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The 2010 Russian drought impact on satellite measurements of solar-induced chlorophyll fluorescence: Insights from modeling and comparisons with parameters derived from satellite reflectances

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ABSTRACT

We examine satellite-based measurements of solar-induced chlorophyll fluorescence (SIF) over the region impacted by the Russian drought and heat wave of 2010. Like the popular Normalized Difference Vegetation Index (NDVI) that has been used for decades to measure photosynthetic capacity, SIF measurements are sensitive to the fraction of absorbed photosynthetically-active radiation (fPAR). However, in addition, SIF is sensitive to PAR as well as the fluorescence yield that is related to the photosynthetic yield. Both SIF and NDVI from satellite data show drought-related declines early in the growing season in 2010 as compared to other years between 2007 and 2013 for areas dominated by crops and grasslands. This suggests an early manifestation of the dry conditions on fPAR. Using MODIS fPAR retrievals, we computed SIF/APAR which is related to light use efficiencies (LUEs) for fluorescence and photosynthesis. We found drought-related losses in fluorescence efficiency for all areas including those dominated by mixed forests. Unlike croplands and grasslands, areas of mixed forest did not show significant drought-related declines in fPAR. We also simulated SIF and Gross Primary Productivity (GPP) using a global land surface model driven by observation-based meteorological fields. The model provides a reasonable simulation of the drought and heat impacts on SIF in terms of the spatial extents of anomalies, but some differences were found in timing of the peak drought response between modeled and observed SIF. Model data also suggested that drought-related declines in LUE for fluorescence and photosynthesis in areas of mixed forest produce losses in SIF and GPP. SIF and GPP losses due to drought in croplands and grasslands result from both LUE and fPAR reductions. The combination of SIF and NDVI or fPAR data is shown to be an important source of information for evaluating model performance.

1. Introduction

For over thirty years, the primary tool for monitoring vegetation globally from space has been reflectance measurements at visible and near-infrared wavelengths (*e.g.*, Myneni, Ramakrishna, Nemani, & Running, 1997; Tucker, 1979). Since 1981, there is a continuous record of the Normalized Difference Vegetation Index (NDVI) from the Advanced Very High Resolution Radiometer (AVHRR) series of instruments on meteorological satellites (Tucker et al., 2005). The NDVI and similar indices utilize visible and near-infrared reflectances on both sides of the so-called red-edge (their difference normalized by their sum) and are sensitive to the amount of green biomass within a satellite pixel. These indices and related parameters have been widely used to examine spatial and inter-annual variations in vegetation and for many other applications including estimation of gross primary productivity (GPP) (*e.g.*, Randerson, Thompson, Conway, Fung, & Field, 1997; Running et al., 2004; Tucker & Sellers, 1986; Zhao & Running, 2010).

Satellite measurement of solar-induced fluorescence (SIF) from chlorophyll has emerged over the last few years as a different method to monitor vegetation globally from space (*e.g.*, Frankenberg et al., 2011; Guanter et al., 2007, 2012; Joiner et al., 2011, 2012). These studies

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have their foundations in many ground- and aircraft-based studies (*e.g.*, Amoros-Lopez et al., 2008; Campbell, Middleton, Corp, & Kim, 2008; Corp et al., 2003; Flexas et al., 2002; Guanter et al., 2013; Lichtenthaler, 1987; Meroni et al., 2009; Plascyk & Gabriel, 1975; Rascher et al., 2009; Zarco-Tejada et al., 2009). SIF measurements are based on the fact that a small fraction of the energy absorbed by vegetation (of the order of a percent) is emitted as fluorescence. The fluorescent emission has two peaks near 685 and 740 nm (Chappelle & Williams, 1987), known as the red and far-red emission features. All of the satellite measurements reported thus far have been in the far-red spectral region, where reabsorption of the fluorescence within the leaves and canopy is relatively small. The GOME-2 SIF measurements used here are from the MetOp-A satellite with a morning overpass time near 09:30 local time (LT).

Relationships between SIF, NDVI, GPP and other parameters can be understood within the context of the light-use efficiency (LUE) model (Monteith, 1972), *i.e.*,

$$\mathrm{GPP} = \mathrm{LUE} * \mathrm{fPAR} * \mathrm{PAR} = \mathrm{LUE} * \mathrm{APAR}, \tag{1}$$

where fPAR is the fraction of absorbed Photosynthetically-Active Radiation, and APAR = fPAR ∗ PAR is the total amount of absorbed PAR. The amount of SIF at the top-of-canopy can be approximated in a similar form, *i.e.*,

$$\mathrm{SIF} = \Theta_f * \mathrm{fPAR} * \mathrm{PAR} * \Omega_c = \Theta_f * \mathrm{APAR} * \Omega_c, \tag{2}$$

(*e.g.*, Lee et al., 2015) where Θ_f is the fluorescence yield at the membrane scale, and Ω_c is an escape probability linking the escape of fluorescence from the top of canopy to the emission of fluorescence at the scale of the chloroplast membranes. It is reasonable to assume that Ω_c remains fairly constant for repeat observations of a vegetated area made from a satellite over a limited period of time when vegetation structure is not changing.

