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Sensitivity of ground heat flux to vegetation cover fraction and leaf area index

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Abstract. Two land-surface models that participated in the recent Project for Intercomparison of Land-Surface Parameterization Schemes (PILPS, phase 2c) are used to investigate the sensitivity of the ground heat flux to the vegetation cover fraction and leaf area index (LAI). The two models are the Biosphere-Atmosphere Transfer Scheme (BATS) and the model developed at the Institute of Atmospheric Physics, Chinese Academy of Sciences (IAP94). The impacts of including transmission of solar radiation through the canopy in the BATS model are also assessed. The ground heat flux is the energy residual of net radiation minus latent plus sensible heat fluxes at the soil surface (also referred to as the soil heat flux). However, the energy residual above the canopy was used as a surrogate for the ground heat flux by the two models in the PILPS 2c study. The two energy residuals (i.e., above the canopy and at the soil surface) can differ depending on the modeled time step, the order in which the canopy and soil temperatures are computed, and whether canopy heat storage is included or neglected. As expected, reducing the areal coverage of vegetation results in an increased daytime soil heat flux, and increasing LAI leads to decreased soil heat flux and greater above-canopy latent heat flux. Both models show a strong sensitivity to LAI when LAI is small and little sensitivity when LAI is large. Allowing transmission of solar radiation through the canopy in BATS reduces the sensible heat flux above the canopy and enhances all the flux terms at the soil surface, especially when LAI is low. This model behavior is similar to that from IAP94, which uses a two-stream radiation scheme. This modification to BATS also results in a soil heat flux that lies within estimated bounds for a wide range of LAI (0.5–5.5).

1. Introduction

The ground heat flux (G) is an important component of the surface energy budget [cf. *Sellers*, 1965; *Arya*, 1988]. The land surface parameterizations used in atmospheric models must parameterize G to calculate the surface temperature and to partition net radiation into latent and sensible heat fluxes, while observational estimates of regional evaporation from land surfaces require an accurate G [*Choudhury et al.*, 1987].

Recent studies by the Project for Intercomparison of Land-Surface Parameterization Schemes (PILPS), [*Henderson-Sellers et al.*, 1993] showed that there is a wide range of variability in both the diurnal amplitude and the phase of the modeled ground heat flux among the 16 participating land-surface schemes [*Liang et al.*, 1998]. This occurred despite the fact that all the models used the same (10 years of) surface meteorological and radiative forcing data, and all specified the same vegetation type and soil characteristics from the Red-Arkansas River basin in the southern Great Plains of the United States. The factors causing this variability include soil thermal properties (conductivity and heat capacity) [*Peters-Lidard et al.*, 1998] and soil model formulation (e.g., force-restore versus explicit heat diffusion equation) [*Viterbo and Beljaars*, 1995; *Liang et al.*, 1999]. Our paper focuses only on the effect of vegetation, expressed via fractional cover and leaf area index (LAI). It involves studies using two of the participating models and the forcing data used in PILPS phase 2c [*Wood et al.*, 1998].

2. Background

This section defines what G is and how it relates, analytically, to the soil surface temperature under conditions of a bare soil surface and a sinusoidal diurnal forcing. The section then reviews the parameterizations of G in land-surface models and discusses the procedures for measuring it.

In general, the ground heat flux is the substratum heat flux into either ground or water, but it is generally referred to as the soil heat flux for land surfaces. It is the energy

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transferred into the underlying surface through conductance, and it is given by

$$G = -\lambda \left(\frac{\partial T}{\partial z} \right)_{z=0}, \qquad (1a)$$

where λ is the soil thermal conductivity, T is soil temperature, and z is soil depth (positive upward). At the surface, G must be balanced by the residual of net radiation minus latent and sensible heat fluxes, that is,

$$G = R_{ng} - LE_g - H_g, \qquad (1b)$$

where R_{ng}, LE_g, and H_g are net radiation and latent and sensible heat fluxes at the surface, respectively.

A simple analysis of the propagation of thermal waves in homogeneous soils can provide much insight. Suppose the surface temperature is assumed to be a sinusoidal function of time

$$T_s = T_m + A_s \sin\left[(2\pi/P)(t - t_m)\right], \qquad (2)$$

where T_m is the mean surface temperature, A_s and P are the amplitude and period of the surface temperature wave, and t_m is the time when $T_s = T_m$. The Fourier's equation of heat conduction can be solved for T and then this solution substituted into (1) to give the ground heat flux as [*Sellers*, 1965]

$$G = \left(2\pi \frac{\rho c \lambda}{P} \right)^{1/2} A_s \sin\left[\left(\frac{2\pi}{P} \right) (t - t_m) + \frac{\pi}{4} \right], \qquad (3)$$

where ρ and c are the soil mass density and specific heat. Equation (3) shows that in this simple case, the peak value of G should lead the peak value of T_s by 3 hours. Equation (3) also shows that the amplitude of G is proportional to the square root of the product of heat capacity and thermal conductivity and that it is inversely proportional to the square root of the period of the surface temperature wave. The amplitude of G is also proportional to A_s.

The above formulation of G (equation (3)) is not used in land-surface models because the surface temperature itself is to be solved and because the surface temperature wave is not exactly sinusoidal. Nevertheless, equation (3) could apply to both bare soil and canopy-covered soil surfaces. *A priori*, the case could be made that vegetation damps and possibly shifts the temperature wave (equation (2)). Therefore the amplitude of G under the canopy is likely to be substantially reduced and its phase to be different compared to that over bare soil, leading to a theoretical basis for the model results in section 5 as explained by (3).

