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A phenomenological model of soil evaporative efficiency using surface soil moisture and temperature data

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ABSTRACT

Modeling soil evaporation has been a notorious challenge due to the complexity of the phenomenon and the lack of data to constrain it. In this context, a parsimonious model is developed to estimate soil evaporative efficiency (SEE) defined as the ratio of actual to potential soil evaporation. It uses a soil resistance driven by surface (0–5 cm) soil moisture, meteorological forcing and time (hour) of day, and has the capability to be calibrated using the radiometric surface temperature derived from remotely sensed thermal data. The new approach is tested over a rainfed semi-arid site, which had been under bare soil conditions during a 9-month period in 2016. Three calibration strategies are adopted based on SEE time series derived from (1) eddy-covariance measurements, (2) thermal measurements, and (3) eddy-covariance measurements used only over separate drying periods between significant rainfall events. The correlation coefficients (and slopes of the linear regression) between simulated and observed (eddy-covariance-derived) SEE are 0.85, 0.86 and 0.87 (and 0.91, 0.87 and 0.91) for calibration strategies 1, 2 and 3, respectively. Moreover, the correlation coefficient (and slope of the linear regression) between simulated and observed SEE is improved from 0.80 to 0.85 (from 0.86 to 0.91) when including hour of day in the soil resistance. The reason is that, under non-energy-limited conditions, the receding evaporation front during daytime makes SEE decrease at the hourly time scale. The soil resistance formulation can be integrated into state-of-the-art dual-source surface models and has calibration capabilities across a range of spatial scales from spaceborne microwave and thermal data.

1. Introduction

To better understanding the water fluxes of crops, and optimizing irrigation in water-limited environments, efforts are being made to estimate both the plant consumption by transpiration (through stomata) and the water losses by evaporation (from soil and in some instances from canopy via interception) (Agam et al., 2012). The partitioning of evapotranspiration into soil evaporation and plant transpiration is needed to assess the crop water use efficiency through its transpiration rate (Hain et al., 2009), as well as to evaluate how much production is derived per unit of crop transpiration (Molden et al., 2010). Such information is also needed at multiple spatial scales, from the field scale where agronomic practices are carried out (Allen, 1990), to the catchment scale where land and water management is operated (Zhang et al., 2001).

Field instrumentation for measuring soil evaporation and plant transpiration separately includes eddy covariance, micro Bowen-ratio energy balance, micro lysimeter, soil heat pulse probe, chamber, isotope and sap flow techniques (Kool et al., 2014). Although those instrumentations have much evolved since the initial experimentations in the 1970s, data collected *in situ* are still very scarse (Schlesinger and Jasechko, 2014) and are generally representative of the local conditions, that is from the leaf/stem to approximately the 100-m scale. This results in a large uncertainty of the transpiration/evapotranspiration ratio (estimated in the range 0.35–0.80) associated with a current lack of observation at the catchment scale (Coenders-Gerrits et al., 2014).

To help evaluate the evaporation/transpiration partitioning at multiple space–time scales, advanced land-surface models are available to simulate energy, water, and carbon fluxes at the land surface-atmosphere interface (Oleson et al., 2013; Boone et al., 2017, e.g.). Simpler models such as two-source surface energy balance models (Lhomme and Chehbouni, 1999) require less input parameters. In general, state-of-the-art models rely on specific assumptions on either the soil evaporation (Caparrini et al., 2004) or the plant transpiration

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(Kustas and Norman, 1999), or base their two-source representation on semi-empirical or semi-physical resistances. Whereas semi-empirical resistances are difficult to generalize in a range of agro-environmental conditions (Ershadi et al., 2014), semi-physical resistances generally depend on soil hydrodynamic properties (Decker et al., 2017), which are highly variable and yet unavailable over large areas (Gutmann and Small, 2007).

To address the above-described difficulties in representing the evaporation/transpiration components across a range of space–time scales using a two-source resistance-based formulation, remote sensing data have great potential. In fact, one way of separating soil evaporation and plant transpiration is to estimate one component independently from the total evapotranspiration. In this regard, the soil evaporation process is quite well constrained by available remote sensing observations. Surface soil moisture derived from microwave data is one main controlling factor of evaporation (Prévot et al., 1984), and the radiometric soil temperature derived from thermal data in the absence of dense vegetation cover is, under non-energy-limited conditions, a signature of the evaporation rate (Norman et al., 1995). However, although thermal-microwave data combining approaches have been imagined since the 1990s (Chanzy et al., 1995; Li et al., 2006), none has been implemented yet. One of the reasons is the lack of remote sensing sensors with sufficient spatio-temporal resolution. Especially, the operational extraction of surface soil moisture at high-spatial resolution remains delicate and there is no thermal mission providing data at high spatio-temporal resolution. As a step forward, recently launched/future satellite missions such as Sentinel-1 (Paloscia et al., 2013) and Trishna (Lagouarde et al., 2013) as well as disaggregation techniques (Peng et al., 2017; Zhan et al., 2013) could solve this issue in the near future.

Another major issue when attempting to integrate thermal data in an evaporation model is the drying (usually around noon) of the top few millimeters of soil which inhibits evaporation, regardless of the availability of the soil water underneath (Mahrt and Pan, 1984; Dickinson et al., 1986; Soarès et al., 1988; Wetzel and Chang, 1988; Van de Griend and Owe, 1994; Heitman et al., 2008; Shahraeeni et al., 2012). Or et al. (2013) identify two regimes: Stage I when both liquid phase continuity and capillary forces sustain evaporation at the top soil and Stage II when the drying front is deeper in the soil and evaporation is mainly controlled by diffusion (Haghighi et al., 2013). In fact, the soil drying during daytime and the uniform rewetting of soil via capillary rises during nighttime is a cyclic phenomenon that is expected to affect the evaporation resistance at the hourly time scale (Tuzet et al., 2003). One challenge is that the radiometric soil temperature is highly variable in time as a result of the diurnal dynamics of meteorological forcing (i.e. solar radiation, wind speed, air temperature, air humidity) and the evolution of soil moisture. Additionally, it is representative of the physical characteristics of the soil skin only. A direct consequence is that a thermal-based evaporation model should beneficially take into account the drying of the top soil during daytime.

