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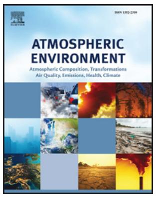

Meridional gradients in aerosol vertical distribution over Indian Mainland: Observations and model simulations

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HIGHLIGHTS

- Ground based and space borne observations supported by transport model simulations.
- Meridional increase in the vertical spread of aerosols over India during spring.
- Dominance of mineral dust aerosols during spring and summer at higher altitudes.

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ABSTRACT

Multi-year observations from the network of ground-based observatories (ARFINET), established under the project 'Aerosol Radiative Forcing over India' (ARFI) of Indian Space Research Organization and space-borne lidar 'Cloud Aerosol Lidar with Orthogonal Polarization' (CALIOP) along with simulations from the chemical transport model 'Goddard Chemistry Aerosol Radiation and Transport' (GOCART), are used to characterize the vertical distribution of atmospheric aerosols over the Indian landmass and its spatial structure. While the vertical distribution of aerosol extinction showed higher values close to the surface followed by a gradual decrease at increasing altitudes, a strong meridional increase is observed in the vertical spread of aerosols across the Indian region in all seasons. It emerges that the strong thermal convections cause deepening of the atmospheric boundary layer, which although reduces the aerosol concentration at lower altitudes, enhances the concentration at higher elevations by pumping up more aerosols from below and also helping the lofted particles to reach higher levels in the atmosphere. Aerosol depolarization ratios derived from CALIPSO as well as the GOCART simulations indicate the dominance of mineral dust aerosols during spring and summer and anthropogenic aerosols in winter. During summer monsoon, though heavy rainfall associated with the Indian monsoon removes large amounts of aerosols, the prevailing southwesterly winds advect more marine aerosols over to landmass (from the adjoining oceans) leading to increase in aerosol loading at lower altitudes than in spring. During spring and summer months, aerosol loading is found to be significant, even at altitudes as high as 4 km, and this is proposed to have significant impacts on the regional climate systems such as Indian monsoon.

1. Introduction

Knowledge on the vertical distribution of aerosols assumes importance in aerosol-climate forcing studies, because a given aerosol layer would impart different forcing, if present at different elevations in the atmosphere. While residing close to the surface, absorbing aerosols can enhance convection by increasing lower atmospheric temperature and hence can favor enhancement in precipitation. But when present at higher altitudes, both, absorbing and scattering aerosols cool the surface and slow down the water cycle by blocking surface reaching solar radiation (Ramanathan et al., 2005). Aerosol absorption at higher elevations is more

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intense when they reside above clouds, as they interact not only with the direct solar radiation but also with the reflected radiation by underlying clouds (Seinfeld, 2008). This aerosol induced heating can sometimes be intense enough to burn the clouds off (Ackerman et al., 2000; Satheesh and Moorthy, 2013). Moreover, exponentially decreasing molecular density makes earth's atmosphere thinner at higher elevations and hence the diabatic heating due to aerosol absorption becomes more significant (Babu et al., 2011; Satheesh, 2012), and it can even alter the thermal structure and stability of the atmosphere (Satheesh and Moorthy, 2013, Babu et al., 2011). Thus, the three dimensional distribution of aerosols is an important information to quantify effects of aerosols on climate (Alpert et al., 2004). Relying largely on model simulated or assumed aerosol vertical profiles, which may deviate from actual scenario, might lead to large uncertainty in aerosol impact assessments on climate and air quality (Yu et al., 2010). An exponentially decreasing concentration with a typical scale height of 1 or 2 km (Penndorf, 1954; Elterman et al., 1969; Shaw, 1975) is still a widely used model for aerosol vertical distribution. But this may lead to erroneous estimates of forcing, especially when distinct elevated layers of aerosols with different properties exist (Muller et al., 2001; Ramanathan et al., 2001; Satheesh, 2002; Satheesh et al., 2009). LIDAR remote sensing (Mishra et al., 2013) and in-situ probing using aircraft (Satheesh et al., 2008) and balloon borne measurements (Babu et al., 2011) are the popular means to retrieve information on the vertical distribution of aerosols. Satellite based lidar measurements made a revolution in this regard, especially after the launch of Cloud Aerosol Lidar with Orthogonal Polarization (CALIOP) in 2006 onboard Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) (Winker et al., 2007). However, lidar-derived information suffer from the major uncertainty, arising due to assumed extinction to backscatter ratio (lidar ratio), which can range significantly over regions such as Indian subcontinent, where different types of aerosols co-exist in different proportions at different elevations in different seasons. Rapid urbanization and population growth makes south Asia, including the Indian subcontinent, one of the regions of high aerosol concentration over the globe (Bollasina et al., 2008). Distinct aerosol sources and contrasting wind patterns in different seasons make aerosol system over the Indian region highly complex and heterogeneous through mixing up of diverse aerosol types of both natural and anthropogenic origins. The present study examines vertical distribution of aerosols over the Indian region in different seasons by integrating data from different observation platforms, such as satellite measurements and ground based network of observatories and aerosol chemical transport model simulations and discusses its plausible implications.

