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[1] National Centers for Environmental Prediction, Environmental Modeling Center, Suitland, Maryland, USA
[2] Meteorology and Air Quality Section, Wageningen University, Wageningen, Netherlands

Evaluation of a land-surface scheme at Cabauw

M. B. Ek[1] and **A. A. M. Holtslag**[2]

With 10 Figures

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Summary

We study the response of the land-surface to prescribed atmospheric forcing for 31 May 1978 at Cabauw, Netherlands, using the land-surface scheme from the Coupled Atmospheric boundary layer-Plant-Soil (CAPS) model. Results from model runs show realistic daytime surface fluxes are produced using a canopy conductance formulation derived from Cabauw data (for 1987, a different year), and *un-tuned* parameterizations of root density (near-uniform with depth) and soil heat flux (reduced thermal conductivity through vegetation). Sensitivity of model-calculated surface heat fluxes to initial values of soil moisture is also examined. Results of this study provide the land-surface 'base state' for a coupled land–atmosphere modeling study.

1. Introduction

Land-surface schemes are an important part of the parameterization in any atmospheric model, and as such, their evaluation has received much attention (e.g. see the PILPS overviews by Henderson-Sellers et al., 1993; 1995). Often these schemes are evaluated for a long period of time, however, mostly only limited long-term data sets are available to test the details of the schemes. In this paper we focus on an evaluation of a state-of-the-art land-surface scheme for a daytime case at Cabauw, Netherlands, but explore the details with an extensive data set. Using *a priori* formulations and parameters for the important land-surface processes, we test sensitivities of modeled surface fluxes. The diurnal variation of the land surface is an important issue because of its influence on atmospheric boundary-layer (ABL) development (e.g. see Ek and Holtslag, 2004).

Developments in numerical weather prediction (NWP) and atmospheric climate models have focused increased attention on land-surface processes (e.g. Viterbo and Beljaars, 1995 and references therein). Many of these developments have been pursued in an effort to bring the parameterization of land-surface processes within NWP models in line with developments in the plant and soil physics communities, thereby recognizing progress in these associated disciplines. For example, Ek and Cuenca (1994) and Cuenca et al. (1996) examined the response of the ABL to variations in soil hydraulic properties; Peters-Lidard et al. (1997; 1998) examined the effect of vegetation and soil thermal properties on soil heat flux; and Beljaars and Bosveld (1997) examined the influence of evaporative control on surface moisture flux by the vegetation at Cabauw.

The case study by Holtslag et al. (1995) examined ABL model runs driven by observed surface fluxes, and reproduced the observed boundary-layer structure for a case study at Cabauw reasonably well. But in coupled land-surface – ABL model runs they found that they could not reproduce observed fluxes and boundary-layer structure using a simpler land surface scheme. Here we use the same case study day as Holtslag et al. (1995), but use the more sophisticated land-surface scheme from the Coupled Atmospheric boundary layer-Plant-Soil (CAPS) model originally developed at Oregon State University. This land-surface scheme has been used in a stand-alone mode for a number of sensitivity experiments under different geophysical conditions (e.g. Kim and Ek, 1995; Chen et al., 1996) and as part of the Project for Intercomparison of Land-surface Parameterization Schemes (PILPS, e.g. Chang and Ek, 1996; Chen et al., 1997; Liang et al., 1998; Lohmann et al., 1998; Qu et al., 1998; Wood et al., 1998; Chang et al., 1999); the study by Chang et al. (1999) includes a comprehensive description of the current physics in the CAPS model land-surface scheme.

The purpose of this study is to examine 'stand-alone' (or 'offline') model runs of the CAPS model land-surface scheme forced by observed atmospheric and downward radiation measurements at Cabauw to assess the ability of our scheme to properly partition the incoming radiation into surface heat fluxes and outgoing radiation. Specifically, we will explore assumptions made and examine alternatives for (1) canopy conductance (which affects the partition between latent and sensible heat flux), (2) root density characterization, and (3) soil heat flux parameterization. These tests allow us to isolate the processes responsible for surface fluxes without ABL interaction in an attempt to determine the 'best' version of the land-surface scheme for coupling with the ABL (e.g. as in Ek and Holtslag, 2004). We first describe the data set at Cabauw (Section 2), then give an overview of the components in the CAPS model land-surface scheme relevant to this study (Section 3), followed by model sensitivity runs (Section 4), and then a summary (Section 5).

2. Cabauw site and data set

In this study we use observations made on 31 May 1978 at the Cabauw site in central Netherlands that provide a comprehensive data set for model initialization and verification. The region surrounding the Cabauw site is rather flat for a distance of at least 20 km, with many fields and scattered canals, villages, orchards and lines of trees. One of the main branches of the Rhine, the River Lek, flows about one kilometer south of the Cabauw site, approximately 45 km east of the North Sea.

The Cabauw site itself is located in an open field nearly completely covered by short grass which extends for several hundred meters in all directions, and a series of shallow, narrow ditches that provide drainage for the site. Under the sod layer (3 cm) the soil consists of heavy clay down to about 0.6 m, with a nearly saturated peat layer below. Soil moisture measurements using neutron probe were taken covering the study day at three sample sites in the micromet tower plot adjacent to the Cabauw tower; measurements were made at 10 cm intervals down to 50 cm, and at 1 m (Wessels, 1983). While 31 May 1978 was during the beginning of a 'dry-down' period, soil moisture values were still sufficiently high so that transpiration was not overly limited. There had not been any precipitation for a week, and this was to last three more weeks into later June before the next substantial precipitation event.

The 213 m tower at the Cabauw site includes sensible and latent heat fluxes determined from profile and Bowen ratio methods. Incoming solar and longwave radiation, low-level surface and soil temperatures, and low-level specific humidity measurements were made at the micrometeorological site adjacent to the Cabauw tower (within 200 m). The downward longwave radiation is suspect, however, being anomalously low. An estimate of downward longwave radiation is made as a residual by taking the difference between the observed net radiation, and the sum of the net solar radiation and outgoing terrestrial (longwave) radiation (computed from the infrared radiometer assuming an emissivity of one). Soil heat fluxes were measured by transducers buried at depths of 5 and 10 cm; surface soil heat flux was inferred from extrapolation of these measurements (Beljaars and Bosveld, 1997). See Monna et al. (1987) and Wessels (1984) for further information on Cabauw observations.

3. Land-surface scheme

The CAPS model land-surface scheme consists of multiple soil layers (Mahrt and Pan, 1984), and a simple plant canopy (Pan and Mahrt, 1987) modified to include the effect of vegetation using a 'big leaf' approach for canopy conductance (inverse of canopy resistance) following Noilhan and Planton (1989; hereafter NP89) and Jacquemin and Noilhan (1990). This more empirically-based approach for canopy conductance follows the original work by Jarvis (1976) and Stewart (1988) where canopy conductance is modeled as a function of atmospheric forcing and soil moisture availability. Alternate more recent 'physiologically-based' formulations for canopy conductance as a function of CO_2 assimilation will not be utilized in this study, e.g. Jacobs (1994), Sellers et al. (1996), Sen et al. (2000), Ronda et al. (2001).

