DUST VARIABILITY OVER NORTHERN AFRICA AND RAINFALL IN THE SAHEL

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Abstract

The Infra-Red Difference Dust Index (IDDI) is a new dataset that uses reductions in atmospheric brightness temperature (derived from METEOSAT IR-channel measurements) to map the distribution of mineral aerosols over continental Africa. The IDDI dataset is described, and the IDDI data are used to identify the major African dust sources, located in the Sahel-Sahara zone. The seasonal variations in these sources are discussed. Annual, seasonal and monthly dust indices are constructed from the IDDI data for different latitudinal zones in the Sahel-Sahara zone. The temporal and spatial variability of dust production in the Sahel and Sahara is inferred from these indices and the latitudes of maximum dust production are identified. Interannual variability of dust production is described in conjunction with a consideration of variations in annual rainfall over the Sahel. Relationships between rainfall and subsequent dust production in the Sahel are investigated by correlating zonally averaged rainfall and IDDI values at lags of one and two years.

The spatial and temporal patterns of dust production suggest that spring and summer deflation is associated with the passage of convective disturbances across the Sahel. There is evidence that wet-season rainfall totals have an impact on dust production in the later part of the following dry season. The results also suggest a cumulative impact of rainfall on December dust production. However, there is no evidence from this study that dust production is associated with widespread land degradation.

KEY WORDS: dust, rainfall, Sahel, Sahara, variability

1. Introduction

The Sahel is the semi-arid transition zone between the Sahara desert and humid equatorial Africa. It is characterised by a steep north-south temperature gradient and high interannual rainfall variability. The timeseries of spatially aggregated rainfall anomalies for the Sahel (Figure 1) suggests that the region has experienced a desiccation since the late 1960s. Rainfall has been below the regional twentieth century mean for most years since 1968. Large rainfall deficits in 1972 and 1973 contributed to famine in the Sahel, and the largest rainfall deficit this century was associated with the Ethiopian famine of 1984. In both of these cases the impact of drought was exacerbated by other factors.

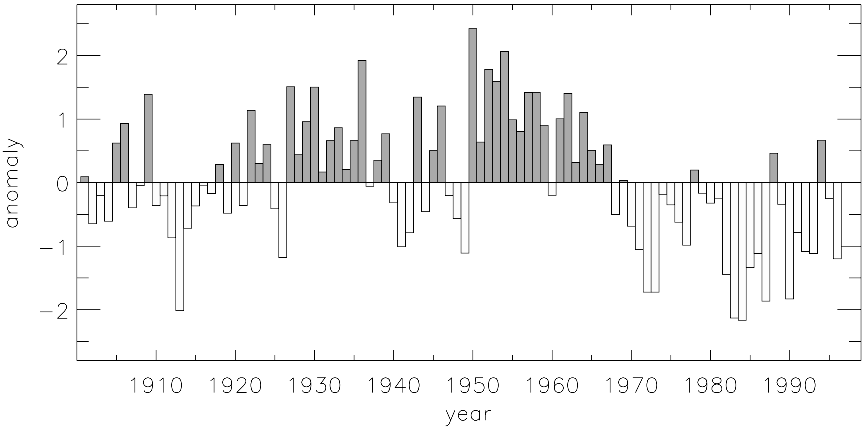

Figure 1: Standardised rainfall anomalies for the spatially aggregated Sahel, liberally defined as the region from the West African coast to 30°E and between 10° and 20° N. Anomalies are calculated with respect to the twentieth century mean. Based on the dataset of New *et al.* (1999).

West African visibility data indicate that levels of atmospheric dust over the Sahel throughout the year have increased dramatically since the 1950s, and it has been suggested that dust loadings over the Sahel now exceed those over the Sahara (N'Tchayi *et al.*, 1994, 1997). Middleton (1985) found an increase in dust storm activity in certain parts of the Sahel during drought years. Prospero and Nees (1986) reported elevated dust concentrations in the atmosphere over the North Atlantic after the deficient wet seasons of the early 1970s. More recently, Tegen and Fung (1995) and Tegen *et al.* (1996) have suggested that 30-70% of the global mineral aerosol budget is the result of deflation from soils which have been degraded by climate change and/or human activity. They invoke human activity in the Sahel, and a climatic shift in the boundary between the Sahel and Sahara, as major factors in determining the global atmospheric dust budget. These studies have resulted in the widely held opinion that dust production in northern Africa has largely shifted from the Sahara to the Sahel as a result of climatic desiccation and inappropriate land-use practices. Until now, it has been difficult to assess such assumptions using observational data as such data have been somewhat limited in spatial extent. However, a new proxy dust-loading dataset for continental Africa now exists, based on METEOSAT infra-red channel measurements. This dataset is known as the Infra-Red Difference Dust Index (IDDI). While the IDDI detects any aerosols which reduce the infra-red radiance at the top of the atmosphere, it may be interpreted in terms of dust concentrations over the arid and semi-arid regions of northern Africa, where mineral dust is the dominant atmospheric aerosol.

The IDDI dataset has been used in a preliminary investigation of spatial and temporal dust variability over the Sahel-Sahara zone of northern Africa (i.e. Africa north of the Equator). This paper presents results detailing the spatial and temporal variability of atmospheric dust loadings for the period 1984-1993. Spatial variability and seasonality are addressed via a visual analysis of dust/IDDI fields. A more quantitative presentation of seasonality and meridional variation in dust production is achieved by plotting mean monthly IDDI values, spatially averaged over different latitudinal zones, against time. A qualitative interpretation of dust variability in response to rainfall is presented, followed by a discussion of correlations between wet-season rainfall and subsequent dust loadings as represented by zonally averaged IDDI values. The short length of the IDDI time series means that many of the conclusions are speculative. However, a consideration of the results within the context of existing knowledge enables a plausible conceptual model of rainfall influences on dust production to be constructed.

This study concentrates on the aerosol signal in the IDDI fields over the Sahel-Sahara zone, because of the recent changes in observed dust concentrations and also because this region contains the major African dust sources. We may also be confident that signals in the IDDI fields over the arid and semi-arid regions of northern Africa are the result of the episodic transport of dust (see below). However, IDDI signals over other parts of Africa are also discussed where appropriate. Possible explanations for the presence of strong signals in the IDDI data where dust is unlikely to be a major atmospheric constituent are presented.

2. The Infra-Red Difference Dust Index

The IDDI dataset has been developed at the Laboratoire d’Optique Atmosphérique at the Université des Sciences et Technologies de Lille, France (Legrand *et al*., 1994). IDDI data represent the reduction in the measured infra-red (IR) brightness temperature (BT) of the atmosphere from that which would result from an aerosol-free atmosphere. Brightness temperature values are derived from METEOSAT IR-channel radiometric count measurements taken daily at approximately 11:30 UTC. Fields of maximum brightness temperature over non-overlapping 15-day periods are constructed. Fields of differences between these composite fields and daily brightness temperature fields within each 15-day period are then calculated. The resulting difference fields are divided into 10x10-pixel boxes and a statistical algorithm based on the spatial coherence method (Legrand *et al*., 1994) is used to classify pixels as cloudy or non-cloudy. Cloudy pixels are assigned a cloud-masking code, and the remaining pixels represent the IDDI values, where brightness temperature reductions are due to the presence of aerosols alone.

