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Dust variability and land degradation in the Sahel

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- 1 Atmospheric mineral dust originating within the Sahara and its borders has become a major feature of the West African climate over the last decades. Dust frequency has often been regarded as one of the most important manifestations of desertification, and interest in this phenomenon has increased in recent years (Pye, 1987; Goudie and Middleton, 1992; N'Tchayi *et al.*, 1998; Ozer, 2000B). Mineral dust increase has many local to global environmental and human-related consequences, most of which are adverse. Mineral dust may play an important role in climate forcing by altering the radiation balance in the atmosphere through the scattering and the absorption of radiation (Andreae, 1996; Li *et al.*, 1996; Tegen *et al.*, 1996; Sokolik *et al.*, 2001). Dust outbreaks may also cause ocean cooling (Schollaert and Merrill 1998). It has also been suggested that mineral dust could affect climate indirectly by reducing rainfall production (Macleod, 1974; Maley, 1982). In addition, deteriorating particulate air quality is a serious health threat in the Sahel because it promotes respiratory infection, cardiovascular disease and other ailments (Coude-Gaussen, 1992; Prospero, 1999; WHO, 2000; Biolders *et al.*, 2001; Griffin *et al.*, 2001). Finally, large and intense dust events may provoke important economic losses when disturbing air traffic and are sometimes responsible for plane crashes due to low visibility (Adedokun *et al.*, 1989; Salama *et al.*, 1991).
- 2 They are a variety of methods for monitoring dust variability, including satellite imagery (e.g. Moulin *et al.*, 1997; Prospero *et al.*, 2002), and ground-based meteorological data (see Ozer, 2000B for a review). The latter method is the basis of this paper. Based on some fifty years of meteorological observations made in 28 synoptic stations of Senegal, Mauritania,

Mali and Niger, this article presents an overview of the dust evolution within the Sahel of West Africa and argues in favour of taking dust production as a synthetic climatic indicator of the global environmental degradation process in arid, semi-arid and dry sub-humid areas and, therefore, of desertification.

Long-term effects of drought and land use in the Sahel

- 3 The Sahelian region has always known an alternance of humid and dry periods (Maley, 1973; Nicholson, 1996, 1998; Boureima, 1992). During the 20th century, three large-scale droughts have affected the studied area. The first one occurred in the 1910s, the second in the 1940s and the last one, called the «big drought», which started in 1968 (Sircoulon, 1976; Lamb, 1982; Ozer and Erpicum, 1995; Morel, 1998) and lasted for about twenty to thirty years with extreme rainfall deficits (Jones and Hulme, 1996; Dai *et al.*, 1998; L'Hôte *et al.*, 2002). Figure 1 illustrates the rainfall evolution from 1921 to 1998 and underlines the extremely intense and long-term drought that affects all the Sahelian countries since the late 1960s. The application of the Pettitt (1979) statistical test on rainfall data of the last eighty years confirms the non-stationarity of the rainfall patterns between 1921-1968 and 1969-1998 periods. Rainfall decreased by 20-25% and almost 110 mm separate these two periods with average yearly rainfall of 488 and 381 mm respectively.
- 4 Mobilisation of soil material by wind is favoured if the land surface is composed of fine-grained, unconsolidated material sparsely covered by protective vegetation. On such potentially wind-erodible land surface, the lack of moisture resulting from drought conditions directly reduces the soil particles aggregation. Moreover, as drought persists, the resulting reduced vegetation will have an effect on the erodibility of the soil (Fryrear, 1995).

Figure 1. Yearly rainfall evolution within the Sahel from 1921 to 1998. Presentation of the three periods used for the study of dust production.

