NOTES AND CORRESPONDENCE

Estimating the Soil Surface Specific Humidity

TSENGDAR J. LEE AND ROGER A. PIELKE

Department of Atmospheric Sciences, Colorado State University, Fort Collins, Colorado

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ABSTRACT

Based on the recent experiment results, a formula is proposed to be used in numerical weather–climate models to estimate the soil surface humidity. The formula has a very simple form and shows a smooth transition in the soil surface specific humidity between wet and dry soil states. The formula is recommended as a replacement to the Philip formula.

1. Introduction

In a numerical weather–climate model, the estimation of soil surface specific humidity is essential to the calculation of the lower boundary moisture and, thus, the latent heat flux. Consider the commonly used bulk transfer formula

$$E = \rho_a C_E u_a (q_{sfc} - q_a), \tag{1}$$

where E is the evaporation rate, ρ_a is the density of air, C_E is an exchange coefficient for moisture, u_a is the wind speed, and q_{sfc} and q_a are the specific humidity of the surface and of the air, respectively. Two methods have been commonly used to estimate the soil surface specific humidity q_{sfc}:

$$q_{sfc} = \alpha q_{sat}(T_g), \quad \text{or} \tag{2}$$

$$q_{sfc} = \beta q_{sat}(T_g) + (1 - \beta) q_a, \tag{3}$$

where α and β are wetness functions and q_{sat} is the saturation specific humidity at the surface temperature T_g. If Eqs. (2) and (3) are substituted into Eq. (1), the following bulk transfer equations are obtained:

$$E = \rho_a C_E u_a [\alpha q_{sat}(T_g) - q_a], \tag{4}$$

$$E = \rho_a C_E u_a \beta [q_{sat}(T_g) - q_a]. \tag{5}$$

Equation (4) describes the α method, and Eq. (5) is called the β method. Notice that the wetness function α acts like a relative humidity. Since the evaporation rate is dependent on the water availability, the wetness functions should take into account the water transport from the inner soil pores to the soil surface, which is in terms of a function of soil-water potential (the amount of energy needed to extract water from a soil sample) and soil hydraulic conductivity (the ease of water movement in the soil). For a detailed description of soil-water transport, the reader is referred to Kohnke (1968). In section 2, we will summarize different formulations for α and β in numerical models along with recent developments. We propose a formula for use in numerical models in section 3.

2. Previous formulations

There have been several formulas proposed for either α or β as can be seen in Table 1. Among the formulas, Deardorff's (1978) formula is rather ad hoc; it simply assumes a linear relationship between β and θ/θ_{fc} (see the list of symbols in the Appendix) when the soil-water content is below the field capacity, where the field capacity is defined as the maximum amount of water a soil sample can hold against the gravitational force. The formula first introduced by Philip (1957) and later used by McCumber and Pielke (1981) and Camillo et al. (1983) is actually describing the specific humidity of the air immediately above the free-water surface in the soil pores. This formula has been misused in numerical models, as suggested by Wetzel and Chang (1987), Avissar and Mahrer (1988), and, recently, Kondo et al. (1990), since it does not represent the air specific humidity at the ground surface and it fails to consider the resistance of water transport from the soil pores to the soil–atmosphere interface. One example can be seen in Fig. 1 for a loam soil where the surface relative humidity α is still close to 1 even when the volumetric soil-water content has dropped far below the permanent wilting point, at which soil-moisture tension is too high for water to be extracted by the plant roots. Notice that at least -1.5×10^6 Pa (-15b) of pressure is necessary to extract water out of the soil when the soil-water content is below the wilting point. Philip's formula is obviously not representative when the soil is dry. Wilting points for various soil types and

Corresponding author address: Tsengdar J. Lee, Colorado State University, Department of Atmospheric Sciences, Fort Collins, CO 80523.

TABLE 1. Collection of various formulas for α and β. Variables are described in the Appendix.

