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Influences of biomass heat and biochemical energy storages on the land surface fluxes and radiative temperature

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[1] The interest of this study was to develop an initial assessment on the potential importance of biomass heat and biochemical energy storages for land-atmosphere interactions, an issue that has been largely neglected so far. We conducted flux tower observations and model simulations at a temperate deciduous forest site in central Missouri in the summer of 2004. The model used was the comprehensive terrestrial ecosystem Fluxes and Pools Integrated Simulator (FAPIS). We first examined FAPIS performance by testing its predictions with and without the representation of biomass energy storages against measurements of surface energy and CO_2 fluxes. We then evaluated the magnitudes and temporal patterns of the biomass energy storages calculated by FAPIS. Finally, the effects of biomass energy storages on land-atmosphere exchanges of sensible and latent heat fluxes and variations of land surface radiative temperature were investigated by contrasting FAPIS simulations with and without these storage terms. We found that with the representation of the two biomass energy storage terms, FAPIS predictions agreed with flux tower measurements fairly well; without the representation, however, FAPIS performance deteriorated for all predicted surface energy flux terms although the effect on the predicted CO_2 flux was minimal. In addition, we found that the biomass heat storage and biochemical energy storage had clear diurnal patterns with typical ranges from -50 to 50 and -3 to 20 W m^{-2}, respectively; these typical ranges were exceeded substantially when there were sudden changes in atmospheric conditions. Furthermore, FAPIS simulations without the energy storages produced larger sensible and latent heat fluxes during the day but smaller fluxes (more negative values) at night as compared with simulations with the energy storages. Similarly, without-storage simulations had higher surface radiative temperature during the day but lower radiative temperature at night, indicating that the biomass energy storages act to dampen the diurnal temperature range. From these simulation results, we concluded that biomass heat and biochemical energy storages are an integral and substantial part of the surface energy budget and play a role in modulating land surface temperatures and must be considered in studies of land-atmosphere interactions and climate modeling.

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1. Introduction

[2] Our current understanding of roles of vegetation in land-atmosphere interactions has overwhelmingly come from previous studies focusing on effects of vegetation on physical evaporation and stomata-regulated transpiration, surface roughness, and albedo, and associated feedbacks. Much less attention has been given to the potential influences of vegetation as energy storage pools. Biomass stores energy in two ways: physical heat energy storage due to changes in biomass temperature (enthalpy) and biochemical energy storage in chemical bonds and its release due to processes of photosynthesis and respiration, respectively. At present, it is not clear how these two energy storage terms affect land surface flux exchanges with the atmosphere and modulate surface temperature regimes.

[3] Some land surface models that have been coupled with atmospheric general circulation models to simulate climate change have not included biomass heat and biochemical energy storages. However, there is evidence indicating that biomass heat and biochemical energy storages

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are not insignificant components of the surface energy budget. For example, *Potter and Zasada* [1999] suggested that biomass thermal inertia may prevent freeze occurrence in forest stands in spring; *Samson and Lemeur* [2001] found that biomass heat storage and biochemical energy storage were up to 60 and 20 W m^{-2}, respectively, in a mixed deciduous forest; *Meyers and Hollinger* [2004] reported that the two energy storage terms could each be over 20 W m^{-2} for maize and soybean canopies. Compared with radiative forcings of atmospheric greenhouse gases and aerosols (less than a few watts per square meter [*Intergovernmental Panel on Climate Change* (*IPCC*), 2001]), these numbers are large, and they suggest that interest in biomass heat and biochemical energy storages is justifiable in studies of land-atmosphere interactions and climate change.

[4] This paper aims to provide insight into and stimulate more research on the roles of biomass heat and biochemical energy storages in land-atmosphere interactions. The objectives of our study were threefold. First, we investigated how the performance of a comprehensive land surface model differed with and without considering biomass energy storages at a forest site in central Missouri, USA. Second, we evaluated the magnitudes and temporal patterns of the calculated biomass heat and biochemical energy storages. Third, we examined the effects of these storages on land-atmosphere exchanges of sensible and latent heat fluxes and variations of land surface temperature regimes. Our main finding was that biomass heat and biochemical energy storages significantly influence land surface sensible and latent heat fluxes and temperatures and must be considered in studies of land-atmosphere interactions and climate modeling.

2. Methods

2.1. Overview

[5] Our main approach involved first testing a land surface model with detailed representation of biomass heat and biochemical energy storages against eddy covariance flux measurements and then conducting simulations using the tested model. Although the biochemical energy storage can be computed from eddy covariance flux measurements of net ecosystem exchanges of carbon dioxide [*Meyers and Hollinger*, 2004], directly measuring forest biomass heat storage is difficult because it requires attaching a large number of temperature sensors to stems, branches, twigs, and leaves in order to capture vertical variations in biomass temperature caused by attenuation of radiation within the canopy. Therefore we combined direct measurements and model simulations in this study. We obtained the measurements from the Missouri Ozark AmeriFlux (MOFLUX) site in the summer of 2004. The model used was the terrestrial ecosystem Fluxes and Pools Integrated Simulator (FAPIS) we developed. Detailed biomass inventory data and plant biochemical measurements were used to parameterize FAPIS while observations of sensible heat flux, latent heat flux, net radiation, outgoing longwave radiation, and CO_2 fluxes were used to validate FAPIS in its prediction of surface energy and mass fluxes and assess how FAPIS performance differs with and without biomass energy storages. After FAPIS was validated, we analyzed the magnitudes and temporal patterns of the predicted biomass heat storage and biochemical energy storage and their contributions to the surface energy budget. For biomass heat storage, we only included the above-ground biomass. Soil heat storage is a different term and is always part of the soil heat diffusion equations; thus our biomass heat storage does not include soil heat storage. However, our biochemical energy storage is the net result of photosynthesis, autotrophic respiration, and heterotrophic respiration and thus should be considered as "ecosystem biochemical energy storage."

[6] Next, we examined how biomass heat and biochemical energy storages affect the land surface energy flux exchanges and radiative temperature by comparing FAPIS simulations with and without these two energy storage terms. Ideally, this issue should be investigated with a fully coupled land-atmosphere model so that feedbacks from these energy storages to atmospheric forcings can be considered. However, a fully coupled model is complicated and the simulations using such a model can be better designed and more efficiently carried out once we have an initial assessment of the issue from off-line land surface model simulations. Therefore, instead of attempting to have a full, comprehensive evaluation of the roles of biomass heat and biochemical energy storages in land-atmosphere interactions, we were primarily interested in developing a first-order, conservative estimate at this stage. In both the with-storage and without-storage simulations, we used the same observed atmospheric forcings, including incident solar and longwave radiations and precipitation as well as air temperature, humidity, CO_2 concentration, and wind speed at a reference level above the canopy. The differences in the modeled surface fluxes and radiative temperature between the two simulations were attributed to the effects of biomass heat and biochemical energy storages.

