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Research papers

Evaluating soil evaporation parameterizations at near-instantaneous scales using surface dryness indices

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ABSTRACT

Soil evaporation is an important component in the water and energy cycles on land, especially for areas that are moderately or densely covered by bare soil. Soil evaporation parameterizations that scale down potential evaporation with the soil surface temperature (T_s) and/or the air humidity are regionally applicable because of the advantage of omitting pixel-scale near-surface soil moisture. In this paper, we provide an intercomparison study among these parameterizations. Potential evaporation indices are estimated from the Priestley-Taylor method, the Penman method, and the mass transfer method (with or without T_s). The surface dryness indices that indicate the water availability of the soil surface are based on T_s and/or the air humidity. We establish and evaluate ten such soil evaporation parameterizations through combinations of different types of potential evaporation indices and surface dryness indices at near-instantaneous scales (30 min). The results show that incorporating the soil temperature in the surface dryness index instead of the potential evaporation index can improve soil evaporation estimations. Poorer but still reasonable estimations are achieved when only the air humidity-based surface dryness index is used. In addition, the energy balance factor is crucial in the surface dryness indices. Our study indicates that the potential evaporation indices that are based on the Penman equation are generally more useful and robust than those that are based on the Priestley-Taylor approach or the mass transfer method. However, when the surface dryness index is only based on air humidity data, the Priestley-Taylor potential evaporation index performs as well as the index that is estimated from the Penman equation. In contrast, a soil evaporation parameterization that estimates the potential evaporation through the mass transfer method (with T_s) and the surface dryness index from the soil moisture content did not perform as well as the above ten parameterizations.

1. Introduction

Evapotranspiration (ET), which includes evaporation from soil and water and transpiration from plants, is a major component in the land surface water cycle and energy balance (Oki and Kanae, 2006; Trenberth et al., 2009, 2007). The spatial estimation of daily ET, especially its partitioning between the canopy and soil layers is therefore useful to improve irrigation design (Colaizzi et al., 2004), climate simulations (Lawrence et al., 2007) and environmental assessments (Newman et al., 2006). Transpiration at daily or smaller time scales has been successfully estimated by using remote-sensing based vegetation indices (VIs) and physiological canopy conductance models (Gan and Gao, 2015; Leuning et al., 2008; Mu et al., 2011; Zhang et al., 2010). However, estimating soil evaporation is more complicated and less constrained compared to transpiration calculations, which may cause great estimation errors in moderately and sparsely vegetative areas.

Evaporation at remote-sensing-pixel scales is usually estimated by tuning down the potential rate of evaporation with the soil moisture availability at the near suface. For example, the Penman hypothesis assumes that the actual evaporation is proportional to the potential evaporation, and one method to estimate the relative evaporation LE/LE_p, where LE and LE_p are the actual and potential ET, respectively, is introducing a function of soil water availability

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(Yang et al., 2006). However, the operational retrievals of regional soil moisture at moderate resolution (approximately 1 km) remain a challenge even with the great development of microwave remote sensing techniques because passive microwave systems measure the soil moisture at relatively coarse resolution (e.g., 25 km) and active microwave systems require local calibration to minimize the effects of vegetation and surface roughness on radar signals (Wagner et al., 2007). In addition, the surface soil moisture may experience rapid changes over short time scales, so the difficulty of this method is further highlighted at near-instantaneous scales (e.g., 30 min in this study).

A possible way to avoid using the pixel-scale soil moisture content is to estimate the actual ET directly from the potential ET. For example, Bouchet (1963) stated that the actual ET is not necessarily proportional to the potential ET; in contrast, as the surface dries, a decrease in the actual ET is accompanied by an identical increase in the potential ET if the total available energy is constant. This is known as the complementary relationship. Thus the actual ET can be readily estimated from the potential ET by using such complementary models (Brutsaert and Stricker, 1979; Granger, 1989a; Morton, 1983). However, such models usually require a hypothesis on the exact relationship between the changes in the energy that is used in the actual ET and the energy that is available for the potential ET, which may not be valid in all spatial and temporal scales.

Another way to directly estimate the actual ET from the potential ET is to return to the relative evaporation perspective but explore the usage of potential evaporation in indicating the surface dryness. The actual evaporation is estimated as the product of the potential evaporation and the relative evaporation, and the latter is estimated from the surface dryness index (SDI), which is parameterized as a function of the potential ET. The key of such parameterizations is to model the SDI from the potential evaporation.

