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North African dust production: Source areas and variability*

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Introduction

Mineral dust has an important impact on the earth's climate system, influencing chemical processes (Schwartz et al., 1995) and modifying heating by direct radiative effects of scattering and absorption (Tegen et al., 1996) and through indirect radiative effects via their influence on cloud microphysics (Rosenfeld, 1999). The total radiative forcing of dust remains a large uncertainty in the prediction of future climate.

The primacy of the Sahara as the planet's largest source of mineral dust has long been known as is well illustrated by the annual mean TOMS Aerosol Index (AI) values (Figure 1). A large component of this dust is transported over the oceans, some reaching the Caribbean and the USA. As such, dust is one of the crucial components by which Africa influences the global climate system.

In this paper we investigate the source regions of North African dust and relate these sources to features of the circulation. We focus on the Bodélé Depression in Chad, the world's single most productive source region, offering a circulation based explanation for its productivity before going on to examine dust transport via a fourth order trajectory model driven by 3 dimensional reanalysis winds for two extreme years of dust output.

North African Dust Sources

Sources of North African dust have, until recently, been determined from surface meteorological observations of current weather codes and visibility. Since observing stations are often remote from dust sources, a full picture of dust generation and distribution has been elusive. The release of the satellite based TOMS AI data over the period 1979-1993 (Herman et al., 1997), while featuring new problems relating to the retrieval process, has helped to fill gaps in previously data sparse areas. Using the TOMS AI data, Washington et al. (2003) have used eigenvector based techniques on the covariance matrix of monthly AI anomalies to determine objectively key North African source regions. These turn out to be 1) The Bodélé Depression in Chad, 2) the Djouf region spanning the northern border of Mali and Mauritania, 3) the Chotts of eastern Algeria and Tunisia and 4) a broad region of central Libya.

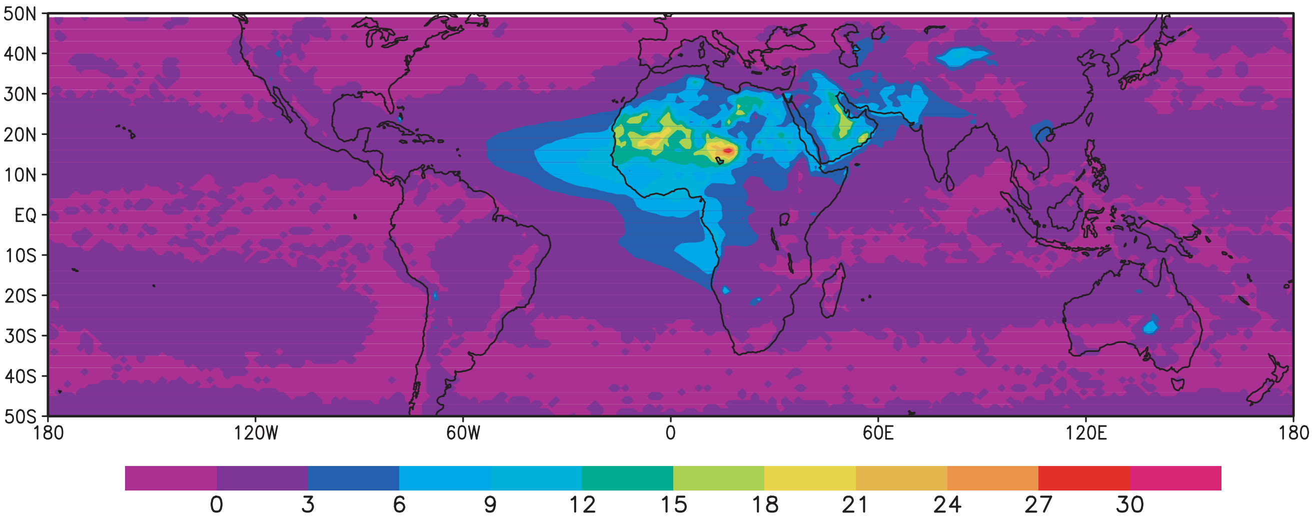

Fig. 1: World map of annual mean Aerosol Index (AI) values (x 10) determined by TOMS.

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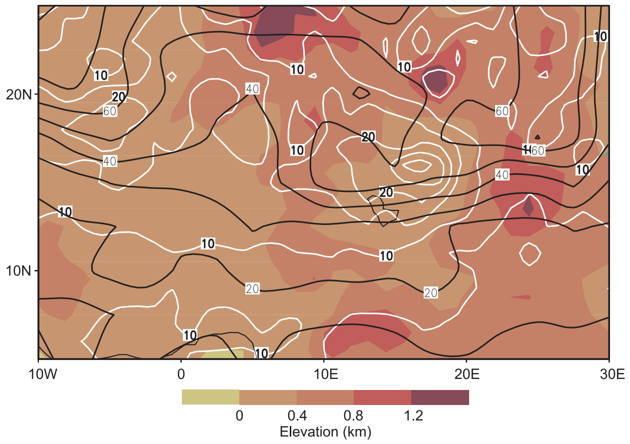

Fig. 2: TOMS AI values (white contours), potential sand flux (black contours) and elevation (colour) in km for the Sahara, long term means, April-June.

