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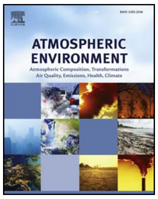

Large-eddy simulation of dust-uplift by a haboob density current

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ABSTRACT

Cold pool outflows have been shown from both observations and convection-permitting models to be a dominant source of dust emissions (“haboobs”) in the summertime Sahel and Sahara, and to cause dust uplift over deserts across the world. In this paper Met Office Large Eddy Model (LEM) simulations, which resolve the turbulence within the cold-pools much better than previous studies of haboobs with convection-permitting models, are used to investigate the winds that uplift dust in cold pools, and the resultant dust transport. In order to simulate the cold pool outflow, an idealized cooling is added in the model during the first 2 h of 5.7 h run time. Given the short duration of the runs, dust is treated as a passive tracer. Dust uplift largely occurs in the “head” of the density current, consistent with the few existing observations. In the modeled density current dust is largely restricted to the lowest, coldest and well mixed layers of the cold pool outflow (below around 400 m), except above the “head” of the cold pool where some dust reaches 2.5 km. This rapid transport to above 2 km will contribute to long atmospheric lifetimes of large dust particles from haboobs. Decreasing the model horizontal grid-spacing from 1.0 km to 100 m resolves more turbulence, locally increasing winds, increasing mixing and reducing the propagation speed of the density current. Total accumulated dust uplift is approximately twice as large in 1.0 km runs compared with 100 m runs, suggesting that for studying haboobs in convection-permitting runs the representation of turbulence and mixing is significant. Simulations with surface sensible heat fluxes representative of those from a desert region during daytime show that increasing surface fluxes slows the density current due to increased mixing, but increase dust uplift rates, due to increased downward transport of momentum to the surface.

1. Introduction

Airborne mineral dust is an important component of the Earth system (Carslaw et al., 2010) and an increasing number of weather and climate models are including prognostic dust, which can improve weather prediction (Rémy et al., 2015). Dust uplift is a highly non-linear function of wind speed, usually parameterized as a threshold cubic function of the friction velocity (e.g. Gillette, 1978; Marticorena et al., 1997). This means that localized high wind-speed events can be important for dust emission (Cowie et al., 2015), making dust modeling a challenge for global models (Doherty et al., 2014).

Cold pool outflows from moist convection, generated by the evaporation, melting and sublimation of hydrometeors, are one important mechanism for generating strong winds and so dust uplift from the surface, with the dusty cold pools referred to as haboobs (Sutton and Inst, 1925; Lawson, 1971; Membery, 1985; Roberts and Knippertz, 2012). Haboobs have been observed in every major dust source region (Knippertz and Todd, 2012). They vary from barely visible dust storms produced by cumulus congestus clouds (Marsham et al., 2009) to storms hundreds of kilometers across that can be seen clearly from space (Flamant et al., 2007; Takemi, 1999; Idso et al., 1972).

The Sahel and Sahara are the world's main dust source (Prospero et al., 2001) and haboobs are a key dust emission mechanism there (Marsham et al., 2008, 2013; Allen et al., 2013; Roberts et al., 2017; Bergametti et al., 2017). Multi-day convection-permitting simulations have shown that haboobs cause around half of modeled summertime dust emission in West Africa, but that this emission is essentially missing in models that use parameterized convection (Marsham et al., 2011; Heinold et al., 2013; Pope et al., 2016) and in analyses (Largeron et al., 2015; Roberts et al., 2017). Convection-permitting simulations (3.75 km grid-spacing) have also been used to study haboobs in the USA (Vukovic et al., 2014).

Observations show that convectively generated cold pools acting as density currents have typical depths of around 1 km (Sutton and Inst, 1925; Idso et al., 1972) with some studies showing depths reaching 4 km (Bryan and Parker, 2010). There are many studies of density

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currents that do not consider dust uplift (Simpson, 1997; Takemi, 2005; Miller et al., 2008; Knippertz et al., 2009). These show how the low-level pressure gradient associated with the cold pool leads to strong low-level winds (see e.g. Fig. 2.2 in Simpson, 1997). The density current "head" is associated with turbulent winds with less turbulent flow behind it. Kelvin-Helmholtz wave-breaking can lead to mixing between the density current and its environment (Simpson, 1972). The leading edge of the density current is composed of so-called lobes and clefts that are unsteady and shifting (Simpson, 1997; Härtel et al., 2000).

Some studies have attempted parameterization of wind gusts from convective downdrafts (Nakamura et al., 1996; Redelsperger at al., 2000; Cakmur et al., 2004) and recently for haboobs (Pantillon et al., 2015, 2016). However, despite the great importance of haboobs for global dust emission, to the best of the authors' knowledge there are no published studies of large-eddy simulations that explicitly resolve the turbulent dust-uplift in haboobs and analyse the role of turbulence for dust emission.

In this paper we use the Met Office Large Eddy Model (LEM) to simulate idealized density currents. Our main focus is on the impacts of small-scale turbulence on the dust emission in haboobs and the effects of surface heat fluxes. We do not attempt to simulate any particular observed case, but rather use idealized simulations of a density current that has properties broadly consistent with those from observations. Section 2 describes the model used and its configuration. Section 3.1 discusses the structure and the development of the density current, dust emission and dust transport from the simulation. The scales of motion, which are responsible for dust uplift, are investigated by means of varying model horizontal grid-spacing in Section 3.2. Section 3.3 briefly examines the impact of surface sensible heat fluxes on haboobs. Section 4 contains a summary and conclusion.