The IDDI signal results from the reduction in the temperature of the underlying land surface by reduced solar insolation (resulting in less emitted IR radiation), and also from the attenuation of the outgoing longwave radiation (OLR) by the aerosol layer. Attenuation of OLR will be greatest when the aerosol particles have effective diameters of the same order of magnitude as the wavelength of the radiation, i.e. of the order of 10 μm. Sub-micron particles are transparent in the infra-red (Maley, 1982). Theoretical considerations and recent, as yet unpublished, modelling studies (Legrand, pers. comm.) indicate that, in the case of mineral aerosols, small dust particles (< 1 μm) cause the greatest reduction in daytime temperatures, while coarse dust causes the greatest daytime reduction in IR radiance at the top of the atmosphere (TOA). The strongest signals in the IDDI will therefore result from dust events with a high proportion of large (~ 10 μm) particles, although events comprised of small particles in high concentrations will be detected due to the reduction in emitted IR radiation from the cooler surface.

The IDDI data are converted to a 1° latitude x 1° longitude geographical grid, and exist over land regions only. The geographical coverage extends from 35° south to 38° north and 18° west to 45° east, covering all of Africa and parts of the Middle East (see Figure 2). The dataset will be updated to the present day in the near future.

The IDDI data have been validated against ground-based visibility and aerosol optical depth (AOD) measurements at a number of sites throughout West Africa (Legrand *et al*., 1994). During these validation studies, it was found that IDDI values correlated well with near-surface visibilities. IDDI values of 5 K and above corresponded to dusty conditions, when visibility was reduced below 10 km, and values of 10 K and above corresponded to severely dusty conditions, with visibility reduced below 5 km. IDDI images have also been compared with fields of AOD over the eastern tropical Atlantic in order to verify continuity across the West African coast.

Nonetheless, there are several potential pitfalls to be considered when interpreting the IDDI data. The detection of aerosols depends on the variability in their concentration. If concentrations are generally elevated over the whole of the 15-day reference period, they will be interpreted as part of the “clear-sky” background, reducing the BT values of the reference field. Long-term dust haze is therefore unlikely to be detected. A similar problem may occur over regions which are covered by cloud throughout the reference period. Long-term cloud cover will result in misleading reference values, and may also affect the efficiency of the cloud-detection algorithm, leading to the erroneous identification of cloud as IDDI (i.e. aerosol) data. Over very cloudy regions such as those near the Equator, the IDDI data may be unreliable due to this “cloud contamination”. Problems may also arise where low, relatively warm, clouds are present; these may be identified as aerosols, resulting in large IDDI values.

Also to be considered is the presence of aerosols resulting from biomass burning, which is widespread throughout much of Africa in the dry season. Such aerosols typically have dimensions of less than 2 μm (Artaxo *et al*, 1994); they will have some impact on the OLR, but their dominant effect will be one of cooling of the land surface. These particles should therefore have a similar effect on the measured TOA radiance to fine dust aerosols. However, because of the extent of burning, they may constitute a constant smoke haze lasting for periods of days to weeks, resulting in their not being detected in the IDDI fields, but rather being incorporated into the reference fields.

The above considerations notwithstanding, the IDDI data represent a useful semi-quantitative measure of dust loadings over the arid and semi-arid regions of Africa. Over the Sahara and Sahel, dust events are highly episodic and contain high proportions of aerosols large enough to strongly attenuate the OLR, resulting in strong IDDI signals. The incidence of cloud over these regions is low enough to present no significant problems of cloud contamination. The issues of biomass burning aerosols and fine dust haze are discussed in more detail below, although these features do not appear to inhibit the detection of episodic dust events over the main regions of interest in this study, which lie north of 10º N.

To date, IDDI fields over the Sahel and Sahara have not been converted to AOD values, and cannot be interpreted in terms of specific volumes of dust or thicknesses of dust layers. The reduction in brightness temperature due to dust aerosols will depend on the vertical distribution of the dust, the particle density and the particle size distribution, as well as the reflective properties of the underlying surface. Nonetheless, IDDI fields reliably reflect the distribution and abundance of atmospheric mineral aerosols over northern Africa, and exhibit a sufficient degree of spatial and temporal invariance to be used in studies of large-scale dust mobilisation and transport (Legrand *et al*., 1994).

3. Distribution of Saharan and Sahelian dust sources

It may be assumed that dust concentrations and particle sizes will be greatest closest to dust source regions. Fields of IDDI data may therefore be employed to identify the major source regions throughout Africa. Use of different averaging periods enables the temporal variation in the activity of dust sources to be analysed. The major dust sources in northern Africa have been identified in this fashion by Legrand *et al*. (1994). This section elaborates on their description, within the context of other studies of dust sources and climatological considerations of known or likely dust mobilisation processes. Discussion of the major dust sources is restricted to northern Africa, focussing on the Sahelian and Saharan zones.

Monthly mean IDDI fields were created by averaging daily IDDI fields for cells where fewer than eighty per cent of days were classed as cloudy. Over most of the Sahel-

Sahara zone, where cloud is scarce, this approach results in continuous spatial coverage in the monthly fields. Annual mean IDDI fields were created for each year by averaging the monthly mean fields over twelve-month periods. Seasonal mean fields were created by averaging the monthly fields over shorter periods for each year. Mean annual, seasonal and monthly fields were created by averaging the yearly fields over the period 1984-1993. The mean annual IDDI field for 1984-1993 is shown in Figure 2.

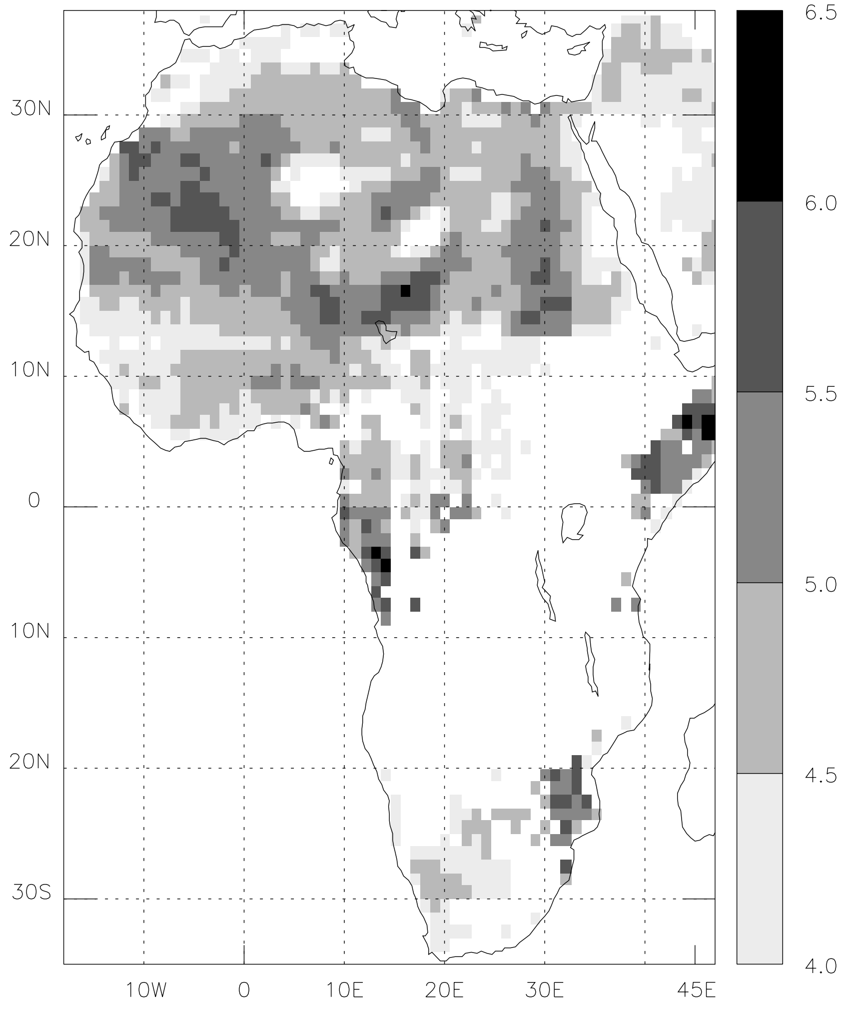

Figure 2: Annual average dust production over Africa as indicated by time-averaged IDDI values for 1984-1993. High IDDI values indicate large atmospheric dust loadings. White areas represent regions where cloud is too frequent to produce meaningful average IDDI values. Scale in Kelvin.

