

**Size-segregated
fluxes of mineral dust
by eddy covariance**

G. Fratini et al.

Size-segregated fluxes of mineral dust from a desert area of northern China by eddy covariance

G. Fratini¹, P. Ciccioli², A. Febo³, A. Forgiione⁴, and R. Valentini¹

¹Department of Forest Sciences and Resources (DiSAFRi), Università della Tuscia, 01100, Viterbo, Italy

²Istituto di Metodologie Chimiche, Area della Ricerca del C.N.R. di Roma, 00016, Monterotondo Scalo, Italy

³Istituto di Inquinamento Atmosferico, Area della Ricerca del C.N.R. di Roma, 00016, Monterotondo Scalo, Italy

⁴FAI Instruments s.r.l., Rome, Italy

Received: 24 January 2007 – Accepted: 6 February 2007 – Published: 14 February 2007

Correspondence to: G. Fratini (gfratini@unitus.it)

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Abstract

Mineral dust emission accounts for a substantial portion of particles present in the troposphere. It is emitted most from desert areas, mainly through intense storm episodes. The aim of this work was to quantify size-segregated fluxes of mineral dust particles emitted during storm events occurring in desert areas of northern China (Alashan desert, Inner Mongolia), known to act as one of the strongest sources of mineral dust particles in the Asian continent. Long-range transport of mineral dust emitted in this area is responsible for the high particle concentrations reached in densely populated areas, including the city of Beijing. Based on a theoretical analysis, an eddy covariance system was built to get size-segregated fluxes of mineral dust particles with optical diameters ranging between 0.26 and 7.00 μm . The system was optimised to measure fluxes under intense storm event conditions. It was tested in two sites located in the Chinese portion of the Gobi desert. During the field campaign, an intense storm event was recorded in one of them. Data obtained during this event indicate that particle number fluxes were dominated by the finer fraction, whereas in terms of volume, coarser particle accounted for the largest portion. It was found that during the storm event, ratios of size-segregated particle volume fluxes remained substantially constant and a simple parameterization of particle emission from total volume fluxes was possible. A strong correlation was also found between particle volume fluxes and the friction velocity. This relationship is extremely useful to investigate mechanisms of particle formation by wind erosion.

1 Introduction

Mineral dust emission is one of the major natural sources of aerosols in the free troposphere (Heintzenberger et al., 2003). According to Penner et al. (2001), it accounts for ca. 37% of all aerosols present in air, with a mean global annual production of ca. 3000 Tg yr⁻¹. The largest portion of this natural emission occurs in desert areas

Size-segregated fluxes of mineral dust by eddy covariance

G. Fratini et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

and is caused by wind erosion. Emission takes place most through acute episodes in which high wind velocities strongly promote creeping and saltation of sand-sized particles and the release of fine particles by suspension. Aerometric concentrations of mineral dust as high as 4.65 mg/m^3 have been recorded in the low troposphere during intense desert storm events (Husar et al., 2001). Emitted particles, made of sand and pans of dry silty soil, are characterized by a size distribution falling most in the coarse mode (Heintzenberger et al., 2003). Under favourable conditions, particles smaller than $10 \mu\text{m}$ undergo long range transport. Since they can travel for thousands of kilometres before they are deposited to the earth surface by dry and wet removal processes (Bates et al., 2006; Bonasoni et al., 2004; Chin et al., 2003), their impact is relevant at a global scale (Bates et al., 2006; Heintzenberger et al., 2003). Mineral dust aerosol particles can thus affect the Earth's climate by changing the radiation budget (Andreae, 1995; Bates et al., 2006; Cziczo et al., 2004; Tegen and Lacis, 1996) and by affecting the balance of atmospheric trace gases in the atmosphere (Bauer et al., 2004; Dentener et al., 1996; Zhang and Carmichael, 1999). In particular, mineral dust can reduce concentration of ozone and some photochemical oxidants in the atmosphere (Bonasoni et al., 2004; de Reus et al., 2005; Gusten et al., 1996; Seisel et al., 2005) and suppress precipitation (Rosenfeld et al., 2001).

Present estimates of mineral dust emission are affected, however, by large uncertainties because of the difficulty to directly measure fluxes of aerosol particles during dust storm episodes (Bates et al., 2006; Chin et al., 2003). Several experimental approaches have been developed and used to evaluate mineral dust emission (Dong et al., 2003; Dong et al., 2004; Li et al., 2004; Ono et al., 2003). Most of them rely on indirect determinations requiring some theoretical assumptions about the way how wind erosion leads to particle emission (Dong et al., 2003; Shao, 2000). However, with these approaches there is no way to verify if the actual emission truly follows modelled processes. So far, the only independent method used to derive fluxes of mineral dust emission from desert soils is the gradient method (Breshears et al., 2003; Houser and Nickling, 2001). Its correct application requires at least two sensors located at different

**Size-segregated
fluxes of mineral dust
by eddy covariance**G. Fratini et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

heights. However, the assumption that the eddy diffusivity, derived for heat and water vapour fluxes from the friction velocity, also applies to particles cannot be easily verified; the derivation itself is critical, because it is usually based on the assumption of neutrally-stratified atmosphere (Stull, 1988). Recently, fast methods exploiting the eddy covariance (EC) approach have been developed and tested to derive time-integrated emission rates of aerosol particles released in urban areas from anthropogenic sources (Dorsey et al., 2002; Martensson et al., 2006; Nemitz et al., 2000). In particular, Nemitz et al. (2000) used an optical particle counter (OPC) to get size segregated fluxes of particles larger than $0.1 \mu\text{m}$ in the city of Edinburgh. While OPC are suitable sensors for the fast detection of particles in the coarse mode (D3 mode), the possibility to apply the EC method to their flux determination needed to be verified because not all particles falling in this range might behave as passive scalars in an atmospheric flow field.

To select the particle range of mineral dust whose fluxes could have been measured by EC, a theoretical analysis was performed. It was concluded that this approach was possible for particles with an optical diameter ranging between 0.26 and $7.00 \mu\text{m}$. An EC system for flux measurements of particles falling in this range was then built. It was specifically designed to measure fluxes during intense desert storm events. It was tested in two sites located in the Alashan plateau (Inner Mongolia, China), where storm events frequently occur in the spring season. This area is known to act as a major source of mineral dust in Asia (Chin et al., 2003; Qian et al., 2002; Wang et al., 2004; Xuan et al., 2004) and its long-range transport is responsible for the dramatic built up of particles in populated areas of northern China, including the city of Beijing. Size-segregated fluxes of particles measured in these two sites are reported and critically discussed. Co-spectral analyses were performed to show the suitability of the EC system to provide reliable values of particle fluxes in the whole range investigated during storm event. Results obtained can be relevant for modelling long-range transport of mineral dust particles in Asia and their impact on densely populated areas. They are also useful for a better parameterization of particle emission by wind erosion.

**Size-segregated
fluxes of mineral dust
by eddy covariance**G. Fratini et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

2 Theoretical constraints to the application of the eddy covariance approach to mineral dust

The eddy covariance approach has been developed and used to derive net vertical fluxes of gases and vapours from forest areas (Aubinet, 2000; Aubinet, 2003; Aubinet et al., 2001; Baldocchi et al., 1988; Valentini et al., 1996). It has been extended to particles under the assumption that they behave as gases. This assumption is substantially valid for ultra-fine aerosols emitted by some stationary sources (such as vehicular emission) or photochemically formed in the atmosphere. It might not be true for mineral dust particles. A theoretical treatment was thus needed to estimate the fraction of mineral dust to which the EC approach could have been safely applied. This can be done starting from the conservation equation of particle concentration in an atmospheric flow field:

$$\frac{\partial c}{\partial t} + u_{pj} \frac{\partial c}{\partial x_j} = S + \gamma \nabla^2 c \quad (1)$$

where c is the concentration of particles expressed in suitable units; u_{pj} , is the j th component of the particle velocity vector $\mathbf{u}_p = (u_p, v_p, w_p)$ in a suitable coordinate system, in which the (x, y) -plane is parallel to the local surface and positive z points out of the surface; γ is the particle diffusivity in atmosphere (m^2s^{-1}), $S = S(\mathbf{x}, t)$ is the source/sink term. By applying the ensemble average operator to Eq. (1) and the Reynolds decomposition to all variables, Eq. (1) becomes:

$$\frac{\partial \bar{c}}{\partial t} + \bar{u}_p \frac{\partial \bar{c}}{\partial x} + \overline{u'_p \frac{\partial c'}{\partial x}} + \bar{w}_p \frac{\partial \bar{c}}{\partial z} + \overline{w'_p \frac{\partial c'}{\partial z}} = \bar{S} + \gamma \nabla^2 \bar{c} \quad (2)$$

where the overbar refers to the ensemble average and primes to the fluctuations around the average. For the sake of simplicity, Eq. (2) was written for the case in which the x -axis was aligned with the mean horizontal velocity.

Size-segregated fluxes of mineral dust by eddy covariance

G. Fratini et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

The vector \mathbf{u}_p , describing the particle velocity in a flow field, can be considered as the resultant of two components:

$$\mathbf{u}_p = \mathbf{u} + \mathbf{u}_r \quad (3)$$

where $\mathbf{u} \equiv (u, v, w)$ is the velocity of the fluid parcel in which the particle is immersed, and $\mathbf{u}_r \equiv (u_r, v_r, w_r)$ is the particle-to-fluid relative velocity. In case of large particles, the last term of Eq. (3) cannot be neglected because they respond to gravity and have a finite response time to velocity changes, due to their inertia. In addition to these processes, a third one also contributes to \mathbf{u}_r . It is the so-called trajectory crossing (*tc*) effect (Yudine, 1959). This accounts for the fact that the fluid surrounding the particles “changes” with time, because – due to inertia and gravity - particles tend to leave their companion eddy (Csanady, 1963; Shao, 2000).