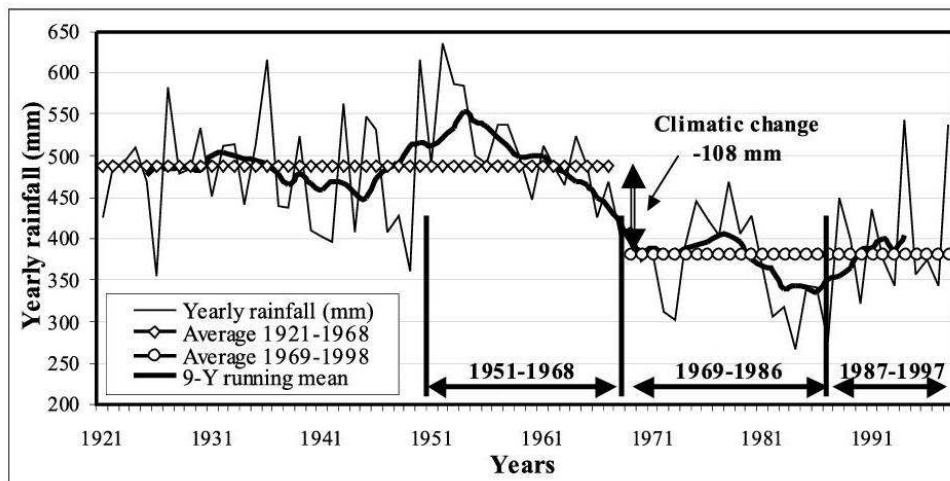


Figure 2. Distribution of the dusty days frequency during the [A] «humid» (1951-1968), [B] drought (1969-1986) and [C] «present» (1987-1997) periods.

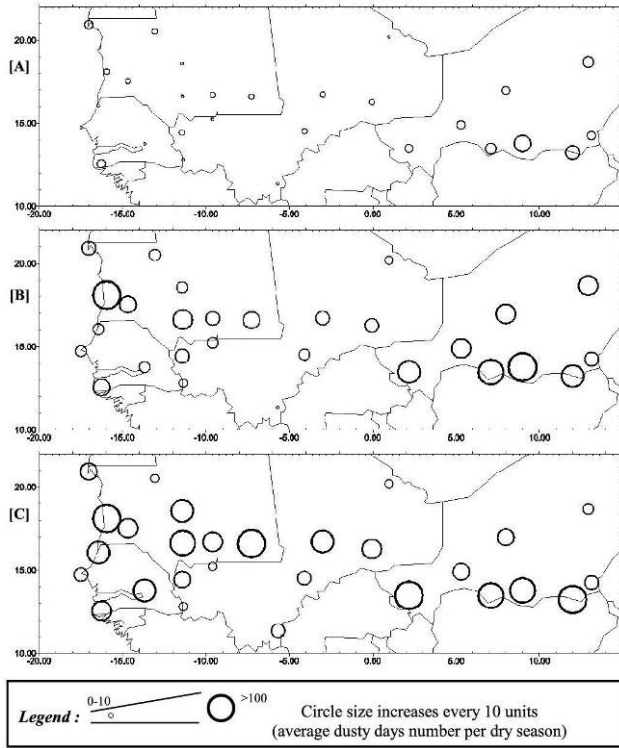


Figure 3. Distribution of the deflation events frequency during the [A] «humid» (1951-1968), [B] drought (1969-1986) and [C] «present» (1987-1997) periods.