Three broad regions in which IDDI values exceed 5 K are apparent. This threshold is arbitrary, but delineates distinct zones within which mean dust levels are elevated above the background. Further detail within these zones is apparent in the form of areas with IDDI values in excess of 5.5 K. These regions are interpreted as coinciding broadly with areas containing dust sources. One such region is the north-central Sahel, between about 5° E and 20° E, and 13° N and 18° N. Two maxima are apparent within this region, centred approximately at 16° E., 17° N and 9° E, 15° N. The former maximum extends over parts of the Erg of Bilma and the alluvial plain northwest of the town of Largeau in Chad. This region has been identified as an important dust source by other authors (e.g. McTainsh, 1980; Drees *et al*., 1993). The latter maximum lies to the south of the Aïr Mountains in Niger, in the vicinity of a region of enhanced generation of convective disturbances (Rowell and Mitford, 1992) which result in spring and summer dust mobilisation (Dubief, 1979; McTainsh, 1996).

A second source region (or collection of sources), which may be labelled the West Sahara region, lies between about 7°-0° W and 20°-25° N. This area corresponds to a region that includes the Erg Iguidi and Erg Chech of northern Mali, northern Mauritania and southwestern Algeria. A nearby maximum in the IDDI field lies over a region of seasonal watercourses in the Morocco-Western Sahara border region. Dust transported large distances over the Atlantic and to Europe has been identified as originating in these regions (Reiff *et al*., 1986; Coudé Gaussen *et al*., 1987; Chiapello *et al*., 1997).

The third major source region extends from about 13° N to 25° N, and some 1° to 3° either side of the 30° E meridian, from northern Sudan into southern Egypt. Hereafter this is referred to as the East Sahel-Sahara region. This region is characterised by the Haboob dust storms of the Nile Valley (McTainsh, 1996), and dust from the northeastern Sudan has been transported to the eastern Mediterranean (Middleton, 1986, 1997).

A minor region of activity is indicated by high IDDI values over a small area centred on 14° E, 22.5° N, between the Plateau de Djado in northern Niger and the Idhan Murzuq erg in southwestern Libya. This region is hereafter referred to as the northern Niger region.

All the source regions identified above are characterised by fields of sand dunes or seasonal watercourses, or both. This suggests that erodible material is supplied by dune fields or by water erosion, or a combination of the two. The source region near the Aïr Mountains extends into the zone of degraded soils as suggested by UNEP (1992), suggesting that land use and climatic desiccation of soils may be partly responsible for deflation in this area. However, the region is dominated by numerous water channels and few permanent human settlements, suggesting that water erosion is an important factor in providing erodible material.

Also present in the annual field are strong IDDI signals over the Horn of Africa, west-central Africa and southeastern Africa. The two former regions exhibit IDDI values as high or higher than the highest Sahelo-Saharan values. Dust transport over the Horn of Africa is associated with the Asian Monsoon circulation in summer (Husar *et al.*, 1997). The west-central African signal is unlikely to be due to dust aerosols, while the reason for the southeastern African signal is open to debate. The high IDDI values over these three regions are discussed further in Section 4, within the context of seasonal changes in the regional environment.

3.1. DUST SOURCES AND LAND DEGRADATION

The northern limit of the region characterised by land degradation is placed in the region of 17° N on soil degradation maps published by UNEP (1992). However, estimates of the extent of soil degradation in the Sahel are extremely unreliable and subjective (Warren, 1996; Williams and Balling, 1996). In the absence of reliable soil degradation data it is impossible to identify new dust sources arising from land-use practices or climatic desiccation, or to quantify the contribution of disturbed soils to the regional dust budget. However, soil degradation is likely to be minimal in regions of low rainfall and outside of the zone of rainfed agriculture, the limit of which is placed at the location of the 300 mm isohyet by WMO (1976). Fields of annual rainfall totals derived from the dataset of New *et al.*, (1999, not shown) indicate that the 300 mm isohyet lies to the south of 17° N. These considerations suggest that the 17° N latitude represents a reasonable and liberal (if somewhat arbitrary) working limit for the zone containing degraded soils. This limit will be employed when the role of soil-state in dust production is considered in Sections 5-8.

Examination of the mean annual IDDI field suggests that the major dust source regions in the Sahel and Sahara conform to the accepted, or “classical”, sources of dust, created by “natural” processes of sediment production and deflation. A possible exception is the source region in the north-central Sahel in the vicinity of the Aïr Mountains.

It is possible that material from anthropogenically degraded soils does not produce a strong signal in the IDDI data, resulting in an underestimation of the extent of the major source regions. Aerosols from degraded soils are likely to be very different in nature from those deflated from arid to hyper-arid desert regions. Dust consisting of such aerosols will contain more organic material and have a higher clay content, resulting in a high proportion of small (< 2 μm) aerosol particles (McTainsh and Walker, 1982). Organic material has been detected in dust deposited in Niger (Drees *et al.*, 1993) and northern Nigeria (McTainsh and Walker, 1982). However, it is not clear whether the organic input is due to the long-term desiccation of vegetated areas or if it is a long-term feature of the soil-dust cycle. As previously discussed, the IDDI signal from dust with a low mean particle size will be predominantly the result of surface cooling. McTainsh and Walker (1982) report a tendency for lower visibility and reduced solar radiation to be associated with finer mean particle sizes. The correlation of IDDI values with measured visibilities (Legrand *et al.*, 1994) suggests that the IDDI are capable of detecting such fine material. It is possible that such fine material from degraded soils exists as a semi-permanent dust haze throughout much of the year, in which case it would not be detected by the IDDI for the reasons outlined above. However, it is reasonable to suppose that episodic dust events would originate over such degraded land in the same fashion as over other regions, and as a result of the same atmospheric processes. This would be particularly true outside of the wet season, when the Sahara and Sahel are both subject to the Harmattan circulation. The lack of a regional signal in the IDDI data over the hypothesised regions of widespread land degradation (the vicinity of the Aïr Mountains notwithstanding) therefore calls into question the assumption that aerosols from degraded soils contribute significantly to the regional dust budget, and the budget of material exported from northern Africa (Tegen and Fung, 1995).

4. Seasonal variations in dust production and non-dust IDDI signals

Seasonally averaged fields of IDDI are presented in Figure 3. Again a threshold of 5 K delineates broad regions of dust activity, with further detail apparent in the form of IDDI values in excess of 6 K. While this analysis focuses on northern Africa, the structure of the seasonal IDDI fields in southern, eastern and central Africa is also discussed where appropriate.

