The UCD Advanced Canopy–Atmosphere–Soil Algorithm: Comparisons with observations from different climate and vegetation regimes

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SUMMARY

The University of California, Davis (UCD), Advanced Canopy–Atmosphere–Soil Algorithm (ACASA) is presented and its output is compared with a comprehensive set of observations at six diverse sites. ACASA is a multi-layer canopy–surface-layer model that solves the steady-state Reynolds-averaged flow equations to the third-order. These equations include an explicit representation of the steady-state, horizontally homogeneous, diabatic set of vector and scalar fluxes and flux transports. ACASA includes a fourth-order, near-exact technique to calculate leaf, stem, and soil surface temperatures and surface energy fluxes at various levels within the canopy. Plant physiological response to micro-environmental conditions is also included using Ball–Berry/von Caemmerer–Farquhar formulations. Observed energy fluxes and microenvironmental conditions from a grass field in the Netherlands, deciduous and coniferous forests in Canada, tropical pasture and forest in Brazil, and an ancient temperate rainforest in the USA are compared with simulated values.

Results indicate that simulated and observed estimates of monthly to annual means of all surface fluxes agree within 95% confidence thresholds for all six sites. Observed and simulated hourly estimates of net radiation are also in excellent agreement for all sites considered. Observed and simulated hourly sensible- and latent-heat flux estimates are in very good statistical agreement in most cases. Differences that exist between ACASA and observed sensible- and latent-heat flux estimates are of the same magnitudes as observational uncertainties. Estimates of observed and simulated hourly values of canopy and ground heat storage are within 95% statistical confidence limits of agreement with observations in most cases. Simulated and measured values of daytime intra-canopy mean wind speed, temperature, and specific humidity agree with 95% confidence within both a tropical and temperate rainforest at all levels. Results also indicate that, in general, ACASA produces flux estimates closer to observations with significantly less scatter than does the Biosphere–Atmosphere Transfer Scheme. Sensitivity tests show that reducing the vertical resolution, linearizing surface temperature calculations, and/or simplifying the treatment of surface-layer turbulence each altered mean sensible- and latent-heat flux estimates by amounts that are statistically significant in many cases. Results show that simplifying the model alters flux predictions in manners not simply related to vegetation character, and that using ACASA at its full complexity for all vegetation regimes is warranted. Increasing the vertical resolution beyond 20 layers improved flux predictions at tropical locations but had little impact elsewhere.

KEYWORDS: Canopy Energy fluxes Higher-order closure Model simulations Observations

1. INTRODUCTION

It is well known that the character of the earth’s surface heavily influences atmospheric circulation. Potter et al. (1975) and Sagan et al. (1979) were among the first to use climate model simulations to demonstrate the overall climatic importance of surface exchange processes influenced by the presence of vegetation. More recent investigations have recognized the potential climate impacts of large-scale differences in vegetation type (Anthes 1984; Avissar and Pielke 1989; Bougeault et al. 1991; Milhalovic et al. 1993). Further investigations have fuelled widespread agreement that better representations of these surface–atmosphere exchanges (flux densities) of moisture, heat, and momentum will yield better climate predictions (Dickinson et al. 1993; Ducoudre et al. 1993; Garratt 1993; Holtslag and Ek 1996; Pielke et al. 1997). There is evidence to suggest that the climate system is sensitive to systematic average differences in surface fluxes of only several W m\(^{-2}\). Polcher (1995) used a general circulation model (GCM) to investigate potential impacts of tropical deforestation and found that significant alterations to the nature of convective activity are associated with 2–5 W m\(^{-2}\) changes in average sensible heating over Amazonia and west-central Africa. In a recent GCM

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investigation Xue and Shukla (1996) report that significant increases in simulated July–August convective precipitation due to afforestation in the Sahel were associated with changes in sensible-heat flux of 3 W m\(^{-2}\).

This paper outlines the structure and performance of the University of California, Davis, Advanced Canopy–Atmosphere–Soil Algorithm (ACASA). ACASA is designed to calculate surface energy, mass, and momentum exchanges, as well as the average microclimatic conditions, trace gas exchanges, and associated turbulence statistics, over vegetated regimes. Although many of its components have been developed and tested previously in singular applications, ACASA is designed as the first version of a comprehensive terrestrial biosphere–atmosphere model which can be used in stand-alone diagnostic tests or be applied generally as a surface-layer component nested within mesoscale climate models.

The current investigation involves testing this multi-layer canopy–surface-layer model in a rigorous statistical fashion for six vegetation and/or climate regimes: temperate grass, degraded tropical pasture, young boreal deciduous forest, old boreal coniferous forest, tropical rainforest, and ancient temperate rainforest. These tests include explicit quantitative treatment of independently gathered observational uncertainties. By considering nearly 100,000 independent hourly measurements in a rigorous statistical fashion, the current investigation is one of the most extensive off-line tests of its kind for any canopy–atmosphere exchange model (e.g. Wilson and Shaw 1977; Meyers and Paw U 1987; Massman and Vandijken 1989; Xue et al. 1991; Baldocchi 1992; Jiang et al. 1992; Yamazaki et al. 1992; Garratt 1993; Borque and Arp 1994; Enger and Koracin 1995; McNaughton and Vandenburh 1995; Xinmei and Lyons 1995; Bernhoffer et al. 1996; Holtslag and Ek 1996; Su et al. 1996; Chen et al. 1997; Katul and Albertson 1998). Results from tests involving surface fluxes and several intra-canopy microenvironmental quantities at all available sites are presented. This investigation also includes preliminary inquiries into the sensitivity of model flux predictions to higher-order turbulent statistics, vertical resolution, and surface temperature estimation techniques.

2. Model features

ACASA has several main components that all contribute to its ability to treat the canopy microenvironment and associated fluxes as an interconnected system. First, the canopy system is represented as a multi-layer regime through which exchanges of energy, mass, and momentum occur. Second, ACASA uses a near-exact quartic energy balance formulation that enables it to calculate surface temperatures accurately, even in situations where leaf, stem, or soil surface temperatures differ from ambient air temperatures. Third, ACASA incorporates a diabatic, third-order closure treatment of turbulent transfer within and above the canopy. A fourth feature is the inclusion of a formulation representing plant physiological responses to changing microenvironmental conditions, including changes to carbon dioxide concentrations. Additional features include a soil model with thermal and hydrological exchanges, calculations of canopy heat storage, and inclusion of canopy interception of precipitation. Although the full set of governing equations of ACASA can be drawn from a number of sources (e.g. Meyers and Paw U 1987; Paw U and Gao 1988; Su et al. 1996), these are listed together in Pyles (2000).

(a) Vertical resolution

The number and thickness of canopy and atmospheric layers in ACASA is adjustable, though tests show that a minimum of ten canopy and ten above-canopy layers
extending to a minimum of twice the canopy height enables accurate vertical
finite-difference calculations. In the current investigation, the above-ground resolution was
kept at ten within- and ten above-canopy layers, despite variations in the vegetation
height or vegetation density. Long- and short-wave radiative transfer, surface energy bal-
ances, physiological responses, and turbulence statistics all take place in this multi-layer
context. Resolution within the soil domain was set to fourteen 15 cm layers. Because
this model contains assumptions pertinent to the surface layer, the domain should extend
to no more than 100 m or so beyond the top of the canopy.

(b) Surface temperature calculations

ACASA employs the fourth-order polynomial of Paw U and Gao (1988) to estimate
leaf, stem, and soil surface temperatures. This best-fit polynomial is expanded around
25 °C for the saturation vapour pressure as a function of temperature. The error is less
than 0.1% for values of temperature between 5 and 45 °C (Paw U and Gao 1988). This
polynomial is then combined with the appropriate energy budget based on energy flux
estimates for shaded and nine sunlit angles at each layer, yielding a quartic expression
for the leaf, stem, and soil surface temperature for each case. Individual shaded and
sunlit values within a layer are combined proportionally to yield average leaf and stem
temperatures within each layer. This technique reduces mathematical errors that arise
from simpler formulations when surface and air temperatures differ by more than several
degrees centigrade (Paw U and Gao 1988).