3.1 Transpiration and canopy conductance

Evaporation in our scheme is calculated as

$$E = \beta_{E_p} f_\Theta E_p \tag{1}$$

where β_{E_p} is the potential evaporation fraction, f_Θ is the fractional availability of root-zone soil moisture (described further below), and E_p is the potential evaporation (a function of atmospheric forcing). The potential evaporation fraction, β_{E_p}, is the ratio of actual evaporation to the potential evaporation and accounts for the reduction in actual evaporation from potential evaporation due to the stomatal control by plants, here related to *atmospheric* conditions; β_{E_p} can be related to canopy conductance (g_c) by equating the bulk aerodynamic forms of E and $\beta_{E_p} E_p$ which yields

$$\begin{aligned}\beta_{E_p} &= E/E_p \\ &= \frac{(\rho\delta q)/(1+g_a/g_c)}{\rho g_a \delta q} \\ &= \frac{g_c}{g_c+g_a}\end{aligned} \tag{2}$$

where ρ is air density, δq is the land-atmospheric specific humidity deficit, and g_a is aerodynamic conductance (inverse of aerodynamic resistance), the product of the wind speed and the surface exchange coefficient, which in turn is a function of surface roughness and atmospheric stability via Monin-Obukhov similarity theory. Surface exchange coefficients (and thus surface fluxes) are calculated by iterating an implicit formula of the Monin-Obukhov similarity functions described in Beljaars and Holtslag (1991).[1]

The 'big-leaf' development for canopy conductance by NP89 follows the original approach of Jarvis (1976) and Stewart (1988) where canopy conductance (g_c) is modeled as a function of the species-dependent maximum stomatal conductance ($g_{c\max}$) and several reduction factors as

$$g_c = g_{c\max} f_{S\downarrow} f_T f_q \tag{3}$$

where $f_{S\downarrow}$, f_T, and f_q are functions of atmospheric forcing (incoming solar radiation, air temperature, and atmospheric vapor pressure deficit, respectively), all functions of plant species, with values between 0 and 1. (In our scheme we exclude the usual dependence of g_c on root-zone soil moisture availability, f_Θ, and instead include it directly as a linear reduction factor in the calculation of E via Eq. (1).) As an alternate to NP89 (yet still following the Jarvis-Stewart approach), we also include the Cabauw-specific canopy conductance formulations for *atmospheric* forcing (as in Eq. (3)) derived by Beljaars and Bosveld (1997; hereafter BB97) based on an evaluation of the annual 1987 Cabauw data set used in PILPS phase 2a (hereafter PILPS2a; Chen et al., 1997). (Note that the BB97 parameterization for canopy conductance is based on an annual data set from 1987, a year different from our case study.) The NP89 and BB97 canopy conductance functions for atmospheric forcing are

$$\begin{array}{lcc} \text{factor} & \text{NP89 formulation} & \text{BB97 formulation} \\ f_{S\downarrow} = & \left(a+\frac{g_{c\max}}{g_{c\min}}\right)(a+1)^{-1} & \left(\frac{S\downarrow(b_{1S\downarrow}-b_{2S\downarrow})}{b_{1S\downarrow}S\downarrow+b_{2S\downarrow}(b_{1S\downarrow}-2S\downarrow)}\right) \\ f_T = & 1.0-a_T(T_{\text{ref}}-T_a)^2 & 1.0 \\ f_q = & 1-a_q(\delta e) & (1+b_q(\delta q_a-\delta q_r))^{-1} \end{array} \tag{4}$$

where $a = (1.1/LAI)(S\downarrow/a_{S\downarrow})$, LAI is leaf area index, $S\downarrow$ is incoming solar radiation, T_a, δe_a and δq_a are the air temperature, and atmospheric

[1] This replaces the previous method in our scheme which used an explicit dependence on the near-surface bulk Richardson number to determine surface exchange coefficients following Louis (1979) and Louis et al. (1982). This step was taken because of a limitation in the application of the Louis formulation for cases where the ratio of the momentum to heat roughness is large, as demonstrated in Holtslag and Ek (1996), and explored further in van den Hurk and Holtslag (1997). See Beljaars and Holtslag (1991) for further discussion on this issue as applied to the Cabauw site.

Table 1. CAPS model land-surface scheme parameters for Cabauw. Note that λ_{T0} is the initial value corresponding to the Cabauw soil type and initial soil moisture content in the upper soil layer

Description	Parameter	Value	Units
Vegetation fraction	σ_f	0.97	–
Momentum roughness	z_{0m}	0.15	m
Thermal roughness	z_{0h}	2.35×10^{-5}	m
Soil moisture (volumetric)			
Porosity	Θ_{sat}	0.600	–
Field capacity	Θ_{fc}	0.491	–
Wilting point	Θ_{wilt}	0.314	–
Vegetation (NP89 formulation with Cabauw (PILPS2a) parameter set)			
Maximum canopy conductance	$g_{c\max}$	0.0426	$\mathrm{m\,s^{-1}}$
Minimum canopy conductance	$g_{c\min}$	5×10^{-5}	$\mathrm{m\,s^{-1}}$
Leaf area index	LAI	1.7	–
Solar coefficient	$a_{S\downarrow}$	100	$\mathrm{W\,m^{-2}}$
Thermal coefficient	a_T	0.0016	$\mathrm{K^{-2}}$
Reference temperature	T_{ref}	298.0	K
Humidity coefficient	a_q	0.024	$\mathrm{mb^{-1}}$
Vegetation (BB97 formulation with Cabauw parameter set)			
Maximum canopy conductance	$g_{c\max}$	0.0386	$\mathrm{m\,s^{-1}}$
Solar coefficient 1	$b_{1S\downarrow}$	1000	$\mathrm{W\,m^{-2}}$
Solar coefficient 2	$b_{2S\downarrow}$	230	$\mathrm{W\,m^{-2}}$
Humidity coefficient	b_q	0.02	$\mathrm{kg\,g^{-1}}$
Humidity deficit threshold	δq_r	3.0	$\mathrm{g\,kg^{-1}}$
Soil heat flux			
Bare soil thermal conductivity	λ_{T0}	0.601	$\mathrm{W\,m^{-1}\,K^{-1}}$
Thermal conductivity coefficient	Λ_T	7.0	$\mathrm{W\,m^{-2}\,K^{-1}}$

vapor pressure and specific humidity deficits, respectively, at the first model level (i.e. 20 m in the study here), and the other coefficients and constants are defined in Table 1.

