Convective Planetary Boundary Layer Interactions with the Land Surface at Diurnal Time Scales: Diagnostics and Feedbacks

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ABSTRACT

The convective planetary boundary layer (PBL) integrates surface fluxes and conditions over regional and diurnal scales. As a result, the structure and evolution of the PBL contains information directly related to land surface states. To examine the nature and magnitude of land–atmosphere coupling and the interactions and feedbacks controlling PBL development, the authors used a large sample of radiosonde observations collected at the southern Atmospheric Research Measurement Program–Great Plains Cloud and Radiation Testbed (ARM-CART) site in association with simulations of mixed-layer growth from a single-column PBL/land surface model. The model accurately predicts PBL evolution and realistically simulates thermodynamics associated with two key controls on PBL growth: atmospheric stability and soil moisture. The information content of these variables and their influence on PBL height and screen-level temperature can be characterized using statistical methods to describe PBL–land surface coupling over a wide range of conditions. Results also show that the first-order effects of land–atmosphere coupling are manifested in the control of soil moisture and stability on atmospheric demand for evapotranspiration and on the surface energy balance. Two principal land–atmosphere feedback regimes observed during soil moisture drydown periods are identified that complicate direct relationships between PBL and land surface properties, and, as a result, limit the accuracy of uncoupled land surface and traditional PBL growth models. In particular, treatments for entrainment and the role of the residual mixed layer are critical to quantifying diurnal land–atmosphere interactions.

1. Introduction

Over the last two decades, a large number of studies have focused on methods to estimate regional land surface energy balance (Humes et al. 1994; Gillies et al. 1997; Norman et al. 2003). Conventionally, such studies use offline models of land surface processes, which require a great deal of observation and parameterization, and are limited by errors in their representation and model physics. Recently, the validity of land surface models that do not include the processes and feedbacks caused by land–atmosphere interactions has been under scrutiny. For example, results from the Project for Intercomparison of Land-surface Parameterization Schemes (PILPS; Henderson-Sellers et al. 1996) experiments have shown that simulated fluxes can be quite sensitive to atmospheric feedbacks (Liu et al. 2003, 2004, 2005). As a result, it is clear that the land surface and planetary boundary layer cannot be realistically simulated independently of one another, and that land surface models must, to some degree, be coupled to the atmosphere (Margulis and Entekhabi 2001). At the same time, fully coupled single-column, regional, and climate models are sub-

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stantially more complex, and therefore require significantly more assumptions, data inputs, and parameterizations for key processes relative to offline land surface models.

In this paper, we consider an approach to estimating land surface fluxes and states based on observations that enables one to identify the critical pathways and effects of land–atmosphere interactions. Specifically, the diurnal evolution of the convective planetary boundary layer (PBL) has been relatively unexplored as a means to infer land surface energy fluxes and moisture states. A variety of studies have shown that the structure of the PBL is influenced by the land surface in ways that can be identified and linked to surface conditions without the need for in situ measurements of such variables (Pan and Mahrt 1987; Oke 1987; Stull 1988; Diak 1990; Dolman et al. 1997; Peters-Lidard and Davis 2000; Cleugh et al. 2003; Ek and Holtslag 2004; Santanello et al. 2005). Further, the PBL integrates land surface processes at scales on the order of 10–100 km, thereby eliminating the need for upscaling of point models and measurements.

The most accurate in situ measurements of vertical gradients of temperature and moisture (and therefore PBL structure) in the lower troposphere come from radiosondes, and numerous attempts have been made to link these observations to land surface processes during short-term field experiments (Betts and Ball 1994; Peters-Lidard and Davis 2000; Yi et al. 2001). Recently, Santanello et al. (2005) evaluated a large sample of PBL and land surface data from the Atmospheric Radiation and Measurement Program (ARM) test bed in the southern Great Plains (SGP) and used these data to derive empirical relationships between PBL evolution and soil moisture on daily and regional scales. Their results suggest that there is significant potential for using observations of bulk PBL properties to gain information on the land surface states and processes.

Here we extend the work of Santanello et al. (2005) and examine the interactions that determine PBL evolution and land surface energy balance from an empirical and modeling perspective. In particular, the relationships among land surface properties and fluxes, PBL structure, atmospheric stability, and soil moisture are addressed. The specific goals of this research are to examine and clarify relationships among PBL and land surface variables across a broad range of conditions, and to identify feedbacks that impact and confound interpretation and prediction of the coupled system. To do this, we employ a single-column PBL model in combination with data from the ARM-SGP site. The strength and robustness of the relationships and coupling between PBL properties and surface conditions for a range of locations and land cover characteristics are explored using the model. Factors that complicate the relationships between PBL evolution, soil moisture, and surface fluxes are then addressed by considering the role of feedbacks between the PBL and land surface, which are then described and quantified using modeled and empirical data. Finally a two-step process to estimate regional surface fluxes is presented based on model results for a wide range of conditions.

2. Background

In this section we provide an overview of previous studies that have examined the relationship between land surface properties and processes and PBL heat budgets. To this end, we distinguish among three main types of studies: 1) those focusing on closure of the PBL heat budget; 2) those using nonconservation approaches; and 3) empirical and model-based studies.

a. Conservation of heat in the PBL

A variety of studies have focused on closure of the PBL heat budget (Stull 1988), which quantifies the manner in which heat is added to the PBL through sensible heating, radiative flux divergence, horizontal advection, and entrainment. Most of the heat input to the PBL comes from surface sensible heat flux (up to 70% under highly convective conditions). However, the remaining terms (e.g., entrainment) are significant and estimating these terms on daily time scales has proven to be a difficult task (Kustas and Brutsaert 1987; Swiatek 1992; Betts and Ball 1994; Hubbe et al. 1997, Peters-Lidard and Davis 2000). In fact, the results from Santanello et al. (2005) suggest that successful parameterization and closure of the heat conservation equation is not feasible at this time scale given current methods of PBL measurement.

Simplified models attempt to minimize parameterization requirements, but are only valid during free convective situations when surface fluxes, rather than mechanically driven flows, dominate PBL growth. The simplest approach in this regard is the encroachment method, which considers heat input to the PBL from the surface and ignores all other energy sources and controls on PBL evolution. A more detailed "slab" model (Tennekes 1973) relates PBL growth to surface sensible heating, ignores advection and radiation, and parameterizes entrainment as a constant proportion of surface heat flux. Slab models do not work well under conditions of low atmospheric stability and will overestimate surface fluxes in such cases.

Recently, Hubbe et al. (1997), Dolman et al. (1997),

and Yi et al. (2001) used a modified conservation approach to infer surface fluxes from PBL observations. However, their results were obtained for small samples (<10 days) of data, and showed only modest success because of limited data availability and accuracy, model simplification, and difficulties in parameterizing conservation terms. Overall, these studies highlight the difficulty in estimating first-order PBL processes, the impact of incomplete treatment of land–atmosphere coupling, and the limited utility of conservation approaches (and their approximations) for inferring diurnal land surface energy balance.

b. Nonconservation approaches

Alternative approaches have focused on extending Monin–Obukhov similarity theory (Monin and Obukhov 1954) from the surface layer into the PBL to estimate surface fluxes using bulk PBL properties (Brutsaert and Sugita 1992; Parlange et al. 1995; Brutsaert 1999). These techniques have been successfully used to estimate surface sensible heat flux during short-term intensive field campaigns, but require detailed measurements and specification of stability correction functions and parameters that are difficult to obtain. Techniques that combine similarity approaches with remote sensing observations (Brutsaert and Sugita 1992) or a slab model (Brutsaert 1999) have been used to estimate surface fluxes, but are also limited by specification requirements for surface and atmospheric properties.

