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ON TRANSPIRATION AND SOIL MOISTURE CONTENT SENSITIVITY TO SOIL HYDROPHYSICAL DATA

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Abstract. Sensitivity of evapotranspiration E and root zone soil moisture content θ to the parameterization of soil water retention $\Psi(\theta)$ and soil water conductivity $K(\Psi)$, as well as to the definition of field capacity soil moisture content, is investigated by comparing *Psi*1-PMSURF and *Theta*-PMSURF models. The core of PMSURF (P*enman*–M*onteith* Sur*face* F*luxes*) consists of a 3-layer soil moisture prediction module based on Richard's equation in combination with the *Penman–Monteith* concept for estimating turbulent heat fluxes. *Psi*1-PMSURF and *Theta-PMSURF* differ only in the parameterization of the moisture availability function F_{ma}. In *Psi*1, F_{ma} is parameterized by using $\Psi(\theta)$ and $K(\Psi)$ hydrophysical functions; in *Theta*, F_{ma} is parameterized by using hydrophysical parameters: the field capacity θ_{f} and wilting point θ_{w} soil moisture contents. Both *Psi*1 and *Theta* are based on using soil hydrophysical data, that is, there is no conceptual difference between them in the parameterization of E even if in *Psi*1 F_{ma} depends on 12 parameters, while in *Theta* only on two soil/vegetation parameters. Sensitivity tests are performed using the Cabauw dataset. Three soil datasets are used: the vG (van Genuchten), CH/vG (Clapp and Hornberger/van Genuchten) and CH/PILPS (Clapp and Hornberger/Project for Intercomparison of Land-surface Parameterization Schemes) datasets. The vG dataset is used in van Genuchten's parameterization, while in Clapp and Hornberger's the CH/vG and CH/PILPS datasets are used. It is found that the consistency of soil hydrophysical data in the simulation of transpiration is quite important. The annual sum of E obtained by *Psi*1, E^{Psi1}, differs from the annual sum of E obtained by *Theta,* E^{Theta}, because of the inconsistency between the fitting parameters of $\Psi(\theta)$ and $K(\Psi)$ and the θ_{f}, and not because of the differencies in the parameterization of F_{ma}. Further, θ_{f} can be estimated not only on the basis of using soil hydrophysical functions (the θ_{f} so obtained is $\theta_{\mathrm{f}}^{\mathrm{Soil}}$) but also on the basis of analysing the transpiration process (the θ_{f} so obtained is $\theta_{\mathrm{f}}^{\mathrm{tr}}$). $\theta_{\mathrm{f}}^{\mathrm{tr}}$ values estimated from the condition $E^{Theta} \approx E^{Psi1}$ are in acceptable accordance with the $\theta_{\mathrm{f}}^{\mathrm{Soil}}$ values proposed by Wösten and co-workers. The results are useful in optimizing the parameterization of transpiration in land-surface schemes.

Keywords: Cabauw site, Field capacity soil moisture content, Soil hydrophysical functions, Soil moisture content in the root zone, Transpiration.

1. Introduction

The representation of water transfer in soil and vegetation as well as the interrelationships between them are of crucial importance in land surface

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schemes. The soil hydrophysical properties are used for evaluating both the soil water movement and the canopy surface resistance. Both subjects are of high concern; in this study we will focus on the latter. Canopy surface resistance r^{v} is often parameterised with Jarvis' (1976) big leaf approach because of its simplicity. In this parameterization, the soil hydrophysical properties are contained in the soil moisture availability function F_{ma}. For F_{ma}, there are two possible formulations: the first uses leaf water potential Ψ_{v} (e.g., Choudhury, 1983; Sellers et al., 1986). In this case Ψ_{v} is a complex function of environmental variables and soil/vegetation parameters, including the soil water retention function $\Psi(\theta)$ and the soil water conductivity function $K(\theta)$. This parameterization type will be referred to as the *Psi*1 parameterization. The second method uses only soil moisture content θ and hydrophysical parameters (field capacity soil moisture content θ_{f} and wilting point soil moisture content θ_{w}). This method does not use any other environmental variables and/or parameters, therefore it is quite simple (e.g., Mahrt and Pan, 1984; Noilhan and Planton, 1989; Chen et al., 1996). This parameterization type will be referred to as the *Theta* parameterization.

Soil hydrophysical properties can be characterised by hydrophysical functions (soil water retention Ψ (θ) and soil water conductivity $K(\theta)$) and/or by hydrophysical parameters (field capacity soil moisture content θ_{f} and wilting point soil moisture content θ_{w}). The hydrophysical functions have to be derived from field measurements. The empirical formulae fitted to the measurements range from the simpler (e.g., Clapp and Hornberger, 1978; Rajkai, 1988) to the more complex (van Genuchten, 1980). In meteorology, the Clapp and Hornberger (1978) parameterization for North American soils (hereafter CH parameterization) is widely applied. It is simple and uses only a few fitting parameters: the saturated soil water retention Ψ_{S} (m, water column), the saturated water conductivity K_{S} (m s^{-1}), the saturated soil moisture content θ_{S} (m^{3} m^{-3}) and the pore size distribution index b. In modelling of soil physical processes, the method usually applied is van Genuchten's (1980) parameterization (hereafter vG parameterization). Its parameters are as follows: the fitting parameter α (m^{-1}), the saturated water conductivity K_{S} (m s^{-1}), the saturated soil moisture content θ_{S} (m^{3} m^{-3}), the residual soil moisture content θ_{r} (m^{3} m^{-3}) and the fitting parameters n and l. Note that K_{S} and θ_{S} are used in both parameterizations although their values are usually different.

Soil hydrophysical parameters have been defined for agronomic purposes and show two intermediate stages during the drying of wet soil. θ_{f} is the moisture content found when a thoroughly wetted soil has drained for about two days. It is determined in the field under conditions that prevent evaporation and allow good drainage (a condition that cannot always be met). θ_{w} is the moisture content found when test plants growing on the soil wilt and do not recover if their leaves are kept in a humid atmosphere over night. θ_f and θ_w are used for making the upper and lower levels of the moisture content of a soil at which water is ordinarily available for plants. It has to be mentioned that these terms do not have precise physical definitions (see Marshall et al., 1996, Section 10.1).

The relationship between hydrophysical functions and hydrophysical parameters is also not precisely defined. So, for instance, according to Lee and Pielke (1992), $\theta = \theta_f$ when $K(\theta) = 0.1$ mm day^{-1}. At the same time, Chen and Dudhia (2001) used Hillel's (1980) criterion for estimating θ_f, according to which $\theta = \theta_f$ when $K(\theta) = 0.5$ mm day^{-1}. These differences are also reflected in the $log_{10}|\Psi(cmH_2O)|$ values (pF values) of the Ψ (θ) curve. The pF values corresponding to θ_f range between 1.7 and 3.0. After Lee and Pielke (1992), $\theta = \theta_f$ when pF $\approx$ 3.0, and pF = 1.7 according to Wösten et al. (1999). Similarly, θ_w is also a changing parameter. After Dolgov (1948), pF values corresponding to θ_w can range between 3.9 and 4.7. According to these estimates, θ_f and θ_w depend only upon soil type. Nevertheless, after Chen and Dudhia (2001) soil hydrophysical parameters depend not only on soil type but also on the inhomogeneous areal distribution of θ. According to this assumption, θ_f and θ_w depend also on transpiration. Because of all these things it is hard to accurately relate the hydrophysical parameters and functions.