The expression for root-zone soil moisture availability (f_Θ) included in Eq. (1) is

$$f_{\Theta_i} = \begin{cases} 1 & \Theta_i \geq \Theta_{fcp} \\ \frac{\Theta_i - \Theta_w}{\Theta_{fcp} - \Theta_w} & \Theta_w < \Theta_i < \Theta_{fcp} \\ 0 & \Theta_i \leq \Theta_w \end{cases} \tag{5}$$

where Θ, Θ_{fcp}, and Θ_w are the volumetric soil moisture contents corresponding to the actual, field capacity, and wilting point values, respectively, and the subscript i refers to a given soil layer in the root zone. The total effect (i.e. on transpiration) of root-zone soil moisture availability is then determined by summing f_{Θ_i} over all (root-zone) soil layers as

$$f_\Theta = \sum_{i=1}^{n} N_i f_{\Theta_i} \tag{6}$$

where n is the total number of soil layers in the root zone (three in the study here, with one sub-root layer, so four total soil layers), and N_i is the fractional root density for a particular soil layer ($\Sigma N_i = 1$).

3.2 Root density and soil hydraulics

Studies have shown the relevance of root density distribution for improved transpiration modeling (i.e. Ács, 1994; Viterbo and Beljaars, 1995; Desborough, 1997; Colello et al., 1998). A uniform root density is assumed where soil layers in the root zone are equally-weighted by their fraction of the total root zone depth. A non-uniform root density may be specified which varies with depth; this is commonly done in many land-surface schemes so that the relative contribution of a particular soil layer to the total transpiration is non-uniform. A non-uniform fractional root density may lead to non-uniform (for a given soil layer) depletion of soil moisture in the root zone, which may be realistic in that plants often have a higher root density near the surface.

For the PILPS2a numerical experiments at Cabauw (Chen et al., 1997), it was suggested that plants could be represented by 70 percent root density in the upper 10 percent of the root zone, and 30 percent in the lower 90 percent of the root zone. As an additional comparison, the land-surface scheme in the ECMWF model had assumed one-third of the root density in each of the three root zone soil layers which corresponds to a decreasing root density with depth since the soil layer thickness increases with depth (Viterbo and Beljaars, 1995); this has been updated to account for differences between vegetation types (van den Hurk et al., 2000).

In contrast, a general concept commonly used among plant and soil scientists (Cuenca, 1999, personal communication) suggests that the fractional root density is assumed to be 40 percent in the upper quarter of the root zone, with the fractional root density decreasing by 10 percent with each subsequent quarter of the soil root zone depth. This ‘quarter-rule’, distribution is much closer to the uniform-with-depth root distribution than in the ECMWF model, or that suggested for PILPS2a at Cabauw. A variation on the quarter-rule root distribution is to exclude the ‘sod’ layer which contains no roots (i.e. the upper 3 cm of the root zone at Cabauw; BB97). For the quarter-rule root distribution used in this study, we take the average root density of the two root density distributions which average both the inclusion and exclusion of the sod layer, which leads to a slightly higher root density in the second soil layer. Figure 1 shows a schematic representation of the various root distributions with depth.

It should be pointed out that our function for root-zone soil moisture availability (Eq. (5)), depends on *relative* soil moisture availability in the root zone and is retained over the corresponding BB97 function derived for Cabauw (formulation not shown) which depends on the *actual* volumetric soil moisture content. The rationale for this is as follows: since no soil moisture measurements were available at Cabauw for 1987, the f_Θ function derived by BB97 was based on ECMWF model-generated soil moisture output. The ECMWF model uses soil-texture-specific hydraulic properties (e.g. saturated soil moisture content) following Clapp and Hornberger (1978) (or Cosby et al., 1984), an approach commonly used in the meteorological land-surface modeling community. However, for the Cabauw site, *in situ* measurements of soil moisture at Cabauw are not consistent with the ‘standard’ values cited in Clapp and Hornberger for a heavy clay soil found at the Cabauw site, e.g. for 31 May 1978 the soil moisture content in lower soil layers at Cabauw *exceeds* the saturated volumetric soil moisture content according to the ‘standard’ clay values cited in Clapp and Hornberger, i.e. $\Theta_{sat} = 0.468$ (Fig. 2). As such, we must either make some sort of relative ad-

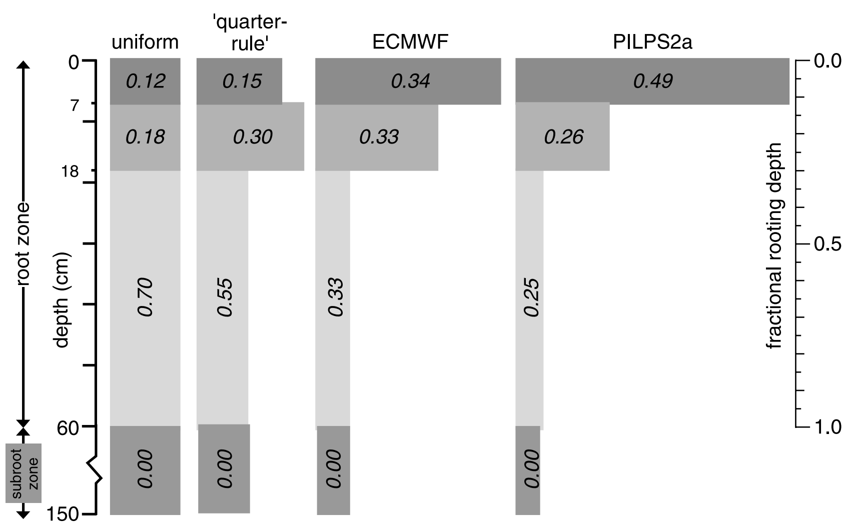

Fig. 1. Schematic representation of various choices for root density distributions for soil layers in the CAPS model land-surface scheme

