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Passive microwave and optical index approaches for estimating surface conductance and evapotranspiration in forest ecosystems

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ABSTRACT

In this study, we evaluated and compared optical and passive microwave index based retrievals of surface conductance (Gs) and evapotranspiration (ET) following the Penman–Monteith (PM) approach. The methodology was evaluated over the growing season at five FLUXNET sites in the USA and Australia encompassing three forest types, deciduous broadleaf forest (DBF), evergreen needleleaf forest (ENF) and evergreen broadleaf forest (EBF). A subset of Gs values were regressed against individual and combined indices of NDWI, EVI, and FI (microwave frequency index), and used to parameterize the PM equation for retrievals of ET (PM-Gs). For this purpose, we used MODIS (MYD09A1) and AMSR-E passive microwave data to compute the VIs. Model performance was quantitatively evaluated through comparative analysis of the regression coefficients (r^2), and root mean square errors (RMSE). All indices correlated well with Gs over deciduous broadleaf forests, explaining 40–60% of Gs variations, however, the optical-based models had lower RMSE than the microwave FI model. In contrast, the FI model yielded the best performance to estimate Gs in evergreen forests (EBF and ENF). Overall, a combined microwave-optical model resulted in the best Gs estimates in these evergreen forests compared with the individual model approaches. In general, the PM-models explained more than 70% of the variance in LE with RMSE lower than 20 W/m^2. Based on these results, we developed a new approach combining optical and passive microwave indices based on their spatial vs. temporal synergies to generate Gs time series. This combined optical-microwave approach produced the best ET estimates for evergreen forest and offered a robust approach for deciduous forest without sacrificing precision.

1. Introduction

The ability to monitor evapotranspiration (ET) from the land surface is relevant for several applications requiring spatially-resolved estimates of moisture availability over large areas (Cleugh et al., 2007; Dodds et al., 2005; Meyer and Wayne, 1999). Remote sensing cannot measure surface turbulent flux exchanges directly; however various methods have been developed using parameterization techniques that vary from purely empirical to more physically based approaches based on the energy balance equation and using vegetation indices (VI) (Yebra et al., 2013) and land surface temperature (LST) (Cleugh et al., 2007; Kalma et al., 2008; Moran and Jackson, 1991).

Among these models, the Penman–Monteith (PM) equation (Allen et al., 1998; Monteith, 1985) is widely used. Cleugh et al. (2007) and Mu (2007) showed that the PM equation is a biophysically sound and robust framework for estimating daily ET at regional to global scales using remotely sensed data. ET estimations from remote sensing data are generally based on parameterizations of PM equation, which rely on the estimation of surface or canopy conductance using measurements at visible (VIS), near-infrared (NIR) and shortwave-infrared (SWIR) wavelengths (Glenn et al., 2011, 2010; Leuning et al., 2008; Yebra et al., 2013). The relation between canopy conductance and optical indices were analyzed by several authors (Grant, 1987; Guerschman et al., 2009; Matsumoto et al., 2005; Yebra et al., 2013).

Methods based on VI have been found useful as a monitoring tool for ecosystem water use (Glenn et al., 2010). Applications in water resource management require ET information over a range of temporal and spatial resolutions, from hourly to monthly time steps

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and from field to global scales. Unfortunately, no single satellite system affords global coverage at both high spatial and temporal resolution. So, methods are needed for combining information at different wavelengths and spatial and temporal resolutions. A higher spatial resolution can be achieved by Landsat (30–60 m), but the frequency (16 days) is a limiting factor for several applications. MODIS products provide information at 250 m, 500 m and 1 km with a temporal resolution between 1 and 16 days, however such optical data are severely limited by their sensitivity to clouds and aerosols. In contrast, passive microwave sensors, although at coarser spatial resolutions, have best temporal resolution (1–3 days) and less sensitivity to atmospheric conditions and thus can be useful in larger scale ecosystem monitoring applications.

In principle, microwave emissivity (defined as the ratio between brightness temperature and physical temperature measured at microwave frequencies) is complex and dependent on both vegetation and soil properties (moisture and structure). However, over forest ecosystems, where vegetation biomass is moderate to high, the canopy contribution is dominant and the microwave signal becomes sensitive mainly to vegetation moisture and structure (Barraza et al., 2014a; Ferrazzoli and Guerriero, 1996; Min and Lin, 2006). Based on this relation, Min and Lin (2006) found that microwave indices, such as the Emissivity Difference Vegetation Index (EDVI) were empirically sensitive to the evapotranspiration and evapotranspiration fraction. Moreover, experimental work by Li et al. (2009) found that fast changes of EDVI represents canopy responses to changes of environmental conditions, such as vapor pressure deficit (VPD), water potential and CO_2 concentration, the same variables that determine canopy resistance.