In a series of studies that motivated the research described in this paper, Diak and Stewart (1989), Diak (1990), and Diak and Whipple (1993, 1994) proposed an approach using a mixed layer growth model that exploited the response of PBL variations to surface forcing. To do this, they simulated diurnal change in PBL height (h) and surface temperature (T_s) across prescribed ranges of Bowen ratio (β) and surface roughness (z_o). Based on these simulations, observations of h and T_s were used to estimate β and z_o. Results were good when convective (surface) forcing was dominant, but much of the variability in h due to the influence and coupling of other surface and atmospheric properties remained unexplained. They also suggest that the derived relationship between β and h is complicated by factors such as the variability in surface moisture conditions and atmospheric stability.

c. Empirical and modeled PBL–land surface relationships

Building upon the work of Diak and coworkers, Santanello et al. (2005) performed an empirical investigation of PBL–land surface interactions and developed a technique to estimate PBL height and near-surface soil moisture from easily observable variables. Using 132 days of data from the central facility of ARM-SGP in Lamont, Oklahoma (36.605°N, 97.485°W, 313-m elevation), statistically significant relationships were found between daily maximum h and near-surface soil water content (w), atmospheric stability (γ), diurnal temperature range (hereby defined as the diurnal change in 2-m potential temperature, $\Delta\theta_{2m}$), and diurnal change in 2-m specific humidity (Δq_{2m}). Based on these results, statistical models were estimated that predict h and $\Delta\theta_{2m}$ across a range of w and γ (Fig. 1). These models showed that observations of w, $\Delta\theta_{2m}$, and γ explained 85% of the variability in h. Further, after inverting the models to solve for w, 92% of the variance in w (averaging w over 0.05 m^3 m^{-3} intervals, the typical measurement uncertainty associated with soil moisture) could be explained using observations of h, $\Delta\theta_{2m}$, and γ.

The results presented by Santanello et al. (2005) suggest that a promising alternative to conservation or similarity approaches may be one based on observable *properties* of the PBL–land surface system rather than *process*-driven methods that are more difficult to measure and parameterize. In particular, Santanello et al. (2005) showed that land surface control on PBL evolution is largely governed by soil moisture (which controls the partitioning of available energy into sensible and latent heat fluxes), while atmospheric control is largely governed by initial γ within the layer of PBL growth [as measured from the morning (1130 UTC) sounding].

While results from the studies discussed above indicate that progress has been made in identifying direct PBL–land surface relationships and interactions over the SGP region, understanding is still confounded by feedbacks and nonlinearities in the relationships among moisture and energy states. For example, Jacobs and DeBruin (1992) indicate that PBL processes such as entrainment can have a significant influence on the sensitivity of surface fluxes to changes in land surface conditions, and highlight the importance of including these processes in land surface models. Entekhabi and Brubaker (1995) and Brubaker and Entekhabi (1996) also performed an in-depth quantitative analysis of land–atmosphere interactions that focused on the impacts of near-surface soil moisture and temperature variability on fluxes and PBL evolution. They found evidence that PBL growth can enhance surface sensible heat flux through a complex set of processes that lead to rapid soil drying and, hence, higher surface Bowen ratios (see also Kim and Entekhabi 1998).

Finally, recent studies comparing large-eddy simulation (LES) model results with traditional flux-profile

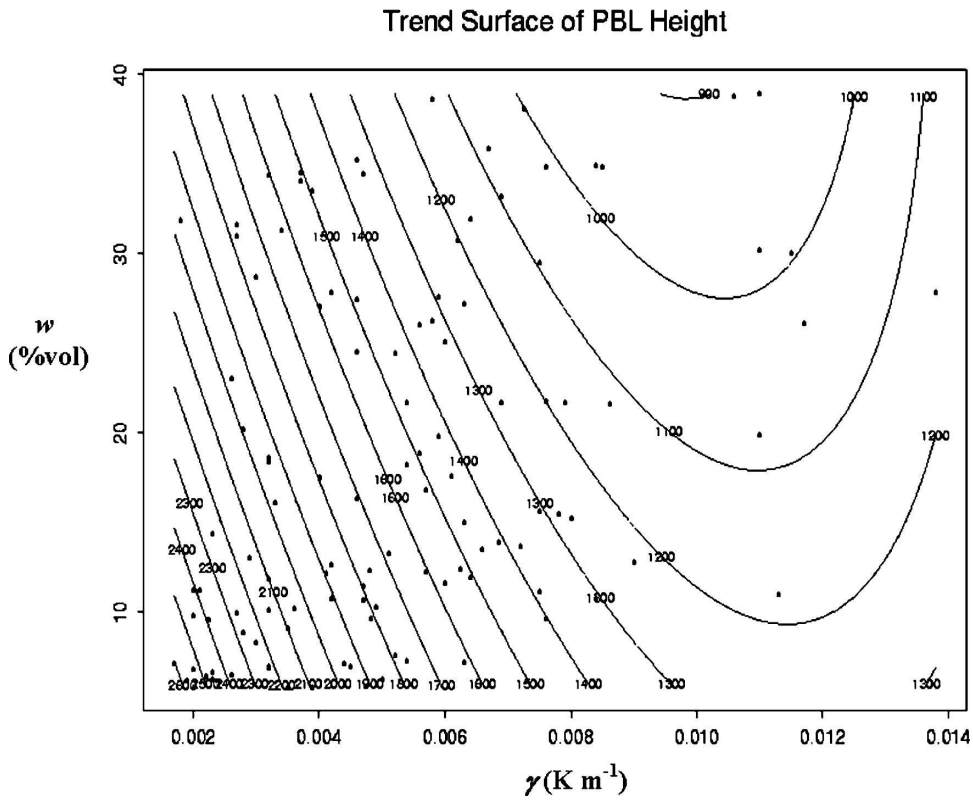

FIG. 1. Contour plot of maximum PBL height (in 100-m intervals) estimated as a function of stability (γ, K m^{-1}) and soil water content (w, m^3 m^{-3} $\times$ 100) using a trend surface for 132 days of radiosonde observations. The highest height values are found under conditions of low soil water content and low stability (Santanello et al. 2005). [Note that this figure is an update of Fig. 7 in Santanello et al. (2005) that includes improved estimates of PBL heights for three points on weakly convective days. Figure 1 here also plots each of the data points, and the slight differences in the contours from the original figure are not considered significant.]

relationships (Businger et al. 1971; Dyer 1974) also indicate that large-scale PBL properties affect surface layer gradient functions of heat and humidity (Albertson et al. 2001; Steeneveld et al. 2005). In particular, for highly convective conditions on diurnal time scales, gradients of temperature and humidity in the surface layer are influenced by the depth of the PBL and the degree of free-atmosphere entrainment. These results highlight the role of PBL feedbacks on surface fluxes, and the need for further empirical investigation of these properties so that proper treatments can be extended to empirical, offline, and coupled single-column or LES models.

Taken as a whole, the studies described above support the idea that relationships between w, h, and surface sensible (H_s) and latent (λE) heat fluxes are nonlinear and are influenced by feedbacks between atmospheric and land surface processes. With the exception of the work of Steeneveld et al. (2005), these studies primarily focused on near-surface interactions, and did not assess large-scale PBL growth and entrainment dynamics that might affect dynamics in the system. Feedbacks such as these (supported by observations) are often overlooked in studies of land–atmosphere interactions, and complicate the direct link between h and H_s that could otherwise be used to estimate surface fluxes from routine observations of PBL structure. In this work we use both models and data from field studies to examine both diagnostics and feedbacks in the land–PBL system.

3. Model and data description

a. Model overview

The Oregon State University 1D PBL model (OSU; Troen and Mahrt 1986) is a diffusion-based coupled atmospheric and land surface model that simulates PBL temperature, moisture, and momentum properties in addition to surface energy balance on diurnal time scales. In the OSU model, parameterizations of eddy

diffusion and countergradient turbulent mixing are employed, yielding a well-mixed PBL for typical daytime and convective conditions. It is coupled to a land surface scheme that uses similarity theory to calculate land surface energy balance, surface temperature, and soil moisture and temperature evolution in multiple layers below the surface. A version of the OSU land surface component is currently used in the National Centers for Environmental Prediction operational North American Mesoscale model, called the Noah land surface model (Ek et al. 2003). Despite its relative simplicity (1D, no treatment of horizontal advection), the OSU model has proven to be a robust and well-tested model for a wide range of conditions (Pan and Mahrt 1987; Ek and Cuenca 1994; Ek and Mahrt 1994; Cuenca et al. 1996; Ek and Holtslag 2004).