In JFM the most active areas are the East Sahel-Sahara, the north-central Sahel and the northern Niger regions. A broad shift in dust activity from east of 5° E in JFM to west of 15° E in AMJ is apparent. The East Sahel-Sahara sources remain active in AMJ, although the geographical extent of IDDI values greater than 6 K is reduced. AMJ IDDI values are high over southern Morocco and western Algeria, and also in the western part of the north-central Sahara.

JAS represents the peak of the Sahelian wet season, when the surface discontinuity between the West Africa Monsoon airmass and the dry Saharan airmass lies at its northernmost limit, around 20° N in August (Hastenrath, 1991). IDDI values greater than 6 K are confined to the west of 5° E and between 17° N and 25° N. The southern limit of this zone is very distinct; the 4 K/5 K boundary occurs close to the 5 K/6 K boundary at approximately the same latitude from the West African coast to 7° E. This suggests that large dust loadings are prevented from occurring south of the northern limit of the monsoon rains, which extend to within several hundred kilometres south of the surface discontinuity (Hastenrath, 1991). The southern latitudes of this region coincide with an area identified by Rowell and Milford (1992) as a region of enhanced generation of convective disturbances or disturbance lines (DLs), encompassing the plains to the north of the Niger Bend.

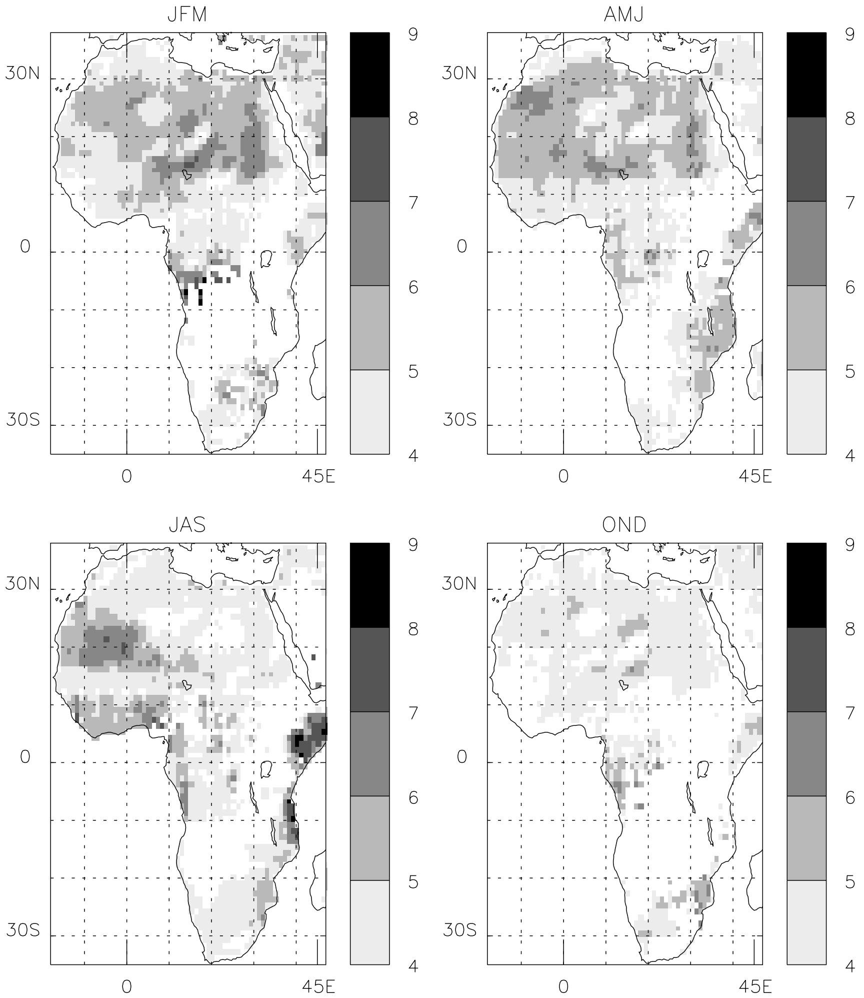

Figure 3: Major seasonal dust distributions over Africa for 1984-1993, represented by mean seasonal fields of IDDI values. High IDDI values indicate large dust loadings. Scale in Kelvin. White areas represent regions where cloud cover is frequent.

Another major feature of the JAS field is the region of very high IDDI values over the Horn of Africa in JAS. These values are considerably higher than the maximum values over the Sahel and Sahara. This signal over the Horn of Africa coincides with very high equivalent aerosol optical thickness (EAOT) measurements over the Arabian Sea (Husar *et al.*, 1997 – based on data from July 1989 to June 1991). The parts of Arabia visible in the IDDI fields exhibit low IDDI values, suggesting that dust transport over the Arabian Sea is predominantly from the Horn of Africa (Sirocko and Sarnthein, 1991). Mobilisation and transport of dust is aided by the East African (or Somali) low-level jet, which is active at this time of year as part of the summer monsoonal circulation (Hastenrath, 1991, Husar *et al*., 1997). Transport of dust over large distances occurs above the monsoon inversion, in a fashion analogous to the transport of Saharan dust above the trade wind inversion in the Saharan air layer (Kalu, 1979; Sirocko and Sarnthein, 1989). The OND field exhibits low IDDI values except in a small region within the north-central Sahel zone and another over northern Niger. Examination of the mean monthly fields (not shown) illustrates that dust loadings are lowest in November, and that the high-IDDI regions in the OND field are due to the “switching on” of sources in these regions in December.

The major IDDI signals outside of the regions discussed above are detailed and interpreted below.

4.1. THE GUINEA COAST

In JAS a zone of relatively high IDDI values exists over the Guinea Coast region, extending in places to some 12° N and exhibiting a maximum in the east over Nigeria. The period JAS corresponds to the “Little Dry Season” (Barry and Chorley, 1995) in this region and it might therefore be expected that widespread biomass burning would be prevalent. Monthly maps of fire distribution are available for some years from the World Fire Atlas, compiled by the European Space Agency and the European Space Research Institute (ESA/ESRIN) as part of the Ionia programme (Arino and Melinotte, 1995; Arino *et al*., 1997). These maps have been produced from AVHRR and ATSR satellite data. A visual comparison of the monthly IDDI fields with monthly fire maps for 1993 suggests that the JAS high IDDI values over the Guinea Coast are not due to combustion products, as fires are almost entirely absent from this region in this period according to the fire maps. At this time of year detectable fires are concentrated between the Equator and 20°S, where IDDI values are low. Strong fire signals in the ESA/ESRIN data occur over and to the east of the Guinea Coast throughout the winter, with fires being most widespread in January. Again, the regions of high IDDI values do not correspond to those characterised by fires; the January 1993 IDDI field exhibits low values over the Guinea Coast. However, the relationship between the distributions of fires as detected by satellite remote sensing methods, and high concentrations of biomass burning aerosol products is not necessarily straightforward. Fires will only be detected if they exist under relatively clear-sky conditions. Both clouds and high concentrations of airborne combustion products will obscure the ground from satellite detectors operating in the visible part of the electromagnetic spectrum. Thus, fires that produce large quantities of aerosols may not be detected. It is plausible that material from such fires is responsible for some of the high IDDI signals apparent in figures 5.4 to 5.6, providing at least a partial explanation for the summer Guinea Coast signal.

