

Hydrological Land Surface Response in a Tropical Regime and a Midlatitudinal Regime

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ABSTRACT

A statistical–dynamical study was performed on the role of hydrometeorological interactions in the midlatitudes and the semiarid Tropics. For this, observations from two field experiments, the First International Satellite Land Surface Climatology Project Field Experiment (FIFE) and the Hydrological Atmospheric Pilot Experiment (HAP-EX)–Sahel, representative of the midlatitudes and the semiarid tropical conditions, and simulated results from a land surface model, Simplified Simple Biosphere (SSiB) model were statistically analyzed for direct and interaction effects. The study objectives were to test the hypothesis that there are significant differences in the land surface processes in the semiarid tropical and midlatitudinal regimes and to identify the nature of the differences in the evapotranspiration exchanges for the two biogeographical domains. Results suggest there are similarities in the direct responses but the interactions or the indirect feedback pathways could be very different. The arid tropical regimes are dominated through vegetative pathways (via variables such leaf area index, stomatal resistance, and vegetal cover); the midlatitudes show soil wetness (moisture)–related feedback. In addition, for the midlatitudinal case, the vegetation and the soil surface acted in unison, leading to more interactive exchanges between the vegetation and the soil surface. The water-stressed semiarid tropical surface, on the other hand, showed response either directly between the vegetation and the atmosphere or between the soil and the atmosphere with very little interaction between the vegetation and the soil variables. Thus, the semiarid Tropics would require explicit bare ground and vegetation fluxes consideration, whereas the effective (combined vegetation and soil fluxes) surface representation used in various models may be more valid for the midlatitudinal case. This result also implied that with higher resource (water) availability the surface invested more in the surrounding environment. On the other hand, with poor resource availability (such as water stress in the tropical site), the surface components retain individual resources without sharing.

1. Introduction

Land surface processes (LSPs) have a significant impact on the meteorological features both in the semiarid Tropics and in midlatitudinal domains. The changes in the surface processes modulate the surface and subsurface hydrological behavior and the surface energy balance. This modulation leads to changes in the overall boundary layer structure. Higher soil moisture and vegetation cover can lead to enhanced water vapor (latent heat) flux, which for the same incoming solar radiation

can lower the sensible heat flux (Entekhabi et al. 1996; Alapaty et al. 1997; Niyogi and Raman 1997).

Several studies have been reported on the sensitivity of land surface processes on the hydrometeorological feedback. For example, using a coupled prognostic modeling study, Deardorff (1978) and Noilhan and Planton (1989) showed that changes in the soil moisture and soil temperature have a direct feedback on the surface energy balance and on mesoscale weather regimes. Using a combination of modeling and analyses data, Pielke et al. (1991) provided evidence that the changes in land use patterns have significant impact on the regional climate and that the effects of small-scale landscape variability need to be resolved explicitly in modeling studies. Using GCMs, Xue and Shukla (1993) and Xue (1997) identified several feedback pathways on the glob-

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al climate using surface roughness and albedo as the modulators. In a similar way, using a mesoscale model, Chen and Avissar (1994) showed that soil moisture changes could have a similar feedback on regional heat fluxes and circulation patterns. This mutual feedback between the soil and regional climate was analyzed further by studies such as Entekhabi et al. (1996) to understand the control on the heat and moisture exchange among soil, vegetation, and the atmosphere. To resolve the feedback pathways further, studies such as Henderson-Sellers (1993), Hu and Islam (1996), and Niyogi et al. (1997a) contained statistical analyses of the interactions between surface variables using different land surface schemes. Such statistical–dynamical studies provide significant understanding of the interaction pathways with multiple variables participating simultaneously (Niyogi et al. 1998; Margulis and Entekhabi 2001).

However, despite compelling evidence that land surface processes have an impact both in the midlatitudinal and in the semiarid tropical regions, there are unresolved questions related to the comparison of these two diverse regions. Some questions include the following. How do the hydrometeorological/surface evapotranspiration features respond in these two different regimes? Is the strategy similar for the system to be in thermohydrodynamic equilibrium both in midlatitudes and in the water-stressed Tropics? Are the land surface parameterizations sufficiently robust to handle these contrasting domains? These and related issues are addressed by comparing the hydrological and surface energy balance strategy for a midlatitude scenario and a semiarid tropical scenario using a combination of observations and a well-tested land surface scheme.

2. Assessing midlatitudinal and semiarid tropical surface effects

What could make the midlatitudes and the semiarid Tropics different, from a hydrometeorological perspective? Some of the discerning factors are discussed briefly here. The soil moisture availability and weather patterns in the semiarid Tropics are dominated by mesoscale convection and monsoonal flow (cf. Bollé et al. 1993; Dolman et al. 1997), whereas the midlatitudinal weather patterns and corresponding soil moisture availability are modulated through synoptic weather and mesoscale frontal activity (Rhome et al. 2000). This difference has far-reaching implications on the diverse hydrometeorological feedbacks in the two domains. The midlatitudes, because of frequent fronts, can typically experience precipitation at a timescale of a one-week interval (Sims et al. 2001) while arid and semiarid Tropics tend to show precipitation variability at the timescale of a season. The evapotranspirative patterns associated with these two domains could also be different. In general, because of a lack of persistent cloudiness and the high solar zenith angle in the Tropics, radiation reaching

the ground will be typically higher than in the midlatitudes (Arya 1988; Goutorbé et al. 1994). As a result, there is higher surface energy available for evapotranspiration and water loss. The differing soil properties for the Tropics and midlatitudes can also contribute to differences in the hydrological cycles associated with these regions. It effectively can be said that the Tropics tend to have more extremes in surface wetness whereas the midlatitudes tend to have more frequent variability due to evapotranspiration and replenishments by frontal rains. Keeping these features in perspective, additional differences such as vegetation phenology, effects of thermal stress, and rooting depth can be deduced for the surface–atmosphere exchanges. Our intent is to analyze the net direct and interactive surface feedback pathways using data from two specialized field experiments, one conducted in the semiarid Tropics [Hydrological Atmospheric Pilot Experiment (HAPEX)–Sahel; Goutorbé et al. 1994; Prince et al. 1995] and the other in the midlatitudes [First International Satellite Land Surface Climatology Project Field Experiment (FIFE); Sellers et al. 1988; Sellers and Hall 1992] using a soil vegetation hydrological scheme [Simplified Simple Biosphere (SSiB) model; Xue et al. 1991]. A series of statistical–dynamical experiments are performed using a combination of modeling and observational approach.

3. Experimental approach

In this section, we first describe the pertinent formulations from the SSiB model, which is used for simulating the soil–vegetation–atmosphere transfer (SVAT) response. This is then followed by a discussion of the experimental design.

a. SSiB model formulation

Because biosphere–atmosphere interactions are a complex set of nonlinear processes, accurate representation of each and every process is not possible. However, the models attempt to represent the net effect of the multiple processes and their dynamic–prognostic variations. SSiB explicitly represents the vegetative processes in a detailed manner and has three soil layers, one canopy layer, and nine prognostic variables: soil wetness in three soil layers; temperature at the canopy, ground, surface, and deep soil layers; water stored in the canopy; and snow stored on the ground.

The water vapor transfer from the surface, which includes canopy, the upper soil layer, and the air close to the surface, is parameterized through a surface-resistant pathway. The stomatal resistance term r_s follows the analytical solution of Jarvis (1976) and Sellers (1985, 1987); the soil surface resistance is parameterized following Camillo and Gurney (1986). Evapotranspiration is dependent on three environmental stress terms: air temperature, soil water potential, and vapor pressure deficit. A detailed radiation transfer submodel is also

coupled within SSiB that includes parameterizations involving optical and geometrical properties of the vegetation, soil, and atmosphere (Sellers et al. 1986).

In SSiB, the surface energy fluxes for latent (LHF) and sensible (SHF) heat flux are estimated as

$$\text{LHF} = \frac{u_*}{(C_{\text{TN}}^{-1} + C_{\text{TT}}^{-1})} (q_m - q_a) \equiv \frac{(q_m - q_a)}{r_s} \quad (1)$$

and

$$\text{SHF} = \frac{u_*}{(C_{\text{TN}}^{-1} + C_{\text{TT}}^{-1})} (T_m - T_a) \equiv \frac{T_m - T_a}{r_a} \quad (2)$$

In the above equations, q and T are specific humidity and temperature, and subscripts m and a are for the reference height and for canopy air space, respectively. Terms C_{TN} and C_{TT} refer to the heat transfer coefficients in the neutral and non-neutral regimes and are given as

$$C_{\text{TN}}^{-1} = \frac{1}{k} \left(\ln \frac{z_m - d}{z_r - d} \right) + g_3 \ln \frac{z_r - d}{z_2 - d} \quad \text{and} \quad (3)$$

$$C_{\text{TT}}^{-1} = f[\text{Ri}(z_m)] + (g_3 - 1)f[\text{Ri}(z_r)] \quad (4)$$

for values of Richardson number Ri between 0 and -10 , where $f(\text{Ri})$ is 0.94Ri ; for Ri between 0.16 and 0,

$$C_{\text{TT}}^{-1} = 66.85\text{Ri}(z_m) \left[1 + \frac{z_r - d}{z_m - d} (g_3 - 1) - g_3 \frac{z_2 - d}{z_m - d} \right], \quad (5)$$

where z_2 is the height of canopy and g_3 is the ratio of the actual canopy airspace resistance r_a to the value obtained using a log-linear wind profiler assumption. It is assumed to be a constant at 0.75. Term z_r is the depth of the transition layer above canopy. Above the transition layer, the log-linear assumption is valid. This depth is calculated following Sellers et al. (1989) as $z_r = z_2 + 11.785z_0$, where z_0 is roughness length.

Another variable required for calculating the energy fluxes is surface friction velocity u_* , and it is estimated using momentum transfer coefficients for neutral (C_{un}) and nonneutral (C_u) conditions (Paulson 1970) as

$$u_* = u_r (C_u^{-1} + C_{\text{un}}^{-1}) \quad \text{and} \quad (6)$$

$$C_{\text{un}}^{-1} = \frac{1}{k} \ln \left(\frac{z_m - d}{z_0} \right). \quad (7)$$

Here $(C_u)^{-1}$ is 0.315Ri for values of Ri between -10.0 and less than 0 and is 66.85Ri for Ri between 0 and 0.16. In the above equations, d is the displacement height, k is the von Kármán constant, and Ri is estimated as

$$\text{Ri} = \frac{g\Delta z\Delta\theta}{\theta(\Delta u)^2}, \quad (8)$$

where g is gravitational constant, u is the wind speed, and θ is the potential temperature in kelvins.

b. Statistical design of experiment

For comparing the differences in the LSP response in the tropical and midlatitudinal regimes, it is important to assess both the direct and indirect components of the feedback pathways (Hu and Islam 1996). This is because often the direct (or the first order) and the indirect (or the interaction) terms can have similar magnitudes but different feedback pathways (Niyogi et al. 1999). Further, their tendency (or directions) can be such that the net effect is either additive or subtractive depending on the variable states (Stein and Alpert 1993; Niyogi et al. 1998). To resolve explicitly these direct and indirect effects, we adopted a ‘‘Level-3’’ response surface methodology (L3RSM)-based design (Niyogi et al. 1999). In the L3RSM approach, the system response is fitted to a second-order polynomial surface in terms of the experimental factors (Box et al. 1978; Haaland 1989). Considering two surface variables V_1 and V_2 in the analysis, a response surface for the effects can be generated following Taylor’s series as

$$E = k_1 + k_2V_1 + k_3V_2 + k_4V_1V_2 + k_5V_1^2 + k_6V_2^2. \quad (9)$$

Terms such as k_1 , k_2 , and k_3 represent the direct or first-order effects; k_4 corresponds to the interaction effect; and the k_5 and k_6 terms represent the second-order effects associated with the variables V_1 and V_2 , respectively. Thus, the L3RSM experiment is a detailed interaction-explicit, nonlinear analysis that resolves both the linear and the second-order nonlinear effects of the response.