Land-surface models seek to provide simulations of G in realistic situations in which the surface may be barren or vegetation-covered or both. Generally speaking, two types of parameterizations of G are used. The first empirically relates G to LAI and net radiation [e.g., *Huang and Lyons*, 1995]. This type of model generally assumes a single temperature for both the canopy and the soil beneath the canopy. In the second approach, G is either computed directly from the temperature at the soil surface and that at some depth close to the surface [e.g., *Viterbo and Beljaars*, 1995; *Bonan*, 1996], or G is calculated as the residual between net radiation minus sensible and latent heat flux [e.g., *Dickinson et al.*, 1993]. In this second approach, models assume separate temperatures for the canopy and the soil beneath the canopy, and these two temperatures are either solved simultaneously [e.g., *Dai and Zeng*, 1997] or calculated in sequence, for instance, first the canopy then the soil [e.g., *Dickinson et al.*, 1993].

One approach to model validation might be to compare simulated to measured G, but this measurement is not an easy task. At the soil surface, G cannot be reliably measured because of the large temperature gradient and because usually the soil heat flux at some level (say, 5 cm) below the soil surface is measured using soil heat flux plates. This measurement, together with an estimate of the change in stored energy above this level, can be used to estimate G. When vegetation is present, the measurement of G is more problematic because it is difficult to obtain adequate samplings for shaded and nonshaded surface. Despite this, such measurements were unfortunately not available with the PILPS 2c data. Therefore this paper is deemed to be a sensitivity study, and the modeled results are compared only with the empirical estimates.

3. Model Descriptions

The land-surface models used in this study are the Biosphere-Atmosphere Transfer Scheme (BATS) [*Dickinson et al.*, 1993] and the scheme developed at the Institute of Atmospheric Physics, Chinese Academy of Sciences (IAP94) [*Dai and Zeng*, 1997]. Both schemes were among the 16 models participating in the PILPS 2c study [*Liang et al.*, 1998], and both use the energy residual of net radiation minus latent and sensible heat fluxes above the canopy as a surrogate for the ground heat flux, which itself is not an output variable in the two models. The PILPS 2c analyses [*Liang et al.*, 1998] showed the two models had features which did not appear in the other models involved in that intercomparison. BATS and IAP94, for example, simulate the peak daytime values of G to occur after noon, later than most of the other models, and the calculated midday value of G given by IAP94 was the largest of all the models compared.

How close the energy residual above the canopy is to the ground heat flux needs to be considered. In addition, several aspects of the two models are parameterized differently, and these can influence the phase and amplitude of G. First, the computation of radiation transfer in the two models is different. In BATS the albedo is prescribed for each vegetation class, and solar radiation is absorbed and reflected, but direct transmission to the soil is neglected. In IAP94, radiation transfer is simulated using the two-stream model [*Dickinson*, 1983; *Sellers*, 1985; *Sellers et al.*, 1996; *Bonan*, 1996] to compute the total albedo of the vegetated surface and to calculate the amount and kind of radiation absorbed by different parts of the canopy and the soil surface.

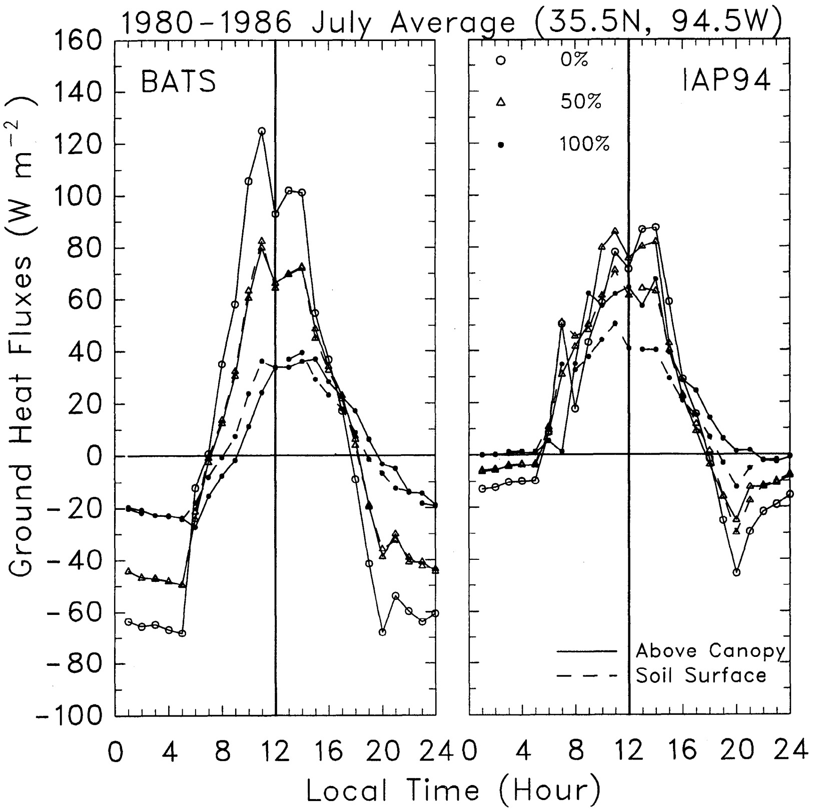

Figure 1. July mean diurnal variations of the energy residuals (of net radiation minus latent and sensible heat fluxes) above the canopy and at the soil surface at a 1° × 1° grid box centered at 35.5°N, 94.5°W (grid A, July leaf area index (LAI) = 5.3). Results are shown for the Biosphere-Atmosphere Transfer Scheme (BATS) and the Institute of Atmospheric Physics, Chinese Academy of Sciences (IAP94) with sensitivity to different values of the vegetation cover fraction.

Second, BATS assumes zero heat storage in the vegetation layer, while IAP94 allows a storage that depends on LAI, similar to the treatment by *Sellers et al.* [1996]. Third, the order in which canopy and soil temperatures are computed is different, as previously mentioned. This third feature may significantly affect the phase of the modeled ground heat flux if the model time step is too large.

4. Methodology

To ease comparison with the results of *Liang et al.* [1998], BATS and IAP94 were both run in off-line mode with the same hourly meteorological data for the period 1979–1988 using the same parameter values. Thus the models were run for 10 years with a time step of 1 hour, but the present analysis is of the period 1980–1986. Following *Liang et al.* [1998], two grid boxes were chosen in this study: the first (grid A) with cultivated crops as the prescribed land cover type with the LAI = 5.3 in July, and the second (grid B) with wooded C_4 grassland with the LAI = 1.3 in July as the prescribed land cover.

