Retrieving the composition and concentration of aerosols over the Indo-Gangetic basin using CALIOP and AERONET data

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[1] Most GCMs (General Circulation Models) fail to reproduce the AOD (aerosol optical depth) peak over the Indo-Gangetic basin (IGB) as noticed through satellite observations. Insufficient data on aerosol composition makes it difficult to improve GCM results over this source region. In this work, we retrieve the composition and concentration of aerosols over the IGB region, to a first order approximation, by combining the spectral measurements of AOD, single scattering albedo and size distribution available from AERONET (Aerosol Robotic Network) and the extinction profile of aerosols from CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization). Comparison of our results with AM2 (Atmospheric GCM) simulations reveal that AM2 is largely underestimating organics and black carbon concentrations over this region during all months. Sulfate is also underestimated during most months but, there is an overestimation from May to September. There is a compelling need for improving the aerosol inventories and dust sources over the region in order to make realistic assessment of the impacts of aerosols on the south Asian monsoon. **Citation:** Ganguly, D., P. Ginoux, V. Ramaswamy, D. M. Winker, B. N. Holben, and S. N. Tripathi (2009), Retrieving the composition and concentration of aerosols over the Indo-Gangetic basin using CALIOP and AERONET data, *Geophys. Res. Lett.*, *36*, L13806, doi:10.1029/2009GL038315.

1. Introduction

[2] The Indo-Gangetic basin (IGB), located along the southern edge of the Himalayas, extending across Pakistan, northern India, and Bangladesh, is one of the most densely populated areas on Earth with a total population around 900 million [*Global Environmental Change and Food Systems*, 2008]. Observations from multiple satellite instruments like CALIOP, Moderate Resolution Imaging Spectroradiometer (MODIS), Multiangle Imaging Spectroradiometer (MISR), Ozone Monitoring Instrument (OMI) and Total Ozone Mapping Spectrometer (TOMS), all show a persistent aerosol haze over the IGB region during the winter months, with AOD values among the highest in the world [*Kaufman et al.*, 2002; *Di Girolamo et al.*, 2004; *Ramanathan et al.*, 2007; *Ahn et al.*, 2008; *Lau et al.*, 2009].

[3] Unfortunately, most GCMs and transport models fail to reproduce this high AOD belt in their simulations for the winter months (see http://nansen.ipsl.jussieu.fr/AEROCOM/). Figures 1a and 1b show the climatological mean AOD for the month of January (2002–2006) over the Indian sub-continent as simulated by the GFDL (Geophysical Fluid Dynamics Laboratory) atmospheric general circulation model (AM2) with online aerosols [*Ganguly et al.*, 2009] and as observed by MODIS respectively. Figure 1c shows the comparison of monthly mean AODs at 0.5 μm for the year 2002 as observed from the AERONET site at Kanpur and those simulated by the AM2 model for the same location. Although it is evident that the AM2 model is underestimating the observed AOD over the IGB region during the winter months, it remains a challenge to find out and quantify the aerosol components causing this discrepancy. Indeed we could not find out any long-term direct measurements of aerosol concentration with detailed chemical characterization from this region. Most of the published data from this region are either limited to measurements of aerosol physical properties or available for short periods of about a month [*Singh et al.*, 2004; *Ganguly et al.*, 2006; *Tare et al.*, 2006; *Rengarajan et al.*, 2007; *Dey and Tripathi*, 2008]. While more such measurements are needed, insufficient data on aerosol composition makes it difficult to evaluate and improve model results over this important source region.

[4] The present work attempts to retrieve the composition and concentration of aerosols over the IGB region by combing the spectral measurements of AOD and single scattering albedo along with their size distribution available from AERONET and the extinction profile of aerosols from CALIOP. Our retrievals involve large uncertainties, possibly due to assumption on aerosol mixing and other properties, as described in detail by *Ganguly et al.* [2009]. However, it provides to a first order approximation, the information needed to improve simulation of aerosol distribution in models. Results here will help us to further investigate the interplay between the ''solar dimming'' and the ''heat pump'' effect of aerosols on the monsoon over the region [*Ramanathan et al.*, 2005; *Lau et al.*, 2009].

