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A numerical study on dust devils with implications to global dust budget estimates

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ABSTRACT

The estimates of the contribution of dust devils (DDs) to the global dust budget have large uncertainties because the dust emission mechanisms in DDs are not yet well understood. In this study, a large-eddy simulation model coupled with a dust scheme is used to investigate DD dust entrainment. DDs are identified from the simulations using various threshold values for pressure drop and vorticity in the DD center. A vortex-tracking algorithm is presented, which automatically detects and tracks vortices based on different pressure drop and vorticity criteria. The results show that DD dust lifting can be largely explained by convective turbulent dust emission. DD dust entrainment varies strongly between individual DDs even for similar atmospheric conditions, but the maximum emissions are determined by atmospheric stability. By relating DD emission and counts to the Richardson number, we propose a new and simple method to estimate regional and global DD dust transport.

1. Introduction

Dust devils (DDs) are small dust carrying vortices. They occur frequently on Earth and Mars, but their contributions to the terrestrial and martian dust budget are so far not well quantified. DDs are subgrid systems in global models and it is not clear how DD dust emission can be parameterized. Renno et al. (1998) developed a thermodynamic theory for DD occurrence and intensity, and based on this theory, Koch and Renno (2005) estimated the contribution of DDs to the terrestrial dust budget to be $\sim 26 \pm 18\%$. In their estimate, DD dust fluxes are determined from the maximum dust concentration and vertical wind speed measured in a small number of strong DDs. The resulting dust fluxes are not necessarily the surface dust fluxes and may lead to an overestimation of the DD dust contribution. Jemmett-Smith et al. (2015) used meteorological criteria to estimate the potential of DD occurrence, and found a much lower global DD contribution of 3.4% (estimates range from 0.9 to 31% depending on the criteria used). To obtain this estimate, Jemmett-Smith et al. (2015) used the same fractional updraft areas and dust fluxes as Koch and Renno (2005).

Dust emission mechanisms in DDs are subject to ongoing research. Saltation bombardment, the process in which dust emission is generated by impacts of hopping sand-sized grains, does not alone explain dust emission in DDs, as the necessary condition to initiate saltation (i.e. the friction velocity, u_*, must be larger than the threshold friction velocity for saltation, u_{*t}) is often not reached. Other mechanisms specific to DD dust emission have been suggested, such as dust uplift due to a vertical pressure drop at the surface (suction), but the significance of this process has not yet been quantitatively determined (Balme and Hagermann, 2006). Also, the vertical pressure drop may be related to the tangential vortex speed, thus the consideration of vortex velocity may be sufficient in the study of DDs (Wang, 2016). As pressure drop is easier to measure than tangential vortex speed, it is often used as a direct indicator for DD intensity and DD dust load (e.g. Neakrase and Greeley, 2010; Metzger et al., 2011; Lorenz and Jackson, 2015).

Klose and Shao (2012) and Klose et al. (2014) have developed a parameterization for the direct aerodynamic dust entrainment by turbulence. The scheme focuses on convective conditions, the situation when DDs develop, and takes account of the stochastic nature of both atmospheric particle lifting forces and surface interparticle cohesive forces.

Large-eddy simulation (LES) is a powerful tool to investigate DDs (e.g. Deardorff, 1970; Kanak, 2005; Zhao et al., 2004; Gu et al., 2008), but apart from few exceptions (Michaels, 2006; Ito et al., 2010), DD dust entrainment has not been included in large-eddy simulation models. In this study, we use the Weather Research and Forecasting (WRF) model in LES mode coupled with the dust emission scheme of Klose et al. (2014) (KS14), denoted as WRF/LES-D (Klose and Shao, 2013). WRF/LES-D contains

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representations of dust emission, transport and deposition. The model is used to investigate DD occurrence, vortex properties, and dust emission for various atmospheric background conditions. By comparing the vortex properties and dust emission fluxes of the individual DDs detected in the LES runs, a new method is proposed to estimate large-scale DD dust transport from regional and global model data.

2. LES experiments

The numerical experiments are set up as described in Klose and Shao (2013). The model is run for various conditions of thermal stability and background wind. Stability is varied by setting different surface heat fluxes, H, for stable, neutral, and unstable stratifications ($H = -50, 0, 200, 400, 600$ W m^{-2}). The background wind is initialized with a logarithmic wind profile determined by $u_* = 0.15, 0.3$, and 0.5 m s^{-1} and a surface roughness length of $z_0 = 0.01$ m, but the flow is allowed to freely develop during the model spin-up. A Rayleigh damping is applied to the top 300 m of the model domain to suppress gravity waves. In total, 15 numerical experiments (Table 1) are conducted for a $2 \times 2 \times 1.5$ km^3 domain (x×y×z) with a horizontal resolution of $\Delta x = \Delta y = 10$ m and a vertical resolution which decreases with height. Assuming that the maximum size of large eddies in a convective boundary layer is comparable to the boundary layer depth, our domain can cover about four of the largest convective cells. This is at the lower limit for LES and a limitation for the experiments to allow for sufficient interaction between the strong convective cells (Schmidt and Schumann, 1989; Moeng and Sullivan, 2015). The simulated flow patterns show reasonable results, however, and we consider the domain size large enough for the purpose of this study. With a horizontal resolution of 10 m, the smallest detectable DDs have horizontal extents of $\sim$ 20–40 m (2–4 times Δx). This may lead to an underestimation of the number of small DDs in our study. The computational time step used in the simulations is 0.05 s and the output time step is 10 s. The simulation time for each experiment is 90 min, of which the first 30 min are used for model spin-up and are excluded from the analysis. The surface is specified as a loam soil.