Required inputs to the OSU model consist of site characteristics (latitude–longitude, roughness length, albedo, surface pressure, soil type, wilting point, canopy resistance) and initialization data (soil moisture profile, and atmospheric temperature, wind, and moisture profiles). The model uses a 3-min time step starting at dawn, and produces half-hourly output of surface and PBL variables. To initialize the model, data acquired at the ARM-SGP site for 132 days in June, July, and August of 1997, 1999, and 2001 were used. In particular, data from radiosondes launched at 1130 UTC from the ARM SGP central facility (Lamont, Oklahoma) were used to initialize the model along with collocated and spatially averaged surface fluxes and soil moisture measurements (Santanello et al. 2005).

b. Model configuration

Up to 20 vertical levels can be used to initialize atmospheric profiles of potential temperature, wind speed, temperature, and specific humidity in the OSU model. Using available radiosonde data at 10-m vertical resolution, 20 levels extending to 10 km above the surface were included, with the greatest concentration below 4 km (the upper limit of h). Four soil layers with thicknesses of 0.05, 0.10, 0.50, and 1.0 m were prescribed in the model, and near-surface soil moisture and temperature were initialized using ARM-SGP observations. In addition, 10-yr spinups of moisture and temperature for all soil types were performed using a 20-layer soil hydrology model (SHAW; Flerchinger et al. 1998) to estimate and initialize the deeper layer profiles in the OSU model and ensure realistic and consistent vertical stratification on each case day. Further testing of the initialization of the OSU model for all soil types revealed that simulated land surface fluxes and PBL properties were primarily sensitive to the top 5-cm layer soil moisture only. As it turns out, the impacts of including a detailed spinup as a reference for the initial profiles as opposed to a using simple linear interpolation from the observed top layer values were minimal.

The default radiation scheme in the OSU model utilizes a diurnal zenith angle correction, and initial evaluations revealed that this simple parameterization overestimated net radiation for this location. Further, the OSU model requires the individual components of net radiation for internal calculations such as canopy resistance, so using the net radiation observed at the ARM-SGP site as a straightforward correction was not possible. Therefore, at each time step in the model, the downwelling shortwave radiation was calculated as the difference between the observed net radiation and the net longwave radiation estimated using surface and PBL temperatures (Brutsaert 1975). Using this approximation for shortwave radiation in the model then improved the final calculation of net radiation to within 3% of the original observations, which is a significant improvement to that of the default radiation scheme at this site.

4. Results

a. Diurnal simulations

The OSU model was used to simulate PBL evolution for 9 days that are representative of typical clear-sky convective conditions at ARM-SGP and that encompass a wide range of observed soil moisture (5.8%–38.9%), surface fluxes (β = 0.05–2.74), and PBL heights (450–2753 m), using a selection process that reduced the potential impact of temperature and moisture advection on our results (clear, smooth radiation, and minimal signal of advection). Vegetation and soil properties were specified according to observations at the ARM-SGP central facility, with a leaf area index of 2.0 and soil type of silty clay loam. Simulated and observed profiles of potential temperature (θ) for 6 June 1997 and 23 July 2001 are shown in Figs. 2a and 2b. The PBL heights and surface conditions are very different on these days, and the OSU simulations closely match the observed PBL structure and development for each. The correlation between measured and simulated values for h (r = 0.99), H_s (r = 0.95), and $\Delta\theta_{2\mathrm{m}}$ (r = 0.93) for all 9 days demonstrates that the OSU model simulates land surface and PBL dynamics well across a wide range of conditions.

Simulated PBL evolution on some days (not shown) predict accurate h but also exhibit profiles of θ in the mixed layer that are consistently biased ($\pm$ several degrees) relative to observations, a possible signature of advection that was not prescribed in this version of the OSU model. A common method to estimate advection

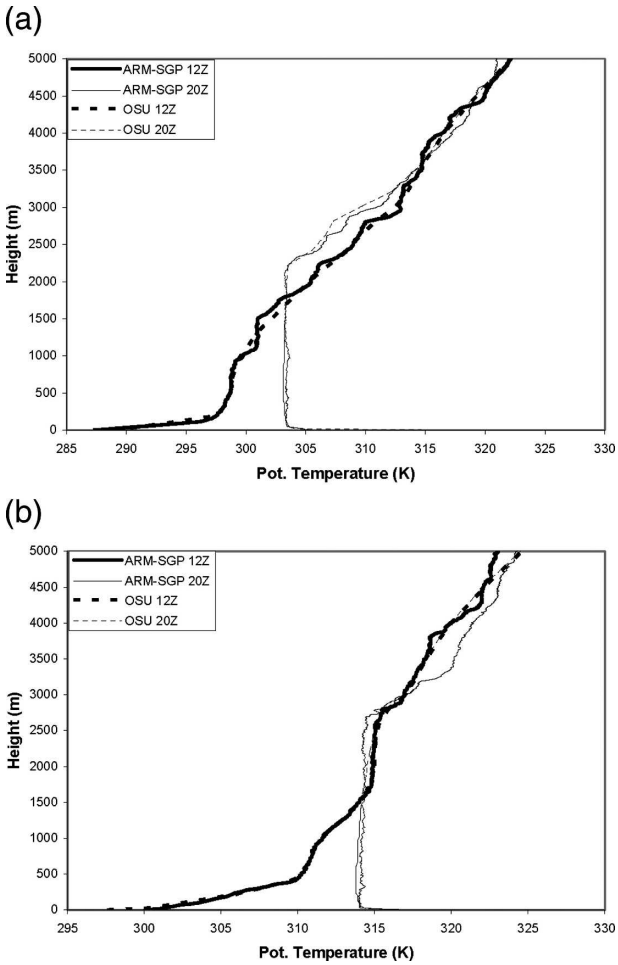

FIG. 2. Observed (ARM-SGP) and simulated (OSU) profiles of potential temperature at 1200 and 2000 UTC on (a) 6 Jun 1997 and (b) 23 Jul 2001.

in the PBL is based on linear interpolation of the diurnal free-atmosphere temperature change based on radiosonde observations to the surface (Swiatek 1992; Santanello et al. 2005). For the days in question, empirical adjustments to mixed layer θ based on this approach closely matched the observed profiles. Indeed, the correlation coefficient (r) between advection estimated in this fashion and the mixed layer temperature bias in simulated profiles was 0.89, and simulated mixed layer temperatures were substantially improved using this approach. Moisture profiles and budgets were not included in this study, but it is likely that combining the signal of free-atmosphere moisture and temperature change would strengthen the advection estimate further.

b. Composite simulations

To further assess the accuracy of the OSU model over the full range of conditions at the ARM-SGP site, the 132 days of data were stratified into 10 groups using 250-m intervals of maximum h. Simulations were initialized using the mean conditions within each group, which are shown in Table 1. Average h, $\Delta\theta_{2m}$, and daily mean Bowen ratio observed in each group are then plotted against those simulated by the OSU model for each composite group in Fig. 3, and show excellent agreement ($r > 0.95$), particularly in simulating h ($r = 0.99$). Interestingly, γ and w are highly correlated in the composite data ($r = 0.86$) compared to individual days ($r = 0.34$), which reflects the ability of composites to filter out much of the day–day variability in the original data. As a result, the seasonal signal of the shared control of γ and w on h, and γ and w on each other, is evident over the period.

