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Actual evapotranspiration in drylands derived from in-situ and satellite data: Assessing biophysical constraints

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ABSTRACT

Improving regional estimates of actual evapotranspiration (λE) in water-limited regions located at climatic transition zones is critical. This study assesses an λE model (PT-JPL model) based on downscaling potential evapotranspiration according to multiple stresses at daily time-scale in two of these regions using MSG–SEVIRI (surface temperature and albedo) and MODIS products (*NDVI*, *LAI* and f_{PAR}). An open woody savanna in the Sahel (Mali) and a Mediterranean grassland (Spain) were selected as test sites with Eddy Covariance data used for evaluation. The PT-JPL model was modified to run at a daily time step and the outputs from eight algorithms differing in the input variables and also in the formulation of the biophysical constraints (stresses) were compared with the λE from the Eddy Covariance. Model outputs were also compared with other modeling studies at similar global dryland ecosystems.

The novelty of this paper is the computation of a key model parameter, the soil moisture constraint, relying on the concept of apparent thermal inertia ($f_{SM\text{-}ATI}$) computed with surface temperature and albedo observations. Our results showed that $f_{SM\text{-}ATI}$ from both in-situ and satellite data produced satisfactory results for λE at the Sahelian savanna, comparable to parameterizations using field-measured Soil Water Content (*SWC*) with r^2 greater than 0.80. In the Mediterranean grasslands however, with much lower daily λE values, model results were not as good as in the Sahel ($r^2 = 0.57$–0.31) but still better than reported values from more complex models applied at the site such as the Two Source Model (TSM) or the Penman–Monteith Leuning model (PML).

PT-JPL-daily model with a soil moisture constraint based on apparent thermal inertia, $f_{SM\text{-}ATI}$ offers great potential for regionalization as no field-calibrations are required and water vapor deficit estimates, required in the original version, are not necessary, being air temperature and the available energy (*Rn-G*) the only input variables required, apart from routinely available satellite products.

1. Introduction

Evapotranspiration (or latent heat flux expressed in energy terms, λE) represents 90% of the annual precipitation in water-limited regions which cover 40% of the Earth's surface (Glenn et al., 2007). In these regions there is a close link between carbon and water cycles (Baldocchi, 2008) where water availability is the main control for biological activity (Brogaard et al., 2005). λE rates also determine groundwater recharge (Huxman et al., 2005) and feedbacks to continental precipitation patterns (Huntington, 2006). The Sahel and the Mediterranean basin are both located in transitional climate regions and are thus expected to be extremely sensitive to climate change (Giorgi & Lionello, 2008). The land surface is a strong amplifier on the inter-annual variability of the West African Monsoon leading to the observed persistency patterns (Nicholson, 2000; Taylor et al., 2011; Timouk et al., 2009). Therefore, improving estimates of temporal and spatial variations of λE is crucial for understanding land surface–atmosphere interactions and to improve hydrological and agricultural management (Yuan et al., 2010).

λE can be estimated at regional scales using remote sensing data. One way is to use models based on the bulk resistance equation for heat transfer (Brutsaert, 1982), relying on the difference between surface temperature (*Ts*) and air temperature (*Ta*) and the aerodynamic resistance to turbulent heat transport. In this case, λE is estimated indirectly as a residual of the surface energy balance equation (Anderson et al., 2007; Chehbouni et al., 1997). This approach circumvents the problem

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of estimating soil and canopy surface resistances to water vapor, needed to compute λ*E*, that tend to be more critical in λ*E* modeling than aerodynamic resistances in dryland regions (Verhoef, 1998; Were et al., 2007). In those regions, two-source models treating the land surface as a composite of soil and vegetation elements with different temperatures, fluxes, and atmospheric coupling provide better results than single-source models (Anderson et al., 2007). However, despite the strong physical basis of two-source models (Kustas & Norman, 1999; Norman et al., 1995) their spatialization is difficult because the task of estimating aerodynamic resistances at instantaneous time scales is not trivial, requiring knowledge about atmospheric stability, several vegetation and soil parameters as well as meteorological data (Fisher et al., 2008). Further complications arise from the partition of *Ts* between soil and vegetation (Kustas & Norman, 1999) because the radiative surface temperature differs from the aerodynamic surface temperature especially over sparsely vegetated surfaces (Chehbouni et al., 1997).

A second group of models using remote sensing data directly solves the λ*E* term using the Penman–Monteith (PM) combination equation. In this case, λ*E* can be partitioned into soil and vegetation components (Leuning et al., 2008). With this approach, the challenge is to characterize the spatial and temporal variation in surface conductances to water vapor without using field calibration (Zhang et al., 2010). A simple way to estimate surface conductances is to use prescribed sets of parameters based on biome-type maps (Zhang et al., 2010). Other approaches perform optimization with field data but can lead to a lack of estimates over vast regions of the globe, such as the Sahel, due to the scarcity of field measurements (Yuan et al., 2010). One of the first attempts to characterize surface conductance without optimization proposed an empirical relationship with *LAI* derived from MODIS (Moderate Resolution Imaging Spectroradiometer) (Cleugh et al., 2007). Mu et al. (2007, 2011) refined this approach using the empirical multiplicative model proposed by (Jarvis, 1976) estimating moisture and temperature constraints on stomatal conductance and upscaling leaf stomatal conductance to canopy. Alternatively, Leuning et al. (2008) used a biophysical model for surface conductance based on Kelliher et al. (1995) method. However, this method required optimization with field data for g_{sx}, the maximum stomatal conductance of leaves, and for the soil water content. As both parameters were held constant along the year λ*E* was overestimated at drier sites. To address this shortcoming, Zhang et al. (2008) introduced a variable-soil moisture fraction dependent on rainfall, and optimized g_{sx} using outputs from an annual water balance model or a Budyko-type model (Zhang et al., 2008, 2010). Although this represented a step-forward for operational applications, results at dry sites were still poorer than at more humid sites (Zhang et al., 2008, 2010).

