GEO 387 H Physical Climatology Fall 2007

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Literature Review:

Simulating land-surface processes in transition zones with enhanced versions of Noah LSM

by

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November 20, 2007

Simulating land-surface processes in transition zones with enhanced versions of Noah LSM

1. Motivation: Relevance of simulating turbulent fluxes in transition zones.

Land surface characteristics, such as topographic features, land cover type, seasonality of vegetation controls, soil type, and soil moisture regulate the partitioning and horizontal distribution of surface fluxes of water and energy. Hence, surface conditions affect boundary layer processes and can influence the initiation and sustenance of convection. In this way, land surface hydrology affects local weather and climate. Particularly in transition zones between dry and wet climates, anomalies in soil moisture are believed to influence precipitation. Koster et al. (2004), as part of the Global Land Atmosphere Coupling Experiment (GLACE), used ensembles of 12 different atmospheric general circulation models (AGCMs) to identify regions where the *land-atmosphere coupling strength* is large. Coupling strength is the degree to which anomalies in land surface state (e.g., soil moisture) propagate to atmospheric variables and can affect rainfall generation. 'Hot spots' are areas in which a significant fraction (0.2) of simulated precipitation variance can be explained by variation of soil moisture alone. They correspond to locations where most of the convection is triggered by a moist boundary layer, where evaporation is high but is often controlled by soil moisture. Three transition zones between arid and humid climates are the major hot spots identified: the U.S. southern Great Plains (SGP), the Sahel and northern India (Fig. 1). If the assertion that hot spots exist is correct, then by monitoring soil moisture to better initialize weather prediction models, the skill of prediction of summertime precipitation could be improved. However, due to the complexity of the climate system, proof of the existence of the land-atmosphere feedback remains elusive. So far, at regional to continental scales, indirect observations of correlation structures of AGCM feedback's signature and daily multi-decadal precipitation reanalysis are limited in the U.S. to the month of July (Fig 2). The evidence is inconclusive and mostly model-based, but it suggests that the feedback of soil moisture on precipitation over the SGP hot spot exists. (Koster et al., 2003). The *recycling ratio* (the ratio of annual precipitation that comes from local evaporation) in SPG is not greater than 10% (Fig. 3). Trenberth et al. (2003) suggest that although most of the moisture supply for annual precipitation events does not come from local sources, local sources may be significant contributors to summer precipitation. Hence, dry conditions in late spring favor the development of droughts during summer, when the importance of large-scale transport to precipitation diminishes.

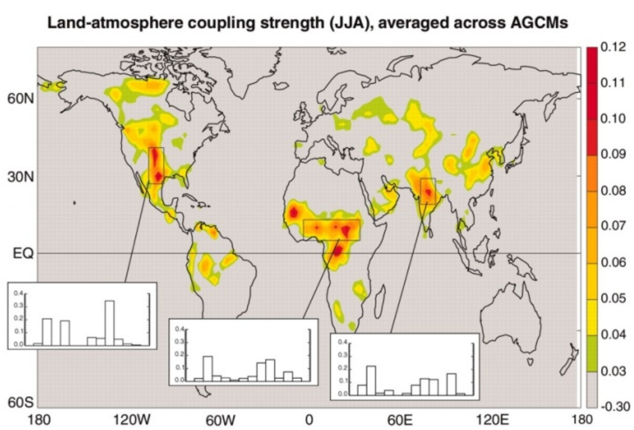


Fig. 1. Worldwide land-atmosphere coupling strength hot spots in red. (Koster et al., 2004)

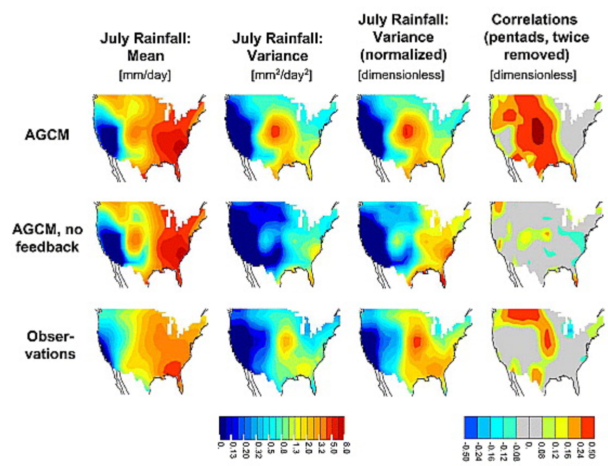


Fig. 2. Correlation structures for July precipitation (Koster et al. 2003)

During summer, most afternoon precipitation in the SGP is of high intensity and stems from surface-based sustained convection initiation episodes, whereas the bulk of the rain falls at night and comes from elevated systems (Wilson and Roberts, 2006). Convection initiation in the SGP is a complex process. Weckwerth and Parsons (2006) reviewed the mechanisms for surface forced convection initiation at boundaries prevalent in the SGP. Due to the relative low topographic relief, local orography does not play a significant role in convection initiation in the SGP. The region has a strong longitudinal atmospheric moisture gradient from the east. Especially during summer, the region is convectively unstable and the warm moist air from the Gulf of Mexico has a strong capping inversion, which makes the triggering of storms by interactions of outflow boundaries the main driver for precipitation. Storm initialization is sensitive to the amount of low-level vertical gradients of moisture and temperature, the strength of convergence, and the low-level wind shear stresses (Fig. 4). Additionally, relevant boundary layer features in this area include: drylines, frontal zones, gust fronts, bores and horizontal convective rolls. Predicting the onset of convection depends on capturing horizontal gradients of turbulent fluxes with an accurate representation of the atmospheric boundary layer (Weckwerth and Parsons, 2006).

