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# Impact of soil water property parameterization on atmospheric boundary layer simulation

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**Abstract.** Both the form of functional relationships applied for soil water properties and the natural field-scale variability of such properties can significantly impact simulation of the soil-plant-atmosphere system on a diurnal timescale. Various input parameters for soil water properties including effective saturation, residual water content, anerobiosis point, field capacity, and permanent wilting point are incorporated into functions describing soil water retention, hydraulic conductivity, diffusivity, sorptivity, and the plant sink function. The perception of the meaning of these values and their variation within a natural environment often differs from the perspective of the soil physicist, plant physiologist, and atmospheric scientist. This article investigates the sensitivity of energy balance and boundary layer simulation to different soil water property functions using the Oregon State University coupled atmosphere-plant-soil (CAPS) simulation model under bare soil conditions. The soil parameterizations tested in the CAPS model include those of *Clapp and Hornberger* [1978], *van Genuchten* [1980], and *Cosby et al.* [1984] using initial atmospheric conditions from June 16, 1986 in Hydrologic Atmospheric Pilot Experiment-Modélisation du Bilan Hydrique (HAPEX-MOBILHY). For the bare soil case these results demonstrate unexpected model sensitivity to soil water property parameterization in partitioning all components of the diurnal energy balance and corresponding boundary layer development.

## 1. Introduction

Proper simulation of diurnal changes in the atmospheric boundary layer over vegetated land surfaces requires consideration of the energy and water continuum from soil layers in contact with the plant root system, through the roots, to the xylem and stomata of the plant, to the internal boundary layer of the plant canopy, and finally to the atmosphere where turbulent processes play a predominant role in mixing. Initial studies and simulation of the atmospheric boundary layer (ABL) considered the surface as either being "wet" (i.e., ocean or sea surface) or "dry" (i.e., land surface). This elementary approach was modified by *Deardorff*'s [1978] work which accounted for stomatal control by the plant canopy in an atmospheric simulation model. This work had been preceded in the Earth sciences by development of the Penman-Monteith equation which included an aerodynamic resistance, generally a function of wind speed and canopy height, and a canopy resistance term [Monteith, 1965]. The canopy resistance was originally developed as a function of plant species, stage of growth (i.e., represented by plant height or leaf area index (LAI)), and soil water availability. This concept has evolved in the biosphere-atmosphere transfer scheme (BATS) developed by *Dickinson et al.* [1993] and the simplified biosphere model (SiB) [*Sellers et al.*, 1986], as well as others. The number of plant and soil parameters required in the BATS or SiB schemes are considerable and often difficult to determine on a field scale or for particular plant or soil environments.

Numerous large-scale experiments in the past decade have aimed at development and testing of parameterizations for soil-vegetation-atmosphere transfer (SVAT) schemes. Experiments in this series include the Hydrologic Atmospheric Pilot Experiment-Modélisation du Bilan Hydrique (HAPEX-MOBILHY) conducted in France in 1986 [*André et al.*, 1988], the First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE) conducted in the United States in 1987 [*Sellers et al.*, 1992], the European International Project on Climate and Hydrologic Interactions between the Vegetation, the Atmosphere and Landsurfaces (ECHIVAL) Field Experiment in a Desertification-threatened Area (EFEDA) conducted in Spain in 1991 [*Bolle et al.*, 1993], HAPEX-Sahel conducted in Niger in 1992 [*Goutorbe et al.*, 1994], and the BOReal Ecosystem-Atmosphere Study (BOREAS) conducted in Canada in 1994 [*Sellers et al.*, 1995]. These were large, multinational experiments combining aspects of hydrology, atmospheric science, ecology, and remote sensing. Ground sites with intensive local measurements were overflown by aircraft and helicopters, while satellite overpasses covered the complete project area which was often on the order of 100 km by 100 km, or the lower limit of a general circulation model grid. These experiments were interdisciplinary by design and allowed for an exciting exchange of ideas and perceptions between the various scientific groups (e.g., *Schmugge and André*, 1991] from the HAPEX-MOBILHY experiment). Through participation in the design and ground and aircraft operations of the above listed experiments the authors



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have become familiar with some key issues involving interaction of the soil and plant canopy with simulation of the ABL. This article addresses interactions of the parameterizations of soil physical processes and atmospheric simulation.

## 2. Representation of Soil Physical Properties

### 2.1. General Concepts

The time rate of change of soil water content for a rigid, isotropic, homogeneous, isothermal, one-dimensional flow domain is given by *Richards'* [1931] equation

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[D(\theta)\frac{\partial \theta}{\partial z}\right] - \frac{\partial K(\theta)}{\partial z} - S(\theta) \tag{1}$$

where

- $\theta$ volumetric soil water content;
- $t$ time;
- $z$ vertical direction;
- $D(\theta)$ soil water diffusivity;
- $K(\theta)$ hydraulic conductivity;
- $S(\theta)$ sink term for soil water extraction by roots.

The soil water diffusivity in (1) may be replaced by the quotient of the hydraulic conductivity divided by the differential soil water capacity,

$$D(\theta) = K(\theta)/C(\theta) \tag{2}$$

where $C(\theta)$ is differential soil water capacity

$$C(\theta) = \partial\theta/\partial h \tag{3}$$

and $h$ is soil water tension, so that (1) becomes

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\frac{\partial h}{\partial z}\right] - \frac{\partial K(\theta)}{\partial z} - S(\theta) \tag{4}$$

If we leave the complexity of the plant sink term for other studies, evaluation of (4) always requires application of the soil water retention function, given as $\theta = \theta(h)$, and the hydraulic conductivity function, given as $K = K(\theta)$. Numerous parameterizations for the soil water retention and hydraulic conductivity functions have been developed. This paper will focus on the *Clapp and Hornberger* [1978], *van Genuchten* [1980], and *Cosby et al.* [1984] functions which are either widely used in atmospheric modeling [*Clapp and Hornberger*, 1978], modeling of soil physical processes [*van Genuchten*, 1980], or which are considered to have potential for simulation model application [*Cosby et al.*, 1984]. Parameterizations which are used in numerous simulations of soil physical processes but are not covered here include the *Brooks and Corey* [1964] equations, *Gardner* [1958] equation, *Green and Ampt* [1911] function, and *Brutsaert* [1967] equation.