For the L3RSM using a modeling approach, the objective is to generate a matrix of results corresponding to different input variable settings: low ($-$), intermediate (0), and high ($+$). However, unlike a traditional one-at-a-time, sensitivity-type analysis, the variables are assumed to alter simultaneously using different combinations. In our analysis, we developed two sets of experiments. In the first experiment, the model is centered over the FIFE region; in the second experiment it is centered over the HAPEX-Sahel domain.

The input variables for the L3RSM matrix (which are common to both the domains) are selected based on several factors. One, the objective is to study the interactions and impact of the surface variables (as opposed to boundary layer or large-scale forcing) on the evapotranspiration. Hence, the variables are a subset of routinely prescribed input surface variables for a land surface model. For example, this eliminated the inclusion of factors such as soil porosity or water retention curve constants (because they are not measured routinely even in special field experiments) that are generally assigned default values following soil type-based specification values (Clapp and Hornberger 1978). Two, the statistical resolution (ability of the analysis to extract first- and higher-order interactions without confounding or aliasing the results) of the experiment depends on the number of matrix variables. For example, considering two levels

TABLE 1. Design matrix for setting the input surface variable values in SSiB. Variables are defined in text.

Run No.	Wet	Alb	Rs _{min}	Veg	LAI	Vpd
1	-	-	-	-	-	-
2	-	-	-	-	+	+
3	-	-	-	+	-	+
4	-	-	-	+	+	-
5	-	-	+	-	-	+
6	-	-	+	-	+	-
7	-	-	+	+	-	-
8	-	-	+	+	+	+
9	-	+	-	-	-	+
10	-	+	-	-	+	-
11	-	+	-	+	-	-
12	-	+	-	+	+	+
13	-	+	+	-	-	-
14	-	+	+	-	+	+
15	-	+	+	+	-	+
16	-	+	+	+	+	-
17	+	-	-	-	-	+
18	+	-	-	-	+	-
19	+	-	-	+	-	-
20	+	-	-	+	+	+
21	+	-	+	-	-	-
22	+	-	+	-	+	+
23	+	-	+	+	-	+
24	+	-	+	+	+	-
25	+	+	-	-	-	-
26	+	+	-	-	+	+
27	+	+	-	+	-	+
28	+	+	-	+	+	-
29	+	+	+	-	-	+
30	+	+	+	-	+	-
31	+	+	+	+	-	-
32	+	+	+	+	+	+
33	-	0	0	0	0	0
34	+	0	0	0	0	0
35	0	-	0	0	0	0
36	0	+	0	0	0	0
37	0	0	-	0	0	0
38	0	0	+	0	0	0
39	0	0	0	-	0	0
40	0	0	0	+	0	0
41	0	0	0	0	-	0
42	0	0	0	0	+	0
43	0	0	0	0	0	-
44	0	0	0	0	0	+
45	0	0	0	0	0	0
46	0	0	0	0	0	0
47	0	0	0	0	0	0
48	0	0	0	0	0	0

(high and low) of setting for five variables, a full-factorial high-resolution experiment requires 32 model simulations. If the number of variables is increased to seven, for instance, the number of possible combinations and corresponding simulations required for full-factorial resolution is 2^7 , or 128. It is generally not feasible to perform such a large number of experiments. Hence, only a fraction of the design runs are performed to review all the first- and second-order interactions, and such a design is called a "fractional factorial" design. Another factor that supports the inclusion of a limited number of variables in the analysis is the difficulty associated with physically explaining and validating the higher-

TABLE 2. Values of the input variables used for SSiB simulations for the high (+), low (-), and median (0) settings corresponding to the design matrix shown in Table 1. Variables are defined in text.

Variable	Setting		
	High (+)	Median (0)	Low (-)
Wet ($\text{m}^3 \text{m}^{-3}$)	0.40	0.24	0.08
Alb (albedo)	0.25	0.20	0.15
Rs _{min} (s m^{-1})	500	300	100
Veg	0.9	0.5	0.1
LAI	3.0	1.75	0.5
Vpd (kg kg^{-1})	0.035	0.0275	0.020

level multiple interactions [see Alpert et al. (1995) and Viterbo and Beljaars (1995) for a discussion]. Hence, it is recognized that it is statistically more efficient and computationally economical to have a lesser number of parameters in the environmental analysis (Box et al. 1978). A practical approach for selecting the variables is to perform a screening experiment, as discussed in Niyogi et al. (1997a). A sensitivity-type "Level-2" fractional factorial experiment (Niyogi et al. 1999) was performed accordingly (not shown) with a number of different input variables using SSiB simulations (cf. Xue et al. 1996). Through the screening experiments, variables such as mean deep surface temperature T_m were found to be of relatively less importance for evapotranspiration results in SSiB simulations and hence were eliminated in the final design (see also Avissar 1995). Thus, six surface variables were varied systematically in SSiB following a matrix approach to develop 48 different combinations: soil wetness (wet), surface albedo (alb), minimum stomatal resistance (Rs_{min}), vegetative cover (veg), leaf area index (LAI), and atmospheric vapor pressure deficit (vpd). The design matrix adopted for providing the combinations is shown in Table 1. In the table, +, -, and 0 refer to high, low, and median values of the variables, respectively. The corresponding values for each of the six variables are given in Table 2.

To confirm the ability of the six study variables to represent the larger group of variables in SSiB (which would include factors such as deep soil temperature or surface roughness not included in the interaction analysis) an analysis-of-variance (ANOVA)-based diagnostic analysis was performed (Box et al. 1978). This approach was to ensure that the variables used in this analysis were not exceptional in terms of their response. The diagnostic plots (not shown) indicated that the six factors considered in the statistical analysis are significantly representative of the *overall* latent heat flux estimation (see also Avissar 1995).

SSiB requires information on additional input variables such as surface roughness, rooting depth, displacement and vegetation height, soil sorption parameter, and vegetation optical properties. For all such input requirements, a combination of the following three options (in order of preference) was sought:

1) actual field observations or estimates from FIFE and

- HAPEX–Sahel data based on Sellers and Hall (1992) and Prince et al. (1995), or
- 2) parametric results from model calibrations and sensitivity studies (Sellers et al. 1989, Dirmeyer and Shukla 1994, Xue et al. 1996), or
 - 3) model parameterization default values for the FIFE and HAPEX–Sahel domain [based on Sellers et al. (1986), Dolman and Sellers (1989), and Xue et al. (1991)].

Also, in this paper, we present results with observations made during FIFE and HAPEX–Sahel as the meteorological forcing for the land surface model. A follow-up study is being designed and will report the analysis of these interactions using coupled SVAT–GCM-based results.

c. SSiB model runs and analysis

SSiB was run offline for a 30-day period based on the FIFE and then HAPEX–Sahel observations as surface meteorological forcing (air temperature, humidity, wind, precipitation, and net radiation). Such offline forcing, using observations rather than a coupled modeling approach, requires additional comments.

The offline approach is a fairly “well-established” and efficient way to test the response of the surface variables (Henderson-Sellers 1993). Another impetus in adopting this approach was the computation cost associated in conducting factorial-based multiple studies with coupled GCM runs [see, e.g., Table 1 and Henderson-Sellers (1993)]. Further, even if a coupled GCM study is undertaken, because of the chaotic nature of the nonlinear modeling system, it often is difficult to develop physical interpretation and surface-variable response attribution under the influence of multiple feedback processes that mask the interactions [see additional discussions by Stein and Alpert (1993), Alpert et al. (1995), and Viterbo and Beljaars (1995)]. Hence, LSP-related studies at different scales [cf. Henderson-Sellers (1993), da Rocha et al. (1996), Meyers et al. (1996), Baldocchi and Meyers (1998), Cooter and Schwede (2000)] have resorted to a noncoupled/offline analysis of the surface response using observed meteorological data. However, note that there are several limitations of such an offline analysis. The coupled feedbacks are especially critical when dealing with the dynamical responses of the surface–atmosphere exchanges. These include analyses of simulations involving cause-and-effect feedback for phenomenon such as deforestation, cloud formation, and moisture transport (cf. Pitman 1994; Kim and Entekhabi 1998). However, for this analysis, the offline approach is adopted because of 1) the computational limitations in performing the large number of simulations following the factorial permutations, 2) the study focus on the role surface processes have when interacting with each other (rather than coupling with the boundary layer processes), and 3) use of the

factorial methodology, which, by its very nature, explicitly resolves the feedbacks and interactions using statistical approaches, thus alleviating the problem posed in traditional one-at-a-time offline analysis (e.g., Niyogi et al. 1997a, 1999). Thus the offline SSiB estimated fluxes for the FIFE and HAPEX–Sahel observations were analyzed for indirect effects and indirect persistence. The methodology aimed at studying the contribution and cascading interactions of the surface variables (in this case: albedo, vegetal cover, leaf area index, soil moisture, surface temperature, and stomatal resistance) on the evapotranspirative fluxes because of the hydrological response of the LSPs.

The output variables (latent heat flux and the evapotranspirative components) were analyzed for direct and indirect (first and second order) effects using a graphical analysis based on main-effect, Pareto, interaction (Ishikawa 1976), and response-surface plots (Niyogi et al. 1999).

The main-effect plots delineate the value of the effect for different settings of the input parameter values. In these, the average of the realizations (specific model output) for “low,” “median,” and “high” parameter settings are determined, and the slope of the line joining these averages provides the sensitivity or the importance assigned to that model input parameter for that effect. The main-effect plot explicitly accounts for the direct effects, and the variable interactions need to be deduced. For example, Fig. 1 shows the main-effect plot for latent LHF for the FIFE case (discussed ahead). Consider the case of soil moisture (“wet”) changes. The slope of the line joining the LHF effects corresponding to 0.08 (low) to the median settings is larger than the slope of the line joining LHF effects from the median to 0.4 (high) soil wetness input conditions. Thus, LHF shows non-uniform response to the soil moisture variations. As such, changes in the low-soil-moisture-availability cases (near wilting) have more effect on increasing the LHF outcome than when the domain already has sufficiently high soil moisture (cf. Brubaker and Entekhabi 1996).