2. Data Sets

[5] The first data set to be used in this study is obtained from the AERONET sites located in the IGB region. AERONET is a federated worldwide network of Sun-Photometers that are monitored and maintained at the NASA

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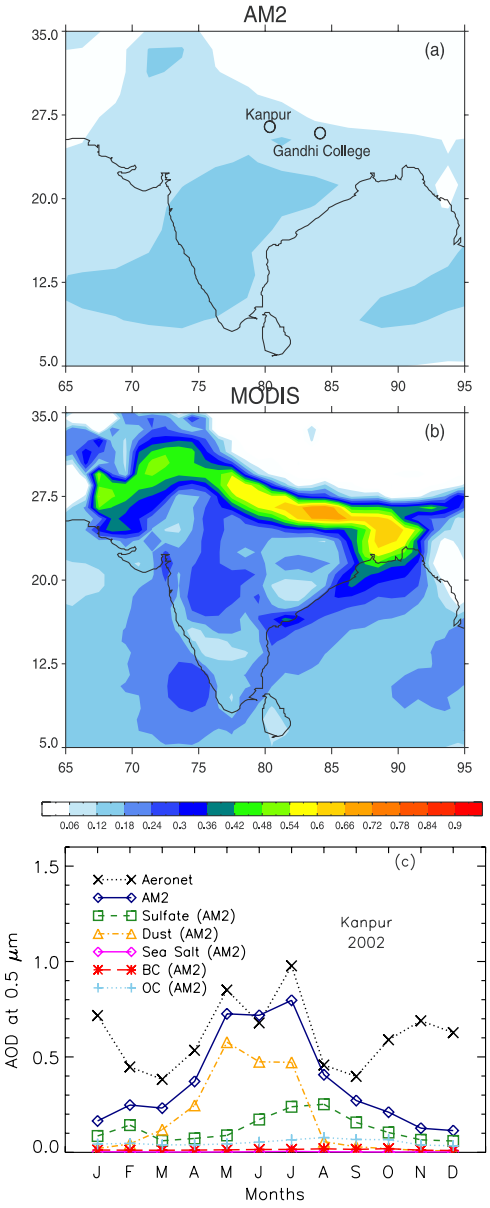

Figure 1. (a) Climatological AOD over the IGB region for the month of January (2002–2006) from (a) AM2 simulation and (b) MODIS observation. (c) Variations in monthly mean AOD at 0.5 μm for the year 2002 from AERONET observations at Kanpur and AM2 simulation.

Goddard Space Flight Center [*Holben et al.*, 2001]. We used the monthly mean values of AOD at 0.34, 0.38, 0.44, 0.5, 0.675, 0.87 and 1.02 μm from the selected AERONET sites. In addition, we also used the data on size distribution and single scattering albedo of aerosols at 0.44, 0.67, 0.87 and 1.02 μm available as inversion products from these sites [*Dubovik and King*, 2000]. From the size distribution of aerosols, quantities actually used in our analysis are the volume fraction of fine (C_{vf}) and coarse (C_{vc}) mode particles, calculated according to the following relation

$$C_v = \int_{r_{\min}}^{r_{\max}} \frac{dV(r)}{dlnr} dlnr \qquad (1)$$

[6] In the Version-2 of AERONET products, the separation radius (r_{sp}) between C_{vf} and C_{vc} corresponds to the minima of size distribution between 0.194 μm and 0.576 μm. In our analysis, we use only quality assured Level-2 (of Version-2) data for all AERONET products. This limits the number of AERONET sites suitable for our study to only two, viz. Gandhi-College (25.87° N, 84.13° E) and Kanpur (23.43° N, 80.33° E).