### 2.2. *Clapp and Hornberger* [1978] Functions

The *Clapp and Hornberger* [1978] functions were developed based on analysis of soil samples taken from 34 localities throughout the United States. They appear to be derived from the earlier *Brooks and Corey* [1964] functions, which had been published in a limited manner, with the residual soil water content set equal to zero. Moisture retention was measured in the laboratory using core samples subjected to 0.1, 0.3, 0.6, 3, and 15 bars tension. The regression coefficients for the functional relationships were determined by performing linear regression analysis on the log transform of the data. Transformed data which were felt to lie beyond the bounds of reasonable expectation were removed from the final data set. The final data set contained 1446 samples out of an initial set of over 1800 [*Clapp and Hornberger*, 1978]. Approximately 20% of the initial samples were thus removed from the final analysis because they were subject to sampling procedure error, analysis error, or deviated significantly from the proposed function.

The soil water retention function derived from Clapp and Hornberger analysis of the final data set is of the form,

$$h(\theta_v) = h_S(\theta_v/\theta_S)^{-b} \tag{5}$$

where

- $h(\theta_v)$ soil water tension as function of soil water content (cm);
- $h_s$ soil water tension at saturation (cm);
- $\theta_v$ volumetric soil water content ($cm^3/cm^3$);
- $\theta_s$ saturated volumetric water content ($cm^3/cm^3$);
- $b$ fitting parameter (dimensionless).

The hydraulic conductivity function reported by *Clapp and Hornberger* [1978] (similar to that of *Brooks and Corey* [1964]) has the following form:

$$K(\theta_v) = K_s(\theta_v/\theta_s)^{2b+3} \tag{6}$$

where $K(\theta_v)$ is hydraulic conductivity as a function of soil water content (cm/d) and $K_s$ is saturated hydraulic conductivity (cm/d). The fitting parameters $h_s$, $\theta_s$, $K_s$, and $b$ are functions of soil texture. *Clapp and Hornberger* [1978] presented a table of the mean and standard deviation of these fitting parameters for 11 classes of soil textures based on the samples analyzed.

The *Clapp and Hornberger* [1978] parameterization and constants tend to be widely used in atmospheric and climatic simulation models where land-surface interactions are considered. Apparently, the first application was made by *McCumber and Pielke* [1981] followed by applications in the simple biosphere (SiB) model [*Sellers et al.*, 1986], the biosphere-atmosphere transport scheme (BATS) [*Dickinson et al.*, 1993], the land-surface parameterization scheme of *Noilhan and Planton* [1989], and models described by *Siebert et al.* [1992], *Kondo et al.* [1990], *Schüdler* [1990], and *Mahrt and Pan* [1984]. *Ek and Cuenca* [1994] recently demonstrated the variation in simulation of the surface energy balance and atmospheric conditions on a diurnal timescale due to the variability shown in the original *Clapp and Hornberger* [1978] data set. A review of soil physics literature reveals that very little application of the *Clapp and Hornberger* [1978] parameterization for soil properties has been made within this discipline during the past decade.

### 2.3. *van Genuchten* [1980] Function

The *van Genuchten* [1980] model for the soil water retention function was developed to derive a closed-form analytical expression for the relative hydraulic conductivity function. The resulting expression contained three independent parameters which may be obtained by fitting the retention model to laboratory or field experimental data. Tabulated constants as a function of 11 soil texture classes [*Rawls et al.*, 1982] or 12 soil texture classes [*Carsel and Parrish*, 1988] have since been developed allowing the van Genuchten function to be applied much in the same way in simulation modeling as the Clapp and Hornberger functions.

The formulation of the *van Genuchten* [1980] soil water retention function is given as

$$h(\theta_v) = \frac{1}{\alpha}[(S_e)^{-1/m} - 1]^{1/n} \quad (7)$$

where

$h(\theta_v)$ soil water tension as function of soil water content (cm);

$\alpha$ fitting parameter (1/cm);

$m$, $n$ fitting parameters (dimensionless);

$S_e$ effective saturation (fraction).

$$S_e = (\theta_v - \theta_r)/(\theta_s - \theta_r) \quad (8)$$

$\theta_v$ volumetric soil water content ($cm^3/cm^3$);

$\theta_r$ residual volumetric water content ($cm^3/cm^3$);

$\theta_s$ saturated volumetric water content ($cm^3/cm^3$).

The hydraulic conductivity function derived by *van Genuchten* [1980] using the Mualem condition [*Mualem*, 1976] is given as

$$K(S_e) = K_s S_e^l [1 - (1 - S_e^{1/m})^m]^2 \quad (9)$$

where

$K(S_e)$ hydraulic conductivity as function of effective saturation (cm/d);

$K_s$ saturated hydraulic conductivity (cm/d);

$l$ tortuosity (fitting parameter, dimensionless);

$m = 1 - 1/n$.

*van Genuchten* [1980] shows that $\alpha$ in (7) can be considered as the inverse of the air entry pressure in the Brooks and Corey equation. While $m$ and $n$ can be considered independent [*van Genuchten et al.*, 1991] the condition for $m$ in the above parameterization is the so-called Mualem condition [*Mualem*, 1976] which is applied in our analysis. Using the Mualem condition, the tortuosity $l$, sometimes referred to as the pore-connectivity parameter, is equal to 0.5 and the exponent on the bracketed term in (9) is 2.