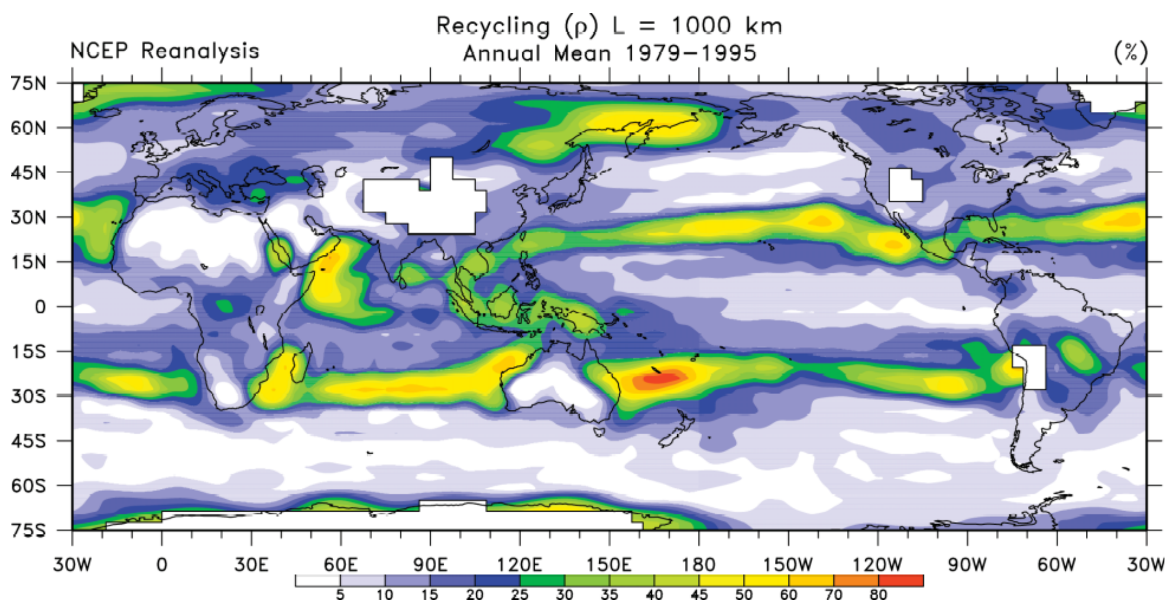


Fig. 3. Annual mean precipitation recycling ratio (Trenberth et al., 2003)

The validity of the results of analysis of research by Koster et al. depends to a certain extent on the realistic representation of both low-level moisture convergence and convective processes in global climate models, which have yet to be shown adequate in simulating diurnal cycle of precipitation. Premature initiation of convection and weaker precipitation (drizzling) have been identified as some of the model shortcomings that influence their ability to reproduce the timing, duration, and intensity of precipitation events (Trenberth et al., 2003). Some of the model biases that affect the key feedback mechanisms (Fig. 5) depend on the way in which the models represent land surface states.

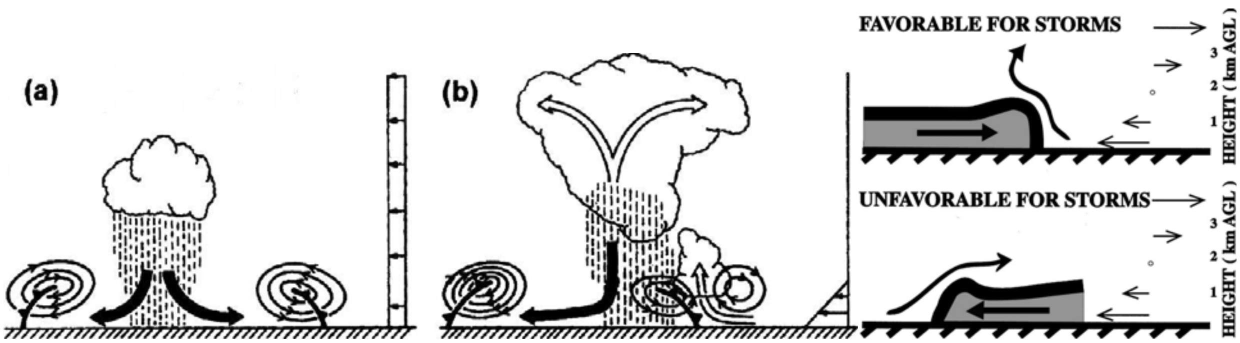


Fig. 4. Effect of low level shear in evolution of convection. a) without, the cold pool inhibits vertical lifting and new convection. b) with shear countering the cold pool. c) favorable conditions for convection initiation. The boundary (density current) in black interacting with the updraft. (Weckwerth and Parsons 2006).

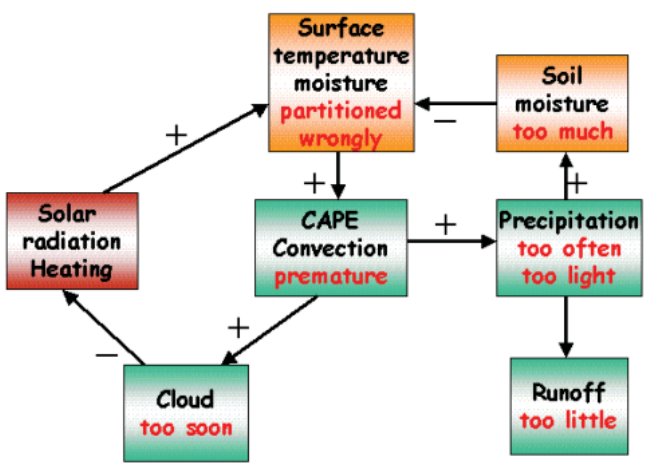


Fig. 5. Key feedback mechanisms in the diurnal cycle of precipitation. Model biases in red. (Trenberth et al., 2003)

Because accurate representation of convective potential energy (CAPE), convective inhibition (CIN), and storm triggers are important for realistic simulation of precipitation, representation within models of the land surface states and fluxes becomes especially important. To better understand the role of land surface properties in determining convective boundary layer structure, boundary layer evolution, and surface fluxes in transition zones, to use that knowledge to improve land-surface and boundary-layer parameterization schemes, and to assess the role of land-surface models (LSM) in improving the skill of warm season quantitative precipitation forecasts in numerical weather prediction models, the International H2O Project (IHOP_2002) field campaign (Weckwerth et al. 2004) collected 45 days of high-temporal-resolution, collocated, multi-sensor, (mesonet, radiosonde, radar, satellite) near-surface measurements. IHOP_2002 data (LeMone et al., 2007) provide an unprecedented look at the interaction of larger-scale moisture evolution with land-surface characteristics. The area spans a strong east–west rainfall gradient across the SGP (Oklahoma, Kansas, and north Texas), which translates to distinct signatures from the different land covers (Fig. 6). Ten surface flux stations were used to fully characterize the vegetated surface and its variability; they included instrumentation to directly compute sensible and latent heat fluxes using the eddy correlation approach. Comprehensive measurements of soil moisture and vegetation characteristics were taken throughout the IHOP_2002 experiment to enable definitive testing and development of land surface models.

