Aeolian Research 23 (2016) 63–78

Contents lists available at ScienceDirect

Aeolian Research

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

Using albedo to reform wind erosion modelling, mapping and monitoring

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ARTICLE INFO

Article history:
Received 14 June 2016
Revised 29 September 2016
Accepted 29 September 2016
Available online 15 October 2016

ABSTRACT

Wind erosion and dust emission models are used to assess the impacts of dust on radiative forcing in the atmosphere, cloud formation, nutrient fertilisation and human health. The models are underpinned by a two-dimensional geometric property (lateral cover; L) used to characterise the three-dimensional aerodynamic roughness (sheltered area or wakes) of the Earth's surface and calibrate the momentum it extracts from the wind. We reveal a fundamental weakness in L and demonstrate that values are an order of magnitude too small and significant aerodynamic interactions between roughness elements and their sheltered areas have been omitted, particularly under sparse surface roughness. We describe a solution which develops published work to establish a relation between sheltered area and the proportion of shadow over a given area; the inverse of direct beam directional hemispherical reflectance (black sky albedo; BSA). We show direct relations between shadow and wind tunnel measurements and thereby provide direct calibrations of key aerodynamic properties. Estimation of the aerodynamic parameters from albedo enables wind erosion assessments over areas, across platforms from the field to airborne and readily available satellite data. Our new approach demonstrated redundancy in existing wind erosion models and thereby reduced model complexity and improved fidelity. We found that the use of albedo enabled an adequate description of aerodynamic sheltering to characterise fluid dynamics and predict sediment transport without the use of a drag partition scheme (R_t) or threshold friction velocity (u_{*t}). We applied the calibrations to produce global maps of aerodynamic properties which showed very similar spatial patterns to each other and confirmed the redundancy in the traditional parameters of wind erosion modelling. We evaluated temporal patterns of predicted horizontal mass flux at locations across Australia which revealed variation between land cover types that would not be detected using traditional models. Our new approach provided new opportunities to investigate the dynamics of wind erosion in space and time and elucidate aeolian processes across scales.

1. Introduction

Wind erosion and dust emission are driven by the turbulent transfer of momentum from the fluid to the land surface (Shao et al., 2015). The aerodynamic turbulence is influenced by surface roughness across a range of scales from the soil grain (mm) to the landscape (km). At these scales, roughness elements comprise individual landforms (e.g., dunes), vegetation (trees, shrubs, grasses) which may be photosynthetic or non-photosynthetic, and the exposed soil surface which may be rough or smooth depending on the presence of physical, chemical or biogenic crusts, the soil texture, natural structures (rocks) or management-induced features (clods, furrows). All of these roughness elements have a spatial arrangement (or spatial dependence) originating from the processes which formed them. Dunes are aligned with wind flows (Lancaster, 2013), vegetation may be aligned with wind, water or nutrient flows (Okin et al., 2015) and the soil surface may have structure within and between vegetation patches due to natural or human-induced patterns (Webb and Strong, 2011). All of these roughness elements are temporally variable or dynamic. Within any particular timeframe the surface roughness causes a highly anisotropic extraction of wind momentum relative to its direction. Natural heterogeneous mixtures of roughness elements produce highly variable aerodynamic turbulence and momentum extraction which are responsible for the magnitude and spatial patterns of wind erosion and dust emission (Gillette, 1999).

The seminal work of Bagnold (1941) provided the foundation for numerous subsequent field studies to investigate the relation between wind velocity profiles, aerodynamic turbulence and

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http://dx.doi.org/10.1016/j.aeolia.2016.09.006
1875-9637/

point-based sediment transport. Much of the knowledge about the spatial and temporal variation of aerodynamic turbulence across scales is gained from point-based field work and wind tunnel studies (e.g. Marshall, 1971; Gillette and Stockton, 1989; Wolfe and Nickling, 1996; Lancaster and Baas, 1998; Gillies et al., 2000, 2007; Crawley and Nickling, 2003; King et al., 2006; Brown et al., 2008; Webb et al., 2014). Wind tunnel studies have also replicated the fieldwork and isolated the controlling factors to improve our understanding of aerodynamic turbulence, roughness (z_0) and transport feedbacks (Duran et al., 2011; Charru et al., 2013; Jenkins and Valance, 2014). Accurate estimation of sediment transport rates is dependent on capturing the aerodynamic roughness feedbacks to saltation, which affect the scaling of transport rates with the area-integrated (areal) momentum flux and ultimately the magnitude of dust emissions from given areas.

