by the canopy, which may further contribute to the possibility of high canopy evaporation

estimation. However, as mentioned in the beginning of this section, because the interactions between the parameters are very complicated, it is difficult to decide, both qualitatively and quantitatively, the final effects that a particular parameter would have on the estimation of canopy evaporation.

c. Experiment with randomly generated parameter sets

Because serious problems do not occur with the default parameter set $\{\theta_{\text{def}}\}$ while they do occur with the optimal parameter set $\{\theta_{\text{opt}}\}$ and a conclusive analysis is not possible, a single run with a specific parameter set, the selected optimal parameter set $\{\theta_{\text{opt}}\}$ or the default parameter set $\{\theta_{\text{def}}\}$, may not be representative, and no conclusions about the energy-partitioning problem of the land surface model can be made. In light of this, 100 experimental runs were conducted for both offline and coupled cases, with randomly generated land-surface parameters to investigate the frequency of the occurrence of the problems. In order to ensure that the experiments are nonbiased, a random-number generator based on uniform distribution was used, and the 32 land surface parameters used for the previous calibration experiment were allowed to vary simultaneously between reasonable lower and upper boundaries, as given in Table A1. Again, appropriate constraints of the parameters were applied to ensure that the randomly generated parameter sets are physically realistic. For each of the 100 experimental runs, two measurements were made to decide the frequency of the occurrence of the problem and how serious it is for that specific run. These two measurements are: 1) the number of time steps for which canopy evaporation increases by more than 150 W m^{-2} compared to the last time step, that is, $\Delta E_v^{\text{va}} = [(E_v^{\text{va}})_{n+1} - (E_v^{\text{va}})_n] \geq 150\text{W m}^{-2}$ (measurement 1); and 2) the number of time steps for which canopy evaporation is larger than the amount of current canopy water (measurement 2). The total number of the simulation period is 1261. The purpose of the first measurement was to examine how frequently the estimated canopy evaporation increased by an unrealistic amount over a single time step, and the second measurement was used to decide how frequently the overestimation of canopy evaporation occurred.

Shown in Fig. 10 are the histograms of the two measurements for both offline and coupled cases. For each of the histograms, the x-axis represents the values of the specific measurement (the bins are centered at 10, 20, 30, 40, . . . , 230 time steps), while the y-axis represents the number of runs. Consequently, the more the centroid of a histogram shifts to the right, the higher the values of the corresponding measurement for most of the 100 runs, and the higher the frequency of the occurrence of overestimation of canopy evaporation due to the parameterization deficiency. The histograms indicate that most of the runs with randomly generated
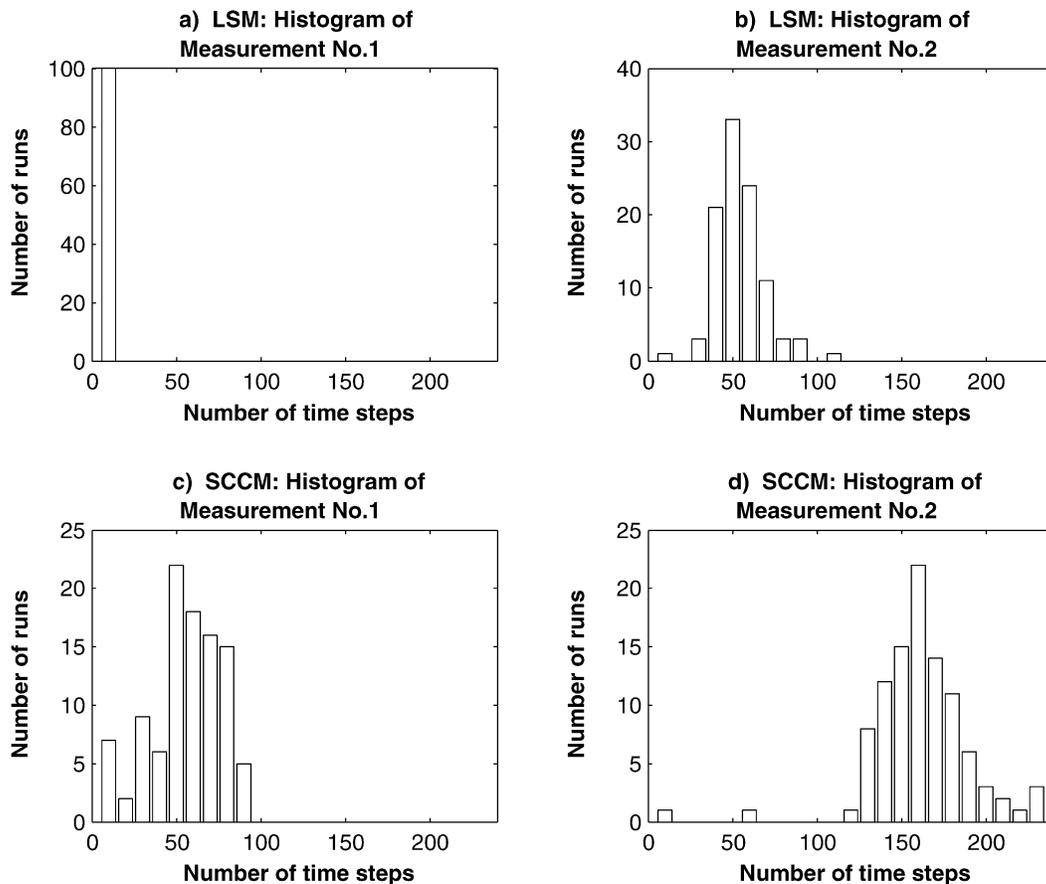
FIG. 10. Histograms of the two measurements (No. 1, No. 2) for the 100 experimental runs of (a), (b) the offline LSM and (c), (d) the coupled SCCM. Measurement 1 is the number of time steps for which canopy evaporation increases by 150 W m^{-2} compared to the last time step; and measurement 2 is the number of time steps for which the estimated canopy evaporation is larger than the available canopy water.