As previously mentioned, the ground heat flux used in the PILPS 2c [*Liang et al.*, 1998] study for both BATS and IAP94 is actually the energy residual of net radiation minus sensible and latent heat fluxes above the canopy. To investigate whether this residual can be used as a surrogate for the ground heat flux, we examined the residual terms both above the canopy (G_t) and at the soil surface (G_g).

In both models, two parameters are used to describe the proportion of the ground that is covered by vegetation, namely, the vegetation cover fraction σ_f, which varies from zero (no vegetation cover) to 1 (full vegetation cover), and the LAI, defined as the one-sided transpiring surface area of vegetation per unit area of ground. We first examine how the two models respond to changes in vegetation cover and then explore the sensitivity of the models to changes in the July value of LAI.

5. Results

5.1. Response to Changes in Vegetation Cover Fraction

Figure 1 shows the 7-year (1980–1986) July average ground heat fluxes plotted as a function of local time for BATS and IAP94 for grid A. Both models show that the ground heat flux (regardless of G_t and G_g) decreases as the vegetation cover fraction increases. This feature may be explained by (3). As the vegetation cover fraction increases, the vegetation damps the solar energy received at the surface, thereby reducing the amplitude of the temperature wave, which, in turn, reduces the amplitude of the

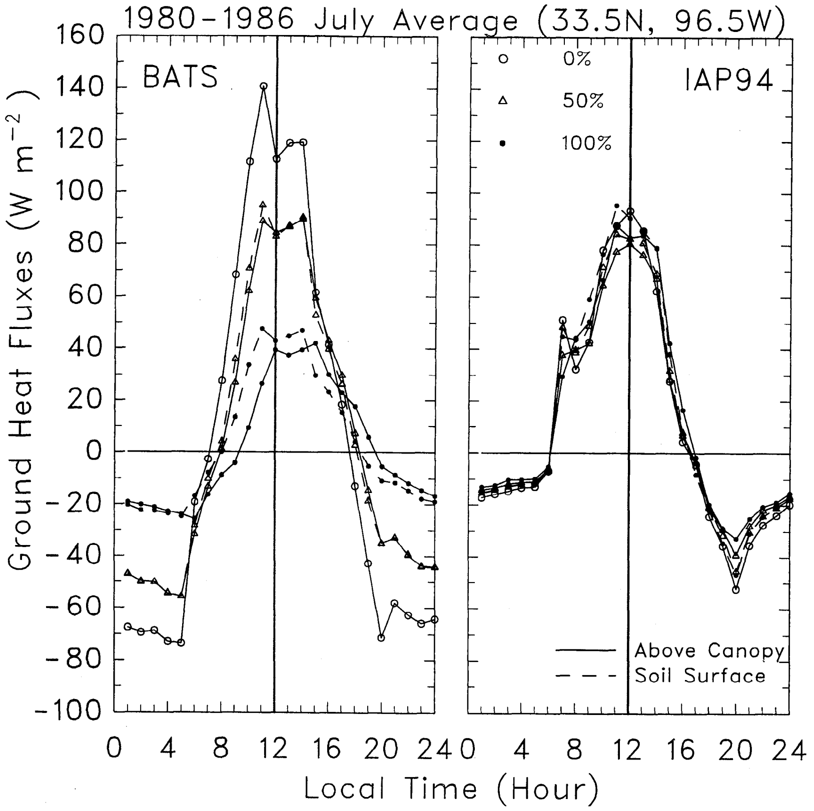

Figure 2. As Figure 1 but for a 1° × 1° grid box centered at 33.5°N, 96.5°W (grid B, July LAI = 1.3).

ground heat flux. The phase of the temperature wave is also shifted (toward noon in BATS) because of the presence of vegetation, thus the phase of the ground heat flux is shifted (toward noon in BATS).

As shown in Figure 1, G_t and G_g can be different. When the ground is fully covered by vegetation (i.e., the vegetation cover fraction $\sigma_f = 1$), there is a slight difference between G_g and G_t in the case of BATS; that is, G_g peaks slightly earlier than G_t, but both have similar magnitude. The requirement of zero canopy heat storage implies that both should be identical because the canopy heat storage is assumed to be zero. The small difference between the two results from the order in which the canopy and soil temperatures are computed, and the difference is expected to be further reduced if a smaller time step is used (say, 20 min, as commonly used in the atmospheric models). For IAP94 the heat storage in the canopy layer leads to the midday G_g being smaller than G_t by up to 30 W m^{-2}. As σ_f decreases, the differences in G_g and G_t in BATS become smaller, and the peak ground heat fluxes shift to before noon. IAP94 shows less sensitivity than BATS to the changes in σ_f. For the much lower LAI of grid B, results are similar (Figure 2). However, for IAP94 the differences between G_g and G_t are much smaller than in grid A because of the smaller value of LAI in July in grid B.

5.2. Response to Changes in Leaf Area Index

To investigate the effect of LAI on G, σ_f was fixed at unity. A series of experiments was carried out in which