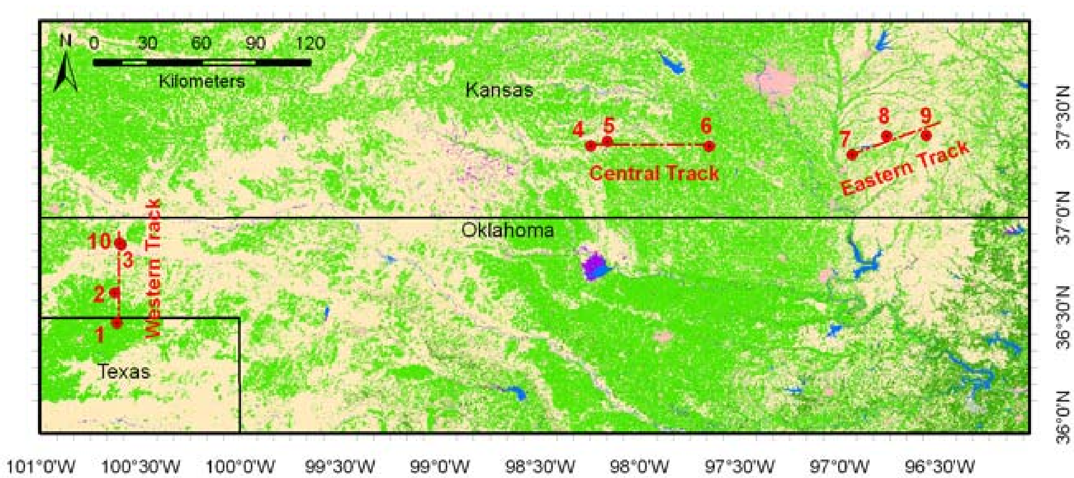


Fig. 6. IHOP_2002 domain and flux tower locations. (LeMone et al., 2007)

Childs et al., (2006) used IHOP_2002 data to show that both soil moisture and soil temperature are important variables in determining the initialization of deep convection in the SGP. Childs and colleagues used data assimilation to improve the accuracy of simulated surface heat fluxes; they attribute the improvement in simulated precipitation to the more realistic surface heat flux representation, mediated by the difference between air and skin temperature. Holt et al. (2006) investigated the effect of land–vegetation processes on the prediction of mesoscale convection by comparing a detailed observations from IHOP_2002 to a simulated convective event in a regional weather forecasting model that used a slab land-surface model to soil moisture, and another simulated using a model including a complex land-surface model (Noah) that had been equipped with a photosynthesis-linked transpiration formulation. They found that, in the mesoscale convective event they focused (characterized by strong dryline synoptic forcing and a quasi-stationary cold front), the slab model was insufficient to account for the interactions that occur at the boundaries and also, that detailed representation of surface vegetative processes improve the accuracy of model forecast. Holt et al. (2006) found that soil moisture did not have a direct effect in the response, but rather it was mediated by the combined effect of latent heat flux, boundary layer growth, CAPE, and CIN. Realistic representation of land surface processes in transition zones is of utmost relevance for accurate simulations of turbulent fluxes.

2. Representing land memory mechanisms with land-surface models

Memory of a system refers to the persistence in time of anomalies, which in turn can propagate to other components of the system. In the climate system, soil moisture memory and eco-hydrological processes that control water storage have the potential to affect weather processes. Representing these effects accurately is important for skillful numerical weather prediction. Land surface models provide boundary conditions in numerical weather forecasting. Land surface models represent the interactions between soil, plants, and the atmosphere at various temporal and spatial scales. They simulate the temporal evolution of energy and water balances at and near the land-surface. They are responsible for simulated near surface weather variables such as low level cloudiness and dew point temperature (Viterbo 2002; Nijseen and Bastidas, 2005). Different parameterizations represent biophysical and hydrological processes to simulate fluxes of moisture (interception, throughfall, infiltration, runoff and snowmelt), energy (absorption of radiation at the surface, partitioning into latent and sensible heat flux, storage of heat), and momentum (frictional drag of surface on the PBL) (Fig.7). There exists a multitude of land surface model that vary considerably in terms of the complexity and sophistication of their biophysical representations. In general, more sophisticated land surface models tend to produce more accurate simulations of air temperature (Yang et al. 2005), runoff (Wood et al., 1998; Boone et al., 2004; Niu et al., 2005), snow (Bowling et al., 2003), turbulent fluxes (Hogue et al., 2006), and states (Niu et al., 2007; Stockli et al., 2007). However, understanding and consequently representing with accuracy the strength of land-memory mechanisms, such as the storage of water near the surface as soil moisture and the nature and seasonal progression of growing vegetation, still remains a challenge in land-surface modeling (Pitman 2003, Yang 2004).

Near-surface atmospheric forcing data (e.g., precipitation, radiation, wind speed, air temperature, humidity) is required to drive the Noah land surface model (Ek et al., 2003), which is a state-of-the-art model that is widely used in both numerical weather forecasting and climate prediction. Noah simulates both liquid and frozen soil moisture and soil temperature (using four layers), skin temperature, snowpack depth, snowpack water equivalent, canopy water content, and the energy flux and water flux terms of the surface energy and water balance. The model applies finitedifference spatial discretization methods and a Crack-Nicholson time integration scheme to numerically integrate the governing equations of the soil-vegetation-snowpack medium, including: the Jarvis equation for the conductance of canopy transpiration, the Richards' equation for soil hydraulics, the diffusion equation for soil heat transfer, the energy-mass balance equation for the snowpack, and the surface energy balance equation.

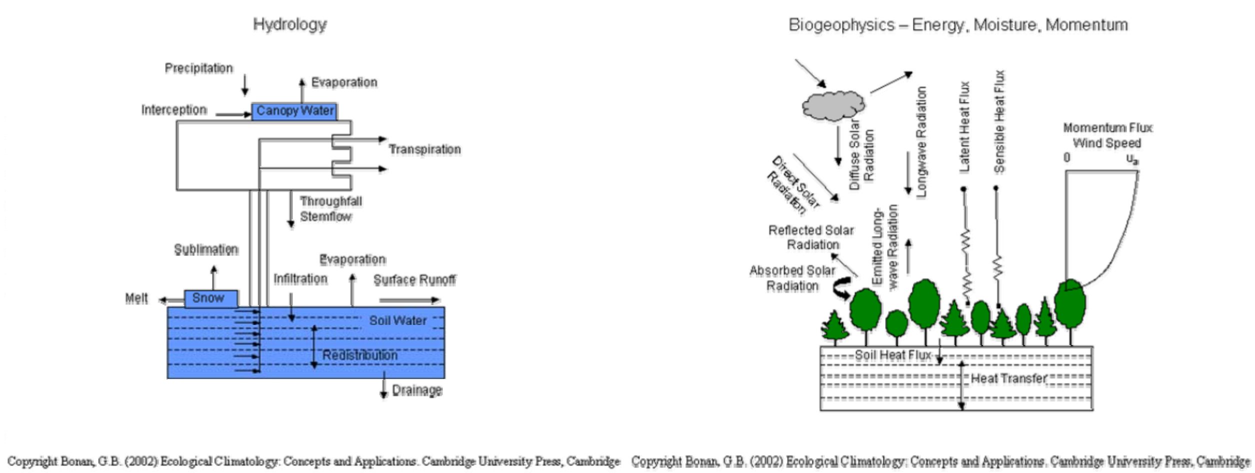


Fig. 7. Schematic representation of a LSM. (Bonan 2002)

2.1 The role of vegetation

Although their study focused only on soil moisture effects, Koster et al. (2004) expected vegetation properties and processes to play a significant role in the predictability of precipitation. Most of the differences between the GLACE participant models were found to be related with the degree to which precipitation parameterizations responds to changes in evaporation (Dirmeyer, 2006). In most vegetated regions, water transpired from vegetation makes up a significant component of the latent heat flux from the land surface, which in turn is controlled by the availability of root zone soil moisture.

Shuttleworth (2007) presents a review on the physics of evapotranspiration. Stomata are pores on leaves that allow plants to exchange gases with the atmosphere. Plants take in carbon dioxide through stomata. Because the interiors of leaves are saturated with respect to water vapor, when stomata are open, plants lose water to the atmosphere. Water transpired helps cool the plant. Stomata are pivotal regulators of the surface energy balance; by changing transpiration in response to variation in near-surface meteorological conditions, stomata link the biosphere and the atmosphere. Because stomata control surface energy partitioning, land surface modelers have recognized the need to adequately represent stomatal processes within the land-surface models that are used in weather and climate simulations. Indeed, vegetation properties and associated processes play a significant role in shaping global climate (e.g. Dickinson and Henderson-Sellers, 1988; Xue et al., 2004). Land surface models parameterize the stomata-mediated latent heat flux using an Ohm's Law analog. Stomatal resistance (or conductance), is a measure of the difficulty (or ease) for the vegetation to transpire. In Land Surface Models, water transpired from vegetation is regulated by a stomatal resistance, which is a function of environmental variation. Changes in stomatal resistance affect partitioning of net radiation and help regulate soil moisture in the rooting zone. Parameterization of stomatal resistance (or its inverse, stomatal conductance) has been done empirically (e.g., Jarvis et al., 1976) and with more physically based methods (e.g., Farquhar, 1982; Ball et al., 1987; Collatz et al., 1991), although such methods still maintain empirical foundations.

One of the most commonly used parameterizations in the land-surface modeling community, the Jarvis parameterization (Jarvis, 1976) represents changes in stomatal resistance as an empirical function of four sources of stress: soil moisture deficits, changes in ambient vapor pressure, variations in net radiation availability and temperature. The Jarvis empirical formulation for calculating stomatal resistance is directly proportional to available net radiation and is inversely proportional to soil moisture, ambient vapor pressure, biomass, and temperature. Most Jarvis-based formulations (Jarvis et al., 1976; Stewart et al., 1988) express stomatal resistance as follows:

$$Rs = R_0 f_D(D) f_T(T) f_S(S) f_W(\theta)$$

where, Rs is the computed stomatal resistance; $f_D(D)$ is a factor that characterizes the stomatal response to the specific humidity deficit of the near-surface air; $f_T(T)$ is a factor that characterizes the response of R to air temperature $f_S(S)$ scales R as a function of incident solar radiation; and $f_W(\theta)$ is a scale factor that relates R to soil moisture, θ. All factors range from 0 to 1 and modify a biome-dependent, prescribed, maximum value of stomatal resistance R_0. In mesoscale atmospheric models, R_0 is parameterized as Rs_{min}/LAI and f_s as a function of net radiation, LAI and the ratio of Rs_{min} to Rs_{max}.

Unlike the purely empirical Jarvis-type equation, Ball-Berry methods (Ball et al., 1987) explicitly link stomatal resistance to the rate of photosynthesis. Philosophically, evapotranspiration is viewed as the unavoidable cost of photosynthesis: stomata open to allow carbon dioxide to infiltrate the leaf for as a necessary input for photosynthesis. They use the following or a similar function to parameterize stomatal resistance:

$$1/Rs = m(A_n / C_S) P_l F_e + 1/R_{min}$$

where, R_{min} is a prescribed minimum stomatal resistance. Slope parameter *m* varies between types of plant; A_n is the net carbon assimilation by photosynthesis; C_S is the partial pressure of carbon dioxide; P_l is the atmospheric pressure immediately outside the leaf; and F_e is a relative humidity–dependent stress factor. A_n is parameterized to reflect limiting assimilation rates due to Rubisco enzyme, light and transport capacity. Variations of the Ball-Berry equation exist. For instance, Dickinson et al. (1998) treat 1/Rs as a function of vapor pressure deficit rather than as a function of relative humidity (expressed in the equation above as F_e). These formulations are 'deceptively simple' (Niyogi et al., 1998) in that require information not routinely available for metereological applications such as cuticular carbon dioxide concentrations or vegetation specific enzymatic controls on assimilation rates.

Niyogi and Raman (1997) suggested that Rs calculation has an impact that on boundary layer processes due to changes in the partitioning of surface energy. They compared different Rs schemes to observed Rs, derived by researchers participating in the First International Satellite Land Surface Climatology Project Field Experiment (FIFE), for the SPG predominant C4 vegetation type. They showed that the Jarvis formulation exhibits poor capacity to represent feedbacks between stomatal resistance and environmental changes and that the photosynthesis-based evapotranspiration formulations are better able to reproduce observed values of stomatal resistance, independent of the descriptor used for humidity. According to Holt et al. (2006), including a photosynthesis-based evaportranspiration module (GEM) (Niyogi et al., 2006) in coupled simulations using the Noah land surface model and the Weather Research and Forecasting (WRF) model improves simulation of air temperature and moisture in the IHOP_2002 convection case over simulations with standard Noah Land Surface Model. The canopy resistance for GEM is 500% larger as the Jarvis, reducing the transpiration rate by 60% and increasing the soil moisture availability by 10% (Fig. 8).

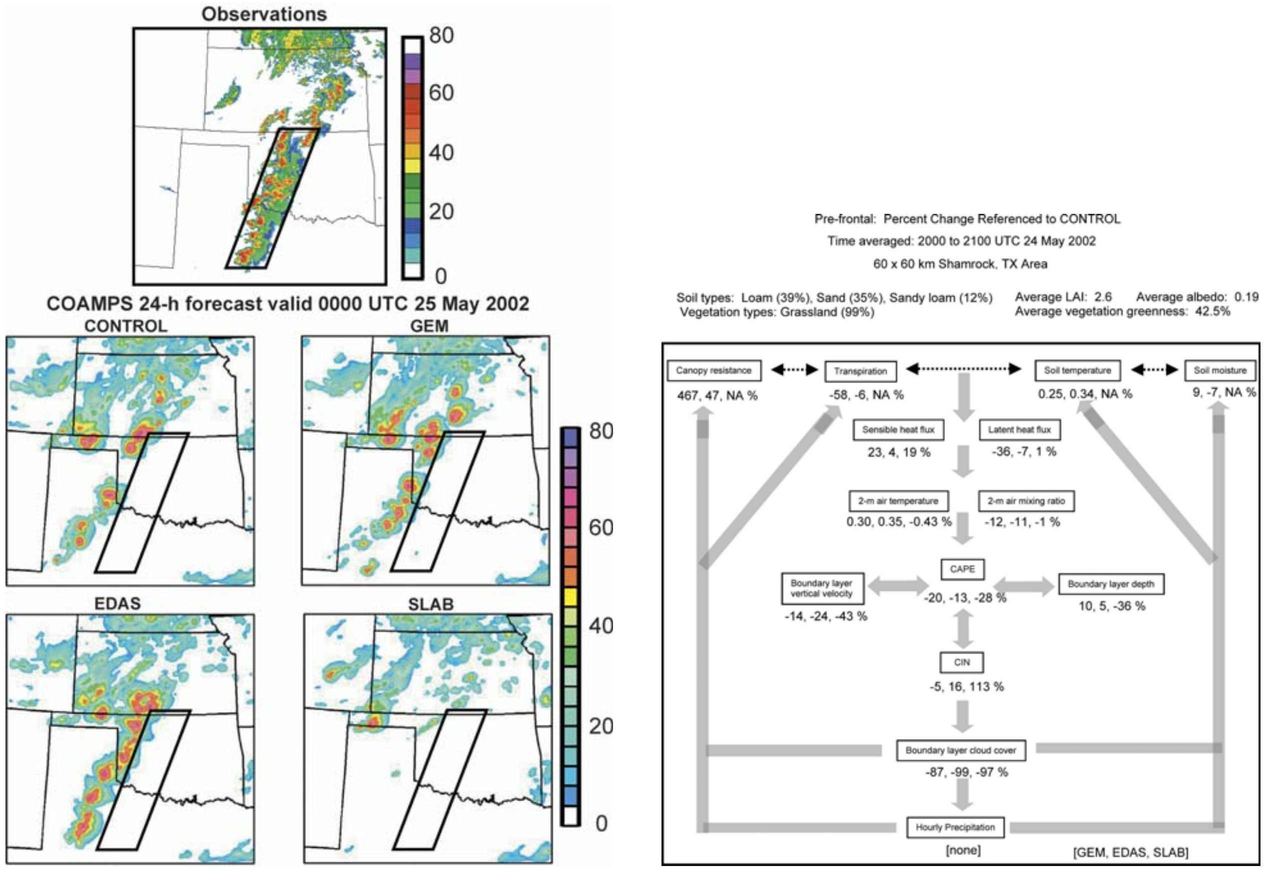
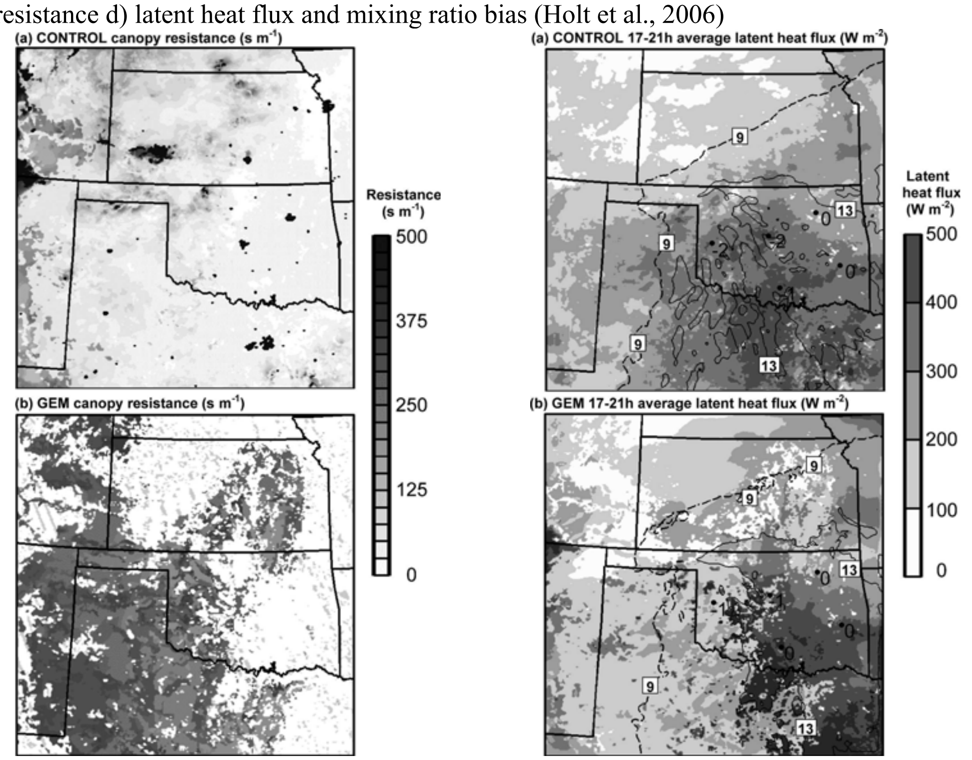