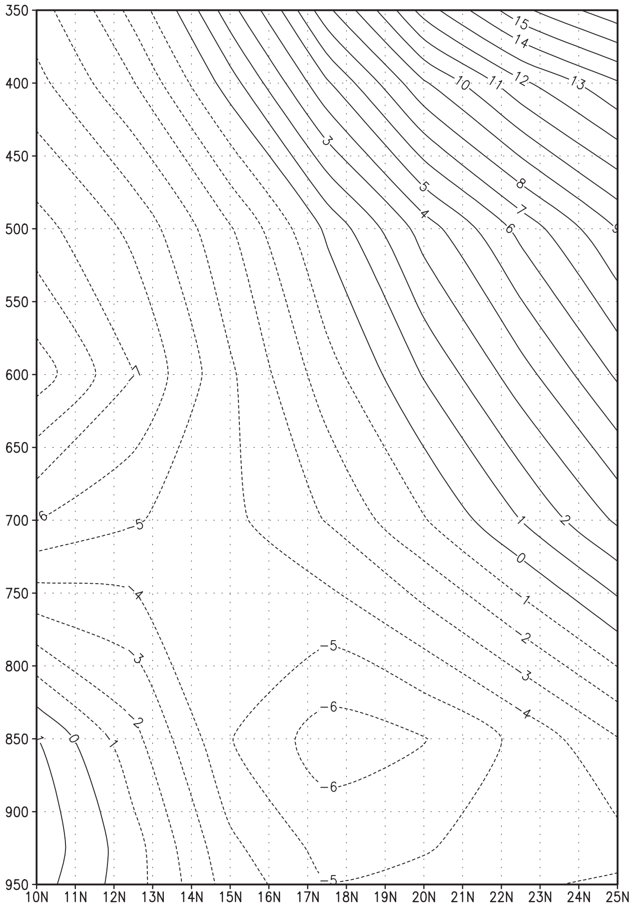

Fig. 3: Latitude-height section along 22°E of the long term mean of the zonal wind (m/s) for May from the NCEP/NCAR data.

The Bodélé Depression is the world's single largest source. Emissions peak in the March to May period and reach a minimum (consistent with North African dust output as a whole) during October to December. The Djouf region peaks between June and August. The importance of palaeo lakes as modern dust sources has been stressed elsewhere (e.g. Prospero et al., 2002; Washington et al., 2003). Such regions are supply unlimited because of the rich deposits of fine materials, in the case of the Sahara dating to the humid period of the mid Holocene. The Bodélé Depression seems unique in the combination of unlimited sediment and the near surface circulation. Using 6 hourly surface wind data from the NCEP/NCAR reanalysis project, potential sand flux

$$q = 2.61\, U^3_*\, p g^{-1}\, (1-U_{*t}/U_*)(1+U_{*t}/U_*)^2$$

(where, q = potential sand flux, g = acceleration due to gravity, p = fluid density and U_{*t}=threshold shear stress and U_* = surface shear velocity given) was calculated for the world's land areas. In the case of the Bodélé Depression, the coincidence of the peak dust emissions, the maximum in potential sand flux and the minimum in topography is remarkable (Figure 2). The coincidence of these fields in North Africa occurs only in the Bodélé Depression.

The large scale structure of the wind in the Sahel and central Sahara, although complicated, is reasonably well described (Burpee, 1972; Cook, 1999). The African Easterly Jet (AEJ) is a prominent feature of the wind with a width of 5 to 10 degrees in most data sets and a jet core near 10°N on the west coast of Africa. Figure 3 shows a latitude-height section along 22°E of the long term mean of the zonal wind for May from the NCEP/NCAR data. The core of the AEJ is clearly evident near 600 hPa, but at this longitude, a secondary maximum extends from 16 to 22°N at a height of 900 hPa. A similar maximum is evident in the meridional wind profile (not shown). This region corresponds to the entry point of low level winds into the extended Bodélé Depression where the zonal wind is concentrated to the south of the Tibesti Mountains and to the north of the Enedi Massif. It is remarkable that the coarse resolution data set captures this channelling so well.

Variability of Dust Emissions and the Atmospheric Circulation

Over the period of the TOMS record, the time series of TOMS AI anomalies reach a peak in May 1991 and a minimum in May 1989. The TOMS record agrees well with surface based met records from Bilma (18.6°N, 12.9°E, in Niger) which is downwind of the Bodélé Depression. Bilma recorded a record 14 sand storms during May 1991 compared with 3 in May 1989. Together, these time series offer a convenient opportunity to study the difference in the circulation for these two months.

