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External supply of dust regulates dust emissions from sand deserts

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ABSTRACT

Dust emission from the sand desert is an important contributor to long-term atmospheric dust loading. The source of desert dust has been previously attributed to the aeolian abrasion of sand grains during wind-blown sand activities. The abrasion rate, however, tends to decrease as the grain roundness increases with abrasion time, and shows unable to produce an adequate supply of dust to support long-term dust emission. Here we show that an external dust supply is also an important dust contributor to the sand desert, and that dust emission from the sand desert will occur if an external dust supply is available and diminish if the external supply is cut off. Our results relate the dust emission from sand deserts to an external dust supply resulting from disturbed processes or changed hydrological processes caused by climate changes or human activities, and also suggest that the dust emission rate of natural sand deserts can actually increase with external dust supply resulting from human activities or climatic changes, rather than with wind energy alone, as is commonly perceived.

1. Introduction

Sand deserts can be the important mineral dust sources with large amount of dust emissions. Some studies have suggested that the relative contribution of long-term dust emissions from the sand deserts to atmospheric dust loading is substantial (Tegen and Fung, 1995). This desert dust has been attributed previously to the aeolian abrasion of sand grains during strong wind events (Bullard et al., 2004; Crouvi et al., 2012; Knight, 1924; Kuenen, 1960; Whalley et al., 1982; Wright et al., 1998). However, some abrasion tests have shown that although angular grains can produce dust materials through aeolian abrasion (Knight, 1924; Kuenen, 1960; Whalley et al., 1982; Wright et al., 1998), rounded or semi-rounded grains show little tendency to do so; furthermore, the abrasion rate decreases as the degree of grain roundness increases (Bullard et al., 2004; Kuenen, 1960; Wright et al., 1998). Because sand deserts typically are composed of rounded or semi-rounded quartz grains, it seems unlikely that the sand desert is sufficient for the production of large quantities of desert dust through aeolian abrasion alone. High dust deposition rates in sand deserts (Fearnehough et al., 1998; O'Hara et al., 2006) led us to propose the existence of large external dust sources, probably located in the regions surrounding sand deserts.

Some evidences have shown that these external dust sources can be disturbed or desertified areas (DDA), or dried alluvial fans, cross-desert stream channels, and terminal lakes or playas (ACP). High dust loadings observed from these DDA or ACP areas (Baddock et al., 2011; Chepil, 1957; Cook et al., 2009; Middleton, 1985; Moulin and Chiapello, 2006; Neff et al., 2008; Schubert et al., 2004) suggest that all or part of released dusts may be deposited on nearby sand desert surfaces during downwind transport and may act as an important external dust supply. This hypothesis differs from the traditional views that argue that dust sources are individual or independent in dust emission (Tegen and Fung, 1995), so, the dust supply from the other dust sources has never been considered as the dust production of the sand deserts. We hypothesize that dust emissions from sand deserts occur primarily because an adequate supply of dust has been deposited, which originate from high-dust content DDA or ACP areas, and that such deposition may occur over small regions or over the entire sand desert surface depending on wind conditions and external dust supplies from DDA or ACP areas.

This hypothesis prompted us to examine whether external dust supply plays an important role in dust production of the sand desert surface. However, it is difficult to isolate the contribution of aeolian abrasion and external supply to dust production of the sand desert surface in the field. We performed controlled wind-tunnel experiments, which focused on dust supply-emission cycles on a glass-bead bed (GBB) to assess the effect of external dust supply in regulating the dust emission of the sand desert. This GBB surface was short enough in length to rule out the aeolian abrasion effect. In addition, we also used a density current box model (Dade and Huppert, 1994; Hallworth et al., 1998) to simulate the dust deposition density on the sand desert surface as the local high-concentration dust storms intrude into a quiescent-aired sand desert. Although this simulation has not been tested in the field, it can shed light on the close link between the dust supply from the DDA or ACP areas and the dust production of the sand deserts.

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2. Theoretical analysis

As a dust plume releases from a DDA or ACP area and intrudes horizontally into a quiescent-aired sand desert, the density contrast between the dust plume and the quiescent-and-clear air leads to the development of a dust density current (Simpson, 1997). This dust density current is driven by a horizontal pressure gradient along the sand desert surface due to the density contrast, and becomes diluted with increasing distance through deposition of dust particles on the sand desert surface. Kármán (1940) argued that the velocity at the front of the plume is related to the depth of the plume:

$$u = Fr\sqrt{g'h} \tag{1}$$

where u is the velocity at the front of the dust plume, h is the depth of the plume, Fr is the Froude number, g' is the reduced gravity:

$$g' = g\frac{\rho_c - \rho_a}{\rho_a} \tag{2}$$

where g is the gravitational acceleration, ρ_c is the density of the dust plume, ρ_a is the density of the clear air. ρ_c can also be expressed as:

$$\rho_c = \rho_p\phi + \rho_a(1-\phi) \tag{3}$$

where ϕ is the dust volume concentration of a dust plume, and ρ_p is the density of dust particles.

