

Environmental change and land-atmosphere interactions in northern Africa: the role of Saharan dust

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The potential of atmospheric dust aerosols to modify the Earth's climate has been appreciated for some time (e.g. Gunn, 1964; Bryson and Baeris, 1967; Kellogg and Schneider, 1977). Recent studies have demonstrated the capacity of mineral dust aerosols to modulate the optical and radiative properties, and hence the thermal structure, of the atmosphere on regional scales (Chen *et al.*, 1995; Li *et al.*, 1996; Overpeck *et al.*, 1996; Alpert *et al.*, 1998; Schollaert and Merrill, 1998). It has been suggested that dust may have acted to exacerbate drought conditions via a process of atmospheric stabilisation in the African Sahel (Brooks, 2000; Nicholson, 1995), a region that experienced dramatic declines in rainfall and increases in dust event frequency in the latter half of the twentieth century (Hulme, 1996; Goudie and Middleton, 1992; N'Tchayi *et al.*, 1994, 1997).

A number of authors have attributed increases in atmospheric dust budgets to land degradation in the Sahel driven by a combination of "inappropriate" land use (for example overgrazing and the clearing of vegetation for fuel wood) and climatic desiccation (Middleton, 1985; Tegen and Fung, 1995; Tegen *et al.*, 1996). However, the very limited data on which theories of land degradation in the Sahel are based have been widely questioned (Goudie, 1996; Thomas, 1997; Tucker *et al.*, 1991, 1994; Williams and Balling, 1996), and it is likely that the importance of degradation, and of overgrazing in particular, has been overestimated (Mace, 1991; Wint and Bourn, 1994; Mortimore, 1998). Studies of the distribution of dust source regions and of seasonal variations in their activity by Brooks and Legrand (2000) call into question the notion that the Sahel has supplanted the Sahara as the principal source of African dust as a result of land degradation (N'Tchayi *et al.*, 1997). Remote sensing based studies of the distribution of atmospheric dust over northern Africa for the period 1984-1993 indicate that latitudinal zones of maximum dust production are determined to a large extent by seasonal variations in the regional synoptic climatology (Brooks and Legrand, 2000).

The reasons for the increase in dust event frequency, and the nature of the impact of dust on atmospheric dynamics, has important implications for the attribution of regional environmental change in the Sahel. This paper examines the extent to which summer dust loadings over the Sahel and southern Sahara are associated with variations in the regional atmospheric circulation, and assesses relationships between the presence of airborne dust and temperature anomalies associated with increased atmospheric stability.

Atmospheric dust concentrations are represented by the Infra-red Difference Dust Index (IDDI), a gridded dataset representing reductions in brightness temperature due to atmospheric aerosols over continental Africa and parts of the Middle East with respect to clear sky conditions. The IDDI is constructed from data collected by METEOSAT in the 10.5-12.5 μm band. The data used here have a resolution of 1° latitude x 1° longitude and represent the period 1984 to 1993. The IDDI is a semi-quantitative measure of the concentration of atmospheric aerosols, which in desert regions are dominated by mineral dust (Brooks and Legrand, 2000; Legrand *et al.* 1994, 2001).

The climatological data used here are from the NCEP/NCAR reanalysis model described by Kalnay et al (1996).

The dominant mechanism of both rainfall generation and dust mobilization in the summer is the passage of organized lines of convective disturbances known as squall lines or disturbance lines (DLs) (Dubief, 1979; McTainsh, 1996; Rowell and Milford, 1992). These are associated with the passage of easterly waves, instabilities in the African Easterly Jet most pronounced at around 3 km or 700 hPa (Tetzlaff and Peters, 1988; Thorncroft and Blackburn, 1999). Summer atmospheric variability is therefore represented in terms of variations in mid-tropospheric zonal wind fields for the region 8.75° - 23.74° N; 21.25° W - 46.25° E, including the entire Sahel region, the southern Sahara and parts of the sub-Saharan zone. Standard deviations in zonal wind values at the 700 hPa atmospheric pressure level are calculated over the 92-day period covering July-September for each grid cell. The standard deviation (σ) in these data for a given grid cell is interpreted as a proxy for the amount of easterly wave activity, with median σ values reflecting the frequency of easterly waves, over that grid cell. As DLs are generated by the passage of easterly waves, variability in the 700 hPa zonal wind field can also be interpreted as a proxy for DL frequency, particularly when data from a large number of grid cells are aggregated. Figure 1 represents such an aggregation, in terms of box plots representing the median, maximum, minimum and upper and lower quartiles of the σ values occurring in each year. Figure 1 also shows mean IDDI values for the same 92-day period, spatially averaged over the region 10° - 25° N; 18° W - 45° E.

