Remote Sensing of Environment 140 (2014) 330–338

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

Using satellite based soil moisture to quantify the water driven variability in NDVI: A case study over mainland Australia

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ARTICLE INFO

Article history:
Received 7 January 2013
Received in revised form 22 August 2013
Accepted 22 August 2013
Available online xxxx

Keywords:
Soil moisture
Vegetation
NDVI
Satellite

ABSTRACT

Soil moisture is crucial in regulating vegetation productivity and controlling terrestrial carbon uptake. This study aims to quantify the impact of soil moisture on vegetation at large spatial and long-term temporal scales using independent satellite observations. We used a newly developed satellite-derived soil moisture product and the Normalized Difference Vegetation Index (NDVI) to investigate the impact of soil moisture on vegetation across mainland Australia between 1991 and 2009. Our approach relied on multiple statistical methods including: (i) windowed cross correlation; (ii) quantile regression; (iii) piecewise linear regression. We found a strong positive relationship between soil moisture and NDVI, with NDVI typically lagging behind soil moisture by one month. The temporal characteristics of this relation show substantial regional variability. Dry regions with low vegetation density are more sensitive to soil moisture for the high end of the distribution of NDVI than moist regions, suggesting that soil moisture enhances vegetation growth in dry regions and in the early stage in wet regions. Using piecewise linear regression, we detected three periods with different soil moisture trends over the 19 years. The changes in NDVI trends are significant ($p < 0.01$) with turning points of soil moisture in the beginning of 2000 and the end of 2002. Our findings illustrate the usefulness of the new soil moisture product by demonstrating the impacts of soil moisture on vegetation at various temporal scales. This analysis could be used as a benchmark for coupled vegetation climate models.

1. Introduction

Knowledge of the response of vegetation to climate change is crucial in understanding ecosystem dynamics. The growth of atmospheric CO_2 concentration has caused green foliage increased at least during the last three decades (Donohue, Roderick, McVicar, & Farquhar, 2013). Water availability, solar radiation and temperature are the main climatic constraints that determine the spatial distribution of ecosystems and plant growth (Churkina & Running, 1998; Nemani et al., 2003; Stephenson, 1990). The impacts of these factors on vegetation are relatively well investigated (Lotsch, Friedl, Anderson, & Tucker, 2003; Mercado et al., 2009; Myneni, Keeling, Tucker, Asrar, & Nemani, 1997; Piao et al., 2008). For example, an increase in plant growth has been observed in high latitudes, and was ascribed to the lengthening of the growing season (Myneni et al., 1997). However, climate–ecosystem interactions are complex and autumn warming could also lead to net CO_2 losses in northern ecosystems (Piao et al., 2008).

The availability of water influences more than half of the primary productivity of the world's terrestrial ecosystems (Heimann & Reichstein, 2008), highlighting the constraints of hydrological processes to vegetation. Unfortunately, this effect is probably the lesser understood of the three above-mentioned constraints on plant growth. Water limitation reduces the ability of leaves to take up CO_2, even under conditions of sufficient light, due to a restriction in stomatal conductance and limited root water (van der Molen et al., 2011). Thus, over regions where temperature and radiation are expected to be non-limiting, water availability is an important factor in determining vegetation dynamics. Almost classic examples are the 2005 and 2010 droughts in the Amazon basin that caused large-scale mortality and associated reductions in living biomass (Lewis, Brando, Phillips, van der Heijden, & Nepstad, 2011; Phillips et al., 2009). An obvious reduction in GPP was found during 2003 across Europe. At the site level, FLUXNET analysis suggests that this reduction was caused by water limitation rather than by high temperatures (Ciais et al., 2005). Further support for a large impact of water availability on the carbon uptake of terrestrial ecosystem can be found in Angert et al. (2005), Phillips et al. (2009) and Reichstein et al. (2007).

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http://dx.doi.org/10.1016/j.rse.2013.08.022

Importantly, these results were often obtained without adequate observations of soil moisture. Model based soil moisture and several drought indices that are related to actual soil moisture in different ways were often used as a proxy (Hirschi et al., 2011; Lotsch et al., 2003; Nicholson, Davenport, & Malo, 1990) to study the relationship between vegetation dynamics and water availability. In addition, other researchers used other components of the water balance like precipitation to capture the hydrological impact on vegetation (e.g. Donohue, McVicar, & Roderick, 2009; Wang, Rich, & Price, 2003) or used a combination of water and temperature in non-linear models to study the leaf phenology (e.g. Choler, Sea, & Leuning, 2011; Williams, Myers, Muller, Duff, & Eamus, 1997) These studies provide insights of ecohydrological processes and they also had their limitations as they were based on models and/or indirect observations of water availability.

Observed soil moisture is arguably the best representation of the actual amount of water contained in the soil, and is the key to understanding the climate–soil–vegetation system both in space and time (Porporato & Rodriguez-Iturbe, 2002; Rodriguez-Iturbe, 2000). Soil moisture is more directly associated with dynamics in plant photosynthesis and respiration processes than precipitation, of which a variable amount will be lost through interception and runoff (e.g., Miralles, Crow, & Cosh, 2010). Until recently, soil moisture product that soil moisture product was available. This situation has changed dramatically in the last few years. Near-surface soil moisture (several centimeters) from space borne passive and active microwave instruments have been shown to provide effective observations at regional and global scales (Gao, Wood, Jackson, Drusch, & Bindlish, 2006; McCabe, Gao, & Wood, 2005; Njoku et al., 2002; Owe, de Jeu, & Holmes, 2008; Wagner et al., 2003; Wen, Su, & Ma, 2003). The passive and active microwave soil moisture products, respectively, give robust estimates over sparsely and moderately vegetated regions (de Jeu et al., 2008; Dorigo et al., 2010). Based on previous studies, further blending passive and active microwave soil moisture retrievals from various satellites have led to a long-term improved product with better spatial and temporal coverage (Liu et al., 2011, 2012). These satellite soil moisture products have shown their value in climate studies (e.g. Jung et al., 2010; Taylor, de Jeu, Guichard, Harris, & Dorigo, 2012) and hydrological studies (Brocca et al., 2011) but are currently still not often used in biogeochemical studies.