An alternative condition for $m$ in (7) and (9) is that derived from the analysis by *Burdine* [1953]. In this case, $m = 1 - 2/n$, the tortuosity is equal to 2, and the exponent on the bracket in (9) is 1. *Fuentes et al.* [1992] show that to maintain consistency with infiltration theory a full range of soil textures including clays, Burdine's condition must be applied in (7), and they recommend use of the Brooks and Corey conductivity equation. *van Genuchten et al.* [1991] indicate some limitations on applications of the Burdine condition to medium-textured soils and also discuss the difficulty in application of soil hydraulic models in fine-textured or heavily structured field soils (e.g., swelling and shrinking clays). However, for coarse- to medium-textured soils, such as those encountered in the HAPEX-MOBILHY experiment, *Fuentes et al.* [1992] show the van Genuchten equation with Mualem's condition to be applicable. *van Genuchten* [1980] shows good results in application of Mualem's condition over a range of soil textures and *Reutenauer and Ambroise* [1992] show particularly good results with the same method in coarse-textured soils.

The values for the fitting parameters used in this study were taken from *Rawls et al.* [1982] as reported by *van Genuchten et al.* [1991]. These parameters were taken from a large data set which included 1323 soils from 32 states in the United States. The values given by *Carsel and Parrish* [1988] were derived from a database compiled by *Carsel et al.* [1988] which came from soil reports developed by the Soil Conservation Service for 42 states. Both the means and standard deviations for the fitting parameters are published in the works of *Rawls et al.* [1982] and *Carsel and Parrish* [1988].

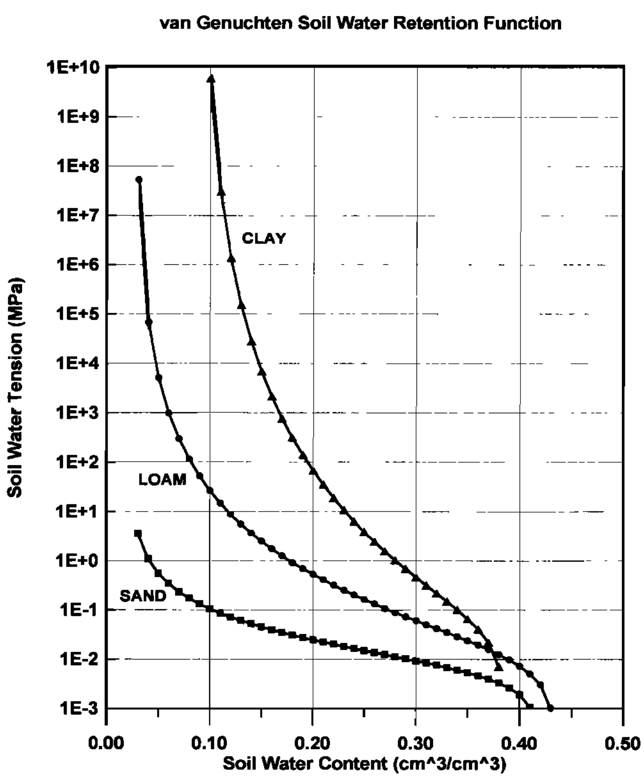


**Figure 1.** *van Genuchten* [1980] soil water retention functions for clay, loam, and sand soil textures using *Rawls et al.* [1982] fitting parameters.