In an earlier study we evaluated vegetation and soil properties that influence the microwave frequency index (FI) (Barraza et al., 2014a) over different ecosystems. Among other results, we found that day to day changes in FI (canopy scattering properties) computed at vertical polarization, using Ka and X bands, for areas with relatively high leaf area index (LAI) were sensitive to canopy moisture and changes in LAI (LAI > 2). It has also been found that changes in canopy (leaves + stems) water content can be monitored using FI at LAI > 2 ecosystems (Barraza et al., 2014a). Since stomata conductance is closely related to canopy moisture (Goldstein et al., 2008, 1998; Pfautsch et al., 2010; Zhang et al., 2013) and structure ((Jarvis and McNaughton, 1986)), we foresee an indirect link between surface conductance (Gs) and FI.

Several studies have been undertaken to relate microwave indices with ET (Jones et al., 2012; Li et al., 2009; Min and Lin, 2006), but there are few studies involving multiyear datasets and no direct attempt to estimate ET based on passive microwave and optical data over different forest ecosystems. New studies that use a synergy of sensors (microwave and optical) might be useful to improve the characterization of land surface conditions at appropriate temporal and spatial scales and thus help to support regional climate modeling applications (Pipunic et al., 2013).

In this work, our aim is to improve satellite-based ET retrievals by combining passive microwave and optical vegetation indices using the Penman–Monteith approach. We assessed individual approaches and combined synergies among the indices over different forest ecosystems in USA and Australia. The objectives were: (1) to assess the capability of microwave and optical indices to estimate Gs and ET; (2) to quantify ET with the PM equation using Gs estimations and meteorological data; (3) to compare both approaches (optical and microwave) and evaluate the error for Gs and ET estimations independently, (4) to address the eddy covariance-remote sensing footprint issues by comparing ET obtained at different scales with in-situ observations, and (5) to propose new models based on the combination of optical and microwave indices.

2. Methodology

2.1. Satellite microwave and optical vegetation indices data set

We used the Frequency Index (FI) (Ferrazzoli and Guerriero, 1996) for our analyses, calculated using the brightness temperatures measured at 37 GHz (Ka Band) and 10.6 GHz (X band) (Paloscia and Pampaloni, 1988) obtained from Advanced Microwave Scanning Radiometer – EOS (AMSR-E/AQUA) (Kawanishi et al., 2003) in ascending overpasses from 2002 to 2006. In Paloscia and Pampaloni (1992) and Barraza et al. (2014a) it was shown that one can monitor plant water status using the FI computed at these frequencies. We used FI calculated at vertical rather than horizontal polarization since this yields a higher correlation with vegetation state properties (Min and Lin, 2006). It was shown that for regions in which vegetation biomass is moderate to high, FI depends mostly on canopy condition (Ferrazzoli and Guerriero, 1996). Therefore, in the above-mentioned cases, FI becomes a function of canopy structure (i.e. leaves and stems geometry) and canopy moisture content (i.e., leaves and stems moisture content). Other passive microwave indices, like the polarization index, are less sensitive to vegetation moisture (Barraza et al., 2014a), and therefore not suitable for this application.

The differential sensitivity of microwave indices to (i) vegetation moisture (Barraza et al., 2014b; Ferrazzoli et al., 1992; Min and Lin, 2006) and (ii) soil moisture (Jackson, 1997) depend on the frequency of the passive microwave sensor and the key geometrical and dielectric characteristics of the land cover. In spite of this, different passive microwave indices, which are mainly sensitive to i or ii, could be applied for ET analysis. However, this sensitivity will define the type of relation between these indices and ET (Barraza et al., 2014a). Moreover, passive microwave indices sensitive to vegetation moisture, canopy structure and biomass changes have been applied for vegetation phenology analysis (Andela et al., 2013; Jones et al., 2012; Min and Lin, 2006), vegetation drought response (Frolking et al., 2011), potential growing season variability (Kimball et al., 2006) and seasonal changes in canopy CO_2 exchange (Min and Lin, 2006).

FI is influenced by land surface properties, such as vegetation, soil and snow. During the growing season, FI variations are generally related to vegetation properties. We excluded snow conditions using air temperature (Ta), obtained from meteorological stations, when Ta < 5 °C as a proxy to remove dormant season and snow periods. In this study, observations during precipitation events were excluded from the analysis with the aid of in situ precipitation data. The emission is strongly affected by the presence of rainfall during an acquisition, due to the important contribution of cold raindrops to the overall emissivity. As we calculated 8-day composite periods of FI (to align with MODIS time series composite criteria), we expect that using these methodology the uncertainties associated with precipitation to be negligible.

Yebra et al. (2013) found that no single Moderate Resolution Imaging Spectroradiometer (MODIS) optical vegetation index (VI) showed the best performance to estimate ET and Gs over all land cover types analyzed. We computed two MODIS satellite VIs (Table 2): the normalized difference water index (NDWI), a canopy moisture-based vegetation index and the enhanced vegetation index (EVI), as a chlorophyll-based greenness index, using the 8-day Aqua-MODIS land surface reflectance product (MYD09A1) with 500 m of spatial resolution from 2002 to 2006. Using the quality assessment (QA), information provided in this product, lower quality data and data with partial or complete cloud cover were removed from the analysis. The quality flags used were: MODLAND QA bits (ideal quality – all bands), atm. corr. Performed (yes), cloud state (clear) and cirrus detected (none). The VI products were aggregated to two different spatial scales, 1 km and also 25 km in order