Granger and Gray (1989) modeled the SDI as a dimensionless index that combines the available energy at the land surface and the drying power of the air. The drying power of the air is an index that indicates the potential ET and is estimated from the mass transfer method by using the air humidity. The air humidity is influenced by land-atmosphere feedbacks through ET (Brutsaert and Stricker, 1979), and thus reflects the surface dryness to some extent (Granger and Gray, 1989). Compared to the soil moisture, the air humidity is a more readily available variable that can be obtained from weather station measurements or regional atmospheric simulations. However, the coupling between the atmospheric humidity and the near-surface soil moisture deviates from the equilibrium state because of the large-scale advection effect, in which case the atmospheric humidity is no longer a good indicator of the near-surface soil moisture content.

Compared to the air humidity, the soil surface temperature is more directly linked to the near surface soil moisture conditions. This factor can be used to scale down the potential evaporation to estimate the actual evaporation, for example, within the LST-VI framework (Long and Singh, 2012; Merlin et al., 2014; Nishida et al., 2003) and the PT-JPL model (Garcia et al., 2013), which was first proposed by Fisher et al. (2008). In addition, a potential evaporation index can be estimated by using the mass transfer method with the land surface temperature thanks to the development of thermal remote sensing techniques. Crago and Crowley (2005) compared several versions of complementary ET models that use different combinations of potential ET indices (with and without land surface temperature) at near-instantaneous time scales. However, their models were applied to estimates the total ET instead of the soil evaporation.

In this study, we focus on the parameterization of soil evaporation. We attempt to directly establish the relationships between the relative evaporation and the surface dryness indices for different situations with different data availability by using model simulations and in-situ measurements. First, we incorporate the land surface temperature (LST) in potential evaporation indices and surface dryness indices and then determine the best incorporation method by comparing the strength of six combinations of potential evaporation indices and surface dryness indices when estimating the soil evaporation. Such formulations can be useful in diagnostic and process-based models, in which energy fluxes and the LST are simultaneously determined. Second, we evaluate the usage of air humidity data in estimating the near-instantaneous soil evaporation and determine the best formulation out of four parameterizations for modeling soil evaporation. When LST data are not available or when the LST is not considered in the surface energy balance, such formulations can be used together with a canopy conductance model to estimate total the ET. Third, the parameterization that uses the soil moisture content is also used for comparison. In this study, the above-mentioned evaluations are performed at pixel scales, in which case a sound thermal-based two-source energy balance model ($TSEB_{TR}$) is used to determine the "actual" evaporation and transpiration at the pixel scale by using the remotely sensed LST, measured energy fluxes and atmospheric conditions.

2. Methods

2.1. Parameterizations of the soil evaporation

The soil evaporation is usually estimated by tuning down the potential rate of evaporation (LE_{s*}) according to the surface dryness indices, i.e., $LE_{s\_predicted} = LE_{s*} \times \text{fun(SDI)}$, in which fun(SDI) is the relative evaporation. First, we introduce three parameterizations of the potential evaporation and then the formulations of the SDI and relative evaporation with respect to the SDI. A summary of all the variables that are used in the soil evaporation parameterizations is shown in Table 1.

The concept of potential ET, which refers to the evapotranspiration rate that would occur for a large uniform surface with an adequate water supply, was first proposed and used by Thornthwaite (1948) for climate classifications. However, as Brutsaert (1982) had indicated, the water/heat feedbacks of the saturated surface to the air are unknown, so the potential rate that is calculated under actual air conditions is not the same as what would occur for a saturated surface. Granger (1989b) noted that the potential rate is indeterminable under the original definition of Thornthwaite

Table 1
Summary of all the variables that are used in the soil evaporation parameterizations.

Variables		Descriptions/Definitions
Potential evaporation LE_{s*}	LE_{s_pt}	Potential LE_s estimated using the PT approach with soil surface available energy, Eq. (1)
	LE_{s_pm}	Potential LE_s estimated using the PM approach with soil surface available energy and the air humidity, Eq. (2)
	LE_{s_mt}	Potential LE_s estimated using the MT approach with soil surface temperature and the air humidity, Eq. (3)
	LE_{s_air}	Potential LE_s estimated using the MT approach with air temperature and the air humidity, Eq. (23)
Surface dryness index SDI	SDI_1	Surface dryness index based on LE_{s_mt} and soil surface energy balance, Eq. (7)
	SDI_2	Surface dryness index based on LE_{s_mt} and relative humidity of the air, Eq. (8)
	SDI_3	Surface dryness index based on LE_{s_air} and soil surface energy balance, Eq. (21)
	SDI_4	Surface dryness index based on LE_{s_air} and relative humidity of the air, Eq. (22)