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Evaluating EO-based canopy water stress from seasonally detrended NDVI and SIWSI with modeled evapotranspiration in the Senegal River Basin

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ABSTRACT

Satellite remote sensing of vegetation parameters and stress is a key issue for semi-arid areas such as the Sahel, where vegetation is an important part of the natural resource base. In this study we examine if additional information can be obtained on intra-seasonal short term scale by using the Shortwave Infrared Water Stress Index (SIWSI) as compared to Normalized Difference Vegetation Index (NDVI). We perform a spatio-temporal evaluation of NDVI and SIWSI using geostationary remote sensing imagery from the Spinning Enhanced Visible and Infrared Imager (SEVIRI). The indices and their seasonally detrended anomalies are evaluated using a gridded rainfall product (RFE2) and modeled actual evapotranspiration (ETa) for the Senegal River basin in 2008. Daily NDVI and SIWSI were found spatially highly correlated to ETa with $r = 0.73$ for both indices, showing the importance of the north/south vegetation gradient in the river catchment. The hypothesis that short term evolution of index anomalies are related to canopy water status was tested by comparing 10-day averages of ETa with short term changes in daily NDVI and SIWSI anomalies, and moderate to strong coefficients of determination where found when anomaly variations where aggregated by Land Cover Classes (LCCs) with R^2 values of 0.65 for savanna, 0.60 for grassland, 0.72 for shrubland, and 0.58 for barren or sparsely vegetated areas. This is higher than for the same method applied to NDVI anomalies, with R^2 values of 0.57 for savanna, 0.50 for grassland, 0.32 for shrubland, and 0.57 for barren or sparsely vegetated areas. The approach of detrending NIR/SWIR based indices and spatially aggregating the anomalies do offer improved detection of intra-seasonal stress. However, quite coarse spatial aggregation is found necessary for a significant analysis outcome.

1. Introduction

Satellite remote sensing of terrestrial vegetation and vegetation status provides essential information for natural resource management and drought early warning systems in global dryland areas (Fensholt et al., 2012). The semi-arid Sahel in Sub-Saharan Africa is amongst the world's largest dryland areas, yet characterized by limited availability of conventional meteorological ground observations. This makes Earth observation (EO) based vegetation monitoring particularly useful. In the Sahel, vegetation growth is highly related to rainfall (Nicholson, Davenport, & Malo, 1990), and rainfall variability is a major challenge for the sustainability of local livelihoods (Mertz et al., 2012).

Many indices have been proposed to study and monitor vegetation health and vigor using information from visible (VIS), near infrared (NIR), and shortwave infrared (SWIR) spectral bands. The most widely applied of these indices is the Normalized Difference Vegetation Index (NDVI), which has been found related to several vegetation parameters like photosynthetic activity, fractional vegetation cover, and Net Primary Production (NPP) (Carlson & Ripley, 1997; Prince, 1991a,b; Tucker, 1979). NDVI has been used to assess changes in phenology and long term vegetation trends using datasets such as the Global Inventory Modeling and Mapping Studies (GIMMS) data from the Advanced Very High Resolution Radiometer (AVHRR) (Fensholt, Sandholt, Rasmussen, Stisen, & Diouf, 2006; Fensholt et al., 2012; Heumann, Seaquist, Eklundh, & Jonsson, 2007; Julien & Sobrino, 2009; Sobrino & Julien, 2011), which now spans several decades.

