Incorporating Hydraulic Lift into a Land Surface Model and Its Effects on Surface Soil Moisture Prediction

DIANDONG REN AND MING XUE

School of Meteorology, University of Oklahoma, Norman, Oklahoma

ANN HENDERSON-SELLERS

Australian Nuclear Science and Technology Organisation, Lucas Heights, New South Wales, Australia

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ABSTRACT

In comparison with the Oklahoma Atmospheric Surface-layer Instrumentation System (OASIS) measurements, the Simulator for Hydrology and Energy Exchange at the Land Surface (SHEELS), a multilayer soil hydrological model, simulates a much faster drying of the superficial soil layer (5 cm) for a densely vegetated area at the OASIS site in Norman, Oklahoma, under dry conditions. Further, the measured superficial soil moisture contents also show a counterintuitive daily cycle that moistens the soil during daytime and dries the soil at night. The original SHEELS model fails to simulate this behavior. This work proposes a treatment of hydraulic lift processes associated with stressed vegetation and shows via numerical experiments that both problems reported above can be much alleviated by including the hydraulic lift effect associated with stressed vegetation.

1. Introduction

A land surface parameterization scheme, or simply a land surface scheme (LSS), is an algorithm for determining the exchanges of energy, mass, and momentum between the atmosphere and the land surface. These exchanges are complex functions of a number of processes (physical, chemical, and biological) that have a range of temporal and spatial scales. Land surface schemes are important for numerical climate predictions (e.g., Dickinson and Henderson-Sellers 1988), hydrology (e.g., Milly and Dunne 1994), and numerical weather forecasts (e.g., Beljaars et al. 1993). In land surface modeling, it is impossible, and probably unnecessary, to incorporate all the details of these processes into a numerical scheme, and hence, land surface schemes have been developed based on various simplifications. Depending on these simplifications, land surface schemes in today's atmospheric models exhibit a wide range of complexity, from classic ''bucket'' models (e.g., Manabe 1969) to detailed soil–vegetation–atmosphere transfer schemes (e.g., Dickinson et al. 1993; Sellers et al. 1986). Properly identifying and implementing the relatively important processes remains an important task, especially for newer-generation LSSs that combine the physical processes with the biophysical exchanges needed to represent photosynthesis, respiration, and, in some schemes, decay (e.g., Xiao et al. 1998; Tian et al. 1999).

Because deep soil moisture (deeper than 50 cm; e.g., Deardorff 1978) seldom varies on a daily basis, numerical weather forecasting, especially for the purpose of predicting warm-season precipitation, requires an accurate description of the surface soil moisture content and hence an improved knowledge of how the net radiation is partitioned among latent, sensible, and ground heat fluxes. Consequently, LSSs have evolved from the bulk methods to force-restore schemes and to multilayer models [see also Program for Intercomparison of Land Surface Parameterization Schemes (PILPS) overview; Henderson-Sellers et al. 1996]. Multilayer models, with commensurate information on the vertical soil profile, are supposed to give more accurate descriptions of soil hydrological/thermal processes. The general philosophy applied in most such models, however, is still that described by the pioneering work of Deardorff (1977, 1978), especially the treatment of vegetation functionality. Recent developments in in situ measurements of surface fluxes, soil temperatures, and moisture content provide good opportunities to verify LSSs and implement new physics if needed.

In this study, we have identified two problems in simulating the superficial soil moisture content at the Oklahoma Mesonet Norman, Oklahoma, site using the Simulator for Hydrology and Energy Exchange at the

Corresponding author address: Dr. Ming Xue, School of Meteorology, University of Oklahoma, 100 East Boyd, Norman, OK 73019. E-mail: mxue@ou.edu

Land Surface (SHEELS; Smith et al. 1993) model when the results are compared against the measurements by the Oklahoma Atmospheric Surface-layer Instrumentation System (OASIS; Brotzge 2000). The first problem is the fast drying of the simulated surface soil moisture; the second is the weaker diurnal oscillations in surface moisture that have an opposing phase to that observed, with the latter showing moistening during the day and drying at night. The second problem was also identified by Brotzge and Weber (2002) in a simpler two-layer land surface model. We found that including the effects of hydraulic lift (Caldwell et al. 1998) helps to address both problems.

Hydraulic lift, a nighttime soil water redistribution process involving the efflux of water from the root system in dry soil layers (Caldwell 1990), has been demonstrated through laboratory and field measurements using instruments sensitive to small perturbations in the soil water content of the root zone (Ishikawa and Bledsoe 2000; Song et al. 2000), and through microbiological studies of the soil nutrient accumulation (Herman 1997). Such research has established that hydraulic lift is beneficial to the plant transporting the water during the dry cycle and may provide precious water and nutrient resources for shallow-rooted neighboring parasite species. However, the magnitude and relative importance of this deep-root-vegetation-induced soil water redistribution process is somewhat debatable. Some researchers have conjectured that hydraulic lift is significant and may have implications for ecosystem nutrient cycling and water balance (Horton and Hart 1998; Herman 1997; Richards and Caldwell 1987), whereas others have considered it to be evident only when plants have wilted (e.g., Song et al. 2000).

Caldwell et al. (1998) believe that hydraulic lift could occur for most plants as long as the active root systems span a gradient in the soil water potential and the resistance to water loss from roots is low, although the documented cases are mostly for arid regions and for limited species. In this study, we followed their generalization of the root osmotic potential as part of the total soil water potential in explaining the downward soil water movement resulting from vegetation activities.