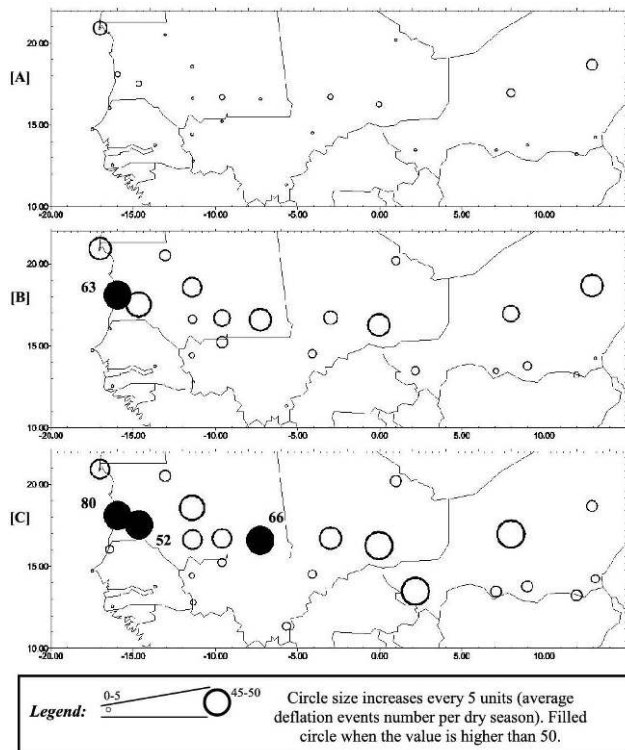
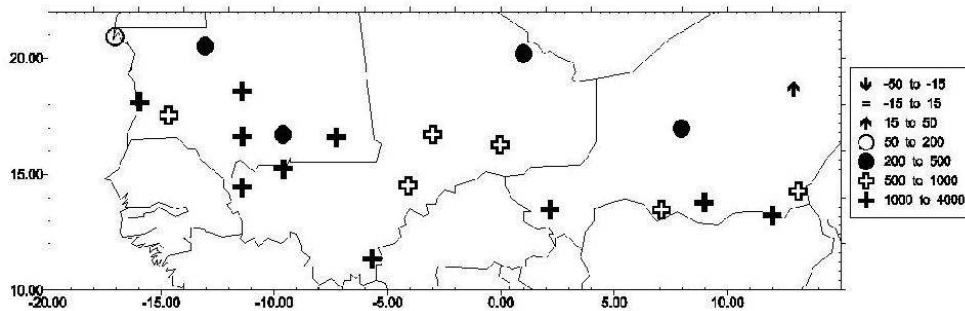


Figure 4. Evolution of the deflation frequency between the «present» (1987-1997) and the «humid» (1951-1968) periods.



THE LEGEND SHOWS THE EVOLUTION (%) BETWEEN THESE TWO PERIODS.

- 5 These effects can be exacerbated by several adverse human actions on the environment. Larger causes are well known and reported in the literature (Mainguet, 1991; Middleton and Thomas, 1997). Pastoralism provokes overgrazing which can lead to a reduction of the protective vegetation cover. Poverty leads to the collection of wood for fuel and construction also resulting in the reduction of the protective vegetation cover. Agriculture plays also a role as tilling of soils breaks down soil aggregates, thus increasing its wind erodibility. In the fragile Sahelian belt, the rapid expansion of human and animal population broadly started in the beginning of the 20th century with the colonialist period and the progresses of medicine (Thomas and Middleton 1994). Much before the onset of the drought, slow land degradation processes and higher vulnerability of the Sahelian region to desertification resulted from anthropogenic pressure on the environment. This pressure was mainly driven by overgrazing and destruction of woody vegetation for cropping extension purposes. This land degradation was noticed by increasing soil surfaces suffering from wind erosion and new dunes development (Stebbing, 1935; Aubreville, 1949; Tricart, 1954, 1959; Dresch and Rougerie, 1960; Grove, 1960; Prescott and White, 1960). Later on, along with severe drought conditions, these anthropogenic factors have dramatically increased. In the Sahel, a 3.2% yearly increase of human population is currently observed (1999-2000); about one more million inhabitants per year. Due to the increased sedentary population, pressure on cultivated land has led to a shortening of the fallow period in the shifting cultivation cycle and to the extension of cropping (multiplied by 3.4 in Niger since 1961 (Ozer, 2002)) into the more precarious drier regions. Nomadic pastoralists were deprived of some of their best grazing lands as the cultivators moved in leading to concentrated effects of overgrazing in many areas.
- 6 Destruction of woody vegetation has been hastened by the ever-increasing need for firewood to meet the demands of the larger population (Thomas and Middleton, 1994; Benjaminsen, 1996; Chamard and Courel, 1999). Many other reasons drive deforestation, among which the expansion of cropped land and pasture and the settlement expansion (Geist and Lambin, 2001). The destruction is especially noticeable around the rapidly growing urban centres, where the circle of deforested lands gets larger every year. About 95% of the woody vegetation has disappeared around Niamey since 1972 (Späth, 1997). A similar evolution is noticed around Bamako (Mainguet, 1991) and other main urban centres of the Sahel (Thomas and Middleton, 1994). The effects of the sedentarisation of nomad populations have also dramatically increased the wood demand for building houses (Giazzi, 1994; Gravier, 1996A, 1996B). In recent years, such urban population needs

