Available online at www.sciencedirect.com
SCIENCE DIRECT®

Global and Planetary Change 52 (2006) 57–70

GLOBAL AND PLANETARY CHANGE

www.elsevier.com/locate/gloplacha

Numerical simulation and synoptic analysis of dust emission and transport in East Asia

Wei Wang [a,*], ZongYi Fang [b]

[a] College of Environmental Science and Engineering, NanKai University, China
[b] National Satellite Meteorological Center, China Meteorological Administration, China

Received 30 November 2004; accepted 9 February 2006

Abstract

This study is concerned with the mechanisms of dust storm development in East Asia and the characteristics of the responsible synoptic systems. Two severe East Asian dust storms which occurred in spring 2002 are analyzed using synoptic and remote sensing data. The relationships between the formation and the movement of the dust storms and the evolution of the synoptic systems are examined. It is shown that a dust storm may develop when a synoptic system moves to the desert area of Northeast Asia with a surface wind speed exceeding 6 m s^{-1}. Numerical simulations of the two dust storms are carried out using a dust storm forecasting model. The performance of the model is verified with observations. The dust sources are found to be consistent with the desert regions in Northeast Asia, but cover a somewhat larger area than the observations suggest. Finally, we present a conceptual model of dust storm generation and movement in East Asia on the basis of numerical modeling and synoptic analysis.

Keywords: numerical simulation; dust storms; synoptic analysis

1. Introduction

In recent years, much attention has been paid to dust storms, as mineral aerosols may affect long- and short-wave radiations and play an important role in climate change (Christopher et al., 2003; Dey et al., 2004). Scientists have attempted to estimate the amount of dust emission using various means, including surface observation, satellite monitoring and numerical simulation (Carlson, 1979; Goudie, 1983; Nickovic and Dobricic, 1996; Husar et al., 1997; Nickovic et al., 2001; Chin et al., 2002). Numerical modelling is an important method for studying dust storms. The simulations with atmospheric GCMs have shown that the global dust source strength is between 1500 and 5000 Mt yr^{-1} and the effective clay radius between 0.3 and 0.7 μm (Joussaume, 1990; Tegen and Fung, 1994).

The study on Asian dust is a particularly active research area (e.g. Liu et al., 2003; Kim et al., 2004). Asia is one of the main dust source areas and Asian dust can be transported over long distances. For example, dust cloud associated with the April 1998 dust storm in Asia reached the western coast of America within 5–6 days. Its travel speed was about 12 m s^{-1}. The simulation of the above dust storm indicates that low-pressure systems, especially cut-

* Corresponding author.
E-mail address: wwei@nku.edu.cn (W. Wang).

0921-8181/$ - see front matter © 2006 Published by Elsevier B.V.
doi:10.1016/j.gloplacha.2006.02.004

off vortices, play an important role in the long-range movement of Asian dust (Husar et al., 2001; Uno et al., 2001; Park and In, 2003).

Since the 1970s, Chinese meteorologists have been studying dust storms through synoptic analysis. They concentrated on the features and evolution of the synoptic systems which generate dust storms. Their investigations showed that the major synoptic systems for East Asian dust storms are cold fronts, cold vortices and meso-scale systems. However, there has been a lack of sophisticated models for the prediction of dust storms in China.

Many issues related to Asian dust storms require quantitative investigation, such as dust source regions, dust emission and deposition, long distance movement etc. To this end, an advanced dust storm forecast model that integrates an atmospheric model with dust emission and transport schemes and land surface data is required (Shao and Leslie, 1997). In a recent study, Shao et al. (2003) demonstrated that the spatial patterns and temporal evolutions of dust events can be quite well predicted using a numerical model.

We have carried out a quasi real-time dust storm numerical prediction in the 2002/2003 spring using an integrated wind erosion prediction model. The results are reported in this paper. On the basis of the numerical results and synoptic analysis, we establish a conceptual model of the Asian dust storms in order to explain its generation and movement, and to help forecasters to better understand the relationship between dust storm occurrences and meteorological conditions.