Different parameterizations of hydrophysical functions and the lack of precisely defined relationships between $\Psi(\theta)$ and $K(\Psi)$ on the one hand and on θ_f on the other can have different implications for the modelling of transpiration and soil moisture content. To this end, the aim of this study is to analyse

- the sensitivity of transpiration and soil moisture content to the parameterization of $\Psi(\theta)$ and $K(\Psi)$,
- the sensitivity of transpiration and soil moisture content to the definition of θ_f and,
- the consistency of soil parameters used in different soil datasets.

The analysis is performed using the Cabauw dataset (Beljaars and Bosveld, 1997). In the analysis, a vertically homogeneous B11 soil type is assumed. The soil type is characterised by three soil datasets. In the comparative analysis, vG and CH parameterizations are used. The transpiration and the surface fluxes are simulated by the *Psi*1- and *Theta*-PMSURF (P*enman*–M*onteith* Sur*face* F*luxes*) land-surface schemes (Ács and Szász, 2002). The two model versions differ only in the parameterization of the *moisture availability* function F_{ma} (see Sections 2.1.1 and 2.1.2). In *Psi*1-PMSURF, F_{ma} is parameterized using soil hydrophysical functions, while in *Theta*-PMSURF by using hydrophysical parameters.

2. Models

The basic equations and parameterizations of the PMSURF land surface scheme are presented in Table I. The movement of water in the soil is represented by Richard's equation, while surface heat fluxes are estimated using *Penman–Monteith's* concept. This means that there is no temperature prediction module, therefore either net radiation or surface temperature is needed as input for its application. PMSURF is similar to Dolman's (1993) model; its structure differs from SSiB-type (Simplified Simple Biosphere Model) models (e.g., Xue et al., 1996) in the sense that PMSURF is designed to require only a minimum of soil vegetation parameters as input. The latent heat flux is determined by the *Penman–Monteith* equation; the soil heat flux at the surface is estimated as a percentage of net radiation, while sensible heat flux is obtained as the residual of the energy balance equation. The diffusion-like movement of soil water is characterised by Darcy's law; the soil hydrophysical functions are described either by Clapp and Hornberger's (1978) or by van Genuchten's (1980) parameterization. The surface and the aerodynamic transfers are parameterized using a resistance representation, and aerodynamic transport is parameterised using Monin–Obukhov's similarity theory taking into account atmospheric stability. The bare soil surface resistance is estimated after Sun's (1982) empirical formula, while the surface resistance of the vegetation canopy r^{v} follows Jarvis' (1976) big leaf approach. The only difference between the *Psi*1-PMSURF and the *Theta*-PMSURF model versions is in the parameterization of moisture availability effect upon stomatal function. This is represented by the *moisture availability* function F_{ma}, see Table I.

2.1. THE F_{MA} FUNCTION

The F_{ma} function is one of the basic functions in Jarvis' (1976) big leaf approach. After Jarvis (1976), r^{v} is parameterized as

$$r^{\mathrm{v}} = \frac{r_{\mathrm{stmin}} F_{\mathrm{ad}}}{(\mathrm{LAI})(\mathrm{GLF}) F_{\mathrm{ma}}}, \tag{1}$$

where r_{stmin} is the minimum stomatal resistance at optimum environmental conditions, *LAI* is the leaf area index, GLF is the green leaf fraction (this expresses the fraction of live leaves), and F_{ad} is the effect of atmospheric demand upon stomatal function. For F_{ma} two possible formulations are used.

2.1.1. *Psi1-PMSURF*

F_{ma} can be estimated via the leaf water potential Ψ_{v} (e.g., Sellers and Dorman, 1987):

TABLE I
Basic equations and parameterizations in PMSURF model.

Models	Basic elements		
	Prognostic equations		
	Water storage on vegetation surface	*Vegetation – ground temperature*	*Soil moisture*
*Psi*1-PMSURF	Budget equation	–	Richard's equation
Theta-PMSURF	Budget equation	–	Richard's equation
	Parameterization		
	Latent heat flux	Sensible heat flux	Soil heat flux
*Psi*1-PMSURF	Monteith (1965)	Residual of energy balance equation	Per cent of net radiation
Theta-PMSURF	Monteith (1965)	Residual of energy balance equation	Per cent of net radiation
	Parameterization		
	$\Psi(\theta)$ *function*	$K(\theta)$ *function*	*Water movement in the soil*
*Psi*1-PMSURF	van Genuchten (1980) and Clapp and Hornberger (1978)	van Genuchten (1980) and Clapp and Hornberger (1978)	Darcy's law
Theta- PMSURF	van Genuchten (1980) and Clapp and Hornberger (1978)	van Genuchten (1980) and Clapp and Hornberger (1978)	Darcy's law
	Parameterization		
	Vegetation surface resistance	*Bare soil surface resistance*	F_{ma} *function*
*Psi*1-PMSURF	Jarvis (1976)	Sun (1982)	Equation (2)
Theta-PMSURF	Jarvis (1976)	Sun (1982)	Equation (8)

$$F_{\mathrm{ma}} = \frac{\Psi_{\mathrm{v}} - \Psi_{\mathrm{cr}}}{\Psi_{\mathrm{SR}} - \Psi_{\mathrm{cr}}}, \tag{2}$$

where Ψ_{cr} is the critical leaf water potential (at $\Psi_{\mathrm{v}} = \Psi_{\mathrm{cr}}$ the stomata are completely closed) and Ψ_{SR} is the saturated soil water potential in the root zone. Ψ_{v} depends upon environmental variables (e.g., net radiation flux, global radiation, air temperature and humidity, as well as soil moisture content in the root zone) and soil/vegetation parameters (e.g., minimum stomatal resistance, leaf area index, $\Psi(\theta)$ and $K(\Psi)$ functions) in the form of a quadratic equation. The parameterization of Ψ_v is presented in Appendix A. This is the *Psi*1 paramaterization.

Hydrophysical functions are parameterised after van Genuchten (1980), van Genuchten et al. (1991) and Clapp and Hornberger (1978). According to van Genuchten (1980) and van Genuchten et al. (1991)

$$\Psi(\Theta) = -\frac{1}{\alpha}\left[\Theta^{-1/m} - 1\right]^{1/n} \tag{3}$$

and

$$K(\Psi) = K_S \frac{\left[1 - (-\alpha\Psi)^{n-1}(1 + (-\alpha\Psi)^n)^{-m}\right]^2}{[1 + (-\alpha\Psi)^n]^{m(l+2)}}, \tag{4}$$

where $\Theta = \frac{\theta - \theta_r}{\theta_S - \theta_r}$ is the scaled water content and

$$m = 1 - \frac{1}{n}. \tag{5}$$

According to Clapp and Hornberger (1978)

$$\Psi(\theta) = \Psi_S\left(\frac{\theta}{\theta_S}\right)^{-b} \tag{6}$$

and

$$K(\theta) = K_S\left(\frac{\theta}{\theta_S}\right)^{2b+3}. \tag{7}$$

2.1.2. *Theta-PMSURF*

F_{ma} can also be estimated by using the soil moisture content θ and soil hydrophysical parameters (e.g., Pleim and Xiu, 1995):

$$F_{ma} = \begin{cases} 1 & \text{for } \theta_f \leq \theta \\ \frac{\theta - \theta_w}{\theta_f - \theta_w} & \text{for } \theta_w < \theta < \theta_f \\ 0 & \text{for } \theta \leq \theta_w, \end{cases} \tag{8}$$

where θ, θ_f and θ_w refer to the root zone. This is the *Theta* parameterization. It has to be emphasised that *Psi*1 and *Theta* differ only in the parameterization of F_{ma}.

