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Modeling vegetation and wind erosion from a millet field and from a rangeland: Two Sahelian case studies

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ABSTRACT

Quantifying wind erosion and dust emissions in the semi-arid Sahel remains challenging because of the large seasonal and interannual dynamics of surface properties. The increasing conversion of rangelands into croplands raises issues for quantifying wind erosion over these two contrasted surfaces. Whereas wind erosion models have been so far applied to these two surface types separately, this study proposes a common modeling approach to represent the horizontal flux from Sahelian rangelands and croplands. Pair simulations of both typical Sahelian land surface types investigate the horizontal flux due to wind erosion over a 3-year period for two instrumented sites in Mali and Niger. Two different vegetation models simulate the specific phenology and growth of a rangeland grass and a millet crop. These models also account for the local cropping and pastoral practices. Compared to field measurements, the vegetation cover is satisfyingly simulated by the models, especially the strong seasonal dynamics. Specific parameterizations of the aerodynamic surface roughness length (Z_0) as a function of vegetation variables are established using measurements from the two sites. The simulated horizontal flux turns out to be higher for a cropland than for a rangeland by approximately a factor 1.5, implying that increasing Sahelian cropped areas would increase dust emissions from the Sahel. This difference is mainly due to the time shift between grass and millet growth: the latter starts growing about 2–3 weeks later than annual grass. The amount of dry vegetation remaining during late dry season is also important for Sahelian wind erosion.

1. Introduction

Dust represents about 40% of the total amount of aerosols injected each year into the atmosphere (about 1.5 Mt yr^{-1}) (IPCC, 2007). It has strong radiative impacts (Tegen et al., 1997), both "direct" by absorption and scattering of the solar and telluric radiations, and "indirect" when acting as cloud condensation nuclei (Haywood and Boucher, 2000). When deposited, dust can provide significant amounts of nutrients such as phosphorus and iron to remote oligotrophic oceanic areas (Jickells et al., 2005) or like phosphorus and potassium in continental environments (Swap et al., 1992; Hermann et al., 2010; Breuning-Madsen et al., 2015). In the semi-arid dust source regions, wind erosion can also decrease soil fertility of already poor soils (Lyles and Allison, 1976; Bielders et al., 2002), and damage crops through abrasion (Sterk, 2003).

At a global scale, the link between human activities and dust emissions – which result from wind erosion – is now recognized (Boucher et al., 2013). Especially, changes in land use influence dust emissions in populated semi-arid areas like the Sahel, where the number of inhabitants has more than doubled over the past

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50 years. Meanwhile, according to many authors, Sahelian dust emissions increased during the early 20th century and started decreasing from the late 1980's on (Moulin and Chiapello, 2006; Foltz and McPhaden, 2008; Mahowald et al., 2010; Cowie et al., 2013; Chin et al., 2014; Doherty et al., 2014; Ridley et al., 2014). Recently, Stanelle et al. (2014) inferred from simulations that dust emissions from the agricultural areas of Northern Africa (including the Sahel) had increased from 2.8 Tg yr^{-1} in 1880 to 8 Tg yr^{-1} today. At a quasi-continental scale, Mulitza et al. (2010) hypothesized that the sudden increase in dust deposition off the West African coast about two centuries ago was linked to the onset of commercial agriculture in the Sahel. However, the relative roles played by climate change and human activities on Sahelian dust emissions are still debated, and no precise quantification of the dust emissions from this region is available (Tegen and Fung, 1995; Tegen et al., 2004; Mahowald et al., 2004; Pierre et al., 2012). At a more local scale, studies based on field measurements performed in the Sahel have provided estimates of wind erosion in croplands (Bielders et al., 2001a, 2004; Sterk, 2003), and rangelands (Tidjani et al., 2009). Several studies have suggested that wind erosion was significantly increased by cropping (Rajot, 2001; Bielders et al., 2002; Ikazaki et al., 2011), but studies on traditionally-managed crop fields are still scarce (Bielders et al., 2001b; Abdourhamane Touré et al., 2011). In addition, cropping (Sterk, 2003) and pastoral practices (Tidjani et al., 2009) can modulate wind erosion.

