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SMAP soil moisture improves global evapotranspiration

Adam J. Purdy[a,b,*], Joshua B. Fisher[b], Michael L. Goulden[a], Andreas Colliander[b], Gregory Halverson[b], Kevin Tu[c], James S. Famiglietti[a,b]

[a] Department of Earth System Science, University of California, Irvine, CA 92697, USA
[b] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
[c] Dupont Pioneer, IA, USA

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ABSTRACT

Accurate estimation of global evapotranspiration (ET) is essential to understand water cycle and land-atmosphere feedbacks in the Earth system. Satellite-driven ET models provide global estimates, but many of the ET algorithms have been designed independently of soil moisture observations. As water for ET is sourced from the soil, incorporating soil moisture into global remote sensing algorithms of ET should, in theory, improve performance, especially in water-limited regions. This paper presents an update to the widely-used Priestley Taylor-Jet Propulsion Laboratory (PT-JPL) ET algorithm to incorporate spatially explicit daily surface soil moisture control on soil evaporation and canopy transpiration. The updated algorithm is evaluated using 14 AmeriFlux eddy covariance towers co-located with COsmic-ray Soil Moisture Observing System (COSMOS) soil moisture observations. The new PT-JPL$_{SM}$ model shows reduced errors and increased explanation of variance, with the greatest improvements in water-limited regions. Soil moisture incorporation into soil evaporation improves ET estimates by reducing bias and RMSE by 29.9% and 22.7% respectively, while soil moisture incorporation into transpiration improves ET estimates by reducing bias by 30.2%, RMSE by 16.9%. We apply the algorithm globally using soil moisture observations from the Soil Moisture Active Passive Mission (SMAP). These new global estimates of ET show reduced error at finer spatial resolutions and provide a rich dataset to evaluate land surface and climate models, vegetation response to changes in water availability and environmental conditions, and anthropogenic perturbations to the water cycle.

1. Introduction

Water movement from land to the atmosphere, or evapotranspiration (ET), is an integral part of earth's ecological and climate systems. This process links the water, carbon, and energy cycles in the earth system. Therefore, accurate observations of ET facilitate detection of the human fingerprint on the water cycle and surface energy budget (Lo and Famiglietti, 2013; Sorooshian et al., 2011), studies on land-atmosphere feedbacks related to heat wave intensity (Miralles et al., 2014), quantification of agricultural and ecosystem water use (Allen et al., 2007; Anderson et al., 2011; Goulden et al., 2012; Goulden and Bales, 2014), identification of droughts where plants may become vulnerable to other biotic stressors and potential mortality (Anderson et al., 2013; McDowell, 2011; Mu et al., 2013), and provide benchmarks to evaluate and improve parameterizations in land surface models (Mueller et al., 2013; Rodell et al., 2011). With increasing global temperatures and the subsequent greater atmospheric capacity for water vapor, ET may accelerate with the water cycle and alter global water distribution making certain regions drier (*Syed et al.*, 2010; *Huntington*, 2006). As land begins to dry, (Greve and Seneviratne, 2015; Jung et al., 2010) quantifying where and to what degree reductions in water availability limits ET becomes increasingly important.

Remote sensing algorithms are an effective way to derive observationally-constrained ET estimates at the necessary spatiotemporal resolutions to support earth observations (Fisher et al., 2017, 2008; Miralles et al., 2011; Mu et al., 2011; Su, 2002). Multiple manuscripts have reviewed the state and needs for ET remote sensing (Fisher et al., 2017; Wang and Dickinson, 2012) and one common theme across many of these remote sensing approaches is a limited or absent representation of soil moisture. Of the ET remote sensing algorithms, few approaches remain both physically defensible and globally applicable without reliance on data assimilation and prognostic land surface models. One model that lacks soil moisture representation and fits the aforementioned description is the Priestley-Taylor Jet Propulsion Laboratory (PT-JPL) ET model.

The PT-JPL ET model, a widely used remote sensing retrieval

* Corresponding author at: Department of Earth System Science, University of California, Irvine, CA 92697, USA.
E-mail address: ajpurdy@uci.edu (A.J. Purdy).

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algorithm, has outperformed many models for the majority of globally distributed eddy covariance towers within model inter-comparison studies achieving both high explanation of variance and low error (Ershadi et al., 2014; Michel et al., 2016; Vinukollu et al., 2011). Despite a strong performance in these studies, the PT-JPL algorithm lacks soil moisture control and is restricted by its dependence on a combination of atmospheric conditions and vegetation characteristics to represent surface conditions. These limitations become especially evident in regions where the coarse near surface air temperature and water vapor pressure deviate from the underlying surface soil water availability at fine temporal frequencies, in areas with highly heterogeneous land covers, in areas of active land management, or in regions prone to atmospheric advection conditions. Therefore, incorporating soil moisture observations has great potential to address these limitations and improve global ET estimates but large challenges exist.

There are two main challenges to improve global estimates of ET using soil moisture: 1) observing accurate integrated values of soil moisture; and, 2) appropriately modeling how limitations from soil moisture interact with other environmental constraints to quantify ET.

The launch of the Soil Moisture Active Passive (SMAP) satellite (2015) addresses the first challenge through providing global soil moisture observations (Entekhabi et al., 2010). The SMAP mission has leveraged lessons from other global soil moisture observing satellites, such as the Advanced Microwave Scanning Radiometer- EOS (Njoku et al., 2003) and the Soil Moisture Ocean Salinity (Kerr et al., 2016) satellites to detect and mitigate potential radio frequency interference and provide observations at relatively high spatio-temporal [9–36 km, 3-daily] resolutions at a depth [5-cm] applicable to improve modeled ET (Johnson et al., 2016; Mohammed et al., 2016; Oliva et al., 2012; Piepmeier et al., 2014). These observations have been extensively evaluated as part of a rigorous calibration and validation campaign and shown to be within mission accuracy requirements (unbiased RMSE < $0.04\,\mathrm{cm^3\,cm^{-3}}$) and thus capable of supporting improvements to global ET quantification (Colliander et al., 2017). Additionally, despite only providing surface soil moisture observations, recent *in situ* analyses have shown that surface soil moisture provides similar amounts of predictive information as rooting depth soil moisture for latent heat quantification (Qiu et al., 2016).

To address the second challenge, model testing and updates needs to be done with coterminous observations of meteorological conditions, soil moisture, and ET. Observations of soil moisture and ET are made globally in distributed networks of eddy covariance (EC) towers as part of FLUXNET and AmeriFlux networks (Baldocchi et al., 2001). However, sites often include measurements of soil moisture at only 1–4 points and these points may misrepresent actual land surface conditions within the EC footprint making model parameterization and calibration difficult. Fortunately, a new observation network from the COsmic-ray Soil Moisture Observing System (COSMOS) provides integrated observations at similar scales to EC tower footprints (Zreda et al., 2012). EC observations of water and energy exchange at the earth's surface co-located with integrated soil moisture observations provide a valuable dataset to compliment satellite observations of environmental variables necessary to test and evaluate ET models (Baldocchi et al., 2001).