parameters have overestimated canopy evaporation to a certain degree, and the problem was more serious for the coupled runs. For the off-line cases, although unrealistic increases of canopy evaporation by 150 W m^{-2} over a single time step did not occur for more than 15 time steps according to Fig. 10a, Fig. 10b indicates that, for more than 95% of the 100 runs, the estimated canopy evaporation was greater than the available canopy water for at least 35 time steps, mostly within the range of 40–70 time steps. The problem for the coupled cases was even much worse as indicated by the corresponding histograms (Figs. 10c,d): about 90% of the 100 runs had problems of sudden increases of canopy evaporation by 150 W m^{-2} for at least 25 time steps, with the maximum reaching 95 time steps; for 97% of the 100 runs, the estimated canopy evaporation was greater than the available canopy water for at least 125 time steps, with the maximum reaching 235 time steps.

The numerical values of these two measurements, not easily observable from the histograms, show that among the 100 runs, there was only one run for which the problem did not occur for either offline or coupled cases. For the selected optimal parameter set $\{\theta_{\mathrm{opt}}\}$ mentioned in section 3, measurements 1 and 2 are 8 and 72 for the offline case and 80 and 165 for the coupled case, respectively. Even for the specific default parameter set $\{\theta_{\mathrm{def}}\}$, the numbers are 0 and 64 for the off-line case and 28 and 209 for the coupled case, respectively. For a simulation period of 1261 total time steps, these numbers are substantial, considering that overestimation of canopy evaporation only occurs under intensive solar radiation during the daytime. Although theoretically land surface parameters can play a significant role in regulating canopy evaporation as explained in section 5a, the consolidated results from this experiment demonstrate that the parameterization deficiency tends to generate serious negative impacts, regardless of the land-surface parameters involved. This suggests the necessity of appropriately parameterizing canopy evaporation to maintain canopy water and energy balances in land-surface models.

d. Offline versus coupled cases

Also demonstrated by Figs. 5–8 is the fact that, for the off-line LSM simulations, problems of unrealistically high latent heat associated with the parameterization deficiency do not occur as frequently as in the coupled environment. Because the same parameter set was applied, any difference between simulations from the off-line and coupled cases can be effectively attributed to the complicated two-way feedbacks between the land surface and the overlying atmosphere available only in the coupled environment. In other words, the negative impacts of the minor deficiency of the LSM are exacerbated by the coupling of the two systems—the land surface and the atmosphere; while in offline cases, the occurrence of the problem has been suppressed by realistic observational atmospheric forcings. Further investigations into the impacts of this minor deficiency indicate that two primary weather conditions are necessary to generate continuous rapid fluctuations in simulated surface sensible and latent heat fluxes as in the coupled cases. First, plenty of solar energy should be available so that vegetation temperature is high and canopy evaporation can easily be overestimated, as explained in section 5a, suggesting that the problem of unrealistically high canopy evaporation can occur only during daytime after early mornings. In addition, for the same problem to occur continuously, enough precipitation should be available simultaneously so that the gap of negative canopy water can be filled over a single or several time steps, easily resulting in alternate positive and negative canopy wet fractions (f_{wet}) and thus overestimations of canopy evaporation.

