Remote Sensing of Environment 114 (2010) 1462–1470

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Estimating aerodynamic resistance of rough surfaces using angular reflectance

Adrian Chappell [a],*, Scott Van Pelt [b], Ted Zobeck [c], Zhibao Dong [d]

[a] CSIRO Land and Water, GPO Box 1666, Canberra, ACT 2601, Australia
[b] Agricultural Research Service, United States Department of Agriculture, Big Spring, TX, 79720, USA
[c] Agricultural Research Service, United States Department of Agriculture, Lubbock, TX, 79720, USA
[d] Key Laboratory of Desert and Desertification, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, No. 320 West Donggang Road, Lanzhou 730000, Gansu Province, PR China

A R T I C L E I N F O

Article history:
Received 23 November 2009
Received in revised form 27 January 2010
Accepted 30 January 2010

Keywords:
Dust emission model
Wind erosion
Sheltering
Erodible
Flow separation
Drag
Wake
Aerodynamic resistance
Aerodynamic roughness length
Shadow
Illumination
Ray-casting
Digital elevation model
Roughness density
Frontal area index
Angular reflectance
Bi-directional reflectance

ABSTRACT

Current wind erosion and dust emission models neglect the heterogeneous nature of surface roughness and its geometric anisotropic effect on aerodynamic resistance, and over-estimate the erodible area by assuming it is not covered by roughness elements. We address these shortfalls with a new model which estimates aerodynamic roughness length (z_0) using angular reflectance of a rough surface. The new model is proportional to the frontal area index, directional, and represents the geometric anisotropy of z_0. The model explained most of the variation in two sets of wind tunnel measurements of aerodynamic roughness lengths (z_0). Field estimates of z_0 for varying wind directions were similar to predictions made by the new model. The model was used to estimate the erodible area exposed to abrasion by saltating particles. Vertically integrated horizontal flux (F_h) was calculated using the area not covered by non-erodible hemispheres; the approach embodied in dust emission models. Under the same model conditions, F_h estimated using the new model was up to 85% smaller than that using the conventional area not covered. These F_h simulations imply that wind erosion and dust emission models without geometric anisotropic sheltering of the surface, may considerably over-estimate F_h and hence the amount of dust emission. The new model provides a straightforward method to estimate aerodynamic resistance with the potential to improve the accuracy of wind erosion and dust emission models, a measure that can be retrieved using bi-directional reflectance models from angular satellite sensors, and an alternative to notoriously unreliable field estimates of z_0 and their extrapolations across landform scales.

1. Introduction

Soil-derived mineral dust contributes significantly to the global aerosol load. The direct and indirect climatic effects of dust are potentially large. A prerequisite for estimating the various effects and interactions of dust and climate is the quantification of global atmospheric dust loads (Tegen, 2003). Recent developments in global dust emission models explicitly simulate areas of largely unvegetated dry lake beds as sources of preferential dust emission (Tegen et al., 2002, 2006; Mahowald et al., 2003). In the case of the Earth's largest source of dust (Bodélé Depression; Warren et al., 2007) there are some significant discrepancies between ground measurements of dust emission processes and model assumptions (Chappell et al., 2008). Dust emission is produced by two related processes called saltation and sandblasting. Saltation is the net horizontal motion of large particles or aggregates of particles moving in a turbulent near-surface layer. Sandblasting is the release of dust and larger material caused by saltators as they impact the surface (Alfaro & Gomez, 1995; Shao, 2001). Naturally rough (unvegetated) surfaces usually comprise a heterogeneous mixture (size and spacing) of non-erodible roughness elements that reduce the area of exposed and hence erodible substrate. When such rough surfaces are exposed to the wind, wakes or areas of flow separation (Arya, 1975) are created downwind of all obstacles. These sheltered areas reduce the area of exposed substrate still further and protect some of the roughness elements from the wind (depending on their size and spacing). This heuristic formed the basis for the dimensional analysis of the Raupach (1992) model where dynamic turbulence was replaced by a concept of effective shelter area and was portrayed as a wedge-shaped sheltered area in the lee of the element. The size and shape of the sheltered area is influenced by the wind velocity (speed and direction) and the heterogeneous nature of the surface (Fig. 1). Consequently, the erodible area and the non-

---

* Corresponding author.
E-mail address: adrian.chappell@csiro.au (A. Chappell).