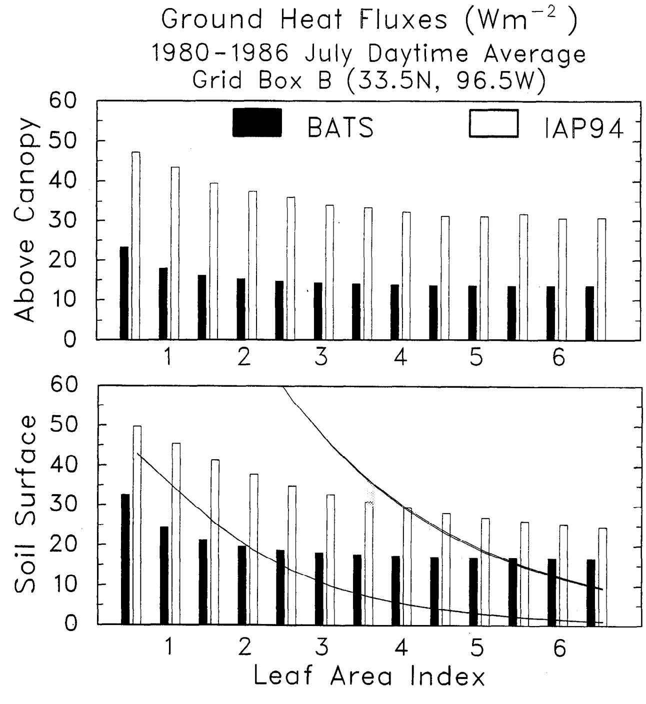

Figure 3. July mean daytime averages of the energy residuals (of net radiation minus latent and sensible heat fluxes) above the canopy and at the soil surface at a 1° × 1° grid box centered at 33.5°N, 96.5°W (grid B, July LAI = 1.3). Results are shown for BATS and IAP94. The curves are calculated using the range estimated by *Choudhury et al.* [1987]. The abscissa labels indicate the values of LAI used in the simulations for July.

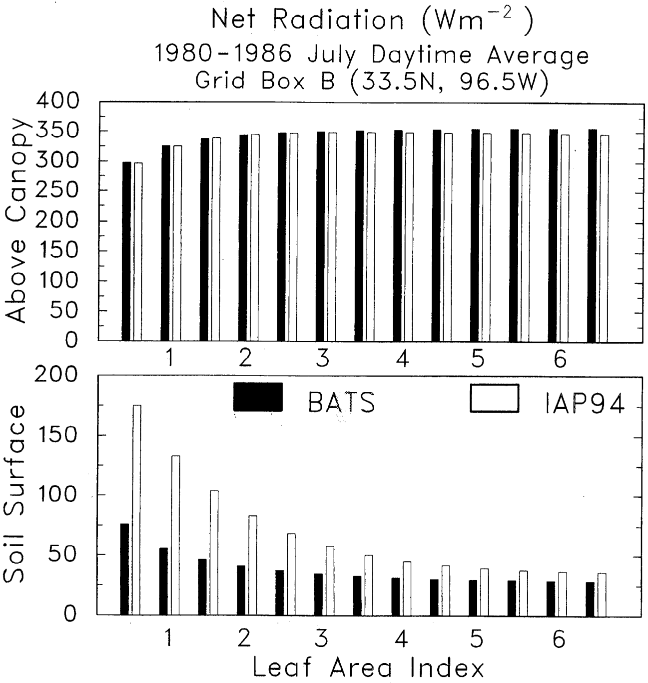

Figure 4. July mean daytime averages of net radiation above the canopy and at the soil surface at a 1° × 1° grid box centered at 33.5°N, 96.5°W (grid B, July LAI = 1.3). Results are shown for BATS and IAP94. The abscissa labels indicate the values of LAI used in the simulations for July.

the July value of LAI was prescribed to vary between 0.5 and 6.5. Figure 3 shows the 7-year (1980–1986) daytime average ground heat fluxes G_g and G_t for July plotted as a function of LAI for BATS and IAP94 for grid B. Both G_t and G_g are greater for IAP94 than their counterparts for BATS, but for different reasons. The larger value for G_t with IAP94 results from the inclusion of heat storage in the vegetation, while the larger G_g in IAP94 results from use of the two-stream radiation transfer model, which allows radiation to penetrate to the ground. Figure 4 shows that the modeled net radiation at the soil surface is larger in IAP94 than in BATS, while the net radiation above the canopy is approximately the same in the two models.

To put these simulations of G_g into perspective, Figure 3 includes the curves that give the estimated lower and upper bounds, these being given by

$$0.2\exp(-0.65\ \mathrm{LAI})R_t \leq G_g \leq 0.5\exp(-0.45\ \mathrm{LAI})R_t, \tag{4}$$

where R_t is the net radiation above the canopy. Equation (4) is an empirical relation suggested by *Choudhury et al.* [1987] and is based on data collected for growing wheat, with LAI varying from zero (i.e., the bare soil) to 4.7; but it is plausible that it also applies at higher LAI. The likely range of G_g for both models is plotted in Figure 3, using R_t computed from BATS and IAP94.

For a range of LAI (from 2 to 5.5) the BATS simulations of G_g are within estimated bounds, but BATS underestimates relative to the lower bound when the LAI is less than 1.5 and overestimates relative to the upper bound when the LAI is equal to or greater than 6. For IAP94 the simulations are within the bounds for LAI less than 4, but the model overestimates for LAI > 4. At high LAI the G_g is driven largely by canopy thermal radiation, which may be overestimated by a one-layer canopy model. Sunlit leaves (i.e., the topmost part of the canopy) intercept more solar radiation and are warmer than the canopy mean, while the bottom part of the canopy in the shade receives less solar radiation and is cooler, hence emitting less thermal radiation to the soil. On the other hand, BATS would be expected to underestimate G_g for a small LAI because it neglects solar radiation transfer through the canopy layer when computing both the canopy and the soil temperatures.

5.3. Impacts of Inclusion of Transmission of Solar Radiation in BATS

To illustrate how transmission of solar radiation through the canopy can affect G_g, a simple correction was introduced into the standard version of BATS. From Beer's law the ratio of the transmitted solar radiation below the canopy to the downwelling solar radiation at the top of the canopy f_t is

$$f_t = \exp\ (-0.5\ \mathrm{SLAI}/0.6), \tag{5}$$

where SLAI is the sum of stem and leaf area index, 0.5 is assumed for the average leaf cross section per unit SLAI, and 0.6 is assumed for the average cosine of solar zenith angle (allowing for both direct and diffuse solar radiation). Once the transmitted energy is included, both the canopy and the ground energy balance equations are modified. Figure 5 shows this modification leads to a substantial increase in R_{ng}, G_g, H_g, and LE_g, especially when LAI is low. The simulated G_g in this modified run exhibits a well-defined exponential decay as LAI increases and for LAI less than 6, G_g value lies within the lower and upper estimates given by the *Choudhury et al.* [1987] formula. In contrast, the original BATS-simulated values of G_g are only weakly sensitive to LAI and fall below the lower bound for small values of LAI. The original BATS produces negative H_g (i.e., pointing downward toward the ground) for LAI from 1 to 6.5, whereas the modified BATS predicts positive H_g (i.e., pointing upward) for LAI from 0.5 to 2.5.

