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Investigating the impact of overlying vegetation canopy structures on fire radiative power (FRP) retrieval through simulation and measurement

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ABSTRACT

Fire radiative power (FRP) retrievals are now routinely made from polar and geostationary instruments, providing a means to estimate fuel consumption and trace gas and aerosol emissions directly from remotely sensed observations. This study presents the first investigation of the impact of vegetation canopy structure (percentage canopy cover and leaf area index, LAI) on FRP retrievals, based on 3D radiative transfer model simulations. The Discrete Anisotropic Radiative Transfer (DART) model is used to simulate above-canopy observations made through 3D vegetation canopies with different structural arrangements, under which a centrally positioned uniform landscape fire is burning. The vegetation canopy is modelled in two ways, as an opaque structure and as a hybrid turbid medium. The percentage canopy cover in each simulated scene is varied between 5 and 95%, and the FRP retrieved above the canopy is found to decrease in proportion to percentage canopy cover when the canopy is opaque, a finding that is in agreement with a series of small scale outdoor measurements conducted to evaluate the realism of the simulations. However, when the canopy is modelled as a turbid medium, which is in some ways a more realistic representation of a real 'gappy' vegetation canopy, the degree of FRP interception occurring at any particular canopy cover decreases by ~ 14%, due to some fire emitted thermal energy being transmitted through the canopy gaps. The simulations also reveal the impact of canopy LAI on above-canopy FRP retrievals, reducing these by 6% when both canopy cover and LAI are low (5% and < 1.0 respectively), but by up to 92% when canopy cover and scene LAI are high (95% and ~8 respectively). We use the derived relationships between FRP interception and canopy structure, along with MODIS LAI and percentage tree cover data, to adjust 2004–2012 fire radiative energy (FRE) estimates calculated from FRP data collected by the geostationary Meteosat Spinning Enhanced Visible and Infrared Imager (SEVIRI) instrument. The adjusted annual FRE is on average 15% greater than estimated, and is characterized by low inter-annual variability as result of the majority of fire activity occurring in areas where percentage tree cover remains below 40%. Landscape burning occurs more frequently in areas of higher tree cover in southern hemisphere rather than northern hemisphere Africa, leading to a larger annual FRE adjustment (18.5% compared to 16.3%). This study illustrates the impact that canopy interception has on FRP for the first time at the satellite scale, and over Africa demonstrates a large but temporally consistent underestimation which can be accounted for using LAI and percentage tree cover metrics when estimating fuel consumption and atmospheric emissions from the FRP retrievals.

1. Introduction

Landscape fire is a global, highly dynamic Earth system process, altering surface structural and radiative properties and releasing aerosols and trace gases into the atmosphere (Arora and Boer, 2005; Bowman et al., 2009). Satellite Earth Observation (EO) has been widely applied to study landscape fires, either through measurements of burned area based on surface spectral reflectance change (Pereira, 1999; Giglio et al., 2013), or via the detection of the thermal energy radiated as the fire burns (Robinson, 1991; Zhukov et al., 2005; Xu et al., 2010). The 'active fire' approach uses thermal infrared observations to estimate the rate at which thermal energy is being radiated

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away from a fire (the fire radiative power). Retrievals of FRP are then used to back-calculate the rate of fuel consumption that must have been ongoing to produce the observed rate of thermal radiant energy release (Kaufman et al., 1996a, 1996b). Small scale experiments have shown strong links between the temporal integral of FRP (so-called Fire Radiative Energy; FRE) and fuel consumption that appear to be independent of vegetation type (Wooster et al., 2005). Landscape fire fuel consumption is most typically derived using burned area (Chuvieco et al., 2016; Giglio et al., 2013) or FRE (Ellicott et al., 2009; Kaiser et al., 2012) based methods, and we focus here on canopy cover impacts on the latter approach and the resulting effect this may have on the information derived from satellite-based FRP retrievals. Numerous studies have utilized FRP retrievals from polar-orbiting (e.g., Vermote et al., 2009; Andela et al., 2016; Schroeder et al., 2014; Ellicott et al., 2009) and geostationary sensors (e.g., Li et al., 2018; Mota and Wooster, 2018) to estimate fuel consumption, and/or smoke emissions, and in terms of fuel consumption many have typically been lower than those from burned area based approaches (Roberts et al., 2011), and also lower than expected from ground-based measures (Andela et al., 2016). A variety of factors may contribute to this apparent underestimation, and to the uncertainty of FRE estimates more generally, for example satellite orbital constraints that limit the number of FRP observations in a given time-period (Andela et al., 2015), sensor optical characteristics (e.g., spatial resolution, point spread function and sensor saturation; Calle et al., 2009; Wooster et al., 2015), active fire detection algorithm performance (Giglio et al., 2016, Freeborn et al., 2014b) and FRP retrieval random error (Boschetti and Roy, 2009; Freeborn et al., 2014a). Vegetation canopy cover masking some of the emitted FRP from view is a further possible and potentially highly significant effect that has so far not been quantitatively studied. We focus on this issue herein, which typically does not affect burned area based estimates of fuel consumption unless the canopy cover results in special approaches being required to identify sub-canopy burned areas (e.g., in thick forests; Morton et al., 2011). A further key advantage of the burned area based approach to fuel consumption estimation is that this method enables identification of short duration fires which may be missed by active fire methods, which is important as it is typically the omission of these fires which is a significant source of FRP underestimation (e.g., Roberts and Wooster, 2008; Zhukov et al., 2006; Freeborn et al., 2014b; Zhang et al., 2017). However, on the other hand, burned area based approaches to total fuel consumption estimation require separate information on fuel consumption per unit area within the burn scar to be provided, which is often difficult to obtain for particular fire-affected locations (van Leeuwen et al., 2014). Recent studies based on satellite-derived FRPs have also suggested a biome-dependence in the relationship between FRP and fuel consumption that remains unexplained (Kaiser et al., 2012; Schroeder et al., 2014; Li et al., 2018). Spaceborne retrievals of FRP are made through the full depth of the atmosphere and through any overlying vegetation canopy that may lie above a surface fire, and these may be responsible for some of the biome-dependence on the FRP-to-fuel consumption relations noted when using spaceborne observations (Kremens et al., 2012; Mathews et al., 2016; Mota and Wooster, 2018).