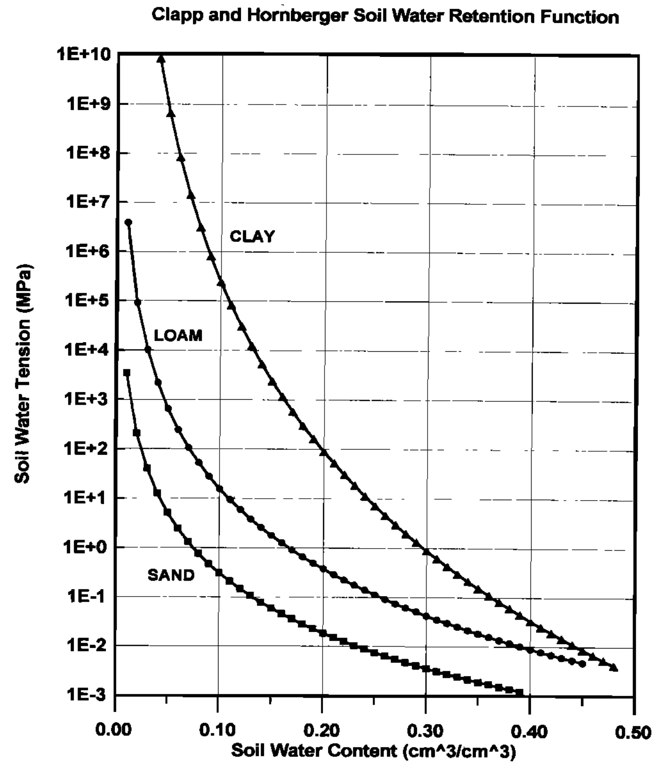


**Figure 2.** *Clapp and Hornberger* [1978] soil water retention functions for clay, loam, and sand soil textures.

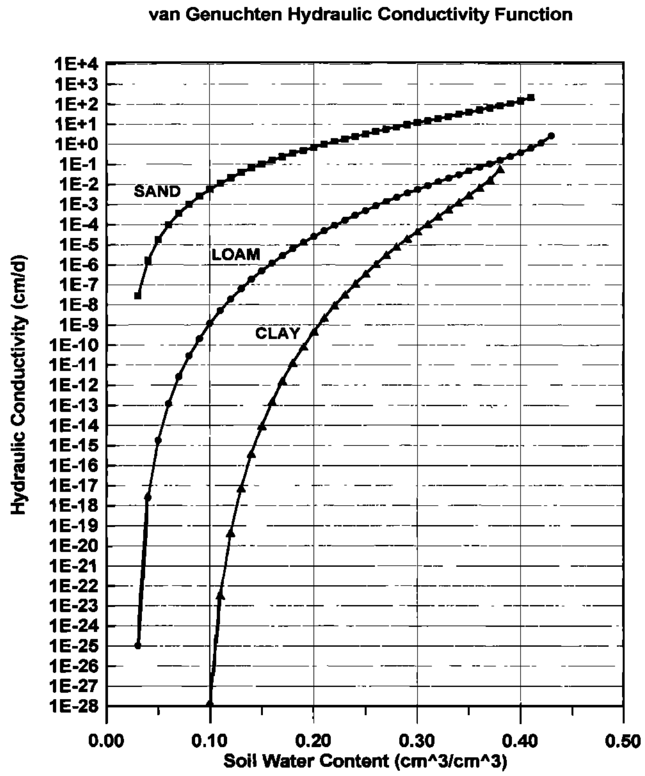


**Figure 3.** *van Genuchten* [1980] unsaturated hydraulic conductivity functions for clay, loam, and sand soil textures using *Rawls et al.* [1982] fitting parameters and *Mualem* [1976] constraint.

Figures 1 and 2 contrast the *van Genuchten* [1980] and *Clapp and Hornberger* [1978] retention functions for three soil textures which span the range of textural response functions. The drawings have been made to the same scale for ease of comparison. It can be noted that the Clapp and Hornberger functions are asymptotic to both axes, while the van Genuchten functions demonstrate an inflection point at high-moisture contents and terminate at the value of residual soil water content. In spite of these distinct differences in the functions they exhibit similar magnitudes through the range of typical field soil water contents, for example, 10–30% by volume.

Figures 3 and 4 contrast the hydraulic conductivity functions using the Clapp and Hornberger and van Genuchten parameterizations for the same textural classes previously demonstrated. Both figures are drawn to the same scale. The asymptotic behavior of the Clapp and Hornberger functions is again apparent, as is the impact of the residual and saturated soil water content in the van Genuchten parameterization. The magnitude of hydraulic conductivity for these two functions for the same soil texture and same value of soil water content is very different. In fact, the function for sand using the van Genuchten parameterization lines up most closely with the function for loam of the Clapp and Hornberger diagram.

The demonstrated differences in the soil water retention and hydraulic conductivity functions are of course due both to the form of the functions and the data sets used for calibration. *Rawls et al.* [1982] give an extensive list of data sources for both the soil water retention and the hydraulic conductivity functions. However, Figures 1 through 4 demonstrate that when published fitting parameters as a function of soil texture are used with the models, there is a significant difference in the results, particularly for the hydraulic conductivity function. In modeling, the different functions are generally used with the published fitting parameters without any effort to collect field or laboratory data to calibrate the functions to a local soil condition. To the authors' knowledge, no comparison has been made of the effects of these different soil property parameterizations which are used in different simulation models of the atmospheric boundary layer.

There are two other factors worth noting with respect to the van Genuchten parameterizations which partly evolve from the application of the functions by different scientific communities. First, within the soil physics community the tabulated values of the fitting parameters are used only in a limited fashion. Although there is some consensus on the values of saturated and residual volumetric water content, even these parameters are often indicated as being fitting parameters with little physical meaning [*van Genuchten and Nielsen*, 1985; *Fuentes et al.*, 1992]. The more common application of the van Genuchten function is as a model which is fit to field and/or laboratory data using a least squares fitting technique (e.g., the RETC code [*van Genuchten et al.*, 1991]). In this type of application the fitting parameters are optimized to force the function to fit the collected data as well as is possible. An example of this procedure is shown by *van Genuchten* [1980], who demonstrates both the van Genuchten and Brooks and Corey function fit to the Brooks and Corey data [*Brooks and Corey*, 1964]. An example of fitting field data to the van Genuchten function at a tower site in the BOREAS project was shown by *Cuenca et al.* [1995].

The second point is that the van Genuchten function is probably the most commonly used parameterization for the retention and conductivity functions in the soil physics com-

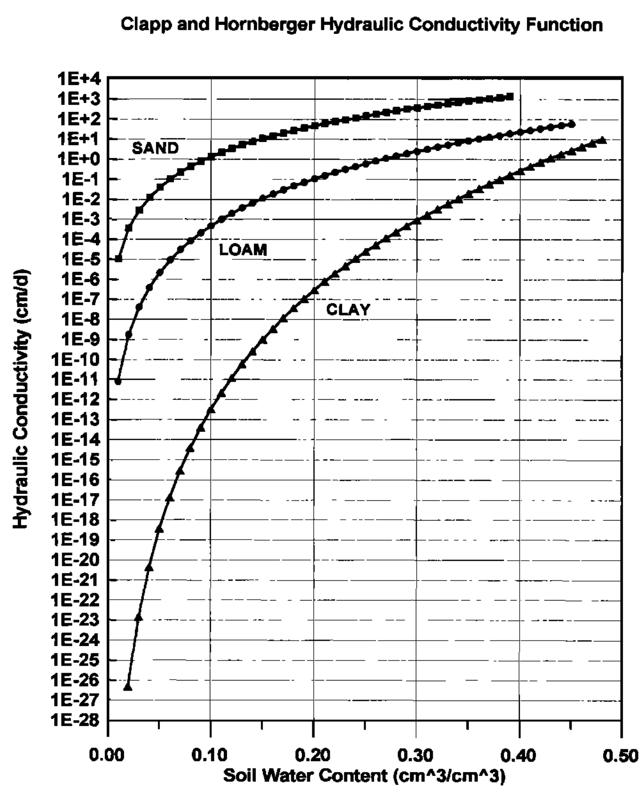


**Figure 4.** *Clapp and Hornberger* [1978] unsaturated hydraulic conductivity functions for clay, loam, and sand soil textures.