To develop explicit interactions to account for multiple parameter changes, Pareto and response-surface plots are used for studying the interactions. The Pareto plot shows the importance of the input variables and their interactions in a decreasing order. The effects of the variables and interactions on the modeled outcome are calculated following the ANOVA approach [Box et al. (1978); see also Henderson-Sellers (1993) for a discussion]. In this approach, the magnitude of (normalized) effect E_j for change in factor j is given as

$$E_j = \frac{\sum_{i=1}^R (S_{ij}V_i)}{P}, \quad (10)$$

where V_i is the value of the model-simulated outcome derived from the i th experiment or run, S_{ij} is the associated sign (+ or –), R is the total number of ex-

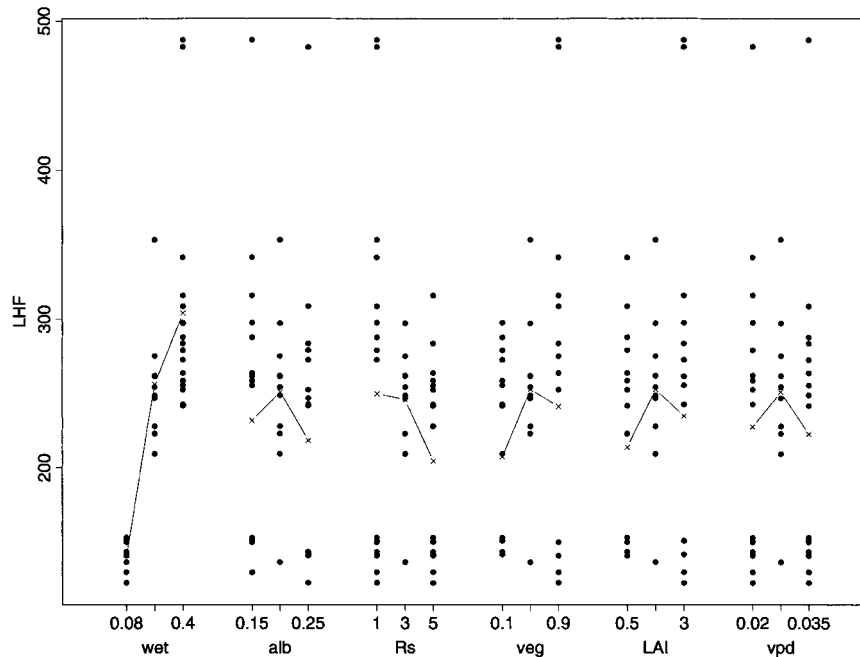


FIG. 1. Main-effect plot for latent heat flux (W m^{-2}) for FIFE domain. The outcome is dominated by changes in soil wetness ($\text{m}^3 \text{m}^{-3}$ wet); all other variables show a strong nonlinear variation.

perimental runs undertaken, and P is the number of + signs in the column (refer to Table 1). As discussed ahead, terms such as E_i are the main- or direct-effect terms and those of the form $E_i:E_j$ are the indirect or interaction terms. The Pareto plots (and the interaction plots discussed ahead) also use a pseudo standard error (PSE) as an indicator for the statistical significance of the outcome [see Lenth (1989) and Haaland (1989) for details].

The interactions identified in the Pareto analysis can be analyzed further in the interaction and response-surface plots. The interaction plot for Pareto interactions such as $E_i:E_j$ delineates the effects for low and high E_i for low E_j and then for high E_j settings. The lines joining the mean values of the outcome for different settings provide insights for interpreting the interactions and the variable pathways. The response-surface plot is similar to the interaction plot except with a three-dimensional surface. The response surfaces show the corresponding change in two variables with the model outcome or effect.

Thus, SSiB was integrated with the variable combinations shown in Table 1 and for ranges shown in Table 2, initially with the observed FIFE and then with the HAPEX-Sahel-based meteorological forcing. The model output for evapotranspiration was then analyzed using a variety of statistical graphical techniques to resolve the differences in the midlatitudinal and the tropical hydrological feedbacks through soil-vegetation-atmosphere transfer processes.

4. Results and discussions

In this section, a summary of the results of the SSiB runs is presented. This summary is followed by a discussion and analysis of the outcome over the two domains.

a. FIFE evapotranspiration case

Figures 1 and 2 show the main-effect and Pareto plots for latent heat flux over the FIFE domain (LHF) as an effect. In the main-effect plots, the direct effects (as resolved in most sensitivity studies) are explicitly shown. Depending on the prescribed surface conditions, the simulated LHF outcome shows significantly variability. These outcomes were further validated for statistical significance (through PSE calculations) and physical consistency (such as the direct relation between soil moisture availability and LHF).

Thus, the results indicate that latent heat fluxes increase with higher soil moisture availability. Higher soil moisture content leads to more evapotranspirative potential that is reflected in higher fluxes. The effect of soil moisture change is largely linear; the other five variables show a significant nonlinear effect on simulated latent heat (evapotranspirative) flux values. The median settings tend generally to correspond to higher latent heat fluxes, as compared with the low and high settings. It is interesting to note that an increase in the vegetation cover or leaf area index leads to enhanced latent heat fluxes only for a certain range, and then, in

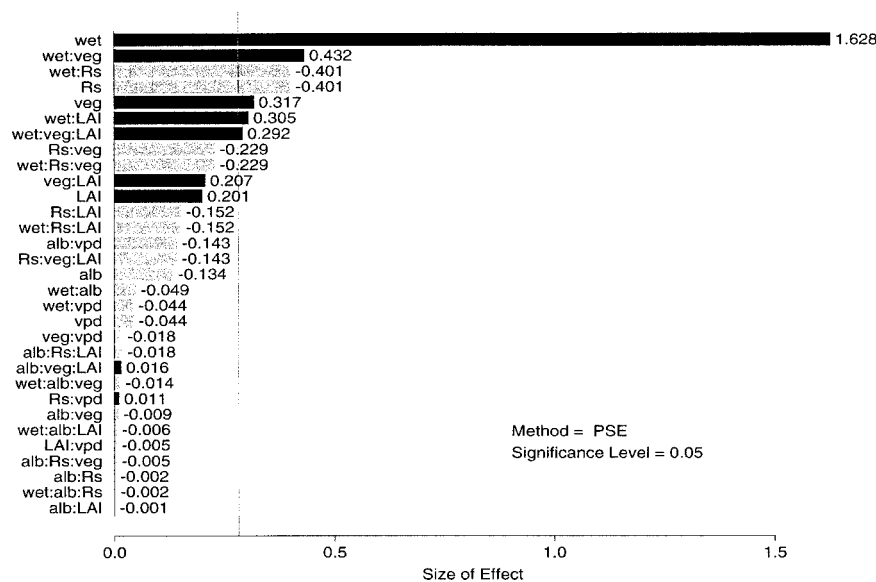


FIG. 2. Pareto plot for FIFE latent heat fluxes. Both the main effect and interactions are explicitly extracted in this analysis. A number of interactive pathways, particularly those related to vegetation and soil wetness, are important.

fact, further increase has a negative feedback on the evapotranspirative flux [see also Niyogi et al. (1997a) for a similar response using the HAPEX-Modelisation du Bilan Hydrique (MOBILHY) observations]. The interactions between the surface variables can be seen in the Pareto plot, shown in Fig. 2. Interaction terms are indicated by variables such as wet:veg (which refers to the interaction between the variables soil wetness and vegetation cover) in the Pareto plot.

The Pareto analysis confirms several of the main-effect plot-based results such as the well-known dominant direct effect of soil wetness on latent heat fluxes (Raman et al. 1997). In a similar way, higher stomatal resistance (Rs), and higher albedo (alb) values lead to lower evapotranspiration as a direct effect (Jacquemin and Noilhan 1990). In converse, increasing vegetal cover (veg) and leaf area index (LAI) values are directly linked with higher latent heat fluxes (as a main effect). These functional dependences are consistent with prior observations and analysis (e.g., André et al. 1986; Dolman et al. 1997; Calvet et al. 1999). In addition, there are a number of significant interactions that dominate the latent heat flux process. These interactions modulate the overall surface energy fluxes by enhancing (synergistic interactions) or decreasing (antagonistic interactions) the net effect (Niyogi et al. 1999). For example, both soil wetness and vegetal cover are individually positively related with latent heat fluxes while the soil wetness and vegetal cover interaction term (wet:veg) is also positively linked to latent heat fluxes. This is a synergistic interaction revealing that the impact of simultaneous increase in soil wetness and vegetal cover will be more than the net effect of the increase in either soil wetness or vegetal cover individually. Similar syn-

ergistic interactions are seen for variables such as vegetal cover and LAI, and a complex triple interaction is seen among vegetal cover, LAI, and soil wetness. This result of the potential for higher evapotranspiration under high LAI and vegetation cover conditions is physically consistent to coupled modeling as well as observational studies (cf. Avissar and Pielke 1989). Another significant interaction terms identified in the Pareto analysis is the antagonistic interactions between soil wetness and stomatal resistance (wet:Rs). This is an interesting and important feedback/feed-forward mechanism involving vegetation, evaporation, and the soil moisture linkage. Soil moisture availability can cause ease in transpiration, a process that leads to depletion in soil moisture, and hence a cyclic balance feedback is expected (Makela et al. 1996; Brubaker and Entekhabi 1996). Such interactions between the vegetation and soil moisture make the surface energy balance over the FIFE domain largely nonlinear.

The vegetation and soil moisture-related interactions are analyzed further using the interaction plots shown in Figs. 3a,b. The interactive role of soil wetness and stomatal resistance with varying vegetal cover is shown in Fig. 3a; Fig. 3b delineates the interaction among soil wetness, vegetal cover, and LAI for the FIFE case. As reviewed in Niyogi and Raman (1997), changes in stomatal resistance significantly modulate surface latent heat fluxes. The interaction plots further suggest that the evapotranspiration generally increases with decreasing stomatal resistance and that the impact of changes in stomatal resistance is higher for increasing vegetal cover with soil moisture not limiting. This is intuitive in that, with high soil moisture availability, lower (higher) stomatal resistance will allow larger (smaller) water

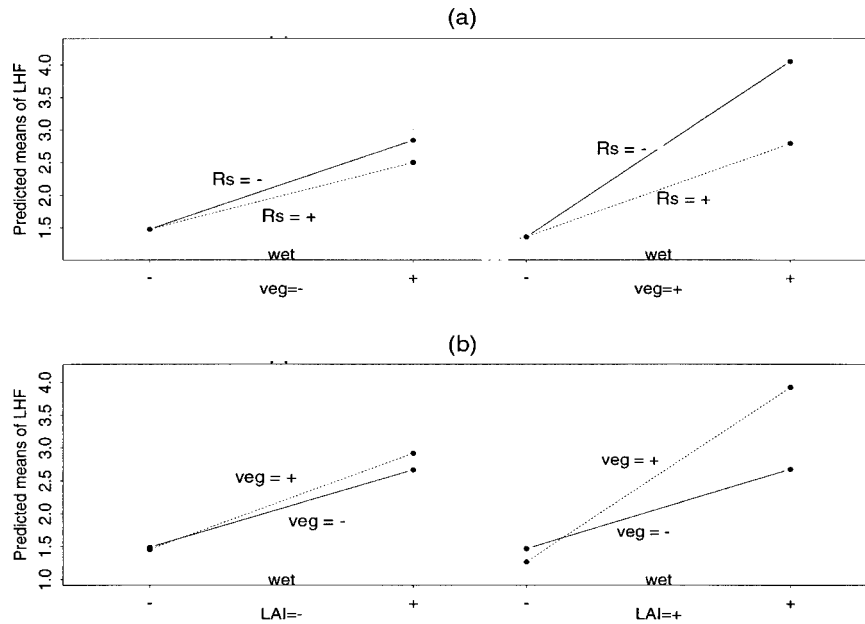


FIG. 3. Two-factor interaction plots showing effect of (a) stomatal resistance pathway in varying soil wetness and vegetative cover and (b) vegetative cover change for varying LAI and soil wetness for latent heat fluxes ($W m^{-2}$, factored by 100) simulated by SSiB for the FIFE domain. Higher vegetative cover and wetter soil conditions show intense interactions.

vapor release leading to higher evapotranspirative flux (Wilson et al. 2000). Also, the stomatal control of the humidity exchange will be proportional to fraction of the vegetative cover, and hence with higher vegetative cover the significance of the stomatal resistance changes also increases (Niyogi et al. 1999). However, the interaction plots (Fig. 3b) further indicate that the evapotranspiration control is more via soil moisture availability than via vegetative cover changes. This is physically realistic, considering that soil moisture is the source of humidity, whereas vegetation and stomates are only conduits for the exchange. Also, as seen in Fig. 3b, the response characteristics are different for low LAI (such as pastures) to high LAI (such as perennial canopies). The impact of vegetative cover change is typically more for canopies with high LAI. As a consequence, for low LAI conditions, an extreme change (0.1–0.9) in fractional vegetative cover produced marginal changes in the latent heat fluxes. This can be expected, considering that higher LAI will correspond to a larger number of stomates modulating the vapor exchange (Niyogi et al. 1997b). Thus, if a change in vegetative cover does not necessarily correspond to a significant change in the available stomatal conduits, the change in evapotranspiration could be minimal, as also seen in the two-factor interaction plots (Fig. 3b). High LAI cases also show an interesting relation among vegetative cover, soil wetness, and latent heat fluxes. Contrary to the direct relation between vegetative cover and latent heat fluxes, for drier soils an increasing vegetative cover with high LAI can correspond to a compensatory *decreasing* latent heat flux. This result could be due to a reduction in the soil evaporation

by a shielding effect of vegetation and the subsequent regulation of the stomatal closure and canopy transpiration as a feedback (Deardorff 1978; Wilson et al. 2000). A similar feature was reported by Niyogi et al. (1997a) for the HAPEX–MOBILHY observations analyzed in Jacquemin and Noilhan (1990) and by Norman et al. (1995) for both the midlatitudinal and the monsoonal regions.