The composite data also offer insight regarding how the controls on PBL growth vary as h changes. The overall trends show that high values of h are associated with high values of β, H_s, and $\Delta\theta_{2m}$ and low values of γ, w, and Δq_{2m}. Further analyses indicate that exceptions to these trends tend to occur in the presence of a significant residual mixed layer in the morning profile. Residual layers are dynamically unstable after sunrise,

TABLE 1. Mean values of PBL and land surface variables from the ARM-SGP site for each of the 10 composite groups (of n days) stratified by PBL height. Surface flux values (H_s, H_i, and β) represent average fluxes over the daytime period of interest (1200–2000 UTC) of PBL evolution.

n	h (m)	γ (K m^{-1})	$\Delta\theta_{2m}$ (K)	Δq_{2m} (g kg^{-1})	H_s (W m^{-2})	β	w (% Volumetric)
14	740.50	0.0076	9.57	0.96	80.49	0.40	26.19
14	1013.86	0.0076	8.47	0.31	84.40	0.43	24.62
15	1190.93	0.0083	11.01	1.08	98.10	0.46	22.51
15	1369.93	0.0064	12.06	0.74	96.39	0.41	22.60
14	1502.21	0.0063	13.87	0.11	120.24	0.50	15.93
13	1660.23	0.0053	14.08	−0.81	112.17	0.53	13.73
13	1816.69	0.0041	12.23	−0.78	111.38	0.57	18.08
13	2087.85	0.0042	14.85	−1.09	102.69	0.45	17.49
11	2397.27	0.0029	14.74	−1.98	144.35	0.85	11.52
10	2831.90	0.0027	16.29	−2.15	116.86	0.63	9.88

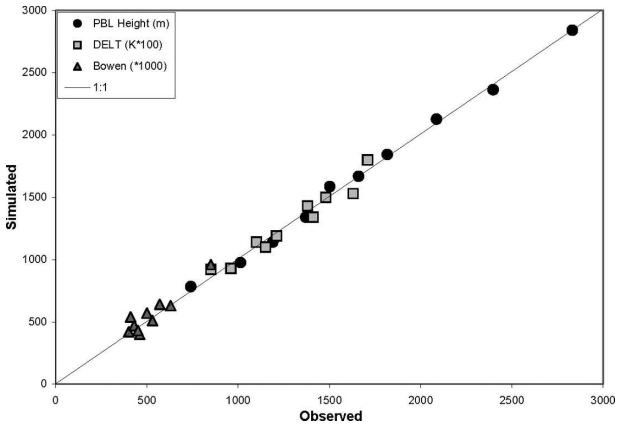

FIG. 3. Observed vs simulated values of daily maximum PBL height, 2-m potential temperature change (DELT), and daily mean Bowen ratio for the 10 composite simulations.

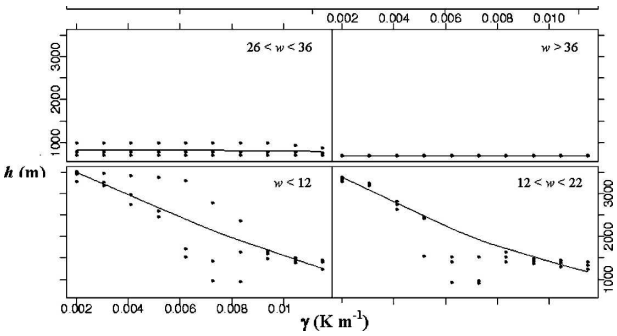

FIG. 4. Relationships between PBL height (h, m) and stability (γ, K m^{-1}) for four ranges of 0–5-cm soil moisture (w, % volumetric) simulated by the OSU model with prescribed LAI equal to 2.0. The lines indicate local regressions on the data.

and therefore can promote significant PBL growth even if there is little surface heating present. This issue is discussed in greater detail in section 4e(2).

c. *Simulations across varied conditions*

These studies and results are specific to the SGP region, which is known to be characterized by strong land–atmosphere interactions (Koster et al. 2004). From a broader perspective, the degree of coupling and precise relationships between land surface and PBL variables is expected to vary depending on factors such as soil properties, vegetation cover, and synoptic conditions, and will be examined next.

1) SOIL MOISTURE AND ATMOSPHERIC STABILITY

To examine relationships that govern the coupled land–atmosphere system in more detail, initial stability and near-surface soil moisture at the ARM-SGP site were varied in the OSU model. Specifically, w was varied from 0.03 to 0.45 m m^{-3} (3%–45% volumetric) and γ was varied from 0.015 to 0.0015 K m^{-1} through 10 intervals each, for a total of 100 simulations. These ranges of w and γ are similar to those observed at the ARM-SGP site and capture the range of variability observed in soil and atmospheric stability conditions. The deep-layer soil moisture was also varied in proportion to the top layer for consistency, and compared with SHAW spinup results (as described in section 3b) to ensure that the profiles were realistic.

The results from these simulations can be used to identify conditions where land–atmosphere coupling is strongest by assessing how w or γ influence h. For example, Fig. 4 shows that for low w, stability is strongly correlated with h, and vice-versa. Conversely, if w is greater than 26%, then h is greatly diminished regardless of the atmospheric conditions, indicating greater soil control on the PBL.

2) VEGETATION AND SOIL CONTROLS

To investigate the effects of different surface types on PBL–land surface interactions, a suite of simulations was performed for varying vegetation and soil conditions. Vegetation cover in the OSU model is principally characterized via the surface leaf area index (LAI), which controls the amount of radiation reaching the soil surface and the partitioning of evaporation between the soil surface and the root zone. Typical midsummer LAI values for the ARM-SGP site are near 2.0, which indicates a low to moderately vegetated surface. To examine how the PBL might respond to changes in vegetation, LAI was varied from 0.5 (bare soil) to 6.0 (full canopy) and simulations were performed over the observed ranges of w and γ for varying soil types.

The simulation results (Figs. 5a,b) show that as LAI increases, h becomes more dependent on γ and less dependent on near-surface w. Interestingly, similar values of maximum h (>3000 m) are evident in Fig. 5b regardless of the level of soil moisture and suggest that thick vegetation cover by itself is not a limiting factor on PBL growth. As such, these relationships demonstrate the nature of the diurnal PBL–land surface equilibrium and feedbacks that develop over highly vegetated surfaces. For example, Betts (2000) also found that high h can be maintained above thick vegetation for low γ, but is dependent on the balance between the atmosphere demand for λE and the canopy resistance (which is a function of the root zone soil moisture) rather than w. In contrast, for bare soil conditions w exerts greater control on h and is a particularly limiting factor for moist soils with high rates of λE.

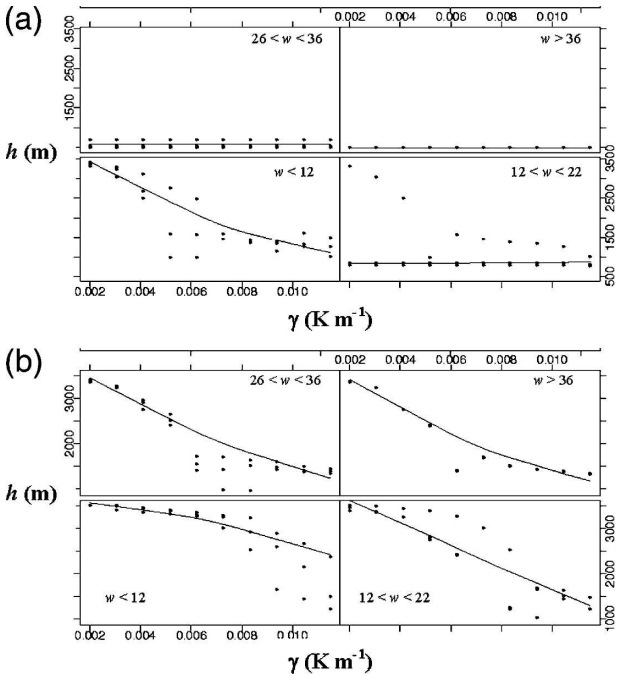

FIG. 5. Same as Fig. 4, but for prescribed LAI equal to (a) 0.5 and (b) 6.0.

