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Progress on relationships between horizontal and vertical dust flux: Mathematical, empirical and risk-based perspectives

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Aeolian processes driving sediment flux and corresponding erosion are inherently 3-dimensional, but are primarily studied either with respect to the horizontal flux component, or to a lesser extent the vertical component. Understanding the relationship between horizontal flux and the vertical component of sediment and dust is critical to predicting fundamental processes such as erosion, and to assessing human and environmental risks associated with contaminated sediment and dust. Multiple mathematical approaches to calculate vertical flux of dust exist but are limited in their ability to predict vertical flux across a wide variety of landscapes and soil conditions. To address these issues, here we explore the relationship between horizontal and vertical fluxes from three perspectives: mathematical, based on existing equations; empirical, based on existing and new data; and risk-based, based on translating the former two into a risk context. Mathematical derivations suggest, depending on the approach, the two components could either be a constant ratio or that the vertical flux could be more dependent on the shear stress and particle size than horizontal flux. Empirical data highlight a wide range of ratios, varying by more than two orders of magnitude, though the ratios can be relatively similar within a given site and set of conditions. Risk-based assessment indicates the vertical flux component is relatively important in dose calculations, and consequently further improvement in mathematical and empirical relationships is needed. Collectively, these three perspectives expand insights on horizontal and vertical sediment fluxes and could aide future risk assessment from dust contaminants.

1. Introduction

Wind erosion and associated aeolian processes influence not only fundamental environmental factors such as site geomorphology and biogeochemical cycling (Pye, 1987; Okin et al., 2004; Goudie and Middleton, 2006; Field et al., 2009; Ravi et al., 2011), but also aspects of environmental health related to contaminant redistribution (Griffin et al., 2001; Pope and Dockery, 2006; Whicker et al., 2006a,b; Breshears et al., 2012; Csavina et al., 2012; Michelotti et al., 2013). A major uncertainty underlying these issues is the relationships for sediment flux between the horizontal component, largely saltation, and the vertical component, suspension (Shao et al., 1993; Gillette et al., 1997; Kok et al., 2012). Aeolian processes associated with wind erosion are temporally dynamic and inherently three dimensional in space. However, current measurement approaches generally focus on either the horizontal component of flux, or on the associated vertical component (Zobeck et al., 2003), with relatively few studies considering both aspects (e.g., Breshears et al., 2003). In addition, in the past decades, the increase in measurements of horizontal flux (reviewed in Breshears et al. (2009) and Miller et al. (2012)) has far outpaced that of vertical flux, yet for some issues, such as global dust loading and public health concerns of respirable dust, determining vertical fluxes is particularly important.

The relationship between horizontal and vertical flux, though assumed to be fundamentally related, (Bagnold, 1941; Gillette et al., 1997; Whicker et al., 2006a; Breshears et al., 2009) is not well understood. Few studies have explicitly evaluated the relationship between the emission of dust-sized particles (vertical flux) and the mass of horizontal sediment flux (Gillette, 1977; Nickling and Gillies, 1989; Shao et al., 1993; Gillette et al., 1997; Houser and Nickling, 2001; Panebianco et al., 2010). Most available data suggests that dust emission rates vary linearly with the saltation transport rate (e.g., Shao et al., 1993). Dust emission rates are expected to increase with the saltation transport rate, although there

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is considerable variation in this relationship, most likely due to textural and structural characteristics of the surface (Kjelgaard et al., 2004). Under disturbed conditions, vertical dust flux (i.e., soil loss per unit area) can be strongly correlated to total dust flux and has been shown to be as much as 55% of the total amount of dust emitted from the surface (Houser and Nickling, 2001). An improved understanding of the relationship between horizontal and vertical flux requires revisiting what is known about aeolian processes.

Aeolian sediment flux from an area depends on amount, type, and spatial arrangements of the vegetation (Okin and Gillette, 2001; Li et al., 2007; Ravi et al., 2011). Sources that have scarce and scattered vegetation cover (Li et al., 2007) with relatively large bare patches can amplify the sediment flux (Field et al., 2012). In addition, lines of relatively open spaces oriented with the predominant wind direction ("streets"; Okin and Gillette, 2001) can also result in increased horizontal flux. In contrast, vegetation patches themselves serves as sinks and can capture sediment flux (Field et al., 2012). Overall, the horizontal component of sediment flux from saltation dominates local redistribution for particle sizes >50 μm and has a range of transport generally on the scale of a few meters (Ravi et al., 2011). The vertical component of suspension moves particle sizes from ~1 to 50 μm and affects regional redistribution on a range of transport of meters to thousands of kilometers (Ravi et al., 2011). The rate of vertical deposition is location dependent, affected by plant/soil characteristics, turbulent deposition as well as gravitational settling (the later being particle-size dependent; Hinds, 1982; Ravi et al., 2011).

Although a suite of mathematical equations exist for predicting either horizontal or vertical flux (e.g., Shao et al., 1993; Okin, 2008; Kok et al., 2012), few relate the two (e.g., Breshears et al., 2003; Whicker et al., 2006a,b), and a general assessment of such relationships is needed. Developing improved relationships between the horizontal and vertical fluxes is particularly needed for dust-related exposure assessments in public and environmental health, but also for other important applications such as climate change modeling and other ecological impacts (Tegen et al., 1996; Prospero and Lamb, 2003; Field et al., 2009; Whicker et al., 2008; Ravi et al., 2011). The goal of this paper is to explore mathematical and empirical approaches for quantifying vertical flux from horizontal flux, aiming for an improved method to use vertical flux for exposure assessment purposes.

