The role of convective plumes and vortices on the global aerosol budget

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[1] Atmospheric aerosols produce both a direct radiative forcing by scattering and absorbing solar and infrared radiation, and an indirect radiative forcing by altering cloud processes. Therefore, it is essential to understand the physical processes that contribute to the global aerosol budget. The International Panel on Climate Change (IPCC) reports that mineral dust contributes to ~1/3 of all primary particle emissions to the atmosphere. The significance of mineral dust aerosol becomes evident when one considers the large surface area of arid and semi-arid regions on most continents. It is evident from observations in the U.S. Southwest that convective plumes and vortices lift large quantities of desert dust. Here, we use a combination of observational data and theory to determine the role of convective plumes and vortices on the global aerosol budget. We show that convective plumes and vortices contribute to about 35% of the global budget of mineral dust. **Citation:** Koch, J., and N. O. Renno (2005), The role of convective plumes and vortices on the global aerosol budget, *Geophys. Res. Lett.*, *32*, L18806, doi:10.1029/2005GL023420.

1. Introduction

[2] In the spring of 2002 we led a pilot field experiment to quantify the intensity and variability of the surface flux of heat and mineral dust in Arizona [*Renno et al.*, 2004]. Data collected during this field campaign shows that the dust flux in coherent (organized over their vertical extension) convective plumes is $\sim$0.1 g m^{-2} s^{-1}, and can exceed $\sim$1 g m^{-2} s^{-1} in convective vortices. Here we refer to strong coherent convective plumes as "dusty plumes" that are typically $\sim$100 meters in diameter and can persist for about one hour, the time scale of boundary layer convection [*Renno and Ingersoll*, 1996]. Dust devils are defined as dusty convective vortices with typical diameters ranging from 3 to 15 meters and lifetimes of only a few minutes [*Williams*, 1948; *Sinclair*, 1966, 1969; *Snow and McClelland*, 1990]. Their lifetime is, in general, much smaller than that of boundary layer convection because they need convection, as well as vorticity and dust sources, to remain active. The largest observed dust devils have diameters of more than 100 meters and lifetimes in excess of 30 minutes [*Williams*, 1948; *Snow and McClelland*, 1990]. Thus, a typical convective plume can pump nearly 3000 kg of dust into the atmosphere during its lifetime, and a typical dust devil can pump 20 kg of dust into the atmosphere in its lifetime. Very large dust devils of $\sim$100 m diameter can pump nearly 15,000 kg of dust in their lifetime. Figure 1 shows a dusty plume and a large dust devil photographed during our 2002 field campaign in Arizona.

[3] Natural dust lifting processes include dust devils, convective plumes, dust storms, and large-scale weather systems. To accurately quantify the global dust cycle we must understand the relative importance of these dust lifting processes and the large spatial and temporal variability of each. Sources of mineral dust and their contribution to the aerosol budget have been studied extensively in recent years [e.g., *Guelle et al.*, 2000; *Ginoux et al.*, 2001]. However, these studies have focused mainly on dust lifting by large-scale processes. Here, we show that small-scale processes are an important component of the global budget of mineral dust.

[4] It is evident from observations in the US Southwest [*Williams*, 1948; *Sinclair*, 1966, 1969; *Kaimal and Businger*, 1970; *Ryan and Carroll*, 1970; *Fitzjarrald*, 1973; *Snow and McClelland*, 1990; *Metzger*, 1999] that convective plumes and vortices lift large quantities of desert dust. Indeed, it has been previously estimated that in the contiguous U.S. alone, approximately 65% of the total dust flux caused by wind action is due to convective vortices [*Gillette and Sinclair*, 1990]. We study the contribution of convective plumes and vortices to the global atmospheric aerosol budget.

2. Dust Flux in Convective Plumes and Vortices

[5] Few systematic observations of dusty convective plumes and vortices have been reported in the literature, none of which includes direct in situ measurements of the dust flux. *Renno et al.* [2004] used remote measurements of perturbations in bulk dust concentration ($\overline{\rho_d'}$) and in situ measurements of vertical velocity perturbations ($\overline{w'}$) to calculate their bulk eddy-correlation dust fluxes

$$F_d = \overline{\rho_d'}\,\overline{w'}. \quad (1)$$

The bulk dust concentrations measured in dusty plumes by *Renno et al.* [2004] were similar to that of dust devils, approximately 1,000 times the background atmospheric value. They also show that a very large dust devil ($\sim$100 meters diameter) with a vertical velocity of 10 m s^{-1} has a dust flux of 1 g m^{-2} s^{-1}. A background dust concentration of 100 μg m^{-3} is typical in areas of active dust devils and dusty plumes in the US Southwest [*Metzger et al.*, 1999]. Using typical vertical velocities in convective plumes and vortices of about 1 m s^{-1} and 7 m s^{-1} respectively [*Kaimal and Businger*, 1970, *Renno et al.*, 2004], we conclude that the average dust flux in dusty convective plumes is about 0.1 g m^{-2} s^{-1} and

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Figure 1. Convective plume and vortex. (top) Large dusty non-rotating convective plume. Plumes are generally 100 m in diameter and persist for nearly an hour. (bottom) Large dust devil. Typical dust devils are generally 10 m in diameter and persist for a few minutes. Both images were taken by N. Renno during the 2002 field campaign near Eloy, Arizona.