Considering all these effects, \mathbf{u}_r can be written as:

$$\mathbf{u}_r = \mathbf{u}_r^g + \mathbf{u}_r^i + \mathbf{u}_r^{tc} \quad (4)$$

in which the components *g*, *i* and *tc* refer to the terms accounting for the gravity, inertia and trajectory-crossing effects, respectively. Equation 4 can be simplified by applying the Reynolds decomposition to \mathbf{u}_r and by analysing the contribution that each process gives to time averaged value of particle velocity ($\bar{\mathbf{u}}_r$) and to its fluctuating components (\mathbf{u}'_r).

Since only gravity affects the average value of particle velocity, we can write:

$$\bar{\mathbf{u}}_r = \bar{\mathbf{u}}_r^g = w_t * \mathbf{k} \quad (5)$$

where w_t is the particle free fall velocity (also called terminal velocity) acting along the vertical axis (\mathbf{k} is the vertical unit vector). As far as fluctuations are concerned, the only components affecting \mathbf{u}'_r are those associated with inertia and trajectory-crossing effects ($\mathbf{u}'_r = \mathbf{u}'_r^i + \mathbf{u}'_r^{tc}$). It has been shown (Csanady, 1963), however, that in the atmosphere the contribution of inertia is negligible for particles with diameters up to about 500 μm . The fluctuating component of \mathbf{u}_r can thus be simplified as:

$$\mathbf{u}'_r = \mathbf{u}'_r^{tc} \quad (6)$$

Size-segregated fluxes of mineral dust by eddy covariance

G. Fratini et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Size-segregated fluxes of mineral dust by eddy covariance

G. Fratini et al.

Taking into account Eqs. (5) and (6), Eq. (2) becomes:

$$\frac{\partial \bar{c}}{\partial t} + \bar{u} \frac{\partial \bar{c}}{\partial x} + \overline{u'_p \frac{\partial c'}{\partial x}} + (\bar{w} + w_t) \frac{\partial \bar{c}}{\partial z} + \overline{w'_p \frac{\partial c'}{\partial z}} = \bar{S} + \gamma \nabla^2 \bar{c} \quad (7)$$

If molecular diffusion is small compared to the turbulent stresses and no horizontal turbulent flux divergence occurs, integration of Eq. (7) along the vertical axes z gives rise to:

$$\int_0^{h_m} S dz = \overline{w'_p c'} \Big|_{z=h_m} + \int_0^{h_m} w_t \frac{\partial \bar{c}}{\partial z} dz + \int_0^{h_m} \frac{\partial \bar{c}}{\partial t} dz + \int_0^{h_m} \bar{u} \frac{\partial \bar{c}}{\partial x} dz + \int_0^{h_m} \bar{w} \frac{\partial \bar{c}}{\partial z} dz \quad (8)$$

I II III IV V

where *I* is the scalar source/sink term; *II* represents the vertical turbulent flux at height h_m ; *III* is the flux due to gravitational advection, *IV* represents the storage of the scalar below the measurement height; *V* is the flux due to horizontal advection and *VI* the one due to fluid vertical advection.

If atmospheric stationarity and horizontal homogeneity are achieved, the last three terms of the right-hand side of Eq. (8) can be neglected, and the working equation for the EC of particles becomes:

$$F_p = \int_0^{h_m} S dz = \overline{w'_p c'} \Big|_{z=h_m} + w_t \bar{c} \Big|_{z=h_m} \quad (9)$$

in which h_m is the height at which measurements are performed. Equation (9) states that the particle source/sink term, equivalent to the net release of particles F_p , equals the sum of the vertical eddy flux and the gravitational settling flux.

This expression reduces to the one commonly used for gases:

$$F_p = \overline{w' c'} \quad (10)$$

when:

$$w_t \cong 0 \text{ and } w_r'^{tc} \cong 0 \Rightarrow w'_p \cong w' \quad (11)$$

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Conditions in Eq. (11) occur when gravitational settling is small with respect to the turbulent flux, and the trajectory crossing effect is negligible.

To assess in which conditions gravitational settling can be neglected, a preliminary analysis was performed by comparing the particle terminal velocity w_t with the mean vertical Lagrangian velocity (Shao, 2000). The following equation can be used to calculate w_t , for small particles subject only to gravity and aerodynamic drag:

$$w_t = -\frac{\sigma_p g d^2}{18\nu} \quad (12)$$

where σ_p is the particle-to-air density ratio, g is the gravity (ms^{-2}) and ν is the kinematic viscosity of the air (m^2s^{-1}).

Since a particle-to-air density ratio of ca. 2200 can be reasonably assumed for mineral dust, particles with optical diameters of 7.00 and 1.00 μm should have settling velocities of ca. $6.8 \times 10^{-3} \text{ms}^{-1}$ and $0.1 \times 10^{-3} \text{ms}^{-1}$, respectively. In a neutrally-stratified atmospheric surface layer, the mean vertical component of the Lagrangian velocity of the air parcel surrounding the particles can be estimated (Hunt and Weber, 1979) by the product κu_* , between the Von Kármán constant ($\kappa \cong 0.4$) and the friction velocity, u_* . By considering that during wind erosion events u_* is always well above 0.2–0.3 ms^{-1} , and that the corresponding Lagrangian velocity is of the order of $8 \times 10^{-2} \text{ms}^{-1}$, gravitational settling can be neglected with respect to turbulent diffusion. These calculations suggested that Eq. (10) could have been safely applied to derive the total vertical fluxes of particles with an optical diameter as high as 7 μm under normal conditions, as long as the tc effect can be neglected.

The aerodynamic diameter (D_{ae}) corresponding to this optical fraction (D_{opt}) can be estimated by recalling that :

$$D_{ae} = D_{opt} \cdot \rho_p^{1/2} \cdot f(D_{opt}, m) \quad (13)$$

in which ρ_p is the normalized particle density and m is the particle refractive index. The function $f = f(D_{opt}, m)$, is usually taken in the form of a 2nd-order polynomial function in

Size-segregated fluxes of mineral dust by eddy covariance

G. Fratini et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

m , the coefficients depending on the diameter range (McMeeking, 2004). For northern Asian dust, the refractive index can be assumed to be $m=1.53$ (Clarke et al., 2004), and $f(D_{\text{opt}}, m)$ is around 0.85. Since the density of fine soil particles measured in the sites investigated was $\rho_p=2.5 \text{ gcm}^{-3}$ (see below), $D_{ae} \cong 1.35 \cdot D_{\text{opt}}$. This means that fluxes of particles with an aerodynamic range up to ca. $9.5 \mu\text{m}$ could have been safely measured by EC.

The equivalence between net fluxes and the co-variance between the vertical wind and particle concentrations requires also that stringent criteria are followed in the selection of the measuring site to meet horizontal homogeneity and isotropy conditions. In the flat, desert areas of northern China where only sparse, short vegetation and small dunes are present (see next section), these conditions are fully met. For the same reasons, footprint assessment is not critical. On the basis of traditional EC practice, it can be estimated by the product $100 * h_m$ (Sozzi et al., 2002). The storage term is also negligible because of the highly turbulent conditions in which emission occurs and substantial lack of any surface where particles could be deposited.

3 Materials and methods

3.1 The eddy covariance system for mineral dust particles

Once the upper limit of the measurable aerodynamic range has been defined, the actual range was selected on the basis of the sensing device used. With the selected OPC, counting efficiencies larger than 90% were possible for particles with an optical diameter ranging between 0.26 and $7.00 \mu\text{m}$. By using the conversion procedures described in the previous section, size-segregated fluxes of mineral dust particles with aerodynamic diameters between 0.35 and $9.50 \mu\text{m}$ could have been measured with our system. It covers the largest portion of mineral dust mass subject to long range transport.

The concentration system, shown in Fig. 1b, includes several parts. The most impor-

**Size-segregated
fluxes of mineral dust
by eddy covariance**

G. Fratini et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

tant are the OPC (CI-3100 series, Climet Instruments Co., Redlands, CA, USA) and the Multi-Channel Analyzers (MCA8000, Amptek Inc., Bedford, MA, USA). To minimize uncertainties, the inlet of the measuring system was directly attached to the anemometer. In our design, sampled particles were split in two channels: the so-called finer channel (D_{opt} from 0.26 to 0.54 μm) and the coarser channel (D_{opt} from 0.54 to 7.00 μm).

The system simultaneously acquires data from the two channels through dedicated MCA devices. “Finer” and “coarser” particle number concentrations are stored every 30 min. This time period, which also corresponds to the averaging time in Eq. (9), was selected on the basis of the experience acquired in the framework of EC applied to gases. It represents the best compromise to achieve a correct sampling of turbulent eddies and to get averaging times short enough to meet the steady-state conditions required by the theory (Aubinet, 2000; Aubinet et al., 2001; Goulden et al., 1996).

The acquisition frequency was also carefully chosen. While high sampling frequencies are needed for an accurate collection of smaller eddies, their use might lead to statistically poor sampling of large particles. In the case of mineral dust, it was found that an acquisition frequency of 5Hz represented the best compromise between these opposite requirements. In any case, the system was built in a way that all acquisition features, with the exception of the “finer” and “coarser” channel selection, could have been changed by the operator. Figure 1b shows details of the pneumatic circuit and the data acquisition system. A pump was used to deliver the sampled air to the sensing device where each particle was counted and sized based on the back-scattered light of a diode laser. To avoid masking effects of particle counting during intense storm events, the sample entering the OPC was diluted by adding air free from particle at a ratio of 20:1. In these conditions, the OPC sizing was accurate to approximately 30%. The system was able to simultaneously record counts of particles falling in 18 size ranges. The number of particles per unit of sampled volume (number concentration) was then obtained. It will be indicated in the text as $N_{a,b}$, where a and b define the range under consideration. N will be conveniently replaced by V or M , when referring to volume or mass concentrations, respectively. These latter values were estimated by

**Size-segregated
fluxes of mineral dust
by eddy covariance**G. Fratini et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

assuming that particles were spherical and exhibited the same, constant density.