Another plausible explanation for the high IDDI values over the Guinea Coast in summer is that dust is transported from the Sahel-Sahara to a zone of relatively stagnant air over this region, where it remains in the atmosphere for some time. Between the Guinea Coast and the Sahel-Sahara transition zone, dust will be removed from the atmosphere by rainfall, resulting in short residence times, low aerosol concentrations and hence low IDDI values. A further possibility is that of cloud contamination arising from persistent cloudy conditions throughout the periods used to create the reference fields. This is most likely over Nigeria, where the highest regional IDDI values exist in the vicinity of a region of frequent cloud cover.

4.2. WEST-CENTRAL AFRICA

Large quantities of combustion aerosols also provide a plausible explanation for high IDDI values over regions where dust is unlikely to be a major feature of the atmosphere. Such values are seen over west central Africa (stretching from Gabon to the Democratic Republic of Congo and southwards over Angola) in all the fields, and are greatest in OND, JFM. Some biomass burning occurs in this region in these periods, particularly in October (based on 1993 data from ESA/ESRIN). However, the frequency and density of fires during the periods in question is far greater between 0° and 15° N, where IDDI values remain low. Again, these discrepancies between the IDDI and fire data may be due to the complex relationship between fire and smoke aerosol distributions. This region is adjacent to a region of frequent cloud cover in JFM and OND (i.e. southern hemisphere spring and summer), when the IDDI values are highest. It is possible that some cloud contamination occurs in these periods.

4.3. EASTERN AFRICA

High IDDI values also occur over many of the eastern coastal regions of Africa south of the Equator, particularly in AMJ and JAS. These regions contain no extensive deserts, but do include semi-arid and dry sub-humid zones. The boreal summer high IDDI signal occurs during the dry season in East Africa. It is possible that dust mobilisation occurs from disturbed soils in these regions, although a complex biomass burning aerosol signal is again highly plausible, as burning is widespread in the dry season. Cloud contamination is likely in JFM and OND, but during AMJ and JAS the elevated IDDI values exist well away from areas of frequent cloud cover.

4.4. SOUTHERN AFRICA

Finally it is worth mentioning the southern hemisphere African deserts in terms of dust sources as defined by the IDDI data. These regions do not stand out in the seasonal or annual fields, although elevated IDDI values are apparent over the Kalahari in JFM. It is striking that the Namib Desert does not appear to be a significant source of dust. The cold Benguela Current to the immediate west of the desert results in a highly stable atmosphere that is not conducive to the generation of the type of large convective events that are responsible for dust mobilisation and transport in northern Africa. While dust storms do occur over the sandy desert in the Namibian interior, it appears that the spatial and time scales associated with these events are such that they do not produce a major signal in the mean IDDI fields. The coastal atmosphere is very different from that over West Africa, and it is likely that the atmospheric environment over the Namib desert is such that dust aerosols are not carried to the elevations necessary for long-range transport. Middleton (1997) states that dust mobilisation and transport from the southern

African deserts is poorly understood, but suggests that the scale of such phenomena is not comparable with that which characterises the northern African regions.

4.5. SUMMARY

The above discussion further illustrates some of the caveats to be considered when interpreting the IDDI data. The question of whether the IDDI is a reliable means of detecting combustion aerosols remains open, and will only be resolved when the relationship between detected fires and the nature and distribution in the atmosphere of their products is better understood. It also appears that the IDDI is less reliable under persistently cloudy conditions. Further work is required to decouple the effects of biomass burning products and cloud contamination from the impacts of dust on the IDDI signal.

However, over the regions of interest in this study, the IDDI appears to perform well, exhibiting cumulative signals from large dust events and identifying the major sources of dust aerosols. It may therefore be used with confidence in studies of Saharan and Sahelian aerosols and their relationships with the regional climate. Seasonal and geographical variations in the IDDI data may also be used to infer information concerning the behaviour of the major aerosol sources in northern Africa.

5. Meridional variation in dust production

In order to assess the seasonal variation in dust production in northern Africa in a more quantitative fashion, several different zones were defined. These zones are the aggregated Sahel (10° - 20 ° N), the aggregated Sahara (20° - 30° N), the South Sahel (10° - 15° N), the North Sahel (15° - 20° N), the South Sahara (20° - 25° N), the North Sahara (25° - 30° N), the zone from 15° - 17° N and the zone from 18° - 20° N. The last two zones are used to examine dust seasonality either side of the suggested limit of soil degradation (Section 3.1).

Spatially aggregated, mean monthly IDDI values over the zones described above (Figure 4) illustrate a broad commonality of dust loadings over the Sahel-Sahara region. Values are generally high in the first half of the calendar year, falling to a minimum in October or November and rising again in December. However, the evolution of the North Sahara zone departs from that of the other zones outside of March-June. This is to be expected as a result of the influence of mid-latitude weather systems such as Mediterranean and Atlantic cyclones.

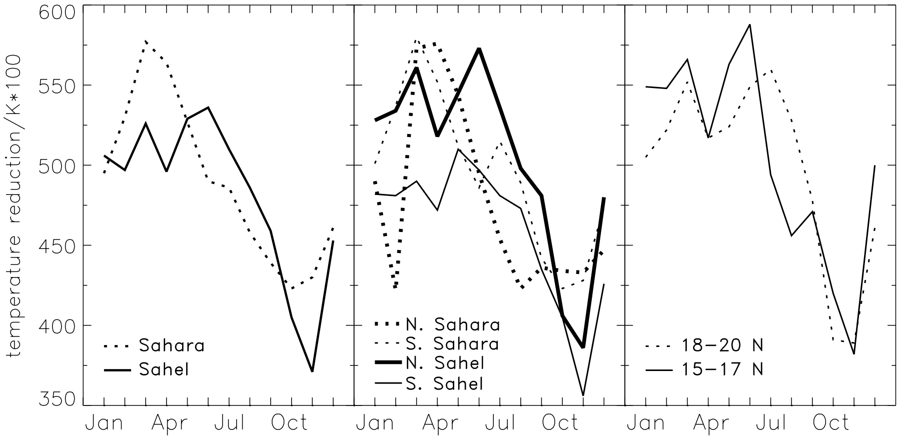

Figure 4: Spatially averaged, mean monthly IDDI values over latitudinal zones within the Sahel and Sahara, as defined in the text.

From June to September, dust levels are higher over the Sahel than over the Sahara. Sahel dust loadings peak in June; Saharan dust loadings are at a maximum in March and April. The lowest dust levels occur in November over the Sahel, and in October over the Sahara.

IDDI values are consistently higher over the North Sahel than over the South Sahel, and the North Sahel exhibits the highest values of all the 5°-latitude zones in December and January and from June to September. The North Sahel contains the transition zone between the Sahel and Sahara and the nominal northern geographical limit of soil degradation. The 15°-17° N band lies to the south of this limit, so variations of IDDI within this band may be interpreted as reflecting variability of dust production from potentially disturbed soils, with a component due to advection from zones to the north, particularly during the dry-season. IDDI values in the 18°-20° N band may be assumed to reflect variability of dust production from undisturbed soils. However, the uncertainties in the estimates of the extent of soil degradation (Section 3.1) should be recalled.