Investigator	Method	Formula
Avissar and Mahrer (1988)	Combination of α and β	$\alpha = \exp\left(\frac{g\psi_G}{R_w T_g}\right)$
		$\beta = a + \frac{1-a}{1+\exp[b(\theta_t - \theta)]}$ *
Barton (1979)	α or β	$\alpha = 1.04[1 - \exp(-0.1\theta)]$
		$\beta = \begin{cases} \frac{1.8\theta}{\theta + 0.3} & \theta < 0.375 \\ 1 & \theta \geqslant 0.375 \end{cases}$
Camillo et al. (1983)	α	$\alpha = \exp\left(\frac{g\psi_G}{R_w T_g}\right)$
Deardorff (1978)	β	$\beta = \min\left(1, \frac{\theta}{\theta_{fc}}\right)$
Jacquemin and Noilhan (1990)	α	$\alpha = \begin{cases} \frac{1}{2}\left[1 - \cos\left(\frac{\theta}{\theta_{fc}}\pi\right)\right], & \theta < \theta_{fc} \\ 1, & \theta \geqslant \theta_{fc} \end{cases}$
Kondo et al. (1990)	α or β	$\alpha = \frac{q_a}{q_{sat}(T_g)} + \beta\left[1 - \frac{q_a}{q_{sat}(T_g)}\right]$
		$\beta = \frac{1}{1 + C_E u_a F(\theta)/D_{atm}}$
McCumber and Pielke (1981)	α	$\alpha = \exp\left(\frac{g\psi_G}{R_w T_g}\right)$
Noilhan and Planton (1989)	β	$\beta = \begin{cases} \frac{1}{2}\left[1 - \cos\left(\frac{\theta}{\theta_{fc}}\pi\right)\right], & \theta < \theta_{fc} \\ 1, & \theta \geqslant \theta_{fc} \end{cases}$
Philip (1957)	α	$\alpha = \exp\left(\frac{g\psi_G}{R_w T_g}\right)$

* For sand $a = 0.3$, $b = 32$, $\theta_t = 0.06$.

other soil-moisture characteristics are listed in Table 2. Another difficulty in using Philip's formula in numerical models is that the results tend to oscillate between wet and dry soil-moisture regimes because of the sharp gradient of the function. This problem sometimes causes the surface energy budget in a numerical model to fail to converge.

An obvious confusion exists between the Noilhan and Planton (1989) and the Jacquemin and Noilhan (1990) formulas, since they use the same equation but different methods. They also did not mention any source for their formulas. Only the formulas suggested by Avissar and Mahrer (1988), Barton (1979), and Kondo et al. (1990) are based on experiments. Avissar and Mahrer (1988) actually introduced both wetness functions to form their unique combined formulation:

$$E = \rho_a C_E u_a \beta[\alpha q_{sat}(T_g) - q_a]. \tag{6}$$

Functions α and β can be found in Table 1. Unfortunately, they have only made measurements for a sandy soil. Barton's (1979) formula was based on measurements taken from low-level flights. No detailed soil-texture class was reported in his paper.

3. New formulation

Recently Kondo et al. (1990) obtained flux measurements from two soil-filled shallow evaporation pans and concluded that a resistance function can be introduced to parameterize the water vapor movement from soil pores to the soil–atmosphere interface. They suggested that a soil class and moisture-dependent resistance function $F(\theta)$ can be used to calculate the α and β functions. Referring to their formulas in Table 1, it is found that β is a function of θ, u, and C_E, while α is a function of θ, u, C_E, and also $q_a/q_{sat}(T_g)$. Since β