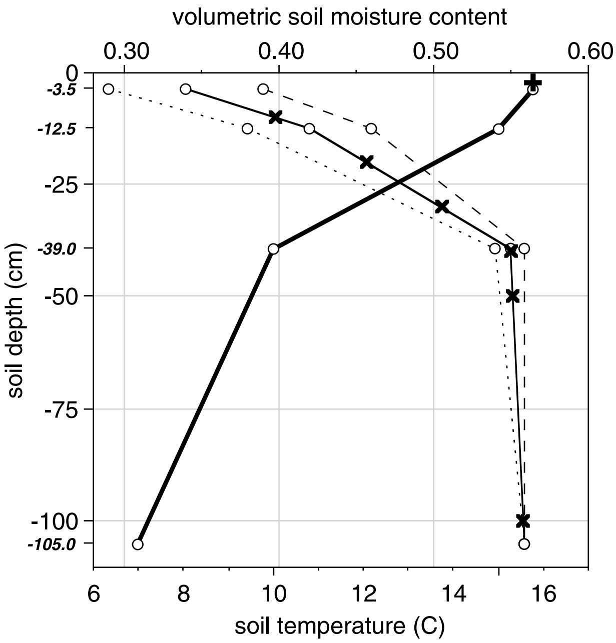

Fig. 2. Initial soil moisture profiles for 31 May 1978 at Cabauw, Netherlands: observed (×), initial model soil moisture reference profile interpolated to model soil level mid-points (○ & solid line), and drier and wetter initial soil moisture profiles used in sensitivity tests (○ & dotted line, and ○ & dashed line, respectively); and observed soil temperature at −2 cm (+) and initial model soil temperature reference profile (○ & heavy solid line)

justment to the Clapp and Hornberger approach to make it applicable to Cabauw, or find a suitable alternative. Since the Cabauw soils have been evaluated in terms of a van Genuchten (1980) formulation for soil hydraulic processes, we adopt this method using locally-derived parameters specific to the clay soils at Cabauw (Jager et al., 1976).[2]

As noted earlier, the Cabauw soil has a heavy clay content in the root zone (upper 60 cm), with an increasing peat content below this level in the subroot zone. In its current form, our land-surface scheme does not accommodate different soil textures with depth, so we must choose soil properties that most appropriately represent the soil at Cabauw for the purposes of this study. On shorter (e.g. diurnal) time scales the root zone will have more direct interaction with the atmosphere through plant transpiration, as compared to the subroot zone which operates on longer (e.g. seasonal) time scales. As such in this study we adopt the properties of a clay soil. We choose the specific soil parameters for the 18–60 cm soil layer at Cabauw, as opposed to the 0–18 cm layer (which differ slightly), since the 18–60 cm layer (although with a lower root density than the 0–18 cm layer) is still expected to dominate root zone processes because of a greater thickness and overall root content.

3.3 Soil thermodynamics

Soil heat flux (G) is often formulated (i.e. from McCumber and Pielke, 1981; following Al Nakshabandi and Khonke, 1965) as

$$G = \lambda_{T0} \Delta T / \Delta z \tag{7}$$

where λ_{T0} is the 'bare-soil' thermal conductivity (a function of soil texture and soil moisture content), and $\Delta T / \Delta z$ is the temperature gradient between the surface and center of the upper soil layer. However, in the presence of a vegetation layer, soil heat flux is reduced because of lowered heat conductivity through vegetation (Peters-Lidard et al., 1997; and others). This has been demonstrated by Viterbo and Beljaars (1995) in the ECMWF model land-surface scheme where they suggest a simpler formulation to deal with this effect where G is computed as the product of an empirical coefficient (appropriate to Cabauw) and the temperature difference between the surface and the (center of the) upper soil layer (3.5 cm), i.e.

$$G = \Lambda_T \Delta T \tag{8}$$

where Λ_T is a fixed constant 'thermal conductivity' (Table 1). This formulation draws upon earlier work by van Ulden and Holtslag (1985), and implicitly accounts for the reduction of soil heat flux in the presence of vegetation. Van den Hurk et al. (1995), van den Hurk and Beljaars (1996), and van den Hurk et al. (2000) describe refinements to this approach where the value of Λ_T varies depending on land-surface classification, e.g. bare ground, sparse vegetation, etc.

3.4 Model geometry and initial conditions

We set the depth of the first soil layer in our model the same as in the ECMWF model (7 cm) in order to use the same coefficient (Λ_T)

[2] An advantage in using van Genuchten (over Clapp and Hornberger) is that van Genuchten is more widely accepted in the soil physics community, with many soil data sets evaluated in terms of van Genuchten, including Cabauw. See BB97 for details on Cabauw soils and the van Genuchten formulation applied to Cabauw soils.

to calculate soil heat flux at Cabauw since this coefficient was calibrated for a 7-cm depth (Section 3.3). Following BB97, our subsequent soil layers match the bottom of the 'higher root density' zone (18 cm depth), a zone of 'lower root density' down to the bottom of the root zone (60 cm), with a subroot zone below (1.5 m total depth), and an implicit soil column bottom (for temperature) at 3.0 m (see Fig. 1).

We initialize our land-surface scheme using soil moisture observations interpolated to the mid-point of the model soil levels (Wessels, 1983; Fig. 2). (Sensitivity of the initial soil moisture conditions will also be explored.) Soil temperature is initialized at the first model soil layer (−3.5 cm) using −2 cm observations; this difference is not expected to be significant at this time of day. Soil temperature observations are not available below 2 cm, so to initialize soil temperatures at subsequent model soil levels we make approximations from the average of the previous week, month, and three-months 2-m air temperatures, respectively, for the lowest three model levels, with the annual 2-m air temperature used as the implicit bottom temperature.

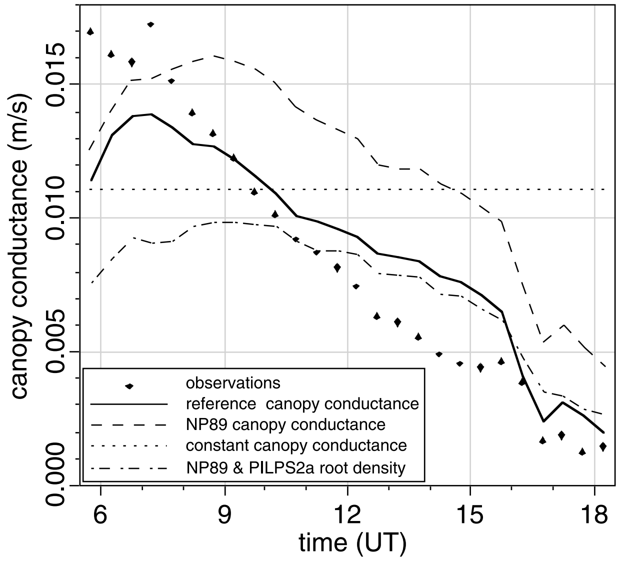

Fig. 3. Canopy conductance inferred from observations for 31 May 1978 at Cabauw (solid diamonds), versus different canopy conductance formulations: reference approach (solid line), NP89 with quarter-rule root density (dashed line), NP89 with PILPS2a root density (dot-dashed line), and constant canopy conductance (dotted line). See text for further details

4. Land-surface modeling sensitivity tests

4.1 Canopy conductance

Before making any model runs, we first examine the observed daytime evolution of surface conductance which can be determined by inverting the Penman-Monteith equation (Monteith, 1965) using the observed surface fluxes, temperature and specific humidity measurements, given the surface roughness for momentum (z_{0m}) and heat (z_{0h}) for the Cabauw site (i.e. from Beljaars and Holtslag, 1990; Beljaars and Holtslag, 1991; De Rooy and Holtslag, 1999). This yields a surface conductance directly inferred from observations ('observed' in Fig. 3) along with an inferred aerodynamic conductance (g_a; not shown). The surface conductance values here are negligibly affected by bare soil fluxes since the vegetation fraction at Cabauw is very nearly equal to one, hence the surface conductance is essentially a bulk *canopy* conductance (g_c). (Unlike canopy conductance, modeled values of g_a cannot be explicitly determined *a priori* in the same manner. Subsequent model runs yield g_a values somewhat underpredicted, though not significantly. As such, use of the prescribed wind speed and the apparently appropriate surface layer stability formulation are suitable for our model runs.)