Sampling was performed at a flow rate of $1.42 \text{ dm}^3/\text{min}$ (corresponding to an inlet velocity of 0.88 ms^{-1} for a tube with an inner diameter of 6.35 mm). It was kept constant by a critical nozzle inserted in the flow path.

5 An ANSI C program was developed to control the hardware devices, to synchronize the acquisition of the two channels and to acquire and store the raw data.

Before calculating fluxes, data were pre-processed in order to account for the time-lag between the acquisition of wind and concentration data. The time-lag was estimated through a covariance analysis. Data were de-trended to eliminate possible long-term trends (Gash and Culf, 1996) and an axis rotation was performed to align the x-axis to the mean wind direction and nullify the covariance between v and w (Kaimal and Finnigan, 1994). Concentrations and fluxes of mineral dust particles were calculated for each of the 18 ranges selected with a 30 min time step. Several turbulence parameters such as the Monin-Obukhov length, the friction velocity and the sensible heat flux, were also calculated. The system was located inside a tough case to protect the instrumentation from shocks or falls occurring during transport or during storm events.

3.2 Investigated sites

Although a total of six sites, all located in northern China, were investigated, we report here only data collected in two sites of the Gobi desert. Both of them (identified in the paper as GB1 and GB2) are located in the Ejin'a area of the Alashan Prefecture. Their exact location is shown in Fig. 2. In all cases land-cover features were those typical of the area. The GB1 site, which is flat and highly homogeneous, is characterized by bare soil where only sparse shrubs are present. The short vegetation is partly covered by small, sandy dunes extending downwind. They originated from deposition of sand and dust transported during previous storm events. The GB2 site is also flat and highly homogeneous, but is comprised only by bare soil free from any vegetation cover. We restrict the discussion to these sites because they allowed to better test

Size-segregated fluxes of mineral dust by eddy covariance

G. Fratini et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

the ability of our system to provide size-segregated fluxes of mineral dust particles by EC because of the frequent occurrence of desert storm events. This, combined with limited interferences arising from human activities allowed to better highlight some features associated with the wind erosion process. Particle density was determined by means of picnometer-based standard procedures (ISO/TS, 2004).

4 Results and discussion

4.1 Cumulated and size-segregated particle concentrations

Figure 3 reports the time series of total particle number concentrations ($N_{0.26-7.00}$) that were recorded by EOLO at the GB1 site. As it can be seen from the figure, only one high concentration event was recorded during the monitoring campaign and it occurred in the last days of May. Particle number concentrations recorded during this event were one to two orders of magnitude higher than those recorded in the previous days.

Since no particle mass monitors were available at the site, a comparison was made with data from the Navy Aerosol Analysis and Prediction System (NAAPS) (<http://www.nrlmry.navy.mil/aerosol/>). The model, developed by Westphal et al. (1988) predicts 6-h averaged data of mineral dust mass concentration smaller than $5.00 \mu\text{m}$ (aerodynamic diameter) at the surface layer. Model outputs have a sufficient spatial resolution to follow mineral dust evolution in the investigated area. Particle mass concentrations lower than $5.00 \mu\text{m}$ were obtained from EOLO by summing particle number contributions from all channels with an optical diameter smaller than ca. $4.00 \mu\text{m}$ and by converting these values into mass ($M_{0.26-4.00}$ in $\mu\text{g m}^{-3}$).

Figure 4 compares the time evolution of particle mass concentration predicted by the NAAPS model (a) with those measured by EOLO (b). Data refer to the storm event recorded at the end of May. Although the time resolution of the model did not allow to verify short-term variations, a good consistency was observed between the two datasets. This suggested that the bulk of mineral dust particles emitted in the

Size-segregated fluxes of mineral dust by eddy covariance

G. Fratini et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

area was falling within the size-range sensed by EOLO. It is worth noting that the good agreement between measured and modelled values was not limited to this episode but was observed in almost all sites in which the impact of anthropogenic sources was limited, regardless from the occurrence of storms events.

5 Data obtained at the GB1 site during the event were also used to evaluate the evolution of mineral dust particles under high emission conditions. N and V values of particles recorded in the 18 size ranges investigated were separated into classes as a function of the friction velocity. Three classes, corresponding to average values of 0.15, 0.30 and 0.45 ms^{-1} , were selected for this analysis. In Fig. 5a data of particle number concentrations are reported, whereas volume concentrations are shown in Fig. 5b. Solid lines with symbols were used to identify averaged values of profiles belonging to each friction velocity class. Dotted lines refer, instead, to individual measurements. Although a general increase of N with the friction velocity was observed, the one occurring in the $0.40\text{--}0.60 \mu\text{m}$ range was suggestive of a substantial generation of finer particles above a certain value of the friction velocity. The release of these particles does not directly come from the wind action. Such particles are, indeed, so strongly attached to large sandy grains, to form a sort of permanent coating hard to be removed even at high wind speeds. Their release can be better explained by the sandblasting process induced by saltating particles (Shao, 2000).

20 As shown Fig. 5b, trends of particle volume concentrations as a function of the friction velocity are quite different from those followed by particle number concentrations. Volume concentrations of coarser particles increase much more rapidly than particle number during the dust event. While in low turbulent conditions the contribution of finer particles ($V_{0.26\text{--}0.90}$) to the total volume is comparable to that of coarser particles ($V_{2.00\text{--}4.00}$), a larger increase in the coarser mode occurs during the dust event. It is such that the total volume concentrations can be considered to be almost exclusively formed by particles falling in the $V_{2.00\text{--}7.00}$ range.

**Size-segregated
fluxes of mineral dust
by eddy covariance**G. Fratini et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

4.2 Co-spectral analysis

A co-spectral analysis was performed on the raw data in order to find out if tc effect was affecting the motion of particles falling in any size range. To focus attention on the vertical dynamics, co-spectra are calculated by using the vertical wind speed, w , as the transporting variable.

Based on the classical theory of turbulence K41 (Kolmogorov, 1941), it can be assumed that trajectory crossing effects are negligible and data statistically valid whenever particle concentrations behave as passive scalars in the inertial frequency sub-range.

Different approaches can be used to find out if particle behave as an ideal scalar. The most used consists in comparing co-spectra of particles determined in the inertial sub-range with those theoretically expected (Martensson et al., 2006). Since theoretical calculations are possible only for specific turbulence conditions, such as neutrally stratified atmospheres (Stull, 1988), this approach is not the most appropriate when, such in our case, rapid changes in turbulence take place. In these conditions, a comparison between the normalized co-spectra of particles with those of an experimental variable known to be passively transported by the air flow represents a better option to analyze the concentration dynamics. If particles behave as a perfect scalar, their co-spectra should match those of the experimental variable in the inertial sub-range.

In our case, co-spectral analysis was performed by comparing normalized co-spectra of particle concentration with those of the sonic temperature, which can be certainly assimilated to a passive scalar. Results obtained are summarized in Figs. 6a and b, where data of regularized and normalized co-spectra of particle concentrations and sonic temperatures are plotted as a function of the normalized frequency f_n . This latter parameter is defined by $f_n = f * h_m / U$, where f is the frequency in Hz, h_m is the measurement height, ($h_m = 12$ m) and U is the horizontal wind speed in ms^{-1} . In the figure, individual symbols are used to indicate co-spectra of particle mass concentrations in the various size ranges, whereas the continuous red lines refer to co-spectra of

Size-segregated fluxes of mineral dust by eddy covariance

G. Fratini et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**Size-segregated
fluxes of mineral dust
by eddy covariance**G. Fratini et al.

the sonic temperature. Data were obtained by processing individual 30-mins datasets according to the following procedure: *i.* Hanning filtering; *ii.* Fast Fourier Transform; *iii.* raw co-spectra calculation; *iii.* raw co-spectra block averaging over exponentially-spaced frequency ranges; *iv.* as single datasets, each raw co-spectrum presents high levels of irregularity; thus, further local filtering (block-weighted average) was applied to highlight the main slopes; *v.* normalization by the relevant covariance.

Plots in Fig. 6a refer to data recorded during the storm event of 25 May 2005, when the maximum particle mass concentrations were reached over the site and the average values of the wind speed and of the friction velocity were 13.9 and 0.6 ms^{-1} , respectively. Plots in Fig. 6b refer to data collected on 28 May 2005 at the GB2 site, when particle mass concentrations were low and averaged values of the wind speed and of the friction velocity were 10.1 and 0.4 ms^{-1} , respectively.

Figures clearly show that under highly turbulent conditions (GB1 site), normalized co-spectra of both finer and coarser particles closely matched those of sonic temperature in the inertial subrange, that approximately extends beyond values of $f_n=1$. This suggested that in these conditions, tc effects were actually negligible and fluxes adequately described by the same equations used for gases. The same good consistency was not found at the GB2 site in which low turbulent conditions occurred during the monitoring campaign. Deviations from a perfect scalar occurred in both the finer and coarser particle ranges. This does not necessarily mean that tc effects affected our determinations, because other effects could have contributed to reduce the correlation between co-spectra of particles and those of the sonic temperature. The most important was associated with the fact that the instrument was specifically designed to measure particles during storm events, when high concentrations are reached. Under low turbulent conditions, particle number concentrations dropped down to values in which the dilution step drastically reduced the number of particles reaching the sensor and counts recorded were not always statistically representative of the actual concentrations. To evaluate sources leading to deviations of particle number concentrations under low turbulence conditions, the dilution step should have been avoided and the

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

whole sample sent to the OPC. Because of these limitations, we will focus our discussion on size-segregated fluxes of mineral dust to data collected during the storm event. Data collected under low turbulent conditions will be only used to provide a general idea of variations occurring over the site.