The 15°-17° N band yields the larger IDDI signal from December to March and in May and June. (The April value is similar to that in the 18°-20° N. band.) This indicates that the meridional maximum in dust loadings lies in the 15°-17° N band in December, January and June, when the maximum values in the 5° latitude zones occur over the North Sahel. Similarly, dust loadings are highest in the 18°-20° N band from July to September. (These results are unchanged if other 2°-latitude bands within the North Sahel are considered.) During the summer the 2°-latitude bands exhibiting the highest IDDI values lie to the south of the average position of the surface discontinuity (Tetzlaff and Peters, 1988; Hastenrath, 1991), i.e. within the monsoonal air mass. It is arguable that these high IDDI values represent advected material from the Sahara overlying the monsoon air. However, if this is the case, still higher IDDI values should be apparent closer to the northerly source regions. Therefore, these meridional maxima in IDDI values may be interpreted as representing meridional maxima in dust levels resulting from dust mobilisation in the shallow northern part of the monsoon air layer.

Thus dust mobilisation is at a maximum within the zone containing potentially degraded soils in the early to mid dry season and in the early phase of the wet season. Mobilisation may remain high in this zone in JAS, but rainfall will remove dust from the atmosphere, shifting the maximum in the IDDI signal to the northern fringes of the active rainfall zone.

It is likely that the June maximum in the 15°-17° N band is due to the intensity of the deflation processes and the balance between dust mobilisation and removal, rather than the sensitivity of the soils to deflation. In June this band corresponds to the northernmost extent of the wedge of monsoonal air (Tetzlaff and Peters, 1988), where the convective disturbances that generate rainfall and mobilise dust are weak due to the small thickness of the monsoon air layer (Hastenrath, 1991). Such weak disturbances may be sufficient to cause deflation, but too weak to produce significant amounts of precipitation. Thus the June maximum may be simply a manifestation of the regional climatology. The same processes are likely to be responsible for deflation in the 18°-20° N band in JAS.

In December and January both the Sahel and Sahara are subject to the regional-scale Harmattan circulation, characterised by northeasterly winds over most of northern Africa (McTainsh, 1996). Deflation processes are therefore associated with large-scale atmospheric circulation patterns, suggesting that dust mobilisation will be greatest where soils are most vulnerable. The December-January maximum in dust production between 15° and 17° N is therefore likely to represent a meridional maximum in the availability of erodible material. This may be due to the fragility of degraded soils in this region, or a maximum in water erosion arising from the action of rainfall and rainfall-runoff on semi-arid surfaces. Low vegetation cover may also play a role; it is likely that the combination of relatively high rainfall (when compared with the dry Sahara) and the lack of vegetation protection of the land surface together result in high water erosion rates. Degraded soils will be more susceptible to water erosion, but it is not necessary to invoke land degradation in order to explain this maximum in dust production.

6. Interannual variability of dust and rainfall

Figure 5 shows rainfall anomalies for the period 1983-1994, standardised with respect to the 1983-1984 mean. This period represents the period over which IDDI data are available, and includes 1983 in order to show all years that may affect dust values at a lag of +1 year.

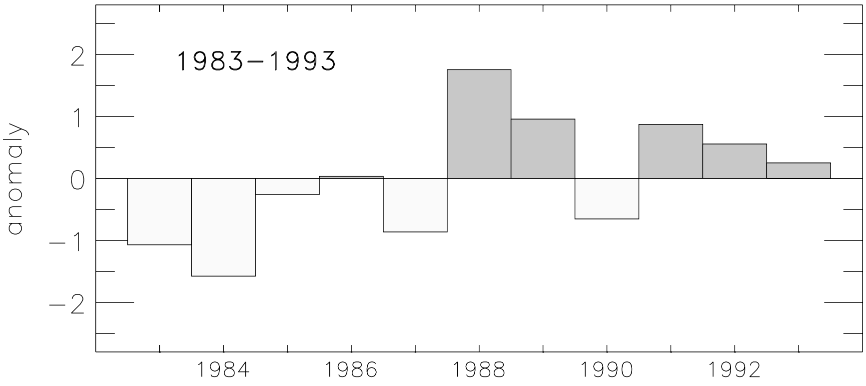

Figure 5: Rainfall anomalies over the Sahel (as defined in the text) for 1983-1993, standardised with respect to the 1983-1993 mean. Based on the dataset of New *et al*. (1999).

Figure 6 shows yearly, spatially averaged annual IDDI anomalies calculated over four different periods, for the various latitudinal zones described in the previous section. The primary objective of such a representation is to illuminate interannual variability of atmospheric dust loadings over bands subject to different rainfall regimes. While the main zones of interest are those in the Sahel, values for Saharan zones are included so that rainfall-dominated regions may be compared with arid regions.

The annual period represents the mean IDDI values over the period November-October, chosen to commence around the beginning of the dry season. The wet-season is liberally defined as the period May-October, during which deflation mechanisms are most likely to be associated with the westward travelling disturbance lines (DLs), which bring the majority of rainfall to the Sahel (Rowell and Milford, 1992). The early dry-season is defined as November-December, the part of the dry season in which the vegetation cover as represented by NDVI values is significantly greater than the dry-season minimum (Hess *et al*., 1996). The late dry-season is defined as January-April, during which vegetation cover is close to the dry-season minimum, and in which dust mobilisation and transport in both the Sahel and Sahara are subject to the Harmattan circulation (Adeyfa and Holmgren, 1996).

In many cases the anomalies over one region reflect those over the other regions, suggesting a common atmospheric influence on the primary deflation mechanisms. Major differences between Sahelian and Saharan regions are likely to be due to the influence of rainfall in the Sahel. The impact of the severe 1984 drought is evident in annual, early dry-season and late dry-season anomalies in 1984/85, 1984 and 1985 respectively. Over the Sahel the anomalies for these years are large and positive. Over the Sahara these anomalies are small or negative. Rainfall influences therefore serve to decouple the Saharan and Sahelian dust signals.

6.1. ANNUAL ANOMALIES

The three driest years in the Sahel in the 1984-93 period were 1984, 1987 and 1990 (Figure 5). The annual periods following these wet-seasons exhibit the largest positive IDDI anomalies in the South Sahel series (Figure 6). The largest-magnitude negative anomalies in the Sahel occur after the wet-seasons of 1985, 1989 and 1991. These IDDI anomalies occur after dry or intermediate-rainfall years. This pattern of large negative IDDI anomalies is also reflected in the South Sahara, suggesting that atmospheric influences (for example a low frequency of strong surface winds) may be partly responsible for these periods of low dust loadings.

6.2. WET SEASON ANOMALIES

The largest positive wet-season IDDI anomalies in the South Sahel occur in 1988, 1989 and 1991, the wettest years in the 1984-93 period. This further supports the hypothesis that DLs (which are more frequent and intense in wet years) are largely responsible for dust mobilisation in the wet-season. For these three relatively wet years, IDDI anomaly magnitude decreases with increasing rainfall. While three years do not represent sufficient data to constitute a trend, this result suggests the possibility that summer dust loadings may be generally higher in wetter years but that, above a certain rainfall threshold, dust levels decline as rainfall increases. This is physically plausible: intense DLs will mobilise greater quantities of dust than weak DLs, but will also produce more rainfall, which will remove dust from the atmosphere. Thus spring/summer Sahel atmospheric dust loadings are likely to be controlled by two processes that act in opposition to each other. The relative strengths of these processes will depend on the frequency and intensity of the DLs in any given wet-season. This conceptual model has important implications for the identification of the mechanisms behind the observed increases in Sahelian dust production. Lamb *et al*. (1998) report a decrease in both the frequency and intensity of DLs over the Sahel since the onset of dry conditions in the late 1960s. Enhanced spring and summer dust loadings over the Sahel may therefore be the result of a change in the balance between processes controlling the mobilisation and removal of dust particles, rather than, or in addition to, changes in soil properties.