[7] The other important data set used in our study is the extinction profile of aerosols obtained from the space-borne lidar CALIOP onboard the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) [*Winker et al.*, 2007]. Details on the instrument, data acquisition, and various science products available from CALIPSO satellite are given by *Winker et al.* [2007, and references therein]. Here we use the CALIPSO Level-2 (Version 2.01) data corresponding to extinction profile of aerosols at 0.532 μm, available at a horizontal resolution of 40 km.

3. Methodology

[8] The methodology of our retrieval is described in detail by *Ganguly et al.* [2009], which also includes various sensitivity tests and validation of results with ground based measurements over the United States. In brief, the technique involves finding the best combination of aerosol concentration by minimizing differences between measured and calculated spectral variation in AOD and single scattering albedo along with the size distribution of aerosols over specific locations. Lidar data on extinction profile provides the vertical constraint on the distribution of aerosols in the atmosphere. Relative humidities from NCEP reanalysis are used to compute the hygroscopic growth factors and associated changes in the optical properties of aerosol components at all vertical levels. In our analysis, we used seven aerosol components viz. sulfate (Slf), black carbon (BC), organic carbon (OC) and two size bins each of dust (DS1, DS2) and sea salt (SS1, SS2). Size parameters of OC are from *Ming et al.* [2005], while for all other components they are obtained from AEROCOM. Refractive indices and mass growth factors of individual aerosol components are same as in AM2 model [*Ganguly et al.*, 2009].

[9] *Ganguly et al.* [2009] obtained the vertical profile of aerosols from the MPLNET (Micro-pulse Lidar Network) stations collocated with the Sun/sky radiometer sites of AERONET over the United States. In the absence of simultaneous collocated ground based lidar data in the IGB region, here we use the extinction profiles from CALIOP. However, *Kim et al.* [2008] has shown that the extinction data from CALIOP exhibit an unusual drop in the lowest few hundred meters (within 0.4 km) above the surface. Therefore, we decided to set all extinction coefficients below 0.4 km to be same as its value around 0.4 km. This could introduce some bias towards lower extinction values near the surface but typically the uncertainty in extinction values from CALIOP is greater than this bias. We believe, this is the safest thing one can assume in a region where otherwise no data on extinction profile is available.

[10] Since an exact CALIOP overpass for a fixed location is possible once in about two months, monthly mean extinction profiles are constructed by averaging multiple