2. Model setup and methods

The model used is the U.K. Met Office LEM version 2.4 (Gray and Petch, 2001). The LEM is a non-hydrostatic numerical model used to simulate a wide range of boundary-layer and cloud-scale problems. The subgrid model used in the LEM is based on the Smagorinsky-Lilly approach (Brown et al., 1994). The LEM equation set is Boussinesq and in this study the incompressible Boussinesq formulation is used. All moist processes are switched off, since the model never reached saturation and an idealized cooling is used to generate the cold pool. Two-dimensional (y-z) simulations are performed throughout this study, except for a single sensitivity study in 3D (S3D in Table 1). The domain is10 km deep, and the horizontal domain length is 450 km. Horizontal grid spacing varies between 100 m and 1.0 km. A grid-spacing of 450 m is used for a standard run (S in Table 1) and runs with varying surface heat fluxes, as well as the 3-D run (Table 1). All runs used a vertically stretched grid with a minimum spacing of 0.5 m in the surface layer and a maximum of 233 m above 6 000 m. Periodic lateral boundary conditions are applied, with a rigid lid at the top of the model domain. To reduce the reflection of internal gravity waves, a Newtonian damping layer is applied above 6 500 m. The model is initialized with a profile characterized by an approximately 6 km deep dry adiabatic and neutral boundary layer with a stable layer above (Fig. 1). This profile is based on an idealized version of those found in the Sahara (Cuesta et al., 2009; Garcia-Carreras et al., 2015). The profile is considerably cooler than that found in the Sahara, but that will not affect our results, as it is the temperature difference not the absolute temperature that is key to density current propagation (Simpson, 1997).

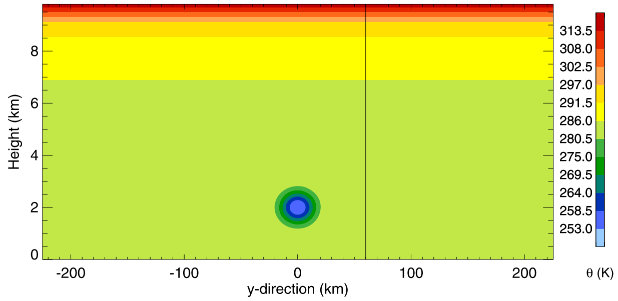

Fig. 1. Potential temperature (K) from the standard run at 1.5 h. The area to the right of the black line ($y > 60$ km) is shown in subsequent figures.

The idealized cooling used to generate the cold pool outflow is identical to that used by Orf et al. (1996). The aim is to generate a density current that was within the range of haboobs seen in observations, without attempting to represent any particular haboob event. The cooling used is,

$$Q(x, y, z; t) = \begin{cases} g(t)\cos^2(\pi R) & R < \frac{1}{2} \\ 0 & R > \frac{1}{2} \end{cases} \tag{1}$$

where R is the normalized distance from the center of cooling, given by

$$R = \sqrt{\left(\frac{y - y_f}{M_y}\right)^2 + \left(\frac{z - z_f}{M_z}\right)^2} \tag{2}$$

where (y_f, z_f) is the location of the center of the forcing function and (M_y, M_z) is the horizontal/vertical half-width and

$$g(t) = \begin{cases} -\cos^2\left[\pi\left(\frac{t-0.5}{2\tau}\right)\right] & 0 \le t < 0.5 \\ -1 & 0.5 \le t < 1.5 \\ -\cos^2\left[\pi\left(\frac{t-2.0}{2\tau}\right)\right] & 1.5 \le t < 2.0 \end{cases} \tag{3}$$

where $\tau = 0.5$ h. A maximum cooling rate of 0.15 $\mathrm{Ks^{-1}}$ is used in this paper, which is comparable with the cooling rates found by Orville et al. (1989), which approach 0.1 $\mathrm{Ks^{-1}}$ e.g. for evaporation of rain in strong microburst cases. In all runs the cooling center is located at $y_f = 0$ km and $z_f = 2$ km. An elliptical cold bubble with horizontal and vertical half-widths of 25 km (M_y) and 1.0 km (M_z) respectively, is used. The constant cooling lasts 1.0 h with a smooth ramp-up and ramp-down during 30min. Fig. 1 shows the cold bubble created using the above method after 1.5 h of the model run. The difference of temperature between the cold bubble (averaged temperature) and the environment is about 9 K. As discussed in Section 3.1, this generates a density current similar to those seen in observations. The three-dimensional simulation (S3D) uses a 450 × 9 km domain. The same cooling rate used in the two-dimensional runs is applied over a 50 km long (in the y-direction) strip extending the full 9 km (in the x-direction) width of the domain, to give a setup analogous to the downdraft from linear convective systems, which dominate the precipitation in the Sahel and generate large cold pools there (Provod et al., 2016).

Based on a widely used parameterization of dust uplift by Marticorena and Bergametti (1995), the vertical dust flux in the LEM is expressed as:

Table 1
Horizontal grid spacing and surface heat fluxes for the sensitivity tests. S is the standard run. Results for the standard run are in bold.

Condition	R1	R2	R3	S	R4	R5	R6	R7	R8	F1	F2	F3	F4	S3D
Grid-spacing (km)	0.1	0.2	0.3	**0.45**	0.5	0.6	0.75	0.9	1.0	0.45	0.45	0.45	0.45	0.45
Surface flux ($\mathrm{Wm^{-2}}$)	0	0	0	**0**	0	0	0	0	0	50	100	200	300	0