2. Mathematical perspectives of relationships between horizontal and vertical flux

Horizontal transport of soil particles by wind is initiated when fluid drag and lift forces overcome gravity and interparticle forces, or secondarily when airborne particles with aerodynamic diameters about 50 μm or greater impact onto soil surfaces and mechanically dislodge other soil particles into the air stream (Bagnold, 1941; Kok et al., 2012). Thus parameters related to these forces, such as the particle size and the sheer stress/friction velocity (u_*) across the soil surface, are generally included in equations for horizontal mass flux (Greeley and Iversen, 1985; Shao, 2008; Kok et al., 2012).

In contrast, for smaller particles (e.g., <20 μm), interparticle electrical forces are significant and are often stronger than the drag and lift forces (Hinds, 1982). Impacts of larger saltating particles are generally needed for suspending these smaller particles, which comprise the majority of vertical mass flux (Bagnold, 1941; Kjelgaard et al., 2004; Ravi et al., 2011; Kok et al., 2012). Because salting particles suspend the smaller particles, vertical flux should be fundamentally related to and perhaps directly proportional to the horizontally transported sediment (Marticornea and Bergametti, 1995), as has sometimes been assumed in absence of quantifying such relationships (e.g., Breshears et al., 2009 and subsequent modeling by Breshears et al., 2012 and Michelotti et al., 2013).

Equations to mathematically describe horizontal and vertical flux individually have been developed and generally contain the same key parameters such as friction velocities, threshold friction velocities, density of air, and the gravitational constant, which govern sediment transport (Kok et al., 2012). From these equations, we focus initially on those with algebraically similar arrangements of the parameters to explore potential relationships between horizontal and vertical flux. For horizontal flux, Eq. (1) (Durán et al., 2011; Kok et al., 2012) predicts the flux as a function of constants such as the air density and gravitational forces, but also includes variables such as friction velocity and impact friction velocity (the friction velocity required to sustain saltation), which are influenced by vegetation and soil and soil surface properties.

$$Q_{\mathrm{DK}} = C_{\mathrm{DK}} \frac{\rho_a}{g} u_{*,it} u_*^2 \left(1 - \frac{u_{*,it}^2}{u_*^2}\right) \quad (1)$$

Here, Q_{DK} is the horizontal flux, C_{DK} is a constant, ρ_a is the density of air, g is the gravitational constant, $u_{*,it}$ is the impact threshold friction velocity, and u_* is the friction velocity.

Vertical flux, F_V, has been described by similar equations, as shown in Eq. (2) (Kok et al., 2012). The parameters are the same as in Eq. (1) except for C_F, which is proportionality constant.

$$F_V = C_F \rho_a u_{*,it} (u_*^2 - u_{*,it}^2) \quad (2)$$

Because the parameters for both equations contain similar parameters and are comparable algebraically, the relationship between the vertical and horizontal fluxes can be simplified to a ratio. To obtain this ratio, first Eq. (1) is simplified by multiplying the square of the friction velocity into the brackets Eq. (3).

$$Q_{\mathrm{DK}} = C_{\mathrm{DK}} \frac{\rho_a}{g} u_{*,it} (u_*^2 - u_{*,it}^2) \quad (3)$$

Now Eqs. (2) and (3) are in similar forms and the ratio of two can be simplified to a constant Eqs. (4) and (5):

$$\frac{F_v}{Q_{\mathrm{DK}}} = \frac{C_F \rho_a u_{*,it} (u_*^2 - u_{*,it}^2)}{C_{\mathrm{DK}} \frac{\rho_a}{g} u_{*,it} (u_*^2 - u_{*,it}^2)} \quad (4)$$

or simplified further to obtain:

$$\frac{F_v}{Q_{\mathrm{DK}}} = \frac{C_F g}{C_{\mathrm{Dk}}} \quad (5)$$

The ratio reduces down to a constant, essentially a dust emissions factor, which predicts that F_V is directly proportional to Q, or some fraction of Q. The emissions factor, while a constant for a site, could vary over several orders-of-magnitude across locations based on available field data provided later in this paper and in Kok et al. (2012). The large variation in the dust emission factor across data sets suggests that the ratio could depend on the site conditions such as soil and vegetation, and it is well documented that saltation flux changes across soils and vegetation types in various ecosystems (e.g., Breshears et al., 2003, 2009).

Another possibility is that horizontal and vertical flux, while fundamentally tied to the same physics of sediment transport, could vary somewhat independently due to particle size and other differences that impact the forces acting on a particle. For example, some equations for vertical flux suggest it may have a stronger dependence on friction velocity, μ_*, than horizontal flux. Additionally, some equations for horizontal flux explicitly include parameters for soil bed characteristics, particularly as a function of particle sizes. Using a similar approach as used in Eqs. (3) and (4), Eq. (6) predicts vertical flux via the approach of Gillette and Passi (1988)