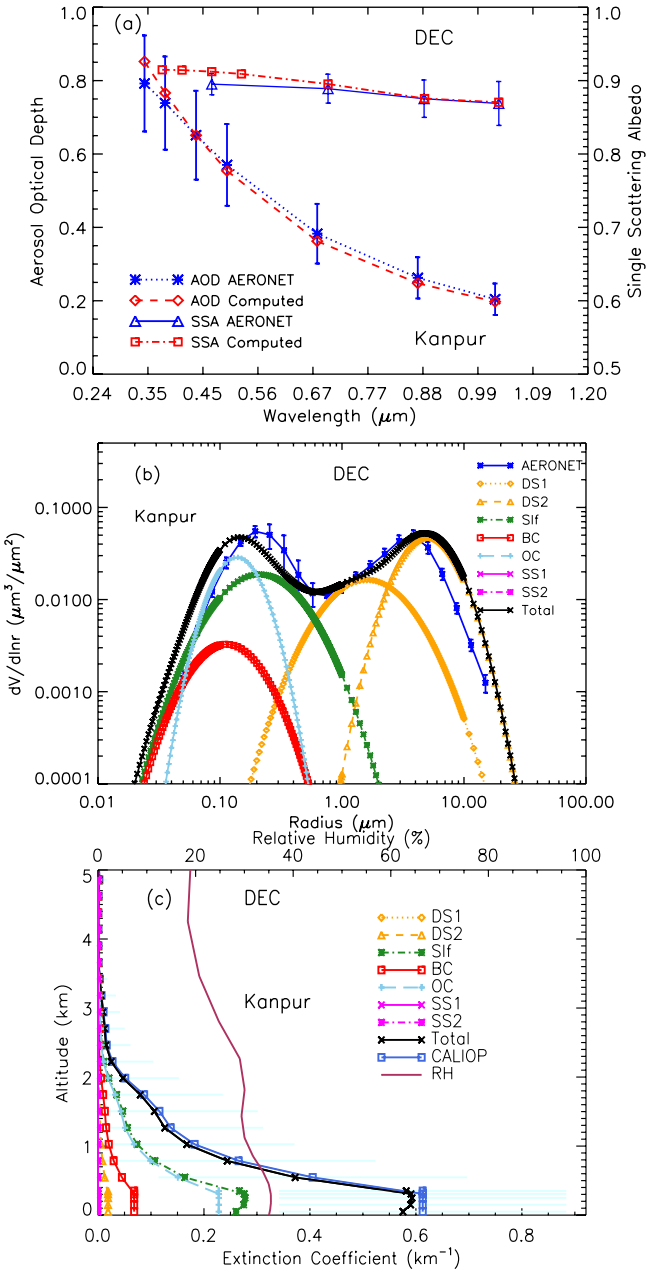

Figure 2. Comparison of AOD, single scattering albedo, and size distribution of aerosols from the AERONET site at Kanpur and the extinction profile from CALIOP with their estimated values based on our retrieval for December 2007. Figures 2b and 2c also show the contribution of individual aerosol components to the total size distribution and extinction profile respectively based on our results. Maroon line in Figure 2c represents the relative humidity profile from NCEP reanalysis.

profiles corresponding to CALIOP tracks inside a 2.5° × 2.5° box centered around each AERONET station. For each day of a month, we search the availability of extinction data over this box. If found, this data is averaged to get a mean extinction profile of the day and normalized to match the AOD from AERONET. In case any unusual peak is noticed in the CALIOP profile at altitudes above 2 km, the data is rejected to avoid any complications due to elevated aerosol layers or cloud contamination. Finally, good quality data for at least six days in a month are averaged to create the monthly mean extinction profile.

4. Results

[11] Due to various limitations in the Sun-Photometer and CALIOP data, currently the retrievals could be made only for eight months over Gandhi-College and five months over the Kanpur site. Here we discuss the concentrations retrieved over these two locations by our minimization method, compare them with those simulated by the AM2 model and issues which need improvement for achieving better performance of GCMs over this region.

[12] Gandhi College is a rural-urban fringe site located in Ballia district of Uttar Pradesh state in India. There are four distinct seasons in the IGB region, winter (Dec.–Feb.), pre-monsoon (Mar.–May), monsoon (Jun.–Sep.) and post-monsoon (Oct.–Nov.). The entire region is characterized by hazy and foggy conditions during the winter season and most rainfall occurs here during the monsoon season. Climatological AODs from the AERONET site at Gandhi College are highest (∼0.9 at 0.5 μm) during December and lowest during August (∼0.35 at 0.5 μm). Aerosol size distributions are characterized by a stronger fine mode during winter and a larger coarse mode during pre-monsoon season. Single scattering albedos are low (<0.9 at 0.675 μm) during winter and marginally higher during monsoon season. Size distribution and single scattering albedos referred here correspond to their column integrated values.

[13] Kanpur is an industrial city with a population ∼3.5 million and located in the central part of the IGB region. Seasonal variation in aerosol characteristics are similar for both these sites, except the AOD values are usually higher over Kanpur than at Gandhi College. *Dey and Tripathi* [2008] presents a detailed climatology of AOD and single scattering from the Kanpur site. Figure 2 shows the comparison of observed values of AOD, single scattering albedo, size distribution and extinction profile of aerosols for the month of December 2007 over Kanpur site with their estimated values based on the results of our minimization. In both these sites, size distribution pattern during all months show the presence of two distinct modes corresponding to fine and coarse range particles with a separation point ∼0.5 μm radius. Figures 2b and 2c also show the contribution of individual aerosol components to the total size distribution and extinction profile respectively based on the results of our minimization.