2.2. Terrestrial Ecosystem Fluxes and Pools Integrated Simulator (FAPIS)

[7] FAPIS is based on the model of *Gu* [1998] and *Gu et al.* [1999]. Compared with the original model, FAPIS contains a couple of new developments, which include replacement of the force-restore method by a multilayer model for predicting soil temperature and hydrology and full separation of sunlit and shaded canopy elements for both carbon assimilation and energy balance calculations. FAPIS has a very flexible setup for representation of ecosystem structures. Any number of vertical layers can be used for vegetation, depending on the desirable amount of leaf area in each layer. Each canopy layer is separated into sunlit and shaded parts with energy balance, biomass temperature, stomatal conductance, intercellular CO_2 concentration, sensible and latent heat fluxes, CO_2 flux, thermal fluxes etc. computed separately for each part during the day but together at night. Shortwave radiative transfer inside the canopy is modeled as two streams while the longwave radiative transfer is described by the matrix method of *Gu et al.* [1999]. The soil component of FAPIS is similar to the Community Land Model [*Dai et al.*, 2003]. Analogous to the canopy layer setup, any number of soil layers can be used, depending on the desirable thickness of each soil layer. Darcy's law/Richards equation with gravitational drainage at the bottom are used to describe soil moisture dynamics while the heat diffusion equation, solved by the Crank-Nicholson method with zero heat flux at the bottom, is used to simulate soil temperature dynamics.

Table 1. Values of Key Parameters in FAPIS Directly Related to Canopy Energy Balance, Particularly Biomass Heat and Biochemical Energy Storages

Parameters	Value	Unit	Source
Specific heat capacity of dry leaves	3.218	$J\ g^{-1}\ K^{-1}$	*Jones* [1992]
Specific heat capacity of dry nongreen biomass	1.256 at 25°C	$J\ g^{-1}\ K^{-1}$	*Forest Products Laboratory* [1999]
Leaf water to dry mass ratio	1.5	N/A	*Ceccato et al.* [2001]
Nongreen biomass water to dry mass ratio	0.7	N/A	*Forest Products Laboratory* [1999]
Biochemical energy conversion factor	0.48	$J\ mol^{-1}\ CO_2$	*Blankenship* [2002]
Leaf reflectance in visible radiation	0.09	N/A	*Oke* [1987]
Leaf reflectance in near infrared radiation	0.45	N/A	*Sellers et al.* [1996]
Leaf transmission coefficient in visible radiation	0.06	N/A	*Oke* [1987]
Leaf transmission coefficient in near infrared radiation	0.25	N/A	*Sellers et al.* [1996]
Slope in the stomatal conductance model	10	N/A	*Leuning* [1995]
Intercept in the stomatal conductance model	0.01	$\mu mol\ m^{-2}\ s^{-1}$	*Leuning* [1995]
Leaf area in each canopy layer	<0.2	$m^2\ m^{-2}$	FAPIS adjustable numerical parameter

[8] Because most details about the main structure of FAPIS are already given by *Gu* [1998] and *Gu et al.* [1999], only the energy balance equations for canopy layers are described here; these equations are directly relevant to this study. For a given sunlit or shaded part of a canopy layer, the conservation of energy requires:

$$\delta R_{as} + \delta R_{al} - \delta S_h - \lambda\delta S_w - \delta S_B - \delta S_M - k\sigma T^4 = 0, \quad (1)$$

where δR_{as} is the amount of shortwave radiation absorbed by the given part; δR_{al} the amount of longwave radiation absorbed (not including the longwave emission from the part itself); δS_h the sensible heat flux; $\lambda\delta S_w$ the latent heat flux; δS_B the biomass heat storage; δS_M the metabolic or biochemical energy storage; σ the Stefan-Boltzmann constant; T the biomass temperature of the given part; k the longwave emission coefficient of the given part. k is derived from the longwave radiative transfer equation [*Ross*, 1981]; it is close but not identical to $2\varepsilon\delta L$, where ε is the biomass longwave emissivity and δL is the plant area (including leaves, stems, branches, etc.) in the given part of the layer [*Gu et al.*, 1999]. δS_B and δS_M are computed from:

$$\delta S_B = \left(C_{pL}\delta M_L + C_{pn}\delta M_n + C_{pw}\delta M_w\right)\frac{dT}{dt}, \quad (2)$$

$$\delta S_M = \beta\delta S_c, \quad (3)$$

where C_{pL}, C_{pn}, and C_{pw} are the specific heat capacities of moist green biomass, moist nongreen biomass (e.g., stems, branches, and twigs) and water, respectively; δM_L, δM_n, and δM_w are the moist green biomass, moist nongreen biomass, and mass of water that may cover the surface of biomass because of dew or rainfall interception in a given layer; β is the biochemical energy conversion factor (0.48 J/mol CO_2 [*Blankenship*, 2002]); δS_c is the CO_2 flux from the given part of the layer. C_{pL} and C_{pn} are further calculated from the following equations, respectively:

$$C_{pL} = \left(C_{pL\_dry} + r_L C_{pw}\right)/(1 + r_L), \quad (4)$$

$$C_{pn} = \left(C_{pn\_dry} + r_n C_{pw}\right)/(1 + r_n) + 100 r_n(-0.06191 + 2.36 \times 10^{-4}T - 1.33 \times 10^{-2} r_n), \quad (5)$$

$$C_{pn\_dry} = 0.1031 + 3.867 \times 10^{-3}T, \quad (6)$$

where C_{pL_dry} and C_{pn_dry} are the specific heat capacities for dry leaves and dry nongreen biomass, respectively; r_L and r_n are the ratio of water to dry biomass for leaves and nongreen biomass, respectively. The second term in (5) represents the additional heat capacity attributable to wood-water bonding. The heat capacity relationships and parameters were taken from the Wood Handbook of *Forest Products Laboratory* [1999].

2.3. Study Site and Measurements for Initializing, Parameterizing, Driving, and Validating FAPIS

[9] We conducted FAPIS simulations for the Missouri Ozark AmeriFlux (MOFLUX) site using data from the summer of 2004 (June to September). Parameters of FAPIS key to this study are listed in Table 1. The MOFLUX site is located in the University of Missouri's Baskett Wildlife Research and Education Area (BREA, Lat. 38°40′N, Long. 92°12′W). BREA is within the Ozark border region of central Missouri. Second-growth upland oak-hickory forests representing the west margin of the eastern deciduous forest biome constitute the major vegetation type at the BREA. The canopy height is about 17m. *Rochow* [1972], *Pallardy et al.* [1988], and *Gu et al.* [2006] provide further descriptions on the site vegetation, soil, and climate conditions.

[10] Leaf area index was estimated to be about 4.2 at the MOFLUX site in the summer of 2004 on the basis of conversion of leaf litter weights to area using measured specific leaf area. We also determined the above-ground nonfoliar biomass from the stand distribution of tree diameter at breast height (DBH) and tree allometric equations. The vertical display of leaves was approximated with a triangular distribution and that of the nonfoliage biomass was determined from tree taper equations [*Botkin*, 1993; *Jenkins et al.*, 2003]. The vertical canopy was then divided into 20 layers each containing about 0.2 m^2/m^2 leaf area. Biomass heat and biochemical energy storages were calculated for each layer and summed up for the whole canopy.

[11] FAPIS was initialized using measured soil moisture and temperature. The initial profile of biomass temperature was assumed to equal air temperature. Measurements of meteorological variables used to drive FAPIS and observations of above-canopy energy and mass fluxes used to validate FAPIS predictions were obtained from a 32-m walkup scaffold tower [*Gu et al.*, 2006]. We installed the instruments at the top of the tower, about 15 m above the top of the canopy. We measured the sensible and latent heat fluxes with the eddy covariance technique. The eddy

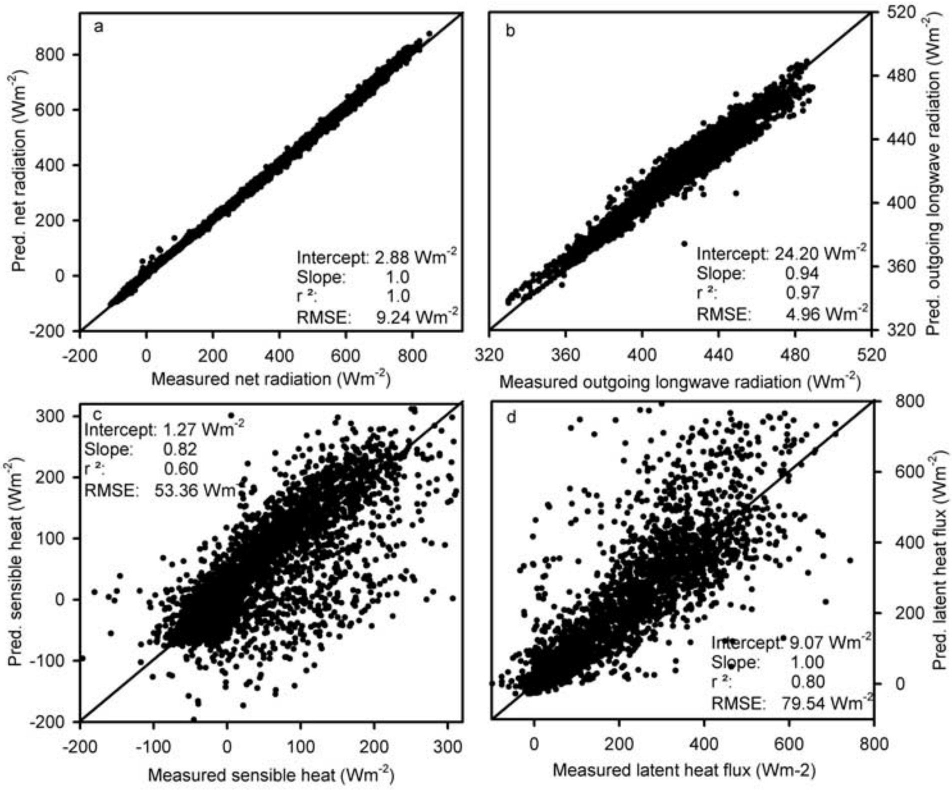

Figure 1. A comparison of predicted and measured energy fluxes at the Missouri Ozark AmeriFlux site for the summer of 2004. (a) Net radiation, (b) outgoing longwave radiation, (c) sensible heat flux, and (d) latent heat flux.

covariance system consisted of a three-dimensional ultrasonic anemometer (Model 81000, RM Young) and a fast responding, open-path infrared gas analyzer (LI7500, Li-Cor). Outputs from the ultrasonic anemometer and the gas analyzer were sampled at 10 Hz using a computer-controlled system. We used Reynolds averaging over half-hour periods to compute scalar fluctuations and flux covariances and applied the density corrections of *Webb et al.* [1980]. In addition, we estimated the canopy air space energy storages with an eight-level temperature/humidity profile system. We also made parallel observations of routine meteorological variables. We measured rainfall with tipping bucket rain gauges. The shortwave and longwave radiation balance was monitored with a 4-way net radiometer (CNR 1, Kipp and Zonen) installed at the top of the tower. This net radiometer includes two pyranometers and two pyrgeometers (upward and downward looking) and outputs incoming and reflected solar radiation and incoming and outgoing longwave radiation simultaneously.

3. Results

3.1. Validation of FAPIS Flux Predictions

[12] Figure 1 compares the predicted and measured net radiation (Figure 1a), outgoing longwave radiation (Figure 1b), sensible heat flux (Figure 1c), and latent heat flux (Figure 1d) for the summer of 2004 (June to September) at the MOFLUX site. Figure 2 compares the predicted and measured net ecosystem exchanges (NEE) of CO_2. In this comparison with measurements, FAPIS predictions are from the run with biomass heat and biochemical energy storages invoked. FAPIS predicts net radiation, outgoing longwave radiation, and latent heat flux well. However, the relationship between the measured and predicted sensible heat fluxes appears to depart from a 1:1 line. Also, the predicted

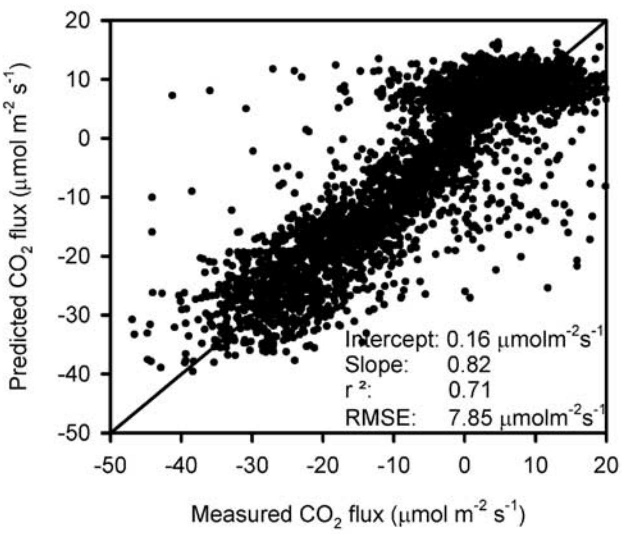

Figure 2. A comparison of predicted and measured net ecosystem exchanges of CO_2 at the Missouri Ozark AmeriFlux site for the summer of 2004.

Table 2. Root Mean Square Errors (RMSE) of Above-Canopy Energy and CO_2 Fluxes and Diurnal Radiative Temperature Range Predicted by FAPIS With and Without Representation of Biomass Heat and Biochemical Energy Storages, as Compared With Measurements

Predicted Variables	With Storages	Without Storages	Unit of RMSE
Net radiation	9.24	9.53	W m^{-2}
Outgoing longwave radiation	4.96	5.68	W m^{-2}
Sensible heat flux	53.36	57.69	W m^{-2}
Latent heat flux	79.54	80.49	W m^{-2}
CO_2 flux	7.85	7.83	μmol m^{-2} s^{-1}
Diurnal radiative temperature range	1.45	1.67	K

nighttime NEE of CO_2 does not agree well with measurements although for daytime there is a good match between the model and measurements. While we acknowledge that these disagreements may indicate that FAPIS can be improved in its process representation or parameterization, we note that eddy covariance flux measurements have difficulties in closing the surface energy budget (an overview of this issue is given by *Wilson et al.* [2002]. Our measurements of net radiation, sensible and latent heat fluxes achieve about 80% of energy budget closure, typical of forest sites) and are less reliable for nighttime than for daytime conditions [*Gu et al.*, 2005]. Despite these uncertainties, the overall performance of FAPIS warrants its use as a tool for analyzing influences of biomass heat and

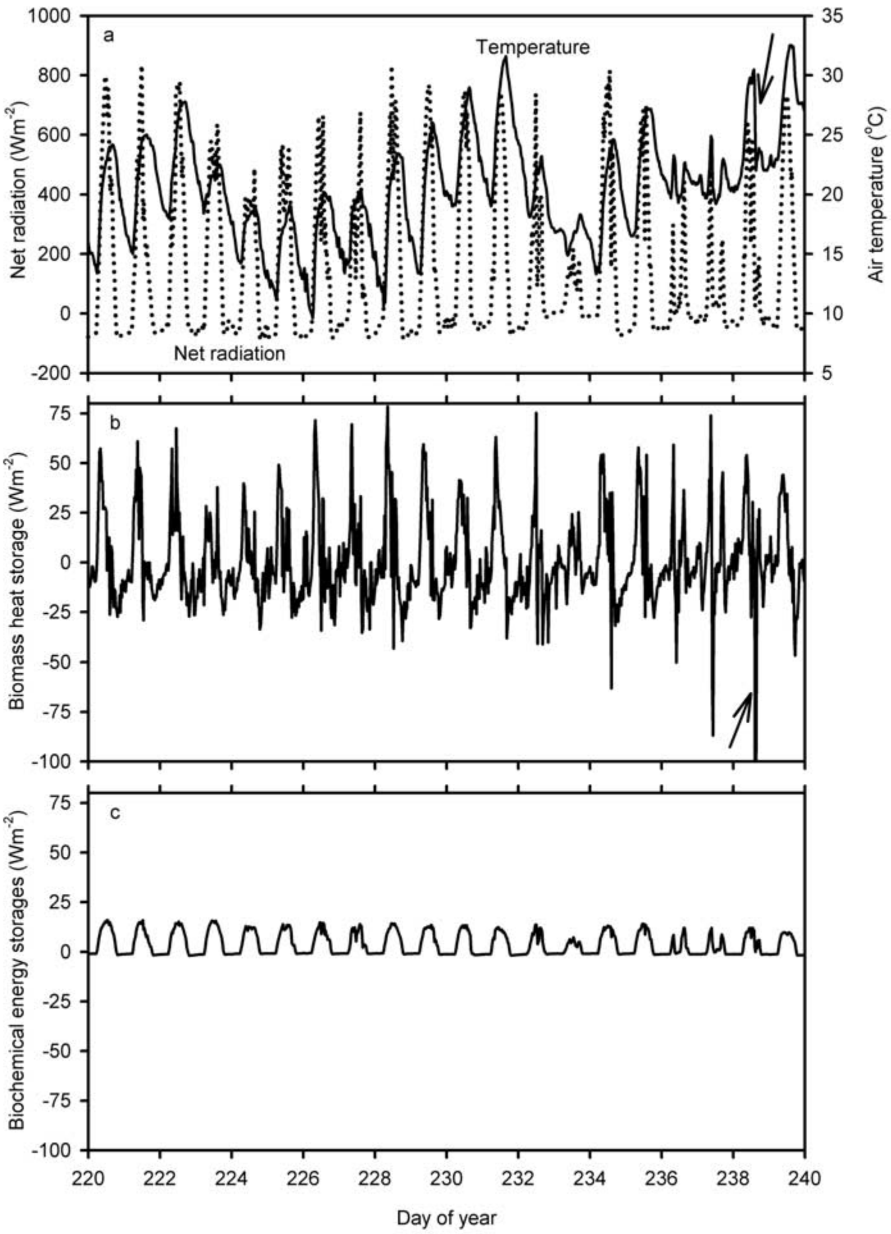

Figure 3. Predicted biomass heat and biochemical energy storages at the Missouri Ozark AmeriFlux site for a sequence of 20 days in the summer of 2004. Also shown are air temperature and net radiation above the canopy. (a) Temperature and net radiation, (b) biomass heat storage, and (c) biochemical energy storage.

biochemical energy storages on land surface fluxes and temperatures.

3.2. Effects of Biomass Energy Storages on Land Surface Model Performance

[13] In the above section, FAPIS performance was examined with representation of biomass energy storages invoked in the model. An interesting question is whether explicit representation of biomass energy storages contributed to FAPIS performance. This question is answered in Table 2, which compares the root mean square errors (RMSE) of FAPIS predictions with and with biomass energy storages. For the predictions of net radiation, outgoing longwave radiation, sensible heat flux, latent heat flux, and surface diurnal radiative temperature range (more details about radiative temperature are given in section 3.5), FAPIS performs better with biomass energy storages invoked (indicated by smaller RMSE). However, the effect on CO_2 flux is minimal.

3.3. Magnitudes and Diurnal Patterns of Biomass Heat and Biochemical Energy Storages

[14] In the summer of 2004, the modeled biomass heat storage typically ranged from -50 to 50 W m^{-2} as shown in Figure 3 for a sequence of 20 days in August. However, at times when there were sudden changes in net radiation or air temperature, the biomass could store heat at a rate over 70 W m^{-2} or release heat at a rate over 100 W m^{-2} for a short period of time. For example, the arrow in Figure 3a points to a sudden drop in air temperature, possibly due to a down draft or a passing front, which resulted in a burst of biomass heat release of over 100 W m^{-2} (the arrow in Figure 3b). With a typical range of -3 to 20 W m^{-2} (Figure 3c), the biochemical energy storage was generally smaller than the biomass heat storage. These estimates were in the ranges of values of biomass heat and biochemical energy storages reported in the literature [*Oke*, 1987; *Potter and Zasada*, 1999].

[15] Averaged over the four months in the study, the biochemical energy storage was about 4.1 ± 0.1 W m^{-2}. As discussed later, this magnitude of energy storage has important implication for long-term climate prediction. Averaging biomass heat storage over a long period of time (>24 hours) is not interesting since biomass heat storage depends only on the enthalpy of the biomass at the beginning and end of a time period; over a long period of time, the averaged biomass heat storage is necessarily small. However, this does not mean that short-term biomass heat storage is not important since it has substantial influence on land surface sensible and latent heat fluxes and temperature on diurnal timescales (see sections 3.4 and 3.5).

[16] Because biomass heat and biochemical energy storages varied substantially, we used a probability-based approach to evaluating their contributions to the surface energy balance. During the whole study period (June–September), the biomass heat storage was more than 20% of the net radiation for about 30% of the time and more than 10% of the net radiation for about 50% of the time (Figure 4a). For about 80% of the time, biomass heat storage and net radiation had the same signs (that is, the cumulative probability for the biomass heat storage as a positive percentage of net radiation is about 80%, as indicated in Figure 4a). That means, when net radiation was positive, the biomass was more likely to store heat; when net radiation was negative, the biomass was more likely to release heat. The cases in which biomass heat storage and net radiation had different signs only occurred infrequently (20%). The biochemical energy storage was a relatively small component of the surface energy budget; it was larger than 10% of the net radiation less than 10% of the time (Figure 4b).

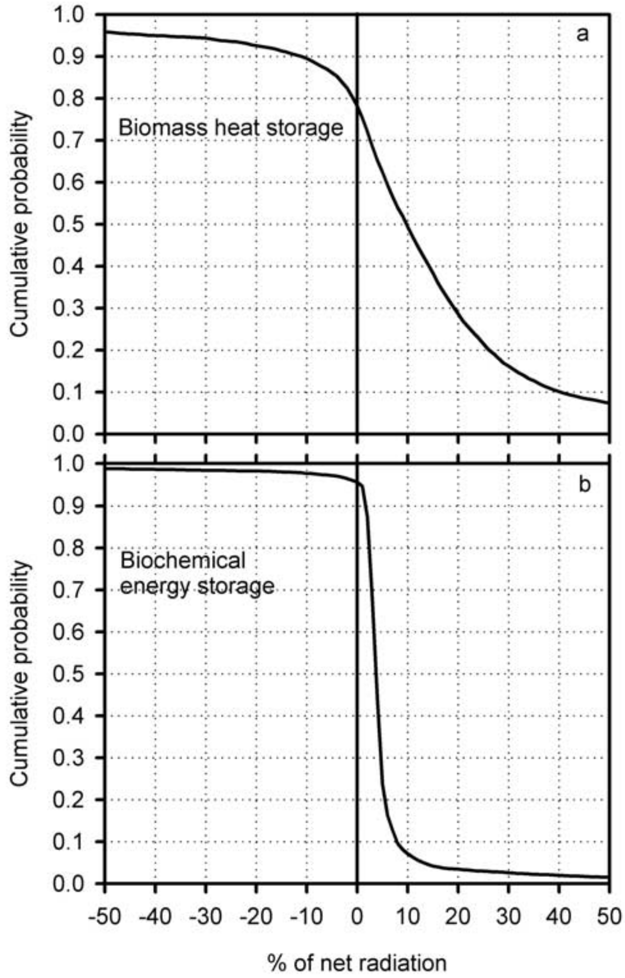

Figure 4. Cumulative probability distributions of (a) biomass heat and (b) biochemical energy storages as percentages of net radiation at the Missouri Ozark AmeriFlux site for the summer of 2004.

[17] Both the biomass heat and biochemical energy storages had clear diurnal patterns which can be seen more easily from the two representative (one clear and one partly cloudy) days shown in Figure 5. The biochemical energy storage tracked the solar radiation available for assimilation of CO_2 and was positive (net storage of energy due to photosynthesis) during the day and negative (net release of energy due to respiration) during the night. The diurnal pattern of the biomass heat storage was more complicated. On clear days when solar radiation changed smoothly with solar elevation angle, the biomass heat storage peaked before noontime and then decreased steadily and turned from accumulating heat energy (positive) to

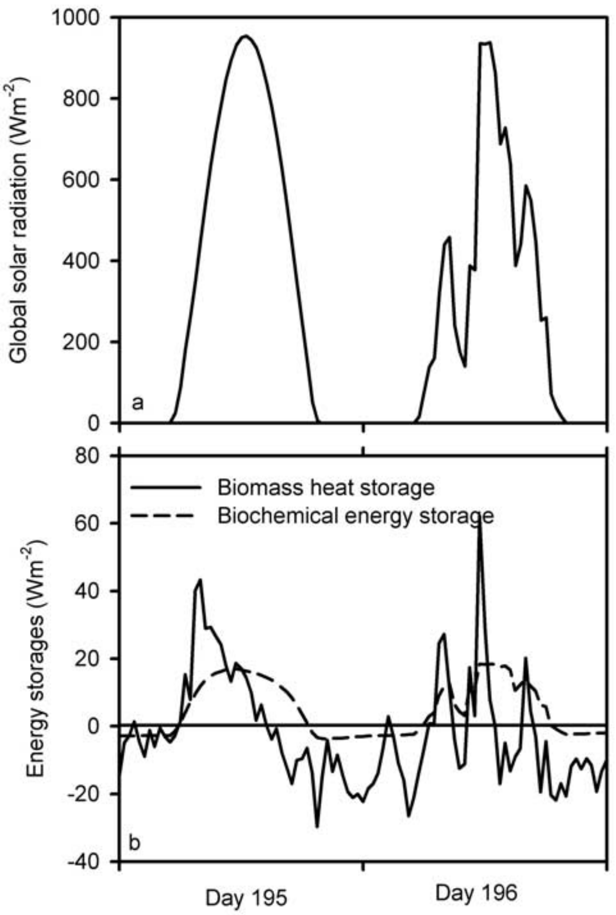

Figure 5. Diurnal patterns of biomass heat and biochemical energy storages for two representative days (one clear and one partly cloudy day). The global solar radiation is used as an indicator of sky conditions. (a) Global solar radiation and (b) biomass energy storages.

releasing heat energy (negative) before sunset. It remained to be negative for most of the time at night. On partly cloudy days, the biomass heat storage fluctuated in response to changes in net radiation and air temperature (Figure 5 and also Figure 3).

3.4. Effects of Biomass Heat and Biochemical Energy Storages on Sensible and Latent Heat Fluxes

[18] FAPIS simulations indicated that biomass heat and biochemical energy storages affected sensible heat flux more than latent heat flux as shown in Figure 6 for a sequence of 20 days in August. The differences between the without-storage and with-storage simulations generally ranged from -25 to 50 W m^{-2} and -10 to 20 W m^{-2} for the predicted sensible and latent heat fluxes, respectively. For the four months simulated, we found that ignoring the two energy storage terms led to overprediction of sensible heat flux by more than 20% at 50% of the time and by more than 10% at 70% of the time while for 10% of the time, sensible heat flux was underpredicted by more than 20% (Figure 7a). For the same four months simulated, the effect of ignoring the energy storage terms on latent heat flux (Figure 7b) was that about 8% of the time, latent heat flux was overestimated by more than 20% and about 12% of the time, latent heat flux was underestimated by more than 10%.

[19] Just as biomass heat and biochemical energy storage terms had diurnal cycles, the differences in sensible and latent heat fluxes between the two FAPIS simulations with and without the storage terms also had diurnal variations as shown for the two representative days in Figure 8. On clear days, ignoring biomass heat and biochemical energy storages generally led to overestimation of both sensible and latent heat fluxes during daytime, particularly in the morning while on partly cloudy days the patterns were more variable but were mostly indicative of overestimation. At night, sensible and latent heat fluxes tended to be underestimated when the two energy storage terms were forced to be zero. Note that at night, sensible heat flux and latent heat flux tended to be negative because of temperature inversion and dew formation (data not shown, but implied in Figures 1c and 1d); therefore underestimation means that sensible heat and latent heat fluxes became more negative but larger in magnitude at night.

3.5. Effects of Biomass Heat and Biochemical Energy Storages on Surface Radiative Temperature

[20] To examine how biomass heat and biochemical energy storages affected land surface temperature regimes, we determined the surface radiative temperature (skin temperature) from the predicted outgoing longwave radiation. FAPIS is a multilayer model and does not have a single canopy biomass or canopy air space temperature. Therefore we used the surface radiative temperature as a diagnostic indicator of surface temperature conditions. In computing the surface radiative temperature, we used the Stefan-Boltzmann law and assumed the surface was a blackbody. This blackbody assumption was needed because determining the overall emissivity over a forest canopy is difficult even though the emissivities of single leaves and soil are known. However, we note that under the blackbody assumption, the actual surface radiative temperature may be underestimated.

[21] Ignoring biomass heat and biochemical energy storages led to errors in surface radiative temperature and the errors had diurnal patterns (Figure 9). In general, when biomass heat and biochemical energy storages were neglected, daytime temperature was overestimated and nighttime temperature was underestimated with the net effect of overestimation of diurnal temperature range (defined here as the difference between the maximum daytime and minimum nighttime surface radiative temperatures) (Figure 10). Averaged over the four months simulated in the study, the overestimation of the diurnal temperature range was about 0.5°C if the two energy storages were forced to zero in FAPIS.

4. Conclusion and Discussion

[22] Biomass heat and biochemical energy storages are an integral and substantial part of the surface energy budget at this Missouri Ozark forest site. During much of the daytime, they compete with sensible heat and latent heat transfers for partitioning net available energy; during the rest of the diurnal cycle, however, they serve as a source of energy

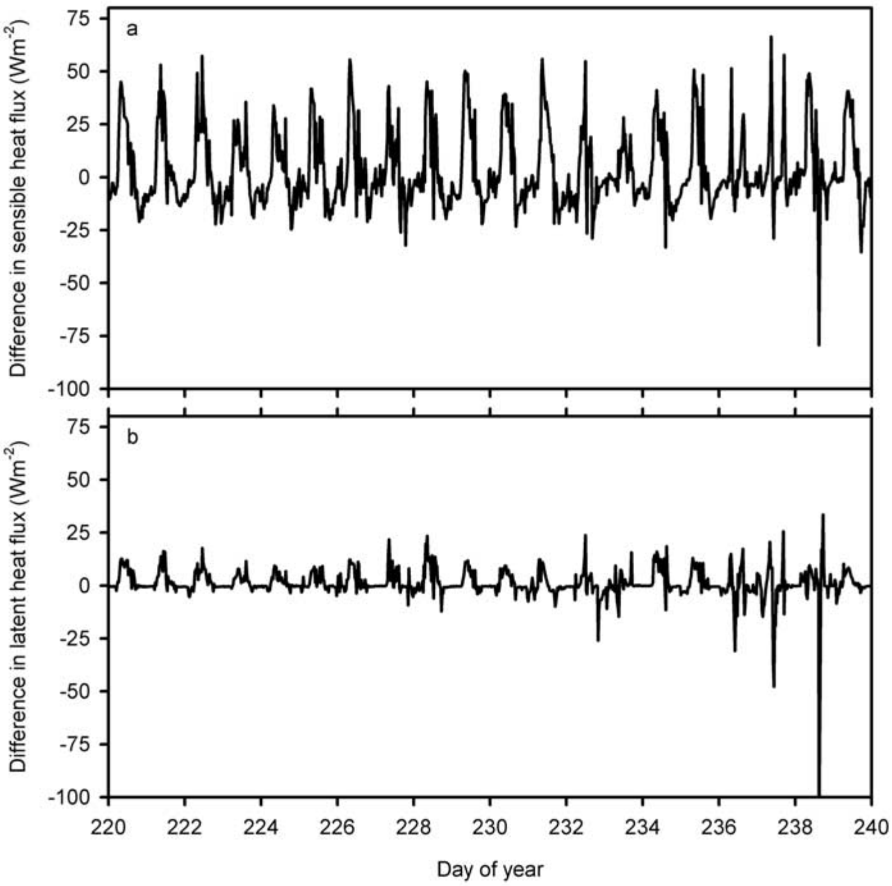

Figure 6. Differences in the predicted (a) sensible and (b) latent heat fluxes between the FAPIS simulation without the energy storage terms and the one with the energy storage terms for a sequence of 20 days in the summer of 2004.

for sensible heat and latent heat transfers. Although averaged over a long time period (24 hours or more), biomass heat storage is negligible, this term is time–biased. In the morning as the Sun rises and heats up the biomass, biomass temperature increases and vegetation stores heat energy. When the surface temperature reaches its peak and starts to decrease in the afternoon, vegetation, in turn, releases heat. At night, biomass temperature generally continues to decrease because of radiative cooling and there is a continuous biomass heat release unless the incoming sky thermal radiation exceeds the outgoing terrestrial thermal radiation. Therefore biomass heat storage has strong diurnal cycles. Our MOFLUX site is located in the transition zone between the eastern deciduous forest and the central grassland region and has less biomass compared with forests in more mesic areas. Even at this site, biomass heat storage has a typical diurnal range of -50 to 50 W m^{-2}. For sites with higher biomass stocks, this range could be even larger. Because of its magnitude and strong diurnal patterns, biomass heat storage could affect boundary layer development and other atmospheric processes through its influence on sensible heat and latent heat fluxes. Thus, for weather forecasts, numerical weather prediction models should include biomass heat storage modeling.