In the North Sahel and South Sahara the dustiest wet-seasons occur in 1987, 1988 and 1991. Dust mobilisation in these regions is likely to be related to DL activity within the vicinity of the surface discontinuity, where the monsoon air layer is not thick enough to allow rainfall generation. Rowell and Milford (1992) have identified August DLs generated as far north as 20° N.

Wet-season dust levels are lowest in 1985, 1986 and 1990 (South Sahel) or 1989 (North Sahel). All of these years are dry except 1989, which follows the wet year of 1988. Low levels of dust in dry years may be explained by weak or infrequent DLs. The low level of dust in 1989, a relatively wet year (Figure 5), suggests that there was not much material available for deflation in this year. This may be due to the removal of such material after heavy water erosion in 1988 and/or a recovery in the vegetation cover of the Sahel over 1988 and 1989. An alternative explanation is that dust levels are high in wet-seasons dominated by weak DLs (which do not produce much rainfall) and low in wet-seasons dominated by intense DLs. If the rainfall in 1989 was the result of a predominance of the latter, removal of dust by rainfall may have dominated over dust mobilisation.

6.3. EARLY DRY SEASON ANOMALIES

The most striking aspect of the November-December anomalies is the switch from positive anomalies in the Sahel until 1988 to negative anomalies from 1989 onwards. This pattern is punctuated by small positive anomalies in the South Sahel in 1985 and 1986 and a small positive anomaly in the North Sahel in 1992.

A single year of drought may not have a long-term impact on soil or vegetation (Bullard, 1997). However, several consecutive years of drought, as occurred in the early-mid 1980s, are likely to have a cumulative impact on vegetation and hence on the organic matrix of the soil, leading to loss of soil cohesion. It is suggested that the wetter conditions prevailing from 1988 onwards led to a recovery in soil cohesion by encouraging vegetation cover, which would result in a greater degree of protection of Sahelian soils from deflation (Bullard, 1997). The dry year of 1990 occurred in isolation, and would not have had a long-term impact on soil properties. The positive IDDI anomaly following the 1988 wet-season is probably due to water erosion caused by the action of heavy summer rainfall on soils with little vegetation cover (either because of the distribution of rainfall or due to the dying off of vegetation under the previous dry conditions). In the short-term this would lead to an increase in the amount of erodible material (Baird, 1997).

The anomaly series for the Saharan regions do not closely reflect those for the Sahelian regions, further reinforcing the interpretation that dust production in this period is largely a function of earlier rainfall. However, the large negative IDDI anomaly in 1989 is apparent in all the series except that representing the South Sahel (where the anomaly is negative but not of great magnitude), suggesting that the regional-scale circulation also modulates dust production in this period. The positive IDDI anomaly of 1988 is also not confined to the Sahel, suggesting a possible atmospheric influence on dust levels throughout the region.

6.4. LATE DRY SEASON ANOMALIES

The Sahel exhibits lower interannual variability in dust loadings over the January-April period than over the other periods described here. As rainfall exhibits considerable interannual variability, these results suggest that rainfall generally has a small impact on January-April dust production. However, a very large positive IDDI anomaly is evident in all Sahelian zones in 1985, after the extremely dry years of 1983 and 1984, providing compelling evidence for a cumulative impact of multiple years of large rainfall deficits. 1987 and 1990 are years characterised by extreme rainfall deficits that follow years that are dry, but not extreme in terms of rainfall. 1987 and 1990 are not followed by large positive late dry season IDDI anomalies. It is speculated that the small 1988 IDDI anomalies in the Sahelian regions may be due to the lack of rainfall and the consequent reduction in erodible material produced by water erosion.

7. Rainfall-dust correlations

Rainfall over the May-October period and monthly mean IDDI values were spatially averaged over the zones defined in Section 5. The resulting timeseries, representing aggregated dust and rainfall values over spatially coincident areas, were correlated. Correlations were performed between rainfall and monthly IDDI values representing twelve months commencing in the November immediately following the wet-season (lag = +1 year), and between rainfall and IDDI values representing twelve months commencing in November of the following year, i.e. thirteen months after the end of the wet-season (lag = +2 years). The results were tested for statistical significance using a simple monte-carlo style randomisation procedure. For each correlated pair, one of the timeseries was randomised 10,000 times and the two series correlated for each randomisation. If the original correlation was exceeded fewer than 500 out of 10,000 times the result was deemed to be significant at the 5 per cent level. Correlations at the 1 per cent level were also noted. Correlations not significant at the 5 per cent level were rejected.

Correlations were calculated for Saharan zones for purposes of comparison: significant relationships would not be expected over Saharan regions where rainfall is low and infrequent. The rainfall averaging period is arbitrary in the case of Saharan rainfall, further reducing the likelihood of meaningful statistical dust-rainfall relationships over Saharan regions. If such relationships were found, they would suggest that statistically significant results over the both the Sahara and the Sahel were artefacts of the statistical procedure employed.

Comparisons with the Sahara notwithstanding, the short length of the timeseries means that the resulting correlations should not be interpreted as demonstrating definite physical relationships between rainfall and dust loadings. Nevertheless, considerations of the probable mechanisms of dust production provide a conceptual context within which such correlations may be interpreted. Significant correlations may therefore be used to infer likely impacts of rainfall on dust production, as well as the temporal distribution of such lagged relationships. Such an approach is useful in reinforcing or rejecting existing hypotheses, and suggesting new hypotheses, of dust variability.

7.1. LAG 1-YEAR RELATIONSHIPS

No significant correlations result from the lag 1-year analysis for the Saharan zones. This is encouraging as it suggests that the Sahel correlations described below are not merely coincidental results arising from an analysis of short time series.

Table 1: Correlations between May-October rainfall and monthly mean IDDI values for the 12-month period following the wet-season (lag of +1 year). Values significant at the 5 per cent level are shown in bold; asterisks denote significance at the 1 per cent level.

Lag = +1	**Latitudinal zone**							
Month	**10-20**	**10-15**	**15-20**	**15-17**	**18-20**	**20-30**	**20-25**	**25-30**
Nov	-0.27	-0.51	-0.34	-0.40	-0.12	0.25	0.35	0.04
Dec	-0.29	-0.28	-0.39	-0.41	-0.27	0.13	-0.20	0.28
Jan	0.06	0.04	0.10	-0.01	0.13	0.04	0.03	0.12
Feb	0.01	-0.27	0.41	0.11	0.65	-0.05	-0.08	0.05
Mar	**-0.82***	**-0.70**	**-0.81***	**-0.81***	**-0.68**	-0.49	-0.56	-0.35
Apr	-0.57	**-0.74**	-0.01	-0.19	-0.10	-0.33	-0.50	-0.17
May	-0.44	-0.44	-0.41	-0.43	-0.43	-0.19	-0.34	0.17
Jun	-0.06	0.29	-0.24	-0.17	-0.36	-0.12	-0.28	-0.36
Jul	-0.17	-0.13	-0.25	-0.35	-0.16	-0.32	-0.39	0.08
Aug	-0.23	-0.27	-0.18	0.08	-0.14	-0.08	0.04	-0.23
Sep	0.17	0.63	-0.36	-0.15	-0.35	0.21	0.18	0.12
Oct	**0.74**	**0.78**	0.43	0.53	0.35	0.60	0.39	0.47

Significant negative correlations at a lag of one year were found for all the Sahelian zones in March, and for the South Sahel in April (Table 1). The strongest apparent relationships occurred in March over the aggregated Sahel, the North Sahel and the 15°-17° N band. These results suggest that what variability there is in dust production throughout the Sahel in March is significantly influenced by the previous year's rainfall. March falls within the period characterised by large dust loadings and low dust variability, so the proportion of the March dust production that results from the influence of rainfall on the soil-state is likely to be relatively small.