0.7 g m^{-2} s^{-1} in dust devils. This dust devil flux is in approximate agreement with earlier observations [*Metzger*, 1999; *Gillette and Sinclair*, 1990].

3. Fractional Area Covered by Plumes and Vortices

[6] We use the theory proposed by *Renno and Ingersoll* [1996] to determine the fractional area covered by convective plumes and vortices strong enough to produce saltation through perturbations in surface velocity. They viewed atmospheric convection as a heat engine and showed that the fractional area covered by convective drafts is

$$\sigma \approx \frac{\tau_{up}}{\tau_R} \approx \left(\frac{\mu}{\eta}\right)^{1/2} \left(\frac{\Delta p}{\rho_{air} g \tau_R}\right)^{3/2} \left(\frac{F_{in}}{\rho_{air}}\right)^{-1/2}, \tag{2}$$

where τ_{up} is the updraft time-scale, τ_R is the radiative time-scale, $\mu \approx 12$ to 24 is a non-dimensional coefficient of frictional dissipation of mechanical energy, $\eta \approx 10$ % is the thermodynamic efficiency, $\Delta p \approx 350$ hPa is the pressure drop from the surface to the top of the convective boundary layer, $\rho_{air} \approx 1$ kg m^{-3} is the air density, $g = 9.8$ m s^{-2} is the gravitational acceleration, and F_{in} is the heat flux into the convective plumes or vortices strong enough to lift surface dust.

[7] We assume that convection is in quasi-steady state; therefore the surface heat flux is approximately balanced by atmospheric radiative flux over the time scale of a convectively active day [*Renno and Ingersoll*, 1996]. Thus, the fractional area covered by convective updrafts is a mean value for the convectively active diurnal period (10:00 to 18:00 local solar time [*Williams*, 1948; *Sinclair*, 1966, 1969; *Metzger*, 1999]). The radiative time-scale is calculated using the Newtonian cooling approximation of an atmospheric slab

$$\tau_R \approx \left(\frac{c_p \Delta p}{8g \in \sigma_R T_c^3}\right), \tag{3}$$

where $c_p \approx 1005$ J kg^{-1} K^{-1} is the heat capacity of dry air, $\in \approx 0.4$ is the emissivity of the convective boundary layer [*McIlveen*, 1992], $\sigma_R = 5.67 \times 10^{-8}$ W m^{-2} K^{-4} is the Stefan-Boltzmann constant, and $T_c \approx 300$ K is the mass-weighted mean temperature of the convective boundary layer. It follows from equation (3) that the radiative time-scale of the convective boundary layer is $\tau_R \approx 9 \times 10^5$ s (~10 days).

[8] *Kaimal and Businger* [1970] and *Renno et al.* [2004] found that the eddy correlation heat flux in dusty plumes is $F_{in} \approx 3 \pm 2$ kW m^{-2} and $F_{in} \approx 11 \pm 5$ kW m^{-2} in dust devils. It follows from equation (2) that the fractional area covered by dusty plumes during the convectively active period of the diurnal cycle is about 5×10^{-5} and the fractional area covered by dust devils is approximately 3×10^{-5}. Below, we show that these predictions are consistent with observations. Thus, given the heat flux into dusty convective plumes and vortices, equation (2) can be used to predict the fractional area covered by them.

[9] Here we use data from dust devil field campaigns [*Sinclair*, 1966, 1969; *Snow and McClelland*, 1990; *Metzger*, 1999] to test the predictions of equation (2). Using the convention of *Snow and McClelland* [1990], we refer to the number of days in which dust devils occurred as dust devil days (DDD) and the area in which they were observed as the area of occurrence (AOC). The AOC of these field campaigns ranged from 30 to 300 km^2. An average of 50 ± 11 dust devils per day was calculated based on the total dust devil count over the entire study and the number of DDD. Given that each study's daily observation period was approximately 8 hours, on average 6 ± 1 dust devils per hour were seen in the AOC. The area covered by a typical dust devil observed in each field campaign ranged from 90 to 220 m^2. We assume that dust devils move with the typical mean wind of ~10 m s^{-1} and become visible from large distances only when passing over strong dust source regions. Then, we calculate the dust devils spatial distribution based on the AOC of each study and the area covered by typical dust devils. These "snapshots" of dust devil occurrence give an indication of the fractional area covered by them. Based on these observations alone, the average fractional area covered by dust devils during their active days is $\sigma \approx 2 \times 10^{-5} \pm 9 \times 10^{-6}$. This value is consistent with that predicted by equation (2). Thus, equation (2) can be used to predict the fractional area.