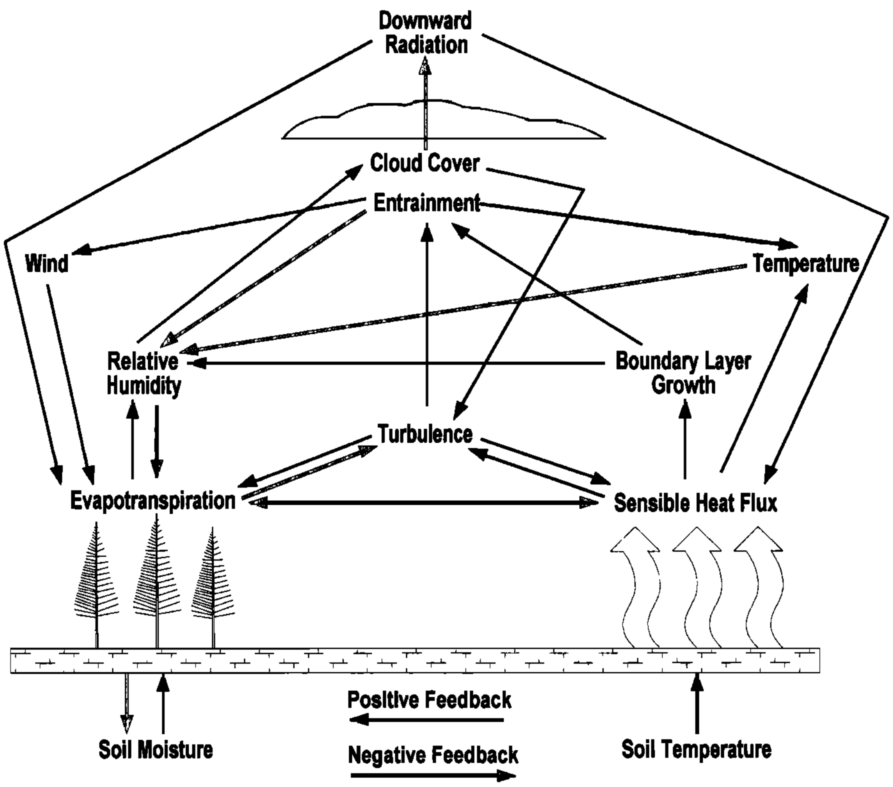


**Figure 5.** Schematic of Oregon State University coupled atmosphere-plant-soil boundary layer simulation model. Positive feedbacks are indicated by solid arrows, and negative feedbacks are indicated by shaded arrows.

munity. This is because the shape of the function, with reasonable fitting parameters, closely represents the shape of field and laboratory soil water retention and conductivity data. The typical S shape of the retention function data is well maintained using the van Genuchten function, and hysteresis effects on the retention function can be accounted for by changing the values of the fitting parameters, particularly $K_{sat}$ [*van Genuchten*, 1980]. The curve in the S shape at high values of soil water content [e.g., *van Genuchten et al.*, 1991, Figures 3–6], where the rate of transport processes is the highest, is not maintained by the Clapp and Hornberger function.

### 2.4. *Cosby et al.* [1984] Function

The *Cosby et al.* [1984] parameterizations for the soil water retention and hydraulic conductivity functions were derived from the same data set as the earlier work of *Clapp and Hornberger* [1978] [i.e., *Holtan et al.*, 1968]. Additional data from *Rawls et al.* [1976] was also analyzed by *Cosby et al.* [1984]. *Cosby et al.* [1984] used the same functional forms as applied by *Clapp and Hornberger* [1978], that is, (5) and (6). The thorough statistical analysis by *Cosby et al.* [1984] quantified the predominance of the soil texture in relation to other variables in defining the hydraulic properties. The analysis technique applied and data included resulted in different values for the fitting parameters indicated in (5) and (6). The shape of the soil water retention and hydraulic conductivity functions are similar to those shown for *Clapp and Hornberger* [1978] in Figures 2 and 4.

### 2.5. Other Parameterizations

Numerous other parameterizations have been applied to quantify soil water properties. Probably the most common in the soil physics community, other than those previously described, is that of *Brooks and Corey* [1964]. This parameterization can be considered as a special case of the van Genuchten parameterization [*van Genuchten et al.*, 1991]. The three parameterizations applied in this analysis were retained because of wide application in the atmospheric science modeling community [*Clapp and Hornberger* 1978], because of wide application in the soil physics community [*van Genuchten*, 1980], or because of recent interest in atmospheric simulation modeling [*Cosby et al.*, 1984]. This does not imply that other parameterizations, particularly that of *Brooks and Corey* [1964], are not of interest. In fact, *Lenhard et al.* [1989] and more recently *Stankovich and Lockington* [1995] indicate procedures to convert between the Brooks and Corey and van Genuchten parameterizations so that the widest use of available fitting parameters may be made.