The surface interactions are delineated further through nonlinear response-surface plots for latent heat fluxes. Three sample response-surface plots are shown in Figs. 4a–c. In these plots, by reviewing the curvature of the response surface, the nonlinearity of the interactions can be assessed. For example, the Pareto analysis (Fig. 2) identified synergistic soil wetness–vegetative cover interactions, which can lead to an enhanced combined modulation of evapotranspiration. In a similar way, the two-factor interaction analysis (Fig. 3) provided additional regimes for the different response pathways to be active. The response-surface plot delineates the nonlinearity of the interactions (Fig. 4a) between vegetative cover and soil wetness. The response surface in Fig. 4a further emphasizes that the effect of the change in soil moisture is more nonlinear and dominant than the vegetative cover change. The more nonlinear the effect, the larger is the parameterization uncertainty, and its representation requires more explicit details in the model (cf. Niyogi et al. 1999). This suggests, for example, models that satisfy surface energy balance constraints may not necessarily be able to simulate soil moisture changes accurately. This result is consistent with the conclusions from a study reported by Henderson-Sellers et al. (1996) using

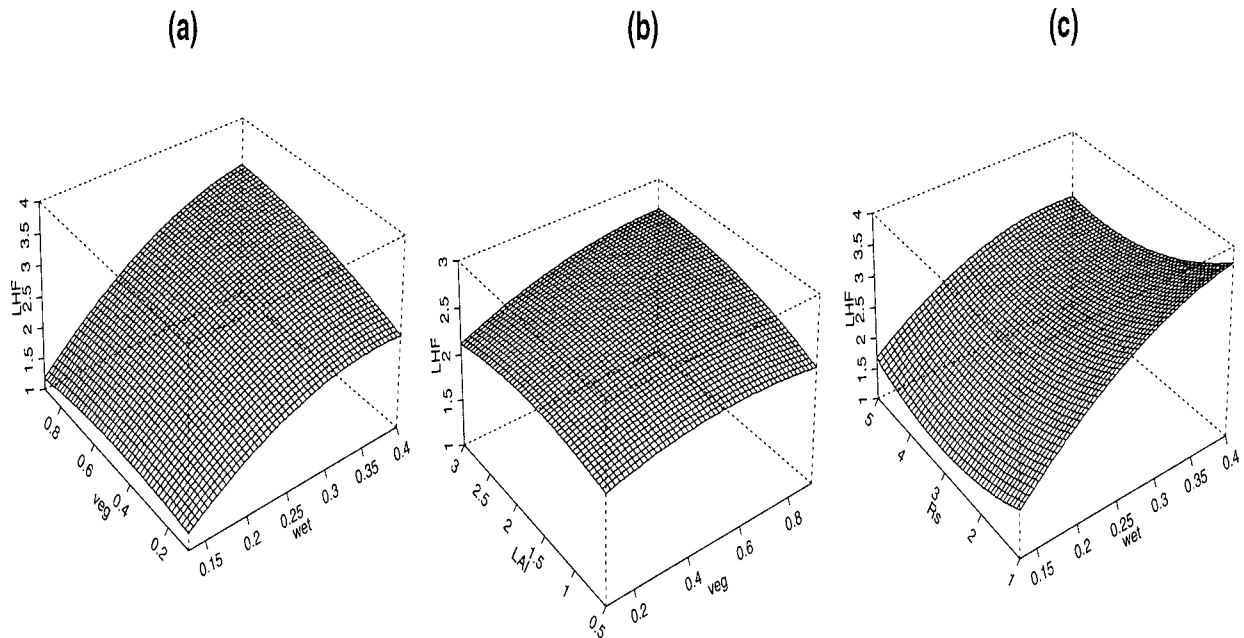


FIG. 4. Response-surface plots for LHF (W m^{-2} , factored by 100) with (a) varying vegetative cover and soil wetness ($\text{m}^3 \text{m}^{-3}$), (b) LAI and vegetative cover, and (c) stomatal resistance ($\times 100$, s m^{-1}) and soil wetness ($\text{m}^3 \text{m}^{-3}$). The curvature of the surface indicates the nonlinear nature of the interactions. The variable response generally has higher uncertainty with higher nonlinearity.

the Project for Intercomparison of Land Surface Process Schemes data and is an important consideration for surface data assimilation procedures in regional and mesoscale models (cf. Alapaty et al. 2001).

Referring to the vegetative cover–LAI response surface (Fig. 4b), it is apparent that the interactions are intensely nonlinear. LAI response is nonlinear over a large range, indicating its representation is complex; on the other hand, vegetative cover interactions are fairly linear for the lower range and become nonlinear with increasing vegetative cover. Thus, the high vegetative cover–high LAI cases would require more detailed models than those needed for other cases. Such a scenario is typical for forest canopies, suggesting that models tested and validated over pastures and grasslands (such as in FIFE) will have to be tested explicitly or calibrated over forest data (such as the Boreal Ecosystem–Atmosphere Study) before being used generalized global applications.

The third response-surface plot analyzed is for changes in latent heat fluxes due to interactions in soil wetness and stomatal resistance (Fig. 4c). This is an interesting variable combination, because both the terms—soil wetness and stomatal resistance—respond through a cyclic cause-and-effect relation. For example, often with higher moisture availability, canopy resistance for water vapor transfer is low (Avisar and Pielke 1989). The decreasing stomatal resistance can lead to higher evapotranspiration, which in turn will decrease the moisture availability. This cyclic response is also seen through the curvatures of the response-surface plots. As a result, the latent heat flux decreases with increasing resistance but only up to a certain limit (300 s m^{-1} , in this study),

after which increasing resistance is once again related to *increasing* latent heat flux. The effects of soil wetness (moisture) changes are fairly consistent and lead to a corresponding rise in latent heat flux values. The impact of increase in soil moisture availability and the corresponding increase in latent heat flux are more for lower values of soil moisture, and the curve flattens as the soil tends to become saturated. This feature is consistent with observations (Calvet et al. 1999; Sellers et al. 1992; Stewart and Verma 1992) and for coupled SVAT model simulations (Wetzel and Chang 1987). Similar response surfaces were analyzed for different variable interactions leading to evapotranspiration. Overall the midlatitudinal land surface exchanges likely are dominated by various active interactions between soil- and vegetation-related surface variables.

In the following section, the evapotranspirative exchanges representative of semiarid–arid tropical regions are analyzed.

b. HAPEX–Sahel evapotranspiration case

The SSiB-estimated latent heat fluxes for HAPEX–Sahel (referred to as SLHF) were analyzed in manner similar to that for the FIFE case described in the previous section. For this case also, a statistical diagnostic analysis was performed. The results (not shown) confirm that the six surface variables (soil wetness, albedo, stomatal resistance, vegetative cover, LAI, and vapor pressure deficit) can significantly represent the SSiB parameters for a reduced statistical analysis.

Figure 5 shows the main-effect plot for the direct, or

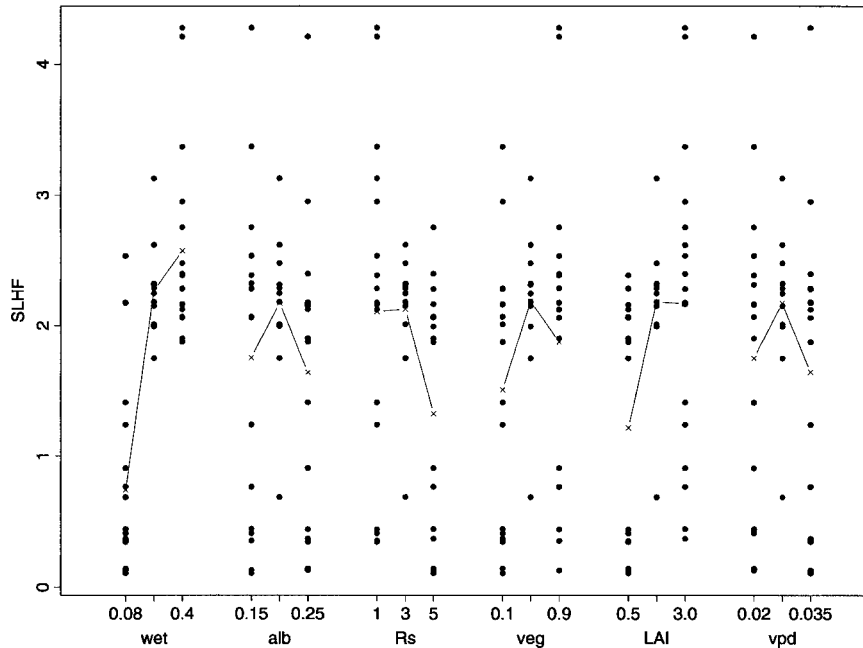


FIG. 5. Same as Fig. 1 but for HAPEX–Sahel. SLHF is latent heat fluxes (W m^{-2}). The main-effects/direct pathways are similar for the semiarid tropical and the midlatitude case.

first-order, effects for the HAPEX–Sahel case. The results are fairly similar to those obtained for the FIFE case (shown in Fig. 1). However, two features stand out in the semiarid tropical case as compared with the midlatitudinal FIFE simulations. First, similar to FIFE, soil wetness is an important variable. However, the effect of changes in low-to-moderate soil moisture availability (taken as average of wilting and field capacity) on enhancing the evapotranspiration is dramatically larger than that seen for the FIFE case. In comparison, a change in soil wetness from moderate to near-saturation values leads to relatively modest increase in the latent heat flux values. Thus, different soil-moisture availability regimes could control different evapotranspiration phases, as discussed in Brubaker and Entekhabi (1996). This soil moisture–evapotranspiration pathway needs to be evaluated further using coupled SVAT and observational analyses. Second, the surface variables show enhanced nonlinearity in their responses for the semiarid case. That is, the extreme conditions show markedly different response as compared with the median values. The possible cause-and-effect features of these nonlinear influences on the surface-variable feedback pathways are discussed ahead in a resource allocation perspective.

Additional differences between the FIFE and the HAPEX–Sahel cases are extracted by comparing the Pareto plots for the two cases. Figure 6 shows the Pareto plot for latent heat fluxes over the HAPEX–Sahel domain. For the FIFE case, the order of importance (of statistically significant variables) was soil wetness, stomatal resistance, vegetal cover, and, to a certain extent,

LAI. For the Sahel case, the order of significant direct effects is soil wetness, LAI, stomatal resistance, vegetal cover, albedo, and vapor pressure deficit. Thus *all* the direct, or first-order, effects are significant for the tropical case. Direct pathways dominate the tropical evapotranspiration, and each of the surface variables independently controls the outcome. In comparison, FIFE outcome was dominated by second-order effects or interactive feedback pathways.

