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Large-eddy simulation of turbulent dust emission

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ABSTRACT

Turbulent dust emission is an important mechanism to be considered in dust models. For example, over a heated desert surface under weak wind conditions, convective turbulence can be highly developed, which generates patches of enhanced shear stresses and entrains dust into the atmosphere. This mechanism of dust emission differs from those considered in existing dust emission schemes because it does not have to involve the saltation of sand-sized particles. In this study, we develop a large-eddy dust model, WRF-LES/D, by coupling the WRF large-eddy flow model with a new dust mobilization scheme. It is then applied to the simulation of turbulent dust emission under various stability and wind conditions. Our aim is to understand how turbulent dust emission occurs and how turbulent dust fluxes depend on atmospheric control parameters. We show that, due to the complexity of turbulent motion and the dust cohesive forces, turbulent dust emission is a stochastic process which needs to be statistically quantified. With the numerical results, we quantify the large-eddy induced shear stresses on the surface and turbulent dust emissions in terms of probabilistic distributions. For a given soil type, it is shown that these distributions can be described in terms of a few control variables, including the friction velocity, u_*, and the convective scaling velocity, w_*.

1. Introduction

Dust emission parameterization schemes (here after dust schemes) for regional and global dust models have been under development since the early 1990s (e.g. Shao et al., 1993; Marticorena and Bergametti, 1995; Alfaro and Gomes, 2001; Zender et al., 2003; Shao, 2004; Kok, 2011). In these schemes, saltation bombardment and aggregates disintegration are considered to be the main mechanisms. The successful applications of these schemes to regional and global dust modeling have been reported in numerous studies (e.g. Tanaka and Chiba, 2006; Reinfried et al., 2009; Darmenova et al., 2008; Uno et al., 2009), but they are not applicable to weak wind conditions when there is no saltation. Experiences show that turbulent dust emission, i.e., dust emission due to convective turbulent motion in the absence of strong mean wind, is not insignificant, as exemplified by the dust devils often observed over heated desert surfaces. On Mars, dust devils are most important to dust emission (Balme and Greeley, 2006; Greeley et al., 2006). Aeolian dust is the primary source of iron supply to the surface oceans, vital to the phytoplankton growth and air–sea carbon exchange (Mahowald et al., 2009; Maher et al., 2010). While strong dust events are important to the episodic increase in atmospheric dust concentration, the weak but frequent dust events may be more important in maintaining the background dust concentration and the continuous dust supply to sustain the ocean biomass productivity.

Convective turbulent dust emission (CTDE) is the most outstanding form of turbulent dust emission. While CTDE is widely perceived to be important, no scheme existed for its quantitative estimate until the recent work of Klose and Shao (2012). The classic view has been that dust emission is related to the motion of sand-sized grains driven by the mean wind (Bagnold, 1941; Shao, 2008), as illustrated in Fig. 1a. The mechanism of CTDE is different, as shown in Fig. 1b: in a convective atmospheric boundary layer, large eddies have coherent structures (e.g. micro-bursts, vortex rolls and vortices) of dimensions comparable to boundary-layer depth. These eddies are efficient entities in generating localized momentum fluxes to the surface. Although the eddies only occupy fractions of time and space, the momentum fluxes to these fractions can be many times the average. Consequently, the surface intermittently experiences patches of strong shear stresses which entrain dust into the atmosphere. The essential differences between CTDE and the dust emission mechanisms considered in "traditional" dust schemes are (1) CTDE is stochastic and (2) it does not have to, although it can, involve saltation.

Research is needed to understand the dynamics of CTDE for its parameterization in large scale models. This is a challenging problem due to the rapid change of turbulence scales close to the surface and the random factors which affect surface properties. To our knowledge, no field or laboratory experiments on CTDE have ever been carried out. Large-eddy simulation provides a powerful

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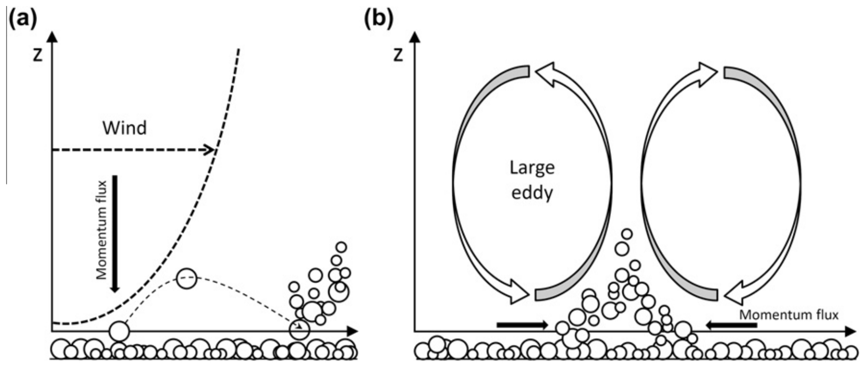

Fig. 1. (a) Conventional view of dust emission via saltation bombardment induced by the momentum flux to the surface by the mean wind. (b) Illustration of particle lifting caused by the momentum intermittently transported to the surface by turbulent eddies. Saltation may be but does not need to be involved.

tool to studying the problems of CTDE. This technique has been widely used to modeling atmospheric turbulent flows (Deardorff, 1970; Moeng et al., 2007), also in relation to dust devils (Michaels and Rafkin, 2004). Kanak et al. (2000) and Kanak (2005) showed that vortices can be generated from convective cells or branches of convective cells forced under the conditions of strong heat flux and weak wind shear. Ohno and Takemi (2010) found that the merge of multiple vortices with the same sign of vorticity is important for strengthening and maintaining intense vortices. While these numerical studies provided a better understanding of dust-devil dynamics, they are done without dust.