The requirement of the concurrence of plenty of solar radiation and intensive precipitation can be further proved by a comparison of Fig. 7 with Fig. 8 for the offline case and the coupled case, respectively. As clearly shown in Figs. 7a,b, during the first 4 days of the simulation period, there are two sudden increases in the simulated latent heat flux and two corresponding sudden decreases in the simulated sensible heat flux, accompanied by two small daytime precipitation events occurring around exactly the same two time points during the afternoons of the first day and the fourth day (Fig. 7d). These two small rainfall events did not result in continuous fluctuations in the simulated surface heat fluxes, because the rainfall amounts were too small to compensate the negative canopy water resulting from previous unrealistic overestimations of canopy evaporation. There are three other much more intensive rainfall events, which occurred during nighttime or early morning when the overestimation of canopy evaporation has been prevented due to lack of external energy, such as solar radiation. For the coupled case, unlike the observed precipitation, which occurred mostly during nighttime or early mornings, the model-simulated precipitation occurs mostly during the daytime, following the diurnal cycle of incoming solar radiation (Xie and

Zhang 2000). This situation satisfies the specific requirement of the concurrences of solar radiation and precipitation, resulting in continuous rapid fluctuations in the simulated time series of surface fluxes (Fig. 8). This suggests that the coupling of the land–atmosphere system may exacerbate the negative impacts of the minor deficiency in canopy evaporation parameterization and greatly degrade model performances. Although it has been pointed out by Xie and Zhang (2000) that the triggering function of convective precipitation in SCCM has a serious problem that is mainly responsible for the erroneous daytime precipitation pattern and the problem can be fixed to some degree, the concurrence of plenty of solar energy and intensive precipitation, such as a summer thunderstorm, is still possible in the real world.

6. A simple adjustment

While the canopy evaporation in the LSM is calculated based on the vapor pressure deficit of air around the canopy, it should be viewed as potential evaporation at a specific temperature T_v, and the actual evaporation can be equal to or much less than the potential value, depending on the current canopy water available for evaporation. Accordingly, in land surface models, it is necessary to constrain canopy evaporation to be less than or equal to the amount of water intercepted by the canopy. Although Bonan (1996) mentioned that taking this into account makes it more complicated to solve the energy balance for vegetation temperature, a simple adjustment made in this study has effectively improved the model performance in simulating the surface energy fluxes. To prevent the occurrences of negative canopy water, at each time step, canopy evaporation is constrained to be less than or equal to the current canopy water storage, which can be determined from the canopy water balance of the last time step. Generally, the larger the wet fraction of the canopy, the higher the evaporation rate and the lower the transpiration rate for the canopy, and vice versa. Accordingly, when the potential canopy evaporation is much higher than available canopy water and the canopy dries fast, canopy transpiration will tend to be underestimated if the original canopy wet fraction is still applied. On the other hand, if it is assumed that the time for evaporating current canopy water is negligible so that the whole canopy is free to transpire ($f_{wet} = 0.0$) for those specific time steps where the maximum evaporation constraint is violated, canopy transpiration will tend to be overestimated. Consequently, an intermediate approach needs to be taken so that the estimated transpiration is as close to the actual value as possible.

