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Changes in Sahelian annual vegetation growth and phenology since 1960: A modeling approach

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ABSTRACT

In semi-arid areas like the Sahel, vegetation is particularly sensitive to climate variability and can play an important role in surface-atmosphere coupling. After a wet period extending from 1950 to 1970, the Sahel experienced a severe drought in the 1970s and 1980s, followed by a partial recovery of rainfall and a "re-greening" of vegetation beginning in the 1990s. This study explores how the multidecadal variability of Sahelian rainfall and particularly the drought period have affected vegetation phenology and growth since 1960.

The STEP model, which is specifically designed to simulate the Sahelian annual vegetation, including the dry season processes, is run over an area extending from 13°N to 18°N and from 20°W to 20°E. Mean values, interannual variability and phenological characteristics of the Sahelian annual grasslands simulated by STEP are in good agreement with MODIS derived production and phenology over the 2001–2014 period, which demonstrates the skill of the model and allows the analysis of vegetation changes and variability over the last 50 years.

It was found that droughts in the 1970s and 1980s shortened the mean vegetation cycle and reduced its amplitude and that, despite the rainfall recovery since the 1990s, the current conditions for green and dry vegetation are still below pre-drought conditions. While the decrease in vegetation production has been largely homogeneous during droughts, vegetation recovery has been heterogeneous over the Sahel since 1990, with specific changes near the western coast and at the eastern edge of the West African monsoon area. Since 1970, the Sahel also experienced an increased interannual variability in vegetation mass and phenology. In terms of phenology, region-averaged End and Length of Season are the most variable, while maximum date and Start of Season are the least variable, although the latter displays a high variability locally.

1. Introduction

The strongest multidecadal drought of the 20th century occurred in the West African Sahel. After a wet period extending from 1950 to 1969, the rainfall series exhibited a marked break (L'Hôte et al., 2002) with extreme droughts in the 1970s and 1980s (Ozer et al., 2003; Nicholson et al., 1998). Since the early 1990s, the Sahel has been experiencing a rain recovery, occurring contrastingly in western, central and eastern parts of the area (Lebel and Ali, 2009). At the same time, a positive trend and a high interannual variability of the Sahelian vegetation greenness have been observed from satellite-based vegetation indices (e.g. Olsson et al., 2005; Anyamba and Tucker, 2005; Philippon et al., 2007; Fensholt et al., 2009; Dardel et al., 2014a; Meroni et al., 2014). This "re-greening" of the Sahel is primarily driven by rainfall (Lotsch et al., 2003; Hickler et al., 2005; Dardel et al., 2014b), but also possibly by human activities such as local projects facilitating the regeneration of natural vegetation (Herrmann et al., 2005).

In semi-arid areas, vegetation growth is controlled primarily by water availability (Lieth, 1975; Hickler et al., 2005; Herrmann et al., 2005), although biogeochemical factors (e.g. nutrient availability, soil types, vegetation types) and/or anthropogenic factors (cropping, grazing, fire regime) also play an important role. Yet, several questions are still under debate due to the scarcity of long-term datasets. Among unsettled questions is the relationship between plant production and rainfall amount, and its evolution in the long term (Le Houerou et al., 1988; Prince et al., 1998, 2007; Diouf and Lambin, 2001; Hein and de Ridder, 2006; Huber et al., 2011; Ruppert et al., 2012; Dardel et al., 2014b), as well as the role and the evolution of intraseasonal variability in occurrences such as dry spells, start dates of the rainy season, and extreme events (Diouf and Lambin, 2001; Ruppert et al., 2012; Bobée et al., 2012). Most studies of the Sahel are limited to the period from 1980 to the present, which leaves mostly unanswered the question of the vegetation 'recovery' compared to pre-drought conditions, as well as its spatial extent. Whether there has been, on the whole, a degradation

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or resilience of Sahelian ecosystems over this longer time period is still unknown.

In addition to trends in annual production or greenness, the Sahelian vegetation phenology has been specifically scrutinized as it is a good gauge of plant response to climate and anthropogenic changes. Analyzing satellite-based Normalized Difference Vegetation Indices (NDVI) over 1982–2005, Heumann et al. (2007) reported two different types of greening: an increase of the amplitude of the vegetation's annual cycle in the Sahel, and an increase of the length of the vegetation cycle in the Soudanian and Guinean area. Following a similar methodology, Butt et al. (2011) observed a high latitudinal variability of phenological characteristics over southern Mali from 2000 to 2010. Whether these features are valid over a longer time scale is unknown.

More generally, a good understanding of the Sahelian vegetation dynamics is necessary to answer several scientific questions. Annual production is a key variable for natural resources and ecosystems services, and for desertification issues (see for instance references reviewed by Dardel et al., 2014a, and Karlson and Ostwald, 2016). Annual Sahelian grass is a key resource for pastoralism, particularly during the dry season. The annual vegetation cycle and its variability is also known to impact surface-atmosphere interaction through the energy and water balance (Zeng et al., 1999; Cayrol et al., 2000; Samain et al., 2008; Timouk et al., 2009, among others). Finally, dry season soil protection via vegetation is important for wind erosion control and Sahelian dust emissions (Sterk, 2003) and surface radiation budget (Samain et al., 2008; Vamborg et al., 2011).