We test the modeled canopy conductance formulations described in Section 3 using observations taken throughout the day (31 May 1978) at Cabauw necessary for these formulations. We use a combined approach with BB97 for maximum canopy conductance ($g_{c\max}$) and the effect of atmospheric conditions on canopy conductance ($f_{S\downarrow}, f_T, f_q$ in Eq. (3)), our expression for the effect of root-zone soil moisture availability on evaporation (Eq. (1) and Eq. (5)) using observed soil moisture (Fig. 2), and the quarter-rule root distribution (all described previously in Section 3). With this approach (hereafter the 'reference' canopy formulation), we see that the canopy conductance is somewhat underpredicted in the morning hours, and slightly overpredicted in the afternoon, though still quite adequately represented (Fig. 3). It is important to re-emphasize that the reference canopy conductance here is calibrated to Cabauw for a 1987 data set, but not specifically to our 31 May 1978 case study day.

The formation of overnight dew and subsequent evaporation from the grass canopy during the first few hours after sunrise is a possible explanation for the lower-than-observed values of modeled canopy conductance during 06–09 UT (Fig. 3). That is, there may be an underestimation of the observed canopy conductance due to evaporation of canopy water after 06 UT, where evaporation of canopy water has a larger moisture conductance value than the conductance for plant transpiration. Lacking an explicit measurement or indicator of canopy wetness, we utilize nighttime observations of the latent heat flux to estimate the canopy water content, which for a period from 00–04 UT was downward (suggesting dewfall). However, calculations indicate that subsequent evaporation starting after 04 UT would have been sufficient to evaporate the accumulated canopy water before 06 UT, the initial time for model runs. As such, our underestimation of canopy conductance during the 06–09 UT period may be attributable to some other reason, perhaps less certainty in the observed surface fluxes at this time.

We also use the NP89 formulation (Section 3.1) for the effect of atmospheric conditions on canopy conductance with the corresponding PILPS2a parameter set for Cabauw which was based on a ‘standard’ grassland category (Eq. (1); Table 1), but using our expression for the effect of root-zone soil moisture availability on canopy conductance, and the quarter-rule root distribution. (In this way, it represents a ‘fair’ test between the BB97 and NP89 canopy conductance formulations for the atmospheric part of the canopy conductance formulations.) In this case the NP89/PILPS2a-Cabauw formulation greatly overpredicts the canopy conductance throughout most of the day. For comparison, the PILPS2a root distribution is substituted for the quarter-rule root distribution, and yields a canopy conductance that is underpredicted in the morning hours, with conductance values similar to the reference canopy conductance approach during the afternoon hours.

Using our reference approach for canopy conductance described above (and in Section 3.1), the quarter-rule root distribution (Section 3.2), and the ECMWF soil heat flux formulation (Section 3.3), we drive our land-surface scheme using the observed atmospheric forcing and downward radiation measurements (Fig. 4) at the Cabauw site at each timestep (hereafter our ‘reference’ model run). This allows us to evaluate the model performance in terms of its ability to properly partition available incoming energy into upward

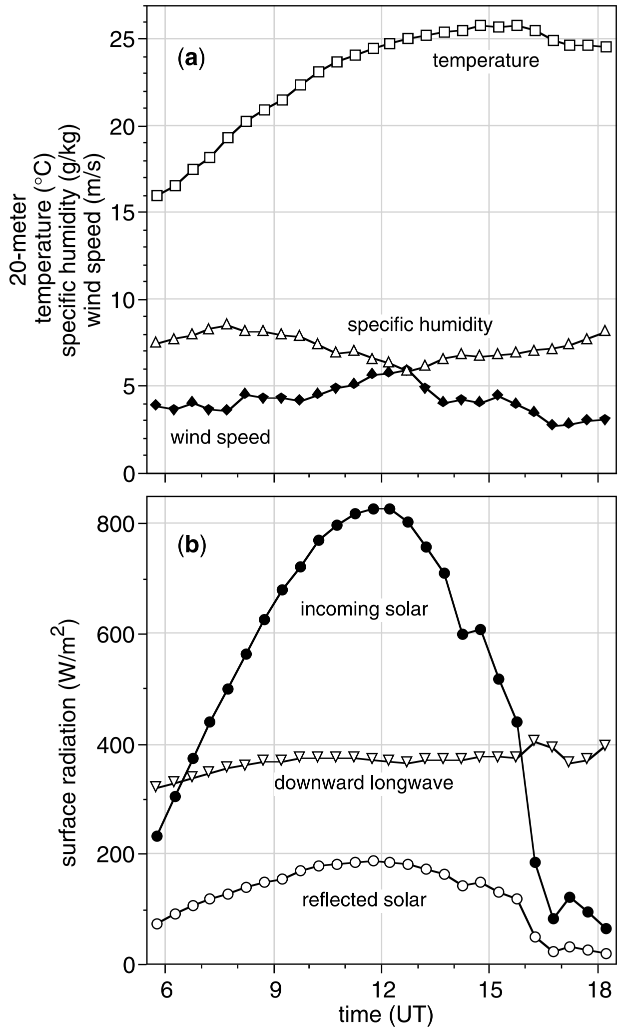

Fig. 4. Atmospheric forcing data for 31 May 1978 at Cabauw, Netherlands: (**a**) 20-meter temperature, specific humidity, and wind speed, and (**b**) incoming and reflected solar and downward longwave radiation

longwave radiation, and sensible, latent, and soil heat fluxes without ABL interaction. In our reference model run, a slight underprediction in canopy conductance in the morning (Fig. 3) leads to an underprediction of the latent heat flux with the opposite case during the afternoon, while sensible heat flux is generally well-predicted, though slightly high during late morning (Fig. 5). Replacing the reference approach for canopy conductance with that by NP89 for Cabauw via PILPS2a, the latent (*sensible*) heat flux is slightly under (*similarly*) predicted in the morning, though greatly over (*under*) predicted in the afternoon. (The effect of using the PILPS2a root distribution will be explored in the next section.)