Significant positive correlations occur in October over the aggregated Sahel and the South Sahel. This result is difficult to explain. If it is physically meaningful, it may be due to rainfall-driven soil erosion in one year sensitising the soil to the particular deflation mechanisms operating in the following October. These mechanisms are likely to be related to DL activity at the end of the wet-season. Such DLs may be strong enough to mobilise dust but too weak to produce much rainfall. The same deflation mechanisms will operate throughout the wet-season, but removal of dust from the atmosphere by rainfall will result in a weak IDDI signal, masking the relationship between soil-state and dust mobilisation. This conceptual model is likely to be appropriate only in an arid regime where soils are fragile and susceptible to rainfall erosion. The higher correlation in the wetter South Sahel therefore suggests that advection from the more arid northern zones may be responsible for this relationship. This assumes that rainfall variability is coherent between the South Sahel and the more northerly regions, as the correlation is the result of consideration of South Sahel rainfall only. This interpretation is highly speculative.

7.2. LAG 2-YEAR RELATIONSHIPS

Significant negative correlations for the 2-year lagged timeseries are observed in December over the North Sahel and over the two narrower bands lying within the North Sahel (Table 2). The North Sahel signal gives rise to a smaller significant negative correlation over the aggregated Sahel. These results suggest that rainfall variability has a cumulative impact on December soil properties and hence on dust production in the northern latitudes of the Sahel, where rainfall is low and where some regions may be characterised by soil degradation (UNEP, 1992).

Table 2: Correlations between May-October rainfall and monthly mean IDDI values for the 12-month period commencing thirteen months after the end of the wet-season (lag of +2 years). Significance levels are as in Table 1.

Lag = +2	**Latitudinal zone**							
Month	**10-20**	**10-15**	**15-20**	**15-17**	**18-20**	**20-30**	**20-25**	**25-30**
Nov	-0.02	0.30	-0.17	-0.31	0.11	0.36	0.38	0.39
Dec	**-0.67**	-0.52	**-0.76**	**-0.72**	**-0.67**	-0.30	-0.42	0.06
Jan	0.30	0.32	0.25	0.10	0.40	0.23	0.24	0.25
Feb	-0.20	-0.19	-0.26	-0.36	-0.03	0.09	0.24	-0.55
Mar	0.33	0.59	-0.13	-0.14	0.14	0.30	0.32	0.26
Apr	0.38	0.30	0.30	0.23	0.26	0.15	-0.15	0.28
May	0.59	0.54	**0.67**	0.59	0.54	0.04	-0.01	0.23
Jun	0.31	0.03	0.29	0.21	0.19	-0.13	-0.13	-0.13
Jul	-0.12	0.11	-0.31	-0.29	-0.25	0.44	0.39	0.39
Aug	-0.08	-0.12	-0.10	-0.31	0.18	**0.73**	0.46	**0.90***
Sep	-0.57	**-0.77**	-0.03	-0.06	0.03	0.22	0.16	0.19
Oct	-0.15	-0.05	-0.39	-0.15	-0.58	-0.28	-0.30	-0.33

A similar relationship is suggested for the North Sahel in September. This may represent the impact of desiccation-related soil degradation on dust production. However, this result is not reflected in the correlations for the 15°-17° N and 18°-20° N bands. Also of note is the fact that a significant positive correlation is observed over the North Sahara for August. This signal results in a smaller significant correlation for the aggregated Sahara. For such short time series, any physical interpretation of this isolated significant Saharan result would be wildly speculative. It is highly plausible that it is a physically meaningless artefact of the statistics. Hence the isolated September result for the North Sahel should also be treated with caution. A positive correlation for May over the North Sahel may reflect a multi-year sensitising of soils to deflation by rainfall erosion (as suggested for the lag 1-year October results), or may also be spurious.

8. Discussion and Conclusions

The IDDI data enable the major dust sources to be identified, and the seasonal evolution of these sources to be described. Dust sources are identified with regions of sandy desert and regions of seasonal watercourses. The distribution of airborne dust in summer is closely associated with the position of the surface discontinuity between the monsoon and Saharan air masses, and suggests a role for convective disturbance lines (DLs) in summer dust production. The role of DLs in dust production is further supported by the northward migration of the meridional dust maximum over the Sahel in the summer months.

The monthly zonally averaged IDDI values indicate that dust production in the Sahel-Sahara zone is at a maximum between 15° and 17° N in December, January and June, and between 18° and 20° N from July to September. Dust levels over the Sahara exceed those over the Sahel in much of the dry Season, and mean zonally averaged dust values between 20° and 25° N (Sahara) exceed those between 10° and 15° N (Sahel) in all months except May and June.

The zonal maximum in dust production is therefore located in Sahelian latitudes only during part of the year, and in the zone of potential land degradation for only three months of the year. In June, this maximum is likely to be the result of the balance between dust mobilisation and wet deposition as determined by the prevailing meteorology. In December and January, the strongest IDDI signals occur over the accepted natural dust sources located in the north-central Sahel. While material from disturbed soils may contribute to the dust budget in these months, the notion that such processes have created major new source regions in areas not previously associated with dust production, and extending throughout much of the Sahel, is not supported by this study. It is possible that the maximum in December/January dust production within the 15º-17º N zone may be the result of a meridional maximum in the generation of deflatable material by water erosion, arising from the balance between rainfall intensity (greater than in more northerly regions) and vegetation cover (less extensive than in more southerly regions). It should also be noted that mean dust concentrations are relatively low in December, and that dust activity in northern Africa as a whole is greater throughout much of the year than in January. This is particularly so in regions near the West African coast. It is therefore unlikely that dust production from disturbed soils in these two months makes a large contribution to the regional and global annual dust budget.

Rainfall-dust correlations indicate that enhanced dust production in April and May is associated with reduced rainfall in the previous year. Limited evidence for a cumulative impact of drought on December dust production is provided by correlations between rainfall and IDDI values at a lag of two years. April falls within the period during which interannual variability in Sahelian dust concentrations is low and dust events in northern Africa are frequent. The component of the April dust budget associated with rainfall in preceding years is therefore likely to represent relatively small percentage changes in the quantities of dust mobilised.

The results of this study suggest that rainfall does exert some influence on dust production during certain parts of the year, although rainfall does not appear to be the dominant factor in determining the amount of dust mobilised in the Sahel on interannual timescales. The research described here does not support the notion that dust-event frequency in the Sahel has increased as a result of widespread land degradation, nor that the Sahel has become a more important source of mineral aerosols than the Sahara. It appears that the role of the land surface (and particularly of human activity) in modulating atmospheric dust concentrations has been over-emphasised, while too little attention has been paid to the role of meterological processes in determining the regional dust budget. In particular, observed changes in the nature of summer rain-bearing disturbances may have played a key role in decadal-scale changes in the amount of dust mobilised within, and exported from, Sahelian regions.

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