NDVI is also commonly combined with information in the Thermal Infrared (TIR) spectrum for drought monitoring (Carlson & Ripley, 1994; Gillies, Carlson, Cui, Kustas, & Humes, 1997; Sandholt, Rasmussen, & Andersen, 2002). The Vegetation Health Index (VHI) (Kogan, 1995) combines NDVI and the Temperature Condition Index (TCI) from AVHRR reflectances and brightness temperatures. VHI has recently been applied for agricultural drought probability mapping of the African continent (Rojas, Vrieling, & Rembold, 2011), thus avoiding the use of potentially unreliable gridded rainfall datasets. Furthermore, the high dependency and sensitivity of vegetation to rainfall in the Sahel has lead studies to suggest using NDVI as a proxy for rainfall to

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compensate for unreliable rainfall data (Anyamba & Tucker, 2005; Proud & Rasmussen, 2010). Although studies of the impact of inter-annual rainfall variability on vegetation indices are most common, NDVI has also been applied in studies on intra-annual timescale of vegetation response to seasonal rainfall patterns e.g. in the Sahel (Proud & Rasmussen, 2010), using data from the Spinning Enhanced Visible and Infrared Imager (SEVIRI) onboard the geostationary Meteosat Second Generation (MSG) platform, and in Kansas (Wang, Rich, & Price, 2003) using AVHRR data.

While NDVI has been found suitable for inter-annual studies on a relatively coarse temporal and spatial resolution in a multitude of studies (Fensholt & Proud, 2012), the red and NIR based NDVI is not necessarily the most useful index for providing information on short term variations in surface water properties, like evapotranspiration, caused by changing water availability and canopy water content. Due to the SWIR spectrum's sensitivity to the amount of liquid water in the canopy (Tucker, 1978; Tucker, 1980), several NIR/SWIR based indices sensitive to canopy water content have been examined for their applicability (Ceccato, Flasse, Tarantola, Jacquemoud, & Gregoire, 2001; Ceccato, Gobron, Flasse, Pinty, & Tarantola, 2002; Ceccato, Flasse & Gregoire, 2002; Fensholt & Sandholt, 2003; Gao, 1996). Amongst these the Shortwave Infrared Water Stress Index (SIWSI) has been studied in a Sahelian context. The evolution of SIWSI over a growing season has been shown to be highly related to the evolution of growing season NDVI, but SIWSI has also proved to be sensitive to short-term changes in canopy water status (i.e. whether the canopy is water stressed or not). This was shown from comparison with observed and modeled soil moisture in northern Senegal, where the SIWSI signal for a herbaceous canopy reflected the periods of low soil moisture (Fensholt & Sandholt, 2003). When implemented using high temporal resolution data (15 min temporal resolution) from the SEVIRI instrument onboard MSG, SIWSI was found to co-vary with short term changes in vegetation water status (Fensholt, Huber, Proud, & Mbow, 2010a).

Timely information provided from EO data has been implemented in early warning systems (EWS) for averting food shortage and famine, e.g. the United States Agency for International Development (USAID) Famine Early Warning System (FEWSNET) and the United Nation's Food and Agricultural Organization (FAO) Global Information and Early Warning System (GIEWS). When using VIS/NIR based indices, canopy water status is assessed from chlorophyll content. However, chlorophyll content responds more slowly and less direct to plant water shortage, as compared to canopy water content. Direct assessment of the canopy water content based upon information from SWIR would potentially shorten the response time required for canopy water stress and drought detection in dryland areas. Currently, global EO-based NPP products using the Production Efficiency Model (PEM) approach are not able to sufficiently integrate short-term, EO-derived, information related to growth constraints (primarily water) in arid and semi-arid areas (Fensholt et al., 2006). If the SWIR sensitivity to canopy water content can be successfully implemented in EO-based monitoring, improvements in dryland productivity assessment could be foreseen.

Data from polar orbiting environmental satellites (POES) are largely influenced by daily variations in the sun-target-sensor geometry (Fensholt, Sandholt, Proud, Stisen, & Rasmussen, 2010b). These wavelength dependent variations (caused by different degrees of absorption/transmittance of a surface) are therefore affecting derived indices (Morton et al., 2014) and can ultimately mask the signal inherent to changes in canopy water content. (Fensholt, Huber, Proud, & Mbow, 2010a) explored the potential of SWIR based canopy water stress detection from geostationary MSG data (fixed viewing geometry) as compared to MODIS (Moderate Resolution Imaging Spectroradiometer) data (being a POES) and found higher usefulness of the geostationary signal. Short term variations of seasonally detrended daily SIWSI and NDVI anomalies, derived from the geostationary MSG data, have been compared to periods of limited plant available water for sites in the Sahel (Olsen et al., 2013). This was based on the hypothesis that anomalies would increase or decrease as a result of changed canopy water status during dry spells. SIWSI anomalies were shown to be better suited for this approach than NDVI anomalies. However, variations in anomalies during non-dry periods resulted in false dry period identifications, thereby making implementation of the method unsuited for robust drought detection on a per-pixel level.

