Dust events in Kanpur, northern India: Chemical evidence for source and implications to radiative forcing

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[1] Dust samples were collected and analyzed during May 2004 in Kanpur (in Ganga basin), Northern India for the first time. Chemical evidence along with the air mass trajectories suggests three major sources of the mineral dusts transported to the Ganga basin. High concentration of Pb and Cd indicates possible mixing with the anthropogenic pollution. The composite aerosol model reveals low single scattering albedo (~0.74) due to the presence of black carbon. During the dust storms, shortwave (SW) clear-sky diurnally averaged top of the atmosphere (TOA) and surface forcing come out to be +11 ± 0.7 and −26 ± 3 W m^{-2}, respectively. Corresponding forcings in the longwave (LW) region are +1.9 ± 0.6 and +1.6 ± 0.4 W m^{-2}. Net atmospheric forcing (i.e., SW+LW, 36 W m^{-2}) corresponds to heating rate of ~1.02° K/day in the lower atmosphere. Dust alone has resulted in the net TOA and surface forcings of +7 and −12 W m^{-2}. **Citation:** Chinnam, N., S. Dey, S. N. Tripathi, and M. Sharma (2006), Dust events in Kanpur, northern India: Chemical evidence for source and implications to radiative forcing, *Geophys. Res. Lett.*, *33*, L08803, doi:10.1029/2005GL025278.

1. Introduction

[2] Mineral dusts, a key component of aerosol-climate system, enter the atmosphere through wind erosion of desert and arid regions and disturbed soils [*Miller et al.*, 2004]. They alter the radiative balance of the atmosphere by scattering and absorbing the sunlight, but are poorly characterized due to their highly variable optical properties. It has been observed that during the long-range transport over the polluted regions, dusts mix with anthropogenic aerosol species, thereby suggesting that the dust radiative impact is highly variable from region to region [*Deepshikha et al.*, 2005].

[3] In the Ganga basin (GB) in Northern India, dust storms occur frequently during the pre-monsoon (April–June) season every year [*Middleton*, 1986; *Dey et al.*, 2004]. Based on the meteorological data, *Middleton* [1986] prepared a dust-storm frequency map of the southwest Asia, locating the key dust-producing areas, where the frequency reduces as we move across the GB toward east.

[4] *Dey et al.* [2004] have shown the effect of the transported dusts on the aerosol optical properties in the GB. They inferred the source of these dusts based on air mass trajectories and satellite data, but felt the need of the chemical data, which adds as an additional support to locate the source more accurately and indicates mixing with anthropogenic pollutants along their transport. Also one study has been done so far on the radiative effect of aerosols during dust events in the GB [*Singh et al.*, 2005]. Here we present the chemical evidences based on the analysis of dust samples collected during May 12–22, 2004 in Kanpur (an urban site in the Ganga basin, Figure 1) to strengthen the inference about the dust sources as indicated by the air mass trajectories. Further, a composite aerosol model has been developed to estimate the radiative forcing in the region during the dust events.

2. Sampling and Analysis

[5] Five dust events, on 12, 15, 18, 19 and 20th May, were observed within the study period. Indian Institute of Technology Kanpur (IITK) campus was chosen for the sampling site, where the aerosol optical properties are being measured simultaneously. Dust samples were collected on Whatmann GF/A filter papers of size 8″ * 10″ using a two-stage PM_{10} Cascade Impactor (Pacwill Tisch Environmental, USA) at a flow rate of 1.13 m^3 min^{-1}. The 1st stage collects fine mode particles ($d \leq 2.5$ μm), whereas the 2nd stage collects coarse mode particles ($2.5 < d \leq 10$ μm). The concentration of seven heavy metals *viz.* Fe (major element), Ni, Cr, Mg, Pb, Zn and Cd (minor elements) were analyzed by Varian SpectrAA 220FS atomic absorption spectroscopy. PM_{10} mass concentration was determined as follows:

$$PM_{10}\left(\mu g\ m^{-3}\right) = (W_f - W_i) \times 10^6/V \quad (1)$$

where, W_f and W_i are final and initial weights of filter paper after sampling and post conditioning and V is the volume of air sampled. All filter papers, used for sampling, were subjected to 24 hrs desiccation to remove the excess moisture absorbed by filter papers before and after sampling.