A solution to overcome those parameterization problems using the Penman–Monteith equation, was the simplification proposed by Priestley and Taylor (1972) (PT) for equilibrium evapotranspiration over large regions by replacing the surface and aerodynamic resistance terms with an empirical multiplier α_{PT} (Zhang et al., 2009). The PT equation is theoretically less accurate than PM although uncertainties in parameter estimation using PM can result in higher errors (Fisher et al., 2008). Fisher et al. (2008) proposed a model based on PT to estimate monthly actual λ*E*. The authors used biophysical constraints to reduce λ*E* from a maximum potential value, λ*Ep*, in response to multiple stresses. One advantage of this approach is that it does not require information regarding biome-type or calibration with field data. The modeling framework can be seen as conceptually similar to the so-called Production Efficiency Models (PEM) for estimating *GPP* (Gross Primary Productivity) (Houborg et al., 2009; Monteith, 1972; Potter et al., 1993; Verstraeten et al., 2006a) where maximum light use efficiency (ε) of conversion of absorbed energy f_{APAR} into carbon is reduced below its maximum potential due to environmental stresses. In fact, part of the formulation from the PT-JPL model has been introduced into some PEM models (Yuan et al., 2010). The main model assumption is that plants optimize their capacity for energy acquisition in a way that changes in parallel with the physiological capacity for transpiration (Fisher et al., 2008; Nemani & Running, 1989). This idea is to some extent related to the hydrological equilibrium hypothesis stating that in water-limited natural systems, plants adjust canopy development to minimize water losses and maximize carbon gains (Eagleson, 1986) but applied over shorter time-scales. The modeling approach described above neglects the behavior of individual leaves and considers the canopy response to its environment in bulk for which it can be referred to as a top–down approach (Houborg et al., 2009). Top–down approaches use simpler scaling rules compared to bottom–up models that require detailed mechanistic descriptions of leaf-level processes up-scaled to the canopy (Schymanski et al., 2009). Although top–down approaches require less parameters than bottom–up approaches, they are subjected to a higher degree of empiricism with high uncertainty on the functional responses of ecosystem processes to environmental stresses (Yuan et al., 2010).

The use of global satellite vegetation products and meteorological gridded databases as input to top–down approaches based on the PM or the PT equations has made possible to obtain regional estimates of evapotranspiration (Mu et al., 2007). However, there are still limitations regarding the use of such databases. One hand, existing global climatic data sets interpolated from observations such as the Climatic Research Unit data set (CRU, University of East Anglia) are available on a monthly but not a daily basis (New et al., 2000). Moreover, data from reanalyses such as ECMWF (European Centre for Medium-Range Weather forecasts) or NCEP/NCAR present coarse spatial resolutions (≈1.25°) (Mu et al., 2007) being desirable to minimize the use of climatic data when possible.

On the other hand, PM and PT satellite-based approaches have taken advantage of optical remote sensing data to estimate vegetation properties but thermal remotely sensed data has been used only marginally and with coarse spatial resolution data such as the microwave AMSR-E at 0.25° (Miralles et al., 2011). Incorporation of longwave infrared thermal data at spatial resolutions of 1–3 km available from the MODIS (Moderate Resolution Imaging Spectroradiometer) or the SEVIRI (Spinning Enhanced Visible and Infrared Imager) sensors could help to track changes in surface conductance (Berni et al., 2009; Boegh et al., 2002), soil evaporation (Qiu et al., 2006), surface water deficit (Boulet et al., 2007; Moran et al., 1994) or soil water content (Gillies & Carlson, 1995; Nishida et al., 2003; Sandholt et al., 2002). In relation to soil moisture a promising approach is the mapping of soil moisture based on soil thermal inertia (Cai et al., 2007; Sobrino et al., 1998; Verstraeten et al., 2006b), following the early work of Price (1977) and Cracknell and Xue (1996).

The objective of this work was to adapt and evaluate a daily version of the PT-JPL model and introduce a new formulation for soil moisture based on the thermal inertia concept. The aim is to minimize the need for climatic reanalyses data by incorporating thermal remote sensing information in order to facilitate future model regionalization. The PT-JPL model in its original formulation has proven to be successful over 36 Fluxnet sites at monthly time scales, ranging from boreal to temperate and tropical ecosystems. However, none of those included semiarid vegetation with annual rainfall below 400 mm (Fisher et al., 2008, 2009). Model performance using in-situ and satellite data was compared with field data from Eddy Covariance systems at two semiarid sites: an open woody savannah in the Sahel (Mali) and Mediterranean tussock grassland (Spain). Finally, to place the results in the context of global drylands, model results were compared to published results from similar models using remote sensing at dryland savanna and grasslands sites across the globe.

2. Field sites and data

Two field sites (Fig. 1) have been used to test the model in semiarid conditions: an open woody savannah in Mali and tussock grassland in Spain. A general description of the sites is included in Table 1.