5 4.3 Cumulated and size-segregated fluxes of mineral dust during storm events

By keeping in mind the considerations above, fluxes measured by EC were first used to check if the gravitational settling was actually negligible with respect to turbulent fluxes. This was obtained by comparing the gravitational settling of particles falling in the coarser mode ($N_{0.54-7.00}$) calculated by using Eq. (9) with net fluxes measured by EC. The comparison was performed on data collected at the GB1 site. They are displayed in Fig. 7, where individual symbols represent hourly data points. It is evident that gravitational fluxes were generally 1 to 2 orders of magnitude lower than net turbulent fluxes and, in most of the instances, their contribution could have been neglected. Only sporadically, gravitational fluxes exceeded the turbulent ones. This happened when both turbulence and particle number concentrations were small. In these cases, however, turbulent fluxes were also affected by a large uncertainty.

The sequence of events that occurred at the GB1 site was also exploited to get information on the way emission occurs in desert areas of northern China and to analyze what happens during storm events. Data reported in Fig. 8 show that total number fluxes ($N_{0.26-7.00}$ flux) do not follow the same trend as the friction velocity. Although several periods were recorded in which high wind speeds and friction velocities were reached, following a daily pattern, only in the last days of measurement huge fluxes were measured. During this episode values as high as 3×10^4 particles $\text{cm}^{-2}\text{s}^{-1}$ were recorded over the site. They were 1 to 2 orders of magnitudes higher than those measured in previous days under similar conditions in terms of wind speed and friction velocity. This is consistent with the fact that other parameters, such as wind direction, air humidity, particle density and the texture, cover, moisture content and roughness of soil, play an important role in the development of desert storm events.

Size-segregated fluxes of mineral dust by eddy covariance

G. Fratini et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**Size-segregated
fluxes of mineral dust
by eddy covariance**G. Fratini et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Focusing on the storm event, we can see that particle fluxes behaved differently from concentrations; indeed, no substantial changes in size-segregated flux profiles were recorded. Data reported in Fig. 9a1 indicate that the profile of particle number fluxes are always dominated by particles falling in the finer range ($N_{0.26-0.30}$) with two maxima peaking in the $N_{0.70-1.00}$ and $N_{1.50-3.00}$ modes. Above $3.00 \mu\text{m}$ optical diameter, a rapid decay occurs in the particle number fluxes. In terms of particle volume (and particle mass), emission fluxes are, instead, definitely dominated by particles falling in the $V_{1.50-3.00}$ mode, with a secondary contribution from particles in the $V_{0.70-1.00}$ range (see Fig. 9a2). Overall, larger particles account for ca. 74% of the entire volume, whereas finer particles contribute only to ca. 7%. In terms of aerodynamic diameters, this means that net vertical fluxes generated during storm events are essentially given by particles falling in the $\text{PM}_{2.5}$ – PM_{10} range. This represents a substantial variation with respect to low turbulent conditions, in which fluxes of coarser particle account for ca. 40% of the total volume and the finer ones for ca. 22%. The relative importance of the $V_{0.26-7.00}$, $V_{0.26-1.85}$, $V_{0.26-0.74}$ modes, roughly corresponding to PM_1 , $\text{PM}_{2.5}$ and PM_{10} in aerodynamic diameter, in determining the total particle volume and their substantial constancy during storm events characterized by high particle emission is well illustrated in Fig. 9b. The good correlation coefficients given by the linear regressions suggest that it is possible to estimate, with good accuracy, size segregated fluxes of mineral dust particles from their total fluxes expressed in terms of both mass and volume.

Data collected are also useful to better understand the role played by the friction velocity in determining particle emission during acute episodes in which wind erosion and sandblasting are, by far, the dominant processes of dust emission. Although several factors are known to affect particle generation in the wind erosion process, their assessment is rather difficult and, sometimes, controversial (Shao, 2000). This explains why many models still use relations between the friction velocity and particle fluxes to parameterize the emission process. Particle fluxes are usually related to friction velocity through a power function, whose exponent was found to vary, from 6.54

to 1.89 (Nickling and Gillies, 1989; White et al., 1996). Such large variations, that have been attributed to inter-particle bonds strength and/or crusting effects (Houser and Nickling, 2001), can introduce large errors in the models. Data collected during the storm event were particularly suitable to investigate this aspect because determinations were made when deposition fluxes were small when compared to emission and the emission process was essentially driven by wind erosion. Under these conditions, other effects, such as those arising from changes in the moisture content of soil, could have been neglected and the relation between particle emission and turbulence better assessed. When particle volume fluxes in three size ranges (namely $V_{0.26-7.00}$, $V_{0.26-1.85}$, $V_{0.26-0.74}$) were plotted against the friction velocity, curves shown in Fig. 10 were obtained. Power regression gave exponents ranging between 3.10–3.36 with a r^2 of 0.732. It is much higher than those found in previous literature (Houser and Nickling, 2001) in which r^2 values of 0.38 were reported. Since in the EC approach the friction velocity is derived independently from vertical dust fluxes, the good correlation displayed in Fig. 10 is suggestive of a genuine physical dependence, and it does not seem to be just a spurious result of the calculations, as suggested, for example, in Houser and Nickling (2001).

5 Conclusions

For the first time, EC has been used to measure size segregated fluxes of mineral dust particles during storm events occurring in desert areas of northern China. Although limited by the number of events recorded, results obtained provided useful information to parameterize the emission process either in global transport models and in models devoted to predict wind erosion and sandblasting. The co-spectral analysis showed that the instrument developed was able to provide quite reliable data when high particle concentrations were reached and under strong turbulence conditions. Its accuracy was definitely much lower when low concentrations and limited turbulence occurred over the site. However, this limitation can be partly circumvented if the dilution step is avoided

Size-segregated fluxes of mineral dust by eddy covariance

G. Fratini et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

and the whole sample sent to the sensor. We believe that an increase of a factor of 20 in the particle number is more than enough to get statistically accurate values of particle concentrations under normal conditions, as it has been shown by previous authors (Dorsey et al., 2002; Martensson et al., 2006; Nemitz et al., 2000). Other limits are associated with the particle sizing capabilities of the OPC and with the impossibility to evaluate errors arising from sub-kinetic sampling occurring in the coarser mode under very high turbulent conditions. These aspects are presently under investigation.

Acknowledgements. We thank the Italian Ministry of the Environment (IMET) for the financial support given through the WinDust project and the Beijing Municipality Environmental Protection Bureau (BJEPB) who supported investigations on dust storms. The authors wish to thank all the scientists, technicians and supporting staff of Beijing Municipality Environmental Protection Institute (BJEPB) and Beijing Municipality Environmental Protection Foundation for the help provided. In particular, N. Lei and D. Jianqi are warmly acknowledged. D. L. Westphal of US NAAPS is also acknowledged for providing information on the NAAPS global dust model.

References

- Andreae, M. O.: Climate effects of changing atmospheric aerosol levels, in World Survey of Climatology, Future Climate of the World, 16, A. Henderson Sellers ed., Elsevier Publ., Amsterdam, 341–392, 1995.
- Aubinet, M.: Estimates of the annual net carbon and water exchange of forests: the EU-ROFLUX methodology, *Adv. Ecol. Res.*, 30, 113–175, 2000.
- Fluxes of Carbon, Water and Energy of European Forests, edited by: Valentini, R., *Ecol. Stud.*, 163, 9–36, 2003.
- Aubinet, M., Chermanne, B., Vandenhaute, M., Longdoz, B., Yernaux, M., and Laitat, E.: Long term measurements of water vapour and carbon dioxide fluxes above a mixed forest in Ardennes's region, *Agric. Forest Meteorol.*, 108, 293–315, 2001.
- Baldocchi, D., Hicks, B. B., and Meyers, T. D.: Measuring biosphere-atmosphere exchanges of biologically related gases with micrometeorological methods, *Ecology*, 69, 1331–1340, 1988.

Size-segregated fluxes of mineral dust by eddy covariance

G. Fratini et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**Size-segregated
fluxes of mineral dust
by eddy covariance**G. Fratini et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Bates, T. S., Anderson, T. L., Baynard, T., Bond, T., Boucher, O., Carmichael, G., Clarke, A., Erlick, C., Guo, H., Horowitz, L., Howell, S., Kulkarni, S., Maring, H., Mccomiskey, A., Middlebrook, A., Noone, K., O'dowd, C. D., Ogren, J., Penner, J., Quinn, P. K., Ravishankara, A. R., Savoie, D. L., Schwartz, S. E., Shinozuka, Y., Tang, Y., Weber, R. J., and Wu, Y.: Aerosol direct radiative effects over the northwest Atlantic, northwest Pacific and North Indian Oceans: estimates based on in-situ chemical and optical measurements and chemical transport modelling, *Atmos. Chem. Phys.*, 6, 1657–1732, 2006,

<http://www.atmos-chem-phys.net/6/1657/2006/>.

Bauer, S. E., Balkanski, Y., Schulz, M., Hauglustaine, D. A., and Dentener, F.: Global modelling of heterogeneous chemistry on mineral aerosol surfaces: influence on tropospheric ozone chemistry and comparison to observations, *J. Geophys. Res.*, 109, D02304, doi:10.1029/2003JD003868, 2004.

Bonasoni, P., Cristofanelli, P., Calzolari, F., Bonafè, U., Evangelisti, F., Stohl, A., Zauli Sajani, S., Van Dingenen, R., Colombo, T., and Balkanski, Y.: Aerosol-ozone correlations during dust transport episodes, *Atmos. Chem. Phys.*, 4, 1201–1215, 2004,

<http://www.atmos-chem-phys.net/4/1201/2004/>.

