The reviewers' comments and suggestions are very insightful and help to improve this paper. We really appreciate the reviewers' efforts and time. In the following we respond to the reviewers' comment (which are shown in blue fonts) and indicate the corresponding text revisions in the quotation marks. All the line numbers mentioned in our reply refer to those in the revisions.

Anonymous Referee #1

Received and published: 17 December 2015

The authors developed a stemflow model based on the SSiB model and run it at two sites with contrasting climates to study the impact of stemflow on soil water dynamics and consequent effect on surface energy fluxes. Though stemflow is insignificant in terms of volume, it is hydrologically and ecologically important for the forest and agriculture ecosystems due to its fast penetration through soil, localized and concentrated enhancement of soil water, the efficient transportation of nutrients along with the water, etc. Yet it is missing or taken account of as a component of throughfall in many modeling practices. This paper is valuable to demonstrate the importance of stemflow in a modeling aspect and I think the topic matches well with HESS. The work is of value is also because it is one of few modeling studies and for the first time to my knowledge develops a detailed parameterization. Also the paper is nicely written with clear logics and structure.

My comments and questions would be:

1. More modeling researches could be cited in the introduction paragraph, like Liang et al. (2009) proposed a 3D model in Journal of Hydrology. Also, a more recent review than the 2003 one is now available to cite, which is Levia and Germer (2015) in Reviews of Geophysics.

Reply: Thank you very much for these useful references. We have cited them in the revised manuscript on lines 36 and 31.

2. The authors proposed a new parameterization scheme describing the stemflow generation and its interaction with soil water, which is a very complex process and thus limitations and assumptions of the simple model should be stated or discussed. For example, the rainfall threshold for stemflow initialization is not taken into account and the variation of SLR is not considered.

Reply: Indeed there are many limitations and assumptions to the stem-root flow process in the simple model. We tried to cover them as much as possible in section 5, but may have missed some. So we appreciate the reviewer for pointing them out. In this example, due to lack of comprehensive measurements of stemflow, we have related the amount of stemflow to leaf drainage. Therefore, there is an implicit threshold for stemflow initiation that corresponding to the threshold of leaf drainage. We have stated this more clearly in the revision (lines 76-77). Meanwhile, we did conduct sensitivity tests to assess the impacts due to the SLR uncertainty. We hope this study may inspire others to carry out more comprehensive measurements on stemflow, with which we can further improve our parameterization.

3. Equations (3) and (4) indicate that the amount of root, in terms of root surface and root length, determines vertical and lateral flows. I am wondering if the vertical profile of root distribution taken into account or if a constant value is used. Since the two sites have different vegetation types, the difference in root

profiles may also be an explanation to the contrast of stemflow magnitude in addition to the precipitation intensity mentioned in the manuscript

Reply: The reviewer is right to point out the root distribution issue. In the SSiB model, there is a parameter to account for the root density. However, due to a lack of observational data, we used a uniform vertical distribution. Nevertheless, different root depths were used based on the measurements (100 cm for LHC and 140 cm for HAPEX). We mentioned this in the revision (lines 88-90). In recent years, U.S. Department of Energy has supported a number of projects to measure the root vertical distribution. With more data becoming available, we should be able to more realistically assess its effects. In the discussion section (lines 324-328), we pointed out this shortcoming and suggested further investigations.

4. The sentence "In Eq.(3), ... And horizontal root flow" (lines 5~7 on page 11788) is not precise since the equation does not show that hi is determined by the horizontal root flow. This sentence and the following one implies that equation (6) is derived from equation (3), which is not the case. It is from the conservation of mass instead.

Reply: Thanks for pointing this out. We have changed this sentence as the following (lines 93-94 in the revision): "The changes in root surface water thickness h_i obey the mass conservation principle and thus are controlled by the vertical and horizontal fluxes of root flow."

5. In Lines 14~16 on page 11790, the authors mentioned that the soil moisture of the second soil layer responds faster to precipitation and fluctuates more pronouncedly than that of the first layer. But it seems to me that Figure 2 does not show the difference in the response speed between different soil layers. (If you look at one precipitation event at the end of August, SM2 even did not respond to it.) Regarding the magnitude of fluctuation, it seems that SM2 fluctuates more pronouncedly during the dry season or the seasons with lower precipitation, while in the rainy season (June to September) SM1 shows stronger fluctuations. I think one of the explanations is that SM2 and SM3 are almost saturated in the rainy season.

Reply: Thanks for the reviewer's very careful observation. We have revised the sentences (lines 153-155) as follows: "However, the LHC measurements (Fig. 2) showed that the soil moisture fluctuation was stronger in the middle layer than in the upper layer during the dry season when the soil moisture was not saturated. Fluctuations were not obvious in rainy seasons when SM2 and SM3 are almost saturated."

6. In Figure 4, the overestimation of soil moisture in SM1 and the underestimation in SM3 in spring, can be explained by the missing of other mechanisms like hydraulic redistribution which provides a bypass of soil water through the inside of the root rather than the exterior surface of the root as in the case of stemflow transport.

Reply: Thanks for providing this explanation. We revised the sentences accordingly as (lines 210-212): "The overestimation of soil moisture in SM1 and the underestimation in SM3 in spring may be coupled, due to mechanisms that are missing in our model. This issue will be elaborated further in the discussion section." In the discussion section (lines 321-324) we stated that: "On the other hand, the overestimation of soil moisture in SM1 and the underestimation in SM3 in spring (Fig 4) may be explained by mechanisms like hydraulic redistribution (cf. Brooks et al., 2002), which provides a bypass of soil water through the inside of the root rather than the exterior surface of the root as in the case of stem-root flow transport."

7. The shading area in Figure 5b seems strange to me. I expect that the 50% curve should be enclosed by the shading area since the shading area shows a range from 0 to 100%. Is the shading area plotted by filling the areas between 0% and 100% curves? Or is it produced by a spectra of SLR values? It seems that latter is the case since it is mentioned in Lines 18~19 on page 11788 that the authors "conducted a series of sensitivity test with systematically varying ratio."

Reply: The shading areas are enclosed by the two extremes (i.e., 0% and 100%). Results with other SLR values (not shown) generally lie within these limits but may occasionally fall out of bound, indicating some nonlinearities. We have made it clearer in the revision (lines 190-192).

Some minor revisions: In Table 1, the units of soil tension and hydraulic conductivity are not given. Also, the annual rainfall at LHC in the table is slightly different from what is given in the text. Units in Table 2 and 3 are also missing. Though they are m2/m2 and m3/m3, would be better to show them.

Reply: Thanks for pointing them out. These units have been provided in Tables 1-3. We also revised the annual rainfall in Table 1 from 2316 mm to 2317 mm to be consistent with the text.

Anonymous Referee #2

Received and published: 19 December 2015

In this paper, a new process about vertical water movement along with plant root was incorporated in a land surface model. Sensitivity tests were conducted at two experimental observation sites, and the impacts were investigated. The results showed better agreement with both sites, and the impacts on the atmosphere-soil interaction were different between the two sites depending on the climatological characteristic.

I liked this paper because the message is straightforward and the method is well targeted. The parameterization of indicated process seems applicable to macro scale models, such as climate models. So there is potential benefit to introduce this scheme to the community by publishing this paper. Here are some major and minor comments for the authors to further improve the manuscript.

Major comments:

1. There have been quite a few studies about partitioning of water transport recently (Jasechko et. al. 2013; Good et al 2015; Wei et al., 2015; etc.). The parameterization proposed in this manuscript should the partition of latent heat (E or T) and runoff (surface or subsurface). In considering those studies, what is additional information/constraint that this paper proposes?

Reply: First, we thank the reviewer for providing these references. They are now cited in the revised manuscript and added relevant comment on lines 286-290: "Regarding the partition of water transport, recent studies (e.g., Jasechko et al., 2013; Good et al., 2015; Wei et al., 2015) explored the dominant role of transpiration in ecosystem evapotranspiration. The results of this work partially concur with these studies. In other words, the stem-root flow in the plant-soil system could enhance the transpiration, and reduce the soil evaporation, which regulated the partition of evapotranspiration."

2. Similar to the first comment, but there are lots of model-intercomparison studies (PILPS1,2, GSWP1,2,3, etc.) in land surface schemes. What is significance of this paper among these intercomparison studies? In particular, in PILPS, experiment at HAPEX was conducted (Boone and Wetzel, 1996).

Reply: We cited Boone and Wetzel's paper and added the following comment in the revised manuscript on lines 290-296: "A number of PILPS studies, including the PILPS-HAPEX experiment (Boone and Wetzel, 1996; Henderson-Sellers, 1995; Shao et al., 1996; Xue et al., 1996) consistently demonstrated that the current land model parameterizations have the weakness in simulating the soil moisture in the dry season. This study, by introducing a parameterization on the stem-root flow mechanisms, wish to help solve this deficiency. With the stem-root flow mechanism, the soil moisture will redistribute in vertical, leading to better simulated results in each layer, which is important for the evapotranspiration partition."

3. Detailed experiment specification is missing. What kind of atmospheric data in which time interval is used to run the model? How long is spin-up period? Is the experiment setup typical offline simulation setup for land surface model?

Reply: Sorry for missed these details. We have revised the text and indicate in lines 117-126 that "Following typical offline simulation procedures for single-column land surface model, in situ atmospheric data were applied to drive the SSiB model in 30 min time resolution. These specified variables include pressure, temperature, humidity, wind speed, net radiation and rainfall. Soil conditions were initialized with each site's measurement data. Fully coupled land surface model typically require a couple of months to over a year to spin up the model, but the spin up time can be shorter when running in off-line (single column) mode and with good initial soil conditions (de Goncalves et al., 2006; Yang et al., 2011; Lim et al., 2012; Angevine et al., 2014). Our simulations applied measurement data for model initialization, and the results show that the soil conditions reached physical balance within a few weeks. So, at the last 10 months results of our simulations are reliable." Note that we also repeated the annual simulation initialized with the end results of the original run. The results are very similar except for the first 2 months of the HAPEX case. But the main discrepancies are not caused by differences in spin-up time but rather the underestimation of deep-soil moisture (which lasted to the end of December) in the original run. This is the reason that we chose to use the original run instead of the repeated annual run for discussion (but we do not want to bother the readers with such details).

Minor comments:

1. Equation (3): what is the relationship between q0, qz and qx?

Reply: We have indicated in lines 90-91 that "$q_0 = q_{x,1} + q_{z,1}$ according to the mass conservation principle."

2. 790L25: I don't understand "SLR; i.e., q0 LD". It's better to use SLR in Equation(2).

Reply: Sorry for the typo. It should be "i.e., q_0/LD" (line 164)

3. P11792L24: Isn't it so obvious that larger the P, stronger the stem-root effect? Throughfall would be stronger too.

Reply: The stem-root flow effects also depend on other conditions such as soil moisture conditions. We simply want to indicate that the difference between LHC and HAPEX is mainly due to rainfall intensity, not other factors. We modified the sentence (line 221) as following to avoid confusion: "This is simply because LHC has more intense rainfall than HAPEX."

4. P11793L27: Is the vapor density changeable in this experiment setup? Humidity is forced to run the model, right? Some sort of nudging (relaxation) method was applied? Please specify the detail of the method in the method section (see Major 3 comment).

Reply: The specific humidity is read in from the meteorological forcing data, while the canopy air temperature is prognostic, so the vapor density is changeable within the canopy. Nudging was not performed. We have indicated this in the method section (lines 109-110).

5. Figure 4: Too small characters to read. (same as Figure 5-9).

Reply: We have modified these figures with larger fonts.

6. Figure 6: Is air temperature changeable? (Similar to above comment about humidity)

Reply: Canopy-top air temperature is read in from the forcing data every 30 minutes, whereas air temperature within the canopy space is a prognostic variable from the SSiB model. We have indicated this in the method section (lines 109-110).

Anonymous Referee #3

Received and published: 20 December 2015

This paper presents a parameterization to represent the impact of stem-root flow, a process that has not been considered by land surface models in the past. While this s an important topic, I have several major comments as follows:

1) The methodology is reasonable, but the lack of field data guiding the selection of parameter values is a major concern I have. Data at the two sites are from bulk measurement with no process-level data to confirm or refute results from the numerical modeling study.

Reply: We fully agree that it is important to have measurements data to validate the modeling on this process eventually. Our current study is an initial attempt, hoping to demonstrate the importance of and uncertainty in current modeling of the stem-root flow processes. We also wish to identify key parameters that lack of verification, and justify for further investigation of this issue through theoretical and observational approach. As indicated in our paper title and in the text, assessing the uncertainty in modeling this process is an important subject of this paper. We have added more discussions in the revision (see other responses below).

2) Related to 1), what kind of field measurement is needed to provide data for such modeling? That might be a real contribution the authors can make through this paper.

Reply: Most of the key parameters are shown in the equations of this paper, including the root distribution, the stemflow to leaf drainage ratio, and root flow velocity. We pointed out this in the Discussion section of the revised manuscript (lines 336-337).

3) Based on results shown, the magnitude of the maximum possible changes caused by stem-root flow is still rather small (relative to the model bias), although qualitatively it does nudge some of the model results closer to observations. This point warrants extensive discussion.

Reply: We agree that introducing this process will not solve all the problems in the soil moisture modeling. As the reviewer pointed out in Specific Comment 1, other factors, such the hydraulic redistribution, as well as the low resolution modeling that pointed out by another reviewer, may also contribute to the deficiencies in soil moisture modeling. We commented these in the discussion section of the revised manuscript. However, a comprehensive discussion on the causes of current modeling deficiencies in soil moisture modeling is out of the scope of this paper.

Here, we also want to provide another supporting evidence for the possible stemflow effect for the reviewer's reference. Figure A shows the correlation between hourly changes in precipitation and soil moisture at Lien-Hua Chih (LHC) station in 2010. The correlations are higher at deeper layers during the stronger rainfall intensities. Such a relationship is a good indication of the stem-root flow mechanism. If the reviewer and editor think this is appropriate, we can include this figure as a supplement.

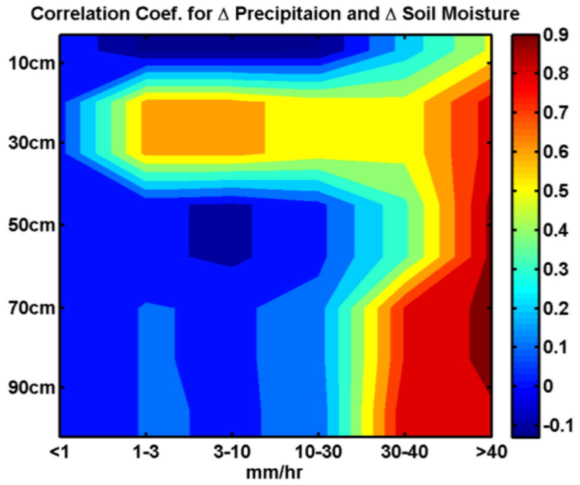

Figure A: Correlation coefficient of hourly △Precipitation and △Soil moisture at LHC, 2010.