The convective turbulent dust emission (CTDE) scheme of KS14 accounts for the stochastic nature of both atmospheric turbulence and inter-particle cohesion. In the scheme, the dust emission flux, F_D, for a given lifting force, f, and cohesive force, f_i, is given by

$$F_D = \begin{cases} \frac{\alpha_N}{2D}\left\{-w_t m_p + T_p\left(f - f_i \frac{d_p}{D}\right)\right\} & \text{for } f > f_t, \\ 0 & \text{else} \end{cases} \tag{1}$$

with particle response time T_p, particle diameter d_p, viscous sublayer thickness D, particle mass m_p, and particle terminal velocity w_t. $f_t = f_i + m_p g$ is the particle retarding force with g being gravitational acceleration. The dust emission flux for a given particle size d_j can be calculated as

$$F_{D,j} = \int_0^f F_D \cdot p_j(f_i) \mathrm{d}f_i \tag{2}$$

In the scheme's setup for use in meso- and large-scale models, f is parameterized to follow a probability distribution. In LES, the lifting force can be directly calculated from the model-resolved and subgrid-scale momentum fluxes as $f = \tau_f \pi d^2/4$ with

$$\tau_f = \rho\sqrt{\left(uw + \frac{1}{\rho}\tau_{sg,x}\right)^2 + \left(vw + \frac{1}{\rho}\tau_{sg,y}\right)^2} \tag{3}$$

where ρ is air density, u, v, and w are the resolved wind speed components respectively in x, y, and z direction, and $\tau_{sg,x}$ and $\tau_{sg,y}$ the components of subgrid-scale momentum flux in x and y direction. The scheme is an upgraded version from that used by Klose and Shao (2013) and has been calibrated against field observations. To the best of our knowledge, these are the first LES experiments including size-resolved DD dust entrainment.

Table 1
Surface heat flux H [W m^{-2}] and friction velocity u_* [m s^{-1}] used to initiate the LES experiments (Klose and Shao, 2013).

	H	u_*
Exp1	−50	0.15
Exp2	−50	0.3
Exp3	−50	0.5
Exp4	0	0.15
Exp5	0	0.3
Exp6	0	0.5
Exp7	200	0.15
Exp8	200	0.3
Exp9	200	0.5
Exp10	400	0.15
Exp11	400	0.3
Exp12	400	0.5
Exp13	600	0.15
Exp14	600	0.3
Exp15	600	0.5

3. Dust devil identification and tracking

DDs exhibit a characteristic pressure drop, Δp, and a maximum of vorticity, ζ, in the center (Sinclair, 1973; Renno et al., 1998). Vortex centers can be identified based on three criteria: (1) a local pressure minimum and vorticity maximum; (2) Δp exceeding a threshold Δp_t; and (3) ζ exceeding a threshold ζ_t (Ohno and Takemi, 2010; Raasch and Franke, 2011). Different threshold values have been proposed in the earlier studies. For example, Raasch and Franke (2011) defined Δp as the pressure perturbation from a base state at the lowest model level ($\sim$1 m) and set $\Delta p_t = 0.04$ hPa and $\zeta_t = 1$ s^{-1}. Ohno and Takemi (2010) used the pressure deviation from the horizontal domain average at 10 m height with $\Delta p_t = 0.1$ hPa and $\zeta_t = 0.15$ s^{-1}.

For a 4 km^2 domain as used in this study, we consider the horizontal domain average pressure as a preferred reference and define Δp as the deviation of pressure from this average. Vorticity at grid point (i,j) is calculated as

$$\zeta(i,j) = \frac{2}{3}\left(\frac{v'(i+1,j) - v'(i-1,j)}{2\Delta x} - \frac{u'(i,j+1) - u'(i,j-1)}{2\Delta y}\right) + \frac{1}{3}\left(\frac{v'(i+2,j) - v'(i-2,j)}{4\Delta x} - \frac{u'(i,j+2) - u'(i,j-2)}{4\Delta y}\right). \tag{4}$$

where $u' = u - \overline{u}$ is the derivation of the wind component in x-direction from its horizontal domain average, and v' that in y-direction. The use of a weighted centered-difference approach increases the robustness for the computation of ζ. Different combinations of $\Delta p_t = 0.05, 0.1, 0.2$, and 0.25 hPa with $\zeta_t = 0.1, 0.2, 0.5$, and 1 s^{-1} are tested for the two meteorological standard heights 2 m and 10 m to investigate the sensitivity of the results to the choice of the identification criteria.

DD motion is tracked by estimating the expected position of the DD center at the following output time step, $(i,j)_{t+\Delta t}$, based on the mean wind. If a DD center is identified within the adjacent 7 grid points (70 m) of $(i,j)_{t+\Delta t}$ in any direction, i.e. within $(i \pm 7, j \pm 7)_{t+\Delta t}$, then both records are assumed to belong to the same track. The limit of 7 grid points is between about 0.5 and 3 times the DD translation distance per output timestep in the different wind settings as estimated from the average and standard deviation of wind speed at 10 m height and the DD positions.