In this study, a simple adjustment has been made to take this problem into account. For each time step, the energy balance as shown in Eq. (1) is solved with the current wet canopy fraction to obtain the potential canopy evaporation (E_{v0}^{va}) and other corresponding energy components (L_{v0}, H_{v0}, and E_{v0}^{tr}). If the potential canopy
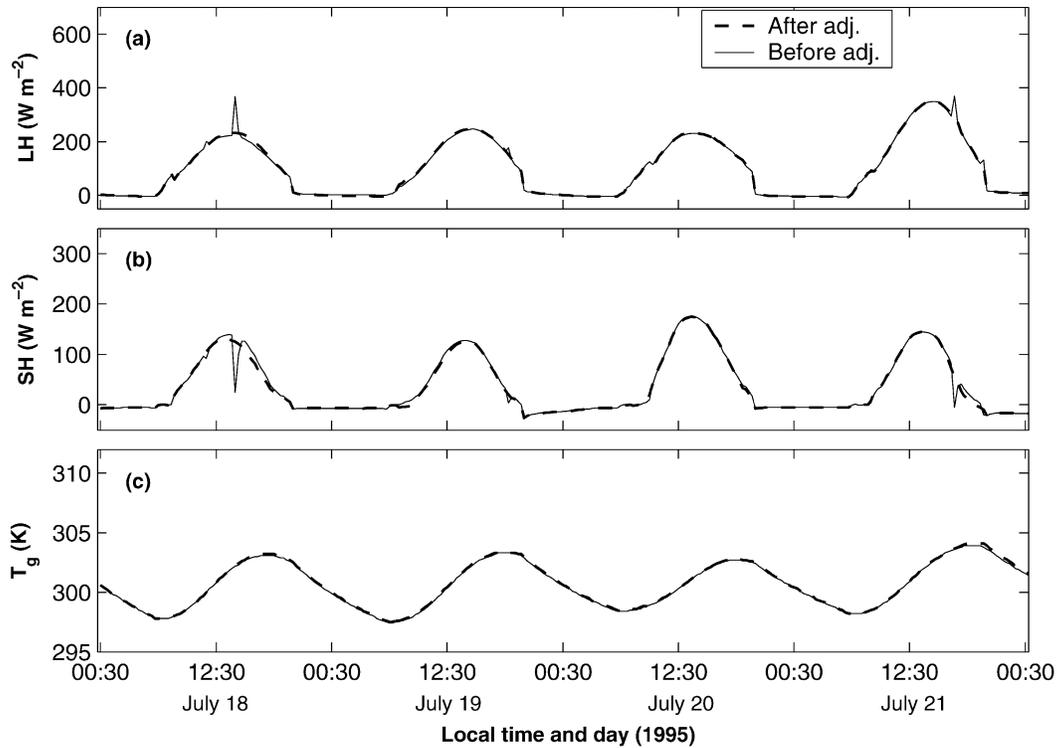
FIG. 11. Time series of (a) latent heat flux (W m^{-2}), (b) sensible heat flux (W m^{-2}), and (c) ground temperature (K), before (solid line) and after (bold dashed line) the parameterization adjustment, simulated by LSM with the optimal parameter set $\{\theta_{opt}\}$.

evaporation amount is larger than the available canopy water, the energy balance equation (1) is solved for a second time with a zero wet fraction to obtain another set of energy fluxes E_{v1}^{va}, L_{v1}, H_{v1}, and E_{v1}^{tr}. The value E_{v0}^{va} should be zero because the canopy wet fraction applied is zero. Assuming that the ratio of the available canopy water flux to the canopy potential evaporation amount E_{v1}^{va} is β (if β is greater than 1, β is set to 1), the overall energy fluxes are obtained from the weighted sums of the two sets of energy fluxes, as follows:

$$E_v^{va} = \beta E_{v0}^{va} + (1 - \beta)E_{v1}^{va}$$

$$E_v^{tr} = \beta E_{v0}^{tr} + (1 - \beta)E_{v1}^{tr}$$

$$L_v = \beta L_{v0} + (1 - \beta)L_{v1}$$

$$H_v = \beta H_{v0} + (1 - \beta)H_{v1}. \quad (2)$$

This equation group implies that, for each time step with a length of Δt, the canopy evaporates at the potential rate first for a period of $\beta\Delta t$ until all of the available canopy water has evaporated; after that, the canopy becomes totally dry, and the whole canopy is free to transpire for the rest of the time step [$(1 - \beta)\Delta t$]. This adjusted scheme will prevent the occurrence of negative canopy water and at the same time allows the canopy to evapotranspirate more realistically, generating more smooth evaporation flux and other surface fluxes. As shown in Figs. 11 and 12, with the adjustment

described above, the surface fluxes simulated by the offline model with the selected optimal parameter set $\{\theta_{opt}\}$ are smooth enough, and the peaks and dips in the time series have been removed. For the coupled case, the seesaw pattern of the surface fluxes disappears, and the remaining small fluctuations should be attributed to the uncertainties in the atmosphere. While this adjustment involves no coupling or decoupling processes, the rapid fluctuations removed can be effectively attributed to the parameterization deficiency, rather than the well-known numerical stability problem associated with the open-explicit coupling of the two interacting systems (the land surface and the atmosphere). What also can be noticed in Fig. 12 is the fact that the simulated ground temperature after the adjustment has been slightly increased compared to what it was before the adjustment. This was mainly caused by the constraint on canopy evaporation that has been reduced from very high values to more reasonable values, resulting in increased vegetation temperature and thus increased ground temperature.