Breshears, D. D., Whicker, J. J., Johansen, M. P., and Pinder, J. E.: Wind and water erosion and transport in semi-arid shrubland, grassland and forest ecosystems: quantifying dominance of horizontal wind-driven transport, *Earth Sur. Proc. Land.*, 28, 1189–1209, 2003.

Chin, M., Ginoux, P., Lucchesi, R., Huebert, B., Weber, R., Anderson, T., Masonis, S., Blomquist, B., Bandy, A. and Thornton, D.: A global aerosol model forecast for the ACE-Asia field experiment, *J. Geophys. Res.*, 108(D23), 8654, doi:10.1029/2003JD003642, 2003.

Clarke, A. D., Shinozuka, Y., Kapustin, V. N., Howell, S., Huebert, B., Doherty, S., Anderson, T., Covert, D., Anderson, J., Hua, Z., Moore, K. G., Mcnaughton, C., and Carmichael, G.: Size-distributions and mixtures of dust and black carbon aerosol in Asian outflow: physiochemistry and optical properties, ACE-Asia project report, 2004.

Csanady, G. T.: Turbulent diffusion of heavy particles in the atmosphere, *J. Atmos. Sci.*, 20, 201–208, 1963.

Cziczo, D. J., Murphy, D. M., Hudson, P. K., and Thomson, D. S.: Single particle measurements of the chemical composition of cirrus ice residue during crystal-face, *J. Geophys. Res.*, 109, D04201, doi:10.1029/2003JD004032, 2004.

De Reus, M., Fischer, H., Sander, R., Gros, V., Kormann, R., Salisbury, G., Van Dingenen, R., Williams, J., Zollner, M., and Lelieveld, J.: Observations and model calculations of trace

gas scavenging in a dense Saharan dust plume during MINATROC, *Atmos. Chem. Phys.*, 5, 1787–1803, 2005,

<http://www.atmos-chem-phys.net/5/1787/2005/>.

Dentener, F. J., Carmichael, G. R., Zhang, Y., Lelieveld, J., and Crutzen, P. J.: Role of mineral aerosol as a reactive surface in the global troposphere, *J. Geophys. Res.*, 101, 22 869–22 889, 1996.

Dong, Z., Liu, X., Wang, H., and Wang, X.: Aeolian sand transport: a wind tunnel model, *Sedim. Geol.*, 161, 71–83, 2003.

Dong, Z., Wang, H., Liu, X., and Wang, X.: The blown sand flux over a sandy surface: a wind tunnel investigation on the fetch effect, *Geomorphology*, 57, 117–127, 2004.

Dorsey, J. R., Nemitz, E., Gallagher, M. W., Fowler, D., Williams, P. I., Bower, K. N., and Beswick, K. M.: Direct measurements and parameterisation of aerosol flux, concentration and emission velocity above a city, *Atmos. Environ.*, 36, 791–800, 2002.

Gash, J. H. and Culf, A. D.: Applying linear de-trend to eddy correlation data in real time, *Bound-Lay. Meteorol.*, 79, 301–306, 1996.

Goulden, M. L., Munger, J. W., Fan, S. M., Daube, B. C., and Wofsy, S. C.: Measurements of carbon sequestration by long-term eddy covariance: methods a critical evaluation of accuracy, *Global Change Biol.*, 2, 159–168, 1996.

Gusten, H., Heinrich, G., Monnich, E., Sprung, D., Weppner, J., Ramadan, A. B., El, E., Din, M. R. M., Ahmed, D. M., and Hassan, G. K. Y.: On-line measurements of ozone surface fluxes: Part II; Surface-level ozone fluxes onto the Sahara desert, *Atmos. Environ.*, 30, 911–918, 1996.

Heintzenberger, J., Raes, F., Schwartz, S. E., et al.: *Topospheric Aerosols, in Atmospheric Chemistry in a Changing World: An Integration and synthesis of a decade of tropospheric research*, edited by: Brasseur, G. P., Prinn, R. G., and Pszenny, A. A. P., Springer-Verlag Publ., Heidelberg, 125–156, 2003.

Houser, C. A. and Nickling, W. G.: The emission and vertical flux of particulate matter <10 μm from a disturbed clay-crusted surface, *Sedimentology*, 48, 255–267, 2001.

Hunt, J. C. R. and Weber, A. H.: A Lagrangian statistical analysis of diffusion from a ground level source in a turbulent boundary layer, *Q. J. R. Meteorol. Soc.*, 105, 423–443, 1979.

Husar, R. B., Tratt, D. M., Schichtel, B. A., Falke, S. R., Li, F., Jaffe, D., Gasso, S., Gill, T., Laulainen, N. S., Lu, F., Reheis, M. C., Chun, Y., Westphal, D., Holben, B. N., Gueymard, C., Mckendry, I., Kuring, N., Feldman, G. C., McClain, C., Frouin, R. J., Merrill, J., Dubois, D.,

**Size-segregated
fluxes of mineral dust
by eddy covariance**

G. Fratini et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

- Vignola, F., Murayama, T., Nickovic, S., Wilson, W. E., Sassen, K., Sugimoto, N., and Malm, W. C.: Asian dust events of April 1998–2001, *J. Geophys. Res.*, 106, 18317–18330, 2001.
- Iso/Ts: 17892-3:2004 - Geotechnical investigation and testing, Laboratory testing of soil, Part 3: Determination of particle density – Pycnometer method, International Organization for Standardization, 7 pp., 2004.
- Kaimal, J. C. and Finnigan, J. J.: Atmospheric Boundary Layer flows: their structure and measurement, Oxford University Publ., Oxford, 1994.
- Kolmogorov, A. N.: Local structure of turbulence in an incompressible fluid at large Reynolds numbers, *Dokl. Akad. Nauk. SSSR*, 1941.
- Li, F., Zhao, L., Zhang, H., Zhang, T., and Shirato, Y.: Wind erosion and airborne dust deposition in farmland during spring in the Horqin Sandy Land of eastern Inner Mongolia, China, *Soil Till. Res.*, 75, 121–130, 2004.
- Martensson, E. M., Nilsson, E. D., Buzorius, G., and Johansson, C.: Eddy covariance measurements and parameterisation of traffic related particle emissions in an urban environment, *Atmos. Chem. Phys.*, 6, 769–785, 2006, <http://www.atmos-chem-phys.net/6/769/2006/>.
- Mcmeeking, G.: Size distribution measurements of wildfire smoke-influenced aerosol at Yosemite national park, MS Thesis, Colorado State University, 2004.
- Nemitz, E., Fowler, D., Dorsey, J. R., Theobald, M. R., McDonald, A. D., Bower, K. N., Beswick, K. M., Williams, P. I., and Gallagher, M. W.: Direct measurements of size-segregated particle fluxes above a city, *J. Aerosol Sci.*, 31, 116–117, 2000.
- Nickling, W. G. and Gillies, J. A.: Emission of fine-grained particulates from desert soils, in: *Paleoclimatology and Paleometeorology: Modern and Past Patterns of Global Atmospheric Transport*, edited by: Leinen, M. and Sarnthein, M., 1989.
- Ono, D., Weaver, S., and Richmond, K.: Quantifying particulate matter emissions from wind blown dust using real-time sand flux measurements, Owens Emissions papers, paper-C, EPA, 2003.
- Penner, J. E., Andreae, M., Annegarn, H., Barrie, L., Feichter, J., Hegg, D., Jayaraman, A., Leaitch, R., Murphy, D., Nganga, J., and Pitari, G.: Aerosols, their direct and indirect effects, in *Climate Change 2001: the Scientific basis*, Contribution of WorkingGroup 1 to the Third Assessment Report of Intergovernmental Panel on Climate Change, edited by: Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K., and Johnson, C. A.: Cambridge Univ. press. Publ., Cambridge, UK and New York, NY USA, 881,

**Size-segregated
fluxes of mineral dust
by eddy covariance**G. Fratini et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

2001.

Qian, W., Quan, L., and Shi, S.: Variations of the dust storm in China and its climatic control, *J. Climate*, 15, 1216–1229, 2002.

Rosenfeld, D., Rudich, Y., and Lahav, R.: Desert dust suppressing precipitation: possible desertification feedback loop, *Proc. Nation. Acad. Sci.*, 98, 5975–5980, 2001.

Seisel, S., Borensen, C., Vogt, R., and Zellner, R.: Kinetics and mechanism of the uptake of N_2O_5 on mineral dust at 298K, *Atmos. Chem. Phys.*, 5, 3423–3432, 2005, <http://www.atmos-chem-phys.net/5/3423/2005/>.

Shao, Y.: *Physics and Modelling of Wind Erosion*, Kluwer Academic Publ., 2000.

Sozzi, R., Georgiadis, T., and Valentini, M.: *Introduzione alla turbolenza atmosferica*, Pitagora eds., Bologna, 2002.

Stull, R. B.: *An introduction to boundary layer meteorology*, Kluwer Academic Publ., Dordrecht, 1988.

Tegen, I. and Lacis, A. A.: Modeling of particle size distribution and its influence on the radiative properties of mineral dust aerosol, *J. Geophys. Res.*, 101, 19237–19244, 1996.

Valentini, R., De Angelis, P., Matteucci, G., Monaco, G., Dore, S., and Scarascia Mugnozza, G. E.: Seasonal net carbon dioxide exchange of a beech forest with the atmosphere, *Glob. Change Biol.*, 2, 199–207, 1996.

Wang, X., Dong, Z., Zhang, J., and Liu, L.: Modern dust storms in China: an overview, *J. Arid Environ.*, 58, 559–574, 2004.

Westphal, D. L., Toon, O. B., and Carlson, T. N.: A case study of mobilization and transport of Saharan dust, *J. Atm. Sci.*, 45, 2145–2175, 1988.