4. Global Dust Flux Due to Plumes and Vortices

[10] The theoretical and observational data summarized above for dusty plumes and dust devils is used to estimate

Table 1. Dust Devil Fractional Area (Theoretical)

Month	Z_{CBL},[a] km	T_h,[b] °C	η,[c] %	σ,[d] Dust Devils
April	3.1	29	10	2.9×10^{-5}
May	3.0	32	10	3.1×10^{-5}
June	3.7	39	12	2.9×10^{-5}
Average	3.3	33	11	3.0×10^{-5}

[a]Convective boundary layer depth for Tucson, 2002 (atmospheric sounding data).
[b]Surface air temperature for Tucson, 2002 (atmospheric sounding data).
[c]Thermodynamic efficiency from equation (4).
[d]Fractional area covered by dust devils from equation (2).

their contribution to the global mineral dust budget. It follows from the heat engine model that the intensity of convective plumes and dust devils is a function of the amount of energy available for them to do work, which in turn, is equal to the product of the thermodynamic efficiency with the heat input (sensible heat flux), that is $F_{av} = \eta F_{in}$ [*Renno et al.*, 1998]. The most important global dust source regions lie between 30 to 40°N [*Prospero et al.*, 2002] and have similar altitudes (~1000 m). These regions are arid or semi-arid and experience similar surface sensible heat fluxes. Thus, the main factor controlling the relative intensity of convective vortices and plumes is their thermodynamic efficiency. The thermodynamic efficiency

$$\eta = \frac{\Gamma_{ad} Z_{CBL}}{T_h} \quad (4)$$

depends mainly on the depth of the convective boundary layer (Z_{CBL}), because changes in the absolute surface temperature (T_h) are relatively small [*Souza et al.*, 2000] and the dry adiabatic lapse rate (Γ_{ad}) is constant at ~10 K km^{-1}.

[11] In the US Southwest, convective plumes and vortices are strong enough to lift dust from approximately May to July [*Sinclair*, 1966; *Snow and McClelland*, 1990]. Our analysis shows that the thermodynamic efficiency is also large enough for dust devils and convective plumes to lift dust during approximately three months of the year in other dust source regions, in agreement with observation [*Prospero et al.*, 2002; *Pye*, 1987]. The fractional areas covered by dust devils during this period are calculated with equation (2) and summarized in Table 1 using sounding data from Tucson, Arizona. As mentioned previously, the predictions of equation (2) are consistent with observations; therefore, the thermodynamic efficiencies seen in the U.S. Southwest during the active dust season are strong enough to initiate strong convection. Thus, the theory can be used to calculate the fractional area covered by both dust devils and dusty plumes in other dust source regions. Calculations based on atmospheric sounding data and theory for a sample of the most important dust source regions are summarized in Table 2. Sounding data for these regions ranges from 12:00 to 20:00 local time, therefore representing a mean thermodynamic efficiency for convectively active days. These results suggest that the thermodynamic efficiency and fractional area covered by dusty plumes and vortices in these regions are similar to that in the US Southwest.

[12] Not all days of the active dust season have dust devils and dusty plumes [*Sinclair*, 1966, 1969; *Hess and Spillane*, 1990]. The ratio of DDD to total days of observation from the census data [*Sinclair*, 1966, 1969; *Snow and McClelland*, 1990] suggests that about 80% of the days of this three month period have dusty plumes and dust devils (72 days per year). During a typical spring/summer day in arid and semi-arid regions, convection is active from approximately 10:00 to 18:00 local solar time [*Sinclair*, 1966, 1969; *Metzger*, 1999]. Thus, dusty plumes and dust devils are likely to occur 8 hours per day during 72 days per year. Globally, dusty plumes and dust devils are likely to occur in arid and semi-arid regions [*Prospero et al.*, 2002; *Joussaume*, 1990; *Tegen and Fung*, 1995; *Matthews*, 1983]. Due to topographical and geological features, these entire regions cannot be considered dust sources. Observations suggest that approximately 40% of global arid and semi-arid regions are active dust sources areas [*Sinclair*, 1966; *Metzger*, 1999; *Prospero et al.*, 2002]. Therefore, the global active dust source regions cover an area of about $1.3 \times 10^7 \pm 2 \times 10^6$ km^2.