3. Model Validation Experiments

*Psi*1-*PMSURF* has been extensively tested in off-line mode using the Cabauw 1987 data. This dataset is suitable because

- it is well known and used in the PILPS (Project for Intercomparison of Land-surface Parameterization Schemes) phase 2(a) project (Chen et al., 1997),
- there are different formulations for its soil hydrophysical data and,
- evapotranspiration consists mainly of transpiration because of surface coverage.

The Cabauw site has a humid, maritime climate, the soil texture in the root zone is silty clay and the plant cover is mainly short grass. The atmospheric and soil/vegetation parameters are specified according to the results presented in Beljaars and Bosveld (1997) and according to the specification used in PILPS 2(a) experiment. This is represented in Table II. In the numerical experiments, PMSURF was always initialised as in all PILPS participating models by saturating all liquid water stores.

The model validation is performed by comparing simulated and observed surface fluxes. Soil hydrophysical properties are simulated by both vG and CH parameterizations. In the vG parameterization, fitting parameters obtained by Wösten et al. (1994) are used; in the simulations a vertically homogeneous B11 soil type (fairly heavy clay) is assumed. In the CH

TABLE II

Atmospheric and soil-vegetation parameters at the Cabauw site.

Name	Method used	Symbol	Value
Reference height for temperature and humidity (m)	–	z_{rt}	20
Reference height for wind (m)	–	z_{rm}	20
Roughness length of vegetation (m)	–	z_0	0.10
Zero plane displacement height (m)	–	d	0
Albedo of vegetation	–	α^{v}	0.22
Albedo of bare soil	–	α^{b}	0.15
Root density distribution coefficient for grass (m^{-1})	*Psi*1	f	12.05
Plant resistance (resistance imposed by plant vascular system) (s)	*Psi*1	r_{P}	2.5×10^8
Critical leaf water potential (m)	*Psi*1	Ψ_{cr}	−230
Maximum water storage capacity per unit LAI (mm)		S^*_{vm}	0.1
Saturated soil hydraulic conductivity for vG ($\mathrm{m\ s}^{-1}$)	*Psi*1	$\mathrm{K}_{\mathrm{S1}} = K_{\mathrm{S2}} = K_{\mathrm{S3}}$	6.09×10^{-7}

TABLE II (Continued).

Name	Method used	Symbol	Value
Saturated soil hydraulic conductivity for CH/PILPS (m s^{-1})	*Psi*1	$\mathrm{K}_{S1} = K_{S2} = K_{S3}$	3.43×10^{-6}
Fitting parameter α (m^{-1})	Psi1	$\alpha_1 = \alpha_2 = \alpha_3$	2.43
Saturated soil moisture potential for CH/PILPS (m H_2O)	*Psi*1	$\Psi_{S1} = \Psi_{S2} = \Psi_{S3}$	−0.045
Saturated soil moisture contet for vG (m^3 m^{-3})	*Psi*1	$\theta_{S1} = \theta_{S2} = \theta_{S3}$	0.6000
Saturated soil moisture contet for CH/PILPS (m^3 m^{-3})	*Psi*1	$\theta_{S1} = \theta_{S2} = \theta_{S3}$	0.468
Residual soil moisture contet for CH/PILPS (m^3 m^{-3})	*Psi*1	$\theta_{r1} = \theta_{r2} = \theta_{r3}$	0.0
Fitting parameter *n*	*Psi*1	$\mathrm{n}_1 = n_2 = n_3$	1.111
Fitting parameter *l*	*Psi*1	$l_1 = l_2 = l_3$	−5.395
Pore size distribution index	*Psi*1	$b_1 = b_2 = b_3$	10.39
Moisture content at field capacity for vG (m^3 m^{-3})	*Theta*	θ_f^{tr}	0.470
Moisture content at field capacity for CH/PILPS (m^3 m^{-3})	*Theta*	θ_f^{tr}	0.310
Moisture content at wilting point for vG (m^3 m^{-3})	*Theta*	θ_w	0.310
Moisture content at wilting point for CH/PILPS (m^3 m^{-3})	*Theta*	θ_w	0.214
Minimum stomatal resistance (s m^{-1})	*Psi*1	r_{stmin}	40
Maximum stomatal resistance (s m^{-1})	*Psi*1	r_{stmax}	20000
Average root cross section (m^2)	*Psi*1	rcs	3.84×10^{-7}
Root density in the surface layer(mm^{-3})	*Psi*1	R_{des}	5500
Depth of root layer (m)	*Psi*1	D_R	1
Thickness of soil layers (m)		D_1, D_2, D_3	0.10, 0.90, 9.00
Site inclination (degree)		x	0.0
Volumetric heat capacity of soil (J m^{-3} K^{-1})		C_m	2.0×10^6
Surface heat capacity of vegetation (J m^{-2} K^{-1})		C_v	2×10^3

parameterization, fitting parameters proposed in PILPS phase 2(a) project are used. The annual mean sensible and latent heat fluxes obtained by *Psi*1-PMSURF/vG and *Psi*1-PMSURF/CH/PILPS are presented in Figure 1 together with the other PILPS results. The PMSURF results are located exactly on the radiation line because net radiation is used as input. The sensible heat flux of *Psi*1-PMSURF/vG is 4.1 W m^{-2}, the latent heat flux is 38.0 W m^{-2} (see also Table IV). The corresponding observed fluxes were 1 and 41 W m^{-2}. The turbulent fluxes simulated by *Psi*1-*PMSURF*/CH/PILPS are in the proximity of the fluxes obtained by *Psi*1-*PMSURF*/vG. The annual runoff versus evapotranspiration is given in Figure 2. The evapotranspiration and runoff obtained by *Psi*1-PMSURF/vG are 481 and 294 mm year^{-1}, while the corresponding observed fluxes were 522 and 250 mm year^{-1} (see Table IV). As in the former case, the results obtained by *Psi*1/CH/PILPS are in close proximity to *Psi*1/vG. The seasonal change of evapotranspiration is presented in Figure 3. For both the *Psi*1/vG and *Psi*1/CH/PILPS, the largest deviation between simulated and observed E values is about 10 mm month^{-1} and this appears in March and November. The agreement between instantaneous values of simulated and observed latent and sensible heat fluxes obtained by *Psi*1-PMSURF/vG and *Psi*1-PMSURF/CH/PILPS is also good. Results obtained by *Psi*1-PMSURF/CH/PILPS are presented and described in the work by Ács and Szász (2002).

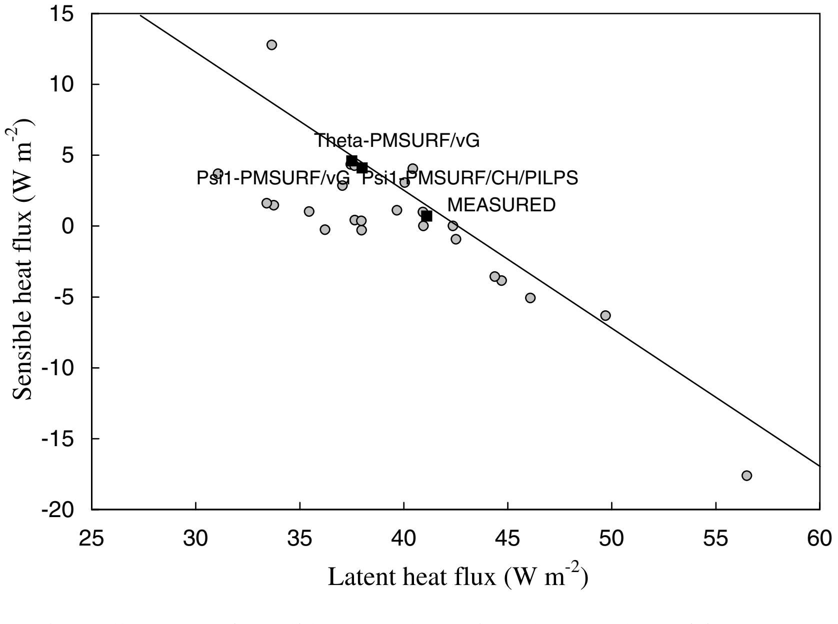

Figure 1. Annually averaged sensible versus latent heat fluxes estimated by *Psi*1-PMSURF using vG and CH/PILPS fitting parameters (*Psi*1-PMSURF/vG and *Psi*1-PMSURF/CH/PILPS) and by *Theta*-PMSURF using θ_f^{tr} value for vG soil dataset (Theta-PMSURF/vG) (black quadrats) along with the equivalent PILPS phase 2(a) results (grey dots; for details see Figure 5 in Chen et al., 1997).