## 3. Boundary Layer Simulation Using the Oregon State University Coupled Atmosphere-Plant-Soil Model

It is clear from the display of the soil water retention and hydraulic conductivity functions for the different parameterizations that there are distinct differences in the shape and magnitude of the functions. Do these differences have any impact on diurnal simulation of the atmospheric boundary layer? Previous work by *Ek and Cuenca* [1994] showed important effects of the range of the *Clapp and Hornberger* [1978] fitting parameters, for example, using plus and minus one standard deviation of the parameter *b* about the mean but no insight as to the effect of parameterization itself. We therefore decided to test the different parameterizations for soil water

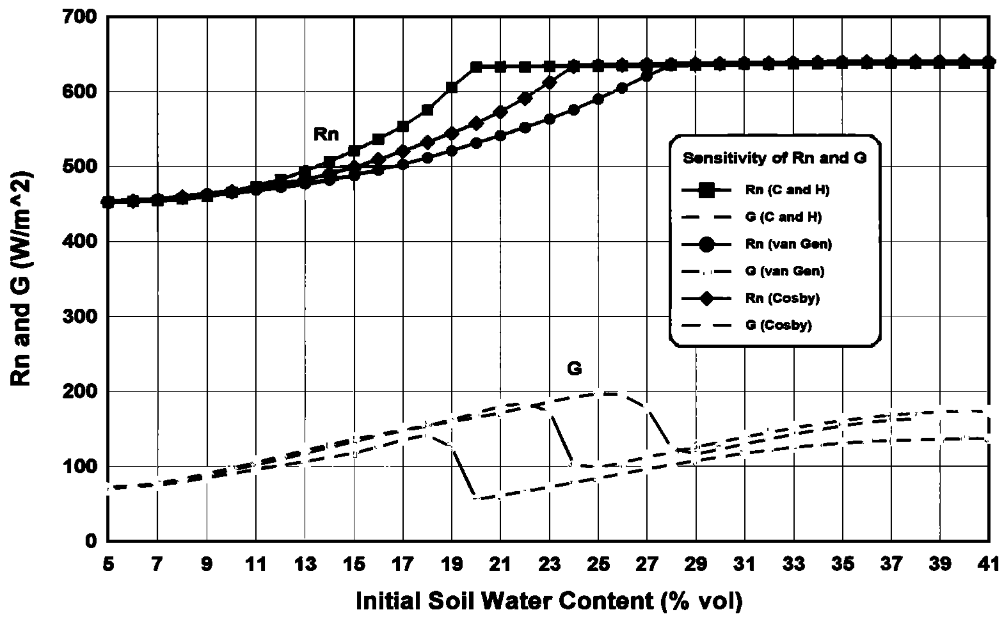


**Figure 6.** Net radiation $R_n$ and soil heat flux $G$ model output at 1200 local standard time (LST) using Hydrologic Atmospheric Pilot Experiment-Modélisation du Bilan Hydrique (HAPEX-MOBILHY) June 16, 1986 initial atmospheric conditions.

retention and hydraulic conductivity in an atmospheric simulation model. We applied the Oregon State University (OSU) coupled atmosphere-plant-soil (CAPS) model (Figure 5) which was developed to simulate the interactions of the atmospheric boundary layer, vegetation, and soil. The atmospheric boundary layer model [*Troen and Mahrt*, 1986] is coupled with an active two-layer soil model [*Mahrt and Pan*, 1984] and a basic plant canopy submodel [*Pan and Mahrt*, 1987] modified to include the interactive effect of vegetation following *Noilhan and Planton* [1989] and *Jacquemin and Noilhan* [1990]. The OSU CAPS model has been formulated for inclusion in large-scale models where the computational efficiency is important, yet the equations used are comprehensive enough to approximate the physical processes thought to be most important. The model has been used as a stand-alone model for a number of sensitivity experiments under different geophysical conditions [e.g., *Holtslag et al.*, 1990; *Ek and Mahrt*, 1991, 1994; *Holtslag and Boville*, 1993; *Huang and Lyons*, 1994; *Holtslag and Ek*, 1994; *Ek and Cuenca*, 1994].

Data from June 16, 1986 from HAPEX-MOBILHY [*André et al.*, 1988] was used to initialize the model. This is an experimental "Golden Day" with clear sky conditions and weak horizontal gradients, which has been simulated in previous studies. A roughness length of $10^{-2}$ m for momentum and $10^{-3}$ m for heat was applied [*Garratt*, 1992]. The effect of an albedo change over bare soil with changing soil moisture was excluded, and the albedo was fixed at 0.15, a representative value for bare soil in HAPEX-MOBILHY [*Bessemoulin et al.*, 1987]. The geostrophic wind was assumed to be constant from the north at about 3 m/s with a prescribed subsidence of about 1.5 cm/s at 2 km, linearly decreasing to zero at the surface [*Jacquemin and Noilhan*, 1990]. The model was initiated using 0600 local standard time (LST) radiosonde data over the pine forest in southwest France for June 16, 1986 [*Brutsaert and Parlange*, 1992].

Simulation runs were made changing only the soil water property parameterization to determine the effects on the day-time evolution of surface conditions and subsequent boundary layer development for bare soil conditions. The soil texture used for simulation was arbitrarily chosen as a sandy loam. This texture does not specifically correspond to any of the Station Automatique de Mesure de l'Evapotranspiration Réelle (SAMER) surface energy balance sites in HAPEX-MOBILHY. The objective of the experiment was not to simulate a particular HAPEX-MOBILHY site, and indeed no site had uniform bare soil conditions over an area sufficiently extensive to dominate conditions in the atmospheric boundary layer. The objective was to test the effect of the different parameterizations with varying initial soil moisture content. Multiple model simulations were made using a wide range of initial soil moisture conditions which were set uniform with depth. We will examine the subsurface, surface, and lower atmospheric conditions and boundary layer depth at 1200 LST, that is, after six hours of model integration.