White, B. R., Cho, G. H., and Kim, D. S.: A wind tunnel study to determine vegetation cover required to suppress sand dust transport at Owens (dry) lake, California, Great Basin Unified Air Quality Control District, Interagency Agreement no. 9464, 1996.

Xuan, J., Sokolik, I. N., Hao, J., Guo, F., Mao, H., and Yang, G.: Identification and characterization of sources of atmospheric mineral dust in East Asia, *Atmos. Environ.*, 38, 6239–6252, 2004.

Yudine, M. I.: Physical considerations on heavy-particle diffusion, *Advances of Geophysics*, 6, 185–191, 1959.

Zhang, Y. and Carmichael, G. R.: The role of mineral aerosol in tropospheric chemistry in East Asia – a model study, *J. Appl. Meteorol.*, 38, 353–366, 1999.

ACPD

7, 2133–2168, 2007

Size-segregated fluxes of mineral dust by eddy covariance

G. Fratini et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**Size-segregated
fluxes of mineral dust
by eddy covariance**

G. Fratini et al.

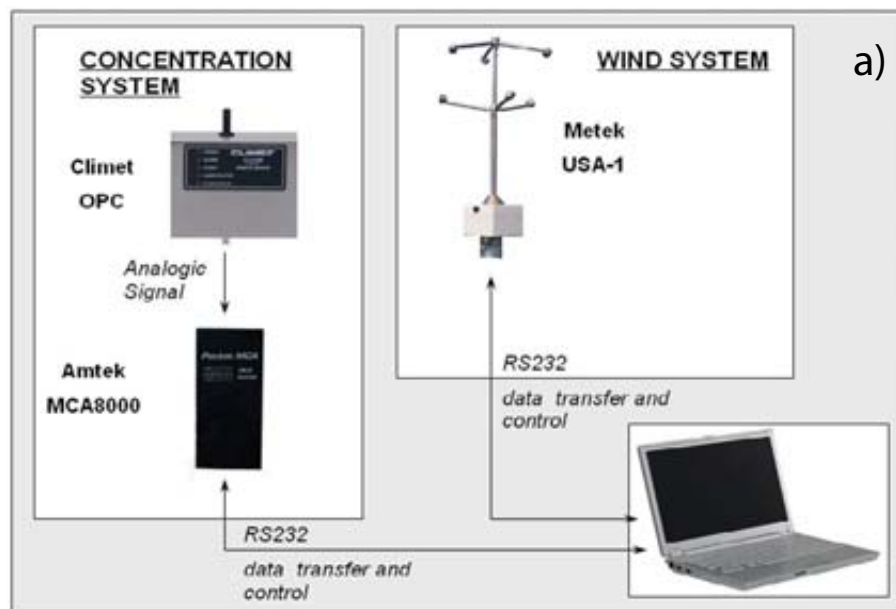


Fig. 1a. Simplified view of the eddy covariance system for measuring fluxes of mineral dust particles (EOLO).

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Size-segregated fluxes of mineral dust by eddy covariance

G. Fratini et al.

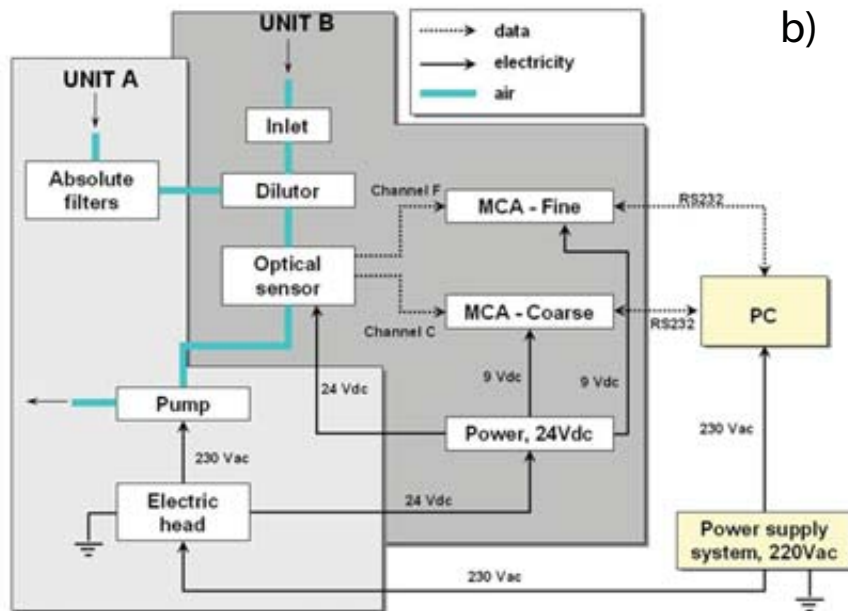


Fig. 1b. Schematic view of the concentrator system of EOLO.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Size-segregated fluxes of mineral dust by eddy covariance

G. Fratini et al.

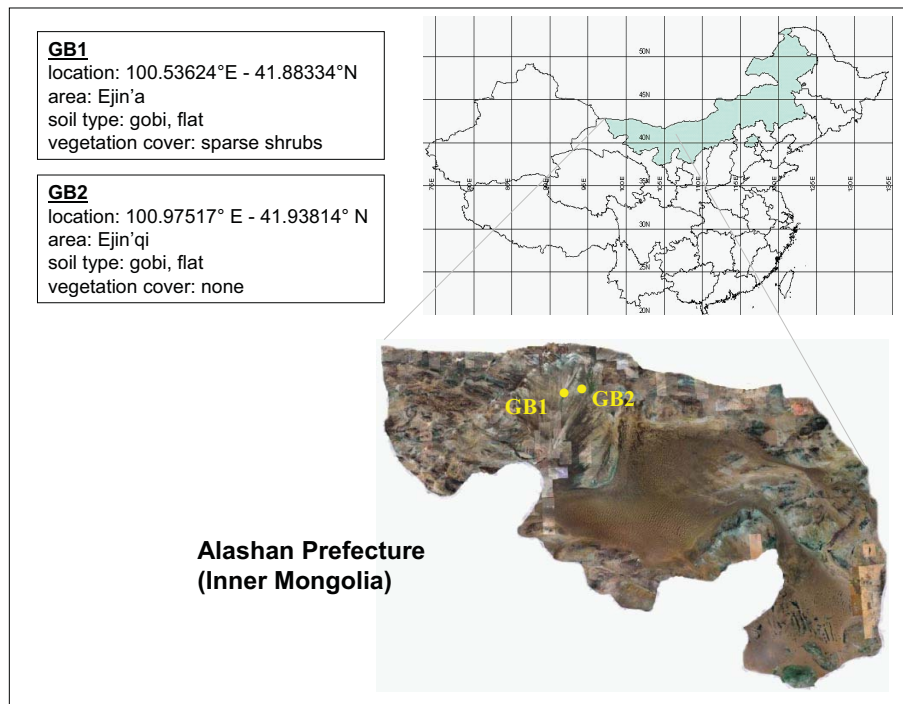


Fig. 2. Location of sites (GB1 and GB2) where mineral dust fluxes were measured by EOLO. These are located in the Ejin'a area of the Alashan Prefecture (Inner Mongolia, China).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Size-segregated fluxes of mineral dust by eddy covariance

G. Fratini et al.

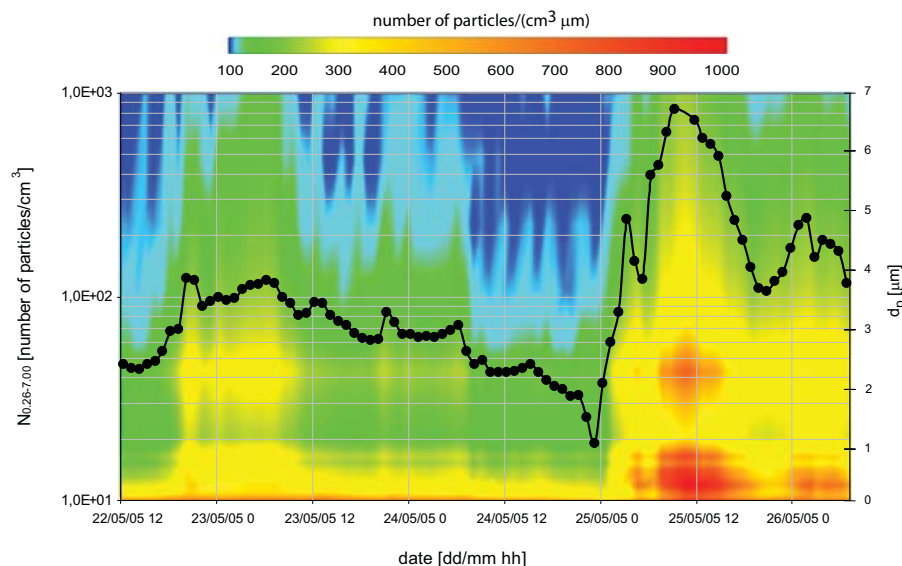


Fig. 3. Time evolution of total particles number concentration sensed by EOLO ($N_{0.26-7.00}$, bold line with circles), recorded from 22 to 26 May 2005 at the GB1 site, Ejina area. Concentrations are represented on a logarithmic scale. On the background, contour plot of size-segregated particle number concentration are reported.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Size-segregated
fluxes of mineral dust
by eddy covariance