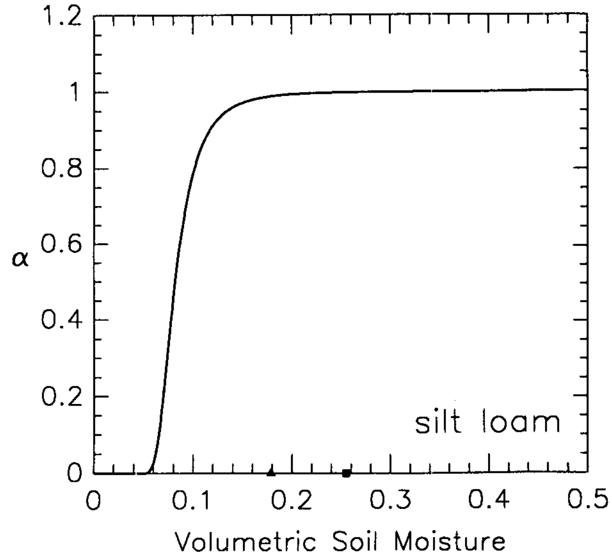

FIG. 1. Relative humidity α versus volumetric soil-moisture content for silt loam. Philip's (1957) formula is used in the calculation. The field capacity, which is associated with a hydraulic conductivity of 0.1 mm day^{-1}, is marked by the square. The permanent wilting point, which is associated with a soil-water potential ψ_G of -15 b, is marked by the triangle.

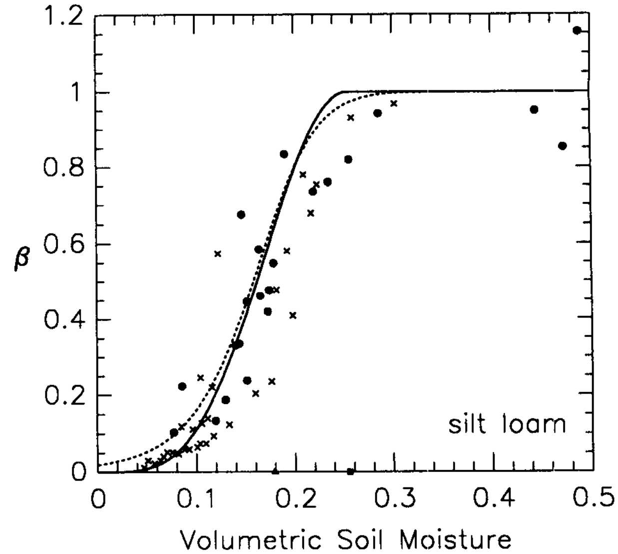

FIG. 2. Wetness function β versus volumetric soil-moisture content for silt loam. The solid line is the proposed generalized form, and the dashed line is the form proposed by Kondo et al. (1990). Their data are also included, with "●" denoting measurements taken when the wind speed was less than 1 m s^{-1} and "X" denoting measurements taken when the wind speed was greater than 1 m s^{-1}. The field capacity and the permanent wilting point are also marked as in Fig. 1.

is easier to use than α, our new empirical formula is based on the β formula by Kondo et al. (1990). Notice that the soil sample used by Kondo et al. is only 2 cm deep so that this resistance function is not intended to be used in soil models that have a deep topsoil layer, as is used in some climate models.

Assuming all different soils should behave the same at some fixed soil-water characteristics, a reference point, namely the soil field capacity, was chosen, where the soil surface specific humidity should begin to change. When the soil-water content is greater then the field capacity, the soil should behave very close to the saturated soil so that the soil surface relative humidity should be close to 1. On the other hand, the wetness function should begin to drop once the soil-water content is below the field capacity. Note that the common practice is to define the field capacity for all soil classes as either a soil-water potential of -0.33 Pa or a hydraulic conductivity of 0.1 mm day^{-1}. Using the field

TABLE 2. Soil-water characteristics of soils derived from the classification of Clapp and Hornberger (1978) plus peat (McCumber and Pielke 1981). Variables are described in the Appendix, and the field capacity θ_{fc} is associated with a hydraulic conductivity of 0.1 mm day^{-1}.