## 4. Modeling Results

The results of simulation runs for June 16 are indicated for components of the energy balance and for meteorological parameters in Figures 6–9. The initial soil water content indicated in Figures 6–9 is for both soil layers of the model. The soil water content was allowed to change as prescribed by the soil water transport equation in the model.

The results for each parameter are shown over a range of initial soil water content by volume varying from a dry value of 5% to a wet value of 41%. There is little difference in the simulated entities at the dry and wet ends of the scale. However, there are significant differences for intermediate values of soil water content in a range of approximately 10–25% by volume, well within the range expected in a natural environment. The solution set of the *Cosby et al.* [1984] parameterization is usually bounded on one side by the Clapp and Hornberger parameterization and on the other by the van Genuchten parameterization.

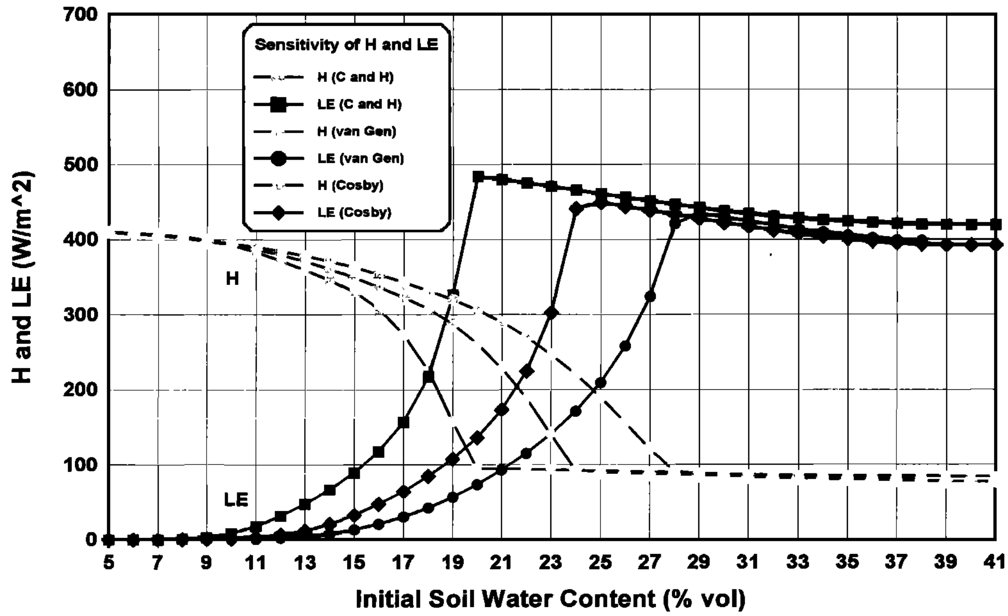


**Figure 7.** Sensible $H$ and latent $LE$ heat flux model output at 1200 LST using HAPEX-MOBILHY June 16, 1986 initial atmospheric conditions.

The variation exhibited in the various terms of the energy balance are unexpectedly large. Net radiation, $R_n$, and soil heat flux, $G$, are plotted in Figure 6. Depending on the parameterization, the soil heat flux is seen to almost double over the range of sensitive soil water contents. The variation in net radiation is not proportionally as large, but typical variations are in the range of 100 W/m$^2$ between the different soil parameterizations. The sensible $H$ and latent $LE$ heat fluxes are plotted in Figure 7. The variation in sensible heat flux is significant and in the range of 100–200 W/m$^2$. The variation in latent heat flux is large with extreme variation toward the wetter end being of the order of over 300 W/m$^2$. These results, as we shall see later, will have significant impact on boundary layer growth.

The surface $T_{sfc}$ and air $T_{air}$ temperatures at the first model level ($z$ = 20 m) also depend significantly on parameterization scheme (Figure 8). The maximum change in $T_{air}$ is about 5°C while the maximum change in surface temperature (i.e., at the soil surface) is of the order of 15°C. The specific humidity of the atmosphere $q$ (Figure 9) varies from approximately 7.5 to 11.5 g/kg at 20% initial soil water content. The much larger sensible heat flux for the van Genuchten formulation for intermediate values of volumetric soil water content (Figure 7)

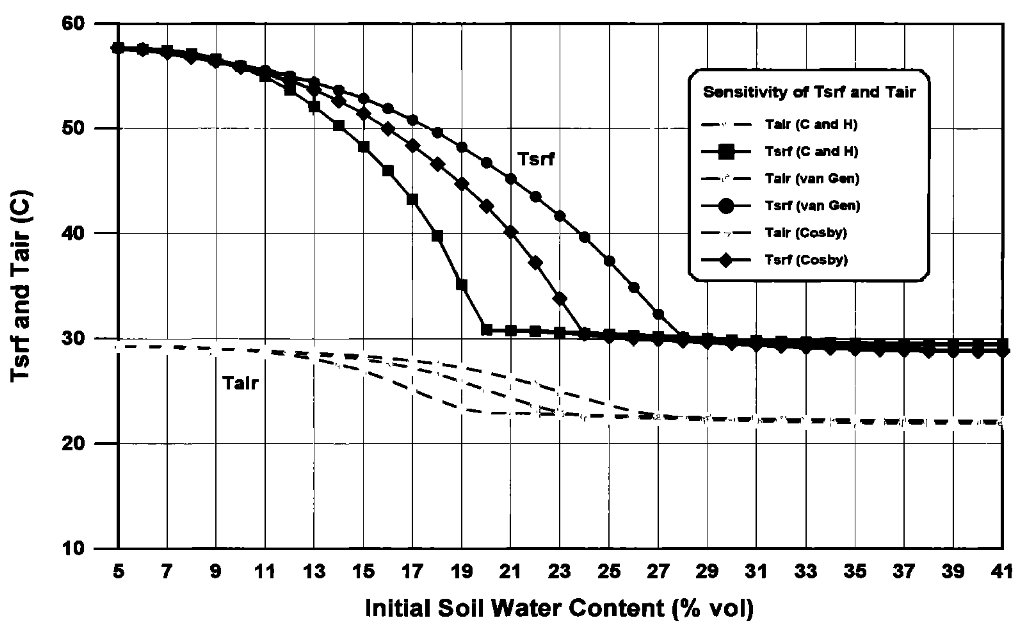


**Figure 8.** Surface $T_{sfc}$ and air $T_{air}$ temperature model output at 1200 LST using HAPEX-MOBILHY June 16, 1986 initial atmospheric conditions.