In section 2, we give a brief description of the land surface scheme used in this study and a detailed description of how the hydraulic effect is implemented in the model. Section 3 provides a description of the dataset we use for testing our improved land surface scheme, with emphasis on how the soil moisture measurements are collected and the quality of the data. Results of numerical experiments are presented and discussed in section 4. A summary and conclusions are given in section 5.

2. Hydrological aspects of the SHEELS model and the inclusion of hydraulic lift

As a multilayer soil hydrological model, SHEELS (the version current as of March 2001) follows a macroscopic description of the root water uptake; that is, it includes a sink term in the Richards (1931) equation. This sink term consists of two parts: the shape factor determined by the root length density function and a soil moisture constraint factor. The root shape factor used in SHEELS is defined in such a way that more water is extracted from the shallow layer than from the deep layer of the root zone (see also Capehart and Carlson 1994). This corresponds to the triangular-shape-factor profile illustrated in Fig. 1. The soil moisture constraint factor is defined in such a way that water is extracted more from the wet layer than from the dry layer, except when the water pressure head lies outside the wilting point and oxygen efficiency points (Feddes et al. 1978). The transpiration rate, which is determined mainly by the atmospheric conditions, is thus distributed among soil layers at different depths. Smith et al. (1993) and Ren (2001) gave detailed descriptions of SHEELS as a complete land surface system.

Inspired by Caldwell et al. (1998), the effects of hydraulic lift have been implemented in SHEELS. This is achieved by including an additional term for osmotic potential in the total water potential in the capacitance form of a modified Richards equation (e.g., Ren and Henderson-Sellers 2004, manuscript submitted to *J. Climate*). To facilitate the following discussion, here we elaborate on our modifications to the original Richards equation, which describes unsaturated liquid flow through porous media derived from the physical laws of hydrodynamics that govern viscous fluid flow. Unsaturated flow is more complicated (than saturated flow) because both soil moisture potential and hydraulic conductivity depend on the moisture content of the soil medium, hence giving rise to a source of nonlinearity.

The Richards (1931) equation, which is the key relationship for addressing basic soil hydrological processes within the rhizosphere and constitutes the basis for multilayer soil hydrology models, is based on the following two facts: (a) the water flux rate inside the soil is proportional to the water potential gradient, the constant of proportionality being called the hydraulic conductivity (Darcy's law; Hillel 1982; Jury et al. 1991), and (b) the change in water content of a specific layer is due to the convergence/divergence of water fluxes (mass conservation).

Vegetation plays an important role in the hydrological cycle mainly through the transpiration process, especially for the root zone soil. Thus, when the transpiration process is considered, a more general form of the Richards equation governing the soil moisture can be written as

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} K \left(\frac{\partial h}{\partial z} \right) + \frac{\partial K}{\partial z} - \omega(h) R_s T_r, \tag{1}$$

where θ is the volumetric water content (volume of water divided by total volume of soil), h is the soil water pressure head in units of length (meters), K is the un-

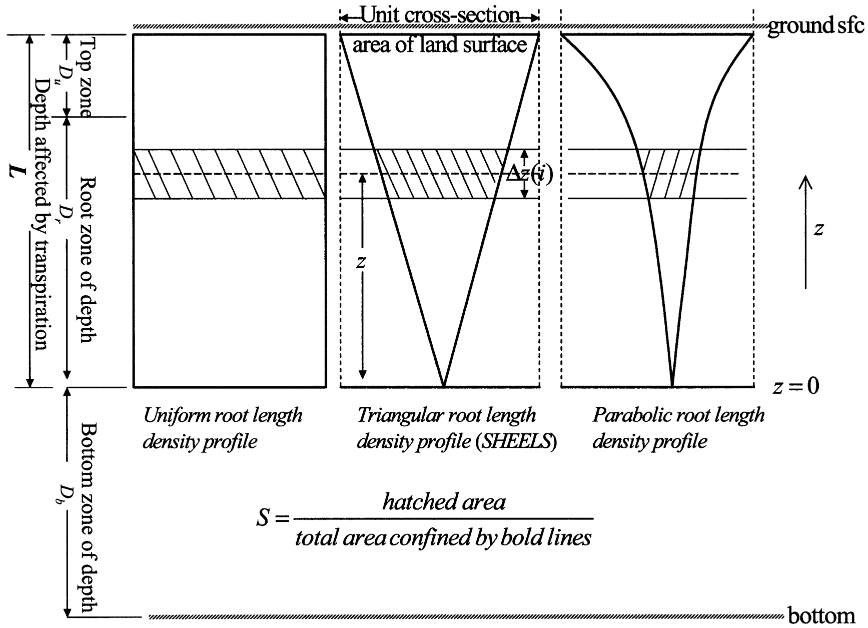

FIG. 1. Sketch of the root length density profiles, where S is the fraction of root length distributed in layer i, which is of thickness Δz and centered at location z.

saturated hydraulic conductivity (meters per second), t is time (seconds), z specifies the vertical coordinate, positive upward (meters), ω is a dimensionless function of soil water pressure head, R_s is the root shape factor (per meter), usually expressed as a function of root length density distribution (Y. Luo 2003, personal communication), and T_r is the transpiration rate (meters per second) by vegetation roots. Note that in Eq. (1), gravitational acceleration is incorporated into K, and the liquid water density is assumed to be a constant. The last term of Eq. (1) may be called the transpiration term. The effects from the soil water content, the ability of the soil to conduct water to the roots, and even water logging and soil water salinity can be incorporated into ω. The contribution from the vegetation type as well as its developmental stage can be incorporated into R_s. The atmospheric demand (e.g., energy supply, vapor pressure deficit, and wind speed), as pioneered by Penman (1948), can be incorporated into T_r.

