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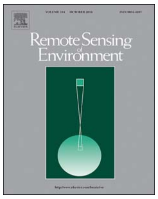

Integrating satellite optical and thermal infrared observations for improving daily ecosystem functioning estimations during a drought episode

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ABSTRACT

Satellite optical and thermal infrared (TIR) spectra are linked to vegetation properties and, therefore, carry valuable information needed for estimating vegetation functioning as expressed in canopy photosynthesis [gross primary production (GPP)] and evapotranspiration (ET). The joint effort is required to fully exploit this satellite spectral information and to demonstrate its capability to reveal ecosystem functioning in various environmental conditions. We investigated the relationship between Landsat (TM5 and ETM7) optical/thermal data and canopy daily functioning of annual C3 grasses at a Fluxnet site (US-Var) during a prolonged drought episode. By using the 'Soil-Canopy Observation of Photosynthesis and Energy fluxes' (SCOPE) model, reference GPP and ET were simulated via locally measured weather data, and then actual GPP and ET were simulated twice: first using the vegetation properties retrieved only from the optical bands, and second using information from both the optical and thermal bands. The outputs of last two simulations were compared to flux tower measurements. For the first simulation, we used the MODTRAN atmospheric model and the optical radiative transfer (RT) routine in SCOPE, RTMo, to perform atmospheric correction and retrieve vegetation properties [notably Leaf Area Index (*LAI*), leaf chlorophyll content (C_{ab}), leaf water content (C_w), leaf dry matter content (C_{dm}), the leaf inclination distribution function (*LIDF*) and the senescent material content (C_s)] by model inversion through optimization. We used the optical bands of 20 Landsat images covering the period from January to August 2004. The model inversion performance was assessed by R^2 (0.86) and RMSE (0.13) between the retrieved and ground-measured *LAI*. All the retrieved vegetation properties were linearly interpolated over time and were used, together with locally measured weather variables, to simulate GPP and ET at half-hourly time steps with SCOPE. For the second simulation, we additionally used TIR information to retrieve the maximum carboxylation capacity (V_{cmax}), the Ball-Berry stomatal conductance parameter (m) and soil surface and boundary resistances (r_{ss} and r_{bs}) by inversion of the energy balance and thermal radiative transfer routines of SCOPE, RTMt, through separate look-up tables. The comparison between simulations and measurements shows that most drought effects on ET, GPP and transpiration are "visible" in the Landsat optical bands. However, the accurate simulation of soil evaporation requires TIR information. The results from this study indicate that the integration of optical and TIR information has a great potential to capture the drought effects on the grass canopy in terms of reductions in daily GPP and ET.

1. Introduction

Exploiting information contained in both the optical and TIR domains of satellite observations to full extent can assist in detecting daily ecosystem functioning – canopy photosynthesis [gross primary production (GPP)] and evapotranspiration (ET) – variations during a drought episode. This is needed by both social and academic sectors (Lewinska et al., 2016) to better understand the carbon and water cycle feedbacks to climate change (Dong et al., 2015).

Drought influences vegetation in several ways: (1) stomatal effects which change the intrinsic water use efficiency and, therefore, the ratio of photosynthesis to transpiration, and (2) non-stomatal effects which change the photosynthetic capacity of the vegetation (Zhou et al., 2013). Both of these effects have been modeled and understood well using experimental data sets (Egea et al., 2011; Keenan et al., 2010; Zhou et al., 2013). However, the question is: can we detect these effects of drought on GPP and transpiration (T), but also on soil evaporation (E), by means of satellite observations? We assume that in grass most of the non-stomatal effects are due to browning and defoliation (Vicca et al., 2016), which are visible in the optical spectra. However, stomatal

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effects and soil evaporation become manifest in the TIR domain (Anderson et al., 2007a, 2007b; Crow et al., 2008).

Two approaches to estimate GPP from satellite data are widely used: (1) using the Monteith production efficiency concept (Monteith, 1972), in which GPP is linked to the absorbed amount of photosynthetically active radiation (APAR) and (2) using empirical models, in which the relationship is explored between ground measured GPP and satellite observed spectral information (Song et al., 2013). Regardless of the methodological differences between these approaches, the remote sensing information has been used in both by means of Vegetation Indices (VIs), mostly by, but not limited to, the Enhanced Vegetation Index (EVI) and Normalized Differences Vegetation Index (NDVI). For instance, Dong et al. (2015) investigated the performance of four EVI-based models to estimate GPP in one grassland and two croplands (maize and soybean) in the US. They examined the relationship between two vegetation indices (NDVI and EVI) and measured GPP under two different conditions; non-drought and drought years. They concluded that satellite information, obtained as EVI and NDVI, could capture GPP changes at different sites, however, the EVI explained more variance of GPP in both non-drought and drought conditions (Dong et al., 2015). In another study, Vicca et al. (2016) extracted the information content of MODerate-resolution Imaging Spectroradiometer (MODIS) reflectance spectra to identify drought effects on GPP. They examined MODIS-derived EVI, NDVI, Simple Ratio (SR), Global Environmental Monitoring Index (GEMI), Normalized Differences Water Index (NDWI) and Photochemical Reflectance Index (PRI) in detecting severe drought effects on annual GPP in a beech forest, an evergreen broadleaved oak forest and a grassland. They concluded that the majority of long-term drought effects on GPP could be detected by EVI and the normalized PRI at the beech forest site and the evergreen broadleaved oak forest, while all of the examined indices captured the drought effects at the grassland site. Overall, the above-mentioned and many more studies (Dong et al., 2015; Gitelson et al., 2014; Maselli et al., 2009; Peng et al., 2011; Verma et al., 2015; Wagle et al., 2014, 2015; Wu et al., 2009, 2011; Xiao et al., 2004a, 2004b) demonstrated the capability of information from optical bands to estimate GPP.