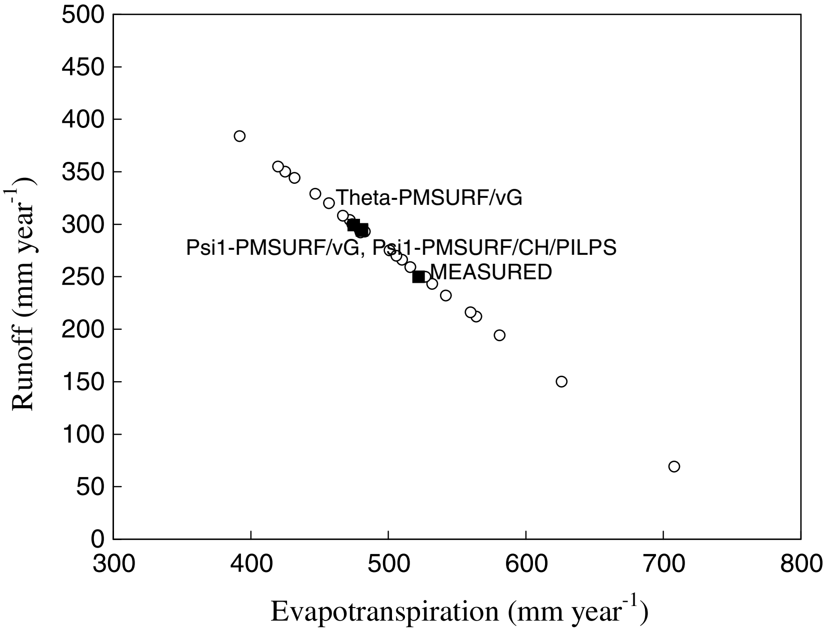

Figure 2. As Figure 1 but for runoff versus evapotranspiration.

4. Sensitivity Analysis

The numerical experiments are performed by running the *Psi*1 and *Theta* models using different formulations for hydrophysical functions and different definitions of θ_f. The sensitivity of transpiration E and soil moisture content θ to the parameterization of $\Psi(\theta)$ and $K(\Psi)$ is investigated by comparing *Psi*1

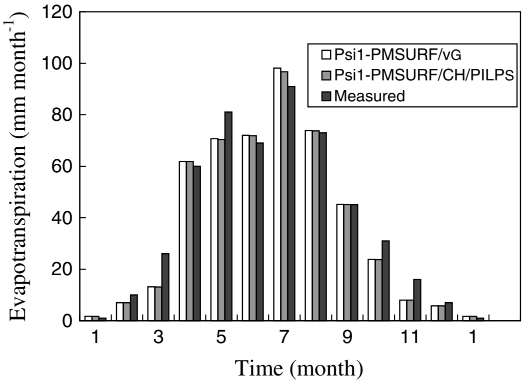

Figure 3. Annual course of evapotranspiration simulated by *Psi*1-PMSURF using vG and CH/PILPS fitting parameters (*Psi*1-PMSURF/vG and *Psi*1-PMSURF/CH/PILPS).

models. The sensitivity of E and θ to the definition of θ_f is analysed by comparing *Theta* models. In these sensitivity tests the Cabauw dataset is used and a vertically homogeneous soil is assumed (see Table II).

4.1. Sensitivity to the parameterization of $\Psi(\theta)$ and $K(\Psi)$

In the simulations vG and CH parameterizations are used. Soil parameters used in vG parameterization are estimated by Wösten et al. (1994). The parameter values used (denoted as vG) refer to soil type B11, and are presented in Table III (see also Table II in the study of Beljaars and Bosveld (1997)). In the CH parameterization, two parameters sets are used (see Table III). The parameter set denoted as CH/vG is obtained by converting vG parameters according to the method proposed by Lenhard et al. (1989), according to which there is an unambiguous relationship between n and α on the one hand and ψ_S and b on the other. Parameter values denoted as CH/PILPS, except field capacity soil moisture content, are used in the PILPS phase 2(a) project (see Table A1 in the study of Chen et al. (1997)). It has to be mentioned that vG soil parameters were

TABLE III

Soil datasets of silty clay at the Cabauw site.

Silty clay			
Parameter	**Soil dataset**		
	Fitting parameters		
	vG	CH/vG	CH/PILPS
Ψ_S (m H_2O)	–	−0.405	−0.045
α (m^{-1})	2.43	–	–
K_S (m s^{-1})	6.09×10^{-7}	6.09×10^{-7}	3.43×10^{-6}
θ_S (m^3 m^{-3})	0.600	0.600	0.468
θ_r (m^3 m^{-3})	0.000	0.000	0.000
b	–	9.09	10.39
n	1.111	–	–
l	−5.395	–	–
	Hydrophysical parameters		
θ_f^{tr} (m^3 m^{-3})	0.470 (K = 0.011 mm day^{-1}) (pF = 2.5)	0.450 (K = 0.119 mm day^{-1}) (pF = 2.7)	0.310 (K = 0.015 mm day^{-1}) (pF = 2.5)
θ_w (m^3 m^{-3})	0.310 (pF = 4.2)	0.310 (pF = 4.2)	0.214 (pF = 4.2)

not known to PILPS when the numerical experiments were designed and run. $\Psi(\Theta)$ and $K(\Psi)$ functions depicted by vG, CH/vG and CH/PILPS soil datasets are presented in Figures 4 and 5, respectively. The values denoted as 'MEASURED' are taken from Figure la of Beljaars and Bosveld (1997).

The annual course of evapotranspiration and soil moisture content obtained by vG, CH/vG and CH/PILPS soil datasets is presented in Figure 6a, b, respectively. There are no significant differences in the course of *E*. Note that evapotranspiration consists mainly of transpiration and that the climate is humid with water excess in the greater part of the year. There are

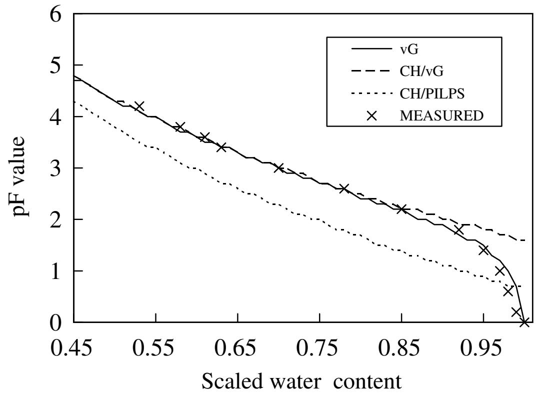

Figure 4. Water retention (expressed as $\log_{10}|\Psi[cmH_2O]|$) versus scaled water content $\frac{\theta-\theta_r}{\theta_S-\theta_r}$ for surface soil type B11 (fairly heavy clay) at Cabauw site. vG = van Genuchten's (1980) parameterization with parameters proposed by Wösten et al. (1994), CH/vG = Clapp and Hornberger's (1978) parameterization with parameters obtained converting vG parameters by Lenhard's et al. (1989) method, CH/PILPS Clapp and Hornberger's (1978) parameterization with parameters proposed in PILPS, MEASURED = values taken from Figure 1 in the study of Beljaars and Bosveld (1997).