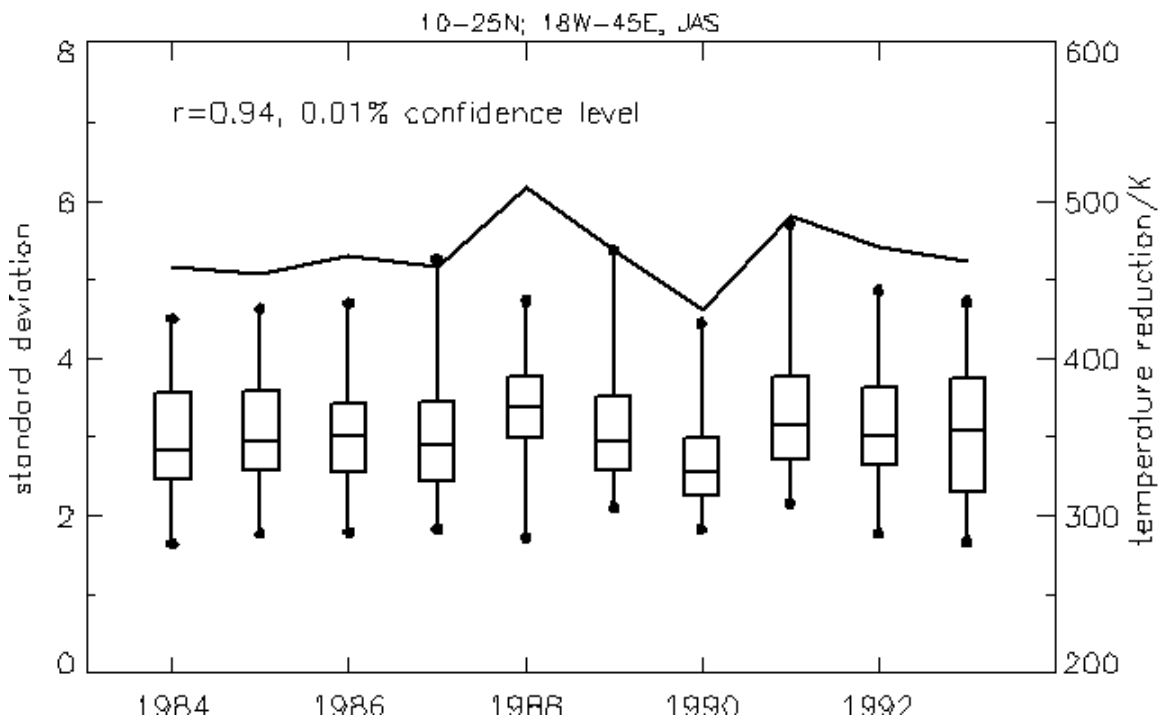


Figure 1. Box plots of standard deviations in the zonal wind field over the Sahel and southern Sahara, and variations in atmospheric dust loadings as represented by the IDDI.

Variations in atmospheric dust loadings as represented by the IDDI closely follow variations in the median of the σ values. While the short length of the time series means that the results must be interpreted with caution, a correlation between these quantities of 0.94, significant at the 0.01

per cent level when tested using a Monte Carlo randomization procedure, does suggest a close coupling between easterly wave frequency and dust production. With such a high component of variance explained by variability in easterly wave activity it seems unnecessary to invoke changes in the land surface, at least on interannual timescales, as a driver of dust production. Furthermore, the statistical relationship between the IDDI and the median τ values is much stronger than that between the median τ values and rainfall over the same period (0.67, significant at the 3 per cent level) and that between the IDDI and rainfall (0.66, significant at the 3 per cent level). This suggests that the passage of easterly waves is more often associated with the mobilization of dust than with the generation of rainfall.

Dry conditions in the Sahel have been associated with an increase in the frequency of weak, poorly organized disturbance lines since the 1960s (Lamb et al, 1998; Nicholson, 2000). The strong correspondence between easterly wave activity and IDDI values, and the weaker relationship with rainfall, suggests that while weak, poorly organized disturbances may fail to generate precipitation, they are still important mechanisms for mobilizing dust. Increases in dust event frequency and atmospheric dust loadings may therefore be due principally to changes in the balance between mobilization and deposition; reduced wet deposition through rainfall events will lead to a dustier atmosphere.