Soil type	θ_{wilt}	θ_{fc}	θ_{sat}
Sand	0.068	0.135	0.395
Loamy sand	0.075	0.150	0.410
Sandy loam	0.114	0.195	0.435
Silt loam	0.179	0.255	0.485
Loam	0.155	0.240	0.451
Sandy clay loam	0.175	0.255	0.420
Silty clay loam	0.218	0.322	0.477
Clay loam	0.250	0.325	0.476
Sandy clay	0.219	0.310	0.426
Silty clay	0.283	0.370	0.492
Clay	0.286	0.367	0.482
Peat	0.395	0.535	0.863

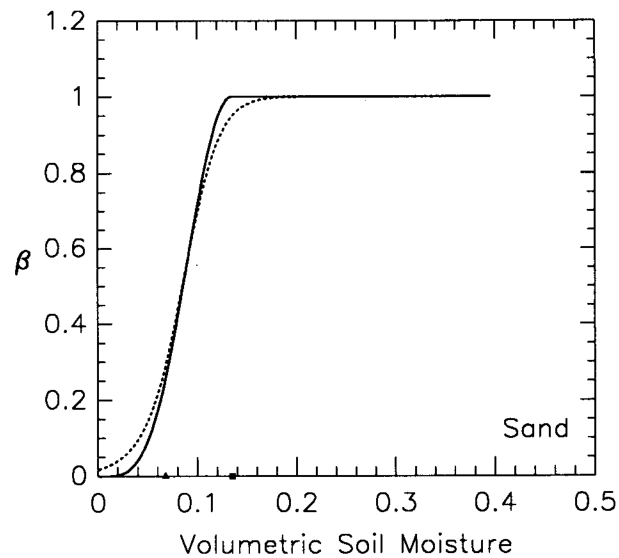

FIG. 3. Same as Fig. 2, but for sand (original paper did not show data points).

capacity as a common reference frame, the dependence on the soil texture has been completely eliminated.

Using the field capacity as a reference point, a simple empirical formula is chosen to fit the data by Kondo et al. (1990) so that

$$\beta = \begin{cases} \frac{1}{4}\left[1 - \cos\left(\frac{\theta}{\theta_{fc}}\pi\right)\right]^2 & \theta < \theta_{fc} \\ 1 & \theta \geq \theta_{fc}. \end{cases} \quad (7)$$

Notice that this formula is actually very similar to Noilhan and Plantons' (1989) formula. A very good agreement is found in Fig. 2 when our proposed formulation is compared to the formula proposed by Kondo et al. for a loamy soil. Then the same formulation is applied to a different type of soil. As expected, the formula still agrees with the formulation proposed by Kondo et al. (Fig. 3). The results support our hypothesis that all the soils should behave the same at certain points, in this case the field capacity. Figures 4 and 5 show the resistance function $F(\theta)$ calculated by our generalized formulation as compared to the experimental data. The resistance functions agree with the observations, except when the soil is extremely dry. For such dry soils, the wetness function β has already become very small and the effect of the error on the soil surface specific humidity should not be large. Most importantly, the proposed β function has captured the slope of β as a function of the soil-moisture content.

4. Summary and remarks

An easy-to-use wetness function for soil surface specific humidity has been proposed to be used in numerical atmospheric models. The formulation agrees with experimental data for two different soil types and uses no tunable constant so that it can be generalized to any soil-texture class. Until more experimental data is available, we propose that this formulation is general and could be used for other types of soil. However, recall that the β function is also a function of wind speed and C_E; thus, the curve should shift with changing wind speed and C_E. Since the original data by Kondo et al. (1990) were taken under light winds, the validity of the formulation for high winds is yet to be determined. Our formulation is recommended as a replacement to Philip's (1957) formulation.