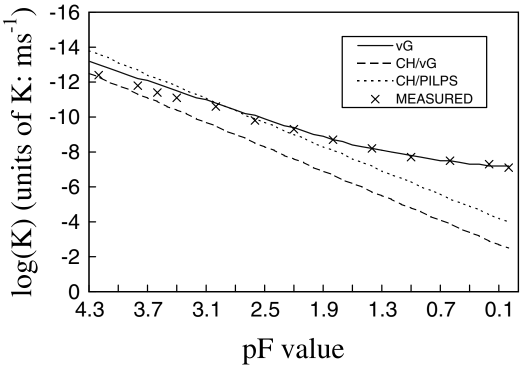

Figure 5. Soil water conductivity (expressed as $\log_{10}K$) versus scaled water content $\frac{\theta-\theta_r}{\theta_S-\theta_r}$ for surface soil type B11 (fairly heavy clay) at Cabauw site. The notation used is as in Figure 4.

practically no differences in the course of E and in the yearly values of sensible heat flux H and runoff R (see Table IV). In spite of this, the root zone soil moisture content θ values obtained by vG and CH/vG are much greater than those obtained by CH/PILPS. The systematic differences amount to about 0.15 m^3 m^{-3}, and can be traced back to the differences in θs values. Unfortunately, there are no measurements of θ to evaluate these results. Nevertheless, the yearly average of $\frac{\theta}{\theta_s}$ is about the same for all three soil datasets (see Table V); $\frac{\theta}{\theta_s}$ values obtained by vG, CH/vG and CH/PILPS are 0.80, 0.80 and 0.75, respectively. The differences are especially great for surface runoff, R_s, and soil water flux at 1-m depth, $Q_{2.}$ R_s and Q_2 obtained by vG are 208 and 4.7 mm $year^{-1}$. In spite of this, R_s and Q_2 obtained by CH/PILPS are 9.8 and 282 mm $year^{-1}$. R_s and Q_2 values obtained by CH/vG

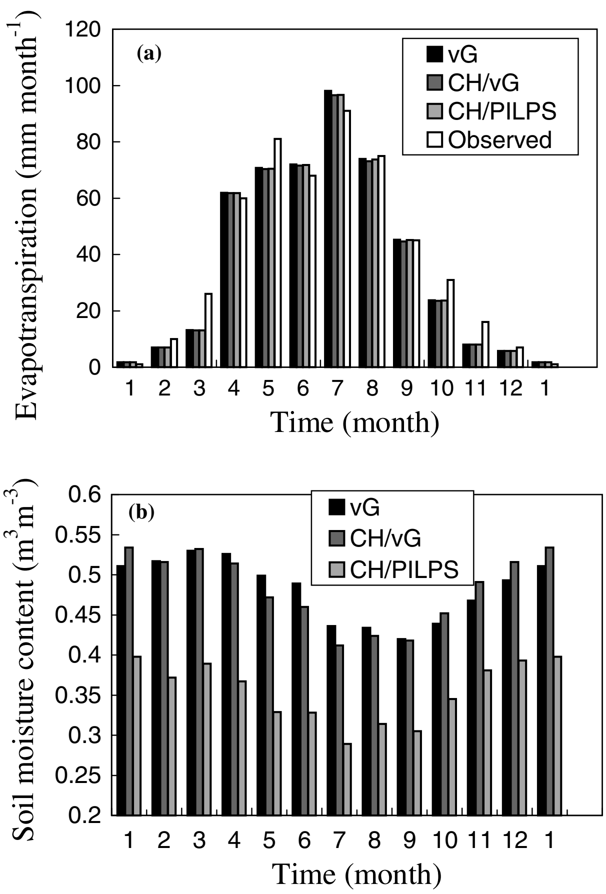

Figure 6. Annual course of (a) evapotranspiration and (b) root zone soil moisture content simulated by *Psi*1-PMSURF using the vG, CH/vG and CH/PILPS fitting parameters (see Table III).

TABLE IV

Annual values of estimated and measured turbulent heat and water fluxes. The fluxes are estimated by *Psi*1- and *Theta* PMSURF using the vG, CH/vG and CH/PILPS soil datasets (see Table III).

Parameter set	Fluxes							
	LE (W m^{-2})		*H* (W m^{-2})		*E* (mm $year^{-1}$)		*R* (mm $year^{-1}$)	
	Models							
vG	*Psi*1	*Theta*	*Psi*1	*Theta*	*Psi*1	*Theta*	*Psi*1	*Theta*
	38.0	37.5	4.1	4.6	481	475	294	299
CH/vG	37.6	37.7	4.4	4.4	477	477	295	295
CH/PILPS	37.8	38.3	4.3	3.7	479	486	293	287
	Measurements							
	41		1		522		250	

are not close to the corresponding values obtained by vG. These differences can be attributed mainly to the differences in $K(\Psi)$ curves obtained by the vG and CH/vG soil datasets (see Figure 5). Since no overland flow has been observed at Cabauw (Chen et al., 1997), the great value for the R_s term obtained by vG seems to be more unlikely. According to our results, in humid climates, as at the Cabauw site, the water balance components are much more sensitive to the parameterization of soil hydraulic functions than the energy balance components. The sensitivity of energy balance components to the parameterization of $\Psi(\theta)$ and $K(\Psi)$ functions is more expressed in less humid climates. Such a case analysis is given, for instance, in the study

TABLE V

Annual values of estimated root zone soil moisture content, surface runoff and soil water flux at a depth of 1 m. The quantities are estimated by *Psi*1- and *Theta*-PMSURF using the vG, CH/vG and CH/PILPS soil datasets (see Table III).

Parameter set	Quantities					
	θ (m^3 m^{-3})		R_s (mm $year^{-1}$)		Q_2 (mm $year^{-1}$)	
	Models					
	*Psi*1	*Theta*	*Psi*1	*Theta*	*Psi*1	*Theta*
vG	0.480	0.483	208	212	4.7	5.0
CH/vG	0.478	0.478	127	127	168	167
CH/PILPS	0.351	0.350	9.8	9.8	282	275

of Cuenca et al. (1996). It is to be noted that their analysis refers to bare soil conditions.

4.2. SENSITIVITY TO THE DEFINITION OF θ_f

θ_f is estimated using two methods: the first one is based on the transpiration process (hereafter transpiration method), while the second one is based on the $\Psi(\theta)$ curve (hereafter soil method). θ_f obtained by the transpiration method is referred to as $\theta_\mathrm{f}^\mathrm{tr}$, while θ_f obtained by the soil method is referred to as $\theta_\mathrm{f}^\mathrm{soil}$. Now let us focus on the methods.