3. Results and Discussion

[6] The pre-monsoon season in Kanpur remains warm and dry (relative humidity < 50%). Mean PM_{10} (particulate matter of size < 10 μm) mass concentration during the entire study period was observed to be very high (525 ± 250 μg m^{-3}), of which the fine mode particles contribute to ~73.6%. PM_{10} concentration during the event days was double than that during the non-event days. Maximum

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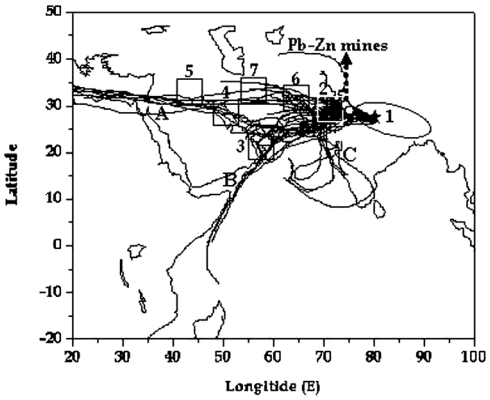

Figure 1. Air mass backward trajectory cluster during the study period originated at 2000 m altitude in Kanpur to illustrate the long-range transport. (A), (B) and (C) mark the major pathways (for details see text). The solid boxes mark the major dust source areas in southwest Asia. The star shows the location of Kanpur (study area) within the GB (the area marked as 1). Locations 2, 3, 4, 5, 6 and 7 represent, respectively, Thar Desert in Rajasthan, India, coast of Oman, coast of Persian Gulf, Tigris and Euphrates basin in Iraq, basins in Pakistan and Afghanistan and basins in Iran.

increase in PM_{10} concentration occurred on May 12, when it crossed 1000 $\mu g\ m^{-3}$.

3.1. Aerosol Chemical Composition During the Dust Events

[7] The mass concentrations of the metals during the study period in fine and coarse mode are illustrated in Figure 2. Zn and Pb concentration is higher in 1st stage (mean values of 0.57 and 1.09 $\mu g\ m^{-3}$) compared to 2nd stage (mean values of 0.08 and 0.26 $\mu g\ m^{-3}$). Cd (1 ng m^{-3}) was almost absent in 2nd stage. The mean concentrations of the rest four metals Fe, Cr, Mg and Ni are higher in 2nd stage (6.05, 1.69, 4.19, 0.96 $\mu g\ m^{-3}$ respectively) compared to 1st stage (3.59, 0.015, 0.39, 0.013 $\mu g\ m^{-3}$ respectively), indicating their crustal origin.

[8] The average concentrations of each metal in both stages during the dust and non-dust event days are summarized in Table 1. Fe, Cr, Ni, Mg and Zn concentration substantially increased (more than 25%) during the event days, whereas total concentration of Pb and Cd decreased. Fe, Mg, Cr and Ni concentrations were highest during May 20 event and Zn concentration during May 12 event. Though Zn concentration increased during all dust storms except the 18th May event, such high concentration, mainly in fine mode, and presence of Pb and Cd, mostly in fine mode indicate anthropogenic sources. The possible source for Cd is household-waste combustion, fossil-fuel burning and refinery and that for Pb includes leaded gasoline, fuel combustion, industrial processes and solid waste combustion [*Banerjee*, 2003]. Pb in coarse mode was probably emitted from the mining activities. Higher concentration of Cd and Pb during the non-event days suggests that possibly, they are emitted within the basin and get mixed with the dusts during the transport over the polluted areas. The correlation matrices both in fine and coarse mode for the heavy metals are shown in Table 2. Better correlation was found between the crustal elements at the coarse mode during the event days indicating their common origin.