G. Fratini et al.

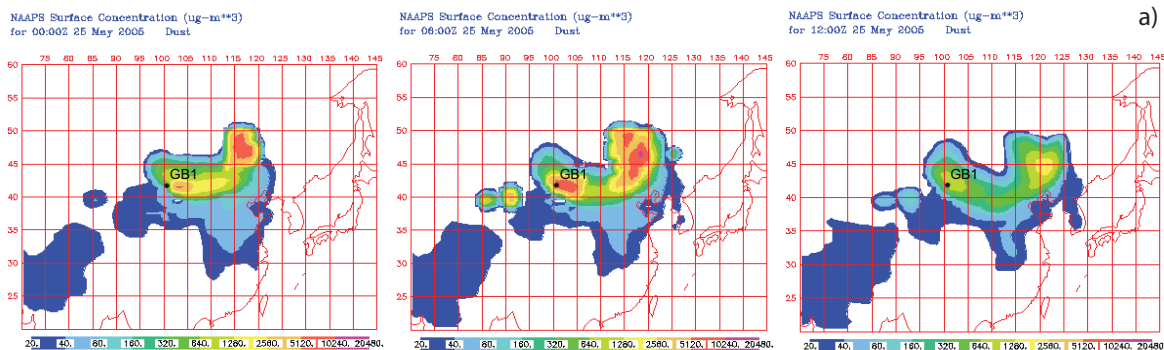


Fig. 4a. Mineral dust mass concentration during the strong dust event of 25 May 2005 at GB1 site: NAAPS “Dust” plots at surface layer; each plot represents 6-hours average concentration values. GB1 site location is also showed.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Size-segregated fluxes of mineral dust by eddy covariance

G. Fratini et al.

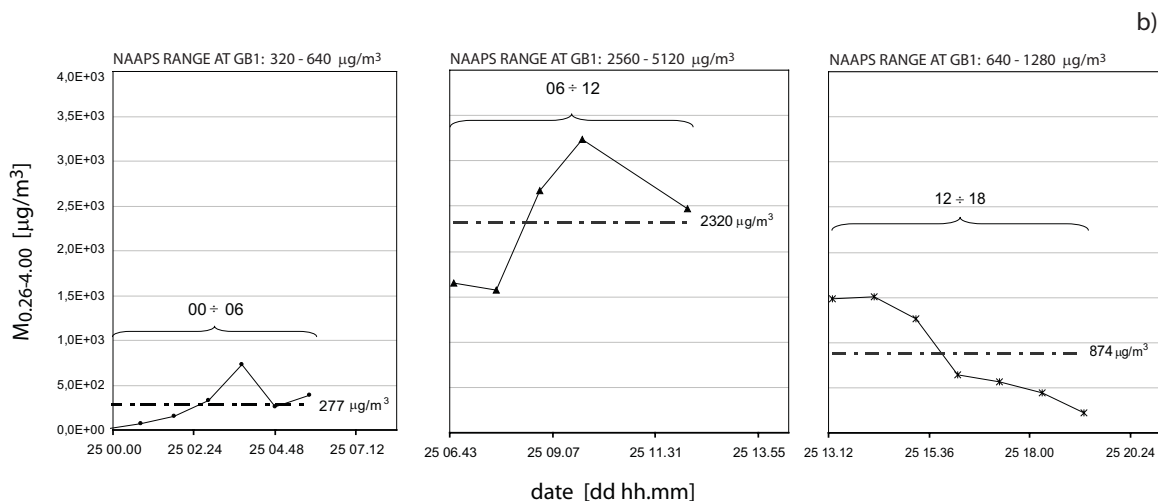


Fig. 4b. Mineral dust mass concentration during the strong dust event of 25 May 2005 at GB1 site: mass concentration time series derived by EOLO. Units are $\mu\text{g}/\text{m}^3$. Over each plot, the corresponding range predicted by NAAPS at the GB1 location is reported, derived from Fig. 4a.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

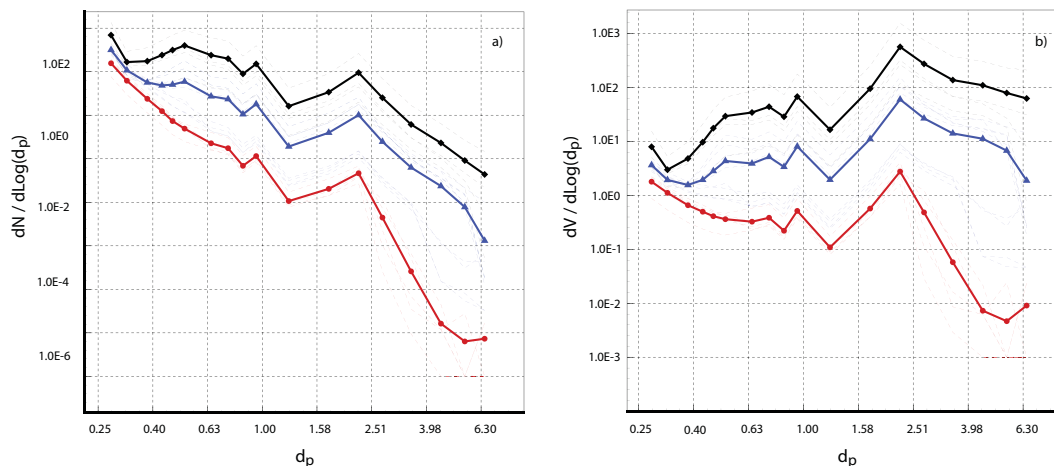


Fig. 5. Number **(a)** and volume **(b)** concentrations vs. particles diameters during dust event at the GB1 site. Units are [number of particles/cm³] and [$\mu\text{m}^3/\text{cm}^3$] for the number and volume concentration, respectively; diameters are expressed in μm . Red, blue and black thick lines with symbols are the average profiles of the 0.15, 0.30 and 0.45 ms^{-1} wind friction classes, respectively. The highest wind friction class refers to the most intense period. Light, dashed lines are examples of profiles in the three classes.

Size-segregated fluxes of mineral dust by eddy covariance

G. Fratini et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Size-segregated fluxes of mineral dust by eddy covariance

G. Fratini et al.

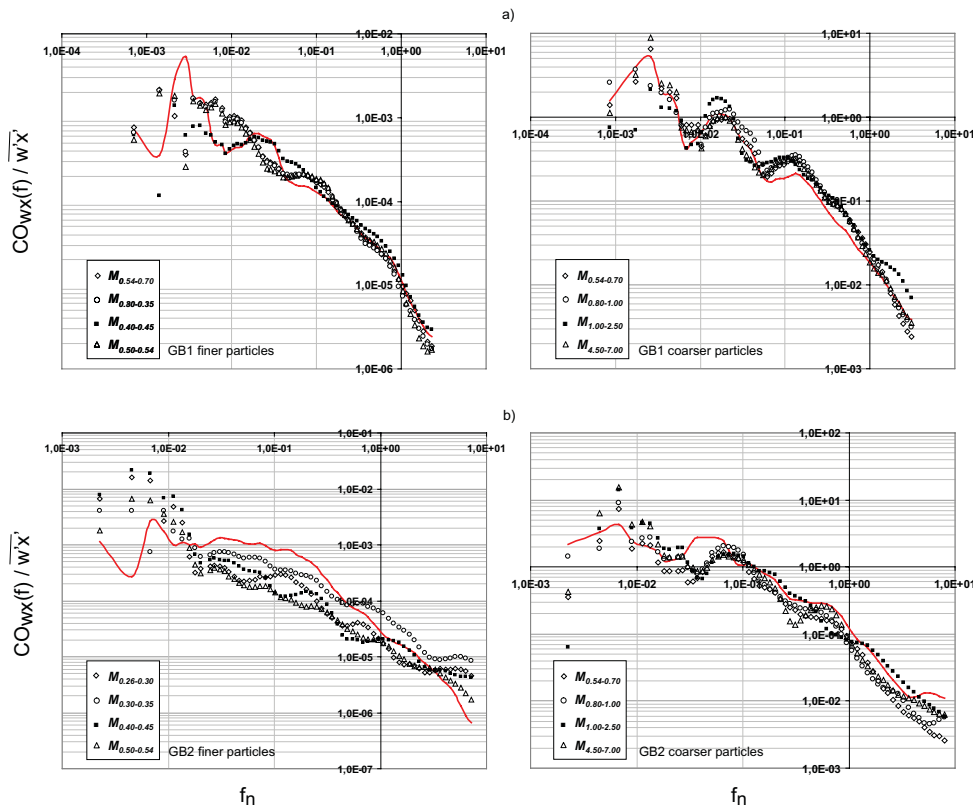
[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


Fig. 6. Normalized co-spectra of vertical wind and sonic temperature (red curves) and of vertical wind and particle concentration (symbols), as a function of the normalized frequency (U is used here to indicate the mean horizontal component of the wind speed). The term “finer particles” indicates all particles ranging between 0.26 and 0.54 μm (optical diameter), whereas the term “coarser particles” is used for the size range between 0.54 and 7.00 μm . Plots refer to co-spectra of 30-minutes datasets for (a) a strong dust event at GB1 site and (b) a weak dust event at GB2 sites. The co-spectra of wind and sonic temperature is used as a reference.