Fig . 8. a) Radar observations and model forecasts b) percent change in simulated quantities respect to control c) canopy resistance d) latent heat flux and mixing ratio bias (Holt et al., 2006)



However, land surface model canopy parameters are in generally very sensitive to seasonal controls and studies have shown that a similar effect could be attained by using fine tuned parameter values. Even simple manual, subjective adjustment of parameters can significantly improve model performance (Hogue et al.,2006). For instance, Demarty et al. (2004) showed that during the wheat-growing period, parameters governing stomatal regulation and water exchanges of deep soil layers were highly sensitivity whereas in the senescent period, parameters describing the canopy structure had high model sensitivity but stomatal regulation and root parameters were not. Hogue et al. (2006) calibrated land surface models of increasing complexity and showed that augmenting a model's complexity (presumably as means for increasing the conceptual physical realism of the model) does not necessarily improve the performance of the model. Hogue et al. also demonstrated that optimal parameters varied significantly across different sites, which underscores the value of calibration of effective parameters for optimal model performance. Hogue et al. calibrated both BATS1e and BATS2; the two models differ only in their parameterization of vegetation. BATS2 uses the dynamic phenology module of Dickinson et al. (1998). As expected, optimal vegetation parameters (e.g., stem area index) changed after the addition of the more complex representation of vegetation; however, with the exception of initial soil moisture conditions, optimal soil parameters did not change significantly between BATS1e and BATS2. Sen et al. (2001) obtained significant changes in global climate simulations by employing off-line calibrated BATS2 parameter values for representative biomes (Fig.10).

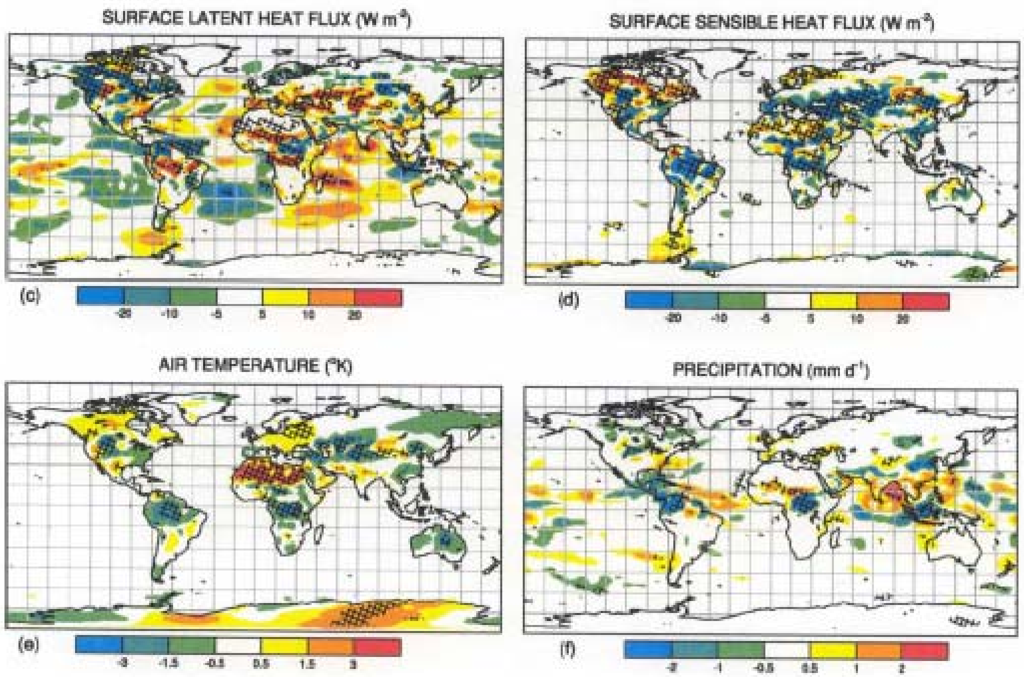


Fig. 10. JJA Differences in model simulations using calibrated parameters respect to control

Alpert et al., (2006) use micro-scale, mesoscale, and global scale models to show that interaction between water and carbon processes drive environmental variation across scales. Including a realistic, physically based representation of phenological variation in a land surface model is therefore important not only for adequate simulation of carbon dynamics but also for realistic representation of the water cycle and the surface energy balance. Dickinson's short term phenology module (Dickinson et al., 1998) varies leaf biomass density as a function of changing soil moisture, changing soil temperature, changing canopy temperature, and the vegetation type. Dickinson et al.'s model distributes photosynthate to plant compontents (leaves, roots, and stems) as a function of the existing biomass density (which Noah represents as vegetation fraction). The model simulates growth and maintenance respiration, slow-turnover and fast-turnover carbon reservoirs, and the response of vegetation to cold stress and drought stress. Kim and Wang (2007) assert that the ability of short-term dynamic phenology models (such as that of Dickinson et al., 1998) to realistically represent changes in leaf biomass in response to a range of climate conditions is not well established (Kim and Wang, 2007). the ecological community has not yet reached clear agreement regarding what controls variation in biomass on short time scales (e.g., Grier and Running, 1977; Gholz, 1982; Leuschner et al., 2006). Because the Dickinson et al. (1998) scheme was designed based on the state-of-the-art understanding of carbon allocation between vegetation reservoirs, we view it as a realistic method for representing changes in phenology on short time scales.