This was the rationale for developing a formulation of soil evaporative efficiency (SEE, defined as the ratio of actual to potential soil evaporation) with a shape that adapts to the soil moisture gradient. Given that the soil moisture profile is generally unknown, and that the drying of the top soil is related to the evaporative demand (in addition to the soil moisture value), Merlin et al. (2011) considered potential evaporation as a proxy for the soil moisture gradient in the topsoil. In fact, a large potential evaporation is associated with a strong moisture gradient in the top soil, which implies a decrease of SEE regardless of the moisture content integrated over the 0–5 cm soil layer. Such a phenomenological modeling approach allows for implicitly representing the drying of the top soil during daytime. The SEE formulation of Merlin et al. (2011) was derived at the daily scale only, which is inconsistent with the subdiurnal availability of thermal data.

In this context, this paper aims to develop a quasi instantaneous model of SEE that has the ability to consistently integrate both near-surface soil moisture and radiometric soil temperature data. In practice, the recent SEE modeling approach of Merlin et al. (2016) is improved by adding a temporal dependence, as well as an additional parameter controlling the cyclic phenomenon of the drying/rewetting of the top soil during daytime/nighttime. The new resistance model is tested in terms of SEE estimates using eddy covariance measurements collected over a bare soil site in central Morocco, and its performance is assessed against two benchmark models. Calibration capabilities of the SEE model from thermal (instead of eddy covariance) data are also investigated.

2. Modeling approach

Soil evaporation can be modeled using a resistance approach:

$$\mathrm{LE} = \frac{\rho C_P}{\gamma} \times \frac{e_{\mathrm{sat}}(T) - e_a}{r_{\mathrm{ah}} + r_{\mathrm{ss}}} \tag{1}$$

with LE (Wm^{-2}) being the soil latent heat flux, r_{ss} (s m^{-1}) the resistance to the diffusion of vapor in soil pores, ρ (kg m^{-3}) the density of air, C_P (J kg^{-1} K^{-1}) the specific heat capacity of air, γ (Pa K^{-1}) the psychrometric constant, $e_{sat}(T)$ (Pa) the saturated vapor pressure at the soil surface, T (K) the soil surface temperature, e_a (Pa) the vapor pressure of air and r_{ah} (s m^{-1}) the aerodynamic resistance to heat transfer from the soil surface to the reference height.

Based on Eq. (1), one may also derive a potential soil evaporation, defined as the soil evaporation that would occur in fully saturated soil conditions so that $r_{ss} = 0$:

$$\mathrm{LEp} = \frac{\rho C_P}{\gamma} \times \frac{e_{\mathrm{sat}}(T_{\mathrm{wet}}) - e_a}{r_{\mathrm{ah,wet}}} \tag{2}$$

with T_{wet} (K) and $r_{ah,wet}$ (s m^{-1}) being the soil temperature and aerodynamic resistance in saturated soil conditions, respectively. The parameters used as input to the LEp model are presented in Appendix A. The ratio of actual to potential soil evaporation, i.e. the SEE, can then be expressed as:

$$\mathrm{SEE} = \frac{e_{\mathrm{sat}}(T) - e_a}{e_{\mathrm{sat}}(T_{\mathrm{wet}}) - e_a} \times \frac{r_{\mathrm{ah,wet}}}{r_{\mathrm{ah}} + r_{\mathrm{ss}}} \tag{3}$$

The soil resistance in Eq. (3) is expressed as a function of soil moisture following Merlin et al. (2016):

$$r_{\mathrm{ss},M16} = r_{\mathrm{ss,ref}} \exp(-\theta/\theta_{\mathrm{efolding}}) \tag{4}$$

with $r_{ss,ref}$ being a hypothetical soil resistance corresponding to dry soil conditions and $\theta_{efolding}$ the soil moisture value at which r_{ss} is equal to $r_{ss,ref}/e$. The present paper aims to intercompare three evaporation models based on the following assumptions for the r_{ss} formulation:

- both $r_{ss,ref}$ and $\theta_{efolding}$ of Eq. (4) are set to constant values (depending on soil texture and structure) as in Passerat de Silans (1986) and Sellers et al. (1992).
- $r_{ss,ref}$ and $\theta_{efolding}$ of Eq. (4) are analytically expressed as a function of meteorological forcing and two observable parameters as in Merlin et al. (2016).
- a correction term ($\delta r_{ss,t}$) is added to $r_{ss,M16}$ to account for diurnal variations in SEE associated with top-soil drying (receding evaporation front) during daytime (Mahrt and Pan, 1984; Dickinson et al., 1986; Soarès et al., 1988; Wetzel and Chang, 1988; Van de Griend and Owe, 1994; Heitman et al., 2008; Shahraeeni et al., 2012).

For clarity, the three above models are named in the following as PdS86, M16 and new model, respectively.

The third and new soil resistance model is written as:

$$r_{\mathrm{ss},t} = r_{\mathrm{ss},M16} + \delta r_{\mathrm{ss},t} \tag{5}$$

with $r_{ss,M16}$ the soil resistance of Eq. (4) and $\delta r_{ss,t}$ a correction term that includes the effect of the receding evaporation front during daytime on