Though direct effects dominate the HAPEX–Sahel case, an interesting triple interaction between stomatal resistance, LAI, and vegetal cover is also statistically significant. This is analyzed in Fig. 7. In this, LAI may modulate the level of biophysical involvement between the surface and the atmosphere. At low LAI (~ 0.5), extreme change in vegetal cover (0.1–0.9) or a fivefold change in stomatal resistance did not lead to any significant change in evapotranspiration. On the other hand, with increasing LAI, the different variables show more interactive feedback to a certain extent. It is intuitive that the reason for the LAI control probably is the same as discussed for the FIFE case. Overall, however, there may be only a limited role for interactions in the semiarid tropical regime as compared with the midlatitudes. This feature is discussed ahead.

c. Analysis of the evapotranspirative components

Analysis of the FIFE and HAPEX–Sahel cases suggests possible differences in the surface–atmosphere exchanges. The FIFE case specifically showed more variable interactions, whereas the tropical HAPEX–Sahel

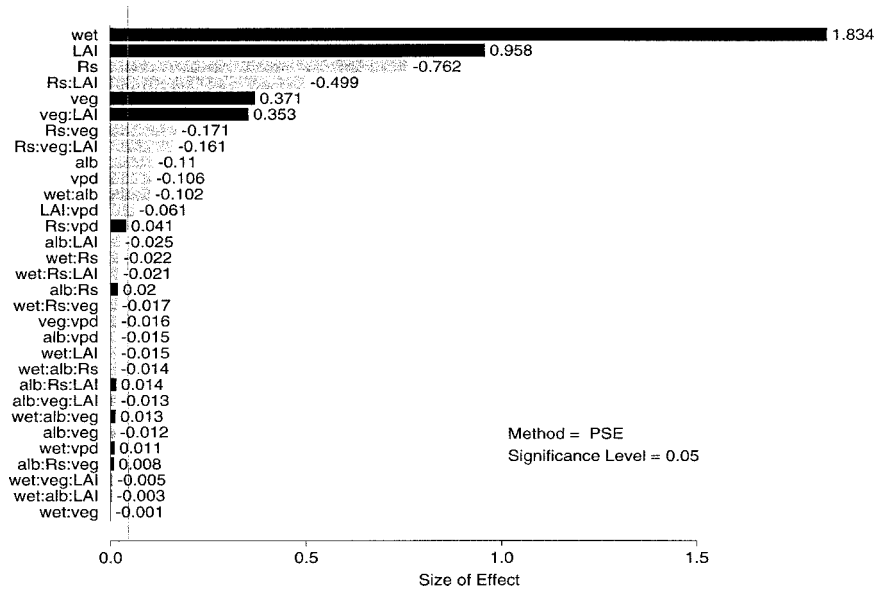


FIG. 6. Same as Fig. 2 but for SSiB over HAPEX-Sahel. As compared with the FIFE case, all the main-effects/direct pathways are important and dominate the outcome.

case showed dominance of direct effects. In addition, the evapotranspiration results show alternating control of soil and the vegetation variables. This result leads to questions related to understanding the contributions and interactions between the soil and vegetation components for the two regimes. These questions are addressed by analyzing the evapotranspirative components, which are calculated explicitly in SSiB for soil and vegetation canopy. We refer to the canopy component as transpiration and the soil component as evaporation.

1) MIDLATITUDINAL FIFE CASE

Figures 8a,b show the main-effect and Pareto plots for the canopy components (for the FIFE case). A distinct feature of the main-effect plots is the almost binary—dominance or independence—interaction of the surface variables leading to the outcome. Consider soil wetness, for example. Increasing soil wetness from near wilting to a median value has a profound impact on the canopy transpiration. However, the effect of increasing

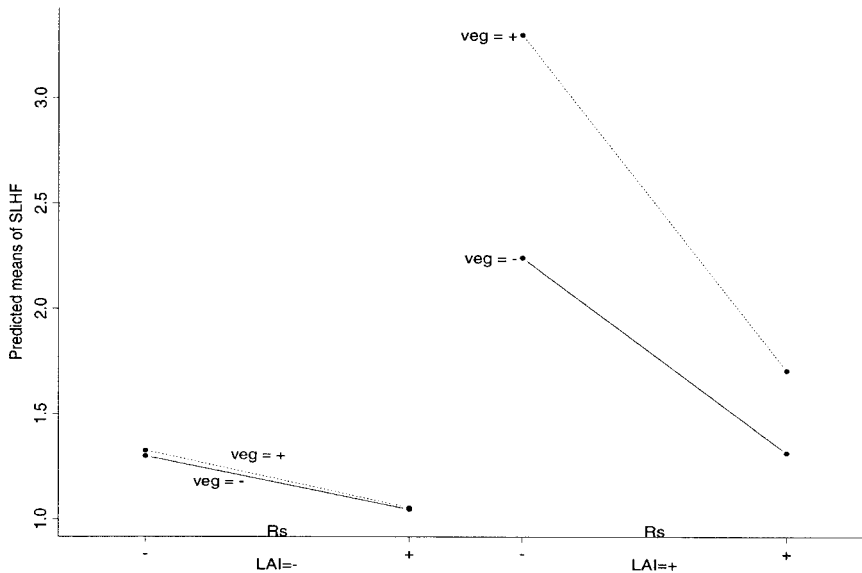


FIG. 7. Interaction plot showing triple interactions among stomatal resistance, vegetal cover, and LAI for the latent heat fluxes over HAPEX-Sahel ($SLHF \times 100, W m^{-2}$). The interactive pathways are significant with increasing LAI.

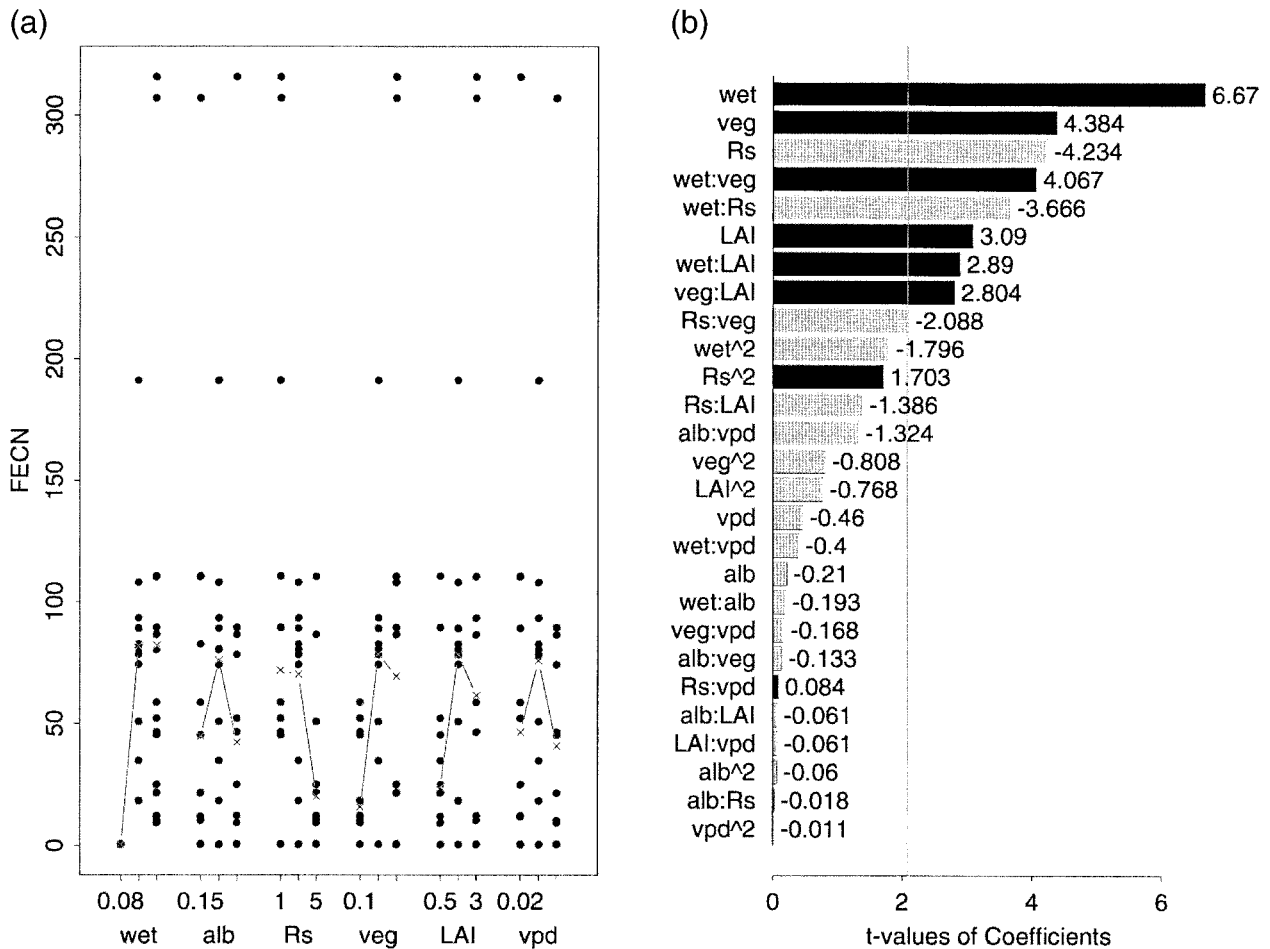


FIG. 8. Analysis of the canopy component of latent heat flux over FIFE domain using (a) main-effect and (b) Pareto plots.

soil wetness from median to near saturation is fairly minimal. Thus from dry to wetter soils, transpiration is dominated by soil moisture availability, but beyond a certain threshold, transpiration may be almost independent of further increase in soil moisture (Niyogi et al. 1998). In a similar way, decreasing stomatal resistance from a high value (such as 500 s m^{-1}) has a strong influence in enhancing transpiration; however, beyond a certain value transpiration is nearly independent of any further reduction in stomatal resistance (Niyogi et al. 1998). Other variables show similar responses (active variable interactions under nonlimiting conditions) as seen for the latent heat flux main effects (shown in Fig. 1).

The Pareto analysis (Fig. 8b) suggests that the transpiration over FIFE domain is dominated by direct or main effects in the following order: soil wetness, vegetal cover, stomatal resistance, and LAI. The interactions between soil wetness and other biophysical variables and the interaction pathways also significantly affect transpiration (though to a lesser extent). With the exception of stomatal resistance (main effect and interactions), all the significant variables positively contrib-

ute to transpiration, and all the interactions are synergistic. With increasing soil wetness, vegetal cover, and leaf area index, the vegetation can transpire with greater ease. On the other hand, by definition, increasing stomatal resistance inhibits transpiration. This is achieved both as a direct feedback and through interactions with other surface variables. Thus, both the interactions and the main-effect responses for transpiration are consistent with the different observations (e.g., Monteith and Unsworth 1990; Jones 1992).

The main-effect and Pareto plots corresponding to evaporation are shown in Figs. 9a,b. As expected, the direct effect of a variable change on evaporation is generally opposite to that for transpiration. Also, soil moisture is a dominant factor in modulating evapotranspiration. Increasing soil moisture availability consistently increased evaporation, whereas the effect of relative increase in soil moisture decreased for transpiration as the soil became more saturated. Thus the vegetation canopy effects or related interactions probably have a relatively minor impact on soil evaporation, as an outcome.