0034-4257/$ – see front matter. Crown Copyright © 2010 Published by Elsevier Inc. All rights reserved.
doi:10.1016/j.rse.2010.01.025

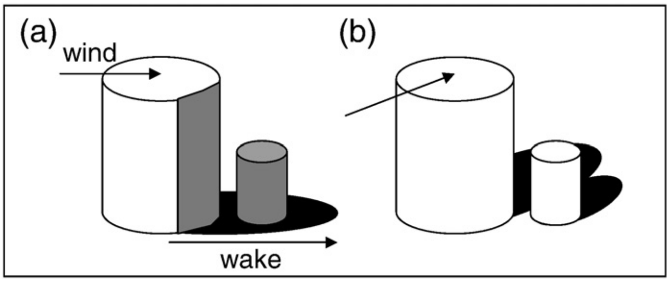

Fig. 1. Cylinders used to represent non-erodible roughness elements in wind tunnel studies and parameterizations for wind erosion and dust emission models protect a portion of the substrate surface that may include all or part of other roughness elements in a heterogeneous surface (a). A change in wind direction redefines the area of the substrate protected from the wind and may expose previously protected roughness elements (b).

erodible roughness elements that are exposed to, and protected from, drag are an anisotropic function of the heterogeneous surface and wind speed.

Central to wind erosion and dust emission models is the turbulent transfer of momentum from the fluid to the bed. The key assumption made by dust emission models (e.g., Marticorena and Bergametti, 1995; p. 16,418) is that the momentum extracted by roughness elements is controlled primarily by their roughness density (λ; Marshall, 1971) and consequently the erodible area is that which is not covered by roughness elements. The λ (also known as lateral cover or the frontal area index) is expressed as $\lambda = nbh/S$ where n is the number of roughness elements inside an area (or pixel) S and b and h are the breadth and height, respectively of the roughness elements. This assumption forms one of the foundations for the dust production model (Marticorena and Bergametti, 1995) and dust emission scheme (Marticorena et al., 1997) upon which many dust emission models are based (e.g., Tegen et al., 2006). The approach assumes that the roughness elements cover part of the surface, protect it from erosion and that they consume part of the momentum available to initiate and sustain particle motion by the wind. The assumption manifests itself in dust emission models (e.g., Marticorena and Bergametti, 1995; p. 16,422; Eq. 34):

$$G_{\mathrm{tot}} = EC\frac{\rho_{\mathrm{a}}}{g}U_*^3\int_{D_{\mathrm{p}}}(1+R)\left(1-R^2\right)dS_{\mathrm{rel}}\left(D_{\mathrm{p}}\right)dD_{\mathrm{p}} \qquad (1)$$

as the ratio of the erodible area to the total surface area (E) and is set to 1 in the absence of information about non-erodible roughness elements and of vegetation and snow (Tegen et al., 2006). The parameter C is a constant of proportionality (2.61), ρ_{a} is the air density, g is a gravitational constant, U_*^3 is the cubic shear stress of the Prandtl–von Karman equation where $U_* = u(z)(k/\ln(z/z_0))$ and u is the wind speed at a reference height z, k is von Karman's constant (0.4) and z_0 is the aerodynamic roughness length. The threshold friction velocity defines $R = U_{*t}(D_{\mathrm{p}}, z_0, z_{0\mathrm{s}})/U_*$ where the threshold shear stress $U_{*\mathrm{t}}$ is a function of particle diameter D_{p}, z_0 and the aerodynamic roughness length of the same surface without obstacles ($z_{0\mathrm{s}}$). The dS_{rel} is a continuous relative distribution of basal surfaces formed by dividing the mass size distribution by the total basal surface and dD_{p} is the particle diameter distribution. This approach includes neither a sheltering effect nor any interaction between the momentum extraction of the roughness elements and the downwind substrate area that they protect (wake). Furthermore, R implicitly assumes homogeneous surface roughness and it does not account for the anisotropy of heterogeneous surface roughness created by changing wind directions i.e., anisotropic z_0.