(c) Turbulence closure

ACASA explicitly calculates the steady-state values of vector fluxes, scalar fluxes,
and their transports to the third-order. The steady-state governing set of equations en-
ables ten second-order and 17 third-order turbulent quantities to be calculated inde-
dependently. Such calculations enable the model to predict the effects that higher-order
turbulent kinetic and thermodynamic processes have on the canopy–surface microen-
vironment and associated fluxes of heat, moisture, and momentum. These explicitly
represented processes include all kinematic and diabatic contributions to the flow field
including, but not limited to, turbulence production and dissipation of turbulence kin-
etic energy, turbulent vertical transports of vertical heat, mass, and momentum fluxes.
Vertical profiles of mean wind, temperature, humidity, and CO₂ concentration are gen-
erated independently from the governing set. Inclusion of these higher-order turbulence
statistics allows for the simulation of counter-gradient transports of heat, moisture, and
momentum that can occur when large eddies are present in the flow field (Meyers 1985).
The ACASA turbulence calculations have as their theoretical basis the work of Meyers
(1985), and Meyers and Paw U (1986 and 1987). The full set of equations, too extensive
to list here, can be found in Meyers and Paw U (1986).

(d) Physiological response

ACASA accounts for the effects that short-wave radiative flux density, CO₂ concen-
trations, temperature, vapour-pressure deficit, and soil moisture content have on transpi-
ration. Stomatal resistances are estimated for each canopy layer for ten leaf angle classes
(nine sunlit and one shaded), using leaf temperatures and radiative transfer estimates for
each leaf angle class in conjunction with air temperature, aerodynamic resistance (mean
wind), humidity, and CO₂ concentrations within each layer. In particular, ACASA treats
plant physiological response to environmental conditions using a combination of the
Ball–Berry stomatal conductance (Leuning 1990; Collatz et al. 1991) and the Farquhar
and von Caemmerer (1982) photosynthesis equations. These formulations were combined to yield estimates of unstressed stomatal resistance in Su et al. (1996). Stomatal control can be modified in this model to reflect species-specific characteristics by altering the slope of the Ball–Berry stomatal conductance relation (Baldocchi, personal communication). Total stomatal resistance estimates reflect the combination of above- and below-ground influences. Soil moisture stress is included in a manner similar to that found in Ek and Mahrt (1991) and Dickinson et al. (1993).

(e) Soil moisture and heat transport

Soil surface evaporation, soil moisture, and soil temperature estimates are adapted from the Oregon State University (OSU) one-dimensional (1D) planetary boundary-layer (PBL) soil module (Ek and Mahrt 1991). The OSU subsurface modules are linked to the canopy proper via the following methodology. The soil surface albedo, $a_s$, is estimated in a similar fashion to that specified in Dickinson et al. (1993). Soil surface temperatures and potential surface evaporation are calculated using the quartic energy budget formulation discussed earlier, using estimated near-ground (10% of canopy height) values of mean wind, temperature, and humidity. These surface temperature and potential-evaporation estimates are then used as boundary conditions for the soil calculations. Drying of the soil in active root zones includes transpiration losses from the canopy. The number of soil layers is adjustable, though 15 layers (0.15 m each) were chosen for this investigation. Root activity is assumed to take place in the upper seven layers (extending down to 1.2 m) for all sites except the temperate grass case, where the Project for Intercomparison of Land surface Parameter Schemes, Phase 2a (PILPS 2a) instructions suggest a much shallower root zone. The depth at the bottom of the lowest soil layer is set to 7.2 m, which effectively shuts off the soil heat flux at the lowest layer. Values of soil moisture and temperature at each layer are updated at the end of a call to ACASA, when iterative convergence for a given time step is achieved. Small modifications to the OSU–PBL soil subsurface module have been added to better couple it to ACASA. These include attenuating the soil thermal conductivity to include effects of soil humus content, at the suggestion of Jury et al. (1991), and fractional leaf litter cover.

(f) Additional features

In addition to the features described in section 2(a)–(d), ACASA includes calculations of: radiative transfer within the canopy, soil thermal and hydrological evolution, plant physiological responses, and canopy heat-storage processes. Radiative transfer calculations are performed separately for three wavelength bands: visible, near infrared, and thermal. ACASA handles beam and diffuse short-wave radiation (both visible and near infrared) in the manner suggested by Meyers (1985). Thermal radiation is also treated using a similar approach, and is adjusted to reflect the evolving leaf and soil surface temperatures within each layer. Modifications to the earlier code of Meyers (1985) include iterative streamlining, improved multi-layer treatment, and also a re-working of radiative divergence calculations within the canopy layers which conserves energy and provides the option of estimating anisotropic long-wave emittance (Paw U 1992).

ACASA simulations also include estimates of canopy heat storage, which can be a dominant component in the surface energy exchange at certain times of the day in tall canopies (Moore and Fisch 1986). In ACASA, the total canopy heat storage, $S$ (W m$^{-2}$),
is the sum of biomass, sensible-, and latent-heat storage:

\[ S = S_c + S_H + S_{LE} = c_{bm} M_c \Delta T_c \Delta t + c_p M_a \Delta T_a \Delta t + \lambda_e M_a \Delta q_a \Delta t, \]  \hspace{1cm} (1)

where \( M_c \) and \( M_a \) (kg m\(^{-2}\)) are the column masses of biomass and air, respectively, in a given layer, \( \Delta T_c \), \( \Delta T_a \), \( \Delta q_a \) are the rates of change in leaf and stem canopy temperature (K s\(^{-1}\)), air temperature (K s\(^{-1}\)), and specific humidity (kg kg\(^{-1}\)s\(^{-1}\)), respectively; and \( c_p \) (J kg\(^{-1}\)K\(^{-1}\)) and \( \lambda_e \) (J kg\(^{-1}\)) represent the specific heat of air at constant pressure and the latent heat of vaporization. The effective canopy heat capacity, \( c_{bm} \) (J kg\(^{-1}\)K\(^{-1}\)), appearing in the biomass thermal storage term \( S_c \) is set to 0.18, which is a normalized value of what Moore and Fisch (1986) suggest for a tropical forest with \( M_c = 70 \) kg m\(^{-2}\).

ACASA includes a crude canopy interception module, in which each of the canopy layers sequesters water from precipitation or dew formation. Inclusion of canopy interception assists in surface energy exchange calculations, as it can involve large fractions of precipitation over time and can influence leaf surface temperatures and physiology (Dickinson 1984). Dew that accumulates on the surfaces of the leaves is treated as precipitation. Water remains on the leaves until evaporation removes all of it. Effects of wind-induced vegetation sway on canopy water storage are not included in the current version. When the canopy water content of a layer is non-zero, separate calculations for flux partitioning under free-evaporation conditions are performed. The resulting flux divergence estimates are then weighted by the fraction of the intercepted water to the maximum capacity within each layer. Water uptake from roots is correspondingly attenuated when the canopy water content is non-zero. Maximum canopy interception capacity is set to 0.1 mm per unit of total leaf area index (LAI) as suggested by Dickinson et al. (1993) and Ubarana (1996).

3. INPUT PARAMETERS AND NUMERICAL PROCEDURES

ACASA requires input quantities that are specific to particular meteorological, hydrological, and physiological conditions. These quantities along with the methods used to measure the meteorological variables appear in Table 1. All site-specific inputs needed to run the model include the upper boundary conditions of mean wind, specific humidity, temperature, pressure, CO\(_2\) concentration, downwelling long- and short-wave radiation and precipitation rate. Input values of bottom soil layer temperature, soil type, LAI and stem area index (STEI) profiles, canopy height, minimum stomatal resistance, fractional soil humus content, ground leaf litter cover, leaf drag coefficient, and visible and near-infrared values of leaf absorbency and transmittance are also required. Additional inputs in Table 1 are quantities that must be initialized for the first call to ACASA, but are updated internally for subsequent calls. These additional inputs include vertical profiles of soil temperature, soil moisture, and intercepted precipitation.