The above-canopy sensible heat fluxes for small values of LAI are significantly reduced by the modification (Figure 6) consistent with less solar energy available for warming the canopy. However, the above-canopy latent heat fluxes show little sensitivity to this modification (Figure 6), suggesting that evaporation is in this case not energy limited.

The soil surface and subsurface temperatures (Figure 7) change following the changes in the energy budget. The July daytime average soil surface temperature with LAI = 0.5 increases by more than 16 K as a result of solar radiation penetration. The soil becomes drier because of the greater evaporation and increase of solar radiation incident on it. There is less energy available to warm the vegetation. Thus the canopy temperature, and hence the effective skin tem-

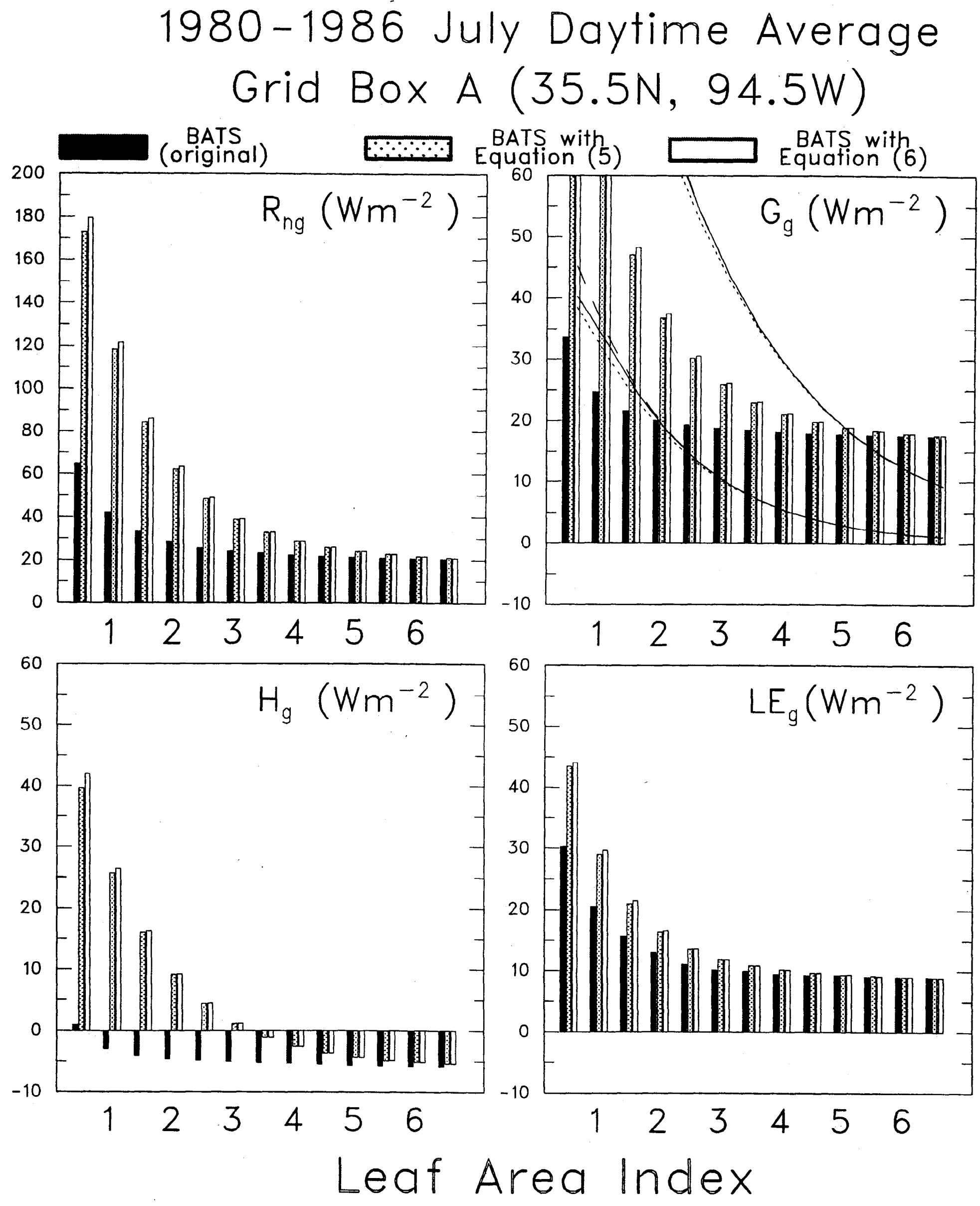

Figure 5. July mean daytime averages of net radiation (R_{ng}), ground heat flux (G_g), sensible heat flux (H_g), and latent heat flux (LE_g) at a 1° × 1° grid box centered at 35.5°N, 94.5°W (grid A, July LAI = 5.3). Results are shown for the original BATS, the BATS modified with (5), and the BATS modified with equations (6a) and (6b). All variables are defined at the ground surface (i.e., beneath the canopy), in watts per square meter (W m^{-2}). The curves are calculated using the range estimated by *Choudhury et al.* [1987], where the solid line is for the original BATS, the dotted line for BATS with equation (5), and the dashed line for BATS with equation (6). The abscissa labels indicate the values of LAI used in the simulations for July.

perature, is significantly reduced for lower values of LAI. It should be pointed out that these results are obtained assuming a 100% vegetation cover. In real applications, small values of LAI correspond to small values of vegetation cover. Therefore, the difference in soil surface temperatures noted here is likely to be reduced in real applications.