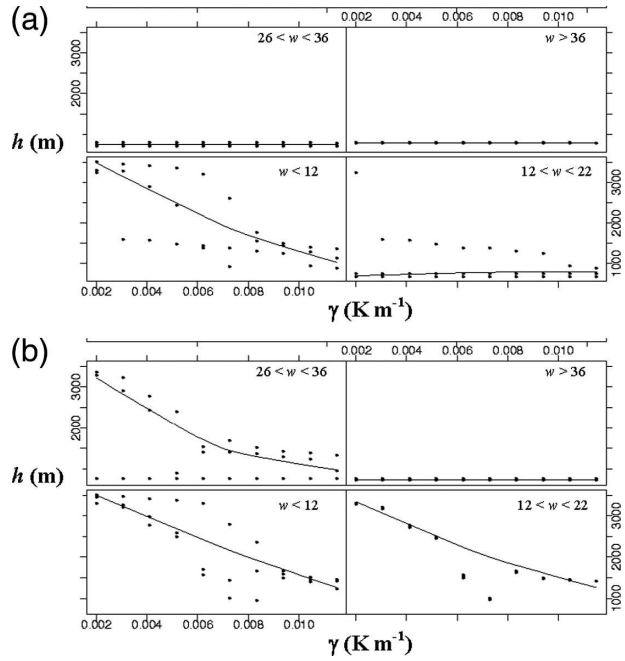

FIG. 6. Same as Fig. 4, but for (a) sand and (b) clay soils with prescribed LAI equal to 2.0.

Using a similar approach for soils, the OSU model was varied across 11 major soil types ranging from sand to clay, and holding LAI constant and equal to 2.0 (Figs. 6a,b). Soil hydraulic parameters were adjusted for each type based on lookup tables within the OSU model (Cosby et al. 1984), with the exception of the wilting point and air-dry evaporation values that were prescribed based on results from Clapp and Hornberger (1978). Overall, the effect of varying the soil type from sand to clay closely resembles the effect of varying LAI from bare soil to full vegetation, wherein h becomes more dependent on the atmosphere. Given the same moisture content, sandy soils will be closer to field capacity (due to low porosity values) and evaporate closer to the potential λE than clays, thereby limiting h and H_s through a greater overall range of w. It is also interesting to note that in Figs. 6a and 6b, there are distinctly different values of h at the same γ for dry soils, which identifies this range of soil moisture as the transition from atmosphere to soil-limited evaporation. Discussion of similar thresholds of soil drying in relation to soil types and hydraulic properties can be found in Santanello and Carlson (2001).

3) INTERACTION EFFECTS

Because the effects of soil and vegetation properties on surface fluxes are not independent, we performed a factorial test to assess the impact of interaction effects on model simulations (Henderson-Sellers 1993; Hu and Islam 1996). To do this, a two-factor, two-level experiment was designed in which LAI was set to its minimum and maximum value (0.5–6.0, respectively) and soil type was varied from sand to clay, and simulations were performed at the ARM-SGP observed limits of w and γ (3, 40% volumetric and 0.0015, 0.015 K m^{-1}). The results from each simulation were then used to assess the "effect" of each parameter and their interaction on simulations of h in the OSU model.

Table 2 presents results from each of the factorial simulations, where the numbers (in meters) represent the parameter effects on h due to simultaneous changes in w and γ. The highlighted values represent statistically significant interactions that impact simulated h. These results indicate that w is the principal control on h for clays, that h over bare sandy soils is small and insensitive to w and γ, and that there is a unique and opposing interaction among w and γ for sandy vegetated soils. While Fig. 6b highlights the sensitivity of h to γ for a particular range of w (with LAI = 2.0), the statistical results in Table 2 confirm that w is, in fact, the principal control on the potential for PBL growth, with γ having an influence only if the soil is dry enough. Also, w is a stronger control on h for clay soils than for sandy soils regardless of vegetation amount because clays exhibit a stronger matric potential during dry-

TABLE 2. Factorial effects of varying soil and vegetation parameters in the OSU model on simulated PBL height (m) from varying leaf area index, soil type, soil moisture, stability, and their interactions. The analysis was performed as in Henderson-Sellers (1993), where the bold type indicates statistically significant effects.

Simulations	LAI	Soil type	w effect	γ effect	Interaction
1–4	0.5	Sand	−25	−217	−23
5–8	6.0	Sand	**−1091**	**−1259**	**−1010**
9–12	0.5	Clay	**−2515**	−90	90
13–16	6.0	Clay	**−2152**	−106	106

downs and drain less quickly than sands. As a result, clays retain more water and are able to tap deeper into the soil for evaporation relative to sands over a larger range of available moisture.

d. Estimation of h and w using simulated relationships

Using the simulation results and relationships described above, polynomial models estimating h as a function of w and γ were estimated using the methodology described in Santanello et al. (2005). Relative to the observationally based model (Fig. 1), the overall contour patterns of OSU-generated h (Fig. 7) are quite similar, and predictions of h using w and γ based on these modeled relationships explain 64% of the variance in an independent dataset of observed data from the ARM-SGP site. Further, the correlation coefficient between predictions of h at ARM-SGP from Figs. 1 and 7 is 0.96, indicating that the simulated relationships capture those that are observed quite well. By inverting the polynomial model to solve for soil moisture, 61% of the variation in w was explained by h and γ using independent data from the ARM-SGP site.

While there is good agreement between simulated and observed relationships, it is also instructive to examine the subtle differences between Figs. 1 and 7. In particular, the regions of minimum h occur, as expected, near maximum w (~40%) but differ by approximately 500 m and occur at different values of γ in the two plots. However, this is an extremely wet soil condition that pushes the limits of the OSU model and results in unrealistically low simulated h (when compared with the observed range at ARM-SGP). Also, the contour pattern suggests that simulated h is slightly more sensitive than observed h to w, particularly for w greater than 25%. This distinction is indicative of differences in simulated and observed land–atmosphere coupling for this location and can be helpful in pointing out model tendencies and deficiencies in model physics.

e. Estimation of H_s and sensitivity to soil moisture

Polynomial models based on observed and modeled data can successfully predict h and w, but attempts to extend these estimates to surface fluxes have been unsuccessful because of the characteristic weak (and complex) relationship between H_s and PBL properties. In particular, H_s measurements are simultaneously affected by a number of variables such as wind speed, canopy resistance to transpiration, surface roughness, net radiation, observational errors, and atmospheric conditions. Because of these complications and the fact that flux measurements are only representative of the grasslands (<50%) of the ARM-SGP region, PBL variables are more strongly correlated with w than with H_s.

At the same time, the general agreement between the observed data and model results suggest that the simulations are representative of average conditions and capture the overall trends in the observations. In fact, the OSU model filters out much of the variability present in observations and is able to closely simulate the overall mean relationship between H_s from w (Fig. 8). Applying a piecewise linear regression to the simulated curve of w versus H_s explains 96% of the variance in simulated H_s for w greater than 10% and 97% of the variance below the 10% threshold. Combined, the piecewise linear regression can be used to predict H_s (and similarly, λE or EF) within reasonable bounds given an estimate of w from observations of PBL structure.

f. Summary of the impact of w on the PBL

The patterns in Figs. 4–6 and Fig. 8 are consistent with the results of Findell and Eltahir (2003b) and Dirmeyer et al. (2005), who suggest that for the SGP region there is a well-defined transition between atmospheric and land surface control of convection. This is also demonstrated well in the simulated relationships from the OSU model that correspond well with data from ARM-SGP and highlight important features of the coupled system. Namely, the land surface (through w) is the principal control on the *potential* for PBL growth through the entire range of soil moisture. When the soil is moist, the high evaporative fraction limits surface heating and therefore the potential for high h regardless of the degree of γ. For intermediate and dry soil moisture conditions, however, deep PBL growth can be supported as there is sufficient surface heating, and is largely dependent on the initial atmospheric state (through γ).

Similarly, it is likely (and suggested by the composite simulation results) that w and γ are interdependent and

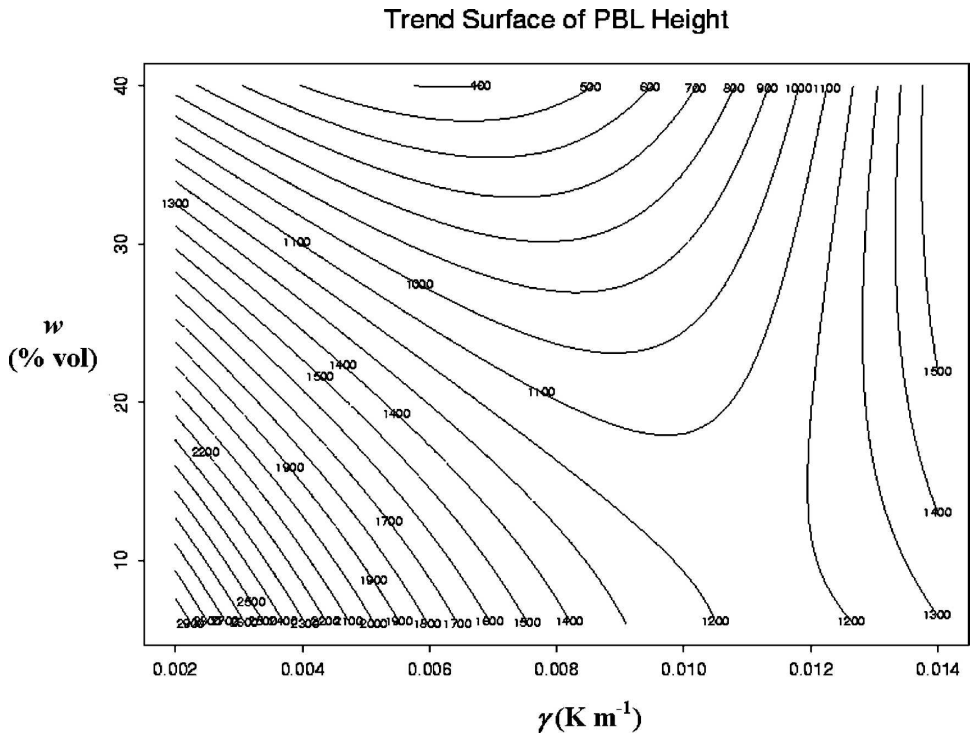

FIG. 7. Contour plot of maximum PBL height (in 100-m intervals) simulated by the OSU model as function of stability (γ) and soil water content (w). The highest values are found under conditions of low soil water content and low stability.

correlated and at seasonal and longer time scales, as the impacts of soil moisture are reflected in PBL evolution and precipitation patterns that ultimately determine the stability over the region. These results are also supported by the conclusions of Koster et al. (2004), who showed that land–atmosphere coupling is strongest for transitional regions where soil moisture exhibits a full range of moisture conditions (e.g., the SGP site).

5. Feedbacks between the PBL and land surface

The results presented in this paper indicate that the OSU model can be used as a tool to gain insight regarding interactions within the coupled land–PBL system, as well as to estimate surface conditions from bulk PBL properties. They also highlight the influence of soil moisture on PBL properties through its fundamental control on evapotranspiration and land surface energy balance. In fact, the results and discussion presented here suggest there are two feedbacks that strongly influence diurnal surface flux and PBL evolution: 1) the rise of H_s is diminished by entrainment for intermediate soil moisture levels, and 2) for dry soils, a threshold of soil moisture exists below which a deep residual mixed layer forms that supports subsequent PBL growth, entrainment, soil drying, and (over longer time scales) drought.

Signals of these feedbacks are evident in a number of flux and PBL variables across a full range of soil moisture. Figures 9a–f show observed relationships between w and H_s, λE, evaporative fraction [EF = $\lambda E(H_s + \lambda E)^{-1}$], Δq_{2m}, h, and the entrainment flux of heat (H_i) for the ARM-SGP site, along with those simulated by the OSU model. Even without tuning of the input pa-

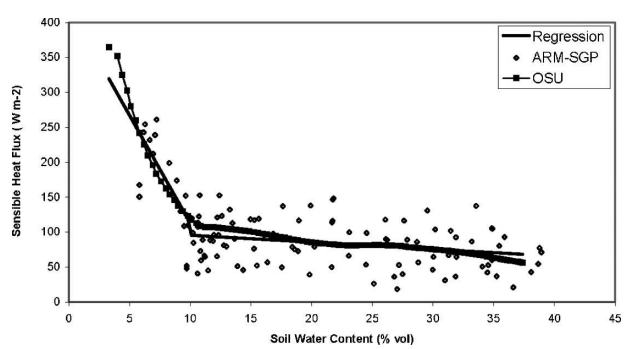

FIG. 8. Piecewise regression of the observed (ARM-SGP) relationship between soil water content and sensible heat flux along with that simulated by the OSU model at Lamont, OK. The LAI is prescribed to be 2.0 for the simulations and the soil type is silt loam.