[23] Biochemical energy storage has both diurnal and seasonal cycles which are associated with diurnal and seasonal variations of ecosystem photosynthesis and respiration. Unlike biomass heat storage, biochemical energy storage does not sum to zero over extended periods as long as the ecosystem is not carbon neutral. Currently, the terrestrial biosphere is believed to be a carbon sink [e.g., *Schimel et al.*, 2001]. If that is the case, then the terrestrial biosphere should be an energy sink also. *Baldocchi et al.* [2001] reported that for a variety of broadleaf forests, the annual carbon uptake ranged from 100 to 700 g C m^{-2} yr^{-1}, which corresponds to annual net biochemical energy storage of 0.1 to 1 W m^{-2}. Averaged over the simulation period (four summer months) in our study, the biochemical energy storage is about 4.1 $\pm$ 0.1 W m^{-2} (we have not estimated the annual biochemical energy storage at the MOFLUX site). For comparison, the radiative forcing of greenhouse gases (CO_2, CH_4, N_2O, and halocarbons together) is about 2.43 W m^{-2} above the preindustrial level [*IPCC*, 2001]; this value could be smaller in the current atmosphere since some of the earlier imbalance presumably has already warmed the climate system. Thus at least at regional scales, biochemical energy storage is on the same order of magnitude as the radiative forcing of atmospheric greenhouse gases. Therefore, for long-term climate system modeling which includes vegetation processes, biochemical energy storage could be important, particularly at regional scales.

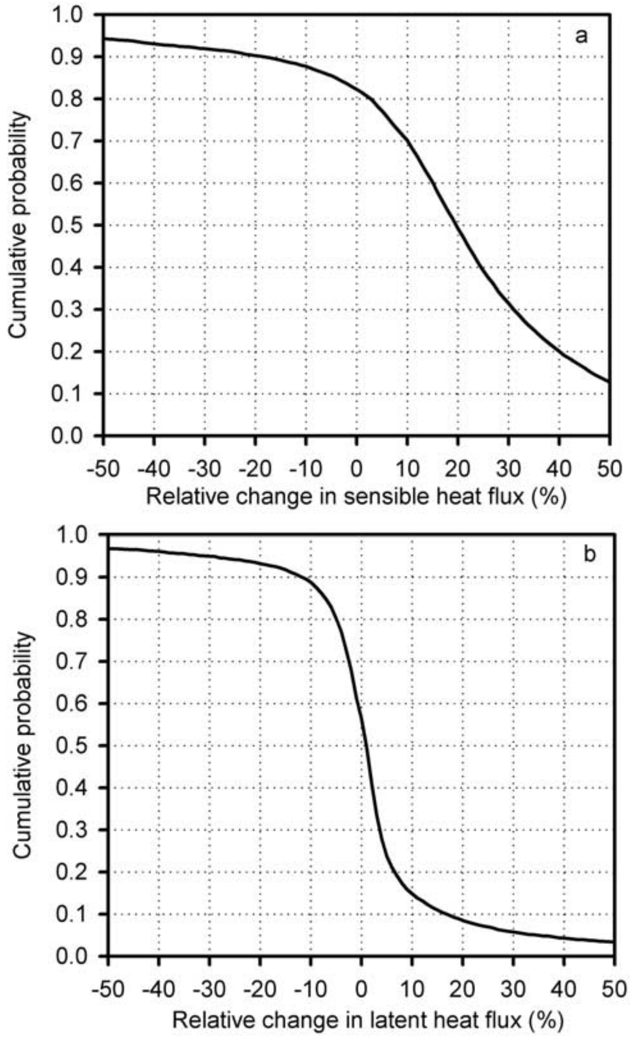

Figure 7. Cumulative probability distributions of the changes in (a) sensible and (b) latent heat fluxes predicted without the energy storage terms relative to the simulation with the storage terms for the summer of 2004.

[24] The diurnal temperature range (DTR) on land has been decreasing since the middle of the 20th century [*Easterling et al.*, 1997]. The cause of this trend is not completely understood even though there have been many studies on this topic [e.g., *Hansen et al.*, 1995; *Dai et al.*, 1999]. *Collatz et al.* [2000] suggested that changes in vegetation cover may have contributed to this trend through controls on latent heat flux and atmospheric stabilities and feedbacks on atmospheric processes. We suggest that changes in biomass heat and biochemical energy storages may be another mechanism for vegetation to influence DTR. Biomass heat and biochemical energy storages act to reduce daytime surface temperature and increase nighttime temperature, thus leading to decreased DTR. Globally, vegetation productivity has been increasing [*Myneni et al.*, 1997; *Boisvenue and Running*, 2006] and therefore should contribute to dampening DTR. We emphasize that our estimate of influences of biomass heat and biochemical energy storages on DTR (0.5°C) is conservative because we did not consider the feedback from changes in biomass temperature on the atmospheric forcing temperature. If this feedback is considered, the effect of biomass heat and biochemical energy storages on DTR might be even larger.