On the basis of the two-stream concept [*Dickinson*, 1983], *R. E. Dickinson* [*personal communication*, 1998] postulated that the effective vegetation albedo varies between values for a full canopy surface and a ground surface. Approximately, this can be formulated as follows:

$$\begin{aligned}\alpha_\lambda &= \alpha_{c,\lambda}\left[1-\exp\left(-\frac{\omega_\lambda\,\beta_0\ \mathrm{SLAI}}{\mu\alpha_{c,\lambda}}\right)\right]\\ &\quad+\alpha_{g,\lambda}\ \exp\left[-\left(1+\frac{0.5}{\mu}\right)\mathrm{SLAI}\right], \qquad (6a)\end{aligned}$$

where $\alpha_{c,\lambda}$ is full canopy albedo, i.e., when LAI approaches infinity. The values of $\alpha_{c,\lambda}$ are taken to be the same as prescribed in previous runs. SLAI is the sum of stem and leaf area index. Because stem area index is here assumed to be a small constant ($\approx$ 0.2), the above formulation is essentially a function of LAI. Value λ is wavelength for

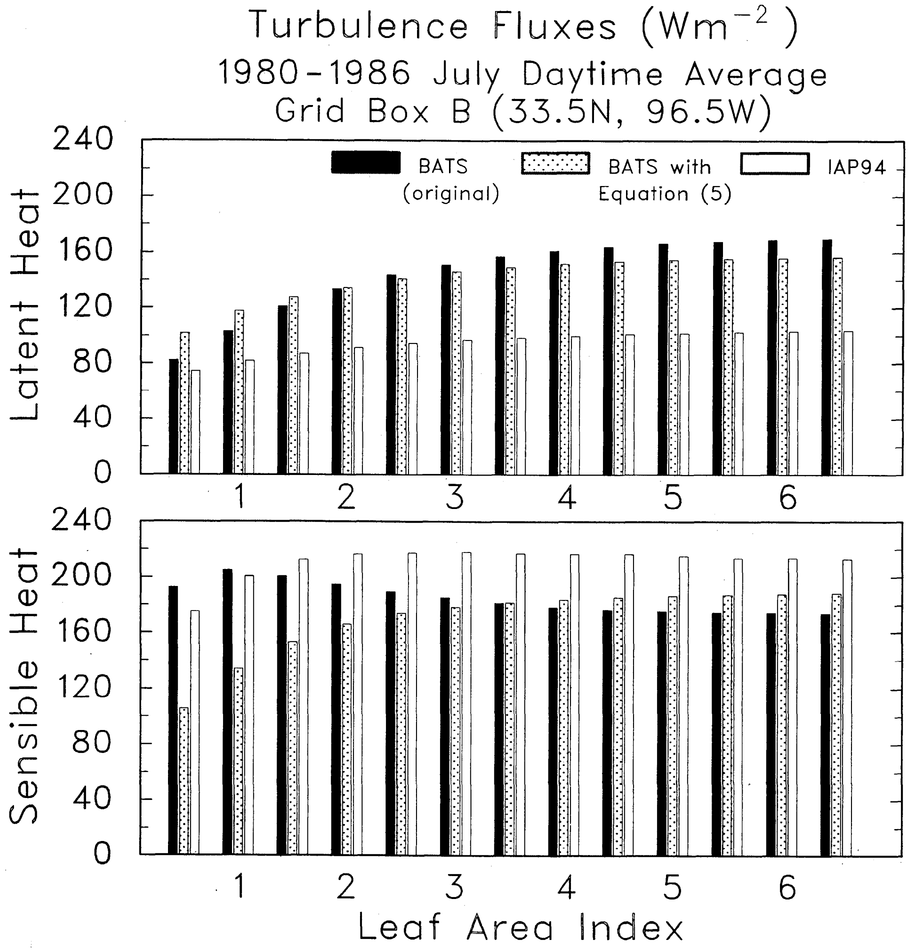

Figure 6. July mean daytime averages of above-canopy latent and sensible heat fluxes at a 1° × 1° grid box centered at 33.5°N, 96.5°W (grid B, July LAI = 1.3). Three models are the original BATS, the BATS modified with equation (5) only, and IAP94. The abscissa labels indicate the values of LAI used in the simulations for July.

solar radiation; $\omega_\lambda \beta_0$ is upward scattering fraction; μ is cosine of solar zenith angle; and $\alpha_{g,\lambda}$ is ground albedo, which assumes a spherical leaf distribution to get the 0.5 multiple scattering, only exact in small and large limits. In this study we assume that $\beta_0 = 0.5$; $\omega_\lambda = 0.15$ if $\lambda < 0.7 \mu m$; $\omega_\lambda = 0.85$ if $\lambda \geq 0.7 \mu m$. The fraction of solar radiation absorbed by canopy is expressed as

$$\alpha_\lambda = 1 - \alpha_\lambda - (1 - \alpha_{g,\lambda}) \exp\left(-\frac{0.5\ \mathrm{SLAI}}{\mu}\right). \quad (6b)$$

The original BATS is then modified to use (6a) for the canopy albedo and (6b) for the canopy- absorbed solar radiation. The results are also given in Figures 5 and 7. Overall, the results are similar to those obtained from using (5), supporting the statement that the radiation transmission through canopy cannot be neglected, especially when LAI is low.

Figure 8 shows diurnal cycles of a selected number of variables from the original BATS, the BATS modified with (6), and IAP94, for LAI varying from 0.5 to 6.5 at an interval of 0.5. Results from BATS modified with (5) are similar to those from BATS modified with (6). Therefore the latter is shown for brevity. Because radiation transmission is not permitted in the original BATS, the model canopy layer receives more solar energy than it would otherwise, leading to great sensitivity in (effective terrestrial) skin temperature to LAI. As a comparison, the variables at the ground surface (e.g., R_{ng}, H_g, LE_g, G, and T_g) show little sensitivity to changes in LAI. However, these conclusions are reversed when the radiation transmission parameterization is implemented in BATS. This modification results in greater sensitivity in the diurnal cycles of those ground surface variables to changes in LAI and a smaller sensitivity in (effective terrestrial) skin temperature to LAI. Qualitatively, results from BATS modified with (6) and IAP94 are similar, particularly in H_g, suggesting that a simple modification in vegetation albedo, as described in (6), or simply using the Beer's law type of parameterization for radiation transmission (equation (5)) can lead to model behavior similar to that from using a full two-stream radiation model such as used in IAP94.

6. Summary and Conclusions

The energy budgets above the canopy and at the ground have been examined to identify the factors that affect the energy residual terms in two land-surface models. An accurate simulation of the energy budgets at both levels is important.

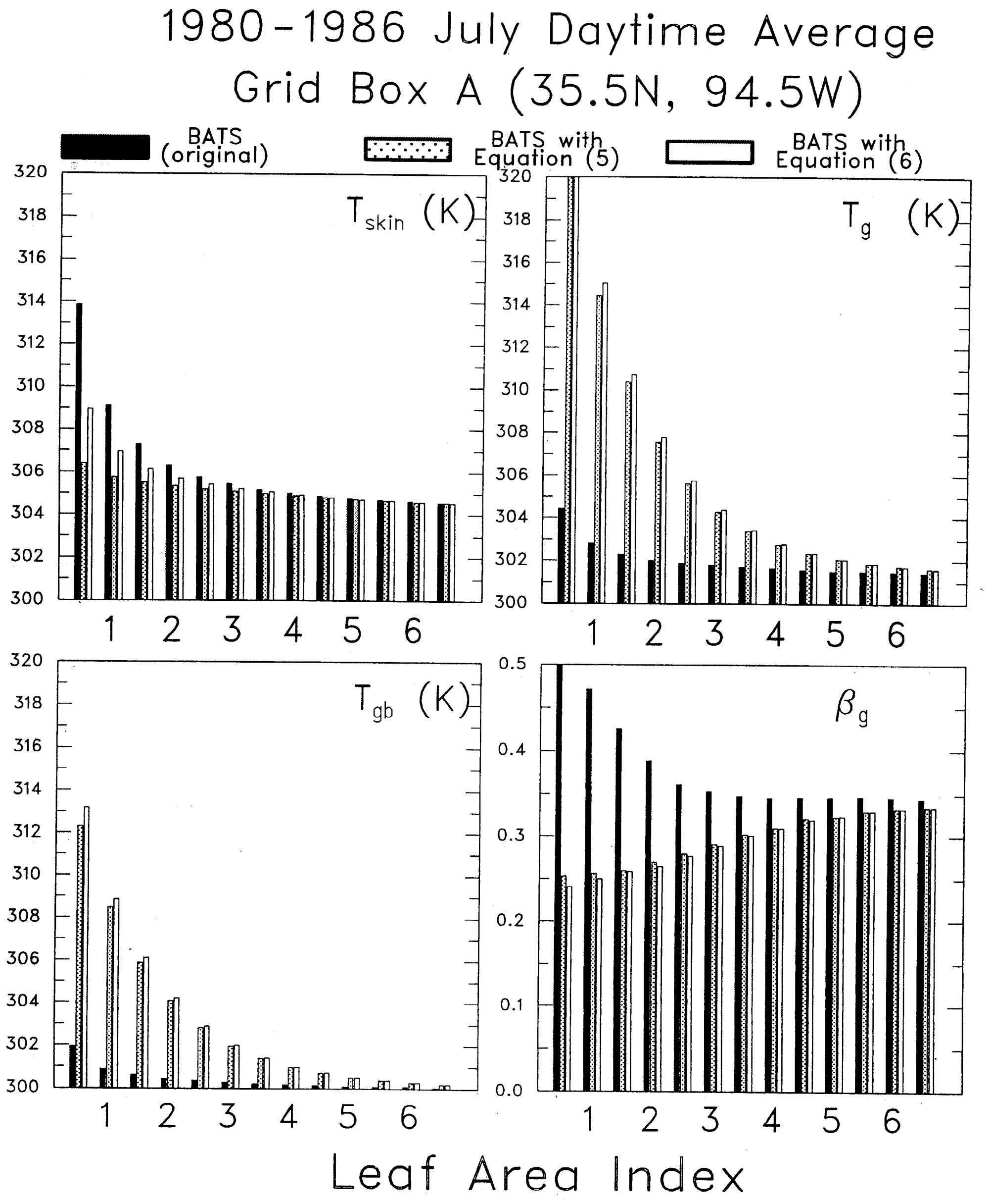

Figure 7. July mean daytime averages of the effective skin temperature ($T_{\rm skin}$), ground temperature (T_g), deep soil temperature (T_{gb}), and ground surface wetness factor (β_g) defined as ratio of ground evaporation to its potential value, at a 1° × 1° grid box centered at 35.5°N, 94.5°W (grid A, July LAI = 5.3). Results are shown for the original BATS, the BATS modified with equation (5), and the BATS modified with equations (6a) and (6b). All temperatures are in degrees Kelvin (°K). The abscissa labels indicate the values of LAI used in the simulations for July.

The above-canopy variables (e.g., latent and sensible fluxes) are those needed to specify the interaction between the land and the host atmospheric models, while the below-canopy variables serve to determine the local interaction between the canopy air space and the underlying soil.

On the basis of the analysis of the two models studied, the energy residuals above the canopy and at the soil surface can differ depending on the order in which the canopy and soil temperatures are computed (in BATS) and because of canopy heat storage (in IAP94). In the case of BATS the residual at the soil surface peaks slightly earlier than the residual above the canopy, although both peak around noon. The difference is expected to be further reduced if a smaller time step is used (say, 20 min, as commonly used in the atmospheric models). Reducing vegetation areal coverage results in an increased daytime soil heat flux, while increasing leaf area index leads to decreased soil heat flux and increased above-canopy latent heat flux. Both models show a strong sensitivity to LAI when LAI is small, and little sensitivity when LAI is large. This result indicates that special care must be taken to accurately specify LAI in the land-surface models, especially when the LAI values are small.