[14] Table 1 lists the surface and total column concentration of major aerosol components viz. sulfate, BC and OC over Gandhi College and Kanpur as inferred using our minimization method and as simulated by the GFDL-AM2 model. Uncertainties assigned with the retrievals are estimated on the basis of a range of sensitivity tests carried out with respect to the error values associated with various parameters used in the minimization process as discussed by *Ganguly et al.* [2009]. *Tripathi et al.* [2005] reported the average concentration of BC over Kanpur to be in the range of 6–20 $\mu g/m^3$ during December 2004, which is comparable with our retrieval of ∼5.5 $\mu g/m^3$ for December 2007, while the AM2 values are almost a factor of ten lower

Table 1. Surface and Total Column Concentration of Major Aerosol Components Over the Two AERONET Sites Derived Using the Minimization Method and As Simulated by the GFDL-AM2 Model With Online Aerosols[a]

		Sulfate				Black Carbon				Organic Carbon			
		Surface		Column		Surface		Column		Surface		Column	
Month	Year	Minz.	AM2	Minz.	AM2	Minz.	AM2	Minz.	AM2	Minz.	AM2	Minz.	AM2
						Gandhi College							
JAN	2007	56 ± 11	1.6	71 ± 14	5.0	5.6 ± 0.5	0.6	4.7 ± 0.4	0.8	82 ± 9	3.6	70 ± 8	6.5
MAR	2007	22 ± 5	2.1	26 ± 6	7.8	2.9 ± 0.4	0.6	3.6 ± 0.5	0.9	32 ± 3	3.5	40 ± 4	7.6
APR	2007	10.5 ± 3	3.4	28 ± 8	12	3.5 ± 0.6	0.6	9.5 ± 1.6	1.3	20 ± 3	3.9	55 ± 8	10.1
MAY	2007	2.0 ± 0.4	5.0	6 ± 1	22	3.0 ± 0.3	0.7	9.7 ± 1.0	1.8	20 ± 3	4.4	63 ± 9	15.2
SEP	2006	3.6 ± 0.6	3.7	10 ± 2	15	3.1 ± 0.3	0.7	9.1 ± 0.9	1.2	25 ± 4	5.0	67 ± 10	11.0
OCT	2006	12 ± 1.4	2.8	27 ± 3	11	2.0 ± 0.3	0.8	3.3 ± 0.5	1.4	45 ± 5	5.4	89 ± 10	12.2
NOV	2006	33 ± 5	2.4	35 ± 5	8.5	7.1 ± 0.8	0.8	7.2 ± 0.8	1.1	65 ± 8	4.5	66 ± 8	9.3
DEC	2006	35 ± 7	2.8	51 ± 10	8.2	6.8 ± 0.5	0.7	9.3 ± 0.7	0.9	50 ± 6	4.2	69 ± 8	7.5
						Kanpur							
MAR	2007	14 ± 2	2.1	21 ± 3	6.3	2.5 ± 0.3	0.43	3.8 ± 0.5	0.6	18 ± 3	2.9	2.7 ± 0.5	5.6
APR	2007	17 ± 2.5	2.8	29 ± 4	9.6	2.5 ± 0.3	0.53	4.3 ± 0.5	1.0	20 ± 3	3.5	3.5 ± 0.5	8.1
SEP	2006	6 ± 1.5	5.5	11 ± 3	14	1.8 ± 0.2	0.7	2.8 ± 0.3	1.2	19 ± 2	5.4	3.5 ± 0.4	11.0
OCT	2006	15 ± 3	2.7	24 ± 5	9.4	2.9 ± 0.3	0.7	4.1 ± 0.4	1.1	19 ± 3	4.7	2.9 ± 0.5	9.2
DEC	2007	60 ± 9	2.8	54 ± 8	6.4	5.5 ± 0.5	0.57	4.8 ± 0.4	0.7	58 ± 7	3.4	5.2 ± 0.6	6.1