in wood have led to the development of a new commerce of firewood which is currently leading to wood cutting far away from large cities. Many protected forests have totally disappeared in Senegal and in Niger (Chamard and Courel, 1999; CNEDD, 2000).

- 7 Desertification is a long-standing problem even in the absence of droughts. The exploding population in these developing countries means that land pressures will continue to build up and that less degraded areas will face soon or later a gradually increasing vulnerability of the land due to desertification processes (Wickens, 1997). In the Sahel, large-scale estimates over long-time series of the extent of land degradation are extremely unreliable and subjective. Studies using low resolution satellite data do not show any substantial change in vegetation cover in the past twenty years or so (Tucker and Nicholson, 1999). However, most localised studies combining aerial photos of the 1950s and more recent high-resolution satellite images clearly show an undeniable environmental degradation. Such studies suggest that wind erosion is the most important geomorphologic feature illustrating the importance of land degradation in the past fifty years. Most of the dunes fixed by the vegetation until the mid-1970s are now one the move (Salama *et al.*, 1991; Karimoune, 1994; Lindqvist and Tengberg, 1994; Herrmann *et al.*, 1997; N'Djafa Ouaga and Courel, 2000; Mainguet *et al.*, 2001).

Data and methods

- 8 Dusty days frequency was initially suggested by Rapp (1974) to assess the evolution of wind erosion magnitude. Such proxy-data is now recognised by the scientific community to be one of the major indicators for the desertification process survey (Berger, 1996). Some remote sensing sensors are able to track dust clouds world-wide. Although satellite images can be used to map the global distribution of major atmospheric dust sources, such data do not provide any information on dust production during pre-drought conditions as they are available since the early 1980s (Moulin *et al.*, 1997; Prospero *et al.*, 2002).
- 9 Meteorological observations permit the study of the dusty days frequency on a long-term period. This method was successfully applied in Australia (McTainsh and Pitblado, 1987), in the United States of America (Gillette and Hanson, 1989) and in other regions of the world (Goudie and Middleton, 1992). Surprisingly, no such study was done in the Sahel on long time periods except at the country level in Mauritania for the 1951-1990 period (Nouaceur, 1999) and in Niger for the 1951-1998 period (Ozer, 2002).
- 10 The evolution of dust production frequency is analysed during the dry seasons, extending from October to April, for the 1951-1952 to 1997-1998 period. The dry season was selected because it is not influenced by any change in the rainfall patterns. Data on dust conditions were taken from the 3-hourly synoptic observations archived at the meteorological offices of Senegal, Mauritania, Mali and Niger. Meteorological data from 28 synoptic stations are used. The international synoptic surface observation code (SYNOP code) (WMO, 1992) allows the identification of four classes of dust-related conditions:
1. blowing dust: dust being raised from the ground at the time of the observation (07, 08) and reducing horizontal visibility to less than 5 km;
 2. dust storms: with various degrees of intensity (09, 30, 31, 32, 33, 34, 35, 36) reducing horizontal visibility to less than 1 km;

