# Thick absorbing aerosol layer observed in the monsoon season over India

A31A-0027

S. N. Tripathi[1,*], Sagnik Dey[2], J. Jaidevi[1], B. N. Singh[1], Marykutty Michael[1] and Tarun Gupta[1]

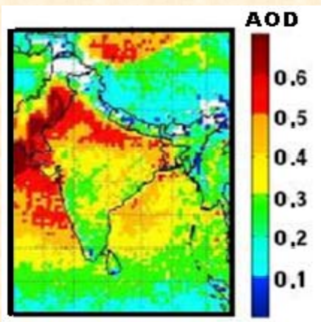
[1]Department of Civil Engineering, Indian Institute of Technology Kanpur, Kanpur, 208016, India
[2]Centre for Atmospheric Sciences, Indian Institute of Technology Delhi, New Delhi, 110016, India
Email* : snt@iitk.ac.in

## Abstract

The link between absorbing aerosols and South-Asian hydroclimate remains debated and unexplained partly due to the paucity of observations during monsoon season. Here we present the first detailed aircraft measurements of 3-D distributions of aerosol propertiesa during the early monsoon season of the year 2009 across the Indo-Gangetic Basin (IGB), where the aerosol optical depth is largest within South Asia. Highly absorbing (single scattering albedo, SSA varies in the range 0.7-0.9) aerosols in the lower troposphere show a gradient from east (low SSA) to west (high SSA), while the size distribution shows a complex 3-D pattern.

## Introduction

Understanding the feedbacks of aerosols on hydroclimate, a key source of uncertainty in quantifying the anthropogenic climate change [*Ramanathan et al.*, 2005; *IPCC*, 2007], is critical in South Asia as more than one-sixth of the world's population rely upon monsoon precipitation that drives the region's economy.



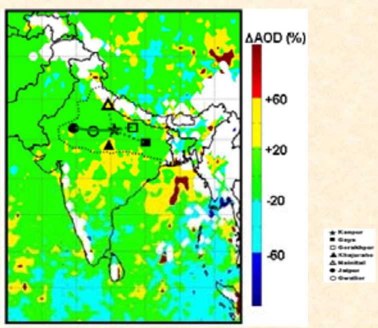




**Fig.1** (a) Spatial distribution of climatological mean midvisible AOD over Indian Subcontinent during the monsoon seasoon over the indian subcontinent retrieved by MISR during the period March 2000 to November 2008. (Dey and Girolamo, 2010) (b) AOD anomaly (in %) during Jun-Jul in the year 2009 compared to 10 year (2000-2009) mean AOD retrieved by MISR.

## Aircraft Experiment

- Multiple instruments deployed onboard the National Remote Sensing Center Beachcraft B-200(SuperKingAirB-200) http://www.nrsc.gov.in/aircraft.html with aircraft were connected to a shrouded community inlet to minimize non-isokinetic losses .
- Aerosol relative humidity (RH) measured by a Photo Acoustic Soot Spectrometer (PASS) was mostly below 50% for 95% of the time and never exceeded 55% during the entire measurement period, thus ruling out any significant effect of RH on particle scattering and mass concentration.

## Measurement and Analysis

- Scattering coefficient ($\beta_{sca}$) and absorption coefficient ($\beta_{abs}$) at 781 nm wavelength were directly measured by a single-channel PASS at 1s interval [*Arnott et al.*, 1999].
- SSA was derived directly by taking the ratio of $\beta_{sca}$ and $\beta_{ext}$ (where $\beta_{ext} = \beta_{sca} + \beta_{abs}$).
- A Magee Aethalometer (AE-21-ER, Magee, Scientific) was used to measure the black carbon concentration ($M_{BC}$).
- TSI Scanning Mobility Particle Sizer (3936, TSI) was used for measuring the aerosol size distribution in the range 0.016-0.57 µm.