Thus, for the FIFE case, both evaporation and transpiration shows relative dominance of the first-order ef-

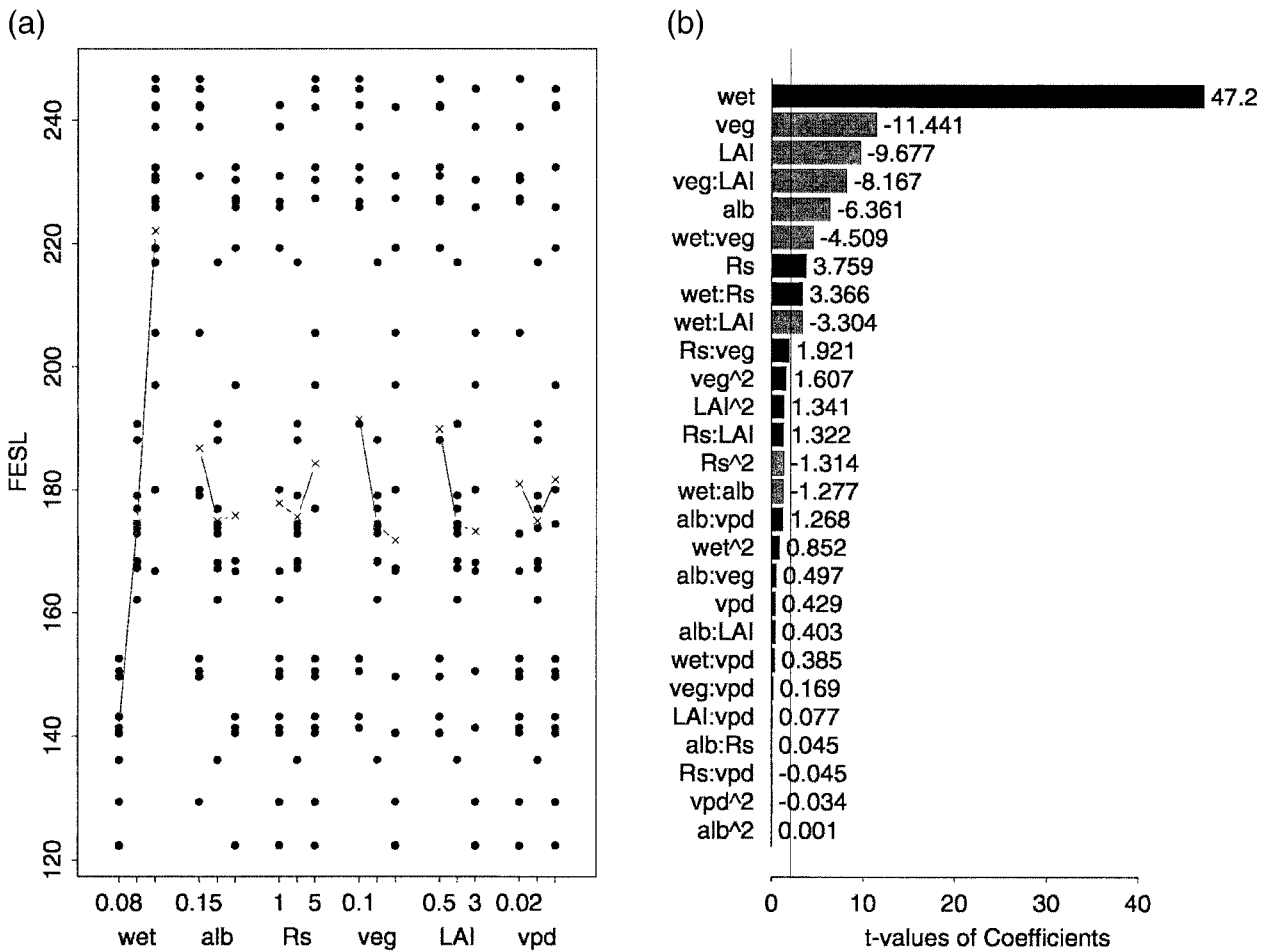


FIG. 9. Analysis of the soil component of latent heat flux over FIFE domain using (a) main-effect and (b) Pareto plots.

fects. Also, both the first- and the second-order soil and vegetation effects complement each other. This further confirms our previous results regarding the vegetation and the canopy being an *effective (unified) surface* for the midlatitudinal case. Thus, evapotranspiration probably is modulated via competing effects between soil and vegetation effects.

2) SEMIARID TROPICAL HAPEX-SAHEL CASE

Figures 10a,b show the main-effect and Pareto plots for the canopy component (transpiration) over the tropical domain. For the prior cases (including the FIFE components discussed in the previous section) all the main-effect plots showed a significant nonlinear variation. This lead to V-shaped main-effect plots, with the extreme values for the variable corresponding to nearly similar outcome and the median corresponding to significantly different value. Hence, an interesting feature of the transpiration main-effect plots over HAPEX-Sahel (Fig. 10a) is the linearity associated with the variable ranges and the corresponding transpiration changes. Further, the change in the variable value either has a

dominant linear impact on the outcome (e.g., changes in stomatal resistance, leaf area index, and vegetal cover), or no significant impact at all (e.g., change in albedo, vapor pressure deficit, and, to a certain extent, soil wetness) as seen in Fig. 10b. Another contrasting feature concerns the dominance of vegetation, even ahead of soil wetness, in controlling transpiration in the tropical setup. For example, even a second-order stomatal resistance term is more active in controlling transpiration than is soil wetness, in this particular case. Two features agree with the previous results: the relatively limited role of soil effects in modulating vegetative feedback, and the dominance of the noninteraction terms in evapotranspiration in the semiarid Tropics.

Figures 11a,b show the main-effect and Pareto plots for soil evaporation component over HAPEX-Sahel. Transpiration was dominated by the linear impact of the vegetative variables; the evaporative component shows strong nonlinear effects. Each of the surface variables shows significant differences in the median values as compared with extreme settings (Fig. 11a). An exception is the changes in soil wetness, which are directly related with evaporative outcome, as expected. Overall,

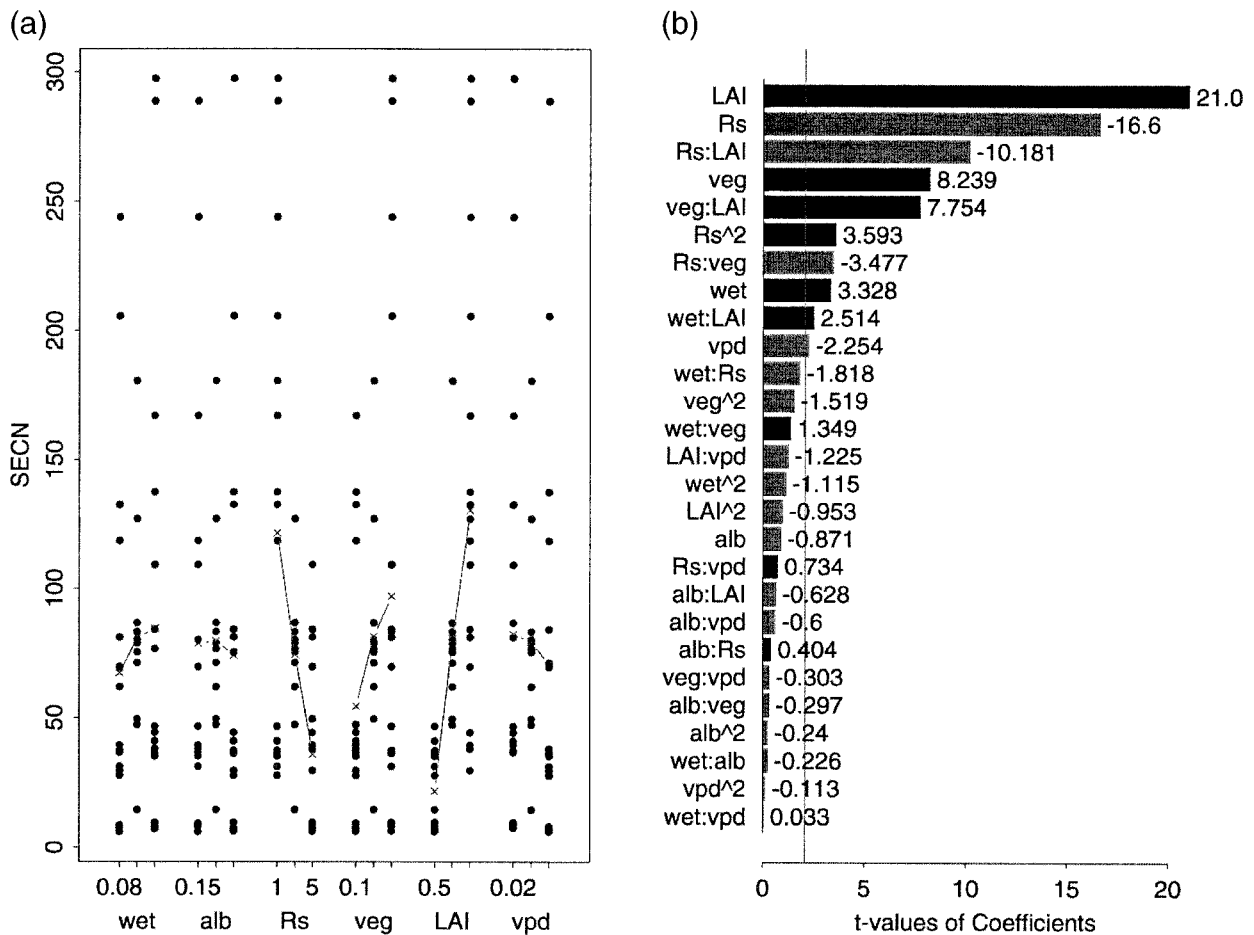


FIG. 10. Analysis of the canopy component of latent heat flux over HAPEX-Sahel domain using (a) main-effect and (b) Pareto plots.

evaporation over the tropical land surface likely is controlled by first-order (and even second-order) soil wetness changes and relatively insignificant interactions between soil wetness and vegetation variables (Fig. 11b). These results provide additional evidence on the inherent complexities and nonlinear pathways associated with the arid-semiarid tropical hydrometeorological scenario as compared with the midlatitudes.

Thus, the analyses suggest several important differences between the semiarid tropical case and the FIFE case. First, leaf area index has a dominant role in controlling soil evaporation, and soil moisture effects modulate transpiration over the tropical domain. Second, for HAPEX-Sahel, the evapotranspiration *components* show more interaction terms to be significant, in comparison with *total* evapotranspiration effect. Yet, there was a lack of interaction between the soil parameters for modulating canopy processes (or vice versa). Thus, in the FIFE case the soil and canopy components complemented each other; for the HAPEX-Sahel data, they behave independently without any apparent interaction between the soil and canopy variables. This result suggests a possibility of the tropical surface being a mosaic

of independent soil and canopy segments, which would have to be represented by parameterizations that consider each of the components explicitly.