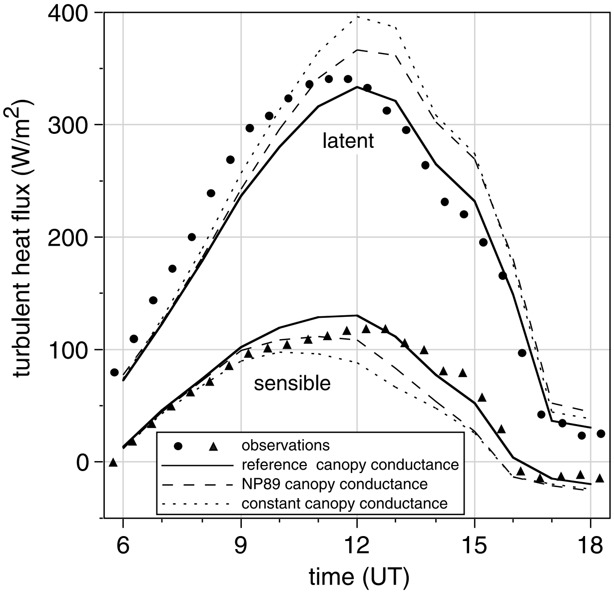

Fig. 5. Observed latent (•) and sensible (solid triangles) heat fluxes, versus modeled heat fluxes for different canopy conductance tests: reference approach (solid line), NP89 with quarter-rule root density (dashed line), and constant canopy conductance (dotted line) for 31 May 1978 at Cabauw, Netherlands

Using a constant value for canopy conductance (Fig. 3) represents the average value for this particular day fairly well, though it underpredicts the observed canopy conductance in the morning and overpredicts canopy conductance in the afternoon, with a corresponding slight under (*similar*) prediction of the latent (*sensible*) heat flux in the morning, and a stronger over (*under*) prediction in the afternoon (Fig. 5). This is consistent with the findings of Holtslag et al. (1995) for this same case study day, though in their coupled land-atmosphere model runs the biases were more exaggerated due to apparently unfavorable feedbacks between the ABL and their simpler representation of the land surface.

The results here suggest that our reference approach for canopy conductance at Cabauw, along with the quarter-rule root distribution and the ECMWF soil heat flux formulation, is the better choice as our reference model run, which we will then compare with subsequent model runs in this study. Three additional sets of sensitivity tests are made where we explore the effect on the surface fluxes of using alternate representations of root distribution, of soil heat flux, and finally sensitivity to initial soil moisture conditions.

4.2 Root distribution

We again drive our land-surface scheme using the observed atmospheric forcing at the Cabauw site, and explore the effect of using different root density distributions. A uniform-with-depth root density distribution yields results that are similar to the reference model run (which uses the quarter-rule root distribution), while using the PILPS2a root distribution yields latent (*sensible*) heat fluxes which are greatly under (*over*) predicted throughout the day (Fig. 6). For the case using the PILPS2a root distribution, soil moisture in the upper soil layers with much higher root density is more quickly depleted (Fig. 7), leading to the underprediction of the latent heat flux and a subsequent overprediction of the sensible heat flux. The re-charge of soil moisture in the upper soil layers is most notable during 06–09 UT, but continues throughout the day for the quarter-rule or uniform-with-depth root distributions because of an excess in upward diffusion of soil moisture over soil moisture loss through drainage, and transpiration and direct soil evaporation. Lacking

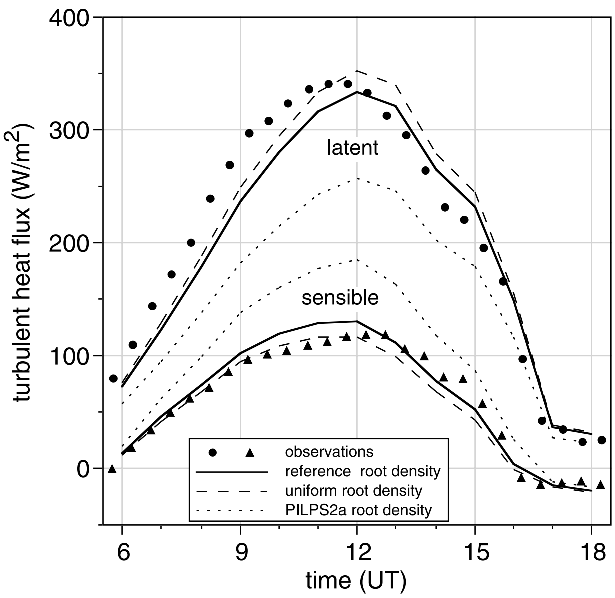

Fig. 6. Observed latent (•) and sensible (solid triangles) heat fluxes, versus modeled heat fluxes for different root density tests: quarter-rule (solid line), uniform (dashed line), and PILPS2a (dotted line) for 31 May 1978 at Cabauw, Netherlands

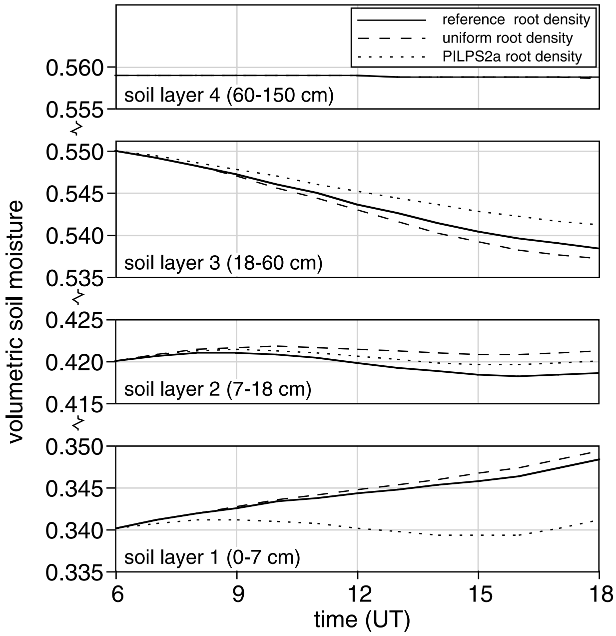

Fig. 7. Modeled values of soil moisture for model soil layers for root density tests: quarter-rule (solid line), uniform (dashed line), and PILPS2a (dotted line) for 31 May 1978 at Cabauw, Netherlands

sub-diurnal time-scale observations of soil moisture makes it difficult to assess the nature of diurnal soil moisture evolution, though there is evidence that such soil moisture re-charge processes do occur (Richard Cuenca, personal communication, 2001).

