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Photographs of dust uplift from small-scale atmospheric features

The photographs show small-scale atmospheric processes resulting in dust uplift into the atmosphere. Such dust is an important component of the climate system and the radiative impact of airborne desert dust can affect regional dynamics (Tompkins *et al.*, 2005).

Figures 1(a) and (b) show dust uplift in cold pool outflows from small precipitating convective clouds in arid regions of the USA and Niger. Although virgae can be seen in Figure 1(a), precipitation does not appear to reach the ground, but dust is still uplifted. A few minutes prior to the photo, a rainbow was visible with the same cloud. In Figure 1(b), the cloud was the first of a number of cumulus congestus and cumulonimbus clouds, which generated precipitation and outflows that resulted in visible dust uplift. The dusty cold-pool outflow is seen below the right-hand tower of the congestus cloud, and is probably contributing to generation of this tower.

The uplift of dust by cold-pool outflows from deep convective systems is a well-known phenomenon, with the earliest published scientific discussion of these features, which the authors are aware of, focusing on the Sudan (Sutton, 1925). There they are referred to as 'haboobs' (from the Arabic *habb***,** meaning 'strong wind') and this term is now used globally to refer to these features. The evaporation of precipitation from convective clouds results in a cold downdraught, and the resultant cold-pool outflow propagates along the land surface as a density current. Large haboobs can often be seen in satellite imagery, particularly in West Africa, where outflows from mesoscale convective systems (MCSs) can travel over

(a)

(b)

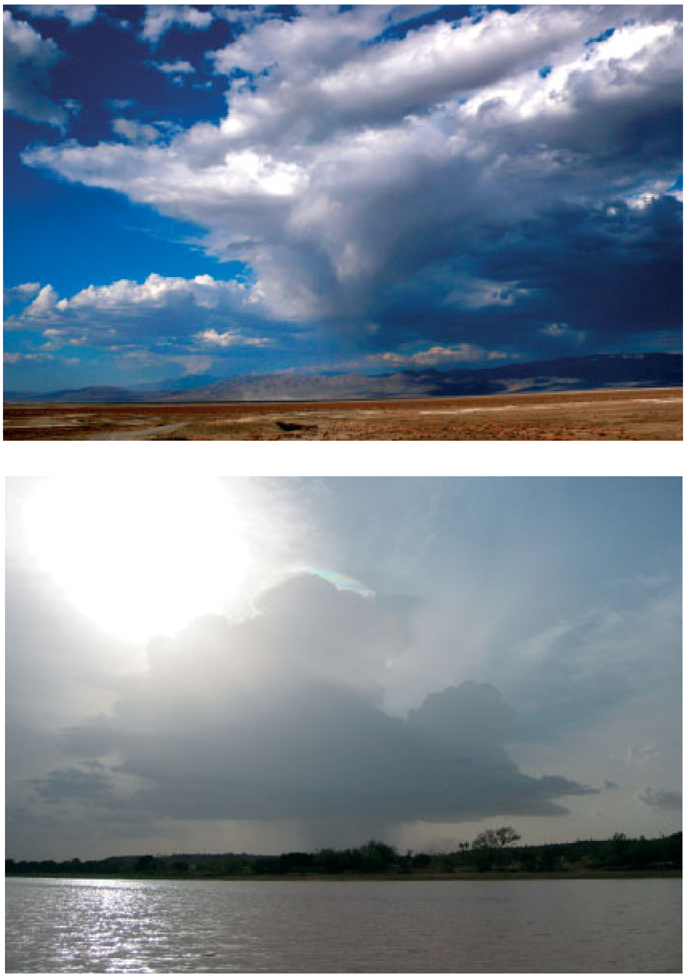

Figure 1. Two photographs showing cold pool outflows from precipitating convective clouds resulting in visible dust uplift. (a) Searles Valley near Death Valley in California, USA, 16 September 2008; (b) West African Sahel near Niamey, Niger, during monsoon onset, 26 June 2007. Figure 1(b) was taken during the GERBILS (GERB Intercomparsion of Longwave and Shortwave radiation) field campaign, aimed at understanding the differences between modelled and observed radiation in West Africa, which may be largely due to the airborne dust (Haywood et al.*, 2005). (© C. M. Grams.)*

Figure 2. Dust devils, near Scotty's Junction in Nevada, USA, 17 September 2008. Similar features were also observed during GERBILS. (© Bernhard Mühr.)

hundreds of kilometres and can lead to major uplift events (Knippertz *et al.*, 2007).

Using an idealized model of haboob dust uplift, Miller *et al.* (2008) estimated that outflows from deep convection result in approximately 30% of dust uplift from the southern Arabian Peninsula and the role of 'haboobs' in West Africa was recently highlighted by Williams *et al.* (2008). Marsham *et al*. (2008) suggested that the annual cycle of dustiness observed in West Africa may be related to the annual cycle in the energy available to downdraughts from convective clouds.

Figure 2 shows dust devils. The left-most dust devil had a large diameter of around 20 metres and up to five individual vortices were observed within the wrapper dust devil. This is indicated by columns of higher dust concentration in the wrapper column reaching into the sky. In the middle of the photograph, a very high and almost vertical dust devil is detectable and, at the right edge, a group of smaller and lower dust devils wander through the plain. The largest dust devil had a lifetime of several minutes. Similar features were observed during GERBILS near Niamey, even on days with thin cloud cover, but they were smaller than those shown in Figure 2.

Dust devils are boundary-layer features of typically three to five metres in diameter and up to few hundred metres in height, with a lifetime of a few minutes (Williams, 1948; Sinclair, 1966, 1969). They occur all around the world where a strong temperature gradient in the lowest levels of the surface layer (below one metre) is possible. However, they only become visible if tracers, such as dust, leaves or hay, are available. In a dry and unstable environment, 'bubbles' of hot air can rise quickly from near the surface and, if there is an initial rotation, the rising air stretches this rotation vertically, which intensifies due to the conservation of angular momentum. Despite being a small-scale and short-lived feature, Koch and Renno (2005) estimated the contribution of dust devils to global mineral dust production to be 26±18%.

What is perhaps most interesting about these three photos is that they show dust uplift from small-scale features, not individually detectable in satellite imagery and not resolved by current weather and climate models. In Figures 1(a) and (b), it is the outflows from small convective clouds (precipitating cumulus congestus) that are producing the dust uplift, not MCSs or even cumulonimbus clouds. Any contribution such small-scale features make to the total dust uplift in any region is not yet well quantified and dust models do not generally parameterise these processes well (Cakmur *et al.*, 2004). It is clearly important for models to account for dust uplift by cold pool outflows more accurately, as concluded by a number of recent papers (Knippertz *et al.*, 2007; Marsham *et al.*, 2008; Miller *et al.*, 2008), and even perhaps by such small-scale features as shown in these photographs.

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