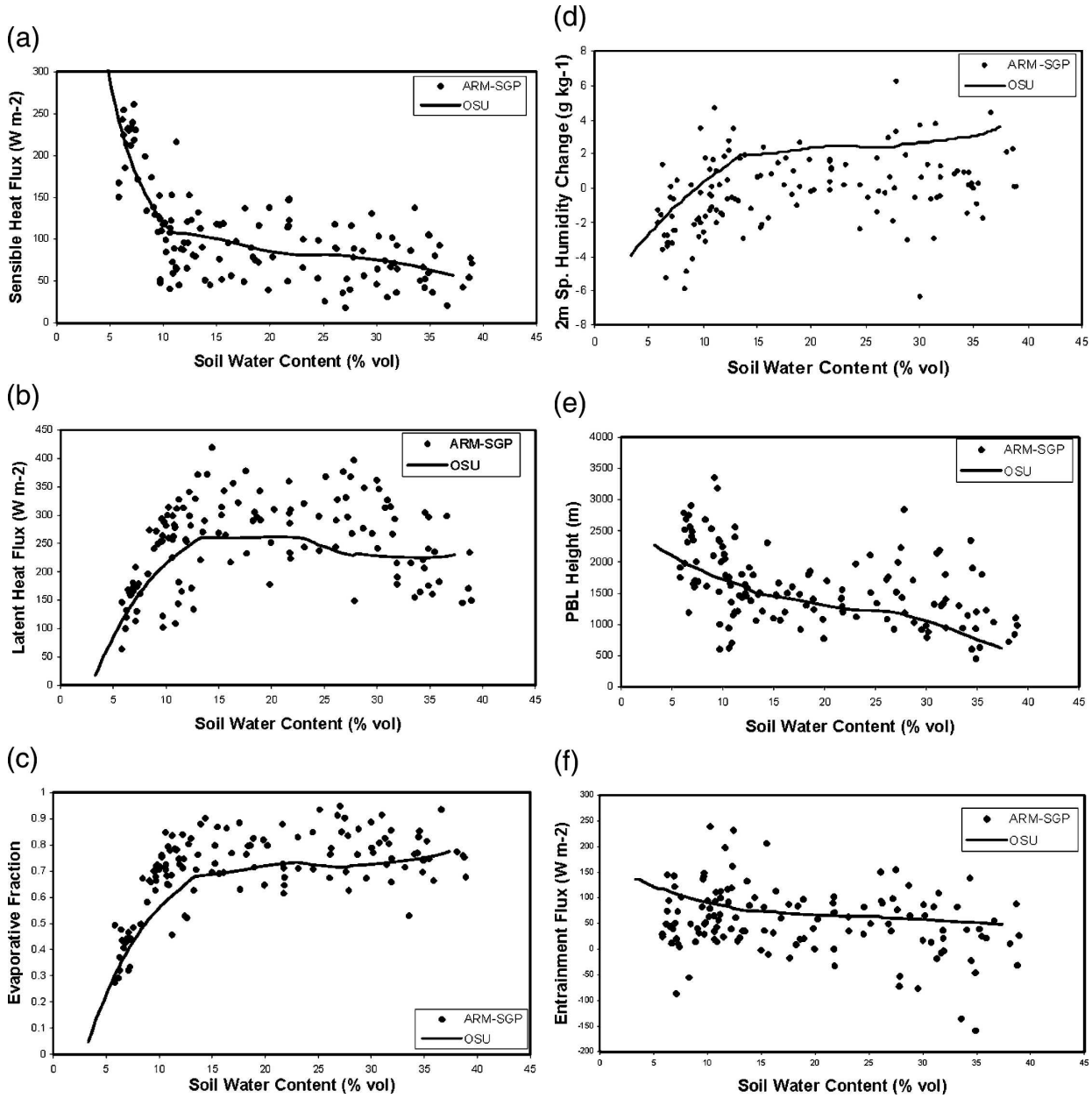

FIG. 9. Relationships between simulated and observed soil water content (% volumetric) and (a) sensible heat flux (W m^{-2}), (b) latent heat flux (W m^{-2}), (c) evaporative fraction, (d) change in 2-m specific humidity (g kg^{-1}), (e) PBL height (m), and (f) entrainment flux of heat (W m^{-2}) at the ARM-SGP site with a prescribed LAI equal to 2.0.

rameters, the OSU model successfully captures the overall mean relationships observed at the ARM-SGP site across the complete range of w.

a. Feedback 1: Atmosphere-limited conditions

Figures 9a–c reveal that w is related to surface sensible and latent heat fluxes in a nonlinear fashion, with a weak correlation when w ranges from 10% to 40%, and a much stronger correlation for w less than 10%. At intermediate and moist w (>10%) there is enough moisture in the soil to provide direct evaporation from the surface to meet atmospheric demand (which is principally controlled by the specific humidity in the PBL). Naturally, the atmosphere becomes more humid as soil water evaporates into the PBL and atmospheric demand decreases, thereby decreasing EF. However, this in turn leads to greater H_s and h, which draws warm and dry air into the PBL through entrainment, reduces

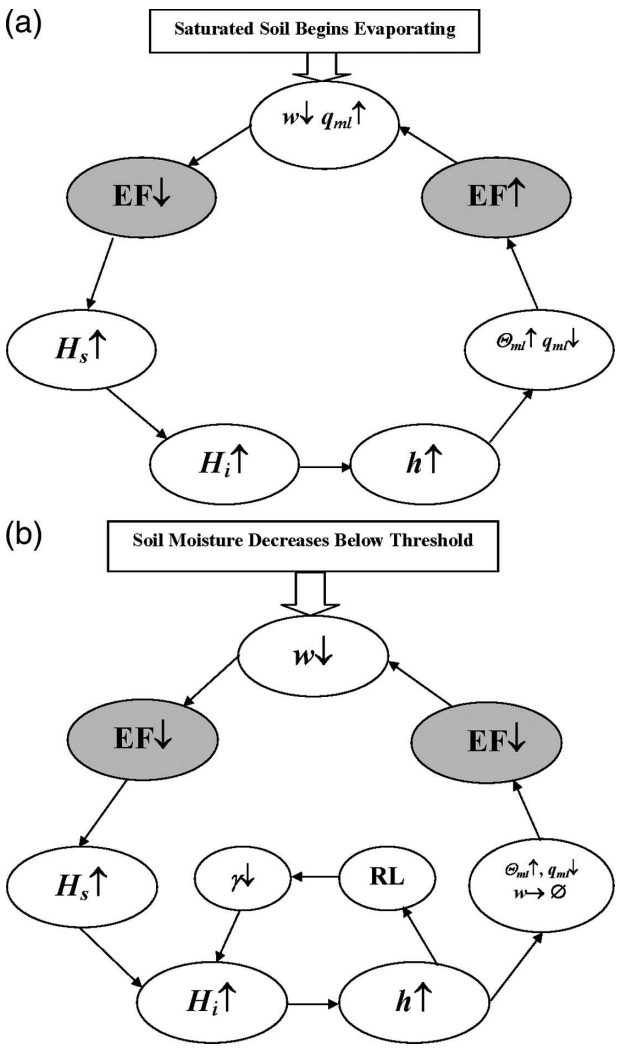

FIG. 10. (a) Schematic of the feedback of entrainment (H_i) and PBL growth (h) on the atmospheric demand for evaporation and subsequent response of surface fluxes (EF) and soil moisture (w) for conditions of intermediate or high soil moisture content. (b) Schematic of the positive feedback of entrainment (H_i) on the atmospheric demand for evaporation and subsequent response of soil moisture (w), surface sensible heat flux (H_s), and PBL growth (h) associated with conditions of low soil moisture content and the existence of a residual layer (RL). In both (a) and (b), the subscript "ml" refers to mixed-layer quantities.

the surface–PBL temperature gradient, raises atmospheric demand for evaporation, and returns EF to near its original level (Fig. 10a).

Using the 132 days of ARM-SGP data, estimates of the entrainment flux of water vapor (λE_i) calculated as a residual of the moisture budget in the PBL indicate that λE_i is of similar (and often larger) magnitude to λE. This suggests that the dry air brought in through λE_i at least balances the flux of moisture from the surface. The effect of PBL dynamics on the surface energy balance in this case is a *negative* feedback on H_s that is partly responsible for the weak relationship between w and H_s for soils wetter than 10%. Without this feedback, the PBL would quickly moisten and EF would decrease rapidly as the soil dries, and a new equilibrium of heat and moisture in the PBL would result as evidenced by mixed-layer q and θ profiles.

To further explore this effect, simulations were performed in which entrainment was set to zero. Thus, there was no flux of warm dry air at the top of the PBL and all surface fluxes of heat and moisture remained in the mixed-layer volume. Results from 10 selected days indicate that near-surface (and mixed-layer) q would increase by 12%–31%, a measure of the moistening of the PBL throughout the day without entrainment. Although the new balance of surface temperature and saturation mixing ratio that would exist under these conditions is difficult to estimate precisely, the new equilibrium would in turn affect the atmospheric demand for evaporation, surface energy balance, and soil water content.

b. Feedback 2: Soil-limited conditions

Figures 9a–f illustrate a similar, but *positive*, feedback of the PBL for very dry surface conditions. Once w decreases below 10%, evaporation becomes soil-limited and λE and EF decrease rapidly as the soil cannot meet atmospheric demand. Accordingly, H_s, H_i, and h increase rapidly as the convective PBL deepens and warm, dry air is brought into the PBL through entrainment. Because there is no surface moisture to maintain the evaporation rate as for intermediate soils, these conditions are favorable to the formation of a deep residual layer upon the collapse of the PBL during the nighttime. While a weak and shallow residual layer can exist even under moist and stable conditions, the deep residual layer exhibited during dry conditions tends to persist over multiple days, is neutrally unstable, and supports and strengthens atmospheric demand, soil desiccation, elevated H_s and h, and therefore a positive feedback on PBL growth (Fig. 10b).

The importance of the residual layer in diurnal PBL evolution has been illustrated by Santanello et al. (2005) and by the results of Findell and Eltahir (2003a), who identified this feature as a major influence on γ calculated from morning soundings. In fact, at the ARM-SGP site, 31 of the morning profiles (26%) had a well-defined residual layer. Table 3 shows that the majority of these correspond to conditions characterized by dry soil conditions, low γ, and high h compared to days with no discernable residual layer. Notably, the range of H_s observed on days with and without a discernable residual layer are almost identical, suggesting

TABLE 3. Comparison of mean values (over n days) of soil water content, stability, and PBL height, and minimum and maximum sensible heat flux on days with a visible residual layer vs those without.

