Aeolian Research 20 (2016) 147–156

Contents lists available at ScienceDirect

Aeolian Research

journal homepage: www.elsevier.com/locate/aeolia

Modeling of particulate matter transport in atmospheric boundary layer following dust emission from source areas

Itzhak Katra [a,*], Tov Elperin [b], Andrew Fominykh [b], Boris Krasovitov [b], Hezi Yizhaq [c,d]

[a] Department of Geography and Environmental Development, Ben-Gurion University of the Negev, P.O.B. 653, 84105, Israel
[b] Department of Mechanical Engineering, The Pearlstone Center for Aeronautical Engineering Studies, Ben-Gurion University of the Negev, P.O.B. 653, 84105, Israel
[c] Swiss Institute for Dryland Environmental and Energy Research, BIDR, Ben-Gurion University of the Negev, Midreshet Ben-Gurion, Israel
[d] The Dead Sea and Arava Science Center, Tamar Regional Council, Israel

ARTICLE INFO

Article history:
Received 2 May 2015
Revised 31 December 2015
Accepted 31 December 2015
Available online 28 January 2016

Keywords:
Dust emission
Aeolian processes
Portable wind tunnel
Wind mast
PM_{10}
Advection–diffusion equation

ABSTRACT

A two-dimensional model for particulate matter (PM) dispersion due to dust emission from soils is presented. Field experiments were performed at a dust source site (Negev loess soil) with a portable boundary layer wind tunnel to determine the emitted PM fluxes for different wind speeds and varying soil conditions. The numerical model is formulated using parameterizations based on the aeolian experiments. The wind velocity profiles used in the simulations were fitted from data obtained in field measurements. Size distribution of the emitted dust particles in the numerical simulations was taken into account using a Monte Carlo method. The PM concentration distributions at a distance of several kilometers from the dust source under specific shear velocities and PM fluxes from the soil were determined numerically by solving advection–diffusion equation. The obtained PM_{10} concentrations under typical wind and soil conditions are supported by PM data recorded over time in a standard environmental monitoring station. The model enhances our capacity of quantification of dust processes to support climate models as well as health risk assessment.

1. Introduction

Mineral dust is a key agent involved in a wide range of physical, chemical and biological processes of the Earth system. Dust particles profoundly affect the energy, carbon and water cycles of the climate system (see e.g., Shao et al., 2011). It has been recognized that dust aerosol can also have significant impacts on human health. During dust storms, concentrations of dust particles having aerodynamic diameter less or equal to 10 μm (PM_{10}) in arid areas can exceed significantly the World Health Organization (WHO) guideline for air quality (Katra et al., 2014a), reaching outdoor and indoor concentrations in arid environments as high as 5000 and 1500 $\mu g/m^3$, respectively (Krasnov et al., 2015). Other studies highlighted the role of PM from natural dust as an important environmental pollutant for human health impacts (Vodonos et al., 2014; Yitshak-Sade et al., 2014).

Modeling of dust transport is of profound importance for understanding the dust cycle at different scales. It requires combined theoretical and experimental study of particle emission (in consequence of wind soil erosion) and dust transport in the atmospheric boundary layer (ABL). In particular, modeling of atmospheric dust dispersion requires reliable data on measured input variables, such as grain size distribution, wind speed, sediment properties, dust-emission rate (see, e.g., Gillies et al., 2006; Shao, 2008; Durán et al., 2011; Kok et al., 2012).

Understanding the role of dust in the Earth system has prompted intensive development of dust emission models since the late 1980s (Shao et al., 2011). These developments spurred the intensive efforts in the modeling of dust transport. Pilinis et al. (1987) developed a mathematical model that describes the evolution of size and chemical composition distribution of atmospheric aerosols based on a sectional representation of the size distribution, and treats dynamics and thermodynamics of multicomponent atmospheric aerosols. Lu and Shao (1999) developed a theoretical model for the prediction of dust emission rate caused by saltation bombardment, based on the dust volume removal caused by impacting sand grains as they plough into the soil surface. In the present study, the dust emission generated by saltation bombardment has been modeled from the perspective of volume removal by saltating particles as proposed by Lu and Shao (1999). As Lu and Shao (1999), Shao (2001) noted, more field measurements are required in order to verify this approach.

* Corresponding author. Tel.: +972 8 6428434; fax: +972 8 6472821.
E-mail address: katra@bgu.ac.il (I. Katra).