3. dust haze: dust suspended in the air but not being raised from the ground at the time of observation (06, presumably remnants of earlier deflation events), reducing horizontal visibility to less than 5 km; and
 4. haze: suspension in the atmosphere of extremely small, dry particles which give the sky an opalescent appearance (05) and reducing horizontal visibility to less than 5 km.
- 11 Further information on dust related conditions used in the literature can be found in Epicum and Ozer (1999) and Ozer (2000B). The purpose of this paper is to analyse the evolution of [i] all these dust-related conditions together (1-4) which will be referred in this paper as dusty events, and [ii] the deflation events alone (1-2), that is to say direct local wind erosion (blowing dust and dust storms).
- 12 The long-term database allows the analysis of the dust related conditions over two contrasting climatic periods of 18 years (Fig. 1). The «humid» period (1951-1968) which was relatively wet and the period of drought (1969-1986) during which nearly every year has been anomalously dry. The 1987-1998 period, named «present» period, was still affected by a chronic rainfall deficit, but without an intense period of drought. This latest period is interesting because some studies suggest that the Sahara desert contracted after the severe drought of the early 1980s (Nicholson *et al.*, 1998; Tucker and Nicholson, 1999). This would suggest that less sources of dust were available.

Results

- 13 Dusty days frequency are plotted on maps (Fig. 2) for the three reference periods. During the «humid» period (1951-1968), dusty days frequency is very low all over the studied area. One exception however is noted in southern Niger which is under the influence of the Bodélé depression, represented here by Bilma (13°E,18°N) in northern Niger, that has always been recognised as the most important dust-raising area of the Sahara Desert (Kalu, 1979; McTainsh, 1980; D'Almeida, 1986; Brooks and Legrand, 2000; Middleton and Goudie, 2001). The contrast between the «humid» (1951-1968) period and the two following ones is evident. The analysis of average dusty days frequency between the drought (Fig. 2B) and the «humid» (Fig. 2A) periods shows a regional increase in all of the 28 stations. Later on, during the «present» period (Fig. 2C), the trend is still on the rise. Some exceptions can be observed in northern stations where dust frequency is broadly stable or slightly decreasing. One explanation could be the weakened wind patterns during the late 1980s and the 1990s as suggested by Stengel (1992) and Ozer (1998).
- 14 In short, between the «humid» (1951-1968) and the «present» (1987-1997) periods, the dusty days frequency has constantly increased up to a factor 10 all over West Africa, except at some hyper-desertic synoptic stations. This increase is mainly taking place in longitude, from east to west as well as in latitude, from the hyper-desertic areas southwards through the Sahelian and Sudanese belts.
- 15 The evolution of the deflation events frequency shows a very important augmentation all over the Sahel (Fig. 3). During the «humid» period (Fig. 3A), the geographical distribution of the deflation events fits well with all the geomorphological and climatic literature relative to the period preceding the drought (Dubief, 1943, 1952; Capot-Rey, 1952, 1957; Grove, 1958; Wilson, 1971, 1973; Mainguet *et al.*, 1979; Karimoune, 1994). Two desert areas, represented here by Bilma (13°E,18°N), northern Niger, and Nouadhibou (17°W,21°N), north-western Mauritania, are clearly the two dust production zones in the studied area.

South of the 150 mm yr⁻¹ precipitation isoline (between 15°N and 17°N, see Grove 1958), all dunes were described as fixed by the vegetation. At the time, very few dust clouds were generated in the Sahel.