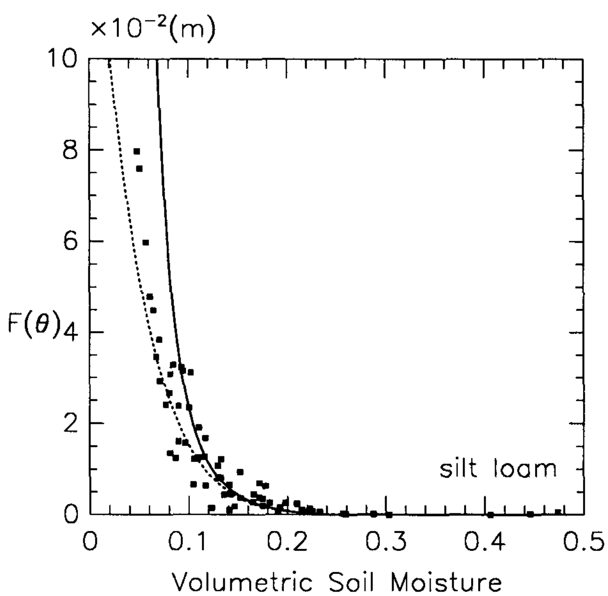

FIG. 4. Resistance function $F(\theta)$ for silt loam calculated from the proposed generalized formula (solid line). Dashed line and data points are from Kondo et al. (1990).

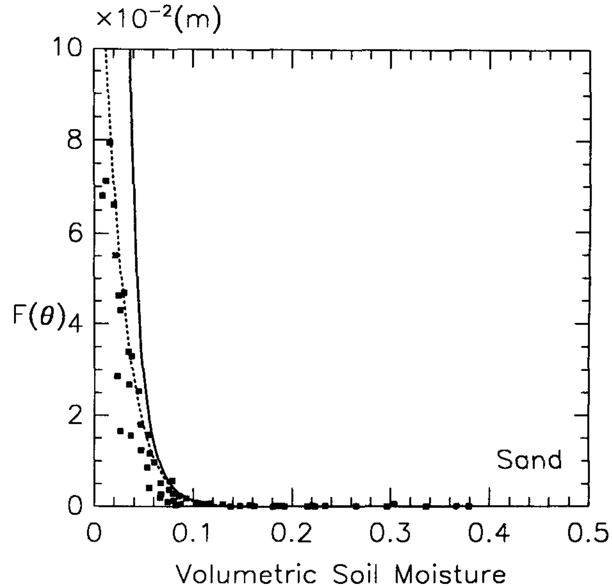

FIG. 5. Same as Fig. 4, but for sand.

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APPENDIX

List of Symbols

Symbol	Unit	Description
α		Surface wetness function
β		Surface wet function
θ	$m^3\ m^{-3}$	Volumetric soil-water content
θ_{fc}	$m^3\ m^{-3}$	Volumetric soil-water content at field capacity
θ_{sat}	$m^3\ m^{-3}$	Saturation soil-water content
θ_t	$m^3\ m^{-3}$	Threshold value for volumetric soil-water content
θ_{wilt}	$m^3\ m^{-3}$	Permanent wilting point
ρ_a	$kg\ m^{-3}$	Density of air

Symbol	Unit	Description
ψ_G	m	Soil-water potential at the ground surface
C_E		Exchange coefficient for moisture
D_{atm}	$m^2 s^{-1}$	Molecular kinematic diffusion coefficient for water vapor
E	$kg\ s^{-1} m^{-2}$	Evaporation rate
$F(\theta)$	m	Resistance function for water vapor movement from the soil pores to the surface
L	$J\ kg^{-1}$	Latent heat for water
R_w	$J\ K^{-1} kg^{-1}$	Gas constant for water vapor
T_g	°C	Ground surface temperature
g	$m\ s^{-2}$	Acceleration due to gravity
q_{sfc}	$kg\ kg^{-1}$	Specific heat of the ground surface
q_a	$kg\ kg^{-1}$	Specific heat of the air
q_{sat}	$kg\ kg^{-1}$	Saturation specific humidity
u_a	$m\ s^{-1}$	Wind speed

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