$\theta_\mathrm{f}^\mathrm{tr}$ is estimated on the basis of the following considerations: F_ma and so indirectly E in *Psi*1 also depends on $\Psi(\theta)$ and $K(\theta)$, but it is independent of θ_f and θ_w. In spite of this, E in *Theta* depends, among the soil parameters, only on θ_f and θ_w. When modelling soil water transfer and predicting soil moisture content there are no differences between *Psi*1 and *Theta*. $\theta_\mathrm{f}^\mathrm{tr}$ is that θ for which

$$E^{Theta/tr} \approx E^{Psi1}, \tag{9}$$

where $E^{Theta/tr}$ is a yearly sum of E obtained by *Theta* using $\theta_\mathrm{f}^\mathrm{tr}$, while E^{Psi1} is a yearly sum of E obtained by *Psi*1. θ_w is assumed to be given for $\mathrm{pF} = 4.2$. $\theta_\mathrm{f}^\mathrm{tr}$ values for vG, CH/vG and CH/PILPS soil datasets are presented in Table III. The corresponding $K(\theta_\mathrm{f}^\mathrm{tr})$ and $\Psi\ (\theta_\mathrm{f}^\mathrm{tr})$ values are also noted. The pF $(\theta_\mathrm{f}^\mathrm{tr})$ values for vG, CH/vG and CH/PILPS are 2.5, 2.7 and 2.5, respectively. The $K(\theta_\mathrm{f}^\mathrm{tr})$ values obtained by vG and CH/PILPS are almost equal, and amount to 0.011 and 0.015 mm day^{-1}, respectively. The difference between $K(\theta_\mathrm{f}^\mathrm{tr})$ obtained by vG and CH/vG is great and is in accordance with Figure 5.

In the soil method, we used a common criterion that is applied, for instance, in the study of Wösten et al. (1999). θ_f is that θ value for which $\mathrm{pF} = 1.7$; the θ_f obtained by this method is referred to as $\theta_\mathrm{f}^\mathrm{soil}$. The $\theta_\mathrm{f}^\mathrm{soil}$ and $\theta_\mathrm{f}^\mathrm{tr}$ values for vG, CH/vG and CH/PILPS soil datasets are presented in Table VI. It is striking that the $K(\theta_\mathrm{f}^\mathrm{soil})$ values for vG, CH/vG and CH/PILPS soil datasets are completely different. Among them $K\ (\theta_\mathrm{f}^\mathrm{soil})$ obtained by CH/vG is the greatest, and amounts to 34.40 mm day^{-1}.

The annual mean turbulent heat and water fluxes obtained by *Theta-PMSURF* using the vG set with $\theta_\mathrm{f}^\mathrm{tr}$ values (see Table VI) are presented in Figures 1 and 2, respectively. According to the condition given by Equation (9), the calculated turbulent and water fluxes are in the proximity of the fluxes obtained by *Psi*1-PMSURF/vG (see also Table IV). The annual course of evapotranspiration and soil moisture content is presented in Figure 7a, b; E obtained by using $\theta_\mathrm{f}^\mathrm{soil}$, $E^{Theta/soil}$, is systematically less than E obtained by $\theta_\mathrm{f}^\mathrm{tr}$ i.e. $E^{Theta/tr}$. The greatest difference appears in July, and amounts to about

TABLE VI

Hydrophysical parameters of silty clay at the Cabauw site.

Silty clay *Parameter*	*Hydrophysical parameters*		
	vG	CH/vG	CH/PILPS
θ_f^{tr} (m^3 m^{-3})	0.470	0.450	0.310
	(K = 0.011 mm day^{-1})	(K = 0.119 mm day^{-1})	(K = 0.015 mm day^{-1})
	(pF = 2.5)	(pF = 2.7)	(pF = 2.5)
θ_f^{soil} (m^3 m^{-3})	0.550	0.580	0.370
	(K = 0.22 mm day^{-1})	(K = 34.40 mm day^{-1})	(K = 1.08 mm day^{-1})
	(pF = 1.7)	(pF = 1.7)	(pF = 1.7)
θ_w (m^3 m^{-3})	0.310	0.310	0.214
	(pF = 4.2)	(pF = 4.2)	(pF = 4.2)

15 mm $month^{-1}$. $E^{Theta/tr}$ is closer to the observations than $E^{Theta/soil}$. Concerning θ courses, it is to be noted that the maxima appear in March and the minima in July (for $\theta^{Theta/soil}$) and September (for $\theta^{Theta/tr}$). The annual course of E and θ obtained by using CH/vG hydrophysical parameters is presented in Figure 8a, b. The $E^{Theta/soil} - E^{Theta/tr}$ differences. are greater than in the former case. The maximum of $\theta^{Theta/tr}$ is in January, though its March value

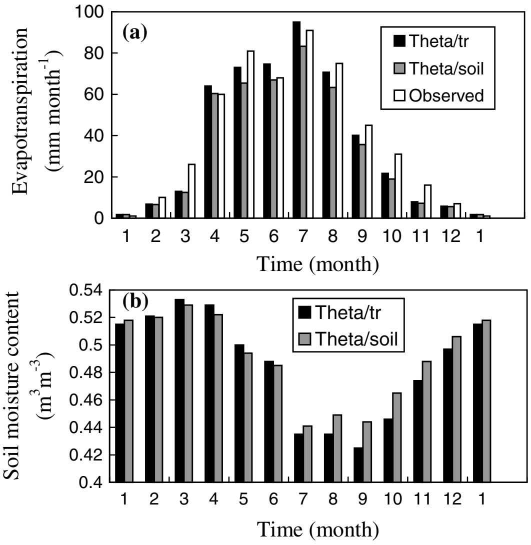

Figure 7. Annual course of (a) evapotranspiration and (b) root zone soil moisture content simulated by *Theta*-PMSURF using the vG set of hydrophysical parameters (see Table VI).

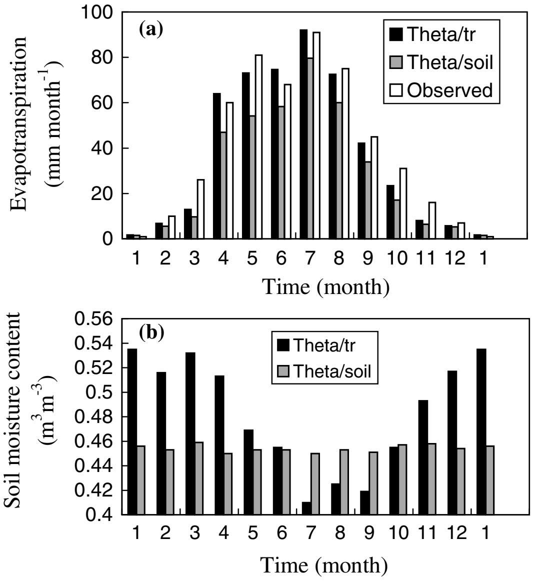

Figure 8. Annual course of (a) evapotranspiration and (b) root zone soil moisture content simulated by *Theta*-PMSURF using the CH/vG set of hydrophysical parameters (see Table VI).

is also large. $\theta^{Theta/soil}$ does not show a yearly course, but fluctuates around 0.45 m^3 m^{-3} and this is presumably related to the parameterization of $K(\Psi)$. From Figure 5, we see that $K(\Psi)$ functions obtained by vG and CH/vG are completely different for low pF values.The annual course of E and θ obtained by using CH/PILPS hydrophysical parameters is presented in Figure 9a, b. It is to be noted that the $\theta_{\mathrm{f}}^{\mathrm{soil}}$ value was used in the PILPS 2(a) phase project. As in the former cases, $E^{Theta/tr}$ is closer to the observations than $E^{Theta/\ soil}$. The maxima of $\theta^{Theta/soil}$ and $\theta^{Theta/tr}$ appear in January, while the minima are in July; the maxima are about 0.4 m^3 m^{-3}, while the minima are about 0.28 m^3 m^{-3}.