**Size-segregated
fluxes of mineral dust
by eddy covariance**

G. Fratini et al.

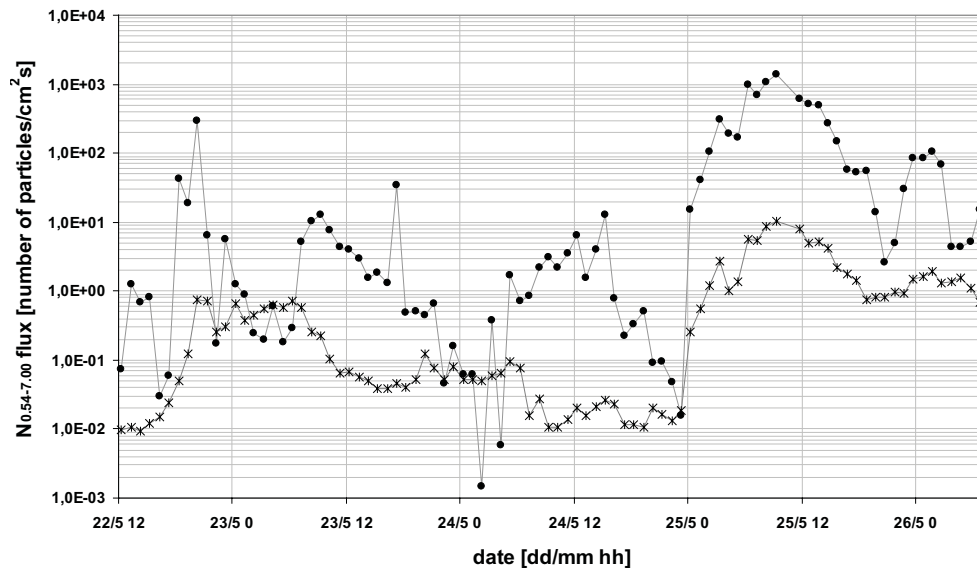


Fig. 7. Time series of $N_{0.54-7.0}$ turbulent number fluxes (black circles) vs. $N_{0.54-7.0}$ gravitational number fluxes (gray stars) during the monitoring period (22–26 May 2005) at the GB1 site. Fluxes are represented as absolute values, on a logarithmic scale.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Size-segregated
fluxes of mineral dust
by eddy covariance

G. Fratini et al.

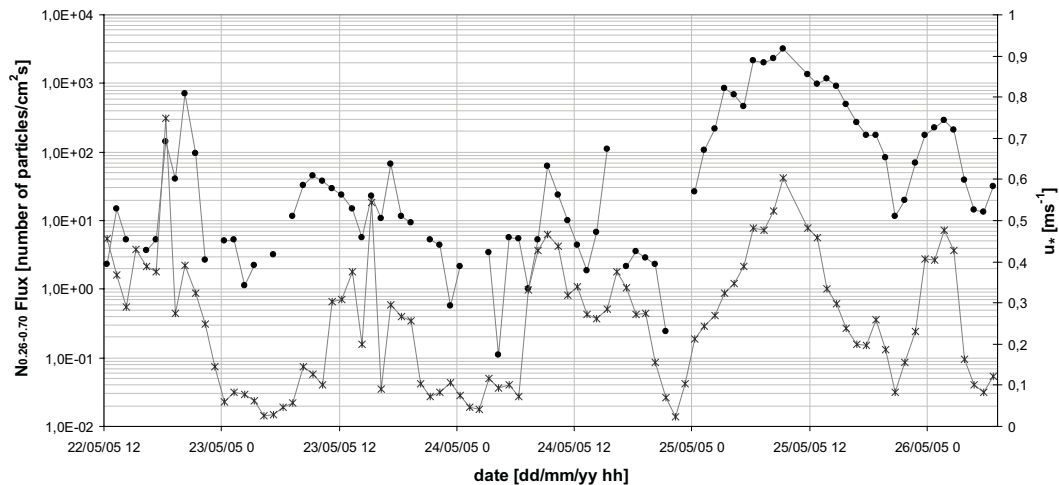


Fig. 8. Time series of particles ($N_{0.26-7.0}$) number fluxes (black circles) and friction velocity (gray stars) during the monitoring period (22–26 May 2005) at the GB1 site. Fluxes are represented on a logarithmic scale; missing values relate to negative (net deposition) fluxes, that are not of interest in this paper.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

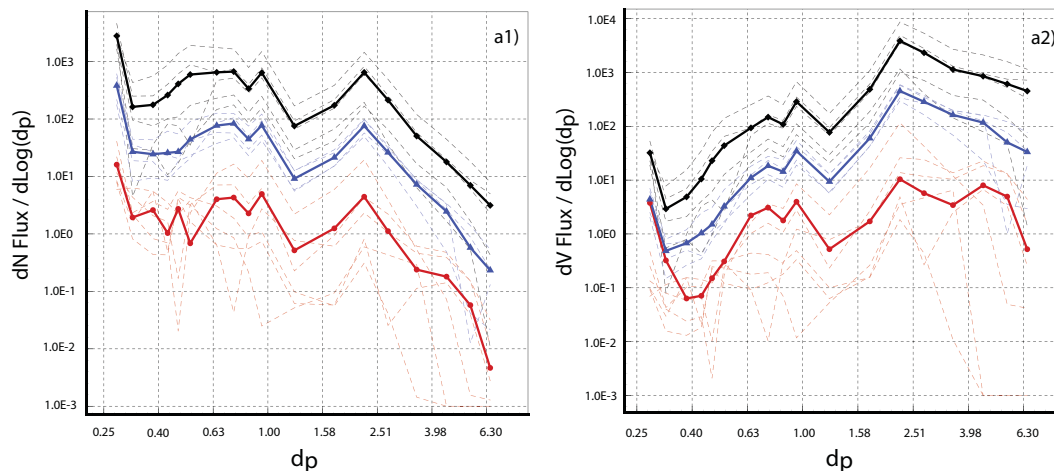


Fig. 9a. Particle number (a1) and particle volume (a2) fluxes vs. particles diameters during the monitoring period at the GB1 site. Units are [number of particles/ cm^2s] and [$\mu\text{m}^3/\text{cm}^2\text{s}$] for the number and volume fluxes, respectively. Red, blue and black thick lines with symbols are the average profiles of the “low”, “medium” and “high” friction velocity classes, respectively. The high friction velocity class refers to the most intense moment of the dust event. Light, dashed lines are examples of profiles in the three classes.

Size-segregated fluxes of mineral dust by eddy covariance

G. Fratini et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Size-segregated fluxes of mineral dust by eddy covariance

G. Fratini et al.

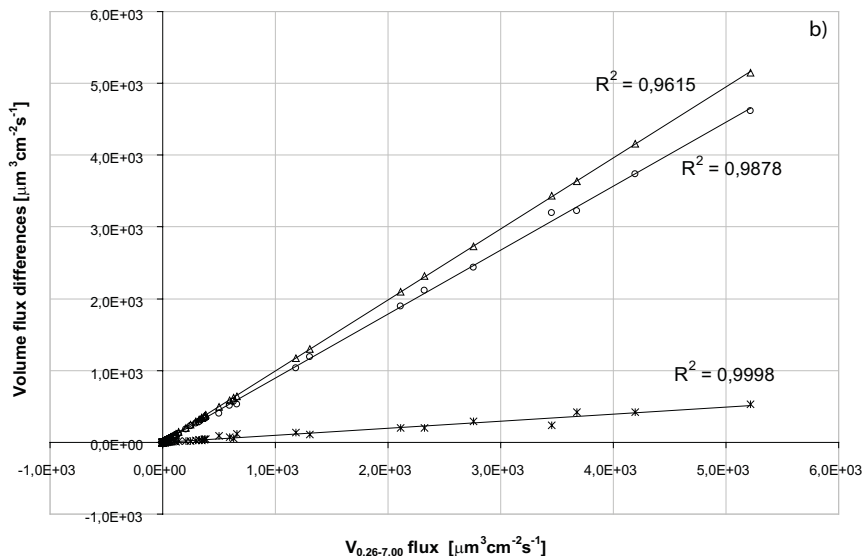


Fig. 9b. Differences in volume vertical fluxes among $V_{0.26-7.00}$, $V_{0.26-1.85}$, and $V_{0.26-0.74}$; $V_{0.26-7.00}-V_{0.26-0.74}$ (triangles), $V_{0.26-7.00}-V_{0.26-1.85}$ (circles), $V_{0.26-1.85}-V_{0.26-0.74}$ (stars) vs. $V_{0.26-7.00}$ net vertical flux, during the strong dust event at GB1 site; solid lines, linear regressions.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

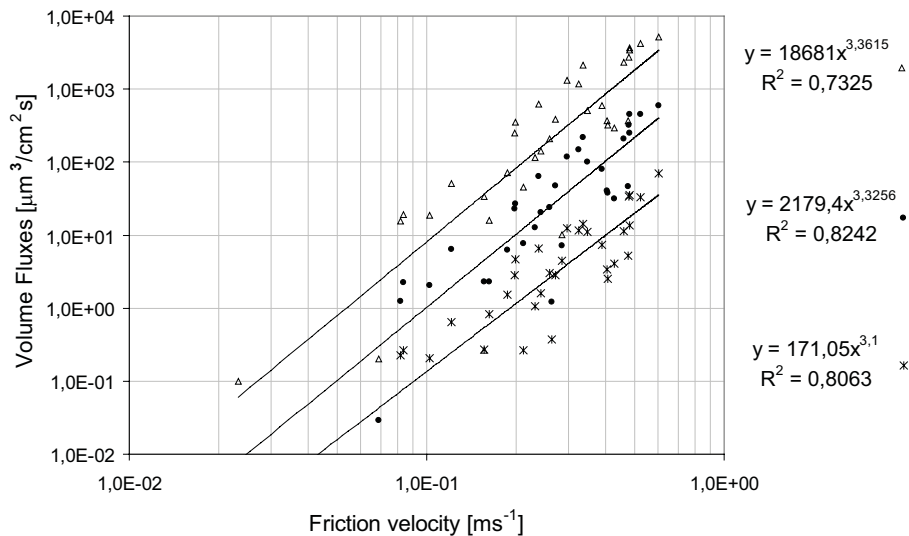


Fig. 10. Net vertical volume fluxes of $V_{0.26-7.00}$ (triangles), $V_{0.26-1.85}$ (full circles), $V_{0.26-0.74}$ (stars) vs. friction velocity during the strong dust event at GB1 site; the three ranges roughly correspond to PM_{10} , $PM_{2.5}$ and PM_1 in aerodynamic diameter; solid lines, power regressions.

Size-segregated fluxes of mineral dust by eddy covariance

G. Fratini et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion