Agricultural and Forest Meteorology 260–261 (2018) 131–143

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Partitioning of evapotranspiration in remote sensing-based models

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A R T I C L E I N F O

Keywords:
Evapotranspiration
Partitioning
Modeling
Remote sensing
Transpiration
Soil evaporation

A B S T R A C T

Satellite based retrievals of evapotranspiration (ET) are widely used for assessments of global and regional scale surface fluxes. However, the partitioning of the estimated ET between soil evaporation, transpiration, and canopy interception regularly shows strong divergence between models, and to date, remains largely unvalidated. To examine this problem, this paper considers three algorithms: the Penman-Monteith model from the Moderate Resolution Imaging Spectroradiometer (PM-MODIS), the Priestley-Taylor Jet Propulsion Laboratory model (PT-JPL), and the Global Land Evaporation Amsterdam Model (GLEAM). Surface flux estimates from these three models, obtained via the WACMOS-ET initiative, are compared against a comprehensive collection of field studies, spanning a wide range of climates and land cover types. Overall, we find errors between estimates of field and remote sensing-based soil evaporation (RMSD = 90–114%, r^2 = 0.14–0.25, N = 35), interception (RMSD = 62–181%, r^2 = 0.39–0.85, N = 13), and transpiration (RMSD = 54–114%, r^2 = 0.33–0.55, N = 35) are relatively large compared to the combined estimates of total ET (RMSD = 35–49%, r^2 = 0.61–0.75, N = 35). Errors in modeled ET components are compared between land cover types, field methods, and precipitation regimes. Modeled estimates of soil evaporation were found to have significant deviations from observed values across all three models, while the characterization of vegetation effects also influences errors in all three components. Improvements in these estimates, and other satellite based partitioning estimates are likely to lead to better understanding of the movement of water through the soil-plant-water continuum.

1. Introduction

The evaporation of water from the Earth's surface to the atmosphere represents a critical link between the global water, carbon, and energy cycles (Oki and Kanae, 2006). An estimated two thirds of terrestrial rainfall returns to the atmosphere as evapotranspiration (ET) from the continents (Hobbins et al., 2004; Teuling et al., 2009) and the associated latent heat flux corresponds to a cooling of the Northern Hemisphere of about 15°–25 °C (Shukla and Mintz, 1982). ET is a critical process governing water resource availability, agricultural productivity, and irrigation efficiency, as well as impacting the severity of droughts, floods, and wildfires (Littell et al., 2016; Molden et al., 2010; Trenberth, 2011; Wallace, 2000). Furthermore, the energy flux associated with ET fundamentally influences the development of the planetary boundary layer and the atmospheric processes contained within it (Ek and Holtslag, 2004; Pielke et al., 1998; Seneviratne et al., 2010). Future climate warming is expected to significantly alter the global water cycle, affecting regional and global rates of ET, precipitation, and streamflow (Huntington, 2006; Zhang et al., 2016). Given the important role of ET in a variety of land surface processes, accurately estimating large-scale fluxes of ET is critical to our understanding of the earth system.

Spatially distributed, remote sensing-based ET models have become a dominant means to estimate catchment and global-scale ET fluxes (Anderson et al., 2007; Fisher et al., 2017; Schmugge et al., 2002). The large spatial extent and fine temporal resolution of these remote sensing products makes them perhaps the only observational means to assess global-scale impacts of changes in ET fluxes. These factors have made remote sensing-based models a powerful tool in both climate and large-scale hydrologic applications. Many of these remote sensing-based models estimate total ET via combination of its separate components: transpiration through plant stomata, soil evaporation from the top layer

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https://doi.org/10.1016/j.agrformet.2018.05.010
Received 1 December 2017; Received in revised form 8 May 2018; Accepted 11 May 2018

of soil, and canopy rainfall interception. However, the wide array of algorithms and choice of forcing datasets have hampered the analysis of model results, as errors in model estimates may come from both forcing errors and/or errors in algorithms and parametrizations (Ershadi et al., 2015). Recent efforts have compared ET fluxes from several satellite-based ET models using a common forcing dataset, simplifying the comparison substantially (McCabe et al., 2016; Michel et al., 2016; Miralles et al., 2016).

These remote sensing-based ET estimates have shown good relative agreement in global estimates, but larger discrepancies regionally (Michel et al., 2016). Interestingly, the limited number of studies comparing individual ET components have shown that the global and regional contribution of transpiration, soil evaporation, and interception vary significantly between models, even where total ET estimates agree (Miralles et al., 2016). The divergence of ET partitioning estimates suggests that some models may contain large ET partitioning errors. Accurate partitioning estimates are highly desired for research related to agriculture, climate and land-use change, hydrology, and water resource availability. ET partitioning is also a crucial factor for global climate models as the partitioning of ET has proven to be a significant source of uncertainty for future climate projections (Lawrence et al., 2007). Incorrect parameterizations within ET models are likely to compromise the accuracy of estimates across ecoregions and through time. Furthermore, any divergence of ET partitioning is certainly an indicator that models may contain systematic errors in their formulations.