We investigate the canopy cover impact on FRP and FRE retrievals using a 3D radiative transfer model. Such models provide key tools for understanding interactions between solar and terrestrially emitted VIS to LWIR radiation and Earth's surface and atmosphere, including the elucidation of atmospheric effects on the measured remotely sensed signals. Radiative transfer models have been applied to simulate fire impacts on surface spectral properties (Disney et al., 2011), to develop algorithms to quantify fire impacts on the land surface from such signals (Chuvieco et al., 2006), and to characterise the detectability of burned areas occurring under forest canopies (Pereira et al., 2004). Here we use the Discrete Anisotropic Radiative Transfer (DART) model (Gastellu-Etchegorry et al., 1996) to simulate the thermal 3D radiative transfer within and above landscapes to investigate canopy impacts on FRP, and to understand the degree to which spaceborne observations of surface fire FRP may be influenced by overlying canopy interception.

2. FRP background

Vegetation is comprised mainly of cellulose, hemi-cellulose, proteins, lignin and water (Stott, 2000), and is approximately 50% carbon by dry mass (Grigal and Ohmann, 1992). During complete combustion the carbon is oxidized to CO_2, with the concomitant release of water vapour, and thermal energy. The heat of combustion ($MJ\cdot kg^{-1}$) represents the total energy available for release upon burning completely in oxygen, and this figure is rather constant between vegetation types, with a minimum of around $16.2\,MJ\cdot kg^{-1}$ for senesced grass and a maximum of around $23.7\,MJ\cdot kg^{-1}$ for oil-rich eucalyptus leaves (Jenkins et al., 1998; Johnson, 1992; Stott, 2000). The radiative component of this heat yield can be retrieved via remote sensing, and the rate of emission of this from a fire containing multiple thermal components, each having different temperatures and areas, is the fire radiative power (FRP, Watts):

$$FRP_{true} = \varepsilon\sigma \sum_{n=1}^{N} A_n T_n^4 \quad (1)$$

where FRP_{true} is the fire radiative power (Wm^{-2}), N is the number of temperature components in the fire, σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8}\,J\,s^{-1}\,m^{-2}\,K^{-4}$), ε is fire graybody emissivity, A_n is the fractional area and T_n is the temperature of the n^{th} thermal component (K). An important assumption in Eq. (1) is that flame behaves as a graybody (i.e., constant emissivity with wavelength). Johnston et al. (2014) provide a recent assessment of flame LWIR and MWIR spectral emissivity, and confirm that the graybody assumption is valid (and that flame emissivity increases with flame depth). They also suggest that the absolute value of flame emissivity at any particular flame depth varies with soot volume fraction, whilst the depth as viewed by a remote sensing instrument depends on the viewing geometry and the flame geometry.

Kaufman et al. (1998) first suggested the use of FRP retrievals to back calculate smoke emission and fuel consumption rates, and the link between the two has since been quantified in numerous studies (e.g., Wooster et al., 2005; Freeborn et al., 2008; Pereira et al., 2011; Kremens et al., 2012; Smith et al., 2013). Fire radiative energy (FRE; Joules) is the temporal integral of FRP, and the type of linear relationship between FRE and fuel consumption shown by Wooster et al. (2005) and Kremens et al. (2012) has been exploited with both polar-orbiting and geostationary satellites to estimate the amount of dry matter consumed and the smoke emissions released by landscape fires (Polar Orbiting: e.g., Ichoku and Kaufman, 2005; Ellicott et al., 2009; Vermote et al., 2009; Freeborn et al., 2009; Kaiser et al., 2012; Schroeder et al., 2014; Boschetti and Roy, 2009; Pereira et al., 2009; Geostationary: e.g., Andela et al., 2016; Mota and Wooster, 2018; Roberts et al., 2005, 2011; Zhang et al., 2012; Roberts et al., 2015; Li et al., 2018; Baldassarre et al., 2015).

The FRE approach a more direct route to estimating landscape scale fuel consumption than burned area based methods, which still require estimates of fuel load per unit area and combustion completeness from models or field data (e.g., Korontzi et al., 2003; Ito and Penner, 2004; Lehsten et al., 2008; van der Werf et al., 2010; Randerson et al., 2012). Whilst FRP retrievals from the MODIS sensor onboard the Terra and Aqua satellites are used for routine fuel consumption and fire smoke emissions calculations however, the linear FRE-to-fuel consumption relationship derived by Wooster et al. (2005) during small scale experiments have tended to strongly underestimate landscape scale fuel consumption when applied to these data (Roberts et al., 2011; Andela et al., 2016). This is expected to be particularly significant in more forested regions (Kaiser et al., 2012), and it is assumed to occur as a result of infrared radiation emitted from the surface fires being intercepted by the overlying tree