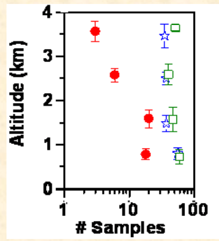



**Fig.2** Total number of measurements (*i.e.* sample density) used to generate the vertical distributions of aerosol properties over the western (red circle), central (blue star) and eastern (green square) parts of the IGB . Western ($75^0$-$78^0$E), Central ($78^0$-$81^0$E) and Eastern ($81^0$-$84^0$E).

## Vertical Distribution of Aerosol Properties

- Fine particles ($R_{eff}$ <0.3 µm) dominate the eastern IGB above 1 km (fine fraction >80%) and is associated with high aerosol absorption (*SSA* ~0.7-0.82), probably due to high $f_{BC}$ (>6%) (Fig.3).

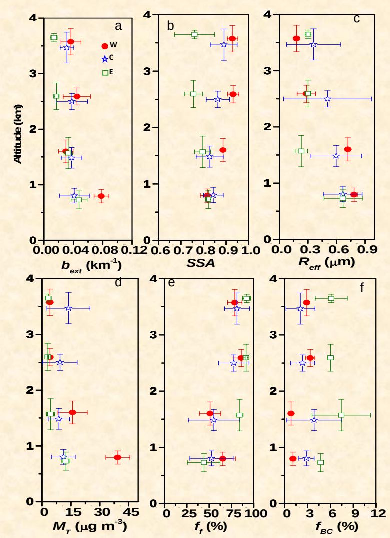



**Fig.3** (a)Vertical distributions of (a) extinction coefficient, $b_{ext}$ (at 781 nm), (b) SSA (single scattering albedo at 781 nm), (c) particle effective radius ($R_{eff}$), (d) total mass of particles ($M_T$), (e) fine mass fraction, $f_f$ (%) and (f) black carbon fraction ($f_{BC}$) over the western (W), central (C) and eastern (E) parts of the Indo-Gangetic Basin during the early monsoon season of the year 2009. The vertical and horizontal bars through each point are $\pm 1\sigma$.

## Model vs Measurement

The modelled extinction coefficient and SSA from SHDOM were compared with the measured ones (Fig 4). Fig 4 shows a very close agreement between modeled and measured SSA and extinction coefficient regarding their values and variation.

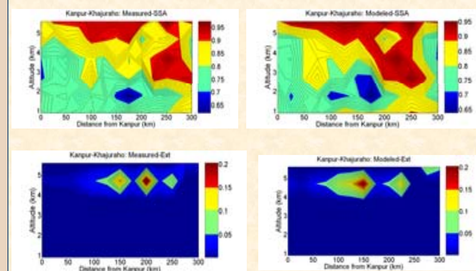



**Fig. 4** Modelled and measured extinction and SSA and extinction coefficient as function of altitude.

## Aerosol Heating Rate

- Spherical Harmonics Discrete Ordinate Method (SHDOM) model (*Evans*, 1998), using an adaptive grid approach that gives desired resolution, is used to calculate three dimensional clear-sky aerosol heating rate.
- In all 623 HR calculations were made covering the entire region (Fig. 5a).

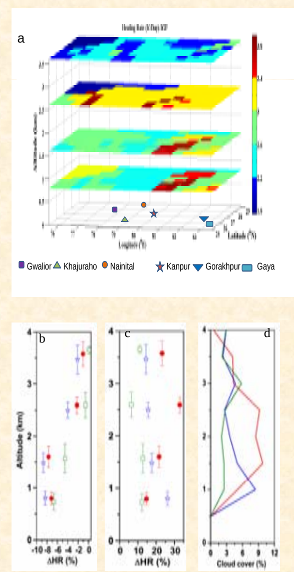



**Fig.5** (a)3-D variation of diurnal, clear-sky aerosol heating over the Indo-Gangetic Basin and Himalayan foothills at $0.5^0 \times 0.5^0$ spatial resolution using SHDOM.
Relative difference in (b) clear-sky aerosol heating rate ($\Delta H_{clr}$) due to absorption associated without and with coarse mode particles (%) as function of altitude for E, C and W segments, (c) cloudy-sky ($\Delta H_{cld}$) and $\Delta H_{clr}$ heating rates and (d) MISR cloud top distributions (in percentage) as function of altitude.