The interactions among the different surface variables have additional implications on modeling uncertainties (Niyogi et al. 1999) and land surface memory regarding error propagation (Pielke 1998). Our results further suggest that the persistence in errors can be higher for the semiarid regimes as compared with the midlatitudes because of the noninteractive nature of the land surface processes. Nicholson (2000) recently provided a summary of the drought persistence in the Sahelian environment. Our results suggest that the lack of interaction between vegetation and the soil surface can be one of the reasons contributing to the persistence outlined in her study. In addition, for the midlatitudinal cases, errors in initial surface conditions in one variable can transfer to another variable, thus altering the uncertainty in the initial surface conditions. It can be hypothesized, as discussed and tested in Niyogi et al. (1999), that for most scenarios such errors can be self-balancing (and compensatory); for extreme cases (such as wilting soil moisture conditions or high-LAI cases) the errors could

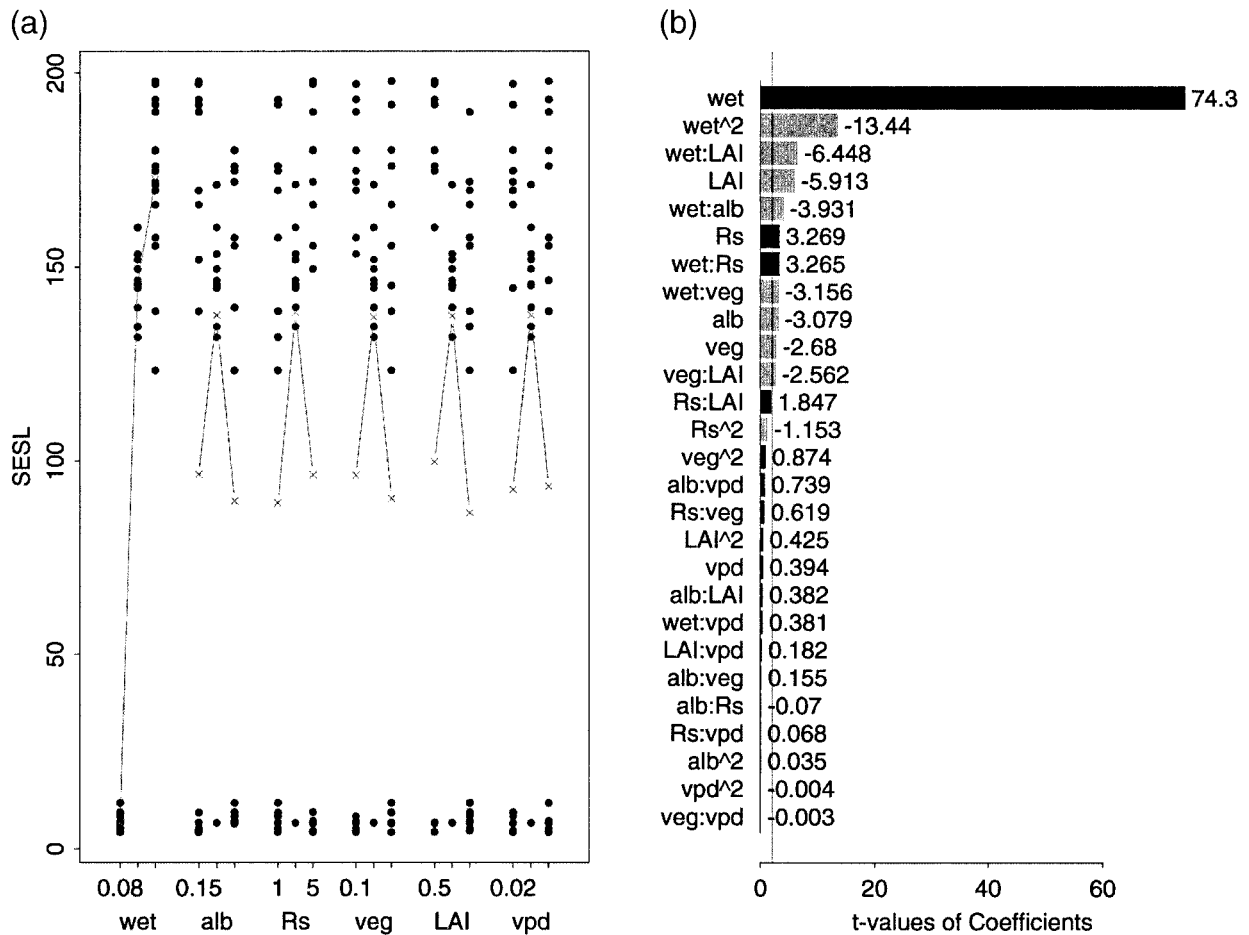


FIG. 11. Analysis of the soil component of latent heat flux over HAPEX–Sahel domain using (a) main-effect and (b) Pareto plots.

be synergistically additive, thereby increasing the overall uncertainty. These results hence pose additional constraints on the limits of climate projections, including considerations of land surface memory, under both the midlatitudinal and tropical regimes. Indeed, the nature of the limits, that is, persistence in the semiarid Tropics and possible compensatory elimination in midlatitude, will need further examination with explicit feedback (coupling) between the surface and the atmosphere, including cloud and precipitation processes (cf. Dolman et al. 1997).

5. Conclusions

Surface processes have significant impact on the surface energy balance and hydrological processes at various scales. The hydrological responses of the land surface processes over midlatitudinal and semiarid tropical sites were studied. Based on the statistical analysis of offline SSiB results for a midlatitudinal (FIFE) and semiarid tropical (HAPEX–Sahel) forcing, the hypothesis tested was, are there any differences in the land

surface processes in the midlatitudinal and the semiarid tropical regimes?

Summarizing the results from the two cases studied here, it is concluded that the first-order, or direct, pathways are fairly similar whereas the indirect, or second-order, pathways and interaction feedbacks are significantly different for the semiarid tropical case and the moist midlatitudinal case.

Further, changes in surface variables have a significantly nonlinear response on the latent heat flux. Low and high variable settings typically show low evapotranspiration values, and the mean initial conditions show peak values in the predicted water vapor fluxes. For the two domains, soil wetness was the only variable that has a direct linear relation with evapotranspiration. That is, higher soil wetness availability lead to higher latent heat flux values almost linearly. Another common feature between the two cases is the opposing response of stomatal resistance and LAI (for the direct feedbacks). High stomatal resistance values lead to lower latent heat fluxes, and higher LAI values corresponded to high latent heat flux simulations. These results are

consistent with prior observational and parameterizations-based model studies and do not yield any significant differences in the tropical or midlatitudinal regimes. However, the nature of the surface variable response is prone to be more nonlinear for the semiarid tropical case, as compared with the FIFE. Further, with regard to evapotranspiration as the effect, the interactive feedbacks are more active in the midlatitudinal FIFE case as compared with the HAPEX–Sahel case. This is true for both first- and higher-order interactions. Overall, the analysis provides discernable differences between the two cases. For the tropical case, there is a significant first-order, or direct effect, dominance; the FIFE case exhibits significant second- and higher-order interactions controlling the effect. In general, the FIFE case is dominated by soil wetness–related interactions and the semiarid tropical/HAPEX–Sahel case shows vegetation-related effects controlling the land surface response (also see Nicholson 2000).

An important feedback pathway is deduced from the analysis of the higher-order interactions. With higher soil moisture values, as generally perceived for the midlatitudinal domain, the soil wetness availability resulted in synergistic interactions with other surface variables. That is, there appears to be more communication between the various land surface variables through biophysical exchanges (including water vapor) in the moist midlatitudinal regime. On the other hand, for semiarid tropical regime, the results suggest there are limited exchanges between the vegetation and the soil surface. That is, the surface components respond directly with the atmospheric forcing *via* limited modulation from vegetation to the bare ground. There can be several interpretations of this result. One, the interactions suggest, is that the midlatitudinal vegetative transfer with higher moisture availability may permit a diversified strategy for the surface. The relatively wetter midlatitudinal conditions (as compared with semiarid Tropics) provide an opportunity for an efficient transfer and higher water use by the vegetation, leading to higher fluxes (Wilson et al. 2000). In addition, it allows involvement and interaction of various biophysical and soil components, thereby creating a unified or effective resistance pathway. Thus, the midlatitudinal vegetation and soil surface moisture transfer may be efficiently simulated by so-called effective surface representation schemes (parameterizations in which soil and vegetation are represented by a single area-averaged surface; see, e.g., Noilhan and Planton 1989; Pleim and Xiu 1995; Alapaty et al. 1997). Because in the dry, semiarid tropical regime there is limited interaction between the vegetation and the bare ground, the surface components conversely may be individually linked with the atmosphere and not as an “effective surface.” Hence the single effective or area-averaged vegetation and bare ground flux representation may have additional limitations in the semiarid tropical conditions. For the tropical regimes, it consequently may be necessary to em-

ploy detailed land surface schemes that explicitly calculate the bare ground and vegetation fluxes [examples include SSiB and a modification of the Noilhan and Planton (1989) scheme that follows Bosilovich and Sun (1995)]. Note that these findings need to be examined further using observations and coupled modeling–interaction-explicit analyses.

This interactive or effective moisture feedback transfer strategy in the midlatitudes and the tropical one-on-one soil–atmosphere and vegetation–atmosphere transfer in the semiarid Tropics can also be viewed in “resource allocation” perspective. The unified response of the various components found in the midlatitudinal regime could play a balancing or compensatory role. A possible strategy could be that the midlatitudinal domain could try to sustain itself, or recover quickly, from external perturbations (such as a meteorological drought) through synergistic interactions. On the other hand, for the semiarid Tropics, the different land surface in its “nondiversified” approach cannot distribute its stress on the different surface variables. That is, the vegetation cannot expect sympathetic response from soil moisture and has to weather the stress independently. This lack of a unified strategy by the plants and soil as an effective surface could make the arid tropical region more prone to desertification and to a slower recovery from external perturbation, as compared with the midlatitudes, under similar water stress situations (cf. Nicholson 2000).

Thus our study suggests that, in comparing the hydrological responses of a midlatitudinal and a semiarid tropical domain, there may be similarities in the direct effects; however, the indirect pathways may be very different. Analysis further suggests there are distinct differences in the interaction pathways for the two cases. The dry, semiarid tropical regimes were dominated through vegetative feedbacks (leaf area index, stomatal resistance, and vegetal cover in this study), whereas the midlatitudes showed soil wetness (moisture)–related interactive pathways. It is concluded that the result may be indicative that the ability of the ecosystem to sustain itself could be related directly to the soil moisture availability. Thus, considering the two experiments (FIFE and HAPEX–Sahel) representative of the respective biogeographical regions—midlatitudinal central United States and semiarid tropical Sahel—the results can be extrapolated further. Overall, the midlatitudinal case showed a “relaxed” vapor transfer between vegetative and ground surface variables, whereas the semiarid tropical case had direct exchange of each surface variable interacting with the atmosphere directly rather than with each other. However, it should be emphasized also that the results presented here are from uncoupled offline modeling results and that further investigation using a coupled SVAT model and field observations is necessary for a more comprehensive investigation.