- 16 A strong augmentation of the deflation events frequency is noticed during the drought period (Fig. 3B). Broadly all the northern Sahelian belt, north of 16°N, has become a large dust-raising area. It seems clear that the effects of drought, reducing soil moisture and vegetation cover, are mainly responsible of this new geographical distribution of wind erosion processes. Moreover, one can see that the largest increase in blowing dust and dust storm events occurred in Nouakchott, exploding new capital of Mauritania. The population of this city rose from 6000 to 535 000 inhabitants between 1962 and 1988 (Salama *et al.*, 1991) and should reach one million people these days. This underlines the role of anthropogenic land degradation in dust production. Over all the studied area, the deflation events frequency has increased, at least, by a factor of five in 12 stations out of 28.
- 17 This tendency on the rise is confirmed during the so called present period (1987-1998). Figure 3B shows that northern Sahel is definitely the main zone of mineral dust production in the atmosphere of West Africa. Most synoptic stations recorded a new increase of wind erosion processes when compared to the drought period. In southern Sahel, like in Niger, the deflation events frequency is still moderated but becomes close to what is observed in the Sahara Desert, in Bilma.
- 18 The evolution of dust generation processes is synthesised in figure 4 which shows the differences in percent in deflation events frequency between the «humid» and the «present» periods. This frequency has increased all over the studied area. In one station out of two, deflation events frequency has been multiplied by ten. This trend is generalised in all stations of the Sahel, while dust production events in northern stations are broadly stable or slightly increasing. Under Sudanese climate (yearly rainfall >800 mm), as in Sikasso (06°W,11°N), in southern Mali, some wind erosion is observed in recent years but remains very limited (less than five deflation events per dry season).
- 19 This dramatic increase of the deflation events clearly shows the advanced state of soil degradation in the Sahelian belt and is in accordance with all environmental and geomorphological observations found in the literature. Most northern Sahelian stations are currently experiencing more deflation events than those in desert areas. Our results, based on long-time series of field observations, confirm and support recent conclusions of Tegen and Fung, 1994, 1995; Tegen *et al.*, 1996; and Andreae, 1996, based on some complex models.

Discussion

- 20 Mean annual rainfall, rainfall fluctuations, type of vegetation and its percentage soil cover, physical soil properties, and soil crusts are considered to control the intensity of the aeolian processes. Those are presented hereafter and discussed with a Sahelian perspective.
- 21 On a world-wide basis, it is admitted that wind erosion processes are determined by the degree of aridity (Goudie, 1978; McTainsh *et al.*, 1989; Brazel, 1989). Goudie's (1983) results suggest that dust storm frequency peaks in semi-arid areas where yearly rainfall is between 100 and 200 mm. Results obtained for deflation events frequency during the

1951-1968 period (Fig. 3A) do not support this hypothesis as mainly desert environments with mean annual rainfall below 50 mm were productive. At the time, in absence of drought and adverse human activities, the 100-200 mm yearly rainfall belt did not experience much wind erosion processes.