Whenever possible, in situ measurements of the above quantities were used to drive ACASA. When such values were not available, choices were made using guidance from literature when possible (see Table 1). These include the vertical profiles of LAI and STEI, leaf optical properties, mean leaf diameter, canopy drag coefficients, and slopes of the Ball–Berry stomatal response line that were not available at some or all of the sites (see; Table 1). In cases where leaf optical properties were not available (degraded tropical pasture, tropical rainforest), values were chosen to calibrate roughly the net radiation. This is the extent to which this model has been calibrated for this investigation.
<table>
<thead>
<tr>
<th>type of vegetation</th>
<th>temperate grass</th>
<th>tropical pasture</th>
<th>deciduous forest</th>
<th>coniferous forest</th>
<th>tropical rainforest</th>
<th>temperate rainforest</th>
</tr>
</thead>
<tbody>
<tr>
<td>site name</td>
<td>Cabauw</td>
<td>ABRACOS NS</td>
<td>BOREAS SSA-YA</td>
<td>BOREAS SSA-OJP</td>
<td>ABRACOS RJ</td>
<td>WRCCRF</td>
</tr>
<tr>
<td>total no. of data points</td>
<td>8760</td>
<td>2236</td>
<td>569</td>
<td>1400</td>
<td>1360</td>
<td>2114</td>
</tr>
<tr>
<td>no. of data points used</td>
<td>8064</td>
<td>2236</td>
<td>338</td>
<td>508</td>
<td>1360</td>
<td>631</td>
</tr>
<tr>
<td>latitude (deg N)</td>
<td>51.95</td>
<td>-10.75</td>
<td>53.66</td>
<td>53.92</td>
<td>-10.08</td>
<td>45.49</td>
</tr>
<tr>
<td>canopy height (m)</td>
<td>0.20</td>
<td>0.84</td>
<td>3.00</td>
<td>13.50</td>
<td>33.30</td>
<td>67.00</td>
</tr>
<tr>
<td>total LAI</td>
<td>0.90 to 3.60</td>
<td>3.30</td>
<td>2.25</td>
<td>1.80</td>
<td>4.00</td>
<td>3.60</td>
</tr>
<tr>
<td>total STEI</td>
<td>0.23 to 0.90*</td>
<td>0.83*</td>
<td>0.53*</td>
<td>0.45*</td>
<td>1.00*</td>
<td>0.90*</td>
</tr>
<tr>
<td>height of LAI max (m)</td>
<td>0.10*</td>
<td>0.40*</td>
<td>1.50*</td>
<td>6.75*</td>
<td>3.00 and 30.00*</td>
<td>15.00 and 35.00*</td>
</tr>
<tr>
<td>biomass (kg m$^{-2}$)</td>
<td>1.0</td>
<td>2.0*</td>
<td>10.0*</td>
<td>20.0</td>
<td>70.0</td>
<td>90.000</td>
</tr>
<tr>
<td>vis. leaf transm.</td>
<td>0.075</td>
<td>0.075*</td>
<td>0.075*</td>
<td>0.168</td>
<td>0.075*</td>
<td>0.075*</td>
</tr>
<tr>
<td>near-IR leaf transm.</td>
<td>0.500</td>
<td>0.500*</td>
<td>0.290</td>
<td>0.168</td>
<td>0.400*</td>
<td>0.300*</td>
</tr>
<tr>
<td>vis. leaf albedo</td>
<td>0.200</td>
<td>0.180*</td>
<td>0.282</td>
<td>0.297</td>
<td>0.150*</td>
<td>0.150*</td>
</tr>
<tr>
<td>near-IR leaf albedo</td>
<td>0.430</td>
<td>0.430*</td>
<td>0.430</td>
<td>0.100</td>
<td>0.250*</td>
<td>0.100*</td>
</tr>
<tr>
<td>stomatal control factor</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>4.000*</td>
<td>2.000*</td>
<td>4.000*</td>
</tr>
<tr>
<td>vis. dry soil albedo</td>
<td>0.100</td>
<td>0.300*</td>
<td>0.300*</td>
<td>0.200*</td>
<td>0.300*</td>
<td>0.300*</td>
</tr>
<tr>
<td>near-IR dry soil albedo</td>
<td>0.200</td>
<td>0.300*</td>
<td>0.300*</td>
<td>0.300*</td>
<td>0.300*</td>
<td>0.300*</td>
</tr>
<tr>
<td>leaf drag coefficient</td>
<td>0.100*</td>
<td>0.100*</td>
<td>0.050*</td>
<td>0.075*</td>
<td>0.050*</td>
<td>0.130*</td>
</tr>
<tr>
<td>mean leaf diameter (m)</td>
<td>0.010*</td>
<td>0.010*</td>
<td>0.050*</td>
<td>0.025*</td>
<td>0.075*</td>
<td>0.005*</td>
</tr>
<tr>
<td>deep soil temp. (K)</td>
<td>279.0</td>
<td>294.0</td>
<td>287.0</td>
<td>287.0</td>
<td>298.0</td>
<td>289.4</td>
</tr>
<tr>
<td>initial soil moisture</td>
<td>0.467</td>
<td>0.300*</td>
<td>0.420*</td>
<td>0.300*</td>
<td>0.420*</td>
<td>0.200</td>
</tr>
<tr>
<td>soil type</td>
<td>clay-loam</td>
<td>sandy loam</td>
<td>clay</td>
<td>sandy loam</td>
<td>sandy loam</td>
<td>sandy loam</td>
</tr>
<tr>
<td>fract. humus content</td>
<td>0.670*</td>
<td>0.670*</td>
<td>0.670*</td>
<td>0.670*</td>
<td>0.900*</td>
<td>0.900*</td>
</tr>
<tr>
<td>fract. leaf litter cover</td>
<td>0.670*</td>
<td>0.670*</td>
<td>0.670*</td>
<td>0.670*</td>
<td>0.900*</td>
<td>0.900*</td>
</tr>
<tr>
<td>depth root zone (m)</td>
<td>0.4</td>
<td>1.2*</td>
<td>1.2*</td>
<td>1.2*</td>
<td>1.2*</td>
<td>1.2*</td>
</tr>
<tr>
<td>meas. height (m)</td>
<td>20.0</td>
<td>5.5</td>
<td>6.0 to 9.0</td>
<td>26.0</td>
<td>35.0</td>
<td>72.0 to 80.0</td>
</tr>
</tbody>
</table>

An asterisk (*) denotes values which, instead of being directly measured at the site, are estimated from values taken from the literature and/or from other characteristics.
<table>
<thead>
<tr>
<th>Type of Vegetation</th>
<th>Site Name</th>
<th>Dates (mm/dd)</th>
<th>Wind Speed</th>
<th>Air Temperature</th>
<th>Specific Humidity</th>
<th>Long-Wave Flux (Rlw)</th>
<th>Short-Wave Flux (Rsw)</th>
<th>Surface Pressure</th>
<th>Rainfall</th>
<th>R_s</th>
<th>L_E</th>
<th>H</th>
<th>G</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperate Grass</td>
<td>Cabauw</td>
<td>1/1–12/31 1987</td>
<td>Gill 8002DX</td>
<td>Thermocouple (dry)</td>
<td>Pl resist. (dry)</td>
<td>Funk Dome</td>
<td>Eppley long wave n.a.</td>
<td>KNMI</td>
<td>Kipp CM 11</td>
<td>REBS Q+6</td>
<td>(see section 4 (a))</td>
<td>(see section 4 (a))</td>
<td>NOASR transducer</td>
<td>none</td>
</tr>
</tbody>
</table>

An asterisk (*) denotes values which, instead of being directly measured at the site, are estimated from values taken from the literature and/or from other characteristics.
Additional arbitrary choices for site-specific parameters were made in a manner that was physically consistent. For example, surface pressure was assumed to be 1000 mb for each time step at the degraded tropical pasture and tropical rainforest sites. The total STEI was taken as 25% of the total LAI, assuming that its vertical distribution peaks smoothly midway through the canopy. An important parameter, which should be specified with great care, is the slope of the Ball–Berry unstressed stomatal response curve (SBB), which varies with plant species. When the stomatal control factor is unity the SBB is 9.29, a value based on crops which have low minimum stomatal resistances (~40 s m⁻¹). This value was doubled for tall deciduous trees and quadrupled for
forests with coniferous trees at the suggestion of Gates (1980) and Baldocchi (personal communication). Canopy drag coefficients were chosen using values for similar species in Meyers (1985). For this investigation, canopy drag coefficients, mean leaf diameter, and leaf optical properties were assumed to be vertically constant throughout the canopy.

Like many turbulence closure models, ACASA requires iterating to arrive at steady-state solutions for the governing set of equations (see Fig. 1). After the calculation of initial stomatal resistances, canopy water storage, short-wave radiative fluxes throughout the canopy, and preliminary surface energy balances, the iteration cycles begin. Each iteration cycle repeats until convergence, i.e. when there is less than 0.5 W m\(^{-2}\) change in the energy flux estimates at the top of the canopy over four iterations. After convergence, ACASA updates the soil conditions and returns any needed outputs.