[13] We use the fractional area covered by dusty plumes and dust devils, as well as the fraction of time in which they are convectively active to calculate their annual dust fluxes. These results are summarized in Table 3. Although there are diurnal and seasonal variations in dust flux, it is difficult to speculate the contribution on smaller temporal scales due to seasonal variations in dust emission based on specific geographical location and meteorological conditions that may hasten or delay active dust seasons.

[14] Uncertainties in the global contribution were calculated based on the variation in observed values of all measurable parameters in equations (1) through (4). The

Table 2. Thermodynamic Efficiency and Theoretical Fractional Area

Location	Z_{CBL},[a] km	η,[b] %	σ,[c] Dust Devils	σ,[c] Plumes
Tucson, AZ	3.7	12	2.9×10^{-5}	5.6×10^{-5}
Albuquerque, NM	3.8	12	2.5×10^{-5}	4.8×10^{-5}
Tamanrasset, Algeria	3.7	12	2.8×10^{-5}	5.3×10^{-5}
Béchar, Algeria	2.7	9	3.3×10^{-5}	6.3×10^{-5}
Tehran, Iran	2.3	7	3.6×10^{-5}	6.9×10^{-5}
Birjand, Iran	2.4	8	3.5×10^{-5}	6.6×10^{-5}
King Khaled Airport, Saudi Arabia	3.8	12	3.1×10^{-5}	5.8×10^{-5}
Dunhuang, China	3.2	10	2.9×10^{-5}	5.4×10^{-5}
Yanan, China	2.2	7	3.2×10^{-5}	6.1×10^{-5}
Average	3.1	10	3.1×10^{-5}	5.9×10^{-5}

[a]Convective boundary layer depth for June (atmospheric sounding data).
[b]Thermodynamic efficiency from equation (4).
[c]Fractional area from equation (2).

Table 3. Global Dust Fluxes

	Dust Flux, g m^{-2} s^{-1}	Fractional Updraft Area	Contribution to Global Mineral Dust Production, %
Dusty Plumes	0.1 ± 0.03	$5 \times 10^{-5} \pm 4 \times 10^{-5}$	8 ± 6
Dust Devils	0.7 ± 0.3	$3 \times 10^{-5} \pm 2 \times 10^{-5}$	26 ± 18
Total	–	–	34 ± 19

Intergovernmental Panel on Climate Change (IPCC) [2001] suggests mineral dust emissions of 2,150 million metric tonnes per year (diameters $\leq$ 20 μm). Table 3 shows that dusty convective plumes and dust devils contribute to about 35% of the global mineral dust budget. Thus, plumes and vortices may contribute up to 13 percent of the total particulate emissions, based on 5,740 million tonnes of total emitted particulate in the year 2000 [*IPCC*, 2001].

5. Further Considerations

[15] The number of convectively active days in dust source regions can be refined with global observations of dust devils and dusty plumes. Similarly, the value of the global dust source area can be refined by a complete geological and meteorological analysis of each region. In addition to arid and semi-arid regions, deforested and agricultural regions, where plumes and vortices can be intense, can contribute to the global dust budget. Indeed, there is evidence that invisible, coherent vortices occur in non-arid regions even at high latitudes [*MacPherson and Betts*, 1997]. Although the concentration of dust is small enough in these regions that plumes and vortices are not visible, fine particles are lifted and can be easily detected by active instruments such as lidars [*Cohn et al.*, 1998]. Land use change in the last 25 years may have increased the global dust source areas by approximately 20% [*Tegen and Fung*, 1995] creating enough loose surface particles that strong plumes and vortices can now lift dust and further contribute to the aerosol budget.

[16] We plan to further constrain the contribution of dusty convective plumes and vortices through detailed measurements in future field campaigns, including longer observation periods and more thorough measurements in various dust source regions. In particular, we will measure the mineral dust size distribution in convective plumes and vortices. Our group is also developing a parameterization of dusty plumes and dust devils to simulate their fluxes in desert and semi-arid regions such as the US Southwest. This parameterization will contribute to improvements in the representation of small-scale processes in the vertical transport of aerosols in climate models.

6. Conclusions

[17] Mineral dust emissions are second only to sea salt emissions in their contribution to the global aerosol budget [*IPCC*, 2001]. The relevance of mineral dust to climate change is compounded by their large spatial and temporal variability as well as their susceptibility to human activities and land use change. We show that dust devils and dusty plumes contribute to about 35% of the global mineral dust budget. Thus, these small scale dust events are responsible for almost 15% of the global aerosol budget. Therefore, we conclude that convective plumes and vortices play an important role in the global aerosol budget.

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