[a]Surface measurements are in $\mu g/m^3$, total column measurements are in mg/m^2, and Minz. is the minimization method.

during the same month. We find that AM2 is largely underestimating organics and BC concentrations over the IGB region almost during all months. Sulfate is also underestimated in AM2 during most months, but there seems to be an overestimation from May to September. Magnitude of these differences are so large that they can not be accounted by any clear sky biases in our retrievals or issues relating to comparison of gridded GCM data with point observations. We find a seasonal pattern in the surface concentration of sulfate, BC and organics over the region with higher values during winter months and lower values from May to September. The same pattern is also noticeable in the column loading of sulfate aerosols. However, the corresponding seasonality seems to be opposite in AM2 results. Interestingly, although the near surface concentration of BC and OC show a decrease during pre-monsoon and monsoon season, their total column loading remains unchanged or show an increase during pre-monsoon period. This is consistent with *Dey and Tripathi* [2008] which showed that due to enhanced atmospheric mixing during summertime, BC is lifted to higher levels such that its columnar loading remains similar as in winter. Further comparison show that AM2 underestimates dust concentrations over the IGB region by a factor of 2–6 during winter, pre-monsoon and post-monsoon months. Presently we are unable to compare our retrievals with any in-situ results due to lack of aerosol composition data over this region.

[15] AOD from AM2 remains almost same even if the relative humidities (RH) in the model are nudged towards the NCEP reanalysis values. Besides, the maximum underestimation of AOD occurring in the dry season tells that the problem is not caused by RH biases or hygroscopicity of aerosols in the GCM. Therefore, it is clear that the differences in AOD from AM2 and observations as shown in Figure 1 are occurring due to a large underestimation of all major aerosol species over the IGB region in the GCM simulation. The problem could be related to production, transport and removal of aerosols in the model. As the discrepancies are observed right over the source region, the problem is least due to transport of aerosols in the model. Removal of aerosols are parameterized in models. But the same discrepancy occurring in most GCMs using different parametrizations suggest that the removal of aerosols is not the primary cause of this problem. Therefore we believe that the noted differences between AM2 results and observations are largely caused by the problems associated with the emission inventories as well as poor characterization of dust sources over this region. As mentioned by *Ganguly et al.* [2006], one of the major sources of carbonaceous and sulfate aerosols over the IGB region is the open burning of dry leaves as part of waste burning activities, particularly carried out during post-monsoon and winter season. *Schmidl et al.* [2008] has shown that organic matter comprises of more than 90% of the aerosols emitted along with the smoke from leaves, significantly higher than from wood burning. Thus, in order to make realistic estimates of the impact of aerosols on the south Asian monsoon, there is a compelling need for improving the existing aerosol inventories and dust sources over the region taking into account the aerosols emitted through such waste burning activities and possibly due to land use changes.

5. Conclusions

[16] Observations from multiple satellite instruments show a persistent aerosol haze over the IGB region during the winter months, with AOD values among the highest in the world. Yet, the most sophisticated GCMs fail to reproduce this high AOD belt in their simulations. Insufficient data on aerosol composition makes it difficult to improve model results over this important source region. In this work, we retrieve the composition and concentration of aerosols over the IGB region, to a first order approximation, by combining the spectral measurements of AOD, single scattering albedo and size distribution available from AERONET stations and the extinction profile of aerosols from CALIOP. Comparison of our results with AM2 simulations reveal that the GCM is largely underestimating organics and BC concentrations over this region almost during all months (almost a factor of 10 during winter months). Sulfate aerosols are also underestimated during

most months however, there is an overestimation from May to September. There is a compelling need for improving the aerosol inventories and dust sources over the region in order to make realistic assessment of the impacts of aerosols on the south Asian monsoon.

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