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The Mechanism of Dust Entrainment under Strong Wind with Gustiness

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Abstract

In East Asia the large range dust storm almost occur after cold front passage in spring. Here, we try to find the mechanism of dust entrainment by the gust wind by analyzing observation data and numerical simulation result. First, the ultra-sonic anemometer-thermometer data during the dust storm periods in 2000-2004 have been analyzed. It is revealed that the air motion during dust storm can be divided into three parts, the turbulent small eddies, the gust wind, and large scale basic flow. In the lower part of atmospheric boundary layer, the descending component of basic flow suppresses the dust particles keeping them within the bottom layers. But the gust wind has coherent structure, and due to the gust wind not turbulence, the dust can entrain from lower to upper levels. Second, we use Lagrangian Stochastic Model to simulate the particle trajectory during dust storm period. The wind condition comes from the observation wind profiles. It includes basic flow profile, gust wind profile and turbulent intensity. When there are only turbulent fluctuations, particles have random trajectories and can reach 250m height. Once adding gust wind, particles are carried in the air stream and have the potential to be transported to great heights (higher than 500m) and over great distances. But if no gust wind and adding descending component of basic flow, particles are only accumulated in the bottom of layer. The simulation result shows that the mechanism of dust entrainment during strong wind is mainly due to the gust wind.

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Keywords: wind gust; coherent structure; dust entrainment; Lagrangian stochastic model

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1. Introduction

In East Asia, especially in Mogolia and North China, most large range dust storm events are in the spring, and all they are accompanied with strong wind after the passage of cold front. There has been build a network system in

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the northern China for monitoring such dust weather. This system consists of a network of ground based stations and the remote sensing by the meteorological satellite. The ground based stations carry out both conventional and special observations, such as, the structure and characteristics of the atmospheric boundary layer and the aerosol optical depth. The description of this system, some application issues and research results have been reported by a book "Gigantic Yellow Cloud" (Zeng et al., 2006) and several special issues of the journals (Dong and Shao, 2006; Zeng et al., 2004, 2007). The dataset obtained by this system is very valuable for the studies of the atmospheric boundary layer. By using these data, a typical case has been analyzed in detail in order to expose the mechanism of sand/dust emission process under the action of strong wind and the relevant atmospheric boundary layer characteristics (Zeng et al. 2007, 2010). Thus some very interesting dynamic pictures and characteristics of such atmospheric boundary layer have been revealed, such as (a) there is descending (ascending) component of the basic flow in the lower (upper) part of the boundary layer, (b) there is some rather regular gust wind disturbances superimposed on the basic flow, and their characteristics are very different from the turbulent fluctuations; (c) the basic flow, gust wind and turbulent fluctuations all make contributions to the sand/dust emission from the ground surface, the dust entrainment is only due to the gust wind disturbances, and so on. In this paper we will give a statistical analysis for all cases of such weather situations in 2000-2004, and present the vertical profiles of these characteristics. Note, unlike the turbulence, there could be found in the world literature only few papers on the gust wind. Some of them were devoted to the correction of vertical fluxes on the surface by taking the gustiness of wind into account (Zeng X. B. et al. 2002; Morcrette J. J. et al. 2008), some others to the numerical simulation of gust wind and its prediction (Brasseur, 2001; Agustsson and Olafsson, 2006; Peinke et al. 2004; Barth et al., 2005; Wang, 2006; Agustsson and Olafsson, 2009; Goyette et al. 2003), and only few papers to the observational studies (Xu et al. 1997; Lauren et al. 2001; Sun et al. 2004; Nakamura and Mahrt, 2005). Fortunately, our observational network provides us good dataset and an opportunity to make the analysis of the observed dynamical structures of gust wind.

Then, we will calculate the dust entrainment by gust wind. One of the first researches to investigate the transport of particles by wind was Bagnold (1941). His classical perception of the process served as a basis for any new developments, and it has been modified and sharpened at important points, in recent years. There are two ways to simulate the process. One is Euler method. It uses two-phase flow model and regards particles as passive scalar (Friedlander and Johnstone 1957, Young and Leeming 1997). But if the relaxation time of scalar is less than the turbulent flow Lagrangian timescale, which leads to the distinction between two speeds obvious such as the particle flow near the scalar source, or in the boundary layer, this model is not suitable. Another is Lagrange method. This method follows every particle's random walk process. The random walk of particles is a Markov process, or a Brownian motion called Wiener type. There are three classical, actually indistinct categories of particle motion determined by the diameter of particles:

- Creep: large particles with $d_p \geq 500\mu m$.
- Saltation: sand – sized grains with $70\mu m \leq d_p \leq 500\mu m$.
- Suspension: dust particles with $d_p \leq 70\mu m$.

During the period of dust storm, particles are usually entrained into the air stream by turbulent eddies and gust wind, suspended in the air and transported to great heights and over great distances. These particles have random trajectories, strongly influenced by the turbulent and gusty fluctuations. Many approaches exist for the calculation of dust particle trajectories. The appeal of the random walk method is its directness, due to which it is relatively free of theoretical obscurity (Kallio and Reeks, 1989; Graham, 1996). This explicitly resolves particle acceleration, but treats the "driving" fluid velocity at the location of the particle as constant across ''patches'' of the fluid, and as changing discontinuously from eddy to eddy. So attentions are paid to model the stochastic particle velocity itself directly. It is usually by means of a Langevin-type equation, which will require to be provided the particle velocity variance and the autocorrelation timescale along the trajectory (Walklate 1987; Wilson 2000). The method is usually named Lagrangian stochastic (LS) models. In the "first-order" LS model, the Markovian state variable is ($\overset{\vee}{z}_i$, $\overset{\vee}{w}_i$), and the velocity evolves in time (Wilson and Sawford, 1996). Thomson (1987) provided a constraint on the model coefficient, to ensure that the LS model has the property that, should it hypothetically be applied to the motion of tracer that is (already) well mixed in position-velocity space, the tracer would remain well mixed. A first-order LS model correctly predicts the rate of dispersion even in the near field of a source, where travel time is not larger than fluid-Lagrangian timescale, in contradistinction to Eulerian models.

But the "first-order" LS model for turbulent dispersion in multidimensional flows remains problematic. This is