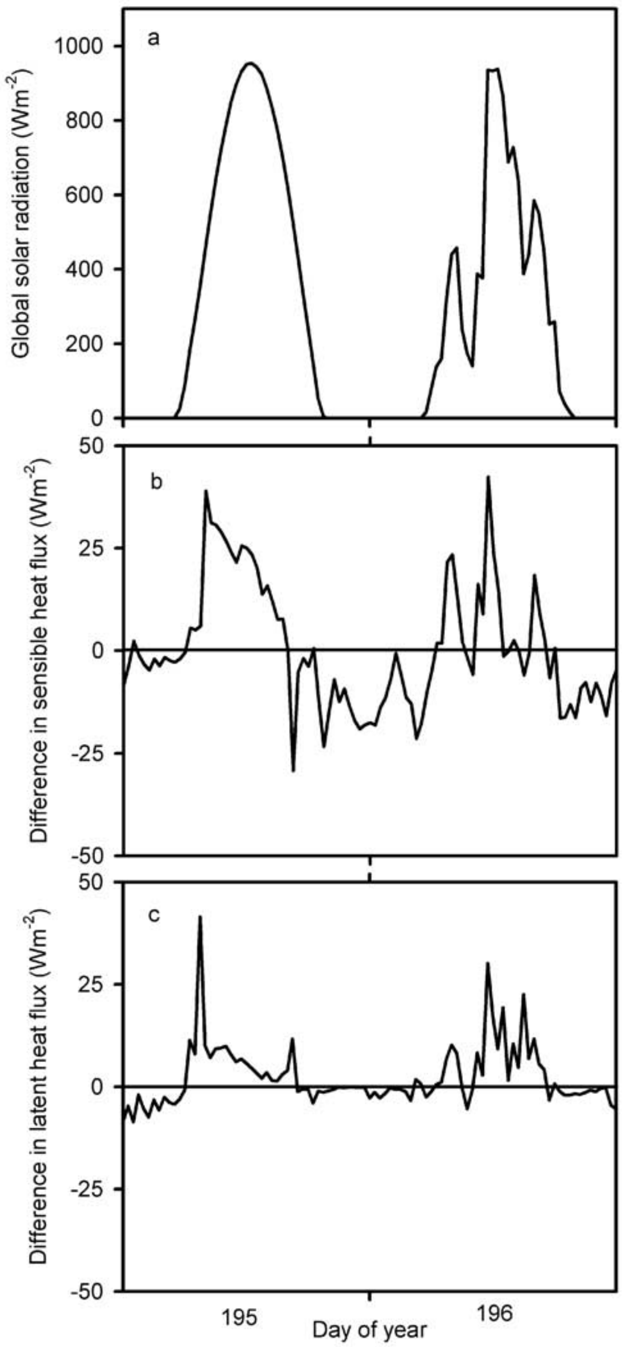

Figure 8. Diurnal patterns of the differences in the predicted sensible and latent heat fluxes between the FAPIS simulation without the energy storage terms and the one with the energy storage terms for two representative days (one clear and one partly cloudy day). The global solar radiation is used as an indicator of sky conditions. (a) Global solar radiation, (b) difference in predicted sensible heat fluxes, and (c) difference in predicted latent heat fluxes.

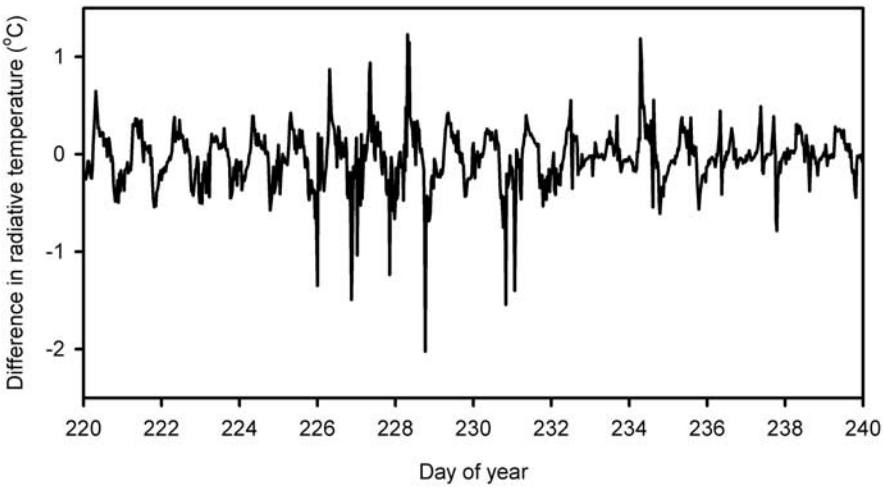

Figure 9. Difference in the predicted radiative temperature above the canopy between the without-storage and with-storage simulation for a window of 20 days in August of 2004.

[25] Finally, biomass distribution is spatially heterogeneous, which means that biomass heat and biochemical energy storages must be also spatially heterogeneous. This heterogeneity is in essence a form of gradient radiative forcing [*Matsui and Pielke*, 2006]. In conjunction with spatial variations in evapotranspiration, albedo, and surface roughness associated with vegetation cover, it can influence horizontal pressure gradients and mesoscale atmospheric circulations and therefore regional climates. More studies are needed in this area.

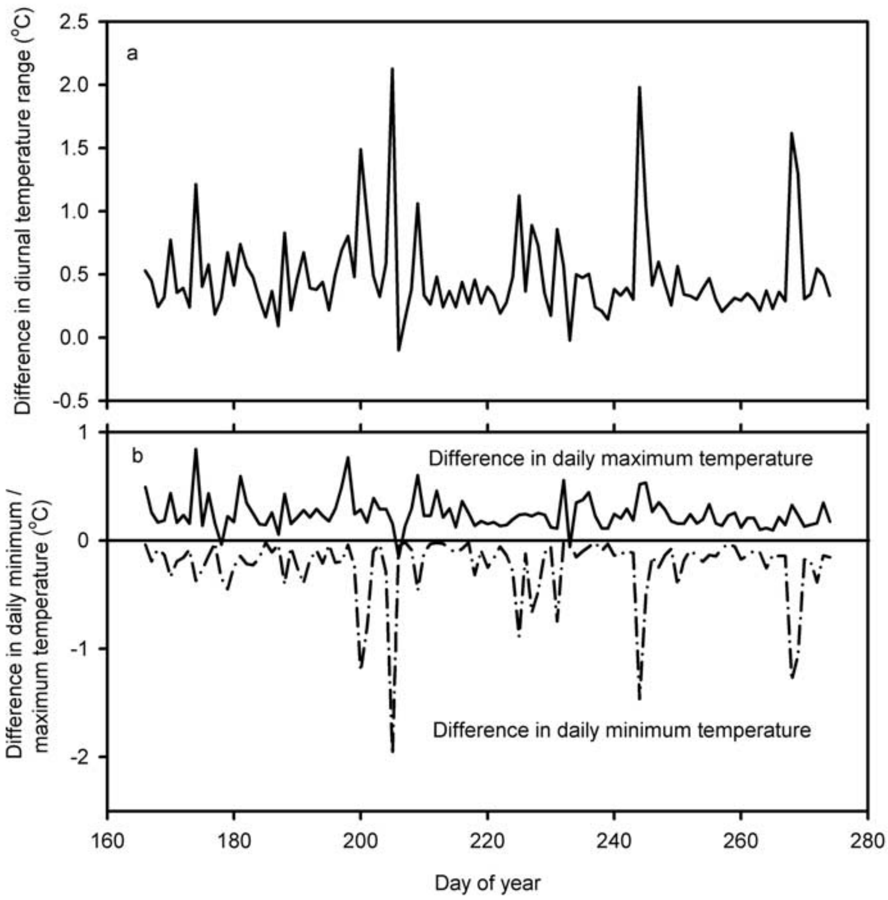

Figure 10. Differences in the (a) predicted diurnal temperature range and (b) maximum and minimum surface radiative temperature between the without-storage and with-storage simulation for the summer of 2004.

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