Generally, land surface and remote sensing models relate the amount of ET to water availability and the atmospheric demand for ET, but vary to what degree and at what point water availability limits and eventually prevents ET. Various adaptations of soil moisture normalized by soil properties to compute the relative extractable water (REW) have been applied to limit transpiration [Fig. S1, Table S1]. Yet, soil moisture is just one of many environmental variables that limits the maximum stomatal conductance, as temperature and vapor pressure extremes have been found to regulate transpiration (Fisher et al., 2008; Jarvis and Mcnaughton, 1986; Monteith, 1965; Mu et al., 2011; Novick et al., 2016). Therefore, modeling approaches that have adopted REW-based stressors are often applied in series with other scalar stressors, such as temperature and vapor pressure, to reduce potential ET based on sub-optimal environmental limitations (Fisher et al., 2008; Jin et al., 2011; Miralles et al., 2011). However, plant access to soil moisture varies with rooting depth and much uncertainty exists with the role deep roots play in mitigating limitations from soil water availability during drought (Schenk and Jackson, 2002). Plant type, canopy height and aboveground biomass provide indicators of rooting depth and the potential to access to deeper soil water (Canadell et al., 1996; Fan et al., 2017; Jackson et al., 1999). Miralles et al. (2011) postulate taller vegetation is less sensitive to soil water deficits compared to shorter canopy plants due to deep rooting potential to alleviate plants from seasonal drought conditions (*i.e.*, when precipitation occurs outside of the of summer maximum atmospheric demand). Recent global observations of canopy height create an opportunity to further inform plant sensitivity to environmental conditions (Simard et al., 2011).

We present an update to the PT-JPL algorithm by incorporating explicit surface soil moisture constraint from SMAP to model ET globally. To address previous model parameterization limitations, we use integrated *in situ* observations of soil moisture and ET to implement soil moisture control within the PT-JPL model. Then, we apply the new PT-$\mathrm{JPL_{SM}}$ model globally using soil moisture data from the Soil Moisture Active Passive mission (SMAP). The following sections will provide: (1) a description of the PT-JPL algorithm with updates detailing soil moisture constraints on evaporation and transpiration, (2) details on the datasets used in this study, (3) results evaluating the updated PT-$\mathrm{JPL_{SM}}$ model compared to the original PT-JPL model using eddy covariance towers from Ameriflux and globally using satellite datasets, and (4) discussion on the implications of soil moisture on global ET quantification improvement.

2. PT-JPL algorithm

2.1. PT-JPL ET algorithm

The Priestley Taylor-Jet Propulsion Laboratory (PT-JPL) ET algorithm applies ecophysiological constraints to model reductions of ET from the atmospheric potential ET due to sub-optimal environmental conditions (Fisher et al., 2008). The model incorporates a variety of data sources from satellite observations and reanalysis datasets [Fig. 1; Table 1]. Potential ET, or latent energy *LE*, is computed using the Priestley-Taylor model:

$$PET = \alpha \frac{\Delta}{\lambda(\Delta + \gamma)}(R_N - G) \tag{1}$$

where PET [$\mathrm{mm\,day^{-1}}$] is the potential ET based on temperature and radiation, α is the Priestley-Taylor coefficient that is set to 1.26, Δ is the slope of the saturated vapor-pressure relationship [$\mathrm{kPa\,^\circ C^{-1}}$], and γ is the psychrometric constant [$\mathrm{kPa\,^\circ C^{-1}}$], and R_N is the net radiation [$\mathrm{W\,m^{-2}}$], G is the ground heat flux [$\mathrm{W\,m^{-2}}$], and λ is the latent heat of vaporization [$\mathrm{MJ\,kg^{-1}}$] (Priestley and Taylor, 1972). The water cycle and energy cycle are linked through ET and latent heat LE such that the latent heat of vaporization ET λ = LE. The PT-JPL algorithm is a three source ET model where each component of ET is used to calculate the total flux:

$$LE = LE_I + LE_T + LE_S \tag{2}$$

where LE_I is evaporation from plant intercepted water, LE_T is transpiration from vegetation, and LE_S is soil evaporation. Ecophysiological *f-functions*, scalars between 0 and 1, limit each component from the potential rate.

Canopy interception is computed as:

$$LE_I = f_{WET}\,\alpha \frac{\Delta}{(\Delta + \gamma)} {R_N}^C \tag{3}$$

where f_{WET} is the fraction of saturated soil computed as $f_{WET} = RH^4$, where RH is the relative humidity of air, ${R_N}^C$ is the canopy net radiation calculated as ${R_N}^C = R_N - {R_N}^S$. ${R_N}^S$ is the net radiation at the soil surface