4) Since most of the differences between control and experiments are rather small in magnitude, it is important that information on statistical significance be presented in the figures.

Reply: We have conducted the statistical tests for Figures 4 and 5. The soil moisture changes are statistically significant (reached 95% confidence level) in all seasons at LHC. However, at HAPEX, the responses of SM2 and SM3 to the stem-root flow are statistically significant (>95% confidence) only during late summer and autumn (the main growing season and relatively dry soil); whereas the responses in SM1 reached only the 94% confidence level. We indicated this in lines 187-188 and 201-203 of the revised manuscript. Figures 8-9 show that the differences due to different V_s are not that large, but this may be model dependent. We do not want to mislead the community that the measurement of V_S is unimportant at this point, so its statistical test was not conducted.

5) If it is not feasible to collect field data to guide the explicit parameterization of this process, a more appropriate approach is probably to relate soil hydraulic conduct over vegetated land to vegetation density (therefore root density). I suspect that might be a more feasible approach that can be tested in the field. Again, this is an aspect that discussion in the paper and suggestions will make a real contribution to the field.

Reply: We have pointed out the key parameters that lacked of data. As for how to do the measurements, we incline not to get into such details as we are not experts in field experiments. Nevertheless, the reviewer's suggestion looks reasonable and is greatly appreciated.

Specific comments:

1. Abstract is extremely confusing, due to the inappropriate use of terminology "soil water" and "vertical redistribution of soil water". This terminology has specific meaning: In the context of "hydraulic redistribution" (including hydraulic lift and hydraulic descent), water becomes soil moisture before it gets redistributed via plant root, a rather slow process. In this manuscript, it refers to flow through preferred conduit (root channel) during infiltration process and happens during or immediately after precipitation events. The abstract led me to expect something totally different than what the authors end up talking about.

Reply: We are not aware that "soil water" has specific meaning. So, we changed all "soil water" to "soil moisture" (except in "soil water potential") in the abstract and in the text to avoid confusion.

2. Line 84: Deff: either in the main text or in the Appendix, a much better explanation is needed for what Deff represents. Not in mathematical terms, but rather, a physically meaningful explanation.

Reply: Agree. We have added a schematic diagram and brief explanation at the beginning of the Appendix to make the D_{eff} concept easy to apprehension physically. As shown in figure A1 below, the part of soil next to the root flow absorbs water and form a thin, saturated boundary of width λ. A gradient of soil moisture is formed in the transition zone (of width δ), with soil moisture potential decrease from the saturated state, Ψ_s, to that of the bulk soil, Ψ_w. Diffusion of soil moisture toward the bulk soil is directly proportional to this gradient."

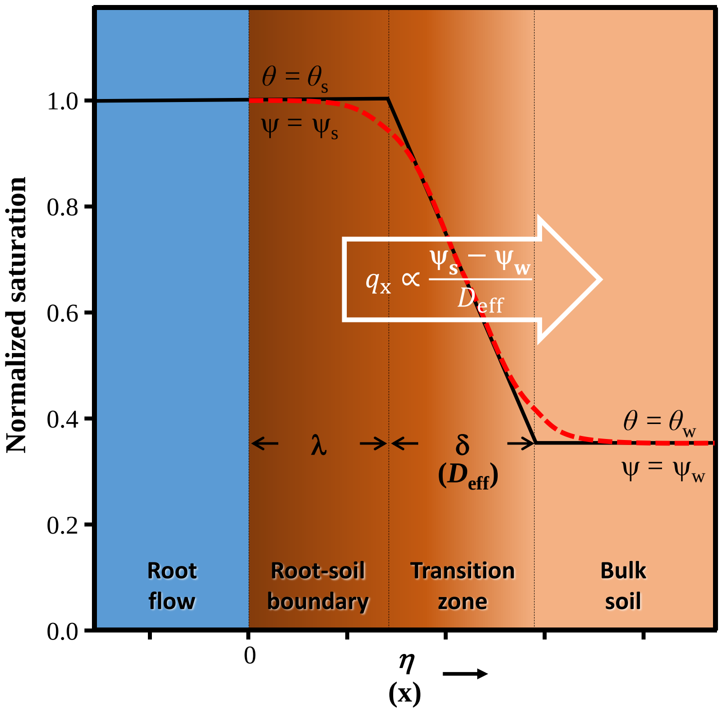

Figure A1: Schematics of the root flow-soil boundary and soil moisture transition for the parameterization of horizontal water flux q_x. The red-dashed line represents the analytical solution, and the black-solid line represents the parameterization. Soil moisture is saturated in the root-soil boundary (width λ), and decreases linearly in the transition zone (δ) before reaching that of the bulk soil.

3. Lines 142- 146 and in other places: The potential role of plant uptake in causing the dynamics of soil moisture in the middle layer is not considered or discussed.

Reply: Yes. We clearly indicated that plant uptake was not considered in this study in lines 208-209 "Note that SSiB does not consider the potential role of plant uptake, which might be potentially important in the middle layer" and 324-326 "On the other hand, the overestimation of the middle-layer soil moisture at HAPEX may be partly contributed from the plant uptake process which was not considered in this study" of the revised manuscript.

4. Lines 160- 167: on comparison between model and observation: Due to the lack of process-level data, there is no way to gage whether this improvement is truly due to improved model physics or due to error compensation related to other model deficit. This point has to be made clear.

Reply: Theoretical studies in many occasions develop in advance before the observation and use the available data to indirectly evaluate their theory. For instance, the development of cloud convective scheme and radiative transfer scheme are developed much earlier than the satellite data are able to make some direct measurements to validate the theory. Otherwise, there will be no scientific development at all. In this paper, we have indicated that in 11796 L15 (lines 330-332 in the revision) that Henderson-Sellers (1996) indicated that a full evaluation of land surface model's simulation against observations can be established only when the initial conditions and all soil parameters are known precisely. We also add that "because this study lack of process-level data to validate, so the improvement should be more prudent to represent" (lines 332-333 in the revision). We wish this paper could stimulate more theoretical study and field measurements which can further evaluate the hypothesis proposed in this study.

5. 1st paragraph on Page 13: what about transpiration increase due to deep soil moisture increase? Should be factored in in this discussion.

Reply: We believe the reviewer was referring to the consideration of deep soil moisture in determining energy-limited versus moisture limited regimes. The original Budyko's curve considered only the top-soil conditions, but the deep soil moisture certainly is very important too. We have added the following statement to stress the role of deep soil moisture (lines 284-285): "Note that this regime separation needs to take into account the contribution of deep soil moisture to transpiration."

Stem-root flow effect on soil-atmosphere interactions and uncertainty assessments

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Abstract

~~Soil water~~ Rainfall that reaches the soil surface can rapidly move~~enter~~ into deeper layers via vertical redistribution of soil moisture ~~water content water~~ through the stem-root flow mechanism. This study develops the stem-root flow parameterization scheme and coupled this scheme with the Simplified Simple Biosphere model (SSiB) to analyze its effects on land-atmospheric interactions. The SSiB model was tested in a single column mode using the Lien Hua Chih (LHC) measurements conducted in Taiwan and HAPEX-Mobilhy (HAPEX) measurements in France. The results show that stem-root flow generally caused a decrease in ~~the~~ soil moisture ~~content~~ at the top soil layer and moistened the deeper soil layers. Such soil moisture redistribution results in substantial ~~significant~~ changes in heat flux exchange between land and atmosphere. In the humid environment at LHC, the stem-root flow effect on transpiration was minimal, and the main influence on energy flux was through reduced soil evaporation that led to higher soil temperature and greater sensible heat flux. In the Mediterranean environment of HAPEX, the stem-root flow substantially~~significantly~~ affected plant transpiration and soil evaporation, as well as associated changes in canopy and soil temperatures. However, the effect on transpiration could be either ~~be~~ positive or negative depending on the relative changes in the soil moisture ~~watermoisture content~~ of the top soil versus deeper soil layers due to stem-root flow and soil moisture diffusion processes.

Key words: stemflow, root flow, soil moisture, evapotranspiration, land-atmospheric interaction, SSiB

1. Introduction

The water stored in the land system is a key factor controlling many physical processes and feedback between the land and atmosphere. Soil moisture is a source of water for the atmosphere through processes that lead to evapotranspiration, including bare soil evaporation, plant transpiration and evaporation from other surfaces such as leaves, snow, etc. The rainfall redistribution process in forest systems affects soil ~~water~~ moisture amount and its distribution (McGuffie et al., 1995; Chase et al., 1996; Chase et al., 2000; Zhao et al., 2001). Rain water entering the forest is redistributed via several pathways before reaching the forest floor, e.g., some is intercepted by the canopy and some reaches the soil as throughfall. A significant amount of rainwater intercepted by the canopy can flow down along tree stems and reach the forest floor in a process termed stemflow. The efficiency of stemflow varies with plant species, seasons, meteorological conditions, rainfall intensity, and canopy structure (Levia and Frost, 2003; Levia and Germer, 2015). Johnson and Lehmann (2006) summarized various field measurements and showed that the fraction of precipitation that becomes stemflow ranges from 0.07% to 22%.

In contrast to the throughfall that infiltrates slowly through the top soil, stemflow can continue via the root system (hereafter called the “stem-root flow”) and quickly reach deep soil layers and the water table (Liang et al., 2007; 2009). It has long been recognized that the stem-root flow can help to store water in deeper soil layers and thus create favorable conditions for plant growth under arid conditions (Návar, 1993; Li et al., 2009). Soil ~~water~~ moisture redistribution by stem-root flow not only affects vegetation growth but also land evapotranspiration and runoff (Neave and Abrahams, 2002). Furthermore, the enhanced water penetration can significantly alter groundwater recharge. Taniguchi et al. (1996) showed that in a pine forest, the stem-root flow contributed approximately 10–20% of annual groundwater recharge even with a stemflow-to-precipitation ratio of only 1%.

Stem-root flow effects have not been considered in most land-surface schemes of climate models. Tanaka et al. (1996) developed a model to evaluate the effect of stem-root flow on groundwater. This model is yet to be implemented in current land surface models. Li et al. (2012) pointed out that stemflow hydrology and preferential flow along roots are intimately linked, but direct integration of these processes into land models, to our knowledge, has not been reported.

In this paper, we parameterized the stem-root flow processes in a land surface model named the Simplified Simple Biosphere Model (SSiB; Xue et al., 1991), and analyzed how stem-root flow affects soil moisture and whether this effect is significant enough to influence atmospheric processes. Soil moisture data from two sites, located at Lien Hua Chih, Taiwan (LHC) and Bordeaux/Toulouse, France (from the HAPEX-Mobilhy experiment, hereafter called HAPEX), were collected for model evaluation. The two sites represent different climate regimes and terrestrial ecosystem, and stem-root flow modifies their surface energy and water processes in somewhat dissimilar ways.

2. Methodology

2.1 The stem-root flow model

In the original SSiB land surface model (Xue et al., 1996), vertical soil ~~water~~ moisture movement is described by the diffusion equations:

$$\frac{\partial \theta_1}{\partial t} = \frac{1}{D_1}\left[P + Q_{12} - E_{SE} - b_1 E_{TR,1}\right]$$
$$\frac{\partial \theta_2}{\partial t} = \frac{1}{D_2}\left[-Q_{12} + Q_{23} - b_2 E_{TR,2}\right] \quad (1)$$
$$\frac{\partial \theta_3}{\partial t} = \frac{1}{D_3}\left[-Q_{23} + Q_3 - b_3 E_{TR,3}\right]$$

where the subscripts 1, 2 and 3 are indices of the top, middle, and bottom soil layers, respectively; θ is the soil ~~water~~ moisture content, expressed as a fraction of the saturated value; D is soil thickness; P is effective precipitation flux on the soil surface, composed of the direct throughfall and the throughfall from leave-intercepted rainfall (cf. Fig. 1); $Q_{ij} = -k[\partial\Psi/\partial z + 1]$ is the flux of water between the i^{th} and j^{th} layers, and is defined to be positive in an upward direction; Ψ (in m) is the soil water potential; E_{SE} is the evaporation rate of bare soil; i is the soil layer index; $E_{TR,i}$ is the transpiration rate in soil layer; b_i is the proportionality factor that accounts for root distribution; Q_3 is the water flux entering the water table. The similar approach has been used by many land surface models. Note that the middle soil layer can be divided into more sublayers with similar formula as used for the middle layer. In these equations, the transfer velocity Q_{ij} considers only the soil diffusion flow. This study develops the parameterizations that include the stem-root flow mechanism which provides a "bypass" for water to channel through the soil on root surfaces (Fig. 1). The stemflow reaching the top soil layer, q_0, is often represented as a fraction of the total precipitation (or, more precisely, the leaf drainage) such that direct rainfall entering the soil becomes

$$P' \equiv P - q_0. \quad (2)$$

By relating the stemflow to leaf drainage, there is an implicit threshold for stemflow initiation that corresponding to the threshold of leaf drainage.

After entering the soil, the root flow is divided into a downward transfer flux q_z (within the root system) and a lateral transfer flux q_x (from the root surface to the soil). These two fluxes can be parameterized as following:

$$q_{z,i} = \alpha_z A_i h_i V_s \tag{3}$$

$$q_{x,i} = \begin{cases} \alpha_x R_i A_i K(\Psi_i)\left(\frac{\Psi_i - \Psi_s}{D_{\text{eff}}}\right), & \text{if } h_i > 0 \\ 0\,, & \text{if } h_i = 0 \end{cases} \tag{4}$$

where α_z and α_x are proportionality coefficients; A_i (in $m^2\ m^{-3}$) is the total root surface area density that varies with vegetation types (Böhm, 1979; Zhang et al., 2005; Li et al., 2013); h_i (in m) is the thickness of water on the root surface; V_s (in m s^{-1}) is the terminal velocity of root flow; R_i (in m) is the root length; K (in m s^{-1}) is the hydraulic conductivity of the soil; Ψ_s (in m) is the soil water potential at saturation; Ψ_i (in m) is the soil water potential; and D_{eff} (in m) is the effective thickness of the water-soil interface. Derivation of D_{eff} is described in the appendix. Due to a lack of observational data, we used a vertically uniform root distribution. However, different root depths were used based on the measurements (100 cm for LHC and 140 cm for HAPEX). Note that $q_0 = q_{x,1} + q_{z,1}$ according to the mass conservation principle. From Eqs. (1), (2), and (4), we have:

$$\begin{aligned} \frac{\partial \theta_1}{\partial t} &= \frac{1}{D_1}\left[P' + Q_{12} - E_{SE} - b_1 E_{TR,1} + q_{x,1}\right] \\ \frac{\partial \theta_2}{\partial t} &= \frac{1}{D_2}\left[-Q_{12} + Q_{23} - b_2 E_{TR,2} + q_{x,2}\right] \\ \frac{\partial \theta_3}{\partial t} &= \frac{1}{D_3}\left[-Q_{23} + Q_3 - b_3 E_{TR,3} + q_{x,3}\right] \end{aligned} \tag{5}$$

T~~In Eq. (3), t~~he changes in root surface water thickness h_i obey~~s~~ the mass conservation principle and thus~~is determined by the input root flow amount (q_0), total root surface area in the soil layer,~~ ~~is~~are controlled by the vertical and horizontal fluxes of root flow. Its tendency can be described as:

$$\frac{dh_i}{dt} = \begin{cases} \frac{(q_{z,i-1} - q_{z,i} - q_{x,i})}{A_i R_i}, & \text{if } h_i > 0 \\ 0\,, & \text{if } h_i = 0 \end{cases} \tag{6}$$

Equations (5) and (6) represent the water budgets in the soil and root flow systems, respectively, and they are linked through the term q_x in Eq. (4).