For a fixed-volume dust emission from a DDA or ACP area, we used the two dimensional box-model to simulate the transport distance of the dust plume by considering the plume to take the shape of a series of non-entraining boxes of constant cross-sectional area A (Dade and Huppert, 1994; Hallworth et al., 1998):

$$l = (1.5Fr)^{2/3}(g'A)^{1/3}t^{2/3} \tag{4}$$

where l is the transport distance of the dust plume, t is the time, and A is the volume per unit width of the dust plume.

According to the model for the settling of suspended particles from a well-mixed turbulent current (Martin and Nokes, 1988), Hallworth et al. (1998) developed the total deposit density function after the density current has ceased:

$$\eta = \frac{25\phi_0\rho_p A}{12 l_{\max}}\left(1 - \frac{8}{5}\xi\,3/2 + \frac{3}{5}\xi^4\right) \tag{5}$$

where η is the total deposit rate with different transport distance, l_{max} is the maximum transport distance of the dust plume, ξ is the non-dimensional transport distance of the density current (l/l_{max}), ϕ_0 is the initial volume concentration of the dust plume released from a DDA or ACP area.

Eq. (5) clearly indicates that the suspended dust deposition rate on the sand desert surface increases with the volume (A) and concentration (ϕ_0) of the dust plume released from an upstream DDA or ACP area. This equation suggests that increased dust emissions from DDA or ACP areas could lead to increased dust deposition on their downwind sand desert surfaces (Fig. 1). However, this external dust supply has never been considered as an important contributor to long-term dust production of the natural sand deserts.

3. Experimental set-up and method

In order to clarify the contribution of external dust supply to dust production of the sand desert surface, we performed experiments in the blowing-type wind tunnel in Key Laboratory of Desert and Desertification, Cold and Arid Regions Environmental and Engineering Institute, Chinese Academy of Sciences. Fig. 2 illustrated our experimental set-up. Because natural sand grains are coated with clay particles, it is very difficult to clean them. In order to avoid the effect of these coated particles on the dust production through aeolian abrasion, and to observe dust deposition on the sand desert surface directly, we instead used black glass beads (0.8 mm to1.2 mm in diameter) to make a tested glass bead bed (GBB, 4 m long, 1 m wide, and 0.1 m thick) on the bed of the experimental section of the wind tunnel. The glass beads were similar to quartz grains in density, and the GBB surface acted as a natural sand desert surface. In addition, the loess dust materials (<50 μm; approximately 18 μm median diameter) were also fed through a dust feeder and piled on the tunnel bed 3 m upwind of the GBB, which represented an external dust source for the GBB surface. At the downwind end of the GBB, a Tapered Element Oscillating Microbalance (TEOM) with a PM10 (<10 μm suspended dust particles) sampler was set (the

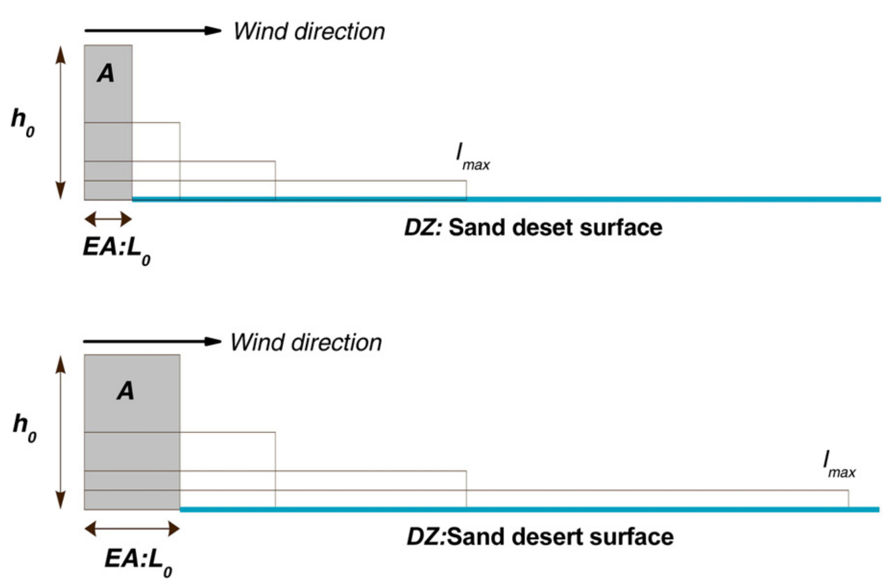

Fig. 1. Illustration showing the box model collapse of a two-dimensional dust density current of initial volume through a series of rectangles of equal cross-sectional area, which indicates that increased dust-emission areas (EA) can lead to expansion of dust deposition zones (DZ) on the downwind sand desert surface. A is the volume per unit width of the dust plume. h_0 and L_0 are the height and length of the initial dust plume released from a DDA or ACP area. l_{max} is the maximum transport distance of the dust plume.