2. Model principle

In this paper, the East Asian dust storm is investigated by using the integrated dust storm prediction model (Shao, 2000). The model consists of three components including a regional atmosphere model, a wind erosion model for dust emission, transport and deposition and a GIS (Geographic Information System) database.

The atmospheric model provides wind velocity and precipitation for the wind erosion model to predict dust emission, concentration, transport, deposition etc. and for the land surface model to predict soil moist, friction velocity etc. The GIS database provides soil type, vegetation cover, vegetation type, leaf area index etc. for the wind erosion and land surface models.

(1) The dust emission scheme proposed by Lu and Shao (1999) is used for the calculation of dust emission. Soil particles are divided into seven size groups, i.e., $d<2$ μm, $2\le d<11$ μm, $11\le d<22$ μm, $22\le d<52$ μm, $52\le d<90$ μm, $90\le d<125$ μm and $d\ge 125$ μm. The total dust flux is given as $F=\sum F_i$, where F_i is the dust flux of the ith size group, given by

$$F_i=\int_{d_i}^{d_2}\tilde{F}_i(d_s)p_m(d_s)\delta d_s \tag{1}$$

where d_s is saltation particles size, p_m is particle size distribution function. $\tilde{F}_i$ is dust flux generated by the saltation of particles of size d_s

$$\tilde{F}_i(d_s)=\frac{C_{\theta_i}gf_i\rho_p}{2S_d}\left(0.24+C_\beta u_*\sqrt{\frac{\rho_p}{S_d}}\right)Q(d_s) \tag{2}$$

In Eq. (2), u_* is friction velocity, g is acceleration due to gravity, ρ_p is dust particle density, S_d is soil plastic pressure and f_i is the mass fraction of dust particles in ith size group. $C_{\theta i}$ and C_β are coefficients, $Q(d_s)$ is sand flux which can be estimated using the following equaion:

$$Q(d_s)=\frac{C_s\rho u_*^3}{g}\left[1-\frac{u_{*t}(d_s)}{u_*}\right]\left[1+\left(\frac{u_{*t}(d)}{u_*}\right)^2\right] \quad (u_*\ge u_{*t}) \tag{3}$$

$$Q(d_s)=0 \qquad (u_*\le u_{*t}) \tag{4}$$

where C_s is a coefficient and u_{*t} is threshold friction velocity.

(2) Dust transport is governed by the dust conservation equation. The mechanisms for dust transport include advection, diffusion and deposition. The total dust concentration is given by $c=\sum c_i$, where c_i is the concentration of the ith particle size group, which obeys

$$\frac{\partial c_i}{\partial t}+u\frac{\partial c_i}{\partial x}+v\frac{\partial c_i}{\partial y}+(w+w_{t,i})\frac{\partial c_i}{\partial z}=\frac{\partial}{\partial x}K_{pxi}\frac{\partial c_i}{\partial x}+\frac{\partial}{\partial y}K_{pyi}\frac{\partial c_i}{\partial y}+\frac{\partial}{\partial z}K_{pzi}\frac{\partial c_i}{\partial z}+S_{ri}+S_{ci} \tag{5}$$

where w_t is the terminal velocity; u, v are the horizon wind speed; w is the vertical wind speed; K_{px}, K_{py} and K_{pz} are the eddy diffusivities for dust particles in the x, y and z directions. S_r is a wet removal term and S_c is the dust source term.

(3) Friction velocity, u_*, is a measure of momentum flux to the surface. For neutral atmospheric surface layers, u_* can be obtained through the logarithmic wind profile

$$u=\frac{u_*}{\kappa}\ln\frac{z-d_z}{z_0} \tag{6}$$

where u is wind speed at z; κ is the von Karman constant; z_0 is aerodynamic roughness length; and d_z is zero-displacement height. The threshold friction velocity, u_{*t},