The NDVI is an indicator of potential photosynthesis or photosynthetic capacity as it is a measure of chlorophyll abundance and energy absorption that varies with abiotic conditions (Myneni, Hall, Sellers, & Marshak, 1995). SIF responds in a fairly linear way to changes in APAR at low to moderate light levels, applicable to morning GOME-2 satellite measurements, and under unstressed conditions. However, this will be convolved with changes in Θ_f that may also be related to stress. NDVI also responds to stress by a reduction of energy absorption, and this occurs on the order of a few days (Tucker, Holben, Elgin, & McMurtrey, 1981).

If Ω_c is assumed constant, and if the ratio LUE to Θ_f also remains constant, then it can be seen from Eqs. (1) and (2) that SIF will be linearly related to GPP. Theory and measurements suggest that under moderate illumination, such as natural illumination present during morning satellite overpasses, the ratio of LUE to Θ_f remains relatively constant (*e.g.*, Van der Tol, Berry, Campbell, & Rascher, 2014; Berry et al., 2013; Porcar-Castell et al., 2014). Previous studies have focused on relationships between GPP estimated from flux tower measurements and satellite-based SIF in terms of both magnitude (Guanter et al., 2014) and seasonal variations (Joiner et al., 2014). These studies have demonstrated that on a weekly to monthly time-scale, there is a high correlation between GPP and SIF.

Other studies have examined relationships between remotely-sensed SIF and LUE including stress. These studies have utilized ground-based measurements (*e.g.*, Damm et al., 2010; Daumard et al., 2010; Louis et al., 2005; Meroni et al., 2008; Middleton et al., 2009, Middleton, Huemmrich, Cheng, & Margolis, 2011) as well as satellite-based SIF (*e.g.*, Lee et al., 2013; Parazoo et al., 2013; Zhang et al., 2014). The latter studies with satellite data have focused primarily on the Amazonia basin and maize and soybean croplands in the midwest US. Some of these studies show that stress, including heat and moisture stress, can manifest itself earlier or be more pronounced in SIF as compared with vegetation indices such as the NDVI (*e.g.*, Daumard et al., 2010). This can occur when there is a decrease in the Θ_f component of SIF rather than, or in addition to, a decrease in fPAR that would be reflected in both SIF and NDVI.

In this work, we examine the relative importance of Θ_f and fPAR to the SIF signal in a situation of high stress: the regional drought and heat wave that occurred in western Russia due to a persistent blocking ridge over central Europe during the months June through August 2010 (*e.g.*, Grumm, 2011). Societal impacts of this event included massive peat and forest fires, a decrease in wheat production of 20–30% relative to 2009, and an increase in death rates in nearby cities including Moscow. Because this drought and heat wave occurred over an extensive region, we can examine its effects on SIF and NDVI over areas covered with predominantly different vegetation types. This allows for an assessment of whether certain vegetation types are more or less prone to stress and damage and whether stress is observed earlier in the SIF data for different vegetation types.

In addition to examining satellite data, we simulate SIF and other parameters using a global land surface model forced by observation-based meteorological fields. Within this simulation, we are able to examine the effects of the drought and heat wave on fPAR and photosynthesis. This provides further insight into the relative effects of the drought on LUE, Θ_f, PAR, and fPAR and demonstrates the skill of the model in predicting drought-induced anomalies. To our knowledge, this region has not yet been examined in detail in the literature with respect to satellite-based SIF observations.

2. Data and methods

We examine data within six regions of size 2° longitude by 1° latitude over western Russia in areas impacted by the drought and heat wave in 2010. Because the GOME-2 SIF observations used here (Section 2.1) have a lower signal to noise ratio as compared with the MODIS NDVI observations, we need to compute averages over spatial domains approximately this size. All pixels meeting the quality control checks and cloud filtering are averaged for each region. The individual regions were chosen because they contain various fractions of different vegetation types as shown in Fig. 1. The location of each box and dominant International Geosphere Biosphere Programme (IGBP) vegetation type, from the MODIS Land Cover Type Climate Modeling Grid (CMG) product for 2010 (Friedl et al., 2010), are listed in Table 1. We compute 8-day averages of various meteorological and satellite vegetation parameters throughout the growing season separately for 2010 (the drought year) and for all other years with available satellite GOME-2 SIF data (2007 to 2013 excluding 2010, hereafter referred to as the climatology).

2.1. GOME-2 SIF

The approach to retrieve the SIF signal from space was first demonstrated by observing the filling-in of the strong oxygen A-band absorption feature (Guanter et al., 2007). As this approach is difficult to implement globally, subsequent satellite retrievals utilized the filling-in of solar Fraunhofer lines surrounding the oxygen A-band (near 758 and 770 nm) using high spectral resolution measurements from a Fourier transform spectrometer on the Japanese Greenhouse gases Observing SATellite (GOSAT) (Frankenberg et al., 2011; Guanter et al., 2012; Joiner et al., 2011, 2012). Later it was shown that SIF could be retrieved at 866 nm using hyperspectral measurements from the SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY) on board the European Space Agency's ENVIronmental SATellite (ENVISAT) (Joiner et al., 2012) and near 740 nm with the Global Ozone Monitoring Instrument 2 (GOME-2) on MetOp satellites (Joiner et al., 2013, 2014). While spatial and temporal variations in SIF from GOSAT and GOME-2 are comparable, GOME-2 SIF has better temporal and spatial coverage than GOSAT owing to greater sampling as well as a longer data record. We therefore use GOME-2 SIF exclusively for this study. The MetOp satellites, like ENVISAT and GOSAT, are in sun-synchronous orbits.