Earlier global vegetation models were shown to simulate the vegetation phenology (i.e. the periodic plant life events and their evolution) in West Africa rather poorly (Bondeau et al., 1999), but attempts have been made to improve phenology modeling in semi-arid areas (Ciret et al., 1999; Jolly and Running, 2004; Brender et al., 2011; Berg et al., 2011; Traore et al., 2014) or globally, with a close-up on the Sahel (Gibelin et al., 2006). Specific models of plant phenology in the Tropics have also been developed from ground-based surveys, but most of these studies focused on woody or perennial plants (e.g. Archibald and Scholes, 2007; Choler et al., 2011).

The objective of this study is to investigate how the multidecadal variability of Sahelian rainfall and the droughts of the 1970s and 1980s have affected vegetation production and phenology. Given that satellite observations started mostly in the 1980s, models must consider the wet period before the drought at a regional and pluriannual scale. The Sahelian Transpiration, Evaporation and Productivity (STEP) model, specifically designed to represent Sahelian annual grasses, is used for that purpose.

First, the STEP model's ability to capture the main phenological characteristics (spatial and interannual variability, length and amplitude of the vegetation cycle) of the Sahelian herbaceous vegetation over the current period (2001–2014) is analyzed. Indeed, spectral indices are well suited to characterizing vegetation phenology, and they are widely used for that purpose (e.g. Moulin et al., 1997; Zhang et al., 2003; among others). Model outputs have been compared to MODerate resolution Imaging Spectroradiometer (MODIS) satellite observations (Section 3.1), which have been shown to match vegetation phenology measurements over two sites in Senegal (Bobée et al., 2012). Then, vegetation changes since 1960, thus including a wet period before the Sahelian droughts, are investigated with a particular focus on vegetation phenology (start, length and end of the season), as well as dry season vegetation and the impact of grazing pressure, which have rarely been studied before now.

2. Materials and methods

2.1. MODIS data

The Nadir BRDF Adjusted Reflectance (NBAR) product (MCD43C4, collection 5, combining TERRA and AQUA observations, Schaaf and Wang, 2015), provides reflectances of MODIS bands 1 (620–670 nm: near infrared), 2 (841–876 nm: infrared), 6 (1628–1652 nm) and 7 (2105–2155 nm, both short waves infrared) at 0.05° and 8-day time resolution over the 2001–2014 period. Two vegetation indices are derived from these observations:

$$NDVI = \frac{B_2 - B_1}{B_2 + B_1} \tag{1}$$

$$STI = \frac{B_6}{B_7} \tag{2}$$

where STI is the Soil Tillage Index (Guerschman et al., 2009).

NDVI is well known for its good representation of green vegetation (e.g. Myneni et al., 1995; Anyamba and Tucker, 2005). It is commonly used to monitor plant phenology of different ecosystems, including Sahelian grasslands (Heumann et al., 2007; Butt et al., 2011). Moreover, the integral of NDVI has been shown to provide good estimates of Sahelian plant production (Tucker et al., 1986; Prince, 1991; Mbow et al., 2013; Dardel et al., 2014a). iNDVI denotes the 'small integral' (Mbow et al., 2013), which is obtained by integrating NDVI above the dry-season value; it is used as a proxy for vegetation production over the entire growth period.

Dry-season vegetation, commonly referred to as non-photosynthetic vegetation (NPV), is receiving increasing attention due to its important role in the carbon cycle, residue management, soil erosion and fire risk assessment. The availability of short-wave infrared bands from MODIS has fostered the development of different techniques, either based on end-members (e.g. Okin and Gu, 2015) or specifically-designed indices (Guerschman et al., 2009; Daughtry and Quemada, 2015). STI has recently been shown to provide accurate estimates of dry vegetation mass and cover fraction in drylands (Guerschman et al., 2009) and in the Sahel (Jacques et al., 2014; Kergoat et al., 2015).

These indices are aggregated at 0.25° for comparison to model outputs (see Section 2.2). Then, a running mean over 5 dates is computed, and grid cells where the annual cycle is low (NDVI amplitude lower than 0.02) are discarded for both NDVI and STI.

2.2. The STEP model

The STEP model (Mougin et al., 1995) has been specifically designed to simulate the growth and senescence of Sahelian annual grass. Previous studies have demonstrated its good skill for local (Tracol et al., 2006; Jarlan et al., 2005, 2008) to regional vegetation modeling through comparison to ground-data and satellite-based indices (Lo et al., 1995; Frison et al., 1998; Jarlan et al., 2002; Pierre et al., 2011).

The STEP model is based on two submodels describing the water budget and vegetation growth. The water module estimates soil evaporation (depending on the soil surface resistance) and plant transpiration following Penman Monteith's approach, runoff, drainage, and soil moisture. The latter is calculated with a tipping bucket approach using up to four soil layers (up to 3 m deep). Soil water content at field capacity and wilting point are derived as a function of soil texture. Seed germination is triggered by soil moisture of the upper soil layer, whereas leaf senescence is controlled by soil water content in the rooting zone.

Vegetation mass is calculated at a daily time step from a set of differential equations relating the different vegetation components (green, standing dry, and litter). Biomass increment results from photosynthesis, from which growth and maintenance respiration are subtracted, and tissue mortality. Photosynthesis depends on the fraction of Absorbed Photosynthetically Active Radiation (fAPAR), water stress, and temperature effect. At the end of the rainy season, senescence is triggered and results in a rapid conversion of biomass to standing straws.

Recent developments have added a detailed representation of the dry vegetation (straws and litter) dynamics, responding to meteorological and biotic factors, including grazing effects (Delon et al., 2015;