Similarly, two widely-used approaches to estimate ET using satellite information are (1) using the surface energy balance (SEB) approach, in which the land surface temperature (LST) information from TIR bands is used and (2) using empirical models, in which the statistical relationship is explored between ground measured ET and satellite observed optical bands (Zhang et al., 2016). The first approach (SEB) makes use of the fact that LST is determined by the partitioning of available energy into latent (*LE*) and sensible heat flux (*H*). This approach has been widely used in previous studies to estimate ET. For instance, Su et al. (2005) reported that the accuracy of The SEB System (SEBS) model in estimating ET could reach 10–15% of in-situ measurements for the range of evaporation fraction from 0.5–0.9 (Su et al., 2005). In addition, The SEB algorithm for land (SEBAL) has been applied to estimate ET under various climatic conditions at the field scale and good accuracy has been reported for daily (85%) and seasonal (95%) estimations (Bastiaanssen et al., 2005; Bastiaanssen, 2000). Based on the SEBAL method, Allen et al. (Allen et al., 2007) proposed the Mapping EvapoTranspiration with high Resolution and Internalized Calibration (METRIC) model in which ground-based ET is used to calibrate the SEB internally resulting in computational bias reduction. How to determine the hot and cold pixels, which are needed for both SEBAL and METRIC, are also discussed in previous studies (Long and Singh, 2012). In another study, Gonzalez-Dugo et al. (2009) compared the performance of the Two-Source Model (TSM_N), that proposed by Norman et al. (Norman et al., 1995), with two one-source SEB model in estimating ET over rain-fed corn and soybean in central Iowa. They concluded that although all three models could estimate ET with reasonable accuracy, the TSM_N model was performed the best (with the lowest RMSE) compared to the ground measurements (Gonzalez-Dugo et al., 2009). Considerable research has been conducted to improve the TSM_N (Kustas and Norman, 1996, 1999; Li et al., 2005; Norman et al., 2000; Sánchez et al., 2008). Many more studies used the above-mentioned SEB models and, therefore, estimated ET variations from satellite TIR data with acceptable accuracy (as reviewed in (Glenn et al., 2007; Liou and Kar, 2014; Zhang et al., 2016)). In the second approach to estimate ET, the optical spectral bands are utilized to relate them to flux tower measurements of ET. For instance, Nagler et al. (2005) established a relationship between MODIS-derived EVI, NDVI and ground measured ET collected at four flux towers at different riparian sites over 4 years located in New Mexico. They have demonstrated that EVI and NDVI were fairly correlated with ET (Nagler et al., 2005). In another study, Cleugh et al. (2007) used MODIS-derived NDVI together with meteorological inputs to estimate ET in two various ecosystems in Australia. They established a relationship between remote sensing and ground measurements, showing their method's validity over regional scales (Cleugh et al., 2007). Overall, there are numerous similar studies using satellite optical data to estimate ET variations in croplands and natural environments (reviewed in Glenn et al., 2010).

As described above in both cases (GPP and ET estimation), only a fraction of the available satellite data, either from optical or TIR domain, is employed in order to explain the changes in carbon and water fluxes. On the one hand, the models simulating GPP and ET from satellite optical data mostly use VIs. These are simple to compute and provide useful information about physiological processes (Glenn et al., 2008). However, there are three limitations for using such VIs; (1) They are only based on a few individual bands located in the optical domain and by adopting them, as a consequence, important pieces of information in the other bands are ignored; (2) the majority of VIs do not include information from the TIR domain and (3) the empirical models which are based on VIs have shown acceptable accuracy only at a time scale of weeks to years and, therefore, are unable to capture ecosystem functioning variations with acceptable accuracy at time scales of days or shorter (Glenn et al., 2007; Liou and Kar, 2014). On the other hand, although the models estimating ET from satellite TIR data through SEB approach showed acceptable performance, the lack of a one-to-one correspondence between the surface temperature and *H* due to mainly the wind and aerodynamic resistance causes considerable uncertainty in the *LE* flux derived with this method (Glenn et al., 2008).

Thus, the potential of utilizing the full spectral information, from the optical and TIR domains together, is still unexplored. An alternative method is to exploit the information from all available optical and TIR spectral bands in a consistent way by means of Radiative Transfer (RT) models and to simulate vegetation functioning by means of a Soil-Vegetation-Atmosphere Transfer (SVAT) model. Limited work has been done in this direction and we address this gap in our study.

Hence, this study intends to use effective tools including an atmospheric RT [the MODerate resolution atmospheric TRANsmission model (MODTRAN)], a canopy RT [PROSPECT + SAIL (PROSAIL) through RTMo] and a SVAT model [Soil-Canopy Observation of Photosynthesis and Energy fluxes (SCOPE) (Van der Tol et al., 2009)] to exploit the information contained in Landsat optical and TIR images to full extent in order to estimate daily GPP and ET simultaneously in a drought episode. This way, it is possible to assess the information of all bands together and to analyze which drought effects can be observed using the optical information offered by a remote sensing satellite and what would be the added value of using TIR data.

2. Data

2.1. Site description

The study focussed on the Vaira Ranch (US-Var) Fluxnet site, hereafter called Vaira site. It is an open grassland, Fig.1, in a Mediterranean climate, at 129 m altitude at the foothills of the Sierra Nevada in California (38.4133° N; 120.9508° W), in the USA (Baldocchi et al., 2004; Ma et al., 2007, 2016; Xu and Baldocchi, 2004). Most rainfall