ACASA employs several constraining methods to enhance numerical stability as the model iterates toward a solution. Velocity and temperature variances are prevented from becoming negative. Mean wind shears are not allowed to become negative above the canopy layers. Such patterns in steady-state vertical wind shears immediately above the canopy top are physically unreasonable and do not appear in observations (Kaimal and Finnegan 1994). In addition, upper-boundary mean wind inputs of less than 0.3 m s\(^{-1}\) are set to 0.3 m s\(^{-1}\). The realizability principles of André et al. (1976a,b) constrain values of the third moments. ACASA uses similar concepts to constrain velocity variances and other second-moment turbulent quantities.

Spin-up time is necessary to avoid flux estimates reflecting the arbitrary initialization of soil moisture and temperature. The year-long time series of the temperate grass site (discussed later) spans a near-equilibrium year in terms of soil thermal balances. This enabled a spin-up time of five repeat years to achieve soil hydrological and thermal balances. For the remaining five sites, the time series were insufficiently long to establish true soil thermal and hydrological equilibrium conditions. In these cases it was found that initializing soil temperatures with observed air temperatures averaged over the entire record, and then using a ten-hour spin-up time, was sufficient to avoid spurious ground heat flux values.

4. THE SIX SITES

The six sites considered in this investigation represent a wide range of climate and vegetation states. Measured canopy heights range from 0.20 to 67 m, and estimates of LAI range from 0.9 to 5.0 in a manner that is not linearly related to canopy height. These widely different values represent much of the range found in terrestrial vegetation communities. Site descriptions and some measurement techniques are given below in order of increasing canopy height.

(a) Temperate grass—Cabauw, the Netherlands

The Cabauw site is a groomed grass field located at 51.95°N, 4.95°E at sea level, where measurements were taken continuously at half-hour intervals. The full annual record enabled testing over longer time-scales than is commonly possible at other sites. Observations from this site were used in PILPS-2a (Chen et al. 1997). Since these data were used for PILPS-2a, the results of that investigation provide insight into how well ACASA performed relative to other models in near-equilibrium conditions. The initialization and input criteria as established by Chen et al. (1997) were therefore followed as closely as possible. Measurements were taken at half-hour intervals for the entire year of 1997, though hourly averages are used in the present study. Sensible-heat
flux was calculated using temperature measurements at 0.6 and 20 m. Latent-heat flux values were estimated from the residual of $R_n - H - G$ (where $R_n$, $H$ and $G$ are net radiation, and fluxes of sensible heat and ground heat, respectively). Gaps in the dataset were filled using a blend of observed and simulated values based on empirical methods derived from observed values. For the months of January, February, and December, these gaps account for 50% of the values, but decline to within 20% for the remaining months. A full description of the site and dataset is given in Beljaars and Bosveld (1997).

(b) Degraded tropical pasture—Fazenda Nossa Senhora, Rondonia, Brazil

Data for this sparsely vegetated location originate from the Anglo-Brazilian Amazonian Climate Observation Study (ABRACOS) Fazenda Nossa Senhora da Aparecida, Ji-Parana (10.75°S, 62.33°W; 220 m elevation). This site was established in October 1991 on a cattle ranch. The site underwent extensive deforestation in 1977 and lies at the centre of a largely deforested 50 km wide area. Clumpy, row-like patches of grass (Brachiaria brizantha) no more than 0.8 m in height dominate the site, with 12% of the soil surface completely barren. Sensible- and latent-heat fluxes were estimated using a combination of temperature and humidity profiles and momentum flux estimates. More information on this dataset can be found in Bastable et al. (1993).

(c) Young boreal deciduous forest—Saskatchewan, Canada

This site contains dense, young vegetation that is recovering from recent logging, thereby representing vegetation that lies somewhere in between a tall forest and grassland. The Southern Study Area (SSA) of the Boreal Ecosystem–Atmosphere Study (BOREAS) lies in a region 130 km by 90 km around Prince Albert, Saskatchewan. The Young Aspen (Populus Tremuloides) site in particular is located in a 2 km² clearing covered by a dense young aspen canopy of 3 m (53.66°N, 105.32°W; elevation 592 m). Measurements used for simulations and comparisons (Table 1) were collected at half-hour intervals, with sensible- and latent-heat fluxes estimated using eddy covariance (EC) techniques (Bessemolin and Puech 1998). Hemispherical spectral reflectance and transmittance factors for individual young aspen leaves at near-normal incidence were collected using a LI-COR LI-1800-12 integrating sphere attached to a Spectron Engineering SE590 spectroradiometer (Mesarch et al. 1998). Rainfall was measured in the SSA by the BOREAS HYD-09 team (see Kouwen et al. 1998).

(d) Old boreal coniferous forest—Saskatchewan, Canada

This BOREAS site contains an 80- to 100-year-old forest whose measured LAI is less than two, and thus it represents sparse canopies. The site (53.92°N, 104.69°W; elevation 579 m) is characterized as a flat, horizontally homogeneous, 13.5 m stand of old Pinus Baksiana (jackpine). Sensible- and latent-heat fluxes were measured using EC techniques. Independently measured estimates of canopy and ground heat storage were also gathered at this site (Baldocchi and Vogel 1998). Site documentation and additional data, including LAI, optical properties and rainfall, can be found in Baldocchi and Vogel (1998), Plummer 1998, Kouwen et al. (1998), and Mesarch et al. (1998).

(e) Tropical rainforest—Rondonia, Brazil

This site is a secondary-growth tropical forest in the humid tropical climate regime of Rondonia, Brazil. Reserva Jaru (10.08°S, 61.93°W; elevation 220 m) is a forest
reserve owned by the Brazilian Environmental Protection Agency and data were gathered there as part of the ABRACOS field campaign. The tallest trees in this secondary-growth forest canopy are approximately 35 m. Total LAI was estimated at 4.0, with most of the vegetation existing above 20 m (Honz et al. 1996). Hourly measurements were taken above the canopy near 53 m beginning in 1991. The dominant tree species in the area are Cedrela odorata Inga, Dioecia cf. bicolor Bih., Strychnos amazonicus Krukov, Protium polystromium and Leonia glycyicarpa Ruiz (see McWilliam et al. 1996) and Roberts et al. (1996) for further details). In addition to measurements given in Table 1, air temperatures at 5, 10, 15, 20, 25, and 35 m were also taken using instruments described in Table 1. Sensible- and latent-heat fluxes were estimated using a combination of temperature and humidity profiles and momentum flux estimates. More information on this dataset can be found in Bastable et al. (1993).

(f) Ancient temperate rainforest—Washington, United States

Multi-layer measurements within the old-growth forest site at the Wind River Canopy Crane Research Facility (WRCCRF) provided data from some of the most extensive canopies found anywhere on earth. The measurements considered here cover an 88-day period between 22 July and 4 November 1998. The WRCCRF is located at 45.49°N, 121.58°W at 355 m elevation within the T. T. Munger Research Natural Area in the southern Cascade mountains. Douglas-fir (Pseudotsuga menziesii) and western hemlock (Tsuga heterophylla) more than half-a-millennium old dominate the site, with the tallest trees piercing the sky at more than 65 m. Various other species of cedar, fir and pine also exist within the forest. Although the vast majority of the canopy is coniferous, the understory contains largely broadleaf species including Pacific dogwood (Cornus nuttallii), vine maple (Acer circinatum), salal (Gaultheria shallon) and dwarf Oregon grape (Berberis nervosa). Total LAI and vertical distribution of LAI were measured using radiative techniques, which indicated that the total LAI is 3.8 (Weiss, personal communication), though other estimates place the total LAI at 11.4 (Paw U et al. 2000). In addition to measurements described in Table 1, mean wind, air temperature, and humidity measurements were taken at 60, 40, 20, 10, and 2 m. Sensible- and latent-heat fluxes were measured using EC techniques (Paw U et al. 2000)

5. COMPARISON METHODOLOGY

Two main sets of observations were used in comparisons with model estimates. The primary set involves comparisons of simulated and observed estimates of various components of the surface energy flux budget:

\[ R_n = H + LE + G + S, \]  

where \( LE \) and \( S \) are the latent-heat flux and canopy thermal storage, respectively. Metabolic and photosynthetic terms are assumed to be negligible. Estimates of \( S \) based on observed biomass temperatures were only available for the old boreal coniferous forest site. The second set of tests includes comparisons of observed and modelled values of intra-canopy mean wind, air temperature, and specific humidity.

Several standard statistical methods were invoked, which are summarized in Table 2. One test included comparing mean (shown with overbars) values of observed (\( \bar{y} \)) and modelled (\( \bar{x} \)) fluxes and microenvironmental conditions. The mean of absolute differences between modelled and observed hourly flux estimates was also calculated. Slopes
<table>
<thead>
<tr>
<th></th>
<th>$R_n$</th>
<th>$H$</th>
<th>$LE$</th>
<th>$G$</th>
<th>$S_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ACASA</td>
<td>BATS</td>
<td>ACASA</td>
<td>BATS</td>
<td>ACASA</td>
</tr>
<tr>
<td>(a) Difference in mean (W m$^{-2}$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperate grass</td>
<td>4.86</td>
<td>-26.10</td>
<td>-6.54</td>
<td>-13.38</td>
<td>8.95</td>
</tr>
<tr>
<td>Young boreal deciduous forest</td>
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<td>-86.82</td>
<td>27.29</td>
<td>6.34</td>
<td>19.53</td>
</tr>
<tr>
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<td>-117.27</td>
<td>69.30</td>
<td>-43.10</td>
<td>-10.70</td>
</tr>
<tr>
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<td>-38.84</td>
<td>14.68</td>
<td>25.29</td>
<td>-13.12</td>
</tr>
<tr>
<td>Ancient temperate rainforest</td>
<td>3.73</td>
<td>-38.14</td>
<td>21.36</td>
<td>-31.86</td>
<td>0.17</td>
</tr>
<tr>
<td>(b) $r^2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperate grass</td>
<td>0.99</td>
<td>0.94</td>
<td>0.64</td>
<td>0.65</td>
<td>0.84</td>
</tr>
<tr>
<td>Degraded tropical pasture</td>
<td>1.00</td>
<td>0.99</td>
<td>0.76</td>
<td>0.18</td>
<td>0.95</td>
</tr>
<tr>
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<td>0.99</td>
<td>0.78</td>
<td>0.61</td>
<td>0.96</td>
</tr>
<tr>
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<td>0.95</td>
<td>0.87</td>
<td>0.79</td>
<td>0.42</td>
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<tr>
<td>Tropical rainforest</td>
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<td>0.99</td>
<td>0.76</td>
<td>0.80</td>
<td>0.97</td>
</tr>
<tr>
<td>Ancient temperate rainforest</td>
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<td>0.99</td>
<td>0.86</td>
<td>0.86</td>
<td>0.47</td>
</tr>
<tr>
<td>(c) Slope</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperate grass</td>
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<td>0.97</td>
<td>0.50</td>
<td>0.68</td>
<td>0.94</td>
</tr>
<tr>
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<td>0.83</td>
<td>1.01</td>
</tr>
<tr>
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<td><strong>1.34</strong></td>
<td>0.51</td>
<td><strong>0.40</strong></td>
<td>0.82</td>
</tr>
<tr>
<td>Old boreal coniferous forest</td>
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<td>1.32</td>
<td>0.68</td>
<td>0.95</td>
<td>0.97</td>
</tr>
<tr>
<td>Tropical rainforest</td>
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<td>1.02</td>
<td><strong>0.55</strong></td>
<td><strong>0.34</strong></td>
<td>1.11</td>
</tr>
<tr>
<td>Ancient temperate rainforest</td>
<td>0.98</td>
<td>1.05</td>
<td>0.59</td>
<td>0.58</td>
<td>0.77</td>
</tr>
</tbody>
</table>

Where emboldened values appear they indicate, with 95% confidence, that: in (a) differences in mean values are significant, in (b) values of $r^2$ are trivial, and in (c) values of $\hat{\beta}_1$ depart from unity.
(\hat{\beta}_1) and coefficients of determination (r^2) from linear regression analyses were used to compare observations and model output. Each comparison was tested for statistical significance using two-tailed Student's t-tests applied at the 95% confidence level (Weisberg 1980). For instance, differences in mean values were considered statistically significant when

$$|\bar{x} - \bar{y}| > t_{\alpha/2} \frac{\hat{\sigma}}{\sqrt{n}},$$

where \(\hat{n}\) represents the total number of points adjusted to account for autocorrelation in the time series following the methodology of Leith (1973). The standard error of the estimate (\(\hat{\sigma}\)) includes contributions of estimated observational uncertainties (\(\sigma^2_{obs}\)) such that

$$\hat{\sigma} = \sqrt{\sigma^2_{obs} + \frac{S_{xy} + S_{xy} - S^2_{xy}}{\hat{n} - 2}}.$$  

Equation (4) represents an effort to incorporate observational uncertainties into quantitative statistical comparisons in an internally consistent fashion. Values of observational uncertainties included in the above calculations are given in section 6.

To test the impacts that various aspects of model sophistication values have on simulated fluxes, simulations using ACASA were compared with simulations using versions of the model in which certain features were either simplified or enhanced relative to those in ACASA. Differences in mean flux values derived from output from ACASA and from simplified versions were tested for statistical significance using t-tests at the 95% confidence level. For instance, mean differences between ACASA and other model estimates were considered statistically significant when:

$$|\bar{x}_{AM} - \bar{x}_{ACASA}| > t_{\alpha/2} \sqrt{\frac{\sigma^2_{AM} + \sigma^2_{ACASA}}{\hat{n}}}$$

where the subscript AM refers to an alternative model.

6. TREATMENT OF OBSERVATIONAL UNCERTAINTIES

Screening of the data was necessary to avoid comparing simulated fluxes with unreliable measurements. Excluded were observations using EC equipment during or within two hours of rainfall, or when observed energy budget closure errors (discussed later) exceeded 100% of the net radiative flux. For the ancient temperate rainforest, significant observational errors were correlated with wind direction, which is thought to be due to tower interference and inadequate fetch in some directions. In this case, only the fluxes measured during times when the wind directions fell between 257 and 287 degrees were considered (King, personal communication). Such screening was not required for intra-canopy mean wind, temperature, and humidity measurements or at sites where EC techniques were not exclusively used. For each site the number of data available and the number utilized for each time series are provided in Table 1. Despite these screening measures, significant uncertainties in observed flux estimates remain.

In order to account for known observational uncertainties, instrumental errors in canopy flux and microenvironmental measurements were used to estimate values of
Figure 2. Scatter diagrams representing observed energy budget closure with 1:1 lines for the: (a) temperate grass, (b) degraded tropical pasture, (c) young boreal deciduous forest, (d) old boreal coniferous forest, (e) tropical rainforest, and (f) ancient temperate rainforest sites. Energy budgets in (a), (b), and (e) have been artificially closed. Here $R_n$, $H$, $LE$, $G$, and $S$ are net radiation, fluxes of sensible, latent, and ground heat, and canopy thermal storage, respectively.
\( \sigma_{obs}^2 \) appearing in Eq. (4). By comparing net radiation measurements from the most commonly used instruments, Halldin and Lindroth (1992) found that these data are accurate to within 15%. Uncertainties in \( LE \) and \( H \), calculated using methods suggested by Wyngaard (1973) and Angus and Watts (1984) for measurements taken using EC and Bowen-ratio techniques, ranged from 13% to 23%, depending upon the site. Measurements of \( G \) were considered accurate to within 10% or 3 W m\(^{-2} \), whichever is greater (Barr et al. 1994). Uncertainties in measurements of \( S \) are based on temperature and humidity uncertainties of 0.1 K and 0.1 g kg\(^{-1} \), respectively (Barr et al. 1994) and amounted to 27% for the old boreal coniferous forest site. Since values of \( S \) for the tropical rainforest site were taken as the residuals of the remaining terms in the surface energy budget, uncertainties were based on the combined absolute errors of \( R_n, H, LE, \) and \( G \). Wind speed measurements using sonic anemometers* were considered accurate to within 1.5%.

To aid the reader in ascertaining the importance of closure errors in the comparisons performed in this investigation, observed values of \( R_n - G - S \) versus \( H + LE \) for each site appear in Fig. 2. A lack of energy budget closure is most evident at the young boreal deciduous and ancient temperate rainforest sites, where linear regression slopes indicate with 95% confidence that at least 29% of measured values of \( R_n - G - S \) remains unaccounted for by the \( H + LE \). The closure discrepancy at the old boreal coniferous forest site is less but still statistically significant (7–10% with 95% confidence). Each of these sites exhibiting unclosed energy budgets exclusively used EC techniques to estimate sensible- and latent-heat fluxes. Energy budgets at the temperate grass and both tropical sites appear much more balanced in Fig. 2 than the boreal and temperate forest cases. For these sites, estimating one of the terms as the residual of the remaining measured fluxes closed the measured energy budgets (Bastable et al. 1993; Beljaars and Bosveld 1997). Inadequate fetch (Moore and Hicks 1973; Fitzjarrald and Moore 1994), a mismatch of net radiometer and EC footprints (Moore et al. 1996), and nonzero mean vertical motions associated with stationary convective cells (Lee and Black 1993) are possible sources of these errors. Another problem, frequently encountered during nights with light winds, is the tendency of mean vertical velocities to negatively bias the magnitudes of EC flux measurements (Lee 1998; Paw U et al. 2000). A thorough survey of the problem can be found in Mahrt (1998). These closure uncertainties are not included in the estimates of \( \sigma_{obs}^2 \).

### 7. Results for Flux Comparisons

Scatter plots of simulated versus observed \( R_n \) for each of the test sites (Fig. 3) summarized in Table 2 show excellent correspondence between modelled and observed hourly values at each site. Departures from long-term means are not statistically significant at the 95% confidence level, nor are they large in comparison to the mean observed values. Departures relative to the observed means range from less than \(-1.4\% \) at the young boreal deciduous forest site to \(+12.0\% \) at the old boreal coniferous forest site, but at most sites they are consistently positive, suggesting a slight though statistically insignificant positive bias in ACASA net radiation. Since leaf optical properties specific to many of the sites were used, and if this slight bias is model-related, then it is likely to be due to uncertainties in the specification of soil surface albedo, stem albedo and stem area. Values of \( r^2 \) close to unity indicate that observed and modelled hourly estimates are

* Gill Instruments Inc. SOLENT Windmaster specification sheet available online at http://www.gill.co.uk/data/windmast.pdf
Figure 3. Scatter diagrams of observed hourly net radiation ($R_n$) values versus ACASA (see text) simulations, with 1:1 lines, for the: (a) temperate grass, (b) degraded tropical pasture, (c) young boreal deciduous forest, (d) old boreal coniferous forest, (e) tropical rainforest, and (f) ancient temperate rainforest sites.
very well correlated with one another. Slopes of regression lines are within observational uncertainties at all sites.

Results appearing in scatter plots in Fig. 4 and summarized in Table 2 show that in general, observed and simulated estimates of $LE$ are linearly related at each of the sites. Observed values exhibit variations in maxima of $LE$ between locations, reflecting the combined influences that differing biophysical and meteorological processes have on evapotranspiration. Mean departures, though not significant at the 95% confidence level, are positive at most sites; they range from $-12.7\%$ at the old boreal coniferous site to $+22.6\%$ at the young boreal deciduous location. High values of $r^2$ at the temperate grass, degraded tropical pasture, young boreal deciduous forest, and tropical rainforest sites reflect good agreement in the direction of hour-to-hour variability between observed and modelled estimates of $LE$. Values of $r^2$ in Table 2 show more relative scatter at the ancient temperate rainforest and old boreal coniferous sites. Figure 4 reveals that the absolute magnitudes of hourly departures are similar to those found at other sites but, because the ranges of $LE$ are small at the old boreal coniferous forest and ancient temperate rainforest sites, values of $r^2$ are lower. Slopes are statistically indistinguishable from unity for all but the old boreal coniferous forest site. However, the amount of energy budget closure error seen in Fig. 2 for this site is more than enough to account for this difference.

Scatter plots and statistics for observed and modelled sensible-heat flux densities given in Fig. 5 and Table 2 also exhibit very good agreement between mean values and hourly correlations at all sites. Regression slopes are statistically different from unity at the tropical rainforest site. Observed ranges for all but the old boreal coniferous forest and ancient temperate rainforest site are small in relation to that for $LE$, and in most cases the observed mean values are less than 30 W m$^{-2}$. Plots in Fig. 5 and high values of $r^2$ confirm a largely linear relationship between observed and modelled estimates in most cases, with the highest $r^2$ values associated with sites that exhibit large ranges in hourly values of $H$.

Simulated and observed ground and canopy heat storage terms ($G$ and $S$) are in very good agreement in most instances. Long-term average differences of $G$ and $S$ are within statistical uncertainties at all sites (Figs. 6 and 7, Table 2). Values of $r^2$ for these terms are comparable to, or greater than, values for $H$ at most locations, though not as high as $LE$. Regression slopes indicate that hourly values of $G$ and $S$ are in agreement with observations at the 95% confidence level at all but the two boreal locations, where there is a tendency to overestimate $G$. For the two tallest, densely vegetated sites, simulated and modelled $G$ were insignificant portions of the energy budgets. Besides observational error, it is possible that the disagreement in hourly $G$ estimates is due to temporally varying soil characteristics, LAI, and leaf litter cover not factored into the model. For example, the temperate grass site's soil character was assumed constant in the model, but in reality changed from one season to the next, which could explain hourly differences in observed and simulated $G$ sometimes exceeding 50 W m$^{-2}$. Results from sensitivity tests (not shown) reveal that ground heat fluxes are sensitive to changes in the organic content of the model's soil, leaf litter cover, and LAI representations. This suggests that the inclusion of these parameters in observational datasets would be helpful. Absolute values of $S$ for the old boreal coniferous forest and tropical rainforest were often greater than 50 W m$^{-2}$. Hourly estimates of $S$ for the ancient temperate rainforest site (not shown) often exceeded 100 W m$^{-2}$, and in some cases were greater than 150 W m$^{-2}$. These results confirm the findings of Moore and Fisch (1986) that $S$ can be a significant component of the surface energy balance for large canopies.
Figure 4. Scatter diagrams of observed hourly latent-heat flux density ($LE$) values versus ACASA (see text) simulations, with 1:1 lines, for the: (a) temperate grass, (b) degraded tropical pasture, (c) young boreal deciduous forest, (d) old boreal coniferous forest, (e) tropical rainforest, and (f) ancient temperate rainforest sites.
Figure 5. Scatter diagrams of observed hourly sensible-heat flux density ($H$) values versus ACASA (see text) simulations, with 1:1 lines, for the: (a) temperate grass, (b) degraded tropical pasture, (c) young boreal deciduous forest, (d) old boreal coniferous forest, (e) tropical rainforest, and (f) ancient temperate rainforest sites.
Figure 6. Scatter diagrams of observed hourly ground heat flux density ($G$) values versus ACASA (see text) simulations, with 1:1 lines, for: (a) temperate deciduous forest, (b) degraded tropical pasture, (c) young boreal deciduous forest, (d) old boreal coniferous forest, (e) tropical rainforest, and (f) incipient temperate rainforest sites.
Figure 7. Scatter diagram of observed hourly total canopy heat storage ($S$) values versus ACASA (see text) simulations, with 1:1 lines, for the: (a) old boreal coniferous forest and (b) tropical rainforest sites.

Figure 8. Average daytime microenvironmental conditions: (a) and (b) show vertical profiles of mean air temperature at the ancient temperate rainforest and tropical rainforest sites, respectively; (c) and (d) show vertical profiles of mean wind speed and specific humidity at the ancient temperate rainforest site. Error bars attached to observed points (full circles) represent 95% confidence intervals. Lines represent ACASA (see text) simulated values. Heights are given in multiples of the canopy height.

8. RESULTS FOR CANOPY MICROENVIRONMENTAL COMPARISONS

Comparisons of simulated and observed intra-canopy microenvironmental conditions provide a second measure of ACASA accuracy (Fig. 8). Vertical profiles of mean wind, temperature, humidity, and CO$_2$ are important factors that contribute to plant
physiological response in the model. Observations of intra-canopy temperature, humidity, and wind speed at the ancient temperate rainforest covered 88 consecutive days at five levels within the canopy. Temperature observations exist for the tropical rainforest site (6 levels, 25 days), and temperature and humidity data were gathered at the old boreal coniferous site (1 level, 45 days).

Average daytime mean wind profiles at the ancient temperate rainforest site (Fig. 8(c)) show very good qualitative agreement between ACASA and observations. Both ACASA and observations show a strong attenuation of wind speeds on the descent though the upper canopy, and a slight sub-canopy maximum in the lower canopy. ACASA and observed mean wind values for daytime conditions agree with more than 95% confidence at all levels. Night-time values (not shown) exhibit a similar pattern.

Simulated profiles of averaged daytime air temperatures both at the tropical and at the temperate rainforest sites (Fig. 8(a) and (b)), and specific humidity at the ancient temperate rainforest site (Fig. 8(d)) agree with the data at greater than 95% statistical significance. ACASA produced night-time air temperature values (not shown) that were statistically indistinguishable from observations at comparable heights within the canopy, despite an observed 3–5 degC diurnal cycle at those locations. Simulated values for mean day and night air temperature and humidity also agree with 95% statistical confidence with observed values at the old boreal coniferous site (not shown). Both results suggest that ACASA and observations realize similar diurnal cycles in temperature. Results were also in statistical agreement with 95% confidence for specific humidity at the ancient temperate rainforest site at all levels for both daytime and night-time periods.

9. Comparisons between ACASA and Biosphere–Atmosphere Transfer Scheme Simulated Fluxes

Flux estimates from the Biosphere–Atmosphere Transfer Scheme (BATS; Dickinson et al. 1993) were derived using the same data for each of the six sites and compared with ACASA simulations. BATS was chosen for this comparison because the code is well-documented, the model has a history of relative accuracy and reliability, and it is used in larger-scale models (Henderson-Sellers et al. 1993; Chen et al. 1997). In addition, many soil and vegetation parameters required by BATS are similar to those required by ACASA.

In each case parameters specifying the soil and vegetation conditions, including soil type, canopy height, leaf optical properties, and leaf area index were identical to those specified for ACASA. BATS also requires a minimum stomatal resistance factor for its physiological representation which differs considerably from that in ACASA. This factor is specified for tropical and temperate deciduous forests in the BATS code. For the temperate grass case the value suggested by PILPS 2a was used. For the ancient temperate rainforest and old boreal coniferous forest sites, minimum stomatal resistances were increased in an analogous fashion to the values chosen for the SBB parameter (Table 1). Statistical significance was established using the same techniques as in the ACASA tests. Table 2 gives results of the BATS runs in parallel with those for ACASA.

A most striking difference between ACASA and BATS simulations is that BATS tended to underestimate net radiation at all sites. These differences are most apparent in the long-term mean values, especially at the two boreal forest locations where mean differences are large though not statistically significant. Values relative to the mean, range from −16.1% at the degraded tropical pasture site to −57.5% at the temperate
grass site. Additional tests (not shown), in which BATS was driven using observed
downwelling long-wave radiation instead of the current empirical estimate, produced
slightly less scatter but had little effect on the tendency for BATS to underpredict net
radiation. Thus these biases originate in the short-wave estimations despite the model
being driven with canopy optical properties identical to those used in ACASA. This
could be due to uncertainties in specifying soil reflectance and fractional vegetative
cover, the absence of separate calculations for sunlit and shaded leaves (Norman
1979), or an underestimation of radiative in-scattering arising from the low vertical
resolution in BATS used in the radiative transfer calculations. Differences were large
enough in a consistent fashion to partially offset the surface energy budget closure
problem at each of the three EC sites, especially for the young boreal deciduous forest
(Fig. 2).

An additional important difference evident is the overall contrast between BATS and
ACASA flux estimates in values of $r^2$ and mean departures (Table 2) at each site. BATS
produced more scatter than did ACASA in 20 out of 24 instances, and mean departures
were larger for BATS than ACASA in 19 out of 24 cases. Differences between BATS and
ACASA mean departures tended to be greatest for $LE$ at the young boreal deciduous
forest, old boreal coniferous forest, and tropical rainforest sites. Differences in $r^2$
were most pronounced for $H$ at the degraded tropical pasture site, with low values for BATS
estimates reflecting much more scatter relative to that found for ACASA. BATS and
ACASA were comparable for estimations of $LE$ at the two shortest canopies, but
BATS produced consistently more scatter for the four taller canopies. Results for $G$
also show more scatter at most of the sites, but BATS did yield less scatter for the two
boreal sites. Simulations with incident long-wave radiation specified by observations in
BATS reduced scatter somewhat, but not enough to alter the general trend of the results
presented here.

Regression slopes for BATS hourly flux estimates are statistically different from
unity in more cases than ACASA values, especially for G, despite less confidence in
the values than for ACASA at most sites. Observed slope values from BATS for $G$
are further from unity than ACASA by a statistically significant extent at all but the old
boreal coniferous site. Slopes show that hourly BATS and observations were statistically
different in a consistent fashion for most fluxes at the young boreal deciduous and
tropical rainforest sites. The slope for hourly $R_n$ values is significantly greater than
unity at the young boreal deciduous forest site, reflecting a consistent hourly trend in
underprediction by BATS for this quantity. Differences between ACASA and BATS
values at the young boreal deciduous and the tropical rainforest sites show that BATS
partitioned more available energy into $H$ and $LE$ than did ACASA, especially at the
latter location where the difference from unity in the $LE$ slope is also statistically
significant but of opposite sign. The small BATS regression slopes for $G$ indicate that
BATS produced a much larger amplitude for the diurnal cycle than ACASA, despite
similar thicknesses of the soil layers in both models. Results given in Chen et al. (1997)
show that overestimations of the diurnal cycle in $G$ are evident for most simple land
surface schemes at the Cabauw site, indicating that this may be a common problem
with these land surface models. ACASA also includes the effects of leaf litter cover
and organic content of the soil, both of which attenuate the soil heat flux. Thus, some
of the improvement in the ACASA simulated diurnal cycle in $G$ may be an artifact
of how soil leaf litter cover and organic content were specified in lieu of observed
values. Since the soil model within ACASA is very similar to those used by simpler
schemes, shortcomings in the simulation of $G$ may reflect a more fundamental soil
physics problem that is beyond the scope of this discussion.
TABLE 3. MEAN DIFFERENCES BETWEEN FLUXES SIMULATED BY ACASA AT DIFFERENT SITES, AND THOSE PRODUCED BY SIMPLIFIED MODEL VERSIONS

<table>
<thead>
<tr>
<th></th>
<th>Temperate grass</th>
<th>Degraded tropical pasture</th>
<th>Young boreal deciduous forest</th>
<th>Old boreal coniferous forest</th>
<th>Tropical rainforest</th>
<th>Ancient temperate rainforest</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) 5 layers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H$</td>
<td>-6.71</td>
<td>-41.70</td>
<td>-5.62</td>
<td>-7.49</td>
<td>-22.54</td>
<td>-18.56</td>
</tr>
<tr>
<td>$L.E.$</td>
<td>7.85</td>
<td>44.50</td>
<td>3.01</td>
<td>7.35</td>
<td>24.02</td>
<td>17.73</td>
</tr>
<tr>
<td>(b) 10 layers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H$</td>
<td>1.21</td>
<td>-2.64</td>
<td>-2.49</td>
<td>-0.22</td>
<td>-2.46</td>
<td>-6.56</td>
</tr>
<tr>
<td>$L.E.$</td>
<td>-2.49</td>
<td>3.12</td>
<td>-0.14</td>
<td>2.10</td>
<td>3.01</td>
<td>7.56</td>
</tr>
<tr>
<td>(c) 40 layers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H$</td>
<td>-6.54</td>
<td>10.00</td>
<td>-5.67</td>
<td>-5.93</td>
<td>-6.58</td>
<td>-0.81</td>
</tr>
<tr>
<td>$L.E.$</td>
<td>5.88</td>
<td>-12.93</td>
<td>3.42</td>
<td>5.96</td>
<td>6.58</td>
<td>1.36</td>
</tr>
<tr>
<td>(d) Jarvis physiology</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H$</td>
<td>-22.89</td>
<td>-2.23</td>
<td>29.13</td>
<td>93.57</td>
<td>3.03</td>
<td>30.93</td>
</tr>
<tr>
<td>$L.E.$</td>
<td>25.11</td>
<td>1.43</td>
<td>-31.49</td>
<td>-94.66</td>
<td>-3.15</td>
<td>-30.54</td>
</tr>
<tr>
<td>(e) Penman–Monteith for temperatures $H$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H$</td>
<td>-22.89</td>
<td>-35.48</td>
<td>-48.29</td>
<td>-40.29</td>
<td>-40.70</td>
<td>-22.83</td>
</tr>
<tr>
<td>$L.E.$</td>
<td>25.11</td>
<td>38.26</td>
<td>53.05</td>
<td>50.21</td>
<td>41.56</td>
<td>23.06</td>
</tr>
<tr>
<td>(f) 2nd-order, neutral turbulence</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H$</td>
<td>2.22</td>
<td>1.20</td>
<td>12.39</td>
<td>1.46</td>
<td>1.65</td>
<td>0.54</td>
</tr>
<tr>
<td>$L.E.$</td>
<td>-2.26</td>
<td>0.70</td>
<td>-15.03</td>
<td>-0.69</td>
<td>-1.64</td>
<td>-0.58</td>
</tr>
<tr>
<td>(g) b, d, e, f combined</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H$</td>
<td>-19.42</td>
<td>-15.07</td>
<td>2.41</td>
<td>65.51</td>
<td>-9.29</td>
<td>35.14</td>
</tr>
<tr>
<td>$L.E.$</td>
<td>12.73</td>
<td>18.10</td>
<td>-2.24</td>
<td>-59.19</td>
<td>9.85</td>
<td>-35.06</td>
</tr>
</tbody>
</table>

Differences are given for sensible- and latent-heat fluxes $H$ and $L.E.$, respectively (W m$^{-2}$). Emboldened values are statistically significant at the 95% confidence level.