http://dx.doi.org/10.1016/j.aeolia.2015.12.004
1875-9637/

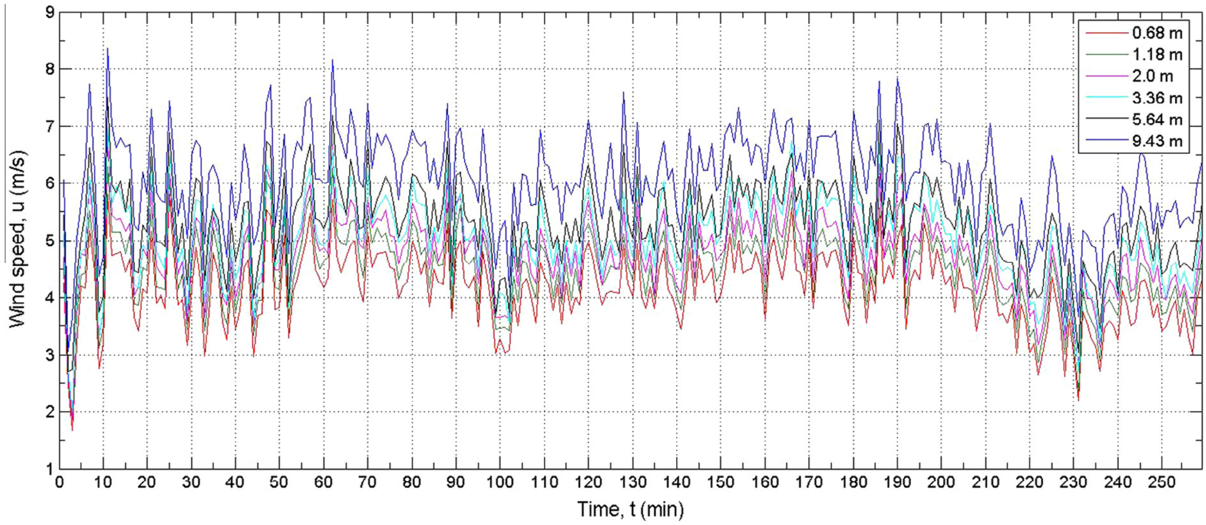

Fig. 1. Example of wind speed measured by the wind mast in the study area (June 12, 2014).

Table 1
Mean wind velocity vs. height based on field experiment of 12 June 2014.

Height, h (m)	Average wind velocity, $\bar{u}$ (m/s)
0.68	4.15
1.18	4.49
2.0	4.76
3.36	5.04
5.64	5.31
9.43	6.09

In spite of intensive development of advanced dust emission models, there is a gap in quantification of dust transport following dust emission from soils. Moreover, the knowledge about the impact of surface-property variability on dust fluxes from source areas is still severely lacking (Katra and Lancaster, 2008).

For individual wind-erosion events, wind shear near the surface is responsible for particle entrainment into the atmosphere, and turbulence in the atmospheric boundary layer is important for particle diffusion and deposition (Shao, 2008). Many of the early experiments on wind erosion (see e.g., Bagnold, 1936; Kawamura, 1951; Lettau, 1969; Lettau and Lettau, 1977; Nickling and Gillies, 1993; Bottema, 1996; MacDonald et al., 1998) show that in the case of negligible wake interference between the surface obstacles the mean velocity profile approaching each obstacle is logarithmic.

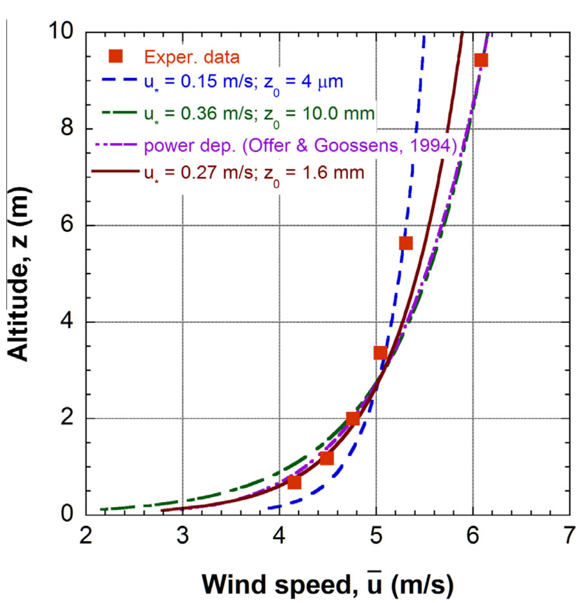

Fig. 2. Dependence of the average wind speed vs. altitude.

In this study, aeolian erosion under different wind and soil conditions in an area located in the northern Negev Desert (Israel) was simulated for modeling dust PM dispersion in the atmospheric boundary layer at a distance of several kilometers from the dust source. Field experiments were used to determine a set of parameters for the dust dispersion model that include dust emission fluxes and velocity profiles.

2. Mean wind velocity profile

The mean wind velocity profile for the studied case is required for simulating the PM dispersion after emission of dust from the soil. To this end we use standard equations of atmospheric boundary layer theory (see e.g., Shao, 2008). Goossens and Offer (1990) showed that in the Northern Negev area the depth of the Atmospheric Boundary Layer (ABL) is on the order of 500–600 m. Since we consider horizontal transport of dust particles over large distances, the assumptions of the validity of the boundary layer approximation are satisfied. Offer and Goossens (1994) showed that in the lowermost 15% of the ABL, the wind profile (in neutral atmospheric conditions) can be described either by the semi-empirical logarithmic law (see, e.g., Oke, 1987):

$$u = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right) \tag{1}$$

or by the power law (see, e.g., Offer and Goossens, 1994):

$$u_1 = u_2 \left(\frac{z_1}{z_2}\right)^{\alpha}. \tag{2}$$

In Eq. (1) $u_* = \sqrt{\tau/\rho_a} \propto \sigma$ is friction velocity, which is a scaling parameter proportional to the velocity gradient in boundary layer flow; τ is the shear stress at the surface level and ρ_a is air density; σ is standard deviation of velocity fluctuations (see e.g., Bagnold, 1941; Shao, 2008; Kok et al., 2012); κ is the von Karman constant, $\kappa = 0.35 - 0.4$; z_0 is the aerodynamic surface roughness length