Here, we used a newly derived merged product of soil moisture (Dorigo et al., 2012; Liu et al., 2012) to quantify the impact of soil moisture on vegetation dynamics with a range of temporal and spatial scales. The Normalized Difference Vegetation Index (NDVI) product derived from the Advanced Very High Resolution Radiometer (AVHRR) instruments was used to represent vegetation conditions (Tucker et al., 2005). Our objectives are twofold. Firstly to determine the usefulness of the satellite derived products in estimating short and long term variability in the relation between soil moisture and vegetation and secondly to shed light on these relations and trends for mainland Australia. We analyzed these relationships with a multi-statistical approach including variation coherence, time scale, trends and extremes. We selected Australia as a case study because the satellite derived soil moisture has been extensively evaluated by ground based soil moisture and rainfall over Australia (Draper, Walker, Steinle, de Jeu, & Holmes, 2009) and the product has an established high data quality over this area (Parinussa et al., 2011). Australia is a water-limited continent (McVicar, Roderick, Donohue, & Van Niel, 2012) where vegetation growth is mainly controlled by water conditions (Donohue et al., 2009; Williams et al., 1997). Australia also contains a large variety in vegetation types, from desert to tropical rainforest. All these components provide an appropriate test bed for this study. Section 2 describes the soil moisture and NDVI products and the statistical methods applied here. Section 3 presents the results, while the last section discusses the results and the performance of the soil moisture product in establishing these relationships.

2. Data and methods

2.1. Data

2.1.1. Soil moisture

The monthly 0.25 degree spatial resolution soil moisture dataset used (1991–2009) was extracted from the European Space Agency Climate Change Initiative data portal (ESA, see http://www.esa-soilmoisture-cci.org). This product was recently developed by merging the active microwave soil moisture products developed by Bartalis et al. (2007) and Wagner, Lemoine, and Rott (1999) with the passive microwave soil moisture products developed by the VU University Amsterdam in collaboration with NASA (de Jeu et al., 2008; Owe et al., 2008), representing surface soil moisture (not deeper than 10 cm, Liu et al., 2011). A short description of this approach is given below and a more thorough description can be found in Liu et al. (2011, 2012). The harmonization approach is based on two steps. At first all individual datasets are converted into one soil moisture range (vol.%) using cumulative distribution functions. Then all the datasets are statistically ranked based on their quality (as derived from triple collocation analysis) and harmonized into one consistent dataset.

This approach primarily addresses three major challenges: i.e., (1) differences in instrument specifications resulting in different absolute soil moisture values; (2) the global passive and active microwave retrieval methods producing conceptually different quantities (expressed in the volumetric soil moisture (m^3 m^{-3}) and degree of saturation (%), respectively); (3) products varying in their relative performances depending on vegetation cover (Dorigo et al., 2010; Scipal, Holmes, de Jeu, Naeimi, & Wagner, 2008). While this approach changes the absolute values of soil moisture, it preserves the relative dynamics (e.g., seasonality and inter-annual variations) of the original satellite derived retrievals and this makes it particularly well suited for our purpose. The long-term changes, as evident in the original soil moisture products, are also preserved (Liu et al., 2012). Although the original data are daily, there are too many gaps because each scan of the satellites can't cover the whole region. Therefore, we averaged the original daily product into monthly data to produce spatially covered maps of mainland Australia. Fig. 1 gives an overview of the general spatial soil moisture conditions over time for this study area with relative wet conditions in the south in the winter (JJA) and wet conditions in the summer (DJF) in the north.

2.1.2. NDVI

The Normalized Difference Vegetation Index (NDVI) is a normalized ratio calculated from reflected radiation in the red and near-infrared spectral regions. In general, productive plants use the energy available in the red part of the spectrum for photosynthesis and reflect the near infrared. NDVI is calculated as (NIR − VIS) / (NIR + VIS), where NIR and VIS indicate the spectral reflectance at the near-infrared and visible (red) spectral band range, respectively. NDVI has been widely used to indicate vegetation dynamics or growth (Donohue et al., 2009, 2013; Myneni et al., 1997; Nemani et al., 2003; Piao et al., 2011; Tucker, Fung, Keeling, & Gammon, 1986). Here we used the long term time series of NDVI observation from the Global Inventory Modeling and Mapping Studies (GIMSS) group derived from NOAA AVHRR imagery (Beck et al., 2011; Tucker et al., 2005). NDVI used here is averaged at monthly and 0.25 degree resolution for direct comparison with the monthly soil moisture maps. In Fig. 1, spatial patterns of annual averaged NDVI were shown to present the general vegetation conditions. In addition the main ecoregions (Department of the Environment, Water, Heritage and the Arts, 2012a) are mapped in Fig. 2.

Both soil moisture and NDVI have a strong seasonal cycle, and here we only used the monthly anomalies (i.e. the monthly anomaly was calculated by subtracting the monthly time series from the monthly climatology based on the 19 year data record).