Testing SIWSI index anomalies on a larger spatial scale has not yet been attempted despite: a) the importance of short-term detection of vegetation stress at the regional scale, and b) that previous studies have presented and supported the hypothesis, that short term variations in index anomalies hold information on changes in canopy water status (Fensholt, Huber, Proud, & Mbow, 2010a; Fensholt & Sandholt, 2003; Fensholt, Sandholt, Proud, Stisen, & Rasmussen, 2010b; Olsen et al., 2013). The purpose of this study is therefore to test this hypothesis by analyzing both NDVI and SIWSI derived from geostationary satellite imagery at a river basin scale (approximately 250,000 km^2). For this purpose NDVI is calculated from the SEVIRI channel 1 (0.6 μm — Red) and channel 2 (0.8 μm — NIR) and SIWSI is calculated from channel 2 and channel 3 (1.6 μm — SWIR). The indices are evaluated during both a well-watered and dry period during the 2008 growing season in the Senegal River Basin. Further, the indices are examined in different forms; both as regular index values and as seasonally detrended anomalies derived from seasonal curve fitting using the TIMESAT software (Jonsson & Eklundh, 2004). For comparison and evaluation, modeled actual evapotranspiration (ETa) from a semi-arid subset of the Senegal River basin area, estimated using a distributed hydrological model (MIKE SHE), is used together with the CPC-FEWS RFE2 gridded rainfall product.

2. Case area description

The Senegal River basin is located in West Africa and has a total drainage area of approximately 350,000 km^2. It covers parts of four countries; Guinea, Senegal, Mali, and Mauritania and is characterized by a strong rainfall and vegetation gradient, with little rainfall and vegetation in the north and increasingly dense vegetation and more annual rainfall towards the south (Fig. 1). The basin can be divided into sub-catchments, see (Stisen, Jensen, Sandholt, & Grimes, 2008), of which the semi-arid ones are of interest in this study and constitutes close to 250,000 km^2. The average annual rainfall for the sub-catchment shown in Fig. 1 is just below 500 mm/year, ranging from <200 mm/year in the north to >900 mm/year in the south. Maximum and minimum temperatures are around 40 °C and 17 °C respectively during the dry season (November to May) and 32 °C and 24 °C during the rainy season (June to October), but cooler close to the coast (weather-and-climate.com). The dominant soils types are arenosols, lithosols and regosols (FAO Harmonized World Soil Database — www.fao.org). The vegetation is predominantly natural and according to the USGS global Land Cover Classes (LCCs) savanna, grassland, shrubland, and barren or sparsely vegetated areas constitutes the majority of the area, with less than 6% identified as cropland (Table 1).

3. Data

3.1. Rain gauges

The rain gauge data are needed for assessing the uncertainties of gridded rainfall data in the case area. Within the Senegal River basin rain gauge data from 9 meteorological stations have been acquired from the NOAA Climate Data Online (CDO) facility http://www7.ncdc.noaa.gov/CDO/cdo (Table 2). Although more stations are present within the basin, many are without data for 2008.

3.2. CPC-FEWS Rainfall Estimation Algorithm version 2 (RFE2)

For this study a gridded rainfall product of high spatial and temporal resolution was needed, to facilitate the comparison with daily satellite data (NDVI and SIWSI) and modeled actual evapotranspiration. The Climate Prediction Center (CPC) Rainfall estimate product (Herman,