3.2. Provenance and Role of Transport

[9] 10 days backward trajectories of the air mass were computed for every 6 hour during the observational period at 2 km (near boundary layer height) altitude (Figure 1), from final run data archive of GDAS model using the NOAA Air Resource Laboratory (ARL) Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) program to study the source of the air masses and the role of long-range transport in the observed variation in chemical composition. The trajectory cluster displays mainly three sources, the southwest Asian basins (A), northeast Africa and Oman (B) and southern peninsula of India (C). The first group got sub-divided along the path, one crossing the Oman region and the other crossing the Afghanistan-Pakistan basins before entering the GB. In case of all events (except 18th May), air masses crossed the Thar Desert region close to the surface. The observed large enhancement in Zn concentration in fine mode during the event days was probably due to the contribution from the mining activities in Rajasthan and coal and fuel combustion, waste disposal, incineration in the surrounding regions. *Pease et al.* [1998] had also found Zn enrichment in the dust samples, collected in the eastern Arabian Sea during the winter time and inferred the Rajasthan region as the major source for anthropogenic Zn pollution. On 18th May, when the air mass path did not cross the mining area, Zn concentration was low (66.4 ng m^{-3}).

[10] Chemical data also supports that Oman is a major source for the dusts, as Cr concentration on event days was found 5 times higher than in the samples on non-dust event days. The major dust–producing areas in Oman include the alluvial/fluvial complexes at the foot of the Al-Hajar Mountains in Northern Oman, the Wahiba sand sea and the coastal lowlands [*Prospero et al.*, 2002]. The Hajar

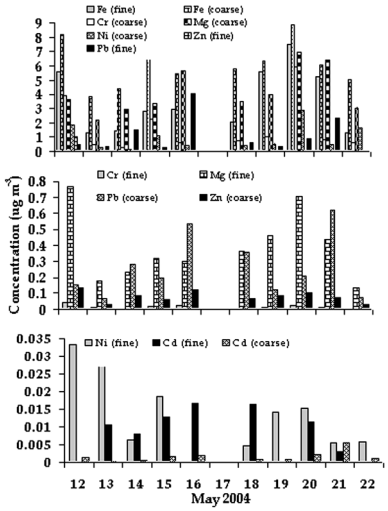

Figure 2. Daily variations of the mass concentration of the metals in the 1st stage (fine) and 2nd stage (coarse mode) of Cascade PM_{10} sampler during the study period. Note that the scale in Y-axis is different in each part of the figure.

Table 1. Mean Concentration of Each Metal in Fine (First Row) and Coarse Mode (Second Row) During Dust and Non-Dust Days[a]

	Fe	Cr	Mg	Ni	Zn	Pb	Cd
Dust	4.74(2.3)	0.02(0.01)	0.52(0.2)	0.02(0.01)	1.09(1.7)	0.51(0.3)	0.008(0.008)
	7.13(1.3)	2.8(2.2)	4.31(1.5)	1.34(1)	0.09(0.03)	0.21(0.1)	0.0014(0.007)
Non-dust	2.44(1.7)	0.01(0.009),	0.26(0.1)	0.01(0.01)	0.14(0.1)	1.66(1.7)	0.0077(0.007)
	4.97(0.9)	0.58(0.2)	4.06(0.9)	0.57(0.6)	0.07(0.04)	0.31(0.3)	0.0018(0.002)

[a]Unit is $\mu g\ m^{-3}$. The standard deviations given after each mean value within the parentheses indicate the range of variability.

Massif is primarily composed of a late Mesozoic ophiolitic complex, which is rich in mafic minerals like Fe, Cr, Mg and Ni. In particular, an average Cr enrichment of 58 times the mean crustal ratio in the fine grained terrestrial sediments of Oman has been found [*Pease et al.*, 1998]. Therefore, Cr can be used as an indicator for the aeolian dust originating from Oman region. The third possible source was probably the southwest Asian basins stretching from Pakistan to Iran, although chemically it was not possible to distinguish. During the non-event days, the origin of the dusts is soil in the surrounding regions.