10. SENSITIVITY TESTS

A series of sensitivity tests was performed to isolate those processes that are important to the accuracy of ACASA flux predictions. These tests involved comparing ACASA results against those from versions with: different vertical resolutions (5, 10, 40, and 100 above-ground layers); a simpler stomatal conductance scheme (Jarvis 1976) for unstressed stomatal resistances; a first-order (Penman–Monteith) method for calculating leaf, stem, and soil surface temperatures (Penman 1948; Monteith 1965, 1973); or no third- and second-order diabatic contributions to the turbulence; or a combination of the above simplifications. Statistical significance was established by comparing simulations using simplified versions of ACASA with those from the full version using Eq. (5). Table 3 contains differences in mean flux values between ACASA and the simplified versions of ACASA used for sections 7–9.

Changing the vertical resolution produced altered estimates of $L.E.$ and $H$ in manners not clearly related to the type of vegetation (Table 3). Reducing the resolution to five layers produced changes to $L.E.$ and $H$ that are comparable with those arising from changing the surface temperature or physiological formulations. In contrast, mean differences were generally smaller upon halving or doubling the vertical resolution, yet most values are statistically significant at the 95% confidence level. A curious result appears in Table 3, where values at both tropical sites appear more sensitive to the most extreme changes in resolution than at the remaining locations. Results for mean vertical temperature profiles (not shown) for higher resolutions show a greater qualitative match with the observed upper-canopy maximum evident in Fig. 8(b). In addition, mean differences (in Table 3), slope and $r^2$ values (not shown) for $L.E.$ and especially $H$ suggest an improved match with observations for both tropical sites with the 40-layer version. In contrast, lowering the vertical resolution at the tropical sites
yielded increased differences between model output and observations as indicated by the mean differences (Table 3), slope and $r^2$ values (not shown).

Flux simulations are generally most sensitive to changes in surface temperature and model physiology calculation techniques (Table 3). Differences from each of the tests are statistically significant at the 95% confidence level in nearly all cases. The simpler scheme for estimating surface temperatures consistently biased the model towards greater $H$, by similar amounts at most sites. Simplifying the plant physiological response produced a less consistent set of changes, with the greatest values occurring in temperate regions but with very different changes to mean $H$ and $LE$ estimates at each site.

Turbulence sophistication is generally less important for $H$ and $LE$ than the previously mentioned features, but is still statistically significant in most cases. Though differences in $LE$ and $H$ mean values are small, simplifying the turbulence produced regression slope changes (not shown) in excess of $\pm 10\%$ at a number of sites. Why this sensitivity is not apparent in mean values is largely due to averaging over diurnal cycles, where differences in hourly flux estimates change sign between day and night. Most of this diurnal phenomenon is related to buoyancy terms shifting sign between stable and unstable conditions. Maximum hourly $H$ and $LE$ differences between ACASA and the simplified turbulence version were found to exceed $\pm 50$ W m$^{-2}$ in many daytime cases. Unlike the cases of simplifying surface temperature and physiological response calculations, mean differences in Table 3 and slopes (not shown) indicate that ACASA is sensitive to simplifying the turbulence in a manner that varies between sites, which reflects the differences that climate and vegetation processes have on the turbulence. This is especially evident at the young boreal forest and degraded tropical pasture sites.

Combining simplified turbulence, low resolution, physiological and surface temperature estimation techniques produced results that were not the arithmetic sums of each mean difference taken separately, nor were the directions of changes the same (Table 3). In some instances, such as the values of $H$ and $LE$ at the ancient temperate rainforest, the sum of results from tests (b), (d), (e), and (f) in Table 3 were radically different from those from all simplifications combined in test (g). This indicates that the main ACASA components of the canopy system are not linearly related; thus simplified parametrization in lieu of the full calculations would be likely to be difficult to calibrate accurately for multiple surface types.

11. CONCLUSIONS

ACASA estimates long-term mean energy fluxes in agreement with observations under widely varying vegetative and climatic conditions. It can also simulate many observed aspects of average canopy microenvironmental conditions at widely different sites to within statistical uncertainty.

Tests comparing BATS with ACASA suggest that ACASA may offer significant improvements in surface flux representations over existing land surface schemes, and that ACASA can be used as a benchmark with which to compare and improve simpler schemes. Despite use of the same leaf optical properties, BATS consistently estimated less net radiation than ACASA, and in some cases this difference is large. ACASA estimates were better correlated with observations than those from BATS simulations with a few isolated exceptions. ACASA diurnal cycles in $G$ were generally much closer to observed patterns than BATS estimates. By optimizing ACASA and BATS, it is possible that both models can perform similarly in terms of mean departures and regression slopes for $H$ and $LE$ partitioning. However, the general pattern of higher
correlations between ACASA and observed values relative to those for BATS represents an improvement that may be difficult to overcome through optimization efforts on BATS.

Results from sensitivity tests suggest that several processes represented by ACASA are important. Simplifying the solution technique for surface temperature calculations and plant physiological response had statistically significant impacts on most flux estimates. Predictions from lower-resolution versions indicate that lowering the above-ground resolution from 20 to ten and to five layers had statistically significant impacts on most flux estimates. Differences arising from increasing the vertical resolution led to the largest changes in flux estimates in the tropics. The trends from low to high resolution at both tropical sites in both flux and microenvironmental estimates suggest that more than 20 layers may be desirable for simulations involving these ecosystems. ACASA is sensitive to third-order and diabatic second-order turbulence calculations in ways that reflect complex relations between canopy microclimate and physiology. Tests combining several simplifications indicate that combinations produced differences that were unlike the linear sum of changes brought about by each simplification individually. The changes to \( H \) and \( LE \) from all the tests are of a similar or greater magnitude than those found to affect climate simulations significantly.

Although these results are very encouraging, more work needs to be done to establish ACASA as a general surface-layer model that can be applied to all vegetated regions at all times of the year. Work is progressing on a version of ACASA that represents soil physics and physiology more completely than the current version. Also needed are improved representations of canopy snow accumulation and ablation, and their effects on the surface-layer energy balances, seasonal and interannual changes to plant physiology and canopy structure, and inclusion of limitations on transpiration due to canopy architecture. In addition, it would be useful to explore avenues for representing subgrid-scale heterogeneity in land-use specification in ACASA simulations. It would also be helpful to perform additional off-line tests to investigate how ACASA treats the exchanges of \( CO_2 \) and other trace gases, and how these relate to plant physiological responses under current and future climate scenarios. Further investigations of the kinematic aspects of ACASA using observed leaf drag properties would also be helpful.

In addition, many physiological and biometric quantities required by ACASA in a continental or global context are not available from field studies. These quantities include canopy height, vertical distribution of leaf and stem area indices, leaf litter cover, leaf optical properties, canopy drag coefficients, mean leaf diameter, species-specific stomatal responses and fractional soil humus content. This lack of observed land surface characterizations remains a major impediment to the implementation of ACASA as a component in weather and climate simulations. However, the use of simpler state-of-the-art models raises the same concern. For instance, most current land surface models such as BATS require the specification of zero-plane displacement heights and roughness lengths, both of which are assumed to be linearly related to canopy height and structure.

At present, current computer limitations may make it impractical to use ACASA for long-term, global-climate studies. Yet this is likely to change as computer technology advances further. Since ACASA is a single-point model, however, it would be best to apply it to simulations with finer horizontal resolutions (less than 40 km) in order to minimize errors due to subgrid-scale horizontal heterogeneities and associated advective effects. Thus, despite the current shortage of adequate land-use characteristics needed by ACASA, this model can serve to improve weather and climate prediction either indirectly by using it to test and improve simpler formulations, or directly by using it to estimate surface-layer processes within atmospheric models.
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