With both the quarter-rule, or with a uniform-with-depth root distribution, soil moisture from *deeper* soil layers is more available for transpiration, and is thus depleted more than with the non-uniform PILPS2a root distribution (Fig. 7). The PILPS2a root distribution, with excessively high root density near the surface, may lead to improper rapid drying of the higher-root-density soil layers in the root zone (Zeng et al., 1998). This can yield less accurate predictions of latent heat flux, and subsequently the surface energy budget. In the study here, our assumption of a near-uniform root distribution (a so-called 'bulk method') is more consistent with the current level of understanding and thus preferred over root-weighted (non-uniform) methods (Desborough, 1997). This may mitigate the problem of treating the root zone as static when in fact it may be rather dynamic in terms of the ability of vegetation to extract water from where it is available in the root zone, despite the root density distribution. In the case of a more non-uniform root distribution, it seems that in coupled land-surface – ABL model runs the evolution of the daytime ABL would be adversely affected, i.e. greater ABL growth due to greater sensible heat flux, though a potentially drier ABL due to smaller latent heat flux.

4.3 Soil heat flux

Modeled surface fluxes using the ECMWF soil heat flux formulation (representing the reference

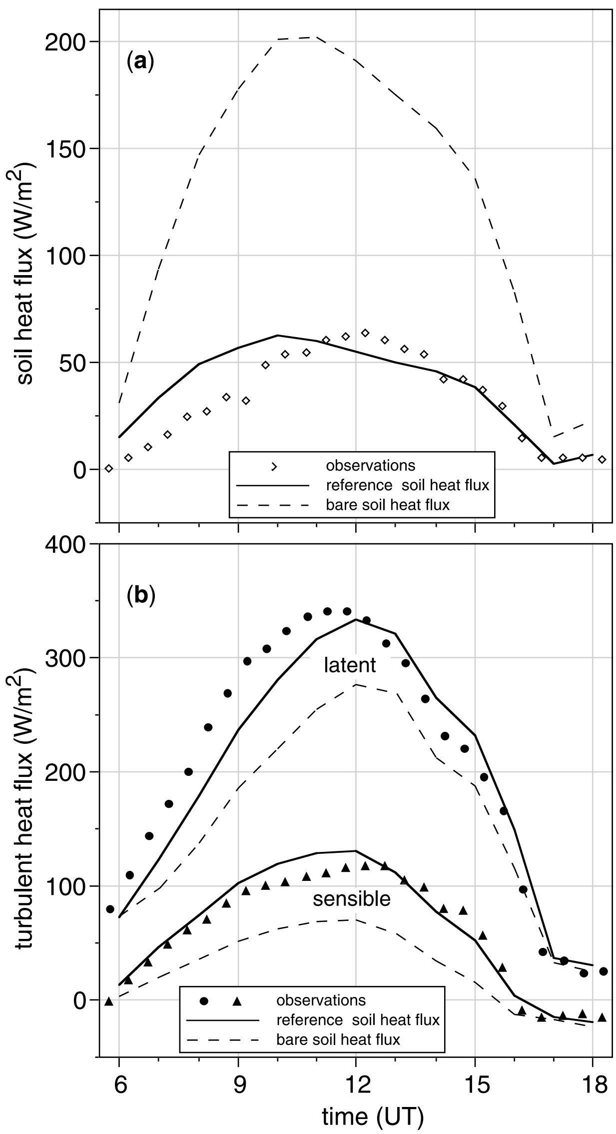

Fig. 8. Observed (**a**) soil heat flux (◇), and (**b**) latent (●) and sensible (solid triangles) heat fluxes, versus modeled heat fluxes for soil heat flux tests: ECMWF formulation (solid line) and bare soil formulation (dashed line) for 31 May 1978 at Cabauw, Netherlands

model run; Section 3.3) are found to more closely approximate observed values, though slightly out of temporal phase (Fig. 8). However, for the case of the soil heat flux formulation for bare soil, the soil heat flux is excessively overpredicted, and as a result of so much more energy going into soil heat flux, both the latent and sensible heat fluxes are significantly underpredicted during most of the day. Net radiation is also modeled well (not shown) indicating that the upward longwave radiation is properly represented. (Recall that the other radiation fluxes are prescribed).

For the case where the soil heat flux formulation for bare soil is used, the thermal conductivity in the upper soil layer is quite high because of a moderate soil moisture content yielding a higher soil heat flux than observed, while in reality the overlying vegetation layer would reduce the thermal conductivity which is implicitly included in the ECMWF formulation used in our reference model run. Because of the excessive soil heat flux using the base soil formulation, the resulting surface (radiative) and model soil (at -3.5 cm) temperatures are then much lower than observed, compared to the reference model run (Fig. 9) using the ECMWF formulation. An overprediction of the soil heat flux would result in modeled values of the sensible and latent heat flux being less than observed; in coupled land-surface – ABL model runs the evolution of the daytime ABL would then be adversely affected, i.e. less ABL growth due to smaller sensible heat flux, and a potentially drier ABL due to smaller latent heat flux.

4.4 Surface fluxes and sensitivity to initial soil moisture

An important uncertainty in the initial conditions in these model runs is in the specification of moisture in the soil column. A change in the volumetric soil moisture by a few percent can have a notable effect on the surface fluxes, observed as well as modeled. Here we make a series of sensitivity tests and examine the 12 UT surface fluxes, varying the initial soil moisture by a realistic $\pm 5\%$ (volumetric) variation in soil moisture in the upper soil layer where it is can be quite variable, with decreasing variation with depth because of the greater certainty in temporal invariance of the measurements; the soil moisture in the bottom soil layer is not varied since it was very near saturation (Fig. 2).

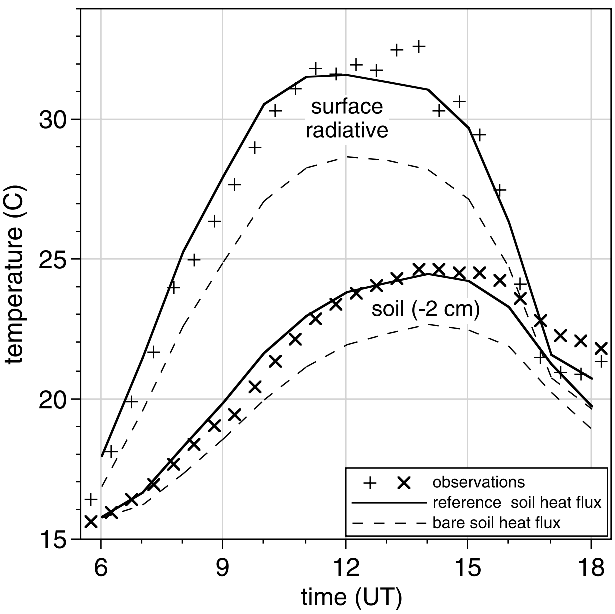

Fig. 9. Observed surface radiative (+) and 2 cm soil (×) temperatures, versus modeled temperatures for soil heat flux tests: ECMWF formulation (solid line) and bare soil formulation (dashed line) for 31 May 1978 at Cabauw, Netherlands