2.2 The role of soil moisture

Dirmeyer et al. (2000) studied the sensitivity of surface fluxes to soil water content. Their results suggest that accuracy in the measurement or model simulation of soil moisture is most critical within the drier portion of the range of variation of soil moisture. Also, accurate measurement of soil moisture and the subsequent use of such measurements in models is particularly important over sparsely vegetated areas, where evapotranspiration is dependent on moisture within a shallower soil column. Evidence shows that initialization of numerical weather prediction models with realistic land surface states improves the skill of numerical weather forecasts (e.g., Betts et al., 1997; Ek et al., 2003). Chen et al. (2007) developed the High Resolution Land Data Assimilation System (HRLDAS) to produce initial land-surface states for use in numerical weather prediction. Their work advances on that of other similar research using the North American Land Data Assimilation System (NLDAS) (e.g., Cosgrove et al, 2003; Mitchell et al., 2004) because of its significant increase in spatial resolution (HRLDAS is run at 4 km; NLDAS is run at 12 km); land surface states vary on a fine spatial scale, and it is likely that this fine-scale variability alters boundary layer development and the initiation of convection (e.g., Weckwerth and Parsons, 2006). Chen et al. used a climatological prescribed green vegetation fraction based on Advanced Very High Resolution

Radiometer vegetation indices to provide vegetation data for the Unified Noah land surface model (Ek et al., 2003), the land surface model used within HRLDAS and as the lower boundary of the Weather Research and Forecasting (WRF) model. They evaluated the performance of HRLDAS using IHOP_2002 flux and land-surface state data (LeMone et al., 2007) as well as soil moisture data provided by the Oklahoma Mesonet (Brock et al., 1995; Shafer et al., 2000). The Noah LSM within HRLDAS tends to overestimate latent heat flux and underestimate the negative nocturnal sensible heat flux. (Fig 11). Although, in general, simulated soil temperature and moisture agree reasonably well with observations obtained from the Oklahoma Mesonet, the amplitude of soil moisture variation that is simulated by Noah within HRLDAS is overestimated, especially in near-surface soil layers, and Noah within HRLDAS appears to represent a delayed diurnal cycle of soil temperature (Fig 12). Despite these limitations in simulating states and fluxes, Chen et al. assert that HRLDAS reasonably simulates surface states and fluxes, presenting a case study in the SGP in which HRLDAS evaporation and radar-derived low-level water vapor fields were well correlated. Because of the overestimation problems with the simulation as well as several data error issues with latent heat flux observations in the IHOP_2002 experiment, they suggest that evaluation using sensible heat fluxes may provide a more accurate representation of model performance.

In the same way that simulations of fluxes were enhanced by calibrating vegetation parameters, ascribing effective soil parameters to modulate the soil moisture signal has been presented as a way for improving model performance. Gutmann and Small (2007) modified Noah LSM to use the van Genuchten formulation instead of Clapp and Hornberger's method to provide soil hydraulic parameters for solving the diffusion form of the Richards equation in one dimension. They calibrated both models (control and modified) to reproduce dry down events in all the IHOP_2002 sites. By using the best-fit parameters, the agreement of simulated latent heat flux with observations significantly improved (Fig. 13). Optimized soil hydraulic parameters enabled both models to produce nearly identical results. Gutmann and Small found that prescribing soil parameters based solely on the texture classification was insufficient to guarantee realistic heat fluxes: texture class accounted only for a small fraction (5%) of the variance, but the van Genuchten parameters explained the majority of variance. Moreover, the researchers showed that as vegetation cover increases, the effect of the curve-fitting soil hydraulic parameters decreases but the saturated conductivity becomes more important.

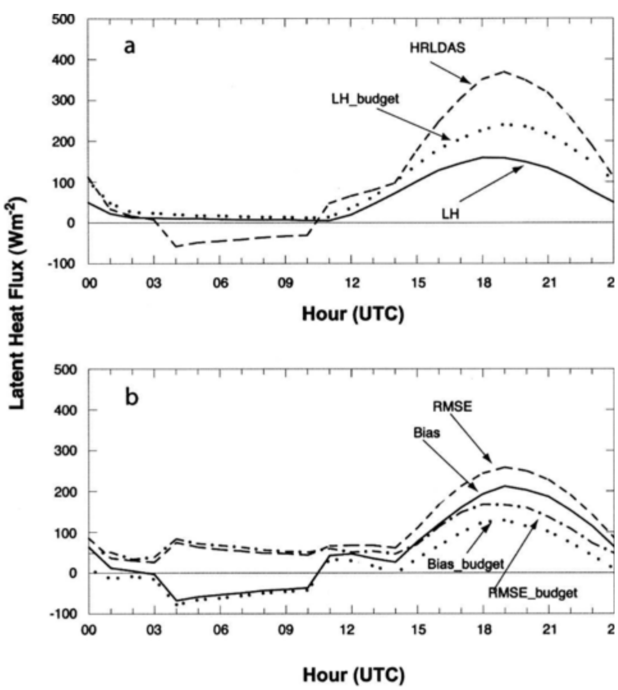


Fig. 11. Diurnal cycle of LE averaged for all 10 IHOP sites, compared to HRLDAS (Chen et al., 2007)

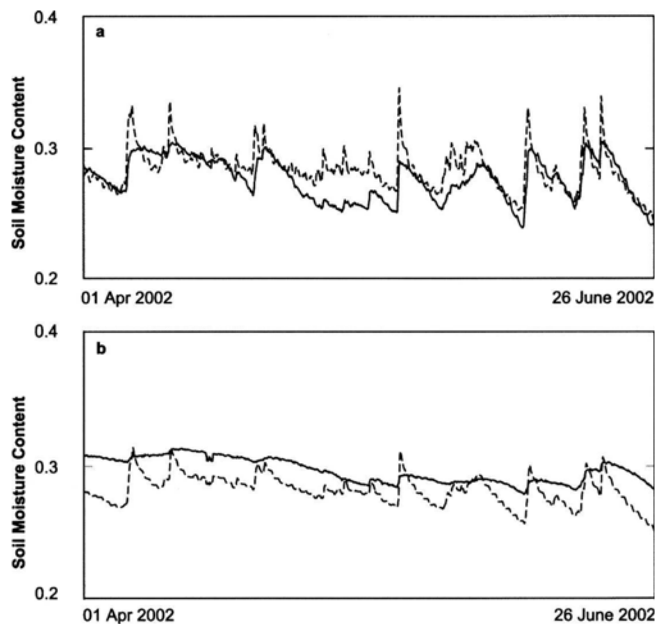


Fig. 12. Hourly volumetric soil moisture averaged for mesonet stations (solid) at a) 5 cm and b) 25 cm (Chen et al., 2006)