Wind erosion and dust emission models should reach a compromise between the realistic representation of the erosion/abrasion processes and the availability of data to parameterize or drive the model (Raupach & Lu, 2004). The requirement here is to reduce the complexity of aerodynamic resistance from an understanding of wake and shelter but capture the essence of the process to make reasonable estimates, particularly across scales of variation. For example, Shao et al. (1996) provided one of the first physically-based wind erosion models to operate across spatial scales from the field to the continent (Australia). One of the main reasons for its success was its approximation of λ using NDVI (Normalised Difference Vegetation Index) data. To improve this approximation Marticorena et al. (2004) argued that a proportional relationship existed between the protrusion coefficient (*PC*) derived from a semi-empirical bi-directional reflectance (BRF) model (Roujean et al., 1992) and geometric roughness. Although Roujean et al. (1992) stated the model's limitation for unvegetated situations and Marticorena et al. (2004) recognised this limitation, they developed a relationship between geometric roughness and z_0. They retrieved the *PC* from surface products of the space-borne POLDER (POLarization and Directionality of the Earth's Reflectances) instrument and compared it to geomorphic estimates of z_0 (Marticorena et al. 1997; Callot et al. 2000). The authors concluded that z_0 could be derived reliably from the PC in arid areas.

The main justification for the simplifying assumption of λ in wind erosion and dust emission models appears to be the hypothesis that the configuration and shape of non-erodible (unvegetated) surface roughness elements are unimportant for explaining the drag partition. The concept of drag or shear stress partitioning (Schlichting, 1936) is that the total force on a rough surface F_{t} can be partitioned into two parts: F_{r} acting on the non-erodible roughness elements and F_{s} acting on the intervening substrate surface $F_{\mathrm{t}} = F_{\mathrm{r}} + F_{\mathrm{s}}$. There is a growing body of evidence that supports this approach. For example, Marshall (1971) studied drag partition experimentally in a wind tunnel and showed no difference between cylinders placed on a regular grid, on a diagonal or at random across the wind tunnel ($\lambda = 0.0002$ to 0.2). Raupach et al. (1993) reached a similar conclusion after inspecting Marshall's data and believed that there was only a weak experimental dependence of stress partition on roughness element shape and the arrangement of elements on the surface. Drag balance instrumentation used by Brown et al. (2008) in a wind tunnel, independently and simultaneously measured the drag on arrays of cylinders and the intervening surface, separately. Results were interpreted as confirmation that an increase in surface roughness enhanced the sheltering of the surface, regardless of roughness configuration i.e., irregular arrays of cylinders were analogous to staggered configurations in terms of drag partitioning.

The role of flow separation and much-reduced drag in sheltered regions, particularly downwind of roughness elements, is significant for drag partitioning. We posit that the sheltered area is required to account for anisotropic variation in aerodynamic resistance for realistic wind erosion and dust emission models. Furthermore, we posit that current estimates of the erodible area using the area not covered by protruding objects is a poor representation of the erodible substrate exposed to abrasion from mobile material. The aim of the paper is to describe and evaluate the basis for using angular reflectance data to quantify the geometric anisotropy of aerodynamic resistance, account for heterogeneity and estimate the area exposed to abrasion.

2. Estimating aerodynamic roughness length (z_0) and erodible area using shadow

2.1. Relationship between reflectance and frontal area index (λ)

A new approach is presented here which is based on Chappell and Heritage (2007). The approach is inspired by the dimensional analysis of the Raupach (1992; p. 377–378) model (effective shelter area) and its replacement of dynamic turbulence with the scales controlling an element wake and how the wakes interact (Shao and Yang, 2005) and by the heuristic model of Arya (1975) and hence its similarity with the scheme of Marticorena and Bergametti (1995). In common with Marticorena et al. (2004), we show the relationship between reflectance and aerodynamic resistance estimated by wind tunnel