## Results

- The west (high) to east (low) gradient in $\beta_{ext}$ diminishes with increasing altitude, while the *SSA* gradient enhances.
- Fine particles ($R_{eff}$ < 0.3 µm) dominate the eastern IGB above 1 km (fine fraction >80%) and is associated with high aerosol absorption (*SSA* ~0.7-0.82), probably due to high $f_{BC}$ (>6%).
- In the central IGB, $f_f$ and SSA increase with altitude.
- In both western and central IGB, the large absorption (SSA ~0.8-0.9) is associated with both fine and coarse particles, thus providing first direct evidence of coarse mode absorption.
- While the TOA forcing over the western, central and eastern IGB are comparable (-6.8±0.6, -6.3±0.6 and -5.1±0.5 W m$^{-2}$ respectively), the atmospheric warming over the western (14.4±1 W m$^{-2}$) and central (16±1 W m$^{-2}$) IGB is twice compared to the eastern (7.8±0.9 W m$^{-2}$) IGB, and are comparable to the aerosol forcing over the Indian Ocean during the winter season [*Ramanathan et al.*, 2001], thus indicating the persistence of high aerosol heating in the monsoon season when aerosols are expected to be washed out.
- The measurements of 3-D distribution of aerosol properties reduced the uncertainty in estimates of $\Delta H_{clr}$ over the IGB to 10% with respect to optical properties.
- $\Delta H_{clr}$ is high (>3 K day$^{-1}$) at ~2.5 km across the IGB, below which $\Delta H_{clr}$ is higher in the eastern IGB compared to other parts. (Fig. 5a).

## Conclusions

- AOD is not anomalously high or low during the observational period relative to ten-year climatology from MISR [*Dey, and Girolamo*, 2010], thus these observations may be used as representative of the early monsoon season
- Thick absorbing aerosol layer well spread in the lower troposphere persists over the IGB (as also seen by satellites) in the monsoon season, indicating a rapid buildup of aerosols from various anthropogenic and natural sources during the break phase of monsoon [*Dey, and Girolamo*, 2010].
- The resulting high tropospheric heating shows a strong longitudinal gradient in aerosol properties. The west (high)-east (low) gradient in cloud cover opposite to the aerosol absorption gradient in the lower troposphere indicates a possibility of semi-direct effect [*Randles and Ramaswamy, 2008*].
- However, the relative role of semi-direct effect due to high aerosol absorption and direct radiative effect in governing the cloud distribution cannot be quantified from the present data set and needs to be examined by climate models incorporating this 3-D distribution of aerosol heating.
- We present the first 3-D aerosol distribution over the Indian monsoon region during the early monsoon season. Aerosol retrieval algorithms for passive sensors (e.g. MODIS [*Levy et al.*, 2007] and MISR [*Kahn et al.*, 2009]) do not have aerosol models that consider significant coarse mode absorption and such high aerosol absorption, which are observed and reported here, and thus may lead to a significant bias in the retrievals.
- Low absorbing aerosol index that quantifies absorption of elevated aerosol layers in clear sky [*Bollasina et al.*, 2008] fails to reproduce the thick absorbing aerosol layer coexisting with clouds.
- Our results can help improve the aerosol retrieval from satellites over this region in the monsoon season, and fill in the gap in observational evidence. Our results further substantiate the importance of consideration of aerosol semi-direct effect on monsoon clouds along with the direct effect to fully understand the aerosol-hydroclimate link.

## Acknowledgements

We thank Bill Lau, Cynthia Randles and Larry Di Girolamo for very useful suggestions. This work was supported by grants from DST, ICRP, IFCPAR, and ISRO GBP Programmes. MISR data were distributed by NASA Langley Atmospheric Sciences Data Center.

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AGU FALL MEETING, 2010