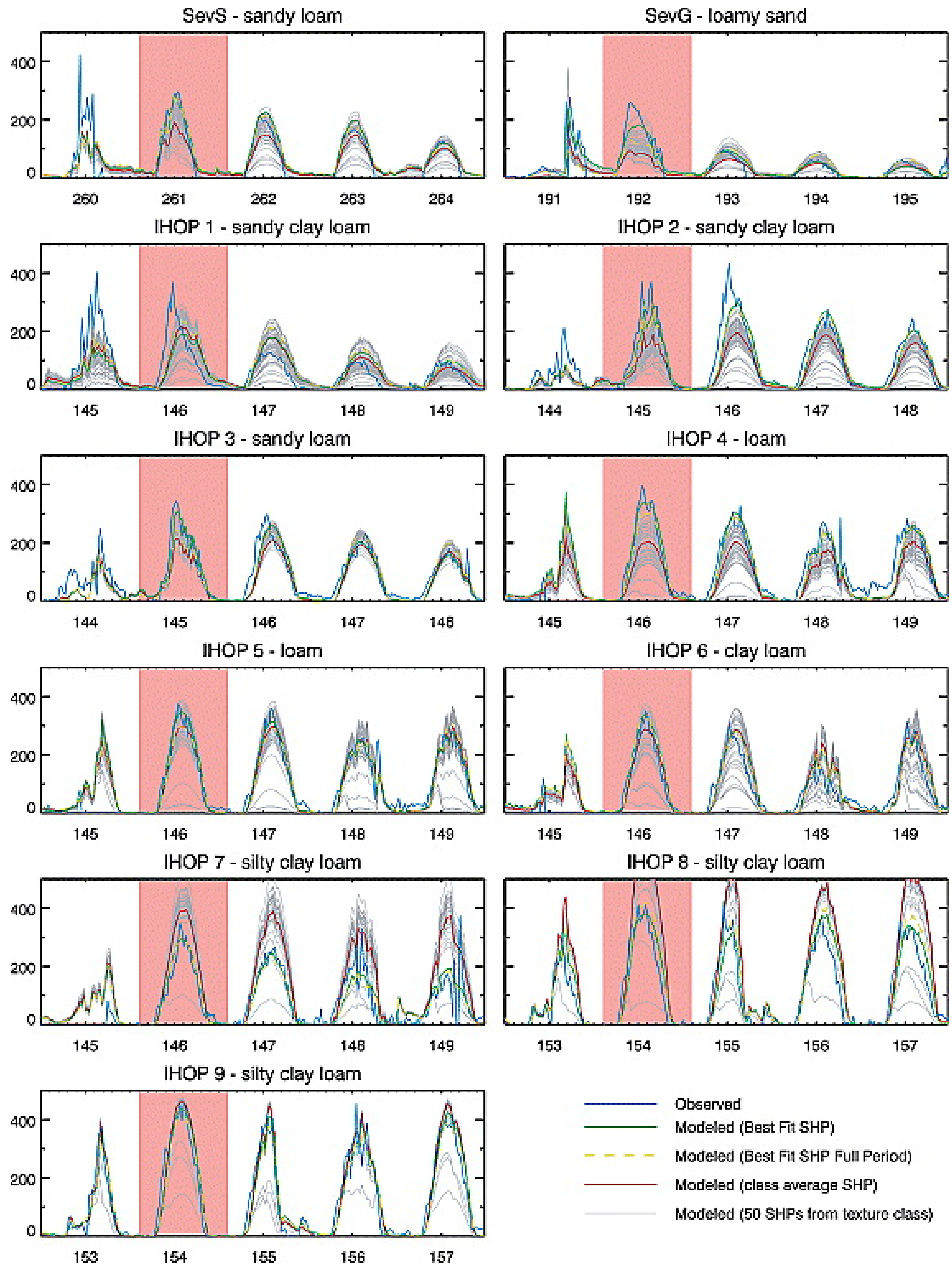


Fig. 13. Observed and simulated latent heat flux time series for IHOP_2002 sites.

A different approach to improve the modeled representation of subsurface hydrology was presented by Niu et al. (2007). They augmented a land surface model with a simple, lumped unconfined aquifer. The aquifer model (SIMGM) replaces the lower boundary of the soil column. Water flows in both directions between the aquifer and the soil column: SIMGM represents water flow down a hydraulic potential gradient. The modeled hydraulic potential is the sum of the soil matric and gravitational potential. If insufficient water is available to maintain a near-surface aquifer, the water table falls below the soil column; when water is plentiful, the water table is within the soil column of the land-surface model. Baseflow ("subsurface runoff", the lateral flow of groundwater toward streams and other discharge points) is parameterized using the statistics of topography.

3. Summary

Especially in regions where spatial variation in land-surface fluxes and characteristics have the potential to significantly alter convection initiation and other characteristics of precipitation (e.g., in the U.S. Southern Great Plains), representation of land-surface processes and effective assessment of parameters to land surface models is of paramount importance for improving skill in numerical weather forecasting and climate prediction. The IHOP_2002 project provides a wealth of data for evaluating the ability of land-surface model physical parameterizations to accurately represent the spatial distribution and magnitude of surface fluxes. Several researchers (e.g., Chen et al., 2007) have shown that existing land-surface models do a competent but not completely realistic job of representing the diurnal cycle of surface fluxes. The forefront of land-surface model development encompasses dynamic phenology modules, groundwater hydrology representations, and improvements to the functional relationship between observable land-surface characteristics and hydrologic properties.

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