The annual values of turbulent heat and water fluxes obtained by using vG, CH/vG and CH/PILPS hydrophysical parameters are presented in Tables VII and VIII. According to the results obtained, *LE, H, E* and *R* are sensitive to the definition of θ_{f}. The greatest differences are obtained for the CH/vG soil hydrophysical parameters; so, for instance, $H^{Theta/soil} - H^{Theta/tr}$ is 7.8 W m^{-2}, while $R^{Theta/soil} - R^{\mathrm{Theta/tr}}$ is almost 100 mm year^{-1}. In spite of this, θ, R_{s} and Q_2 are not so expressly sensitive to the definition of θ_{f}, that is, the changes are much smaller with respect to the former case. Among θ, R_{s} and Q_2, Q_2 shows the greatest changes. So, for instance, for the CH/PILPS soil hydrophysical parameters $\theta^{Theta/soil} \approx \theta^{Theta/tr}$, $R_s^{Theta/soil} - R_s^{Theta/tr}$ is only 1.7 mm year^{-1} and $Q_2^{Theta/soil} - Q_2^{Theta/tr}$ is about 50 mm year^{-1}.

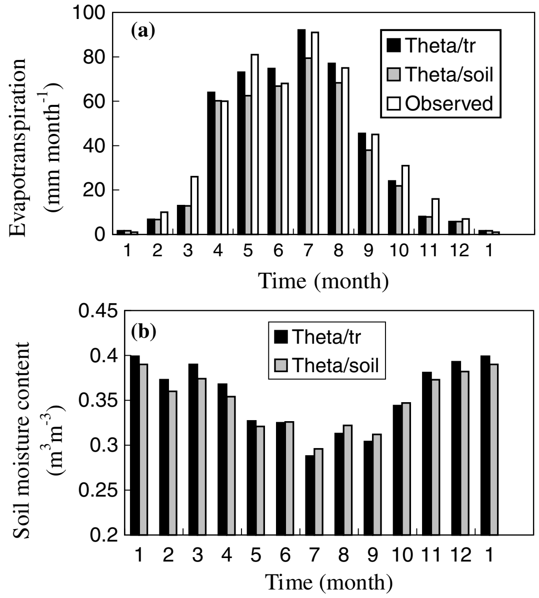

Figure 9. Annual course of (a) evapotranspiration and (b) root zone soil moisture content simulated by *Theta*-PMSURF using the CH/PILPS set of hydrophysical paxameters (see Table VI).

4.3. On the consistency of soil parameters

As already mentioned, F_{ma}, and so E obtained by *Psi*1, depends, among the soil properties, on $\Psi(\theta)$ and $K(\Psi)$. For the vG parameterization, α, K_s, θ_s, n and l

TABLE VII

Annual values of estimated and measured turbulent heat and water fluxes. The fluxes are estimated by *Theta*-PMSURF using the vG, CH/vG and CH/PILPS hydrophysical parameters as given in Table VI.

Parameter set	**Fluxes**							
	LE (W m^{-2})		*H* (W m^{-2})		*E* (mm year^{-1})		*R* (mm year^{-1})	
	Theta-PMSURF							
	θ_f^{soil}	θ_f^{tr}	θ_f^{soil}	θ_f^{tr}	θ_f^{soil}	θ_f^{tr}	θ_f^{soil}	θ_f^{tr}
vG	33.8	37.5	8.3	4.6	428	475	345	299
CH/vG	29.9	37.7	12.2	4.4	379	477	394	295
CH/PILPS	34.1	38.3	7.9	3.7	432	486	340	287
	Measurements							
	41		1		522		250	

TABLE VIII

Annual values of estimated root zone soil moisture content, surface runoff and soil water flux at a depth of 1 m. The fluxes are estimated by *Theta*-PMSURF using the vG, CH/vG and CH/PILPS hydrophysical parameters as given in Table VI.

Parameter set	Quantities					
	θ (m^3 m^{-3})		R_s (mm $year^{-1}$)		Q_2 (mm $year^{-1}$)	
	Theta-PMSURF					
	θ_f^{soil}	θ_f^{tr}	θ_f^{soil}	θ_f^{tr}	θ_f^{soil}	θ_f^{tr}
vG	0.488	0.483	225	212	31.3	5.0
CH/vG	0.454	0.478	123	127	270	167
CH/PILPS	0.346	0.350	11.5	9.8	327	275

fitting parameters are used for calculating $\Psi(\theta)$ and $K(\Psi)$. For the CH parameterization, Ψ_s, K_s, θ_s and b are fitting parameters. E obtained by *Theta* depends, among the soil properties, only on the hydrophysical parameters θ_f and θ_w.

As mentioned, there is no a generally accepted definition or procedure for relating fitting and hydrophysical parameters. Therefore, the question arises whether θ_f^{tr} or θ_f^{soil} is the 'right' value. The 'right' θ_f value shoud be that θ_f value that is more consistent with the corresponding fitting parameters of hydrophysical functions. In the following, we shall provide some facts as to why θ_f^{tr} appears to be more reliable than θ_f^{soil}.

Evapotranspiration curves obtained by *Psi*1-PMSURF and *Theta*-PMSURF using θ_f^{tr} and θ_f^{soil} for vG, CH/vG and CH/PILPS soil datasets are presented in Figure 10a–c, respectively. The atmospheric forcings used are presented in Table IX. A basic feature of these curves is their average slope $S = \frac{\partial E}{\partial \theta}$. In *Theta*-PMSURF S is determined by both θ_w and θ_f; for constant θ_w and potential evapotranspiration $E(\theta_s)$, S is determined only by θ_f. Examining the curves, it is obvious that $S^{Psi1} > S^{Theta/tr} > S^{Theta/soil}$ irrespective of which soil dataset is used. The condition $E^{Theta/tr} \approx E^{Psi1}$ is a condition that forces $S^{Theta/tr}$ to S^{Psi1}. Therefore, the estimate of θ_f^{tr} seems to be reliable if $E^{Psi1} \approx E^{measured}$ and $E(\theta_s)^{Psi1} - E(\theta_s)^{Theta}$ differences are not great. So, a comparison of $E(\theta)$ curves obtained by *Psi*1 and *Theta* enables us to obtain a qualitative estimate of θ_f^{tr}. Furthermore, as has already been noted, pF(θ_f^{tr}) for the vG, CH/vG and CH/PILPS soil datasets is 2.5, 2.7 and 2.5, respectively; pF(θ_f^{tr}) for CH/vG differs from 2.5 because of the weaknesses in the parameterization $K(\Psi)$. It could be said that for the B11 soil type at Cabauw θ_f^{tr} is equivalent to θ_f^{soil} when pF = 2.5; this is in accordance with the results obtained by Wösten et al. (1994). Note that corresponding K values are significantly more different.

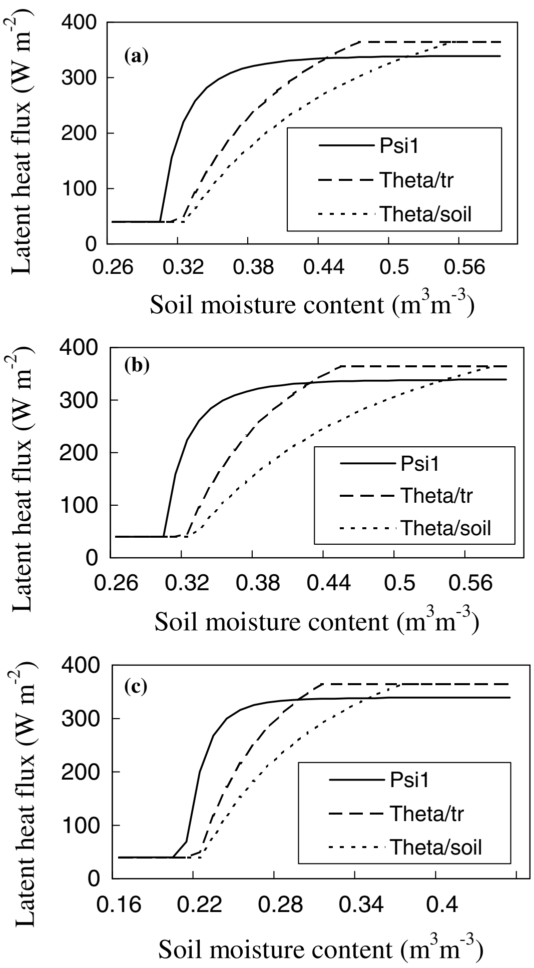

Figure 10. Transpiration versus soil moisture content for strong atmospheric forcing conditions simulated by *Psi*1-PMSURF and *Theta*-PMSURF using the (a) vG, (b) CH/vG and (c) CH/PILPS soil datasets (see Tables III and VI).