Allowing transmission of solar radiation through the

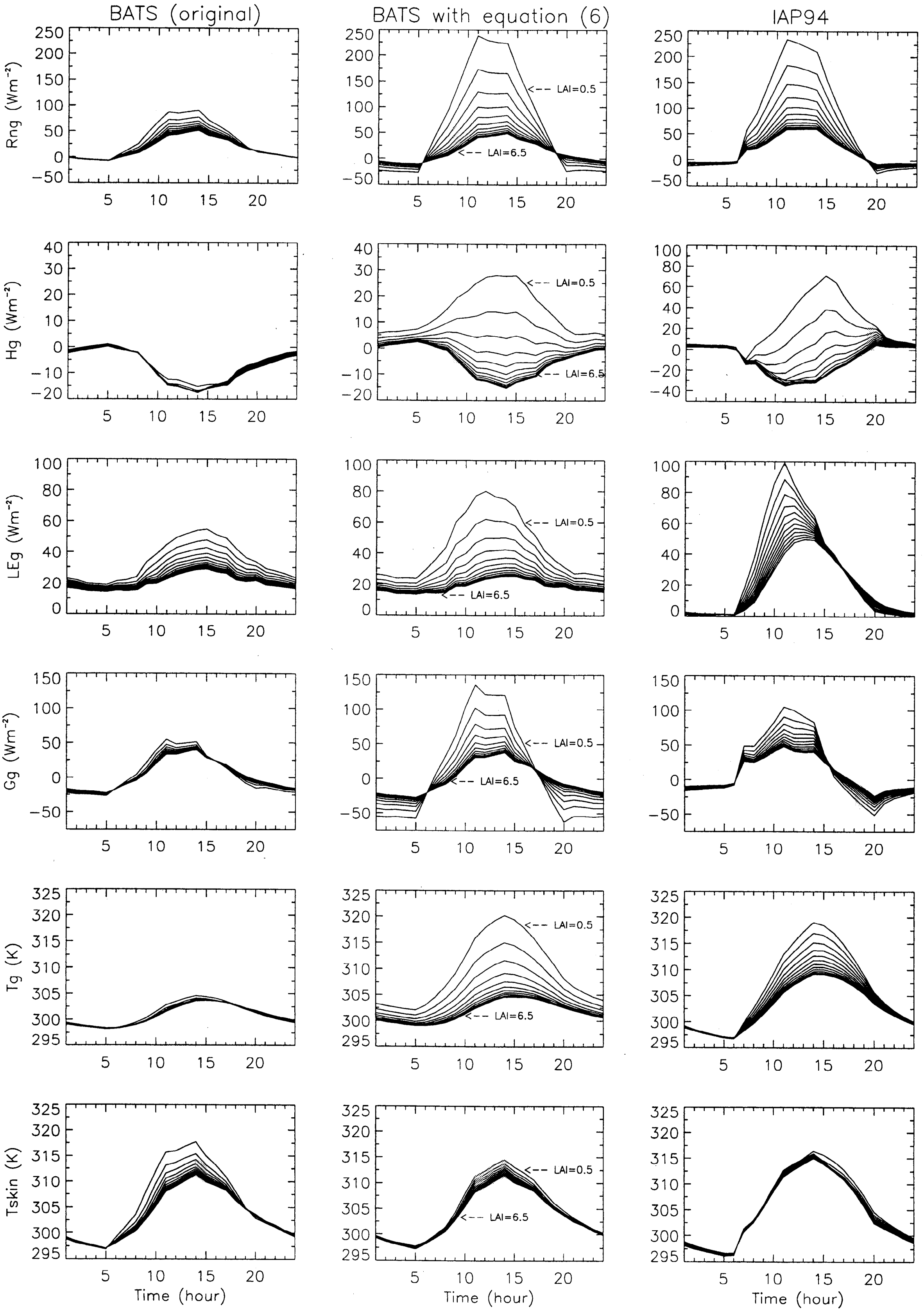

Figure 8. July mean diurnal variations of net radiation at the ground surface (R_{ng}), sensible heat flux (H_g), latent heat flux (LE_g), ground heat flux (G_g), ground temperature (T_g), and effective skin temperature (T_{skin}) at a 1° × 1° grid box centered at 35.5°N, 94.5°W (grid A, July LAI = 5.3). Results are shown for the original BATS, the BATS modified with equation (6) only, and IAP94. Results illustrate the sensitivity of the models to different values of LAI from 0.5 to 6.5 at an interval of 0.5.

canopy in BATS leads to reduced sensible heat fluxes above the canopy and enhanced flux terms at the soil surface, the results being most noticeable when LAI is small. This modification is carried out in two different ways: one by directly applying the Beer's law for radiation transmission through the canopy, the other by changing the canopy albedo and absorption as described in (6). Both methods produce similar simulations of ground temperature and fluxes at the soil surface for a wide range of LAI, and these simulations are comparable to the counterparts from IAP94. The soil heat flux computed from the modified versions of BATS lies within the bounds given by *Choudhury et al.* [1987] for a wide range of LAI (0.5–5.5). However, when LAI is high (e.g., 6–6.5), both BATS and IAP94 simulate a soil heat flux that is arguably high, this likely being due to the fact that a single temperature is used for the whole canopy.

This study indicates that a careful treatment of canopy radiation transfer in the land-surface models, such as *Nijssen and Lettenmaier* [1999], is needed to obtain realistic energy balances above and below the canopy, especially for the land covers that have low LAI, such as in the semiarid regions. Field data, which include concurrent measurements of net radiation, soil heat flux, LAI, and routine meteorological variables, are required to evaluate and develop the parameterization of the soil heat flux under vegetated surfaces.

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