The mechanisms that govern the individual ET components of transpiration, soil evaporation, and canopy interception operate on varying spatial scales from relatively small (i.e. stomata, single plants) to larger regional scales (i.e. climate system) (Good et al., 2017; Pieruschka et al., 2010; Wang and Dickinson, 2012; Wang et al., 2014). Field methods for measuring transpiration typically measure at the scale of an individual leaf or plant (Rana and Katerji, 2000; Schlesinger and Jasechko, 2014). Such field techniques include: sap-flow measurements, diurnal water table changes, water-balance approaches, and isotope based approaches (Gibson and Edwards, 2002; Lautz, 2008; McJannet et al., 2007; Nizinski et al., 2011). Measurements from such studies are extrapolated to larger spatial scales through assumptions about the variability of sap-flux densities (Dye et al., 1991; Fernández et al., 2006), changes in isotopic composition of water within the plant (Brunel et al., 1997), and general homogeneity of vegetation and stomatal response to environmental conditions. The spatial scale of these measurements remains a limitation for ET partitioning validation, as research into regional hydrologic and climatic processes often requires estimates of partitioned fluxes at much larger spatial scales.

Furthermore, field studies of ET partitioning often focus on a single component such as transpiration or interception, and rarely attempt to estimate all contributing ET components. Canopy interception, for instance, is a well-developed field of study (Carlyle-Moses and Gash, 2011; Crockford and Richardson, 2000; Levia and Frost, 2006; Muzylo et al., 2009), and is often estimated as the difference between rainfall above and below the canopy. However, few canopy interception studies attempt to quantify the role of interception as part of the ET flux. Similarly, transpiration studies are often focused on the physiologic processes of vegetation and disregard the role of transpiration in larger hydrologic and atmospheric cycles. Some field methods do not directly measure soil evaporation, and instead quantify it as the residual of ET and transpiration. Due to the fractured nature of the ET partitioning research, few field studies are available quantifying transpiration, soil evaporation, and interception simultaneously.

To address the uncertainty surrounding ET partitioning in remote sensing-based ET models, we evaluate three models and their partitioning strategies against a compilation of field studies. We hope to contextualize partitioning comparisons made by Miralles et al. (2016) using empirical field methods. While previous studies have attempted to compare specific model estimates of either canopy interception or transpiration against field data, few have jointly assessed errors in remote sensing-based estimates against transpiration, soil evaporation, and interception. In comparing model performance against compiled field estimates we hope to (1) reconcile the deviations between each model partition against a field standard, (2) determine if the modeled errors are consistent or vary across different land surface or climate conditions, (3) identify assumptions or parameters within the model that contribute to error, (4) and contextualize some of the partitioning comparisons made by Miralles et al. (2016).

2. Methodology

We compared ET components from three remote sensing-based models against a compilation of field estimates of soil evaporation, transpiration, and interception. We assessed the Priestley-Taylor Jet Propulsion Lab model (PT-JPL)(Fisher et al., 2008), the Penman-Monteith MODerate Resolution Imaging Spectroradiometer (PM-MODIS) (Mu et al., 2011), and the Global Land Evaporation Amsterdam Model (GLEAM) (Martens et al., 2017; Miralles et al., 2011, 2010) model. Each model is widely used to estimate ET and provide relatively comparable estimates of the total ET flux (Miralles et al., 2016). Global annual mean values of ET for each model have been estimated at 54.9, 72.9, and $72.5 \times 10^3\,km^3$ for PM-MOD, GLEAM, and PT-JPL respectively (Miralles et al., 2016).

2.1. Evaporation models

Each model evaluated for this study adopts a similar structure to estimate total ET fluxes as well as the individual components of ET. The model structure may be categorized into three separate functions: (1) quantifying potential ET, (2) partitioning the potential ET into its given components to be aggregated as total ET, and (3) translating the potential ET into an actual ET based on the constraints of the component processes. Different models employ different strategies in accomplishing these basic functions but individual model parameters often fall into a single categorical function.

2.1.1. Priestley-Taylor Jet Propulsion Lab (PT-JPL)

The PT-JPL model utilizes the Priestley-Taylor equation (Priestley and Taylor, 1972) to estimate potential ET flux and is described in depth in Fisher et al. (2008). The model uses ecophysiological and atmospheric constraints to reduce the potential ET flux to an actual ET flux. The total ET is partitioned between soil evaporation, E_s [m/s], canopy transpiration , E_v [m/s], and canopy interception, E_i [m/s] as

$$E_s = (f_{wet} + f_{SM}(1-f_{wet}))\alpha\frac{\Delta}{\lambda_v\rho_w(\Delta+\gamma)}(R_{ns}-G) \tag{1a}$$

$$E_v = (1-f_{wet})f_g f_T f_M\,\alpha\frac{\Delta}{\lambda_v\rho_w(\Delta+\gamma)}R_{nc} \tag{1b}$$

$$E_i = f_{wet}\,\alpha\frac{\Delta}{\lambda_v\rho_w(\Delta+\gamma)}R_{nc} \tag{1c}$$

where a is the Priestley-Taylor coefficient (considered equal to 1.26), Δ is the slope of the vapor pressure curve [Pa/K], γ is the psychrometric constant [Pa/K], R_n is the net radiation [W/m^2], G is the energy flux into the ground [W/m^2], λ_v is the latent heat of vaporization[J/kg], f_{wet} is a relative surface wetness parameter (see below), f_{SM} is the soil moisture constraint, f_g is the green canopy fraction, f_T is the plant temperature constraint, and f_M is the plant moisture constraint.

PT-JPL effectively accomplishes its partitioning using a canopy extinction equation to estimate the radiation penetrating through the canopy. This canopy extinction equation utilizes the leaf area index (LAI) in conjunction with the Beer-Lambert law of light attenuation (Norman Ay et al., 1995) to partition net radiation between the canopy and soil. Canopy processes (interception and transpiration) are