5. Conclusions

The sensitivity of E and θ to the parameterization of hydrophysical functions and to the definition of θ_f is investigated using *Psi*1-PMSURF and *Theta*-PMSURF models. The sensitivity of E and θ to the parameterization of $\Psi(\theta)$ and $K(\Psi)$ is analysed by using the *Psi*1 model. The sensitivity of E and θ to the definition of θ_f is investigated by the *Theta* model. The tests are performed using the Cabauw 1987 data (Beljaars and Bosveld, 1997) representing humid, water excess climate conditions. Three soil datasets are used: vG, CH/vG and CH/PILPS datasets. The vG dataset is used by van

TABLE IX
Atmospheric forcing conditions.

Variables	Strong atmospheric forcing
Global radiation flux (W m^{-2})	850
Air temperature at reference level (°C)	25.8
Vapour pressure at reference level (hPa)	31
Wind velocity at reference level (m s^{-1})	6

Genuchten's (1980) parameterization, while the CH/vG and CH/PILPS datasets are used by Clapp and Hornberger's (1978) parameterization. The main results and conclusions are as follows:

- E^{Psi1} is not sensitive to the parameterization of $\Psi(\theta)$ and $K(\Psi)$ if the fitting parameters used in the vG, CH/vG and CH/PILPS soil datasets form a coherent unit, that is, their values are consistent with each other. In spite of this, the surface runoff R_s and the soil water flux at 1-*m* depth Q_2 are sensitive to the parameterization of $\Psi(\theta)$ and $K(\Psi)$ (see Tables IV and V).
- E^{Theta} is sensitive to the definition of θ_f (see Table VII).
- A new procedure for estimating θ_f is proposed. The θ_f^{tr} value obtained from Equation (9) ($E^{Theta/tr} \approx E^{Psi1}$) agrees well with the θ_f^{soil} value for pF = 2.5. This is in accordance with the results obtained by Wösten et al. (1994).
- It is demonstrated that the convergence of *Psi*1 and *Theta* depends primarily on the consistency between soil hydrophysical data and not on the differencies in the complexity between them. If there is a consistency between the fitting parameters of hydrophysical functions and the hydrophysical parameters, then *Theta* should converge to *Psi*1.
- It is shown that different sets of consistent soil parameter values can exist for a given soil type. In this study, for the B11 soil type, three such datasets (see Table III) are analysed.
- It is recommended to use *Theta*-PMSURF because of its simplicity if the values of θ_f and θ_w are reliable. In the opposite case, *Psi*1-PMSURF has to be used in spite of its greater complexity.

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Appendix A: Parameterization of Ψ_v in PMSURF

Water transfer through plants is characterized by the transpiration E and root water uptake Q_R. It is well known that the water storage in the plants is negligible with respect to water influxes and outfluxes, so that it is reasonable to use a water flow continuity assumption (Rutter, 1975):

$$Q_R = (1 - wif)E. \tag{A1}$$

Q_R is parameterized by

$$Q_R = \varrho_w \frac{\delta\Psi_R - \delta\Psi_v}{r_R + r_P} \tag{A2}$$

where

$$\delta\Psi_v \equiv \Psi_v - \Psi_{cr}; \quad \delta\Psi_R \equiv \Psi_R - \Psi_{cr}, \tag{A3}$$

while E is obtained from *Penman–Monteith's* equation:

$$E = \left(\frac{1}{L}\right) \frac{r^a \Delta R + \varrho c_p \delta e_r}{r^a [\Delta + \gamma(1 + \frac{r^v}{r^a})]}. \tag{A4}$$

In the above, *wif* is the surface fraction of the intercepted water, ϱ_w is water density, Ψ_R is soil moisture potential in the root zone, r_R is root resistance in the root zone, r_P is the plant resistance, r^a is the aerodynamic resistance, L is the latent heat of vaporization, $\Delta = \partial e_S(T)/\partial T$, where $e_S(T)$ is the saturated vapour pressure at air temperature T, R is surface net radiation, ϱ is air density, c_p is the specific heat of air at constant pressure, δe_r is the vapour pressure deficit and γ is the psychrometric constant. Both fluxes depend on leaf water potential; Q_R explicitly while E implicitly via resistance r^v. r^v is parameterised using Jarvis' (1976) formulation as follows:

$$r^v = \frac{r_{\mathrm{stmin}} F_{\mathrm{ad}}}{(\mathrm{LAI})(\mathrm{GLF}) F_{\mathrm{ma}}}, \tag{A5}$$

with

$$F_{\mathrm{ma}} = \frac{\delta\Psi_v}{\delta\Psi_{SR}}, \tag{A6}$$

where

$$\delta\Psi_{SR} \equiv \Psi_{SR} - \Psi_{cr}. \tag{A7}$$

Here, $\delta\Psi_v$ can be expressed inserting Equations (A.2) and (A.3) in Equation (A.1). Then

$$\varrho_w \left(\frac{\delta\Psi_R - \delta\Psi_v}{r_R + r_P}\right) = \frac{(1 - wif)(r^a \Delta R + \varrho c_p \delta e_r)}{L r^a [(\Delta + \gamma) + \gamma X \delta\Psi_{SR}/\delta\Psi_v]}, \tag{A8}$$

where

$$X \equiv \frac{r_{\mathrm{stmin}} F_{\mathrm{ad}}}{r^{\mathrm{a}}(\mathrm{LAI})(\mathrm{GLF})}. \tag{A9}$$

Introducing

$$\frac{\gamma}{\Delta + \gamma} \equiv \xi \tag{A10}$$

and

$$\left(\frac{1 - wif}{L\varrho_{\mathrm{w}}\gamma}\right) \frac{r_{\mathrm{R}} + r_{\mathrm{P}}}{r^{\mathrm{a}}} \equiv Y, \tag{A11}$$

Equation (A.8) after some rearranging can be written as

$$(\delta\Psi_{\mathrm{v}})^2 - B\delta\Psi_{\mathrm{v}} - C = 0, \tag{A12}$$

where

$$B \equiv \delta\Psi_{\mathrm{R}} - \xi X\delta\Psi_{\mathrm{SR}} - \xi Y(r^{\mathrm{a}}\Delta R + \varrho c_p \delta e_{\mathrm{r}}), \quad C \equiv \xi X\delta\Psi_{\mathrm{SR}}\delta\Psi_{\mathrm{R}}. \tag{A13}$$

The solution of Equation (A12) is,

$$\delta\Psi_{\mathrm{v}} = \frac{B}{2} + \sqrt{\frac{B^2}{4} + C}. \tag{A14}$$

The C parameter is positive, while B is negative. Since $\delta\Psi_{\mathrm{v}}$ has to be positive, the sign before the square root has to be positive to obtain a physically based solution.

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