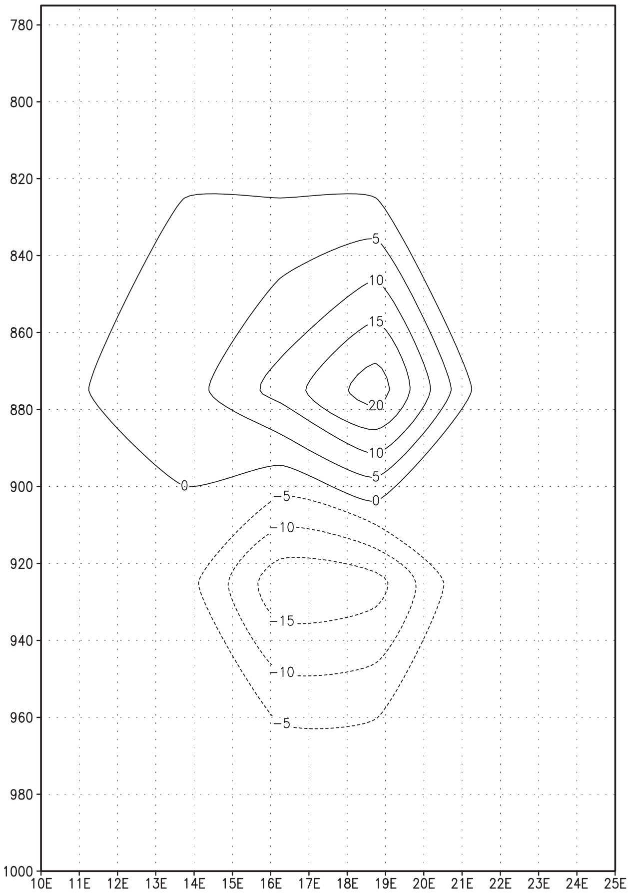

Fig. 4: Longitude-height section of trajectory densities differences between May 1991 and May 1989 at 12 hours following release from the Bodélé Depression. The section is averaged between 10°N and 27° N.

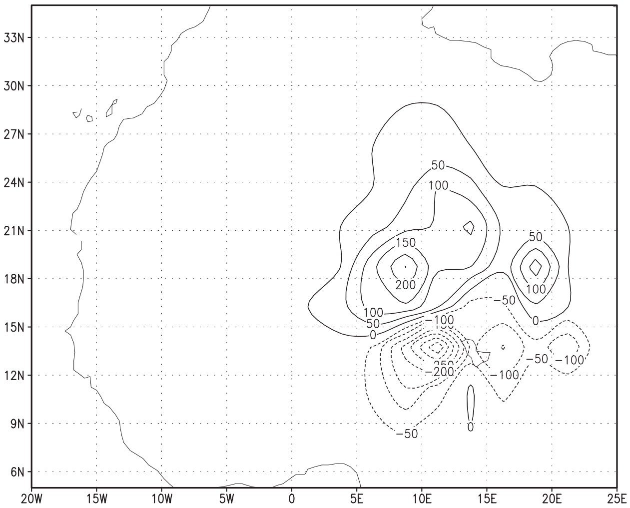

Fig. 5: Trajectory densities differences between May 1991 and May 1989 at 48 hours following release from the Bodélé Depression.

During May 1991, the topographically confined low level jet maximum (identified in Figure 3) at the entrance to the Bodélé Depression was accelerated and the vertical velocity profiles showed considerably more ascent in a broad band across the southern edge of the Sahara. In order to quantify the likely effect on dust emissions, we ran a fourth-order, three dimensional trajectory model initialised by 6 hourly NCEP/NCAR winds for the period 1979 to 1990. Trajectories in packets of 20 were released from the Bodélé Depression with the position calculated at 15 minute intervals. We show the difference in the trajectory densities for May 1991 and May 1989 at 12 hours following release in Figure 4. Enhanced convection has led to a higher density of trajectories at 870 hPa in May 1991 whereas in May 1989 trajectories remained much closer to the surface. Two days following release, the trajectories in May 1991 were transported westwards near 20°N, while in May 1989, southward transport in the low level winds led to a clearer atmosphere over the Sahara. (Figure 5).

Summary

Dust is an important unknown in the climate system. North Africa is the leading source of global dust emissions and within North Africa, the Bodélé Depression is the world's single largest source of dust. This is a major example of the way in which African climate influences the global climate system. Understanding the circulation mechanisms which generate dust is clearly important for reducing uncertainty in climate change predictions.

We have shown that the Bodélé Depression is characterised by a remarkable co-location of maximum near surface wind transport potential, a minimum in topography and a maximum in the TOMS AI loadings. Variability of the dust output is also subject to large scale adjustments to the low level winds and convective environment suggesting that dust sources may be represented with the current available resolutions in GCMs.

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