3.3. Aerosol Radiative Forcing

[11] As we do not have the optical properties of the aerosols during the dust events, a probable aerosol composite model was established using the Optical Properties of Aerosols and Clouds (OPAC) model of *Hess et al.* [1998]. We have considered the urban aerosol model of OPAC (comprising of water-soluble, insoluble and black carbon, BC species), where the 'mineral dust' component was introduced. The components were adjusted until the modeled spectral aerosol optical depth (AOD) and Ångstrom wavelength exponent, α match with the observed data. Mean AOD (at 0.5 μm) and α during the study period were 0.58 ± 0.2 and 0.21 ± 0.1, as measured by CIMEL radiometer installed in IITK under AERONET program. Average BC concentration in our model comes out to be 4.4 $\mu g\ m^{-3}$, which agrees well in the range with the estimation from AERONET measurements during May 2001–2003 [*Dey et al.*, 2006].

[12] The single scattering albedo (SSA) and the asymmetry parameter (g) of composite aerosol (0.55 μm) during the event days were found to be 0.74 and 0.75. During the pre-monsoon season in Delhi, another city in the GB situated ~500 km northwest of Kanpur, *Singh et al.* [2005] have found the model derived values for SSA and 'g' to be 0.672 and 0.79. During the event days, unfortunately simultaneous measurements of the optical properties (except AOD) by AERONET are missing, ruling out direct comparison. Although model-derived SSA values for the composite aerosol during the event days are lower compared to total SSA as retrieved by AERONET, *Dey et al.* [2005] have pointed out that due to presence of BC in association with dust particles, SSA becomes significantly low (<0.85) at the coarse mode (dominated by dust). The AERONET retrievals of SSA are not direct as compared to the retrieval of AOD, but depend on several assumptions, which may cause some discrepancy in the absolute values. Nevertheless, both model-derived and AERONET-retrieved SSA show similar spectral pattern (increasing trend with wavelength [*Dey et al.*, 2004]) during the observational period.

[13] The spectral AOD, α, SSA and g are incorporated in Santa Barbara Discrete Ordinate Radiative Transfer (SBDART) model developed by *Ricchiazzi et al.* [1998] to estimate the clear-sky radiative forcing at the top of the atmosphere (TOA) and surface at shortwave (SW) and longwave (LW) regions. We have computed the TOA and surface forcing for solar zenith angle (SZA) at each 5° interval for the days, when spectral AOD values become available and presented as diurnal average (Figure 3). During the computation, surface albedo value of 0.3 was considered for this region, which was taken from MODIS surface albedo product (MODIS/Terra Albedo; 16-Day; level-3 Global 1 km SIN Grid). In the SW region, the TOA and surface forcing during the event days are $+11 \pm 0.7$ and $-26 \pm 3\ W\ m^{-2}$. The corresponding forcings in the LW region are $+1.9 \pm 0.6$ and $+1.6 \pm 0.4\ W\ m^{-2}$. The net atmospheric absorption ($36 \pm 4\ W\ m^{-2}$) during the dust events corresponds to a heating rate of ~1.02° K/day. The

Table 2. Correlation Coefficient Matrix for the Elements at Fine (First Row) and Coarse Mode (Second Row) During the Event (First Value) and Non-Event (Second Value) Days