7. Summary and conclusions

In coupled land surface modeling studies, unexpected fluctuations in the simulated quantities are commonly attributed to the numerical stability problems associated with the explicit coupling of the land surface and the
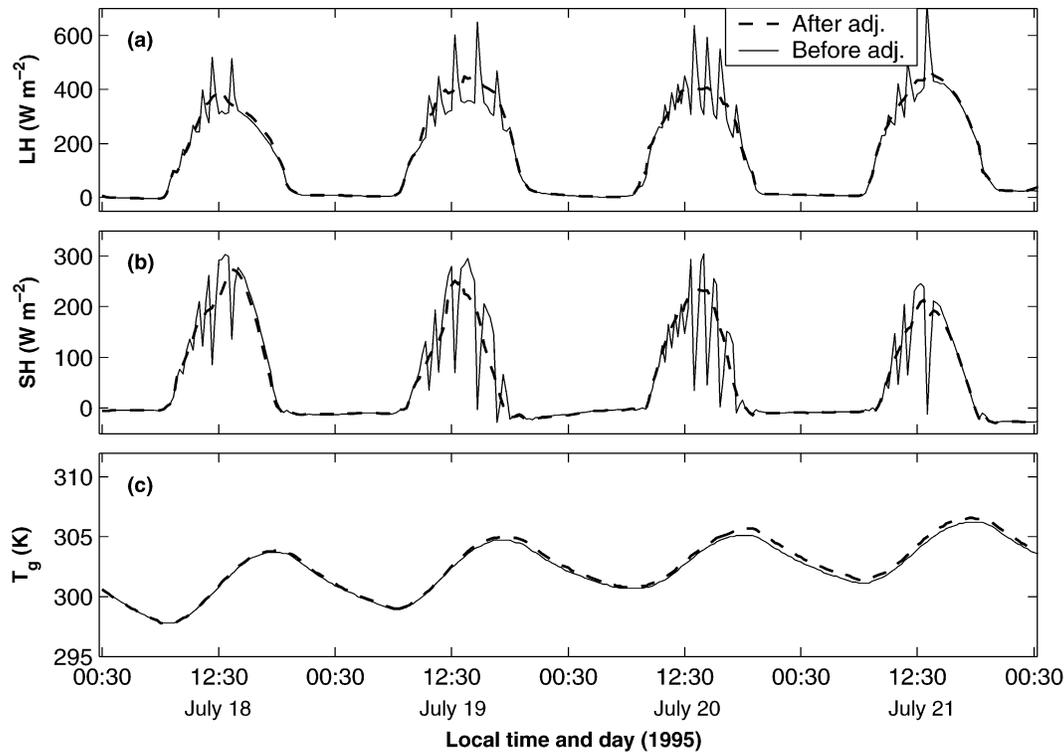
FIG. 12. Same as in Fig. 11 but for the coupled SCCM.

atmosphere. In addition, although some land surface model users may have been aware of the existence of some minor parameterization deficiencies in the models, the serious negative impacts of these deficiencies are usually unexpected and not well known. The model deficiency described in this paper is associated with an inappropriate assumption about the canopy evaporation that allows the canopy water storage to be negative and has resulted in significant negative impacts on model performances; therefore, this model deficiency should be viewed as a parameterization deficiency rather than a programming bug or a technical problem. This research provides insights into the importance of appropriately parameterizing canopy evaporation to maintain canopy water and energy balances in land surface models, especially in coupled land surface–atmospheric models. In land surface modeling, the evaporation of vegetation can be readily overestimated because of the specific dependence of canopy evaporation on vegetation temperature and incoming solar radiation, and also because of the very limited canopy water storage capacity. Using the NCAR LSM and the NCAR SCCM as examples, this study shows that the coupling of the land surface to the atmosphere can significantly exaggerate the negative impacts of a minor deficiency in implementing canopy evaporation parameterization, that is, the allowance of negative canopy water storages, thereby greatly degrading model performances in terms

of simulating surface latent heat flux and sensible heat flux.