- 22 In addition, it is widely accepted that dust production in the Sahel is controlled in major part by rainfall fluctuations (Prospero and Nees, 1977; Goudie, 1978; Bertrand *et al.*, 1979; Middleton, 1985, 1989; McTainsh *et al.*, 1989; Goudie and Middleton, 1992; N'Tchayi *et al.*, 1994). Bertrand *et al.* (1979) and Middleton (1989) found, analysing short databases not exceeding 20 years, that dusty days frequency is closely linked to the average annual rainfall over the previous three years. Although such assumptions may be realistic in undisturbed environments, the reality observed in figure 3 shows that the Sahelian belt is currently experiencing more deflation events than during the period of drought. However, the late 1980s and the 1990s have been more humid than the 1969-1986 period (Fig. 1) and recent studies suggest that the drought period could be over since the early 1990s (Sene and Ozer, 2002). Our findings suggest that a long-term (10 to 15 years) rather than a short-term (1 to 3 years) correlation between rainfall and dust production exists. This would mean that wind erosion processes are more likely dependent on the long-term environment change due to the vegetation response to the drought and to the increasing anthropogenic degradation than directly on the rainfall variations.
- 23 The type of vegetation and its percentage soil cover have an important role in dust generation (Fryrear, 1995; Musik *et al.*, 1996; Lancaster and Baas, 1998; Musik, 1999). These two parameters have been seriously reduced over the last 30 years characterised by severe and prolonged drought and by intensified human pressure on the environment (Chamard and Courel, 1999; Valentin and d'Herbes, 1999). This obviously facilitated the aeolian processes in the study area. The degradation of the ecosystems is such that their regeneration should take several years or even some decades to come back to the pre-drought state (Le Houerou, 1993; Karimoune, 1994; Warren, 1996).
- 24 Evidence exists that physical properties of the soils and particularly the soil crusts protecting the soil from the wind erosion are disturbed by intensified land use such as overcropping, overgrazing and stepping (Nickling and Gillies, 1993; Coude-Gaussen *et al.*, 1993; Valentin, 1994; Karimou Ambouta *et al.*, 1996).
- 25 It is therefore very likely that the increasing deflation events frequency in the study area reflects the combined effects of the long-term rainfall reduction started in the late 1960s and the anthropogenic negative impacts on the environment through inappropriate land-use practices such as overexploitation of soils for agriculture purposes, deforestation, overgrazing, migration of populations to the south or to urban areas, settlement of nomad populations, etc. However, it is very complex to quantify the role of natural and human-related aspects in dust production in West Africa. It is probable that wind erosion processes have progressively increased as a result of intense rainfall deficits in the early 1970s. Later, the deflation events frequency has reached previously unrecorded levels because of the always increasing anthropogenic mismanagement of the environment. For future perspectives, such stating suggests that eventual wetter conditions in the Sahel would not lead to a direct substantial reduction of dust production. Indeed, vegetation will need from several years to few decades to be as healthy as forty years ago. Moreover, the human pressure on its immediate or even remote surrounding environment seems ineluctable and should negatively influence the vegetation natural recovery (Wickens, 1997; Ozer, 2000B).

- 26 Derived effects of increasing atmospheric dust are numerous and sometimes emerging. Many of them were described in the introduction but within northern Sahel, local population displacements are caused by derived impacts of wind erosion processes such as lower productivity of soils, decrease of crop production, oases and villages threatened by moving dunes, disrupt local social and economic structure. This becomes one additional impediment for developing affected countries. These populations usually move towards large cities or further south where the situation is less precarious and the environment less degraded. These migrations contribute to the acceleration of the environmental degradation processes. This leads to the onset of dust production, uncommon in the past.

Conclusion

- 27 Over the last decades, it has been recognised that dusty events frequency analysis was one of the major indicators to assess the evolution of the desertification process. This article proposes the use of deflation events (blowing dust and dust storms) to estimate the trend in direct local wind erosion. As wind erosion depends on the state of the environment, the recognition of dust frequency is suggested as a relevant synthetic climatic indicator of the progressive degradation of the environment and, thus, of desertification in the arid and semi-arid environments. This indicator is available at the global scale for long-term periods of observations. Its application should help decision-makers estimate the trend of desertification which is, in many countries, one of the most severe impediments to poverty reduction, quality of life of local populations improvement and sustainable development.

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ABSTRACTS

Since the late 1960s, West-Africa is affected by the most severe and prolonged drought of the 20th century. In addition intensified anthropogenic environmental degradation processes are progressively leading to a widespread desertification of the study area. This paper presents and discusses the evolution of dusty events and deflation events variability since 1951. Deflation events frequency is proposed as a climatic indicator to assess the trend of land degradation in arid and semi-arid areas within the Sahelian context.

Depuis la fin des années 60, l'Afrique de l'Ouest est en proie à la plus sévère et la plus longue sécheresse du XX^e siècle. En outre, l'intensification de processus anthropogéniques nuisibles à l'environnement induit peu à peu une vaste désertification de la zone d'étude. Cet article présente et analyse l'évolution des phénomènes générateurs de poussières et de la variabilité des épisodes déflatoires depuis 1951. La fréquence de ceux-ci est proposée comme indicateur climatique dans l'évaluation de la tendance du sol à la dégradation dans les zones arides et semi-arides du Sahel.

INDEX

Mots-clés: production de poussières, érosion éolienne, désertification, indicateur, Sahel

Keywords: dust production, wind erosion, indicator

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