Stemflow input into the first soil layer (q_0) is represented as a fraction of the leaf drainage (LD), which is the portion of precipitation that is intercepted by the canopy minus leaf evaporation and can be calculated in SSiB. LD is similar to canopy drip in some other models, and is represented mainly as a function of the leaf area index (LAI). The ratio of q_0 to LD depends mainly on plant type, as well as meteorological conditions such as wind speed (Levia and Frost, 2003; Johnson and Lehmann, 2006; André et al., 2008; Siegert and Levia, 2014). Unfortunately, there is still insufficient information to determine the ratio of q_0 and LD. We conducted a series of sensitivity tests with systematically varying ratio between the q_0 to LD to assess the uncertainty.

The stem-root flow parameterization was tested using the offline SSiB, which is a simplified version of the land-biosphere model developed by Sellers et al. (1986). The model recognizes 12 different vegetation types according to Dorman and Sellers (1989), and is set up with 3 soil layers and 1 canopy layer. The SSiB model has 8 prognostic variables: soil wetness for 3 layers; temperature at the canopy, ground surface and deep soil layers; snow depth at ground level; and water intercepted by the canopy. An additional variable – h_i – was added for each soil layer to account for the stem-root flow mechanism. An implicit backward scheme was used to calculate the temperature tendency in the coupling of the lowest atmospheric model layer with SSiB, such that energy conservation between the land surface and the atmosphere was satisfied. Soil temperature was calculated using the force-restore method, and water movement in the soil was described by the diffusion equation as shown in Eq. (5).

Following typical offline simulation procedures for single-column land surface model, in situ atmospheric data were applied to drive the SSiB model in 30 min time resolution. These specified variables include pressure, temperature, humidity, wind speed, net radiation and rainfall. Soil conditions were initialized with each site's measurement data. Fully coupled land surface model typically require a couple of months to over a year to spin up the model, but the spin up time can be shorter when running in off-line (single column) mode and with good initial soil conditions (de Goncalves et al., 2006; Yang et al., 2011; Lim et al., 2012; Angevine et al., 2014). Our simulations applied measurement data for model initialization, and the results show that the soil conditions reached physical balance within a few weeks. So, at the last 10 months results of our simulations are reliable.

2.2 Experimental design and site information

Two sites with different climate and vegetation conditions were selected to test the stem-root flow parameterizations in the SSiB model. The first is a site with warm-to-temperate mountain rainforest condition from the Lien Hua Chi (LHC; 23°55'N, 120°53'E), Taiwan. LHC is located in the Central Mountain Range of Taiwan, with a hilly terrain and a mean altitude of 770 m above sea level in the surroundings. The average annual rainfall at LHC is 2317 mm, with rain falling predominantly in late summer and early autumn (Fig. 2). With ample rainfall, LHC is covered with dense forest with an average canopy height of approximately 17 m. The vegetation cover is comprised of mixed evergreens and hardwood species, including *Cryptocarya chinensis, Engelhardtia roxburghiana*, *Tutcheria shinkoensis*, and *Helicia formosana*. The soil has a loamy texture with an average bulk density of 1.29 g cm^{-3} and a porosity of 0.53 over the top 1.0 m (Chen, 2012). Soil moisture measurements were collected at depths of 10, 30, 50, 70 and 90 cm~~, and hourly precipitation was measured on site~~.

The second is the HAPEX-Mobilhy data collected at the Caumont site (SAMER station No. 3; 43°41'N, 0°6'W) with an elevation of 113 m above sea level and relatively flat terrain. This site has a Mediterranean climate, with an annual rainfall of 856 mm, most of which occurs in spring and winter (Fig. 3). In contrast to the LHC site with dense forest, the HAPEX site is covered mostly with short and sparse soya crops, and the surface albedo stays nearly constant at 0.20 throughout the year (Goutorbe et al., 1989). The soil type is mainly silt, mixed with sand and clay (see Table 1). Soil moisture content was measured every 10 cm from the surface to a depth of 1.6 m using neutron sounding probes on a weekly basis~~; precipitation was recorded at 30 min intervals.~~ (Goutorbe, 1991; Goutorbe and Tarrieu, 1991). Note that the HAPEX data have higher vertical resolution in the soil column but lower temporal resolution compared with the LHC data. To simplify comparisons, the soil moisture data were converted into three vertical layers. For the HAPEX data, the top (SM1), middle (SM2) and bottom (SM3) layers correspond to the 0–20 cm, 20–50 cm, and 50–150 cm depths, respectively. For LHC, SM1 corresponds to a depth of 10 cm, SM2 is the average of the 30 cm and 50 cm soil layers, and SM3 corresponds to a depth of 90 cm.

Figures 2 and 3 show the seasonal variations of precipitation and soil moisture at different depths. It is generally expected that soil moisture response to rainfall should be faster in the upper than in the lower layers. However, the LHC measurements (Fig. 2) showed that the soil moisture fluctuation was stronger in the middle layer than in the upper layer during the dry season when the soil moisture was not saturated. Fluctuations were not obvious in rainy seasons when SM2 and SM3 are almost saturated. This phenomenon is likely an indication of the preferential flow due to the root flow mechanism. This phenomena, however, was not observed in the HAPEX data (Fig. 3), which may be due to the coarse temporal resolution (weekly) of the data or a weaker root flow effect from the soya crop, and the latter will be discussed later.

To test the response of soil moisture to precipitation in these two sites using the modified SSiB model, a set of parameters have to be selected. These include the soil and terrain properties listed in Table 1, as well as the monthly LAI coefficients in Table 2. In addition, some parameters in Eqs. (3)-(6) have to be decided. Two required but little-known parameters are the root-flow velocity V_s and the stemflow to leaf drainage ratio (SLR; i.e., q_0/LD). The root-flow velocity V_s is related to root structure and soil texture, but such information is very limited. Studies have indicated that water flow in the root-channel is approximately 100 times higher than the soil diffusion flow (Beven and Germann, 1982; Liu et al., 1994; Jarvis and Dubus, 2006; Köhne et al., 2009; Gerke, 2014). The maximum soil diffusion flow can be represented by the saturated hydraulic conductivity, which was measured as 4×10^{-6} m s^{-1} at HAPEX and 1×10^{-6} m s^{-1} at LHC. Therefore, we set the root-flow velocity V_s as 10^{-4} m s^{-1} in the simulation, and will discuss the associated uncertainty later.

The SLR value depends on a number of parameters as discussed in the previous section. This study evaluated SLR-introduced uncertainty by conducting sensitivity tests with systematically varying SLR from 0 to 100%, and identified optimal value that yielded the best soil moisture profiles compared with the observations. The optimal SLR value for the HAPEX experiment was approximately 50%, compared with 90% for the LHC case. These values reflect the large contrast in leaf coverage and plant type between the two sites. In these experiments, we set A_i to 0.5 m^2 m^{-3} based on the Li et al. (2013) and the proportionality coefficients, α_z and α_x, are set to 1. The uncertainty discussion for V_s and SLR should include the uncertainty caused by these parameters. When more observational data are available, we could revisit these issues further. All simulations used integration time step of 30 minutes.

3. Effect of stem-root flow on soil moisture

The modified SSiB model was used to simulate the intra-annual variations in soil conditions for the 2010 LHC case and the 1986 HAPEX case. For the LHC case, the simulation well captured the soil moisture increase associated with precipitation events followed by rapid drying (Fig. 4). Changes in SM1, SM2 and SM3 all reached the 95% confidence level in all seasons. In many instances, the simulated soil moisture fluctuation was stronger in the middle layer than in the top or bottom layers, as found in the observations. The shading shows the range of ~~uncertainty due to different SLRs (from 0 to 100%).~~ values enclosed by the two extremes of SLR (i.e., 0% and 100%). Results with other SLR ratios (not shown) generally lie within these limits but may occasionally fall out of bound, indicating some nonlinearities. When SLR is zero, which has no stem flow effect and is referred to as the control run in this paper, the soil moisture of the middle layer is very low and fluctuates less in response to rainfall events (Fig. 4). The simulation generally underestimated the soil moisture in the bottom layer even with the root-flow mechanism. In the top layer, the model overestimated soil moisture in spring and winter, but underestimated it during autumn. Such discrepancies are generally less substantial when the stem-root flow mechanism is included, as indicated by the generally lower bias and root-mean-square error shown in Table 3. The possible causes of error will be elaborated in the discussion section.

For the HAPEX case, the simulations also well captured the seasonal cycle as well as the sharp fluctuations in the top layer (Fig. 5). The responses of SM2 and SM3 to the stem-root flow are statistically significant (>95% confidence) during late summer and autumn (the main growing season and relatively dry soil); whereas the responses in SM1 reached only 94% confidence level. Without the stem-root flow mechanism, soil moisture was generally overestimated in the two upper layers and underestimated in the bottom layer, except during April and May when all layers were too dry. When stem-root flow with SLR=50% was considered, the model performed better in all layers (see Table 3). Stem-root flow with a much higher SLR (e.g., SLR=100%) produced worse results for soil moisture in the surface and middle layers. Note that SLR=50% produced the driest middle layer, indicating that the stem-root flow effect is nonlinear because both stem-root flow and diffusion, as well as their interactions, ~~such as the potential role of plant uptake,~~ play role in soil moisture variations. Note that SSiB does not consider the potential role of plant uptake, which might be potentially important in the middle layer. In the bottom layer, more accurate soil moisture was obtained with SLR=100%, but this does not necessarily mean that the stem-root flow was underestimated. The overestimation of soil moisture in SM1 and the underestimation in SM3 in spring~~,~~ may be coupled, due to mechanisms that are missing in our model. This issue will be elaborated in the discussion section~~We suspect that the discrepancy in the bottom layer was caused mainly by the excess drainage of soil water from the lower boundary in the model and will elaborate this issue in the discussion section~~.

It is also worth mentioning that both the observation and simulation showed weaker soil moisture fluctuations in the middle than in the surface layer, a feature very different from the LHC case. It is likely that there is a weaker stem-root flow associated with plant and soil types in the HAPEX case. Figures 4 and 5 demonstrate that the strength of the stem-root flow is greater in LHC, with associated changes in soil moisture of up to 0.1 $m^3\ m^{-3}$ compared with the maximum changes of 0.05 $m^3\ m^{-3}$ at

HAPEX. This is simply because LHC has more intense rainfall than HAPEX~~This stronger stem-root flow effect was mainly associated with the more intense rainfall at LHC~~.

4. Effect of stem-root flow on energy flux

The results in last section show that stem-root flow can alter the vertical profile of soil moisture. It is important to know whether such a modification has significant effects on evapotranspiration and associated interactions between the land and atmosphere. The soil moisture in the top soil layer in the LHC case generally decreased due to stem-root flow, except in some instances (e.g., mid-September, the later dry season) when the enhanced moisture storage in the deep layers replenish the moisture in the drying surface soil through moisture diffusion. The changes in plant transpiration, however, were insignificant (red curve in Fig. 6a), as this process is associated with soil moisture not only in the top layer but also in the deeper layers that are within the reach of the root system. Therefore, the effect of surface layer drying on transpiration may be compensated by the moistening of the lower layers. Soil moisture in these layers are well above the wilting point to support the normal transpiration. Meanwhile, the drying of the surface soil resulted in less soil evaporation (Fig. 6a), which heavily relies on soil moisture near soil surface, and thus weaker the total latent heat release (see Table 4 for the mean and maximum changes in daily temperatures and energy fluxes). This led to a higher soil surface temperature and consequently stronger sensible heat flux (blue curve in Fig. 6b), which resulted in warmer air (magenta curve in Fig. 7b) and thus stronger rainwater evaporation from the leaf surface (green curve in Fig. 6a).

~~The drying of the surface soil resulted in less soil evaporation (Fig. 6a) and thus weaker latent heat release (see Table 4 for the mean and maximum changes in daily temperatures and energy fluxes). This led to a higher soil surface temperature and consequently stronger sensible heat flux (blue curve in Fig. 6b), which resulted in warmer air (magenta curve in Fig. 7b) and thus stronger rainwater evaporation from the leaf surface (green curve in Fig. 6a). However, changes in plant transpiration were insignificant (red curve in Fig. 6a), as this process is associated with soil moisture not only in the top layer but also in the deeper layers that are within the reach of the root system. Therefore, the effect of surface layer drying on transpiration may be compensated by the moistening of the lower layers. Furthermore, in the LHC case, the moisture of all soil layers was maintained well above the wilting point, and normal transpiration could be maintained throughout the year. The decrease in latent heat therefore resulted mainly from changes in soil evaporation in the LHC case.~~

In the HAPEX case, the stem-root flow caused a general drying of the top soil, except for a brief period in mid-October (Fig 7a). However, responses in soil evaporation were not as straightforward as in the LHC case. For example, in late July (just after the start of the growing season) there was a spike in the evaporation but a reduction in the moisture of the top soil layer (blue curve in Fig 7a). As wind speed is the same for both cases, the increase in soil evaporation must be due to either a higher soil temperature and/or a lower water vapor density in the air near the soil surface. This was indeed the case (magenta and black curves in Fig. 7b) and found to be driven by changes in transpiration.

Soil moisture in the HAPEX case was generally much lower than in the LHC case and occasionally fell below the wilting point. The stomatal resistance that controls transpiration is very sensitive to the soil moisture near the wilting point. As such, a slight decrease in the moisture of the top soil layer can dramatically reduce transpiration. When soil moisture approached the wilting point in late July, plant transpiration reduced sharply in response to the stem-root flow effect (red curve in Fig. 7a). Such a change in plant transpiration caused an increase in the air temperature near the soil surface (magenta curve in Fig. 7b) and a decrease in air humidity, which increased soil evaporation (blue curve in Fig 7a). In early August, however, soil ~~water~~ moisture accumulated in the bottom layer through the stem-root flow (cf. Fig. 5c) and the stomatal resistance began to decrease such that transpiration recovered and soon dominated the overall evapotranspiration throughout the rest of the growing season. The increased transpiration also caused a reduction in air temperature and surface temperature and thus the associated sensible heat flux (blue curve in Fig. 7b). During late August to mid-September, surface soil moisture was so low in some instances (cf. Fig 5a), transpiration was shutdown with or without the stem-root flow effect. In these instances, the net energy flux was controlled by soil evaporation (Fig 7b).