A solution to Eq. (1) requires knowledge of a relation between θ and h—that is, a soil water characteristic or retention curve—and knowledge of the relation between K and h or θ—that is, the hydraulic conductivity function. This difficulty may be overcome by eliminating either h or θ through the matric potential water content relationship. In addition, K should be related to either one of them (e.g., Brooks and Corey 1964; van Genuchten 1980). In SHEELS, K is parameterized using the saturated hydraulic conductivity K_s by the relation $K = K_s\Theta^{2b+3}$ (Clapp and Hornberger 1978), where Θ is the volumetric water content relative to saturation (water volume per pore space), and b is the Clapp–Hornberger parameter (the slope of the retention curve on a logarithmic graph). The h is similarly parameterized as $h = h_s\Theta^{-b}$, and θ is related to Θ by total porosity ψ, $\theta = \psi\Theta$. Transpiration extracted by plants in the root layer is usually weighted by a root shape function (as is discussed further below).

To further include the hydraulic lift effects, we add the hydraulic head (h_V) due to vegetation to h and give this part of the soil water potential a vertical structure as centered on the top of the root zone and decreasing above and below according to a cosine function. A zero potential ($h_V = 0$) is enforced from the bottom of the root zone downward. The temporal structure of this water potential is assumed to vary as a sine function during the daytime and to shut down abruptly at dusk, in order to simulate the abrupt stomatal closing (Y. Luo 2003, personal communication):

$$h' = h + h_V, \quad \text{and}$$

$$h_V = h_V^0 \cos\left\{\left[0.5 - \frac{z}{2(L - D_u)}\right]\pi\right\} \times \min\left[0.0, \sin\frac{\pi(t_0 - t)}{43\,200}\right], \qquad (2)$$

where h' is the new total hydraulic head. In Eq. (2), h_V^0 is the daily cycle magnitude of the hydraulic head introduced by hydraulic lift (h_V); z is the vertical coordinate, which is positive upward and has an origin set at the bottom of the root zone; L is the distance between the surface and the base of the root zone; D_u is the depth of the upper zone; and t_0 is time at dusk (~2000 LST or 0200 UTC at the Norman site). The way to determine

TABLE 1. Soil and vegetation parameters at the Norman mesonet site (elev 360 m; lat 35°15′20″; lon 97°29′; slope 0.0). Note that K_s is saturated hydraulic conductivity; h_s is saturated soil suction; ϕ is porosity; b is the Clapp–Hornberger parameter; veg is vegetation coverage; LAI is leaf area index; R_s^{min} is minimum stomatal resistance; and R_s^{max} is maximum stomatal resistance.

Soil profile properties	K_s (10^{-5} m s^{-1})	h_s (m)	ϕ (unitless)	b (unitless)	Components		
					Sand	Silt	Clay
Upper zone (0–15 cm)	1.6	0.2	0.63	5.5	19.1	56.6	24.3
Root zone (15–65 cm)	0.32	0.2	0.51	7.6	18.5	39.7	41.9
Bottom zone (65–100 cm)	0.32	0.2	0.51	8.0	16.5	41.3	42.2
Vegetation properties	veg (unitless)	LAI (m^2 m^{-2})	R_s^{min} (s m^{-1})	R_s^{max} (s m^{-1})	Canopy height (m)		
	0.75	0.6	240	5000	0.5		

the magnitude of this hydraulic head h_V^0 will be further discussed. This form [Eq. (2)] is also chosen on the basis that water movements among soil layers by roots occur mainly during periods when the plant is not transpiring. Because we use the capacitance form of the Richards equation and choose to keep Θ as the sole independent variable, the new equation will be formally identical to Eq. (1) except that h' replaces h in the equation.

We also tried to modify the root shape factor (see Fig. 1). To date, the description of the soil water uptake by roots is mainly macroscopic, using root length density (4–8 cm cm^{-3} for most vegetation; Y. Luo 2003, personal communication) as an indicator. Empirical relations are then applied to fit the transpiration data. Capehart and Carlson (1994) proposed a conic or triangular weighting function that varies from a maximum at the surface to zero at the bottom of the root zone,

$$S_{\text{triangular}}(i) = \frac{[2z(i) - \Delta z(i)] \times \Delta z(i)}{L^2}, \qquad (3)$$

where S [discrete form of $R_s(z)dz$] is the fraction of the total root length that lies within layer i [located at $z(i)$ and of thickness $\Delta z(i)$]. This expression for S corresponds to a root length density profile $r(z) = z/L$ and to $R_s = 2z/L^2$ [$r(z)$ normalized by its total vertical integration area]. The shape factor as represented by Eq. (3) is used in SHEELS and is called the triangular shape factor here. We test here two other root shape factors to see how the shape factor affects the solution (Fig. 1). First, a rectangular shape factor [i.e., $r(z) = 1/L$] signifies a uniform water extraction by vegetation over the root zone,

$$S_{\text{uniform}}(i) = \Delta z(i)/L. \qquad (4)$$

The other is a parabolic root shape factor [i.e., $r(z) = (z/L)^2$], which sharpens the triangular shape factor, thus allowing even more water to be extracted from the shallow layers,

$$S_{\text{parabolic}}(i) = [z(i)^3 - z(i + 1)^3]/L^3. \qquad (5)$$

Both parabolic and triangular root shape factors are expressions that emphasize the water extraction from the near-surface (shallow) soil layers, with the latter less concentrated near the surface. A rectangular shape factor is actually rather unrealistic because it assumes uniform water extractions among soil layers. Here we use this extreme example to demonstrate the relative importance of the root shape factor.

The SHEELS model was used in its one-dimensional vertical-column mode throughout this study. The soil column of 1 m was evenly divided into 20 layers with 3, 10, and 7 layers in the upper, root, and bottom zones of 15-, 50-, and 35-cm depths, respectively (see Fig. 1). The vertical profiles of saturated hydraulic conductivity, maximum soil suction, and porosity were determined from the tabulated values of Dickinson et al. (1993), and the value of the Clapp–Hornberger (1978) ''b'' parameter was based on the continuous parameterization of Noilhan and Mahfouf (1996) as summarized in their appendix A.3. For the soil textural profile at the Norman site, the above values are listed in Table 1, together with seasonally varying vegetation properties set according to the biweekly OASIS observations.

The top two layers were initialized using the OASIS measurements (more on these data later) at 5 cm. Layers 15–20 were initialized using measurements at 75 cm. The initial values of the remaining soil layers were linearly interpolated from the two adjacent measurements according to distance. The time step is adjustable in SHEELS. The outputs were recorded every 30 min, in order to facilitate comparison with the corresponding measurements. The values of vegetation parameters for the test period can be found in Table 1.

3. Data

OASIS (Brotzge 2000) provides year-round continuous and direct measurements of soil moisture and temperature at four different depths and for all four components of the surface energy fluxes. Thus it provides a valuable opportunity for rigorously testing and improving the dynamic framework of LSSs. In this study, observed surface meteorological variables are used to drive the SHEELS model, while the soil moisture measurements are used for both initialization and verification.

The OASIS dataset at the Norman supersite used here was provided by J. Brotzge and has been used for model calibration purposes (e.g.; Brotzge and Weber 2002). Additional data for other sites were acquired from the Oklahoma Climate Survey (OCS), which runs the OA-

SIS network. Besides the routinely available OASIS meteorological parameters (solar radiation, surface temperature, relative humidity, wind, surface pressure, and precipitation rate), the SHEELS model also requires downward longwave radiation, which in this study is estimated using Crawford and Duchon's (1999) empirical scheme.

At the Norman site, the upper 15 cm of the soil column is classified as silt loam (fraction of clay and sand in the soil is 24% and 19%, respectively), and the soil is largely clay loam below 20 cm. Vegetation at the Norman site is classified as shrub (tall grass studded with sagebrush).

The soil water measurements were made using individually calibrated Campbell Scientific 229-L heat dissipation sensors (Basara 2001) every half an hour at 5-, 25-, 60-, and 75-cm depths. The probe measures one soil temperature and heats the surrounding soil for 21 s before taking another soil temperature measurement. The soil temperature increment is transformed into a "ΔT reference temperature" according to a linear regression relationship that utilizes individually calibrated coefficients for the sensor. Using instrument coefficients (uniform to 229-L sensors), the ΔT reference temperature is mapped into the soil water potential. This soil water potential is then used together with information about the soil structural properties to infer the soil moisture content according to the expressions given by van Genuchten (1980). Since only soil temperature increments, rather than the temperatures themselves, are involved in the procedure, the measurements are consequently not sensitive to soil temperature daily variations (see also Illston et al. 2004). This is true inasmuch as the natural soil temperature variations within the 21 s are negligible compared with those caused by the electronic heating.

According to the Oklahoma Climatological Survey documentation, the soil water content values obtained using a 229-L sensor (with measurement accuracy of $\sim$0.005 m^3 m^{-3}; J. Basara 2003, personal communication) compare well with validation data, which consist of soil water content data derived from gravimetric and neutron probe samples at a large number of sites at the same four depths. Unlike the soil data, vegetation parameters such as vegetation type, leaf area index (LAI), vegetation coverage, and Normalized Difference Vegetation Index (NDVI) are estimated biweekly.

Compared with the model validation period used by Brotzge and Webber (20–22 May 2000), our selected period (i.e., 12–27 August 2000) represents a soil dry-down period with much lower soil wetness but higher air temperatures (maximum temperature of 42°C) and stressed vegetation (NDVI = 0.5 rather than 0.55 for the 20–22 May period) because the soil moisture contents at the top measurement depth (5 cm) fall near the wilting point value of 0.24 (volumetric water content, i.e., volume of water per total soil volume) for silty clay soil at the driest hours of each day. That the vegetation is stressed is also shown by the Halstead coefficient, which is around 0.06 for this period. Since dew formation is insignificant, the stomatal resistance is nearly 20 times that of the aerodynamic resistance. The behavior of the soil water content indicates that the drying process easily enters stage II of drying as defined by Idso et al. (1974). Dry-down stage II is characterized by drying of the soil surface and hence a significantly reduced evaporation rate. Although the vegetation starts wilting during this period, the same vegetation cover of 75% was estimated based on the study of Brotzge and Weber (2002). The selected period signifies a synoptically quiescent period with clear sky and wind speed generally less than 5 m s^{-1}. Under periodical (daily) radiative forcing, air pressure, air temperature, water vapor mixing ratio, and soil temperatures within 25 cm all show apparent daily cycles.

4. Results

In this section, we present modeling results showing the effects of including the hydraulic lift process. The SHEELS calculation uses soil moisture contents in relative saturation form (i.e., volume of liquid water per volume of pore space), whereas in the following discussions we translate them into volumetric soil water contents (volume of liquid water per total soil volume) by multiplying the porosities.

As discussed earlier, in the SHEELS model, root length density is expressed as a root shape factor that distributes the transpiration rate among the root zone soil layers. Roots are assumed to exist from the surface to the bottom of the root zone (i.e., the top 65 cm of the 1-m soil column in our model configuration), with a preselected maximum density at the surface that corresponds to the triangular shape factor in Fig. 1. Figure 1 also illustrates two other root shape factors that we tested, that is, the rectangular and parabolic ones. In no case are there more dense roots in the deeper layers, because we are using the macroscopic description for the majority of real plants. With the shape factors that weigh more heavily toward the upper layers, the soil wilting points and "*b*" parameter values at the top two zones control the maximum transpiration rate that can be sustained for a given soil moisture distribution.

Figure 2 shows the SHEELS-simulated soil moisture contents for a continuously drying down period of 12–27 August 2000. With careful vertical profile soil properties and soil sublayer specifications, SHEELS gives a good description of the general evolution of soil moisture at 25-cm depth (Fig. 2b) when the triangular root shape factor (the default of SHEELS) is used, but much less so with the other two shape factors, with the rectangular shape factor performing the worst. The dry-down trend is captured in all three cases, but only the triangular shape gives a good magnitude of the trend.

The predictions of the superficial soil moisture (Fig. 2a) are much poorer with all three shape factors, with

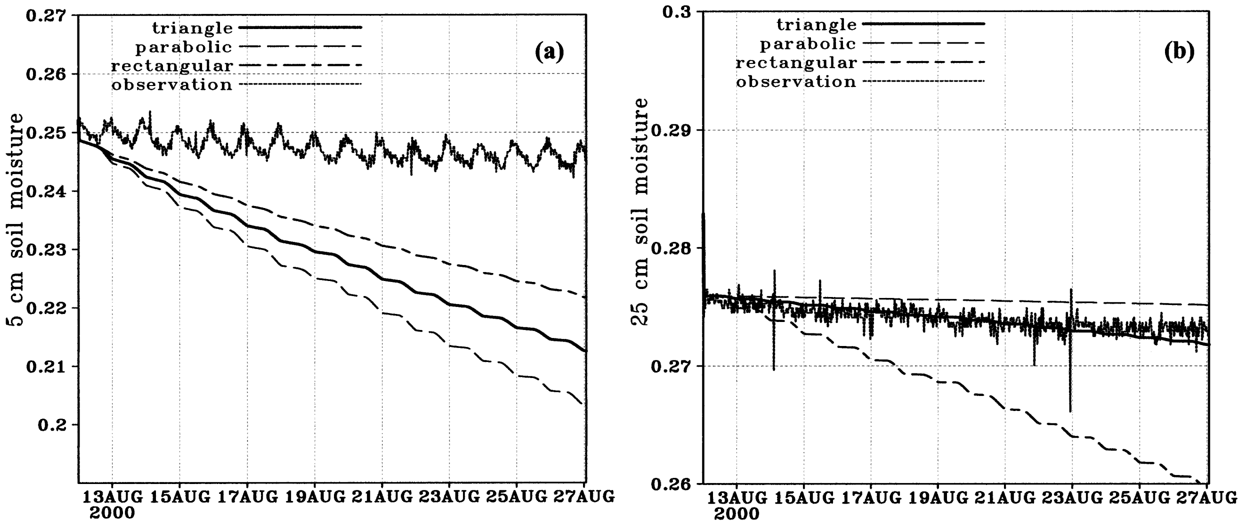

FIG. 2. Observed and SHEELS simulated (a) 5- and (b) 25-cm soil moisture time series for the Norman site. Three root shape factors are applied. The effects of root shape factor, which determines the distribution of transpiration among soil layers, are evident. The model-simulated surface soil moisture decreases faster than and lacks the daily cycle found in the observations.

the predictions exhibiting much faster drying and weaker diurnal cycles than measurements. Fast drying of the ground surface during the extended drought period is realistic for less vegetated surface, and its accurate simulation is an important component for accurate prediction of daytime temperature, surface fluxes, and the planetary boundary layer development (Santanello and Carlson 2001). The drying simulated here is obviously too much. Surface evaporation is clearly the cause of the rapid drying, especially since it continues beyond the wilding point of 0.24. The lack of a hydraulic lift process that would cause redistribution of water in the soil is believed to be the cause of the overdrying. This process is effective only when the vegetation is stressed but not wilted.

It is believed that the simulated fast drying of the surface layer is not due to possible errors in the solar radiation that penetrates the vegetation canopy. For rhyzosphere soil hydrology, SHEELS solves a full form of the Richards equation with variable profile soil properties. For the evapotranspiration (ET) calculation (root zone), it follows a supply–demand contest philosophy. The gravitational term (not significant in this study) is a further adjustment to the soil water content [for a detailed discussion, please see Ren (2001)]. The ET parameterization was verified in several published papers (e.g., Smith et al. 1993).

To further examine the performance of SHEELS with respect to ET parameterization, we performed another run for a wet period (results not shown). The soil moisture contents are simulated accurately, and as a result, the surface latent and sensible heat fluxes are also reasonably accurate. Further, before implementing the hydraulic lift effects, the thermal effects (Philip and de Vries 1957; Milly and Eagleson 1980) on soil moisture transfer were suspected to play a role, and the parameterization of Milly (1982) was implemented. It turns out that model still simulated too fast drying, and to make things worse, the out-of-phase error gets slightly larger because of the nighttime condensation within the soil mediums.

In addition to the too-fast-drying problem, the simulated 5-cm soil moisture exhibits a diurnal cycle that is in an opposite phase from the observed one. Near 0000 UTC of each day, which is 6 P.M. LST, the OASIS data show peaks in the near-surface soil moisture, which is counterintuitive because of the general drying due to surface evaporation. The model prediction shows minimum values (after removing the trend) near 0000 UTC, more consistent with the effect of afternoon drying. Either the OASIS data are wrong or the model is missing a certain process(es) that could cause this behavior. Scrutiny of OASAS data records for an extended period covering July through September—an extended drought period for Norman, Oklahoma—shows that such a behavior is persistent and is therefore unlikely to be due to instrumentation error. In fact, this out-of-phase behavior was also noted by Basara (1998) and Brotzge and Weber (2002). Basara and Brotzge worked extensively with the instrumentation of Oklahoma Mesonet and its data. We attribute the observed behavior to hydraulic lift processes that recharge the near-surface layer under dry conditions.

To help better understand the causal mechanism, we further examined data from three other sites in Oklahoma, namely, the Bois (Boise City), Mars (Marshall), and Bixb (Bixby) sites. Bois has very similar vegetation to that of the Norman site and has a slightly more clayey (wilting point of 0.245 and saturation point of 0.46 $m^3\ m^{-3}$) root zone soil. Except for vegetation (short grass), the Mars site has exactly the same root zone soil type as that of the Norman site and experiences

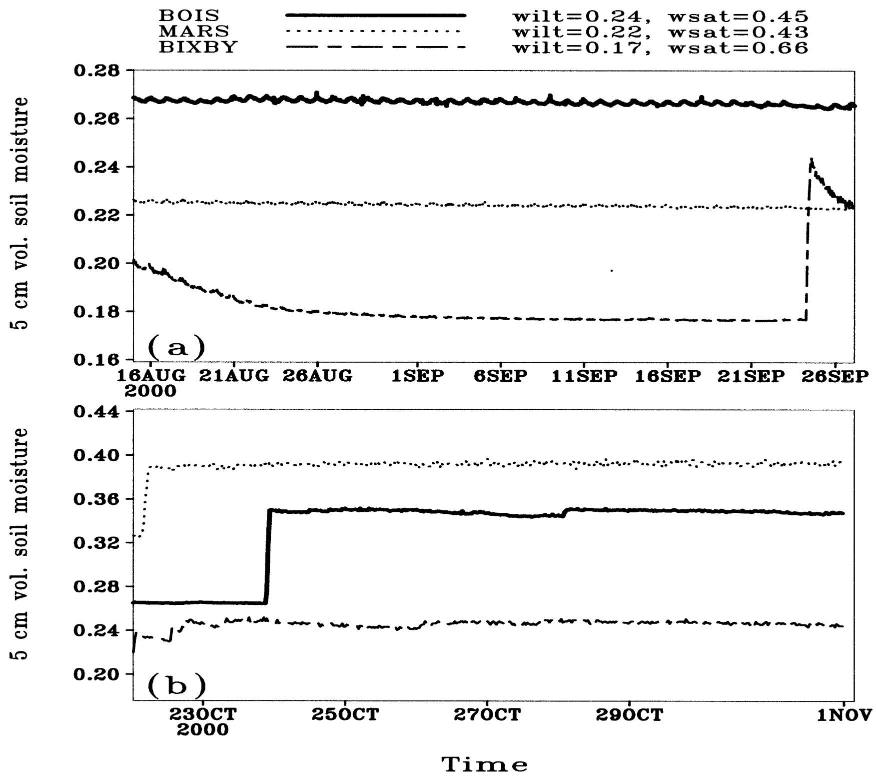

FIG. 3. OASIS-measured 5-cm volumetric soil moisture content for Bois (solid line), Mars (dotted line), and Bixb (dot–dot–dash line) sites for the (a) 15 Aug–26 Sep 2000 period and (b) 22 Oct–1 Nov 2000 period.

very similar micrometeorological forcing conditions due to their proximity. The Bixb site has silt loam soil type at the root zone that helps it to retain water in the deep layer. Because of that, even though the superficial soil moisture was close to wilting point, the vegetation was never stressed during 2000 at Bixb.

In Fig. 3, we plot the time series of 5-cm soil moisture for Bois, Mars, and Bixb for a drier summer period from 15 August to 26 September and a wet winter period from 22 October to 1 November 2000. For the summer period (Fig. 3a), the 5-cm soil moisture at the Bois site shows clear daily cycles that are out of phase with radiation forcing, while oscillations at the Mars site are also present but much weaker. Mars has a soil moisture value that is very close to the wilting point. At the Bixb site, no clear signal of daily cycles is present, because of unstressed condition of vegetation we believe. For the wet winter period (Fig. 3b) when the vegetation was not stressed, clear signal of daily cycles is observed at none of the three sites. On 25 September 2000, there is 0.96 in. of precipitation at the Bixb site, while there is insignificant (0.01 in.) precipitation at the Bois site. The discontinuous increase in soil moisture content after rainfall is clearly shown in Fig. 3a for the Bixb site, attesting to the proper response of the soil moisture instrument. The above data point to stressed but not wilted relatively deeper-rooted vegetation activities as being the possible cause of the observed near-surface soil moisture behavior.

Figure 2a also shows that using different root shape factors does not change the out-of-phase or the too-much-drying behavior of predicted surface soil moisture. Using rectangular weights somewhat slows the drying-down process but gives poorer deep soil prediction (Fig. 2b). The parabolic root profile worsens the problems with the surface prediction. Furthermore, soil-matric-potential-based diffusion processes are usually too slow to have a significant effect during this short 10-day period. For example, using the soil parameters for silt loam in Table 3 of Dickinson et al. (1993) and our soil column of 1 m, for the 12–27 August period, a conservative estimate for the time constant describing the soil water movement (Hillel and Elrick 1990) is about 600 h, so that soil water movement due to this mechanism is more than one order of magnitude too slow to account for the observed daily cycle in surface soil moisture during this dry period.

As indicated earlier, what we believe to be the most probable cause is the hydraulic lift, a water redistribution mechanism for plants growing under water-stressed environments. As discussed earlier, we added the effect of this process into the SHEELS model as

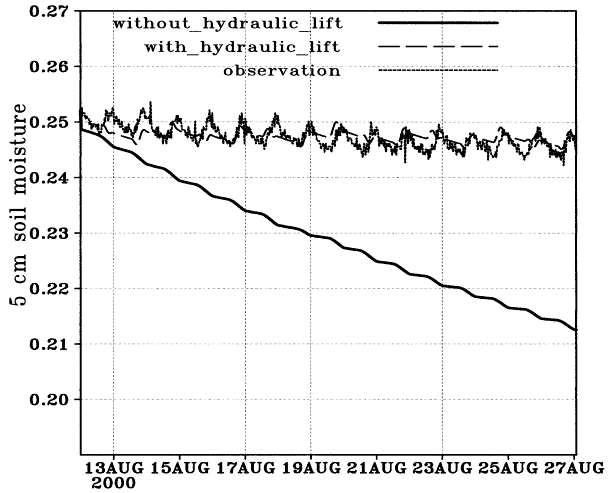

FIG. 4. Near-surface, 5-cm, soil moisture predictions with and without hydraulic lift effect as compared with observations for the 12–27 Aug 2000 period, using the triangular shape factor.

part of the total water potential in the Richards equation. Since lifting the water head from −0.55 MPa (1 MPa = 102 m of water column pressure), an approximate value for silt loam soil under dry conditions during 12–27 August 2000, to −0.2 MPa can reduce the time constant describing the soil water movement to less than a week, vegetation-caused hydraulic lift can therefore be an effective way to facilitate water movement through the soil–plant–atmosphere system and significantly prolong and slow the drying-down process. We therefore implemented the hydraulic lift effects according to Eq. (2) and chose to use the triangular shape factor, which worked best for deep soil moisture prediction in our test case (Fig. 2b) and is the original formulation in SHEELS. The amplitude of the vegetation-induced hydraulic head h_V^0 is set to 1.2 MPa and its maximum placed at 0.15-m depth [at the top of the root zone; D_u in Eq. (2)]. Figure 4 shows that after the hydraulic lift effects are included, the misfit between the model simulation and observations is very much reduced for surface soil moisture, especially during daytime. Furthermore, the rapid drying-down trend is essentially gone, and diurnal oscillations are now in phase with the observations.

The soil moisture at 5 cm increases during the daytime period because the vegetation can take water from a larger depth, while roots in the shallower layer can release water to the environment (Fig. 1 of Caldwell et al. 1998). Daytime excessive extraction of soil moisture may result in a much drier deeper layer where the soil moisture needs to be replenished during the nighttime. This may be accomplished by moisture convergence from both above and below. The downward moisture flux near the surface implies a drying-down process for superficial soil moisture (i.e., the 5-cm measured value) during the nighttime. The uplifting of water from the deeper layer due to the convergence process helps prevent too much drying of the upper layers. For a numerical model, including hydraulic lift is beneficial for long-period integrations also because the vegetation rehydration permits the next day's integration to start from a less dry condition and thus prevents the unrealistic tendency of rapid drying.

Figure 5 shows predictions of 5- and 25-cm soil moisture using three different shape factors but with hydraulic lift included. Compared to Fig. 2, the effect of the root shape factor, measured in terms of the spread among the predictions, is about the same for 5-cm predictions and somewhat reduced for the deep soil moisture predictions. The prediction of 25-cm soil moisture using the triangular shape factor is also improved (cf. Fig. 2b), especially toward the end of the period.

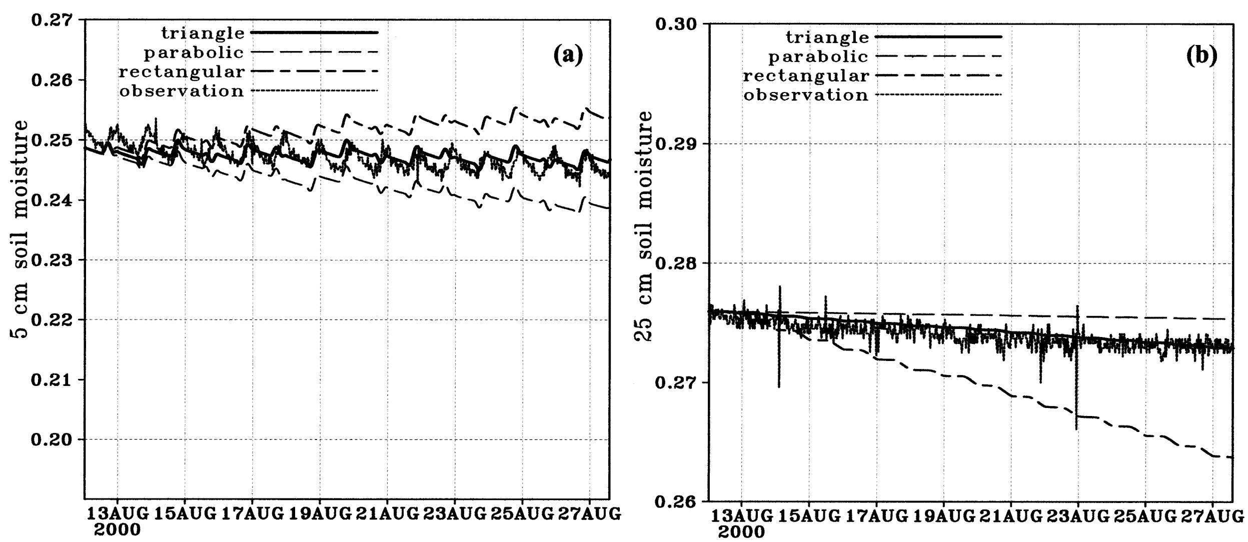

FIG. 5. As in Fig. 2, but with hydraulic lift effect included in the experiments.

We also performed similar numerical experiments for the Bixb site (sandy loam soil for at least the top 20 cm), for which observations show no clear sign of a daily cycle. The inclusion of the hydraulic lift process is found to have no negative effect on the model simulation. This is because the higher (two orders of magnitude larger than clay soil) hydraulic conductivity essentially prevents the hydraulic lift from occurring. This also explains why the soil moisture measurements do not exhibit daily cycles. We believe the reason that we did not find a hydraulic lift phenomenon for the Mars site is that the soil moisture is too close to wilting point, the hydraulic lift process requires stressed but not wilted vegetation conditions.

Finally, we note here that a uniform treatment (either temporally or spatially) of hydraulic effects is apparently not suitable. This calls for a more objective determination for the amplitude of the hydraulic lift. Considering that the hydraulic lift is one component of a self-constrained system, the nocturnal recharge is largely caused by the ET moisture depletion on the previous day (Caldwell et al. 1998), and the magnitude of the hydraulic lift may be related to the magnitude of the latent heat flux of the previous day, that is, $h_V^0 = C \times \mathrm{LE}^{\max}$. Here $\mathrm{LE}^{\max}$ is the maximum value of the latent heat flux of the previous day, and C is a proportionality coefficient connecting $\mathrm{LE}^{\max}$ and h_V^0. For a specific site, coefficient C can be determined by the parameter retrieval technique as described by Ren et al. (2002). As a test of this technique, data from 5 to 12 August are used to determine the coefficient. A coefficient value of $C = 5.6$, corresponding to $h_V^0 = 1.12$ MPa for $\mathrm{LE}^{\max} = 200\ \mathrm{W\ m^{-2}}$, is obtained. When this value of C is applied to the ensuing 12–27 August 2000 period with larger $\mathrm{LE}^{\max}$, we obtain $h_V^0 = 1.45$ MPa, which is close to our empirically determined value $h_V^0 = 1.2$ MPa, used in our experiments reported earlier.

5. Further discussion and summary

In the introduction, we pointed out that it is often impossible, and probably unnecessary, to incorporate all the details of complicated physical, chemical, and biological processes into a land surface scheme. This does not mean, however, that existing land surface schemes are necessarily overparameterized. Inasmuch as the physical process is implemented properly, the more physical mechanisms that are included in a numerical scheme, the better it should perform. In comparison to the improvements achieved through parameter calibration, the improvements achieved through implementing proper physical mechanisms should be more universally applicable and less case dependent (in terms of both spatial locations and temporal scales). Result of the PILPS (Henderson-Sellers et al. 1996) study, which investigated the impact of parameter calibration on scheme simulations, has further confirmed this assertion.

Experiments with the Chameleon Surface Model (CHASM; Desborough 1999) using data from the Thorne River basin, used for PILPS Phase 2(e), also show that the simulation of latent heat flux depends on the complexity of the land surface scheme. Furthermore, it was found that calibrating the parameters (here based on streamflow measurements) improves the performance of the schemes, but it does not fully eliminate the residual errors in the simulations. These facts call for proper implementation of new physics into LSSs in order to improve these schemes further. Having noted the above, we also point out that there exist different schools of thought in the literature, some of which (e.g., Beven 1989) argue for better estimation of uncertainties with existing physically based models before making them more complicated. But the same papers also acknowledge the continued need for physically based models, and the continued improvements of them. We believe our work represents a step in this direction.

Hydraulic lift has not been widely implemented in LSSs for either numerical weather forecasting or climate studies. In this paper, we have shown the potential usefulness of implementing this mechanism. This study also lends support to the assertion made by Caldwell et al. (1998) regarding the possibly downward-pointing water flux associated with hydraulic lift effects exerted by some deep rooted plants.

For some locations (the combination of dry climate, deep-rooted vegetation cover, and more clayey soil type), we believe that in order to accurately simulate the surface soil moisture evolution over long periods, even the most sophisticated multilayer land surface models should include the hydraulic lift effect in order to avoid steady overdrying in soil moisture. In our case, hydraulic lift signifies a rehydration mechanism that guarantees that the next day's model prediction starts from a more accurate superficial soil moisture content and hence avoids any steady down drift of the estimation. Of equal importance, the inclusion of hydraulic lift also corrects most of the phase problems in the surface soil moisture prediction.

The simplistic treatment of hydraulic lift as performed in this study leaves much room for improvement. The quantitative results of this study must be interpreted with caution. The prediction of the surface soil moisture is still not perfect, indicating either that the switch on and off of the sinusoidal osmotic potential does not accurately mirror reality or that the nighttime evolution of the hydraulic lift is not of a sinusoidal nature. It merits further endeavor to find out how the significance of hydraulic lift is related to soil moisture stress and what the quantitative relationship is. With the physical mechanisms identified and properly implemented, some uncertain parameters can be retrieved using parameter-retrieval tools.

Despite the evidence we presented in this paper, land surface models include many complicated processes, and it is not impossible that some other processes rather than the hydraulic lift are responsible for some of the observed behaviors. Additional work is obviously needed.

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