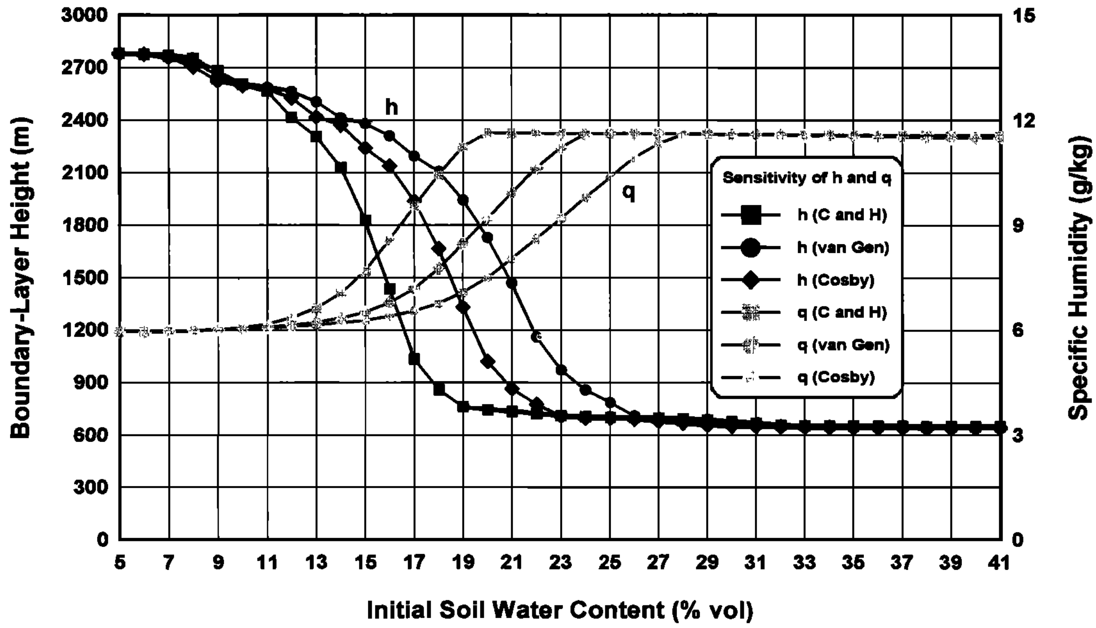


**Figure 9.** Specific humidity $q$ and boundary layer height $h$ model output at 1200 LST using HAPEX-MOBILHY June 16, 1986 initial atmospheric conditions.

leads to significantly deeper mixed layers (Figure 9). For 20% volumetric water content the mixed layer top for the van Genuchten model is 1700 m compared to 750 m for the Clapp and Hornberger model. Such differences in boundary layer depth will depend significantly on the stratification of the free atmosphere. The smaller surface evaporation and larger entrainment of dry air, due to more rapid boundary layer growth, combine to cause a significantly drier atmospheric boundary layer with the van Genuchten model (Figure 9).

## 5. Summary and Recommendations

The variation in energy balance components, meteorological variables, and simulation of the boundary layer is surprisingly sensitive to different parameterizations of the soil water processes. Such results emphasize the strong influence of the soil profile on atmospheric simulations. Integration of these results for multiday simulations or over a region have not been attempted but a persistent tendency due to application of one or another parameterization of soil water properties is expected. Such a tendency would naturally have an impact on the final results of a climate simulation.

The above results are an extreme case scenario in that the addition of vegetation with roots having access to the deeper soil layer would probably reduce the differences between the predictions of the different soil schemes. Furthermore, the greater evaporation predicted by the Clapp and Hornberger model would dry the soil more quickly and reduce the surface evaporation. After a few days of simulation the Clapp and Hornberger soil may no longer predict greater evaporation than that predicted by the van Genuchten model. Finally, the greater boundary layer growth predicted using the van Genuchten soil model may initiate boundary layer clouds [*Ek and Mahrt*, 1994] which would reduce the surface heat flux and therefore reduce temperature differences between the two models.

The unanswered question is which of the parameterizations is "correct"? The shape of the retention function exhibited by the van Genuchten equation is more realistic when compared to laboratory and field samples than the shape given by the Clapp and Hornberger function. This is one reason for the more common application of the van Genuchten parameterization within the soil physics community. However are the variations indicated by application of the OSU CAPS model to be expected in other ABL simulation schemes? The OSU CAPS is a unique model but is used by many research groups in the world and shares common elements with many other models. In this respect, the range of results shown due to different parameterizations of soil water properties may very well be exhibited in other models.

Only by formulating the individual physical components of the numerical simulation models to be as realistic as possible can we expect to make progress in understanding the interactions of linked soil-plant-atmosphere processes. This type of reasoning calls for the most realistic component to be incorporated into the modeling process at each level. Such logic warrants incorporation of a parameterization like the van Genuchten into ABL simulation, much as it is currently applied by the soil physics community. It also calls for continued interdisciplinary studies and communication between the soils, plant, and atmospheric science communities to develop the most realistic simulation of coupled land surface processes.

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