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REFERENCES

- Alapaty, K., S. Raman, and D. S. Niyogi, 1997: Uncertainty in specification of surface characteristics: A study of prediction errors in the boundary layer. *Bound.-Layer Meteor.*, **82**, 473–500.
- , N. Seaman, D. S. Niyogi, and A. Hanna, 2001: Assimilating surface data to improve the accuracy of atmospheric boundary layer simulations. *J. Appl. Meteor.*, **40**, 2068–2082.
- Alpert, P., M. Tsidulko, and U. Stein, 1995: Can sensitivity studies yield absolute comparisons for the effects of several processes? *J. Atmos. Sci.*, **52**, 597–601.
- André, J., B. Goutorbe, and A. Perrier, 1986: HAPEX-MOBILHY: A hydrologic atmospheric experiment for the study of water budget and evaporation flux at the climatic scale. *Bull. Amer. Meteor. Soc.*, **67**, 138–144.
- Arya, S., 1988: *Introduction to Micrometeorology*. Academic Press, 308 pp.
- Avissar, R., 1995: Which type of soil–vegetation–atmosphere transfer scheme is needed for general circulation models: Proposal for a higher-order scheme. *J. Hydrol.*, **212/213**, 136–154.
- , and R. A. Pielke, 1989: A parameterization of heterogeneous land surface for atmospheric numerical models and its impact on regional meteorology. *Mon. Wea. Rev.*, **117**, 2113–2136.
- Baldocchi, D. D., and T. P. Meyers, 1998: On using ecophysiological, micrometeorological, and biogeochemical theory to evaluate carbon dioxide, water vapor, and trace gas fluxes over vegetation: Synthesis and application. *Agric. For. Meteorol.*, **90**, 1–25.
- Bollé, H., and Coauthors, 1993: EFEDA: European Field Experiment in a Desertification-Threatened Area. *Ann. Geophys.*, **14**, 795–806.
- Bosilovich, M., W. Sun, 1995: Formulation and verification of a land surface parameterization for atmospheric models. *Bound.-Layer Meteor.*, **73**, 321–341.
- Box, G., W. Hunter, and J. Hunter, 1978: *Statistics for Experimenters: An Introduction to Design, Data Analysis, and Model Building*. John Wiley and Sons, 672 pp.
- Brubaker, K., and D. Entekhabi, 1996: Asymmetric recovery from wet versus dry soil moisture anomalies. *J. Appl. Meteor.*, **35**, 94–109.
- Calvet, J., and Coauthors, 1999: MUREX: A land-surface field experiment to study the annual cycle of the energy and water budgets. *Ann. Geophys.*, **17**, 838–854.
- Camillo, P., and R. Gurney, 1986: A resistance parameter for bare-soil evaporation models. *Soil Sci.*, **2**, 95–105.
- Chen, F., and R. Avissar, 1994: The impact of land-surface wetness heterogeneity on mesoscale heat fluxes. *J. Appl. Meteor.*, **33**, 1323–1340.
- Clapp, R., and G. Hornberger, 1978: Empirical equations for some soil hydraulic properties. *Water Resour. Res.*, **14**, 601–604.
- Cooter, E. J., and D. Schwede, 2000: Sensitivity of the National Oceanic and Atmospheric Administration multilayer model to instrument error and parameterization uncertainty. *J. Geophys. Res.*, **105**, 6695–6704.
- da Rocha, H., C. A. Nobre, J. P. Bonatti, I. R. Wright, and P. J. Sellers, 1996: A vegetation–atmosphere interaction study for Amazonia deforestation using field data and a single column model. *Quart. J. Roy. Meteor. Soc.*, **122**, 567–594.
- Deardorff, J., 1978: Efficient prediction of ground surface temperature and moisture, with inclusion of a layer of vegetation. *J. Geophys. Res.*, **83**, 1889–1903.
- Dirmeyer, P., and J. Shukla, 1994: Albedo as a modulator of climate response to tropical deforestation. *J. Geophys. Res.*, **99**, 20 863–20 877.
- Dolman, A., J. Gash, J. Goutorbé, Y. Kerr, T. Lebel, S. Prince, and J. Stricker, 1997: The role of the land surface in Sahelian climate: HAPEX–Sahel results and future research needs. *J. Hydrol.*, **188/189**, 1067–1079.
- Dolman, J., and P. Sellers, 1989: A global climatology of albedo, roughness length and stomatal resistance for atmospheric general circulation models as represented by the Simple Biospheric Model (SiB). *J. Appl. Meteor.*, **28**, 833–855.
- Entekhabi, D., I. Rodriguez-Iturbe, and F. Castelli, 1996: Mutual interaction of soil moisture state and atmospheric processes. *J. Hydrol.*, **184**, 3–17.
- Goutorbé, J., and Coauthors, 1994: HAPEX-Sahel: A large scale study of land atmosphere interactions in semi-arid Tropics. *Ann. Geophys.*, **12**, 53–64.
- Haaland, P. D., 1989: *Experimental Design in Biotechnology*. Marcel Dekker, 259 pp.
- Henderson-Sellers, A., 1993: A factorial assessment of the sensitivity of the BATS land-surface parameterization scheme. *J. Climate*, **6**, 227–247.
- , K. McGuffie, and A. Pitman, 1996: The Project for Intercomparison of Land-surface Parameterization Schemes (PILPS): 1992 to 1995. *Climate Dyn.*, **12**, 849–859.
- Hu, Z., and S. Islam, 1996: A method to evaluate the importance of interactions between land surface and atmosphere. *Water Resour. Res.*, **32**, 2497–2505.
- Ishikawa, K., 1976: *Guide to Quality Control*. Asian Productivity Organization, 226 pp.
- Jacquemin, B., and J. Noilhan, 1990: Sensitivity study and validation of a land surface parameterization using the HAPEX-MOBILHY data set. *Bound.-Layer Meteor.*, **52**, 93–134.
- Jarvis, P., 1976: The interpretation of leaf water potential and stomatal conductance found in canopies in the field. *Philos. Trans. Roy. Soc. London*, **B273**, 593–610.
- Jones, H., 1992: *Plants and Micro Climate: A Quantitative Approach to Environmental Plant Physiology*. 2d ed. Cambridge University Press, 456 pp.
- Kim, C., and D. Entekhabi, 1998: Analysis of feedback mechanisms in the uncoupled and coupled land surface and mixed layer energy budgets. *Bound.-Layer Meteor.*, **88**, 1–21.
- Lenth, R., 1989: Quick and easy analysis of unreplicated fractional factorials. *Technometrics*, **31**, 469–473.
- Makela, A., F. Berninger, and P. Hari, 1996: Optimal control of gas exchange during drought: Theoretical analysis. *Ann. Bot.*, **77**, 461–467.
- Margulis, S., and D. Entekhabi, 2001: A coupled land surface–boundary layer model and its adjoint. *J. Hydrometeorol.*, **2**, 274–296.
- Meyers, T., P. Finkelstein, J. Clarke, T. Ellestad, and P. Sims, 1998: A multilayer model for inferring dry deposition using standard meteorological measurements. *J. Geophys. Res.*, **103**, 22 645–22 661.
- Monteith, J., and M. Unsworth, 1990: *Principles of Environmental Physics*. 2d ed. Edward Arnold, 291 pp.
- Nicholson, S., 2000: Land surface processes and Sahel climate. *Rev. Geophys.*, **38**, 117–139.
- Niyogi, D. S., and S. Raman, 1997: Comparison of four different stomatal resistance schemes using FIFE data. *J. Appl. Meteor.*, **36**, 903–917.
- , —, K. Alapaty, and J. Han, 1997a: A dynamic statistical experiment for atmospheric interactions. *Environ. Modell., Assess.*, **A**, **2**, 307–322.
- , —, A. Prabhu, U. Kumar, and S. Joshi, 1997b: Direct estimation of stomatal resistance for meteorological applications. *Geophys. Res. Lett.*, **24**, 1771–1774.
- , —, and K. Alapaty, 1998: Comparison of four different stomatal resistance schemes using FIFE data. Part II: Analysis of terrestrial biospheric–atmospheric interactions. *J. Appl. Meteor.*, **37**, 1301–1320.
- , —, and —, 1999: Uncertainty in the specification of sur-

- face characteristics. Part II: Hierarchy of interaction-explicit statistical analysis. *Bound.-Layer Meteor.*, **91**, 341–366.
- Noilhan, J., and S. Planton, 1989: A simple parameterization of land surface processes for meteorological models. *Mon. Wea. Rev.*, **117**, 536–549.
- Norman, J. M., W. Kustas, and K. Humes, 1995: Source approach for estimating soil and vegetation energy fluxes in observations of directional radiometric surface temperature. *Agric. For. Meteorol.*, **77**, 263–293.
- Paulson, C. A., 1970: Mathematical representation of wind speed and temperature profiles in the unstable atmospheric surface layer. *J. Appl. Meteor.*, **9**, 857–861.
- Pielke, R. A., 1998: Climate prediction as an initial value problem. *Bull. Amer. Meteor. Soc.*, **79**, 2743–2746.
- , G. Dalu, J. Snook, T. Lee, and T. Kittel, 1991: Nonlinear influence of mesoscale land use on weather and climate. *J. Climate*, **4**, 1053–1069.
- Pitman, A., 1994: Assessing the sensitivity of a land-surface scheme to the parameter values using a single column model. *J. Climate*, **7**, 1856–1869.
- Pleim, J., and A. Xiu, 1995: Development and testing of a surface flux and planetary boundary layer model for application in mesoscale models. *J. Appl. Meteor.*, **34**, 16–32.
- Prince, S., and Coauthors, 1995: Geographical, biological and remote sensing aspects of the Hydrologic Atmospheric Pilot Experiment in the Sahel (HAPEX-Sahel). *Remote Sens. Environ.*, **51**, 215–234.
- Raman, S., D. S. Niyogi, A. Prabhu, S. Ameenulla, S. T. Nagaraj, S. Jayanna, U. Kumar, and S. Joshi, 1997: VEBEX: A vegetation and energy balance experiment for Tropics. *Proc. Indian Acad. Sci. (Earth Planet Sci.)*, **107**, 97–105.
- Rhome, J., D. S. Niyogi, and S. Raman, 2000: Mesoscale analysis of severe weather and ENSO interactions in North Carolina. *Geophys. Res. Lett.*, **27**, 2269–2272.
- Sellers, P., 1985: Canopy reflectance, photosynthesis and transpiration. *Int. J. Remote Sens.*, **6**, 1335–1372.
- , 1987: Canopy reflectance, photosynthesis and transpiration, II, The role of biophysics in the linearity of their independence. *Remote Sens. Environ.*, **21**, 143–183.
- , and F. Hall, 1992: FIFE in 1992: Results, scientific gains, and future research directions. *J. Geophys. Res.*, **97**, 19 091–19 109.
- , Y. Mintz, Y. Sud, and A. Dalcher, 1986: A simple biosphere model (SiB) for use within general circulation models. *J. Atmos. Sci.*, **43**, 505–531.
- , F. Hall, G. Asrar, D. Strelbel, and R. Murphy, 1988: The first ISLSCP field experiment (FIFE). *Bull. Amer. Meteor. Soc.*, **69**, 22–27.
- , W. Shuttleworth, J. Dolman, A. Dalcher, and J. Roberts, 1989: Calibrating the simple biosphere model for Amazonian tropical forest using field and remote sensing data. Part I: Average calibration with field data. *J. Appl. Meteor.*, **28**, 727–759.
- , M. Heiser, and F. Gall, 1992: Relations between surface conductance and spectral vegetation indices at intermediate (100 m² to 15 km²) length scales. *J. Geophys. Res.*, **97**, 19 033–19 060.
- Sims, A. P., D. S. Niyogi, and S. Raman, 2001: Adopting drought indices for estimating soil moisture: A North Carolina case study. *Geophys. Res. Lett.*, in press.
- Stein, U., and P. Alpert, 1993: Factor separation in numerical simulations. *J. Atmos. Sci.*, **50**, 2107–2115.
- Stewart, J., and S. Verma, 1992: Comparison of surface fluxes and conductances at two contrasting sites within the FIFE area. *J. Geophys. Res.*, **97**, 18 623–18 628.
- Viterbo, P., and A. Beljaars, 1995: An improved land surface parameterization scheme in the ECMWF model and its validation. *J. Climate*, **8**, 2716–2748.
- Wetzel, P., and J. Chang, 1987: Concerning the relationship between evapotranspiration and soil moisture. *J. Climate Appl. Meteor.*, **26**, 18–27.
- Wilson, K., D. D. Baldocchi, and P. Hanson, 2000: Spatial and seasonal variability of photosynthetic parameters and their relationship to leaf nitrogen in a deciduous forest. *Tree Physiol.*, **20**, 565–578.
- Xue, Y. K., 1997: Biosphere feedback on regional climate in tropical North Africa. *Quart. J. Roy. Meteor. Soc.*, **123B**, 1483–1505.
- , and J. Shukla, 1993: The influence of the land surface properties on Sahel climate. Part I: Desertification. *J. Climate*, **6**, 2232–2245.
- , P. Sellers, J. Kinter, and J. Shukla, 1991: A simplified biosphere model for climate studies. *J. Climate*, **4**, 345–364.
- , H. Bastable, P. Dirmeyer, and P. Sellers, 1996: Sensitivity of simulated surface fluxes to changes in land surface parameterizations—a study using ABRACOS data. *J. Appl. Meteor.*, **35**, 386–400.