5. Discussion

The above analyses indicate that stem-root flow affects the energy flux mainly through changing the balance between surface soil evaporation and sensible heat fluxes in the humid environment of

LHC, and through changing plant transpiration and sensible heat fluxes over the relatively dry environment at HAPEX. The associated changes in annual energy flux to the atmosphere are strongly positive at LHC, but nearly balanced at HAPEX. However, the magnitude of the changes of the individual energy flux component was significantly higher for HAPEX (peaked at approximately -67 and +51 W m^{-2} for transpiration and sensible heat, respectively) than for LHC (peaked at approximately -16 and +31 W m^{-2} for evaporation and sensible heat, respectively) due to its drier Mediterranean environment.

Another interesting contrast between the two cases is the relationship between sensible heat and total heat (sensible heat plus latent heat). In the LHC case, the responses of sensible heat and total heat to the stem-root flow are generally of the same sign (Fig. 6b), whereas they have opposite signs in the HAPEX case (Fig. 7b). Furthermore, the net change in heat flux is dominated by sensible heat at LHC but by latent heat at HAPEX. Budyko (1974) proposed two main evapotranspiration regimes: soil moisture-limited and energy-limited. As summarized by Seneviratne et al. (2010), when soil moisture remains above a critical value, the fraction of evapotranspiration of the total energy flux is independent of the soil moisture content (energy-limited regime); below the critical soil moisture value, the soil moisture content provides a first-order constraint on evapotranspiration (soil moisture-limited regime). Therefore, the evapotranspiration responses to the stem-root flow as discussed above imply that HAPEX is in the soil moisture-limited regime, whereas LHC is in the energy-limited regime. Note that this regime separation needs to take into account the contribution of deep soil moisture to transpiration.

Regarding the partition of water transport, recent studies (e.g., Jasechko et al., 2013; Good et al., 2015; Wei et al., 2015) explored the dominant role of transpiration in ecosystem evapotranspiration. The results of this work partially concur with these studies. In other words, the stem-root flow in the plant-soil system could enhance the transpiration, and reduce the soil evaporation, which regulated the partition of evapotranspiration.

A number of PILPS studies, including the PILPS-HAPEX experiment (Boone and Wetzel, 1996; Henderson-Sellers, 1995; Shao et al., 1996; Xue et al., 1996) consistently demonstrated that the current land model parameterizations have the weakness in simulating the soil moisture in the dry season. This study by introducing a parameterization on the stem-root flow mechanisms, wish to help solve this deficiency. With the stem-root flow mechanism, the soil moisture will redistribute in vertical, leading to better simulated results in each layer, which is important for the evapotranspiration partition.

By including the stem-root flow mechanism, the land surface model appears to better simulate the vertical distribution of soil watermoisture. However, significant discrepancies still exist in the model based on comparisons with observed data. The discrepancies may be associated with uncertainties in soil-related physical parameters, such as a few that we listed in the earlier sections. For example, a wide range of values have been reported in the literature for the parameter V_s. In the above simulations, we assigned $V_s = 10^{-4}$ m s^{-1}, which is probably at the low end of the documented values.

An additional simulation was performed using a 10-fold higher V_s value (i.e., $V_s = 10^{-3}$ m s^{-1}), and the resulting soil moisture changes were similar to those presented in Figs. 4 and 5 with differences of only a few percent and thus are barely legible in Figs. 8 and 9. When a smaller value of $V_s = 10^{-5}$ m s^{-1} was used, the effect of stem-root flow on soil moisture was similar but the magnitude of the changes was reduced by approximately 50%. These sensitivity tests give an indication of the uncertainties associated with V_s.

Even with the maximum V_s, the simulated soil moistures at the bottom layer are still lower than observed. More realistic values for other soil physical parameters and/or optimizations of these parameters are required. Xue et al. (1996) pointed out that land surface models such as SSiB are quite sensitive to soil-type dependent parameters such as the hydraulic conductivity at saturation and the coefficient used to calculate soil water potential. Such parameters can vary significantly from place to place, and sufficient information to assign appropriate values is usually lacking. This is particularly true for LHC where the soil types exhibited a rather inhomogeneous vertical distribution, and some humus layers could exist to retard surface drainage. Another critical issue is the treatment of water flow across the bottom soil layer. In our current model, soil ~~water~~ moisture can leave the bottom layer with a fixed efficiency, but no recharge from the water table below is allowed. These issues might cause the model to underestimate the soil moisture in the bottom layer (regardless of the presence of stem-root flow), which occurred in both the LHC and HAPEX simulations (cf. Figs. 4c and 5c). ~~o~~On the other hand, the overestimation of soil moisture in SM1 and the underestimation in

SM3 in spring~~,~~ at LHC (Fig 4) could also be explained by missing mechanisms such as hydraulic redistribution (cf. Brooks et al., 2002), which provides a bypass of soil ~~water~~moisture through the inside of the root rather than the exterior surface of the root as in the case of stem-root flow transport~~.~~. On the other hand, the overestimation of the middle-layer soil moisture at HAPEX may be partly contributed from the plant uptake process which was not considered in this study. Besides, due to a lack of observational data, we used a uniform vertical distribution of root, which might be the other issue on different effects on two sites from stem-root flow. In recent years, U.S. Department of Energy has supported a number of projects to measure the root vertical distribution. With more data becoming available, we should be able to more realistically assess its effects.

Henderson-Sellers (1996) indicated that a full evaluation of land surface model's simulation against observations can be established only when the initial conditions and all soil parameters are known precisely. Because this study lacks of process-level data, so the improvement should be more prudent to represent. Since this exploratory study focuses on introducing the stem-root flow mechanisms in a land surface model and test its possible impact, we will not further test the uncertainty due to other parameters in this paper. We hope more relevant measurements (such as the root distribution, stemflow to leaf drainage ratio, and root flow velocity) will provide useful information to study these issues further.

6. Conclusion

In this study, a stem-root flow mechanism, which provides an efficient water channel for rain to penetrate into deep soil, was formulated and implemented into an offline version of the SSiB land-atmosphere model. The model was used to simulate soil moisture variation at two sites with different climate and ecology conditions: LHC with a mountain rainforest climate and HAPEX with a Mediterranean climate. The results showed that the inclusion of the stem-root flow mechanism substantially improved the capability of the model to simulate vertical soil moisture profiles. Stem-root flow generally caused a drying of the top soil layer (upper 20 cm) and a moistening of the bottom layer (below 50 cm) in the model. On a few occasions, such as after a long dry period, the surface layer may be less dry than without the stem-root flow due to greater water supply from the lower layers. The middle soil layer at LHC was also moistened and, in many instances during rainfall events, the moisture in this layer fluctuated more intensely than in the top layer in response to the stem-root flow. However, in the HAPEX case, the middle layer became dryer with less fluctuation. Due to differences in plant and soil types, the strength of the stem-root flow was greater at LHC than at HAPEX.

The change in soil moisture associated with the stem-root flow leads to significant modifications in heat and moisture fluxes between the land and atmosphere. The general drying of the surface soil leads to reduced soil evaporation and thus increased soil temperature. Plant transpiration at LHC was not significantly affected by the stem flow because the soil moisture content was maintained well above the wilting point. Therefore, the stem-root flow related to energy flux between the soil and atmosphere is mainly controlled by sensible heat. In this sense, LHC may be considered as having an energy-limited evapotranspiration regime. In contrast, the HAPEX soil (especially the top layer) was generally dryer and sometimes fell below the wilting point. Plant transpiration can thus be substantially affected by the stem-root flow. Changes in transpiration lead to changes in air temperature, which, in turn, influence soil temperature. This effect is stronger than that resulting from the soil evaporation associated with changes in the soil moisture of the top soil layer. At the HAPEX site, evapotranspiration was more soil moisture-limited than energy-limited, and its net change in heat flux associated with the stem-root flow was dominated by latent heat. While the stem-root flow effect on soil moisture was weaker there than at LHC, the energy flux exchanges were actually stronger due to the sensitive transpiration process.

Through the impact on soil moisture profiles, stem-root flow can significantly affect evaporation and transpiration processes. The associated changes in moisture and energy fluxes between the land and atmosphere may affect boundary-layer stability and convective processes. As evapotranspiration returns as much as 60% of the precipitation back to the atmosphere over land (Oki and Kanae, 2006), the stem-root flow mechanism may be a key factor in controlling the surface water budget and hydrological cycle. The enhanced storage of water in deep soil layers may have a long-term effect on the climate system. These issues are worthy of further investigation through more relevant observations and testing by coupling the stem-root flow mechanism with global climate models.

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Appendix. Derivation of D_{eff}

The parameter D_{eff} in Eq. (4) was derived in a similar fashion as in Zimmerman and Bodvarsson (1991). As shown in Figure A1, the part of soil next to the root flow absorbs water and form a thin, saturated boundary of width λ. A gradient of soil moisture is formed in the transition zone (of width δ), with soil water potential decrease from the saturated state, Ψ_s, to that of the bulk soil, Ψ_w. Diffusion of soil moisture toward the bulk soil is directly proportional to this gradient.

The soil ~~water~~ moisture horizontal (x-direction) movement can be express as following:

$$\rho \frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}\left[K(\Psi)\frac{\partial\Psi}{\partial x}\right] \quad \text{(A1)}$$

where ρ is soil porosity; θ is the ratio of soil ~~water~~ moisture content to its saturated state; K (in m s^{-1}) is the hydraulic conductivity of the soil; and Ψ (in m) is the soil water potential. Equation (A1) is subject to the following initial and boundary conditions:

$$\theta(0,t) = 1,\ \theta(x,0) = \theta_w\ ,\ \theta(x \to \infty, t) = \theta_w\ . \quad \text{(A2)}$$

The first condition means that, when the root-flow occurs, soil at the root-soil interface ($x = 0$) is saturated. The next two conditions specify the initial bulk soil ~~water~~ moisture content, θ_w, and this value remains unaffected by the root flow at a far distance from the root-soil interface throughout the integration time period.

The hydraulic conductivity and water potential of the soil can be represented with the empirical relationship of Clapp and Hornberger (1978):

$$K(\Psi) = K_s(\Psi / \Psi_s)^{-\frac{3}{b}+2} \tag{A3}$$

$$\Psi = -\Psi_s \theta^b \ , \tag{A4}$$

where K_s (in m s^{-1}) is hydraulic conductivity at saturation; b is an empirical constant dependent on the soil type. By introducing a similarity variable η and two normalized variables $\widehat{\Psi}$ and $\widehat{K}$:

$$\eta \equiv \sqrt{\frac{\rho}{K_s \Psi_s t}}, \ \widehat{\Psi} \equiv \frac{\Psi}{\Psi_s}, \ \text{and} \ \widehat{K} \equiv \frac{K}{K_s}, \tag{A5}$$

Eq. (A1) can be transformed into

$$\frac{d}{d\eta}\left(\widehat{K}(\widehat{\Psi})\frac{d\widehat{\Psi}}{d\eta}\right) + \frac{\eta}{2}\frac{d\theta}{d\eta} = 0, \tag{A6}$$

whereas the initial and boundary conditions in Eq. (A2) reduced to

$$\theta(0) = 1, \quad \theta(\eta \to \infty) = \theta_w \tag{A7}$$

Zimmerman and Bodvarsson (1991) showed that the solution for Eq. (A6) with conditions in Eq. (A7) can be approximated as:

$$\begin{cases} \theta = 1, & \text{if } 0 \le \eta \le \lambda \\ \theta = 1 - (1-\theta_w)\frac{\eta-\lambda}{\delta}, & \text{if } \lambda < \eta \le \lambda + \delta \\ \theta = \theta_w, & \text{if } \lambda + \delta < \eta < \infty \end{cases} \tag{A8}$$

where

$$\delta = 2\sqrt{\frac{b}{1+\frac{2}{b(1-\theta_w)}}} \quad \text{and} \quad \lambda = \frac{\delta}{b(1-\theta_w)} \tag{A9}$$

That is, within the root-soil boundary ($0 \leq \eta \leq \lambda$), θ is saturated (=1); whereas in the transition zone ($\lambda < \eta \leq \lambda + \delta$), θ decreases linearly from 1 to θ_w. Here, δ is the "effective thickness" of diffusion in the η cooridnate, and it can be revert back to the *x* coordinate using the similarity conversion in Eq. (A5):

$$D_{\text{eff}} = \delta\sqrt{\frac{K_s \Psi_s t}{\rho}} \tag{A10}$$

By applying the actual rainfall duration for *t* into Eq. (A10), we calculated the mean values of D_{eff} = 0.005 m for the HAPEX site and D_{eff} = 0.03 m for the LHC site.

Reference

André, F., Jonard, M., and Ponette, Q.: Influence of species and rain event characteristics on stemflow volume in a temperate mixed oak–beech stand, Hydrological Processes, 22, 4455-4466, 10.1002/hyp.7048, 2008.

Angevine, W. M., Bazile, E., Legain, D., and Pino, D.: Land surface spinup for episodic modeling, Atmos. Chem. Phys., 14, 8165-8172, 2014.

Beven, K., and Germann, P.: Macropores and water flow in soils, Water Resources Research, 18, 1311-1325, ~~10.1029/WR018i005p01311,~~ 1982.

Böhm, W.: Methods of studying root systems, Springer-Verlag, 1979.

~~Beven, K., and Germann, P.: Macropores and water flow in soils, Water Resources Research, 18, 1311-1325, 10.1029/WR018i005p01311, 1982.~~

Boone, A. and Wetzel, P. J.: Issues related to low resolution modeling of soil moisture: experience with the PLACE model, Global and Planetary Change, 13, 161-181, 1996.

Brooks, J. R, Meinzer, F. C., Coulombe, R. and Gregg, J.-: Hydraulic redistribution of soil water during summer drought in two contrasting Pacific Northwest coniferous forests. Tree Physiology, 22, 1107-1117, 2002

Budyko, M. I.: Climate and Life, Academic Press, New York, 1974.

Chase, T. N., Pielke, R. A., Kittel, T. G. F., Nemani, R., and Running, S. W.: Sensitivity of a general circulation model to global changes in leaf area index, Journal of Geophysical Research: Atmospheres, 101, 7393-7408, ~~10.1029/95jd02417,~~ 1996.

Chase, T. N., Pielke Sr, R. A., Kittel, T. G. F., Nemani, R. R., and Running, S. W.: Simulated impacts of historical land cover changes on global climate in northern winter, Climate Dynamics, 16, 93-105, ~~10.1007/s003820050007,~~ 2000.

Chen, Y.-Y.: Investigating the Seasonal Variability of Surface Heat and Water Vapor Fluxes with Eddy Covariance Techniques: a Subtropical Evergreen Forest as an Example, Doctoral, Graduate Institute of Hydrological and Oceanic Sciences, National Central University, 149 pp., 2012.