Relationships between dust and temperature were assessed using gridded IDDI values and gridded six-hourly NCEP/NCAR reanalysis temperature data representing the 1000, 850, 700, 600 and 200 hPa pressure levels. Temperature values at midday and 6 am were interpolated onto a 5° latitude x 5° longitude geographical grid encompassing the regions from 5° to 35° N and 20° W to 45° E. These pressure levels represent altitudes in the vicinity of the near-surface, 1.5, 3, 4 and 12 km respectively (Kalnay et al., 1996). The middle three altitudes are associated with dust transport (Bergametti et al., 1989; Kalu, 1979; Schütz et al., 1981), while the surface is associated with a reduction in incoming solar radiation (Tanré and Legrand, 1991). The impact of dust is expected to be minimal at 200 hPa (Schütz et al., 1981). Daily IDDI data were averaged to the same geographic grid as the interpolated reanalysis data. The 5° x 5° resolution was chosen in order to minimise the amount of interpolation required (due to the high spatial variability of the IDDI data), and also to examine dust-temperature relationships over large areas significant in terms of regional climate-modification. For each month, the daily data were pooled over the ten years from 1984-1993, resulting in monthly IDDI-temperature timeseries pairs each containing some 300 values for each grid-square. The linear Pearson correlation coefficient between each IDDI-temperature series pair was calculated. In the case of the 6 am temperature data, the monthly series were trimmed before the data were pooled, in such a way that each IDDI value was associated with a temperature value for the following morning. A “Sahel” region was defined between 10° and 20° N, and a “Sahara” region between 20° and 30° N. Both of these regions contained 26 grid squares, each represented by a correlation value. For each region, the correlations were pooled over three-month periods to produce seasonal groups of 78 values. The periods discussed here are April-June and July-September, representing the onset period of the West African Monsoon (N’Tchayi et al., 1997) and the subsequent Sahelian wet-season. The statistical distributions of the seasonal groups of correlation values for July-September and April-June are displayed in terms of box-plots containing median, upper and lower quartile, maximum and minimum values in Figures 2 and 3.

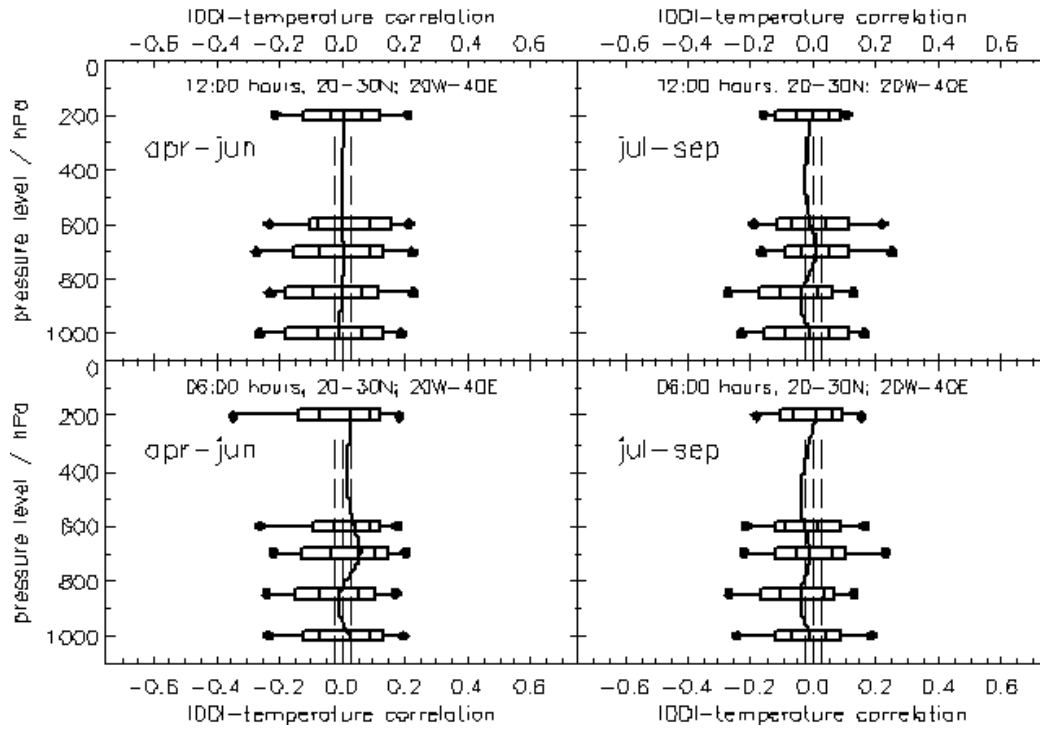


Figure 2. Box plots of correlations between temperature and IDDI values at different atmospheric pressure levels over the Sahara (20° - 30° N).