As demonstrated by the 100 experimental runs with randomly generated land surface parameter sets, the frequency of the occurrence of unrealistically high canopy evaporation is too high for this minor deficiency to be ignored, with only 1 out of 100 runs being completely free of the problem of unrealistic overestimation of canopy evaporation. The results from these experimental runs indicate that land surface parameters are not the only important factors in triggering the problems associated with the parameterization deficiency. In addition, much effort has been placed on exploring the mechanisms and sources that are primarily responsible for the overestimation of canopy evaporation. According to our investigation, the concurrence of two specific weather conditions is necessary to generate continuous rapid fluctuations in simulated surface energy fluxes: plenty of solar energy absorbed by vegetation and enough precipitation during the daytime. In the coupled cases of the NCAR SCCM, this requirement is satisfied, and continuous severe fluctuations have been resulted in the simulated surface heat fluxes. Finally, in this study, a simple adjustment made to the parameterization of canopy evaporation has effectively prevented the occurrence of negative canopy water, leading to significantly improved model performances. Better adjusting approaches might be possible but are not the main fo-

cuses of this study and should remain for further research.

APPENDIX

Parameter Boundaries, Default Values, Optimal Values, and Descriptions

	Parameter	Lower	Upper	Default $\{\theta_{def}\}$	Optimal $\{\theta_{opt}\}$	Descriptions
1	zomvt	0.01	0.1	0.06	0.07	Momemtum roughness length of crop (m)
2	zpdvt	0.2	0.4	0.34	0.31	Displacement height for crop (m)
3	bp	1000	3000	2000	2319	Minimum leaf conductance for crop (umol m^{-2} s^{-1})
4	rhol1	0.07	0.11	0.11	0.09	Leaf reflectance in VIS
5	rhol2	0.35	0.58	0.58	0.44	Leaf reflectance in NIR
6	taul1	0.05	0.07	0.07	0.06	Leaf transmittance in VIS
7	taul2	0.1	0.25	0.25	0.16	Leaf transmittance in NIR
8	xl	−0.4	0.6	−0.3	0.35	Leaf orientation index
9	ch2op	0.09	0.5	0.1	0.04	Maximum intercepted water per unit lai+sai (mm)
10	hvt	0.35	1	0.5	0.62	Top of canopy (m)
11	avcmx	1	3	2.4	1.37	q10 for maximum rate of carboxylation at 25°C
12	cover	0.3	0.98	8.50E-01	0.70	Vegetation cover fraction
13	rlsoi	0.004	0.1	0.05	0.05	Roughness length of soil (m)
14	watsat	0.33	0.66	0.43482	0.63	Porosity
15	hksat	1.00E-05	0.1	4.19E-03	0.06	Saturation hydraulic conductivity (mm H_2O s^{-1})
16	smpsat	−750	−30	−207.348	−469.21	Soil matrix potential at saturation (mm)
17	bch	3	10	5.772	6.87	Clapp and Hornberger "b"
18	watdry	0.02	0.3	0.12212	0.16	Water content when evapotranspiration stops
19	watopt	0.2	0.8	0.33107	0.66	Optimal water content for evapotranspiration
20	tksol	4	10	7.06491	7.74	Thermal conductivity, soil solids (W m^{-1} K^{-1})
21	tkdry	0.1	3	0.15	0.95	Thermal conductivity, dry soil (W m^{-1} K^{-1})
22	csol	200 000	5000 000	2203 836	1550 000	Specific heat capacity, soil solids (J m^{-3} K^{-1})
23	albsat1	0.05	0.12	0.05	0.08	VIS saturated soil albedo for soil color = 8
24	albsat2	0.1	0.2	0.1	0.16	NIR saturated soil albedo for soil color = 8
25	dzsoi1	0.05	0.2	0.1	0.17	Soil thickness, first layer (m)
26	dzsoi2	0.08	0.8	0.2	0.27	Soil thickness, second layer (m)
27	dzsoi3	0.1	1.5	0.4	0.54	Soil thickness, third layer (m)
28	dzsoi4	0.6	2.0	0.8	1.19	Soil thickness, forth layer (m)
29	h2osoi1	0.01	0.66	0.3	0.33	Initial volumetric soil water, first layer
30	h2osoi2	0.05	0.66	0.3	0.18	Initial volumetric soil water, second layer
31	h2osoi3	0.05	0.66	0.3	0.33	Initial volumetric soil water, third layer
32	h2osoi4	0.05	0.66	0.3	0.30	Initial volumetric soil water, forth layer

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