Until now, wind erosion modeling approaches have been developed for croplands and rangelands separately (Li et al., 2014). However, a common approach would help estimating wind erosion on these typical Sahelian surfaces, and their differences in terms of amounts and temporal dynamics. Another issue consists in representing the impacts of pastoral and cropping practices on wind erosion. The objective of this study is to model the horizontal fluxes of aeolian sediment of Sahelian croplands and rangelands with consistent modeling tools, and to discuss the differences of the simulated fluxes between these two surface types. Section 2 describes the data and the models development and setup. Results of the simulations are shown and evaluated in Section 3 and further discussed in Section 4.

2. Materials and methods

2.1. Study sites and data

The Sahel is characterized by a short rainy season lasting from approximately June to October, and a long dry season during the rest of the year (Lebel and Ali, 2009). Annual precipitation ranges from about 100 to 600 mm, allowing the growth of seasonal vegetation. Most of this rain is provided by a few mesoscale convective events, commonly accompanied by strong winds caused by systems outflows. The duration of these gusts ranges from a few minutes to more than one hour. Although the monsoon wind blows from South-West during the rainy season, the convective outflows are most often easterly winds, because convection mixes the African Easterly Jet down to the surface (Guichard et al., 2009). During the dry season, the Harmattan wind blows from North-East, while most plants wilt and progressively degrade. The main Sahelian land use is cultivation, usually with an alternance of cropping and fallowing periods over several years (e.g. Hiernaux and Turner, 2002), and grazing in the rangelands. After harvest, fields are open to grazing too.

Ideally, experimental sites would provide a full set of wind erosion measurements, meteorological data and soil description for pairs of cropped/non-cropped plots. Yet, experimental sites where both vegetation characteristics and wind erosion horizontal fluxes have been monitored are scarce in the Sahel, and no paired-experiment (monitoring vegetation and wind erosion over a cropland and a rangeland in the same area) has been documented so far. Given these constraints, two sites where at least some of these data were acquired have been selected (Table 1).

The first site is the Agoufou rangeland (15.3°N, 1.5°W), a study site of about 1 km^2 located in the Gourma area in Mali (e.g. Mougin et al., 2009). Agoufou is located in a typical pastoral Sahel area with annual rainfall averaging 350 mm. The dominant land use is extensive grazing. Numerous measurements were performed at this site during the AMMA campaign (Multidisciplinary Analysis of the African Monsoon): meteorological variables from a station and a rain gauge (wind speed, rain amount, temperature, and solar radiation), soil texture, and soil moisture at the same location. Wind speed has been measured at 3.5 m height using a cup anemometer. Wind data provided by a 3D sonic anemometer were available during part of this period. Grass measurements have been performed along 1 km lines at about 15 dates each year of 2006–2008, and livestock observations have been collected at the nearby (2.5 km) permanent pond in 2010–2011 (Diawara, 2015). For this study, years 2006–2008 are retained because of their good data sampling and their contrasted rainfall conditions.

The second site is a rectangular traditionally-managed millet field (about 100 m by 150 m) located in the Fakara region in Niger, in the vicinity of the village of Banizoumbou (13.5°N, 2.7°E). This site is fairly representative of agropastoral Sahel and receives 500 mm of annual rain on average. The millet field is embedded in a typical crop/fallow/rangeland mosaic, where fields are protected from grazing during the rainy season and open to grazing during the dry season. On this site, meteorological data (wind speed, wind direction, rain amount, air temperature), millet height during growth, crop residues cover fraction, and horizontal fluxes have been monitored from 2006 to 2008 (Abdourhamane Touré et al., 2011). Wind speed has been monitored at 4 heights

Table 1
Available datasets and their characteristics (temporal coverage, time resolution) for Agoufou and Banizoumbou (U: wind velocity; u_*: wind friction velocity).

	Agoufou (Mali)	Banizoumbou (Niger)
Wind	U at 3.5 m 2006–2008 15 min u_* part of 2005, 2006, 2007 5 min	U at 4 heights (0.35, 0.70, 1.20, 2.50 m) 2006–2008 5 min wind direction 2006–2008 5 min
Rain	2006–2008 15 min	2006–2008 5 min
Air temperature		
Solar radiation		2006 15 min
Soil moisture		No
Vegetation	Grass mass 2006–2008 43 dates	Millet height 2006–2008 39 dates during rainy season
Horizontal flux	No	2006–2008 daily