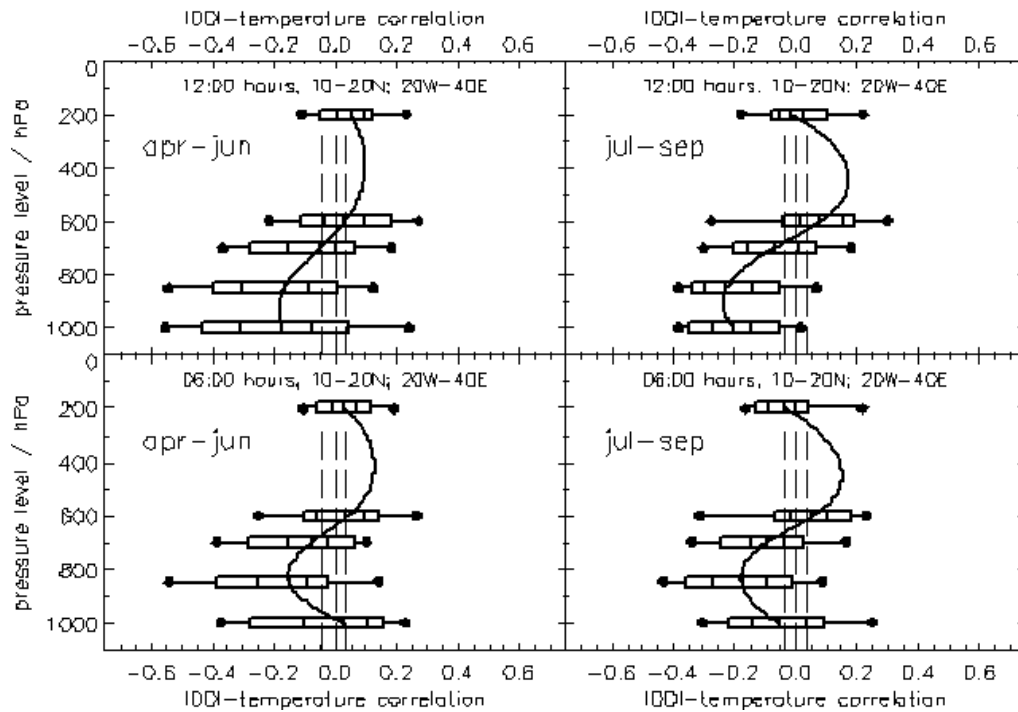


Figure 3. Box plots of correlations between temperature and IDDI values at different atmospheric pressure levels over the Sahel (10° - 20° N).

Correlations over the Sahara for both periods are distributed fairly evenly around zero, suggesting that there is no systematic relationship between atmospheric dust and atmospheric temperature structures over scales of hundred of kilometers between 20° and 30° N. Very low dust-temperature correlations over the Sahara may be a result of the presence of dust throughout the atmospheric column, resulting in a balance between the reduction of solar insolation and heating due to emittance of longwave radiation, or simply of a lack of data for the Sahara, leading to poor representation of the region in the reanalysis model.

In contrast, over Sahelian regions, large departures of the median values from zero are apparent, particularly at 1000 and 850 hPa. At these levels a strong tendency for correlations to be negative indicates widespread cooling associated with the presence of dust in the first 1.5 km of the atmosphere. This cooling is most dominant at 850 hPa, where it characterises both the 12:00 and 06:00 data, although it is stronger at 12:00 near the surface. Median values are negative at 700 hPa and positive at 600 hPa, indicating that cooling predominates at around 3 km and warming at around 4 km.

The above results are consistent with dust transport over the Sahel in an elevated layer in the mid-troposphere, above 1.5 km and including the 3 and 4 km levels. The strongest daytime cooling signals are likely to occur away from the dust layer, where the dominant mechanism of temperature modification is a reduction in solar insolation (Alpert et al., 1998; Chen et al., 1995; Schollaert and Merrill, 1998). In the vicinity of the dust layer, this will be offset by a warming due absorption and re-radiation in the infra-red. The balance between these two processes provides a possible explanation for the reduction in the magnitude of the signal at these higher levels.

These results indicate that summer dust loadings in and at the fringes of the Sahel for the period under investigation are determined overwhelmingly by the amount of easterly wave activity over northern Africa. In Sahelian regions, the presence of dust is associated with persistent cooling in the lower troposphere, and a transition from cooling to warming in the middle troposphere, and thus with an increase in atmospheric stability that is likely to inhibit convection. Dust is therefore a plausible mechanism of rainfall suppression, and provides a possible explanation for the persistence of drought conditions in the late twentieth century. An initial shift in the regional climate favouring weak, poorly organised convective disturbances (Lamb et al., 1998) might in theory be a consequence of atmospheric stabilization caused by higher dust concentrations resulting from processes operating at the land surface. However, the association of drought in the Sahel with large-scale changes in sea-surface temperatures and atmospheric circulation (Folland et al., 1986; Giannini et al., 2003), and the lack of evidence to support claims of widespread land degradation, suggest that such a shift has its origins outside the African continent. Once drought conditions are established as a result of large-scale climatic variability or change, they may be reinforced by high atmospheric dust loadings in a positive feedback driven predominantly by atmospheric mechanisms.

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