	N	w (% Volumetric)	γ (K m^{-1})	h (m)	Min H_s (W m^{-2})	Max H_s (W m^{-2})
Days with RL	31	13.1	0.0035	2177	36.8	242.1
Days without RL	101	20.8	0.0065	1424	33.9	243.8

that the presence of a residual layer is not necessarily associated with high surface heating, and that the properties of the PBL exert significant control on PBL development under such conditions. Perhaps most importantly, of the 31 days identified, 27 were consecutive and 4 were nonconsecutive. This pattern suggests that the residual layer sets up a positive feedback that (in combination with dry soils) promotes and enhances its existence over multiple days.

Figure 11 shows the correlation between the depth of the morning residual layer and h for the 31 days selected ($R^2 = 0.65$) at the ARM-SGP site. The relatively low scatter in Fig. 11 indicates two things: 1) the depth of the residual layer can be a good predictor of h and 2) the PBL does not tend to grow significantly beyond the height of the residual layer. The second result is a consequence of the sharp inversion in θ at the transition from the residual layer (unstable/near-neutral) to the free atmosphere (stable), which is not easily penetrated by thermals rising through the mixed layer.

To further investigate the sensitivity of PBL growth to the presence and depth of a residual layer, OSU simulations were performed for a day with a deep initial residual layer (from ARM-SGP, 23 July 1997). Simulations show that even for saturated soils and low surface heating, h reaches over 1500 m when a significant residual layer is present. These results are consistent with those of Medeiros et al. (2005), who noted the importance of the residual layer as the primary factor controlling diurnal PBL evolution over land at the GCM scale. These simulations demonstrate that in the presence of a deep residual layer, the PBL becomes insensitive to H_s and w (provided that there is enough H_s to erode the nocturnal inversion), and in effect shifts control of PBL growth from the land surface to the atmosphere.

c. Implications of feedbacks

While these results are limited by the available 0–5-cm layer soil moisture measurements, they are appropriate due to the observed strong control exerted by near-surface moisture on the fluxes and PBL evolution for this site. However, it is important to consider the potential impact of root zone soil moisture and applicability to more highly vegetated locations. The sensitivity of the entrainment feedbacks on surface fluxes to vegetation cover can be explored using the OSU model and is illustrated in Fig. 12. Here, the simulated relationships between w and H_s for different specified LAI in the OSU model show how the stages of drying vary according to vegetation cover amount and stress. As expected, for bare soils the residual-layer feedback occurs at a higher threshold of w than for vegetated regions. Indeed, the threshold between stages of soil drying for sparse vegetation (LAI = 0.50) is near 24%, compared to 10% at the ARM-SGP site. Also, a third stage of soil drying is evident in bare soils that are desiccated, where evaporation has completely shut down and sensible heat flux levels off near its maximum value. For surfaces with higher LAI (LAI > 2.5), roots are able to transport deep soil water to the surface for evaporation so the threshold exists at very low values of w (<10%). If an observable indicator of the transition from atmosphere to soil-limited evaporation exists (such as the sharp decrease in Δq_{2m}, or as changes in surface albedo, temperature, and moisture), it may be possible to identify what feedback regime the system is in.

Thus, a key conclusion from these results is that the effect of entrainment on atmospheric demand for evaporation is a major factor that influences coupling of

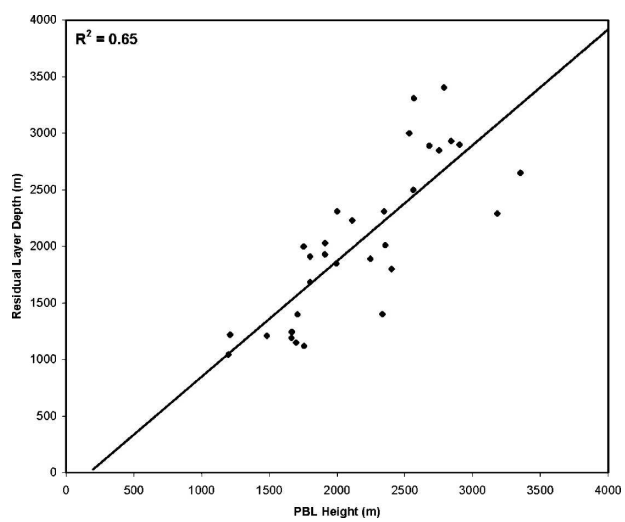

FIG. 11. Observed PBL height vs the initial depth of the residual layer measured at the ARM-SGP site.

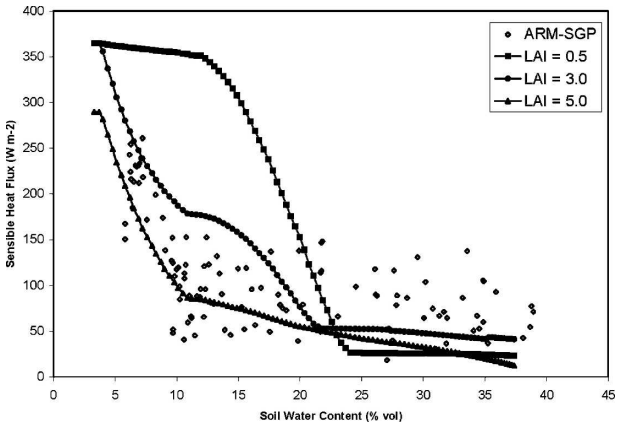

FIG. 12. Simulated relationships of soil water content to sensible heat flux for different prescribed LAI values in the OSU model. As in Fig. 8, the curves are overlain on the observed data points at ARM-SGP.

the PBL and land surface. These results offer strong evidence (both observed and modeled) of the importance of including PBL feedbacks with the land surface, and that these interactions confound direct interpretation of observed relationships among land surface properties. As a consequence, traditional PBL growth and offline land surface models have trouble capturing these processes and difficulty estimating PBL evolution and surface energy balance. Stated another way, if the mechanisms described above did not occur, w would be linearly correlated to EF (and consequently land surface energy balance) through its entire range, and such models would be more reliable. By pinpointing the critical feedback processes, the relevance of uncoupled to coupled model simulations on all scales can be more easily assessed.

6. Conclusions

In this paper, interactions between PBL height, initial stability, and soil moisture were examined using observed data and simulations from the OSU 1D PBL model. This model was able to reproduce surface and PBL conditions accurately at the ARM-SGP site, and statistical methods that relate PBL height to soil moisture were applied to a variety of surface and atmospheric conditions. Two feedbacks were identified that help to explain the manner in which interactions between the land surface and the atmosphere influence surface energy balance: 1) The negative feedback of PBL growth on soil drying and surface heating for intermediate soil moisture and 2) the positive feedback of entrainment on soil drying, surface heating, and residual layer growth for dry soils. These results were used to develop a framework for estimating surface moisture and sensible heat flux from observations of PBL properties. These techniques offer a strategy to obtain land surface information on daily and regional scales that does not require in situ observations, and also would provide results that satisfy the current needs of the meteorological and hydrological modeling communities.

Identification of the residual layer offers the opportunity to identify dry surfaces, predict future PBL growth, and assess the likelihood for drought. In the absence of significant changes in atmospheric forcing (frontal passage, rainfall, etc.), a strong and persistent residual layer can help to support drought conditions during soil moisture drydowns. The relationships and feedbacks examined here also highlight the fact that the PBL serves as a memory for surface conditions on diurnal scales (through h), and on longer time scales (through the interaction and feedback between the land surface and PBL). As a result, diurnal conditions such as atmospheric stability, and longer-time-scale processes such as soil moisture, are reflected in the evolution of PBL. Thus, the understanding and techniques developed here may also lead to a methodology to diagnose diurnal to seasonal changes in atmospheric and surface moisture conditions.

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