	Fe	Cr	Mg	Ni	Zn	Pb	Cd
Fe	1						
Cr	0.34/0.13	1					
	0.95/0.64						
Mg	0.67/0.93	0.68/0.13	1				
	0.54/0.86	0.6/0.51					
Ni	0.16/−0.15	0.94/0.28	0.44/−0.14	1			
	0.94/0.05	0.99/0.19	0.63/0.01				
Zn	0/0	0.93/0.35	0.39/0.01	0.97/0.71	1		
	0.68/0.16	0.47/0	0.11/0.4	0.45/0.32			
Pb	0.13/0.35	0.02/0.59	0.15/0.48	−0.14/−0.2	0.03/0.16	1	
	−0.14/0.65	0.08/0.21	−0.1/0.9	−0.07/0.15	−0.22/0.61		
Cd	−0.28/0.01	−0.44/0.52	0.27/0	−0.43/0.54	−0.29/0.26	0.2/−0.56	1
	0.57/0.77	0.77/0.54	0.48/0.78	0.78/0	0.09/0.08	−0.05/0.68	

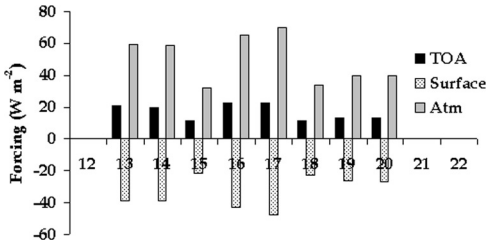

Figure 3. Day-to-day variation in net radiative forcing at TOA, surface and net absorption in the atmosphere calculated for composite aerosol model during the observational period.

mean forcing efficiency at the TOA and surface are 18.5 and -36 W m^{-2} per unit AOD at 0.5 μm. *Singh et al.* [2005] have found a value of -16.1 W m^{-2} for surface radiative forcing efficiency with SZA in the range 30–60° in Delhi during dust-loading season. The net atmospheric absorption during the non-event days is even higher by 72%.

[14] The atmospheric absorption during the dust events in Kanpur is mainly due to the SW absorption. The absorbing nature of mineral dust depends on its mineralogy (in particular iron oxide content [*Dey et al.*, 2004]. In Kanpur, higher Fe mass fraction in aerosol during the dust events (0.84%) compared to that during the winter time (0.53%, personal communication), suggests moderately absorbing nature of transported dust in the region during the pre-monsoon season, also supported by observations by *Deepshikha et al.* [2005]. SW forcing at TOA and surface due to dust only are +4 and -14 W m^{-2}, whereas the corresponding LW forcing are +3 and +2 W m^{-2}. In a global study, *Miller et al.* [2004] have found that the dust radiative forcing during June–August in the GB at the TOA and surface are in the range -2 to +2 and -5 to -10 W m^{-2}. It should be noted here that SSA of dust in this region considered by *Miller et al.* [2004] is ∼0.9, whereas SSA obtained from OPAC model in our study is 0.84. The high positive net TOA forcing is primarily due to high BC concentration and high surface albedo. *Liao and Seinfeld* [1998] have demonstrated that with increase in surface albedo, the surface cooling in SW region decreases due to enhanced multiple scattering between surface and aerosol layer and TOA forcing becomes positive (warming effect). Considering the fact, that the GB experiences frequent dust storms during the pre-monsoon season, when the surface albedo is high, the radiative impact could be significant in the context of long-term climate change of the region.

4. Conclusions

[15] 1. The dusts transported to the GB originated from three major sources, Oman, southwest Asian basins and Thar Desert in Rajasthan as suggested by chemical composition and air mass trajectories. Chemical data also indicates mixing of anthropogenic pollutants with the dust during transport.

[16] 2. A composite aerosol model during the dust storms in Kanpur, best represented by incorporating mineral dust in 'urban' aerosol model of OPAC, results in low SSA (∼0.74). Aerosols reduce the radiation reaching the surface by 26 and 1.6 W m^{-2} in the SW and LW region in clear-sky condition. The corresponding TOA forcings are +11 and +1.9 W m^{-2}.

[17] 3. The net atmospheric absorption (36 ± 4 W m^{-2}) translates to a ∼1.02° K/day heating rate. The net TOA and surface forcing due to dust alone are +7 and -12 W m^{-2}.

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