Clapp, R.B. and Homberger, G.M.: Empirical equations for some soil hydraulic properties, Water Resour. Res., 14: 601-604, 1978.

de Goncalves, L. G. G., Shuttleworth, W. J., Burke, E. J. , Houser, P., Toll, D. L., Rodell, M. and Arsenault, K.: Toward a South America Land Data Assimilation System: Aspects of land surface model spin-up using the Simplified Simple Biosphere, J. Geophys. Res., 111, D17110,2006.

Dorman, J. L., and Sellers, P. J.: A Global climatology of albedo, roughness length and stomatal resistance for atmospheric general circulation models as represented by the Simple Biosphere Model (SiB), Journal of Applied Meteorology, 28, 833-855, ~~10.1175/1520-0450(1989)028<0833:agcoar>2.0.co;2,~~ 1989.

Gerke, H.: Bypass flow in soil, in: Encyclopedia of Agrophysics, edited by: Gliński, J., Horabik, J., and Lipiec, J., Encyclopedia of Earth Sciences Series, Springer Netherlands, 100-105, 2014.

Good, S. P., Noone, D., and Bowen, G.: Hydrologic connectivity constrains partitioning of global terrestrial water fluxes, Science, 349(6244), 175–177, ~~doi:10.1126/science.aaa5931,~~ 2015.

Goutorbe, J.-P., J. Noilhan, C. Valancogne, and Cuenca, R. H.: Soil moisture variations during HAPEX-MOBILHY, Annals of Geophysics, 7, 415-426, 1989.

Goutorbe, J. P.: A Critical assessment of the Samer network accuracy, in: Land Surface Evaporation, edited by: Schmugge, T., and André, J.-C., Springer New York, 171-182, 1991.

Goutorbe, J. P., and Tarrieu, C.: HAPEX-MOBILHY data base, in: Land Surface Evaporation, edited by: Schmugge, T., and André, J.-C., Springer New York, 403-410, 1991.

Henderson-Sellers, A., Pitman, A. J., Love, P. K., Irannejad, P. and Chen, T. H.: The Project for Intercomparison of Land Surface Parameterization Schemes (PILPS): Phases 2 and 3. Bull. Amer. Meteor. Soc., 76, 489-503, 1995

Henderson-Sellers, A.: Soil moisture simulation: Achievements of the RICE and PILPS intercomparison workshop and future directions. *Global Planet. Chang.*, **13**, Issues 1–4, 99-115~~. http://dx.doi.org/10.1016/0921-8181(95)00035-6~~,1996

Jarvis, N. J., and Dubus, I. G.: State-of-the-art review on preferential flow, www.eu-footprint.org, 60 pp., 2006.

Jasechko, S., Sharp, Z. D., Gibson, J. J., Birks, S. J., Yi, Y. and Fawcett, P. J.-: Terrestrial water fluxes dominated by transpiration, Nature, 496(7445), ~~347–350, doi:10.1038/nature11983,~~ 2013.

Johnson, M. S., and Lehmann, J.: Double-funneling of trees: stemflow and root-induced preferential flow, Ecoscience, 13, 324-333, 2006.

Köhne, J. M., Köhne, S., and Šimůnek, J.: A review of model applications for structured soils: a) Water flow and tracer transport, Journal of Contaminant Hydrology, 104, 4-35, ~~http://dx.doi.org/10.1016/j.jconhyd.2008.10.002,~~ 2009.

Levia, D. F., and Frost, E. E.: A review and evaluation of stemflow literature in the hydrological and biochemical cycles of forested and agricultural ecosystems., Journal of Hydrology, 274, 1-29, 2003.

Levia, D. F., and S. Germer, . S.: A review of stemflow generation dynamics and stemflow-environment interactions in forests and shrublands, Rev. Geophys., 53, 673–714, doi:10.1002/2015RG000479,2015.

Li, J., He, B., Chen, Y., Huang, R., Tao, J., and Tian, T.: Root distribution features of typical herb plants for slope protection and their effects on soil shear strength, Transactions of the Chinese Society of Agricultural Engineering, 29, 144-152, 2013.

Li, X.-Y., Yang, Z.-P., Li, Y.-T., and Lin, H.: Connecting ecohydrology and hydropedology in desert shrubs: stemflow as a source of preferential flow in soils, Hydrology and Earth System Sciences, 13, 1133-1144,2009.

Li, X.-Y., Lin, H., and Levia, D. F.: Coupling ecohydrology and hydropedology at different spatio-temporal scales in water-limited ecosystems, in: Hydropedology, edited by: Lin, H., Academic Press, Boston, 737-758, 2012.

Liang, W.-L., Kosugi, K. i., and Mizuyama, T.: Heterogeneous soil water dynamics around a tree growing on a steep hillslope, Vadose Zone J., 6, 879-889, 10.2136/vzj2007.0029, 2007.

Liang, W.-L., Kosugi, K. i., and Mizuyama, T.: A three-dimensional model of the effect of stemflow on soil water dynamics around a tree on a hillslope. J. of Hydro., 366(1-4):, 62-75., doi:10.1016/j.jhydrol.2008.12.009,2009.

Lim, Y.- J., Hong, J., Lee, T.-Y.: Spin-up behavior of soil moisture content over East Asia in a land surface model, Meteorology and Atmospheric Physics, 118(3), 151-161, 2012.

Liu, I.-W. Y., Waldron, L. J., and Wong, S. T. S.: Application of nuclear magnetic resonance imaging to study preferential water flow through root channels, Tomography of Soil-Water-Root Processes, 135-148, 10.2136/sssaspecpub36.c11, 1994.

Liu, S., Hu, F., Zhang, C. Liu, H. Liang, F.: Research of spin-up processes of land surface model of

RAMs for different initial soil parameter. Acta Meteorologica Sinica, 66(3):, 351-358, 2008.

Lim, Y.- J., Hong, J., Lee, T.-Y.: Spin-up behavior of soil moisture content over East Asia in a land surface model, Meteorology and Atmospheric Physics, 118(3), 151-161,2012.

McGuffie, K., Henderson-Sellers, A., Zhang, H., Durbidge, T. B., and Pitman, A. J.: Global climate sensitivity to tropical deforestation, Global and Planetary Change, 10, 97-128, http://dx.doi.org/10.1016/0921-8181(94)00022-6, 1995.

Návar, J.: The causes of stemflow variation in three semi-arid growing species of northeastern Mexico, Journal of Hydrology, 145, 175-190, http://dx.doi.org/10.1016/0022-1694(93)90226-Y, 1993.

Neave, M., and Abrahams, A. D.: Vegetation influences on water yields from grassland and shrubland ecosystems in the Chihuahuan Desert, Earth Surface Processes and Landforms, 27, 1011-1020, 10.1002/esp.389, 2002.

Oki, T. and Kanae, S.: Global Hydrological Cycles and World Water Resources. *Science*, **313,** 1068-1072, 2006.

Sellers, P. J., Mintz, Y., Sud, Y. C., and Dalcher, A.: A Simple Biosphere Model (SIB) for use within general circulation models, Journal of the Atmospheric Sciences, 43, 505-531, doi:10.1175/1520-0469(1986)043<0505:ASBMFU>2.0.CO;2, 1986.

Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., Orlowsky, B., and Teuling, A. J.: Investigating soil moisture–climate interactions in a changing climate: A review, Earth-Science Reviews, 99, 125-161, http://dx.doi.org/10.1016/j.earscirev.2010.02.004, 2010.

Shao, Y., Anne, R. D., Henderson-Sellers, A., Irannejad, P., Thorton, P., Liang, X., Chen, T. H., Ciret, C., Desborough, C., Barachova, O., Haxeltine, A. and Ducharne, A.-: Soil Moisture Simulation, A report of the RICE and PILPS Workshop. GEWEX Tech. Note, IGPO Publ. Ser., 14, 179 pp, 1995.

Siegert, C. M., and Levia, D. F.: Seasonal and meteorological effects on differential stemflow funneling ratios for two deciduous tree species, Journal of Hydrology, 519, Part A, 446-454, http://dx.doi.org/10.1016/j.jhydrol.2014.07.038, 2014.

Tanaka, T., Taniguchi, M., and Tsujimura, M.: Significance of stemflow in groundwater recharge. 2: A cylindrical infiltration model for evaluating the stemflow contribution to groundwater recharge, Hydrological Processes, 10, 81-88, 10.1002/(sici)1099-1085(199601)10:1<81::aid-hyp302>3.0.co;2-m, 1996.

Taniguchi, M., Tsujimura, M., and Tanaka, T.: Significance of stemflow in groundwater recharge. 1: Evaluation of the stemflow contribution to recharge using a mass balance approach, Hydrological Processes, 10, 71-80, 10.1002/(sici)1099-1085(199601)10:1<71::aid-hyp301>3.0.co;2-q, 1996.

Wei, Z., Yoshimura, K., Okazaki, A., Kim, W., Liu, Z., and Yokoi, M.: Partitioning of evapotranspiration using high-frequency water vapor isotopic measurement over a rice paddy field, Water Resources Research, doi:10.1002/2014WR01673751, 3716–3729, 2015.

Wu, B.-Y.: Simulations of Land Surface Fluxes of the Lien Hua Chih Experimental Watershed with Land Process Models, Master, Graduate Institute of Hydrological and Oceanic Sciences, National Central University, 100 pp., 2011.

Xue, Y., Sellers, P., Kinter, J., and Shukla, J.: A simplified biosphere model for global climate studies. *J. Climate*, **4**, 345-364, 1991.

Xue, Y., Zeng, F. J., and Adam Schlosser, C.: SSiB and its sensitivity to soil properties—a case study using HAPEX-Mobilhy data, Global and Planetary Change, 13, 183-194, http://dx.doi.org/10.1016/0921-8181(95)00045-3, 1996.

Yang, Y., Uddstrom, M., and Duncan, M.: Effects of short spin-up periods on soil moisture simulation and the causes over New Zealand, J. Geophys. Res., 116, D24108.

Zhang, Y.-Q., Q. K. Zhu, and Qi, S.: Root system distribution characteristics of plants on the terrace banks and their impact on soil moisture, Acta Ecologica Sinica, 25, 500-506, 2005.

Zhao, M., Pitman, A. J., and Chase, T.: The impact of land cover change on the atmospheric circulation, Climate Dynamics, 17, 467-477, ~~10.1007/pl00013740,~~ 2001.

Zimmerman, R. and Bodvarsson, G.: A simple approximate solution for horizontal infiltration in a Brooks-Corey medium. *Transport in Porous Media*, **6**, 195-205, 1991.

Table 1. Basic parameters used for describing the LHC and HAPEX sites. LHC data were obtained from Wu (2011); HAPEX data were obtained from Goutorbe et al. (1989).

Location	**LHC**	**HAPEX**
Annual rainfall	231~~6~~7 mm	856 mm
Mean temperature	19.7°C	8.6°C
Altitude	770 m	113 m
Vegetation cover	Rainforest of mixed evergreens and hardwoods	Soya crop
Soil type	Loam	17% clay content, 46% silt, 37% sand
Soil moisture measurement depth	10, 30, 50, 70, 90 cm	Every 10 cm down to 160 cm
Soil wetness exponent	2.5	5.66
Soil tension at saturation	-0.1 m	-0.30 m
Hydraulic conductivity at saturation	1×10^{-6} m s^{-1}	4×10^{-6} m s^{-1}
Soil porosity	0.530	0.446
Slope	0.55	0.05

Table 2. Monthly leaf area index values (in m^2 m^{-2}) for LHC in 2010 and HAPEX in 1986. LHC data were obtained from Wu (2011); HAPEX data were obtained from Goutorbe et al. (1989).

Month	1	2	3	4	5	6	7	8	9	10	11	12
LHC	3.34	3.08	3.06	3.04	4.35	4.77	4.84	4.91	4.66	4.4	4.2	4.25
HAPEX	0	0	0	0	1	3	3	3	3	0	0	0

Table 3. The mean bias, root-mean-square error (RMSE), and standard deviation (STD) in simulated soil moisture comparing to observations (obs). "Control" stands for simulations without the stem-root flow mechanism, and "SLR90%" or "SLR50%" are simulations with the optimal stemflow to leaf drainage ratio. Unit: m^3 m^{-3}

	SM1			**SM2**			**SM3**		
	bias	RMSE	STD	bias	RMSE	STD	bias	RMSE	STD
LHC control-obs	-0.003	0.142	0.142	-0.098	0.153	0.012	-0.141	0.193	0.131
LHC SLR90%-obs	0.023	0.056	0.051	-0.034	0.050	0.036	-0.038	0.048	0.029
HAPEX control-obs	0.018	0.036	0.032	0.032	0.037	0.019	-0.057	0.085	0.063
HAPEX SLR50%-obs	0.009	0.030	0.029	0.024	0.030	0.018	-0.049	0.074	0.056

Table 4. Mean and maximum changes in daily temperatures and energy fluxes due to the stem-root flow (between optimal SLR run and control run) during the growing season. Canopy air temperature (T_C), soil surface temperature (T_S) and leaf temperature (T_L) are in °C; Transpiration (TR), soil evaporation (SE), leaf evaporation (LE), sensible heat (SH) and latent heat (LH) are in W m^{-2}.

	ΔT_C	**ΔT_S**	**ΔT_L**	**ΔTR**	**ΔSE**	**ΔLE**	**ΔSH**	**ΔLH**
LHC mean	0.32	0.31	0.34	0.20	-1.19	0.31	2.02	-0.68
LHC maximum	2.90	2.59	3.18	1.01	-15.50	11.34	31.44	-16.81
HAPEX mean	0.04	0.11	0.03	1.06	-2.17	0.28	0.52	-0.82
HAPEX maximum	1.27	1.63	1.70	-66.74	-19.5	9.95	51.16	-66.29

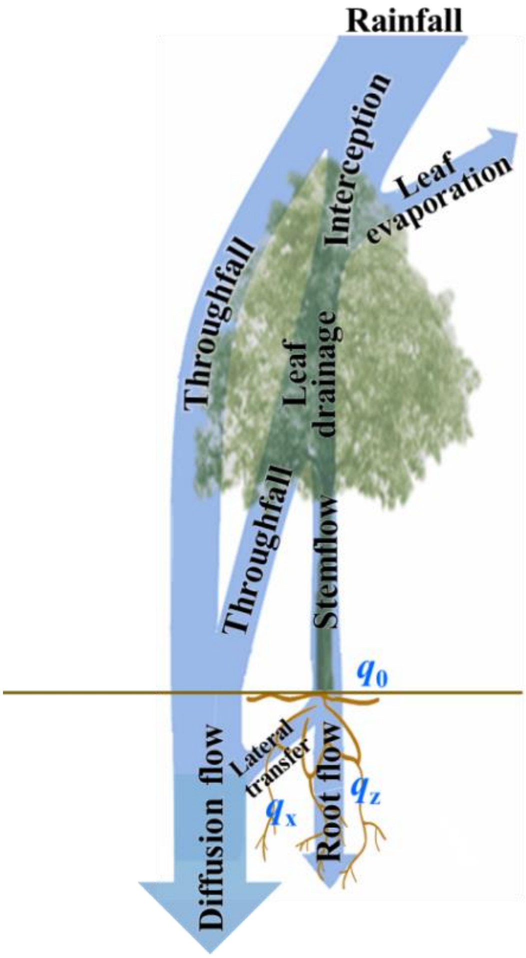


Figure 1. Stem-root flow conceptual diagram. Leaf drainage in the model can be separated into throughfall and stemflow. Following the stemflow path, rainwater can continue via the root system to reach deep soil layers and the water table. The stemflow that reaches the soil top, q_0, is divided into a downward transfer flux (i.e., the root flow) q_z and a lateral transfer flux q_x (from the root surface to the soil), and the two transfer fluxes regulate the root flow thickness.

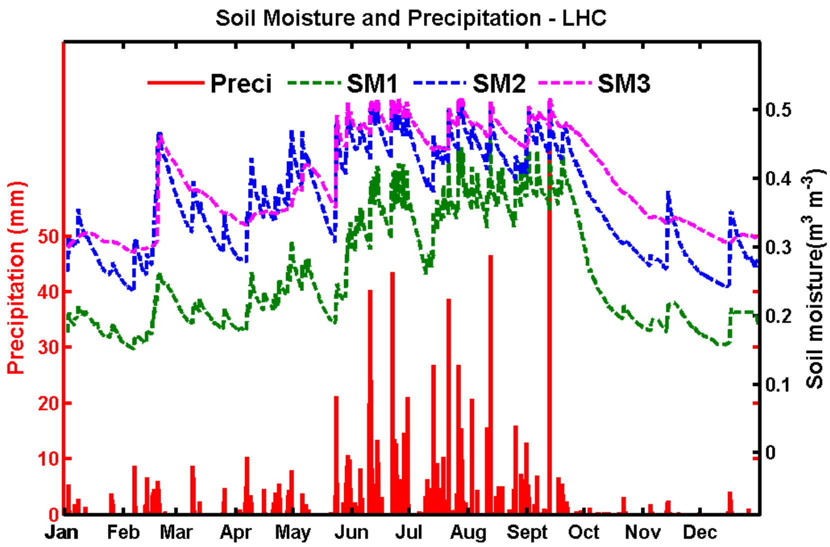


Figure 2. The hourly soil moisture (curves, right axis) and precipitation (red bars, left axis) observed at LHC during 2010. SM1, SM2 and SM3 represent soil moisture at 10 cm (green-dashed curve), 40 cm (blue-dashed curve; average of 30 cm and 50 cm observations) and 90 cm (magenta-dashed curve), respectively.

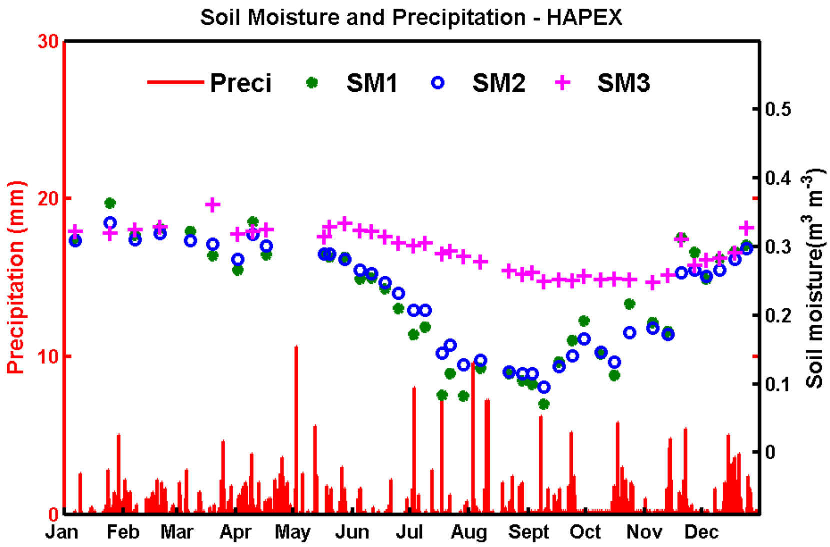
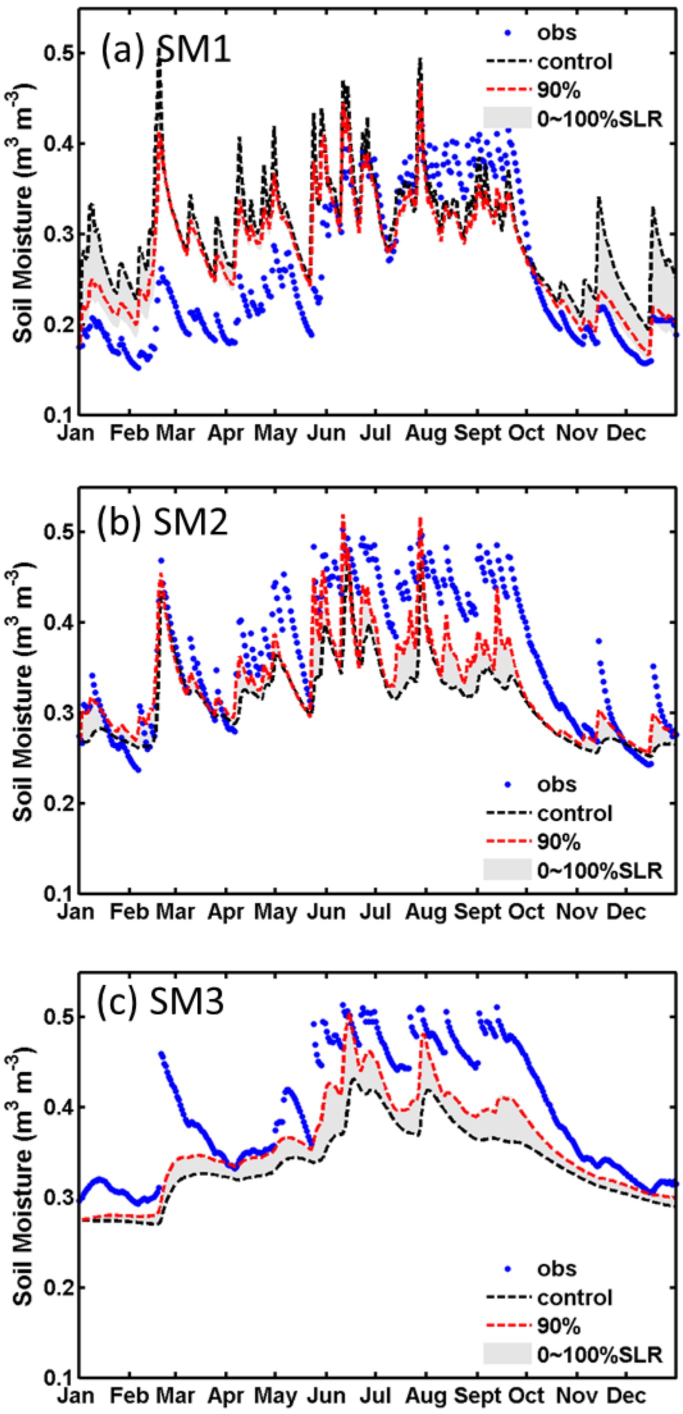


Figure 3. The weekly soil moisture (symbols, right axis) and hourly precipitation (red bars, left axis) observed at HAPEX during 1986. SM1 SM2 and SM3 represent the mean soil moisture in the 0–20 cm (green dot), 20–50 cm (blue circle), and 50–160 cm (magenta cross) layers, respectively.


(a) SM1
(b) SM2
(c) SM3
obs
control
90%
0~100%SLR
Soil Moisture (m^3 m^-3)
0.1
0.2
0.3
0.4
0.5
Jan Feb Mar Apr May Jun Jul Aug Sept Oct Nov Dec

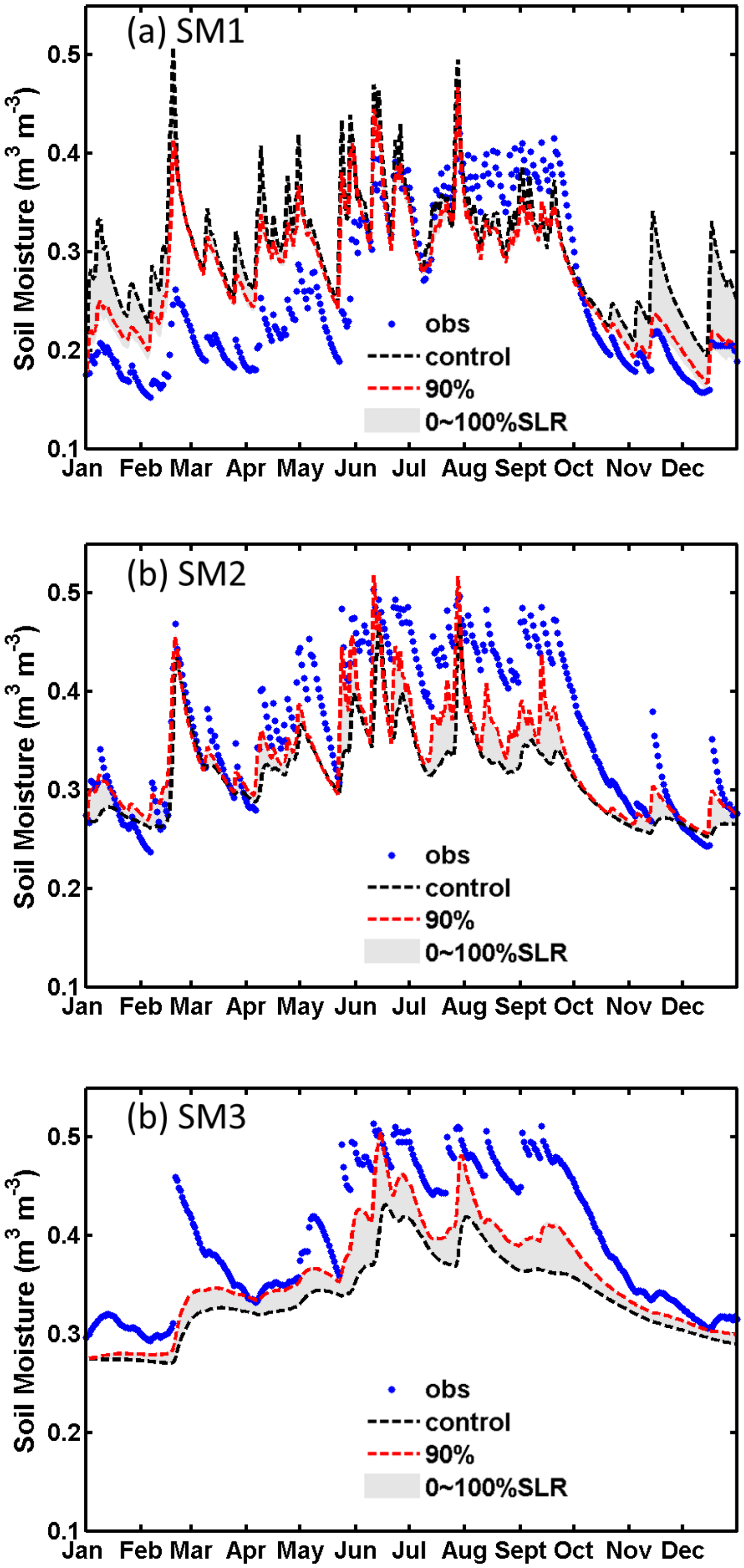
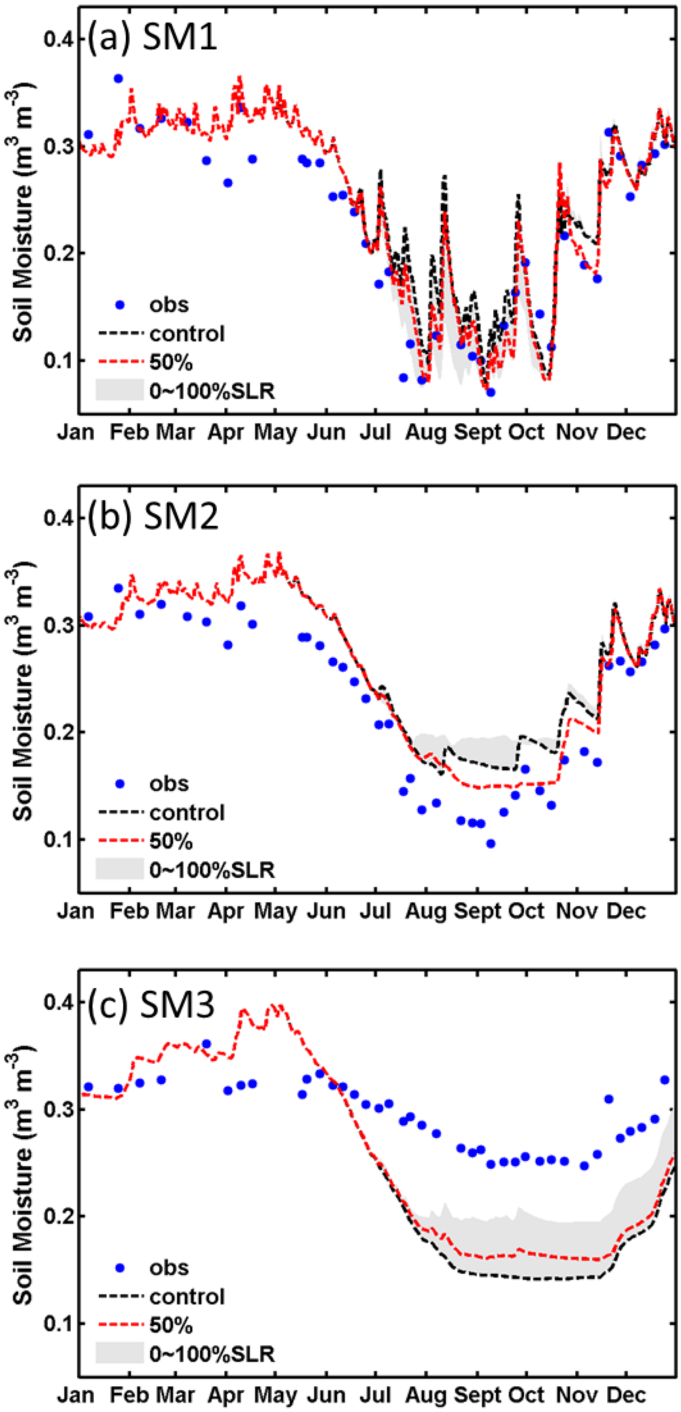

(a) SM1
(b) SM2
(b) SM3
Soil Moisture (m^3 m^{-3})
0.1
0.2
0.3
0.4
0.5
Jan Feb Mar Apr May Jun Jul Aug Sept Oct Nov Dec
obs
control
90%
0~100%SLR

Figure 4. Simulated and observed soil moisture for the LHC site at depths of (a) SM1 (0-20 cm), (b) SM2 (20-70 cm), and (c) SM3 (70-170 cm). Observed results are shown as blue dots. Simulations with SLR=0 (i.e., control run, without stem-root flow) and SLR=90% are shown as black-dashed and red-dashed curves, respectively. The area of grey shading enclosed by SLR=0% and 100% indicates the possible range of the stem-root flow effects. All simulation results are daily averages.



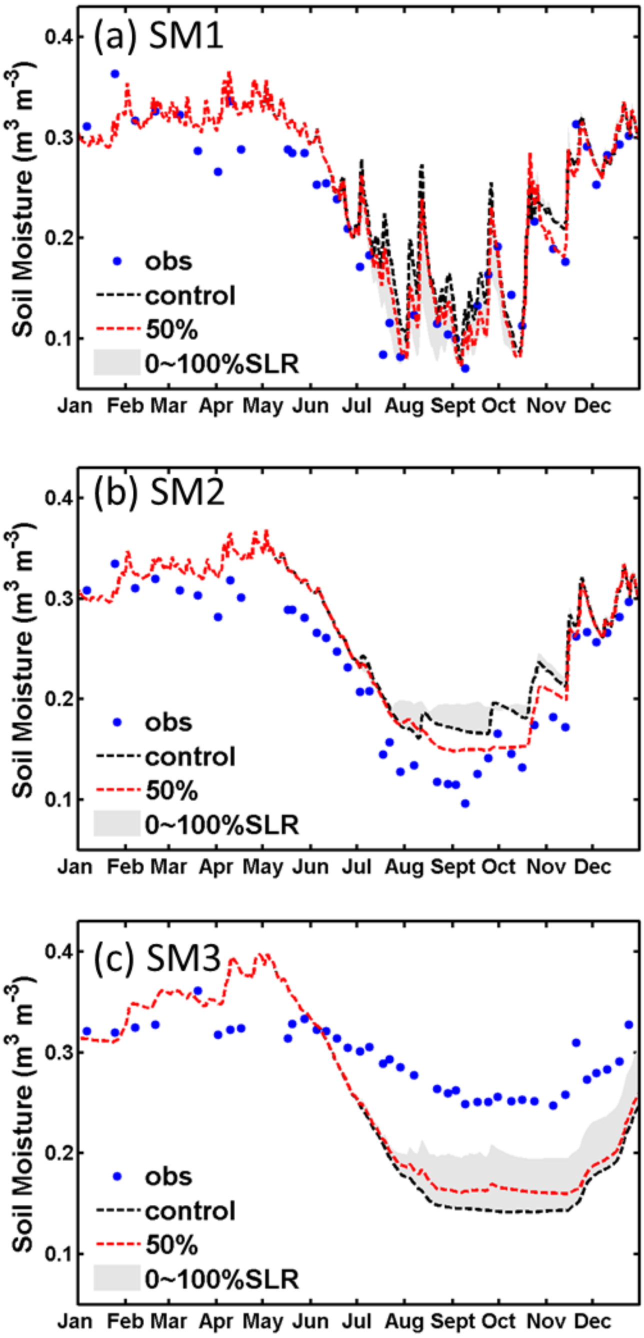
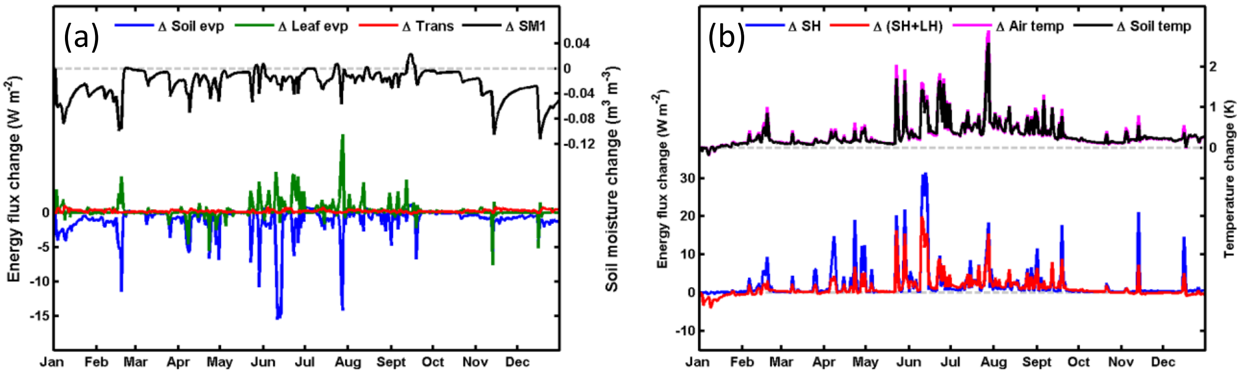
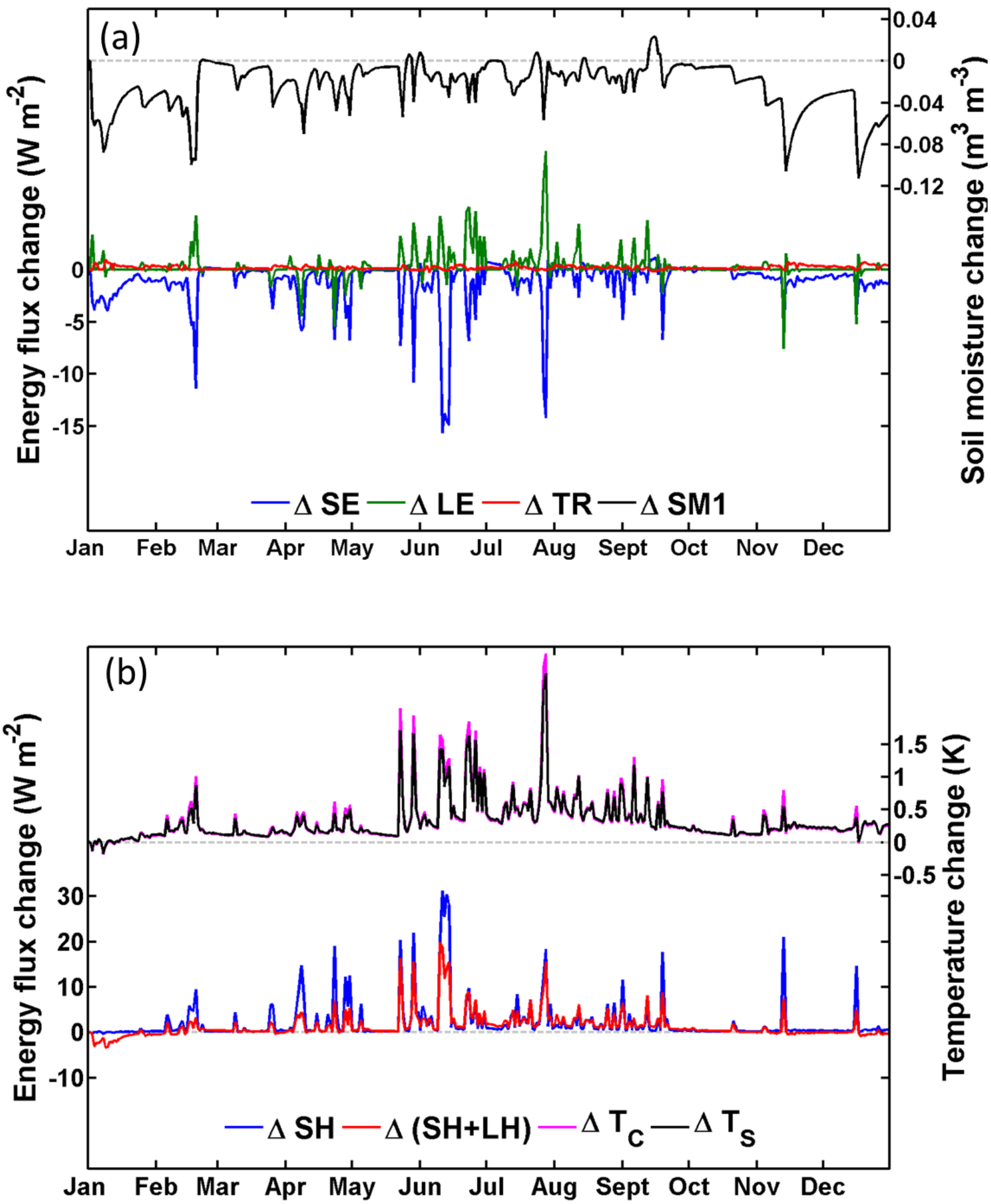


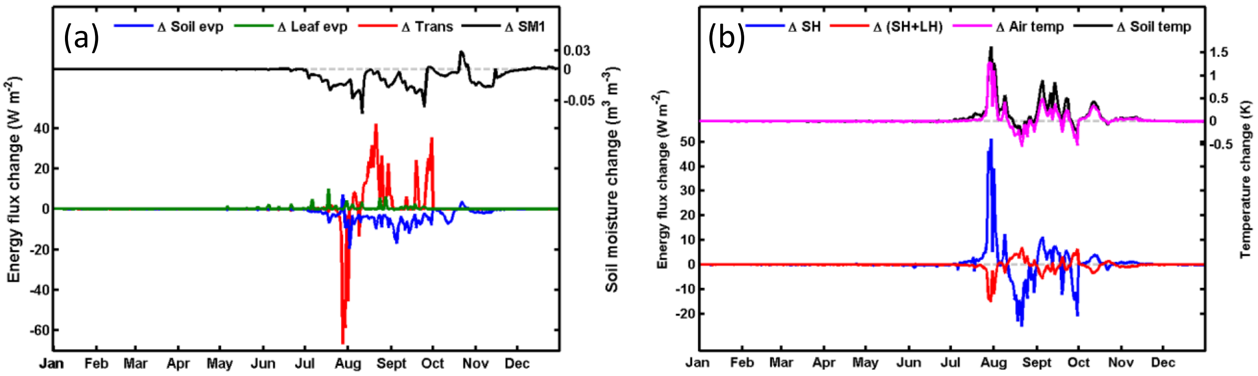
Figure 5. Same as Fig. 4, but for the HAPEX case at depths of (a) SM1 (0-20 cm), (b) SM2 (20-50 cm), and (c) SM3 (50-160 cm). Red-dashed curves are results with SLR=50%.


(a)
Δ Soil evp
Δ Leaf evp
Δ Trans
Δ SM1
Energy flux change (W m-2)
Soil moisture change (m3 m-3)
0.04
0
-0.04
-0.08
-0.12
0
-5
-10
-15
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sept
Oct
Nov
Dec
(b)
Δ SH
Δ (SH+LH)
Δ Air temp
Δ Soil temp
Energy flux change (W m-2)
Temperature change (K)
2
1
0
30
20
10
0
-10
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sept
Oct
Nov
Dec



(a)
Energy flux change (W m-2)
Soil moisture change (m3 m-3)
0.04
0
-0.04
-0.08
-0.12
0
-5
-10
-15
Δ SE
Δ LE
Δ TR
Δ SM1
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sept
Oct
Nov
Dec
(b)
Energy flux change (W m-2)
Temperature change (K)
1.5
1
0.5
0
-0.5
30
20
10
0
-10
Δ SH
Δ (SH+LH)
Δ TC
Δ TS
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sept
Oct
Nov
Dec

Figure 6. Difference in daily mean heat fluxes and soil moisture due to stem-root flow at the LHC case. (a) Changes in soil evaporation (SE; blue curve), leaf evaporation (LE; green curve), transpiration (TR; red curve) and soil moisture of the surface layer (SM1; black curve; right axis); (b) Changes in sensible heat (SH; blue curve), total heat (sensible heat plus latent heat (LH); red curve), canopy air temperature near the soil surface (T_C; magenta curve; right axis) and soil temperature (T_S; black curve; right axis). Grey dashed lines indicate the zero baseline.



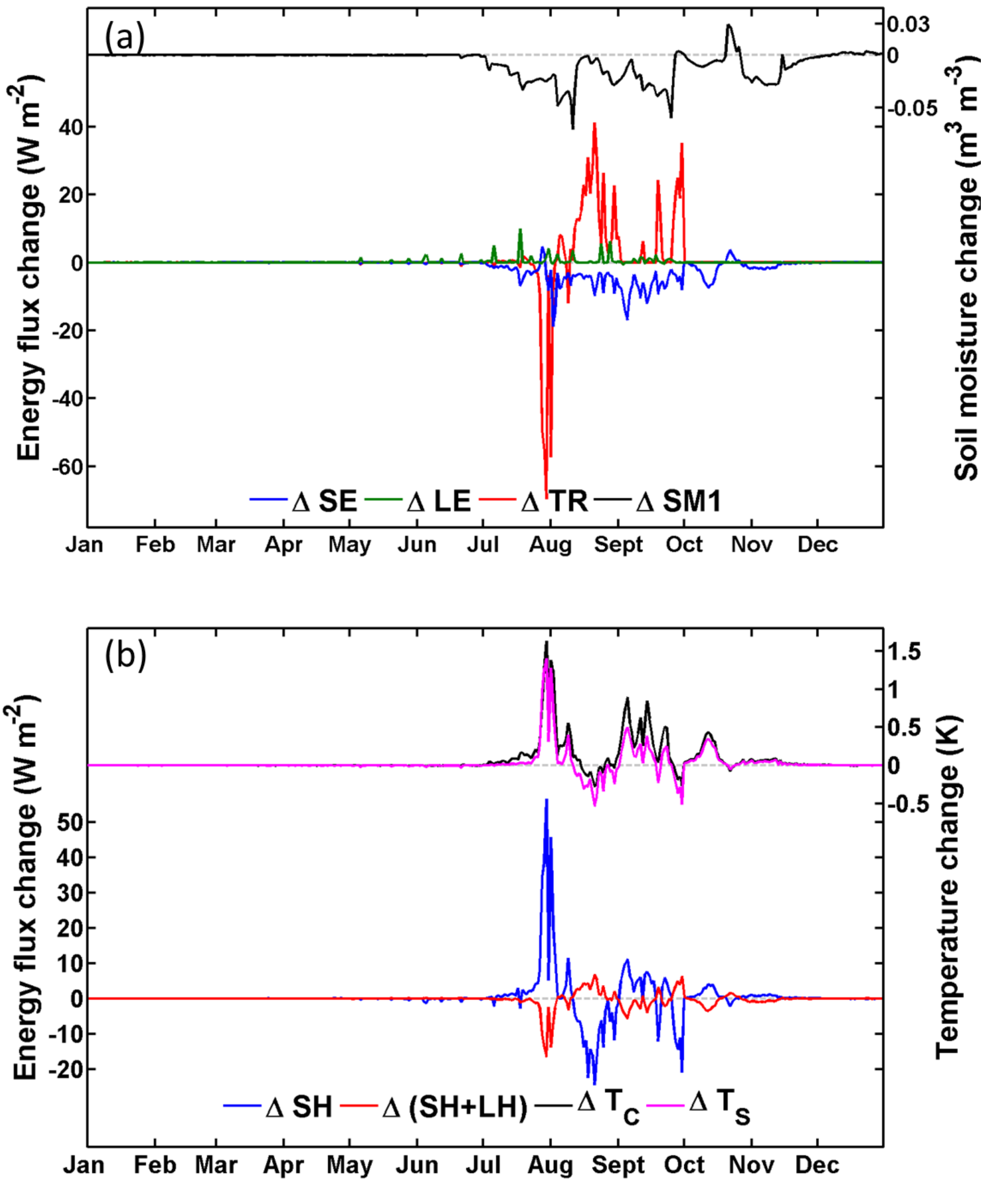
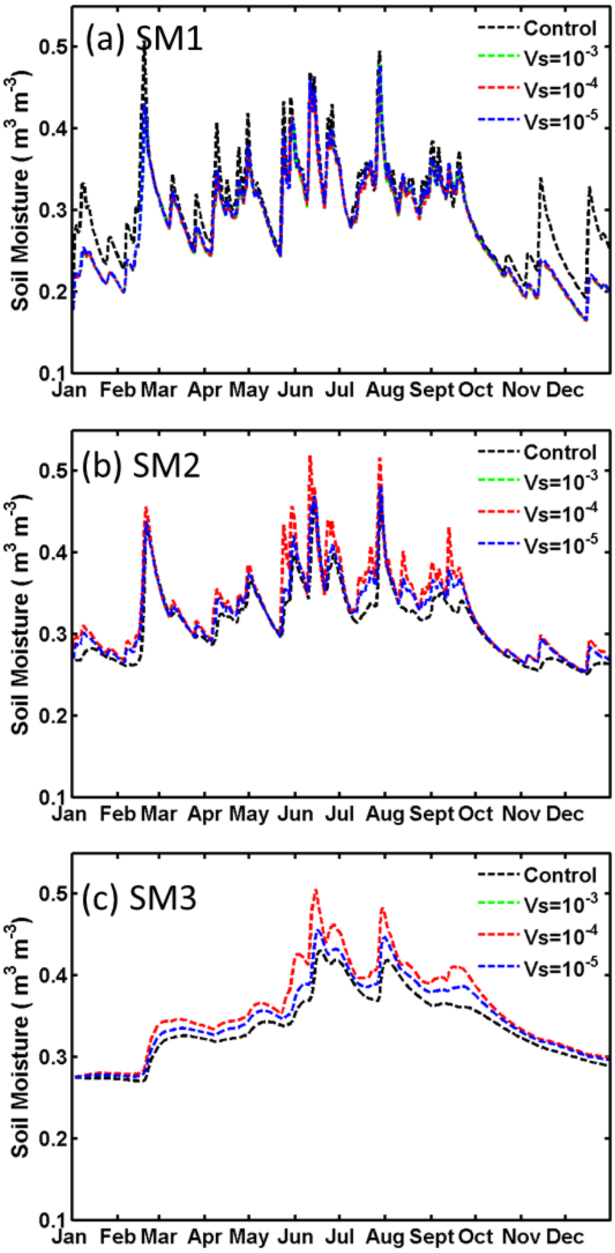


Figure 7. Same as Fig. 6, but for the HAPEX case.


(a) SM1
(b) SM2
(c) SM3
Control
Vs=10-3
Vs=10-4
Vs=10-5
Soil Moisture (m3 m-3)
0.1
0.2
0.3
0.4
0.5
Jan Feb Mar Apr May Jun Jul Aug Sept Oct Nov Dec

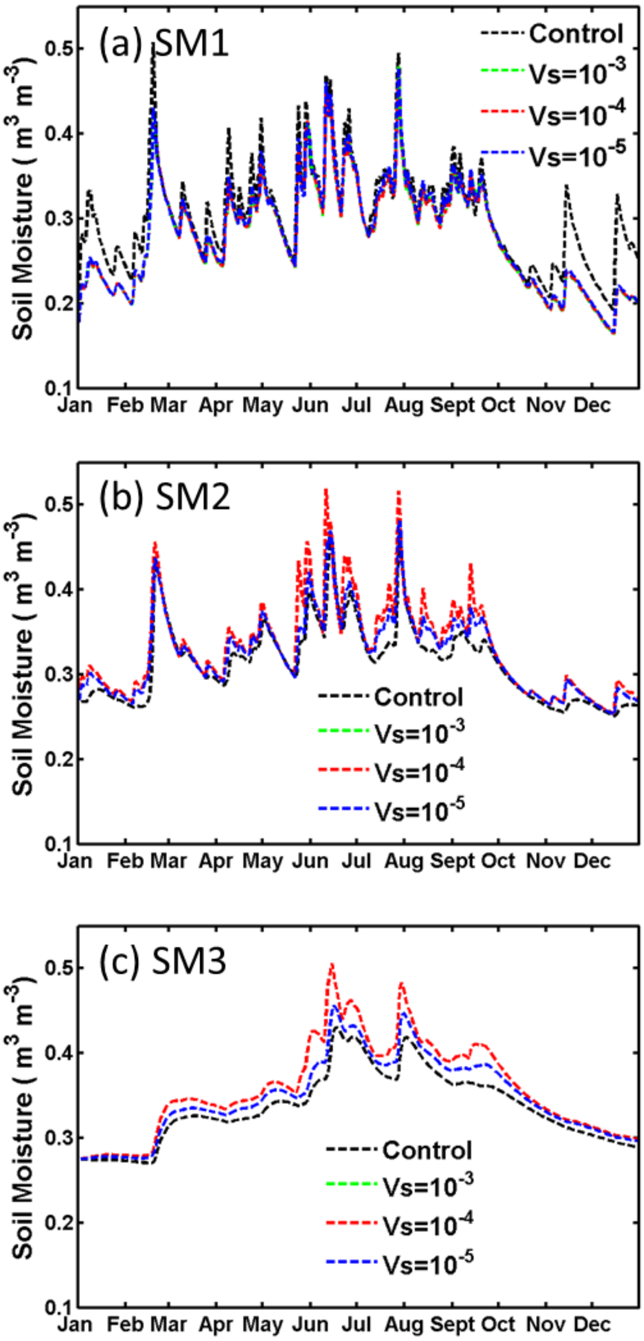
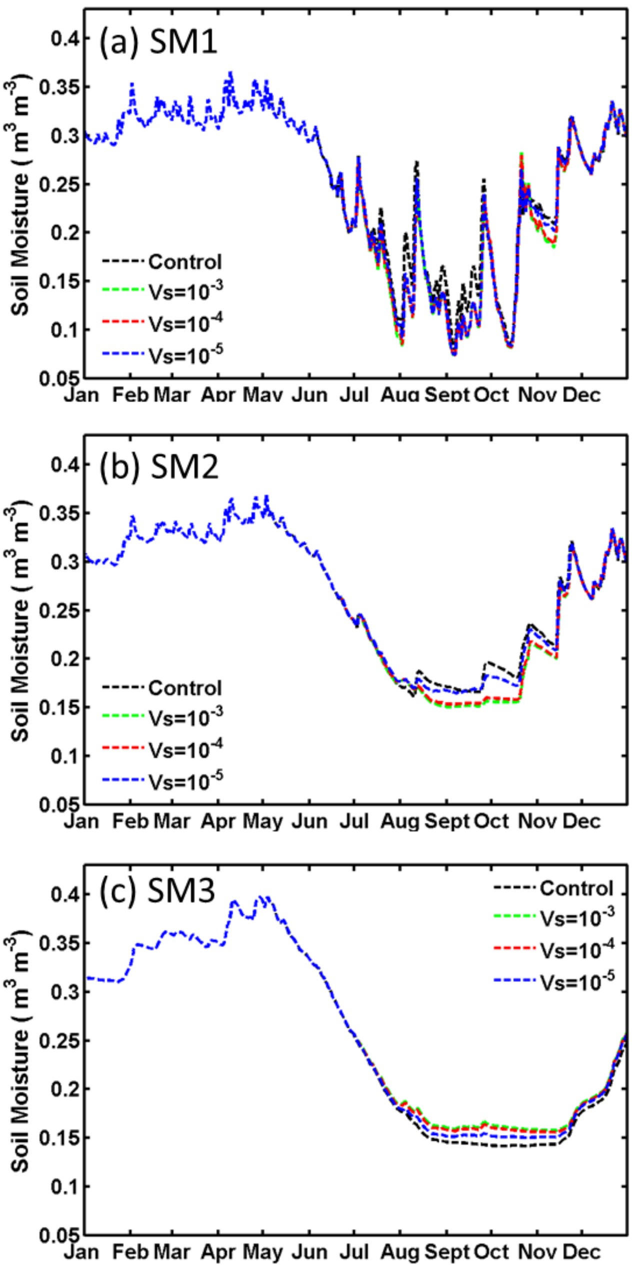


Figure 8. Sensitivity test on V_s for the LHC case with optimal SLR=90% at depths of (a) SM1 (0-20 cm), (b) SM2 (20-70 cm), and (c) SM3 (70-170 cm). The green-dashed, red-dashed and blue-dashed curves are for V_s = 10^{-3}, 10^{-4}, and 10^{-5} m s^{-1}, respectively. Also shown in black-dashed curves are the control run results (i.e., SLR=0).


(a) SM1
Soil Moisture (m^3 m^-3)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
Jan Feb Mar Apr May Jun Jul Aug Sept Oct Nov Dec
Control
Vs=10^-3
Vs=10^-4
Vs=10^-5
(b) SM2
(c) SM3

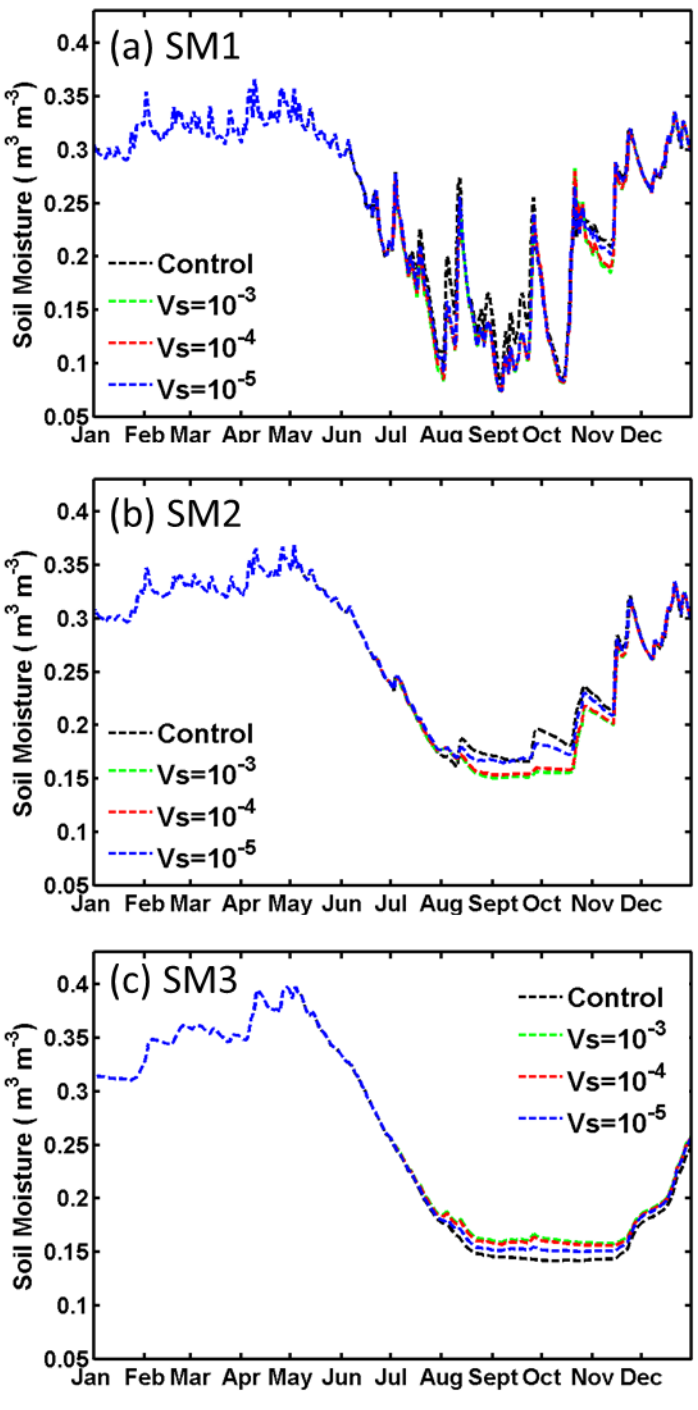


Figure 9. Same as Fig. 8, but SLR=50% for the HAPEX case at depths of (a) SM1 (0-20 cm), (b) SM2 (20-50 cm), and (c) SM3 (50-160 cm).

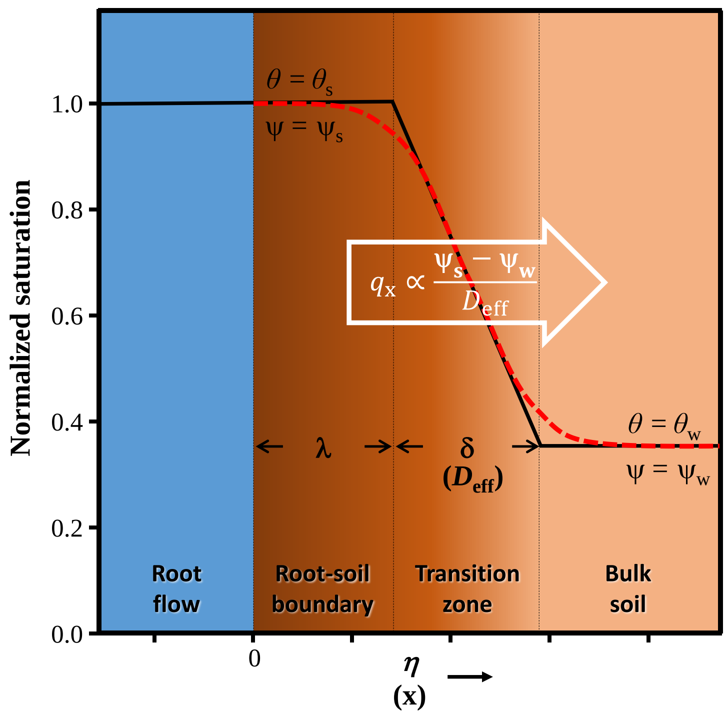


Figure A1: Schematics of the root flow-soil boundary and soil moisture transition for the parameterization of horizontal water flux q_x. The red-dashed line represents the analytical solution, and the black-solid line represents the parameterization. Soil moisture is saturated (= $_s$) in the root-soil boundary (width), and decreases linearly in the transition zone (width δ) before reaching that of the bulk soil (θ_w).