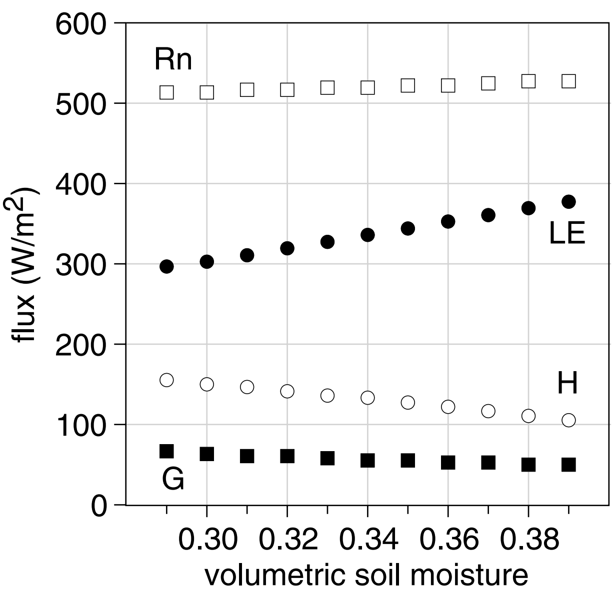

Fig. 10. Modeled values of surface energy budget components for sensitivity tests varying initial soil moisture (Fig. 2): net radiation (R_n), and sensible (H), latent (LE), and soil (G) heat fluxes for 31 May 1978 at Cabauw, Netherlands

In a series of model runs, as the initial soil moisture is changed from drier to moister, as expected sensible heat flux decreases (by about $50\,\mathrm{W\,m^{-2}}$, -32% from drier to moister soil conditions), while latent heat flux increases ($80\,\mathrm{W\,m^{-2}}$, $+28\%$) (Fig. 10). There is a subtle increase in net radiation ($15\,\mathrm{W\,m^{-2}}$, $+3\%$), because the surface temperature and thus outgoing longwave radiation decreases (note that the other radiation fluxes are prescribed). With a decrease in surface temperature, the gradient in soil temperature near the surface is reduced, so soil heat flux decreases ($20\,\mathrm{W\,m^{-2}}$, -28%). These differences in surface fluxes are within the uncertainty of the observed flux measurements; changes here are rather linear with changing soil moisture because these model runs are for the land-surface only, that is, without ABL *interaction*.

5. Summary

In this study our goal was to properly represent the soil-vegetation system in offline model runs for Cabauw (Netherlands) using a land-surface scheme driven by atmospheric forcing for the case study day examined (31 May 1978). Results indicate that in land-surface-only model runs, realistic daytime surface fluxes are produced using the land-surface scheme from the Coupled-Atmospheric boundary layer-Plant-Soil (CAPS) model with existing or alternate formulations, but using *un-tuned* model parameters. Model sensitivity tests included:

(1) modifications to the parameterization of canopy conductance. The locally-derived formulation specific to Cabauw (using an annual *1987* data set) was more successful in representing the canopy conductance at Cabauw than the ‘off-the-shelf’ formulations. This suggests that classifications covering a broad land-surface category (e.g. ‘grassland’) should be re-examined perhaps in terms of locally-derived data sets. Future work should investigate a more physically-based approach for canopy conductance based on CO_2 assimilation (e.g. Ronda et al., 2001) as an alternative to the current widely-used Jarvis-Stewart empirical approach.

(2) changes to the soil heat flux formulation. Accounting for the effect of overlying vegetation on the reduction of soil heat flux (via the ECMWF formulation) is important since this affects the amount of available energy that must be further partitioned into surface latent and sensible heat fluxes. As such, a simple representation of the soil heat flux as some set fraction of the net radiation is not adequate. As an alternative to the favorable ECMWF soil heat flux formulation used in the study here, vegetation can be explicitly included where the bare soil thermal conductivity is reduced by an exponential function of *LAI* and an empirical coefficient (described in Peters-Lidard et al., 1997). A similar method uses green vegetation fraction (σ_f; $0 \le \sigma_f \le 1$) instead of *LAI* (Ek et al., 2003).

(3) alternatives for plant root density distribution. Nonlinear distributions that include a much higher root density near the surface, decreasing in density with depth, may not be appropriate for use in current land-surface schemes where the static treatment of roots can lead to rapid drying of the higher-root-density soil layers, and thus less accurate predictions of latent heat flux (and subsequently the surface energy budget). The ‘quarter-rule’ used in this study is a near-uniform-with-depth root distribution, and performed quite well compared to more nonlinear distributions. A more uniform root distribution may in fact mitigate the problem of treating the root zone as static when in fact it may be rather dynamic in terms of the ability of vegetation to extract available soil water for transpiration.

(4) sensitivity to initial soil moisture. The sensitivity of modeled surface fluxes to a variation (e.g. $\pm5\%$ volumetric in the upper soil layer) in the initial soil moisture conditions was explored, with the resulting mid-day surface latent, sensible and soil heat fluxes varying by up to about 30% of the observed fluxes, though with the net radiation varying by less than 5%. These findings seem reasonable considering the accuracy of the surface flux and soil moisture measurements.

Regarding the use of the van Genuchten (1980) formulation for hydraulic conductivity (used in this study) as an alternative to Clapp and Hornberger (1978), IJpelaar (2000) examined regional climate model runs during the European summer of 1995, and found generally favorable results using van Genuchten. In a sensitivity study, Cuenca et al. (1996) used van Genuchten versus Clapp and Hornberger in coupled land–atmosphere column model runs, and noted large differences in surface fluxes and atmospheric boundary-layer development, particularly under moderate soil moisture conditions. As such, it would be useful to repeat the study here using our 'reference' model formulations and parameters to test van Genuchten versus Clapp and Hornberger, and revisit the PILPS2a (Cabauw, 1987) data set, or seasonal or annual model runs for a Cabauw data set where soil moisture observations (along with surface fluxes) are available for validation, e.g. June–November 1977 and March–November 1978.

Finally, in a coupled land–atmosphere study, Ek and Holtslag (2004) used the land-surface scheme in the study here (with the 'reference' model formulations and parameters) in their one-dimensional (column) land-surface – ABL model runs. In their sensitivity tests, they explored the role of soil moisture in ABL evolution and cloud development, where the outcome depends on many possible land–atmosphere interactions.

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Authors' addresses: M. B. Ek (e-mail: Michael.Ek@noaa.gov), University Corporation for Atmospheric Research Visiting Scientist, National Centers for Environmental Prediction, Environmental Modeling Center, 5200 Auth Road, Room 207, Suitland, Maryland 20746, USA; A. A. M. Holtslag (e-mail: Bert.Holtslag@wur.nl), Meteorology and Air Quality Section, Wageningen University, Duivendaal 2, 6701 AP Wageningen, Netherlands.