At the landscape scale, wind velocity profiles have been used to determine the aerodynamic roughness for diverse vegetation and surface roughness conditions (e.g. MacKinnon et al., 2004; Gillette et al., 2006). These measurements include heterogeneous combinations of roughness scales, orientations and anisotropic responses to roughness elements. However, little consideration has been given to the upstream area, and therefore which mixtures of roughness elements, influence z_0 and hence which scale has contributed most. André and Blondin (1986) and Taylor (1987) suggested that the integrated roughness length is strongly influenced by its spatial variability. Wieringa (1993) indicated that relatively rough patches contribute more to the effective aerodynamic roughness of a surface than their area fraction. The confounding anisotropic interaction between wind direction, contributing area and roughness scale is consistently omitted from studies (Chappell et al., 2010; Smith et al., 2016). Raupach and Lu (2004) questioned the extent to which wind erosion and dust emission models, developed to represent processes at the point scale, are applicable to heterogeneous situations over large areas or pixels. Although improved accuracy of measurement and statistical modelling (Bauer et al., 1992) has reduced uncertainty in the estimation of z_0 from wind velocity profiles, this standardisation may have distracted research in this field from establishing the uncertainty from the many sources of variance. For example, if masts of anemometers were placed at different locations within a given area or pixel (measuring at the same time without interfering with the wind flow) they would most likely provide wind velocity profiles with different z_0; its spatial variability. If those estimates of z_0 from within that area were unbiased samples and adequately represented the spatial variation, then the average and variance of z_0 would accurately and precisely characterise the area. Similarly, it is difficult to use a wind velocity profile from a single location to estimate the surface shear stress of an area if it is influenced by spatially varying soil surface roughness and heterogeneous vegetation elements.

There is evidently a need to establish the spatial variability or the areal average (integrated) of aerodynamic properties to more accurately account for their influence on wind erosion and dust emission. Researchers have looked to remote sensing to provide area average estimates of z_0 on the basis that light is scattered in proportion to the size and number of roughness elements within a pixel. However, the challenge, in common with many aspects of remote sensing, is to find a property that can be retrieved from reflectance data, which is related to z_0, robust across scales and may be transferred to other places or times. Greeley (1991) linked wind velocity profile estimates of z_0 to radar backscatter cross sections from airborne and space borne platforms (Greeley et al., 1997). Marticorena et al. (2006) showed significant relations between radar backscatter coefficients and z_0 and proposed an empirical relation to retrieve z_0 using radar observations in the C band from operational sensors. Marticorena et al. (2004) suggested a proportional relationship between the protrusion coefficient derived from a bi-directional reflectance model and geometric roughness and then to z_0. Chappell et al. (2010) established a physically-based relation between sheltered area and single scattering albedo from bi-directional reflectance models. These approaches have all shown promise for overcoming the limitations of field measurements of z_0 and direct application in representing momentum transfer in wind erosion and dust emission models.

Perhaps one of the most influential approximations in aerodynamic turbulence is that momentum extracted by roughness elements can be represented by roughness density (lateral cover or the frontal area index L; Marshall, 1971; Wooding et al., 1973). However, L omits the interaction between roughness elements i.e., ignores the orientation of objects and assumes that they are isotropic within a pixel. In practice, the estimation of L over large areas (regions, continents) is difficult and often approximated using classifications of cover and vegetation type from satellite remote sensing and in the case of bare surfaces, using geometry (cf. Shao et al., 1996; Marticorena et al., 2006). These practical approximations create discontinuities between land surface classes for the models and largely exclude heterogeneity due to mixtures of different surface types. This uncertainty is significant because these models are used to predict regional and global wind erosion and dust emission (e.g., Marticorena and Bergametti, 1995; Alfaro and Gomez, 1995; Shao et al., 2011).

There remains a need to reduce the uncertainty associated with the estimation and parameterisation of aerodynamic turbulence for aeolian process studies using a holistic approach that works across scales of roughness. The objectives of this paper are to: outline the basis for the established method of reducing the complexity of aerodynamic turbulence using lateral cover (Raupach et al., 1993), reveal weaknesses in the lateral cover and thereby provide the rationale for a new approach based on shadow (Section 2); outline the foundation for the shadow-based approach and describe its physically-based development from Raupach's concept and show how it can be used to estimate key aerodynamic parameters (Section 3); demonstrate how wind erosion modelling can be more parsimonious than current approaches whilst retaining the fidelity of the processes (Section 4); illustrate the use of shadow with estimates from the Moderate Resolution Imaging Spectroradiometer (MODIS) (every 8 days and every 500 m) to map and monitor areal aerodynamic parameters for wind erosion (sediment flux) across a range of land surface types and demonstrate their dynamics in space and time (Section 5); consider the implications and opportunities that this new shadow-based approach provides for aeolian research across scales of variation (grain to landscape; Section 6).

2. Lateral cover and its weaknesses for wind erosion modelling

In his seminal work, Raupach (1992) reduced the complexity of aerodynamic roughness by characterising the wake of an isolated roughness element placed on the surface using an effective shelter area (A; Fig. 1a). He used cylinders to represent roughness elements, assuming that they were an adequate approximation of the plant structure. He reasoned that the ground surface shear stress (τ_S) within A should be zero and idealised A as a wedge-shaped "shadow" in the lee of the roughness element (Fig. 1a). Raupach (1992) provided a physical basis for this scaling (Hypothesis I) in which the shear layers bounding the wake spread at an angle of order $\alpha = U_h/u_*$ (where U_h is the mean wind velocity at height h) to the streamwise direction, similar to the inner layer of modified wind flow over a hill (Finnigan et al., 1990).

Raupach (1992) assumed that the ground surface shear stress reductions in the wake of an element are spread over a region considered large relative to A (Hypothesis II). This assumption