We study the mechanisms of CTDE by means of large-eddy modeling, focusing on two important issues, namely, (1) how convective turbulence produces surface shear stresses and how the probability distributions of the shear stress can be statistically quantified, and (2) how convective turbulence generates dust emission and how size-resolved dust emission depends on macroscopic atmospheric conditions. Our hypothesis is that the impact of large eddies on dust emission can be statistically evaluated from the model simulations and CTDE can be expressed in terms of a small number of environmental control parameters. To this end, we develop a large-eddy dust model (WRF-LES/D) by coupling the Advanced Research WRF (Weather Research and Forecasting) large-eddy model (Skamarock et al., 2008) Version 3.2 with a new dust module. WRF-LES/D is then applied to simulating turbulent dust emission for various conditions of boundary-layer stability and flow speed for a given soil type. The numerical results are evaluated to answer the above listed questions. The purpose of this paper is not to validate WRF-LES/D, but to use it as a tool to establish a conceptual basis for the parameterization of CTDE and more generally of turbulent dust emission.

2. Large-eddy dust model

The large-eddy dust model, WRF-LES/D, couples the WRF large-eddy model with a new dust mobilization scheme.

2.1. Dust mobilization scheme

The ansatz of the new dust scheme differs from that of traditional dust emission schemes, in that the stochastic nature of dust emission is considered. This is done by taking into account the statistical distributions of turbulent shear stress and retarding forces on dust particles. We distinguish between turbulent shear stress and Reynolds shear stress. The latter on the surface is

$$\tau = -\rho\sqrt{(\overline{u'w'})^2 + (\overline{v'w'})^2} \quad (1)$$

where ρ is air density, u' and v' are the horizontal velocity derivations from the horizontal mean wind components $\bar{u}$ and $\bar{v}$, and w' is the vertical. The over-line denotes the Reynolds averaging (approximated in atmospheric boundary-layer studies by an averaging over 20 min). τ is the shear stress exerted by the mean wind on the surface, which is considered in traditional dust schemes to be the primary driver for the dust emission process. However, τ is not the suitable quantity for driving turbulent dust emission, because the motion and emission of dust particles respond to shear stresses varying on much shorter time scales. We thus define the instantaneous shear stress vector as

$$\vec{\tau}_f = \rho(uw)\,\vec{i} + \rho(vw)\,\vec{j} \quad (2)$$

with $u = \bar{u} + u'$, etc. Note that the direction of $\vec{\tau}_f$ is irrelevant to dust emission, but its magnitude

$$\tau_f = \rho\sqrt{(uw)^2 + (vw)^2} \quad (3)$$

is. The aerodynamic force that acts on a particle on the surface, f, is proportional to τ_f

$$f = \tau_f \pi d^2/4 \quad (3a)$$

Due to turbulent fluctuations, f is a stochastic quantity which obeys a pdf (probability density function), $p(f)$.

Two retarding forces act on a dust particle on the surface: the gravity force, $f_g = m_p g$ with dust particle mass, m_p, and gravitational acceleration, g, and the inter-particle cohesive force, f_i, i.e., $f_t = f_g + f_i$. For small particles, f_i dominates but depends on many factors, ranging from particle shape to soil mineralogical composition, and is best characterized as a stochastic variable. Suppose the pdf of the retarding force is $p(f_t)$. Then, dust emission due to turbulence must be proportional to the overlapping area between $p(f)$ and $p(f_t)$ as depicted in Fig. 2a.

Dust emission is the vertical dust mass flux at the surface. We interpret the "surface" as the top of the viscous layer adjacent to the ground (i.e., D in Fig. 2b). Suppose the dust particle number flux through that surface is n (m^{-2} s^{-1}) and the dust particle mass is m_p. Then the dust flux is

$$\tilde{F} = n \cdot m_p = N w_p m_p \quad (4)$$

where w_p is the vertical component of the dust particle velocity at the surface and N the dust particle number concentration in the viscous layer. The equation w_p obeys is

$$\frac{dw_p}{dt} = -\frac{w_p - w}{T_p} - \frac{f - f_t}{m_p} \quad (5)$$

with T_p being the particle response time. As f_i is zero as soon as the particle leaves the ground, by integrating Eq. (5) over the depth of D, we obtain an approximate solution for w_p