2. Data and methodology

To improve on the assessment of radiative and dynamical impacts of aerosols on climate, it is necessary to have a synergy of different means of observations, using satellites and ground based measurements, and modeling (Kaufman et al., 2002). The present study is carried out using long term aerosol optical depth (AOD) data from the network of aerosol observatories under Aerosol Radiative Forcing over India (ARFI) project of ISRO GBP (ARFINET, Moorthy et al., 2013; Babu et al., 2013), spread with more than 30 observatories over the Indian region, along with satellite based measurements of aerosol properties from Cloud Aerosol Lidar with Orthogonal Polarization (CALIOP) and model simulations from Goddard Chemistry Aerosol Radiation and Transport (GOCART). The CALIOP data used is the level 3 all sky aerosol extinction coefficient profiles at a spatial resolution of 2° latitude × 5° longitude for the period June 2006 to December 2013. AOD data is obtained from the Multi Wavelength Solar Radiometer (MWR) and Microtops sun-photometer (MTOPS) operated at different stations of ARFINET (shown in Fig. 1). MWR measures direct solar radiation reaching the surface at ten different wavelengths centered at 380, 400, 450, 500, 600, 650, 750, 850, 935 and 1025 nm with narrow band interference filters mounted on a filter wheel that is moved sequentially and aligned towards the sun using suitable control systems (Moorthy et al., 1999). AOD is estimated from radiation attenuation in cloud free atmosphere using Langley plot technique, removing the contribution of molecular scattering and absorption from the total optical depth (Shaw et al., 1973). Microtops sun-photometer is a well calibrated hand-held instrument that derives the instantaneous aerosol optical depths measuring the direct solar radiation and internal calibration constants at five different wavelengths centered about 340,380, 500, 675 and 870 nm (Morys et al., 2001). A Global Positioning System (GPS) receiver attached with the sun-photometer gives information on the position, altitude and time of the measurement. The altitude distribution of extinction coefficient is derived from CALIPSO observations at 532 nm. Since the AOD measurements in ARFINET did not include the wavelength at 532 nm (corresponds to the wavelength used in CALIPSO), the AOD at 532 nm is estimated using the Angstrom exponential relation (Ångström, 1964).

One of the major uncertainties in the altitude profiles of extinction coefficient derived from CALIPSO is due to the assumed lidar ratio (extinction to backscatter ratio), which vary over a wide range (20–70 Sr), over different regions during different seasons depending on the size and composition of the aerosol system. While examining the seasonal differences in vertical distribution of aerosol extinction coefficient over Indian region, uncertainties in the magnitude of extinction coefficient can lead to significant errors due to the assumed values of lidar ratio and its seasonal variation. This uncertainty is significant over the Indian region where aerosol abundance and characteristics vary radically in different seasons due to the influence of different sources and prevailing meteorology. Errors in retrieval due to the uncertainty in lidar ratio is resolved in the present study by normalizing CALIPSO derived aerosol extinction profiles using measured AOD values from ARFINET during January 2006 to December 2013.

Aerosol extinction coefficient profiles from CALIPSO, during the period from June 2006 to December 2013, over the region between 70°E to 90°E are averaged for different seasons in each 2° latitude band from 7°N to 33°N. In this way, mean vertical profiles are generated in each latitude band (7–9°N, 9–11°N, 11–13°N,....,31–33°N) for different seasons, December - February (DJF), March - May (MAM) and June - September (JJAS). To normalize the seasonal mean CALIPSO extinction coefficient profiles, long term AOD measurements from the ARFINET observatories, during the same period, over Indian land mass and adjoining oceans, are averaged for each 2° latitude band, between 7°N and 33°N in the longitude band, 70ºE – 90ºE for different seasons. Seasonal mean AOD values thus generated in each latitude band are used to normalize corresponding seasonal mean vertical profiles of aerosol extinction coefficient from CALIPSO. Thus, the normalized profiles yielded the same vertical structure as that of CALIPSO-derived aerosol extinction coefficient profiles, but with an integrated columnar extinction that matches with seasonal mean AOD values for the latitude band from ARFINET. ARFINET observatories in each latitude band and corresponding seasonal mean AOD values for respective seasons used for the normalization of CALIPSO derived aerosol extinction profiles are given in Table 1.

Level 2 Particulate Depolarization Ratio (PDR) profiles, which give information on non-sphericity of aerosols, from CALIPSO observations during the period, June 2006–September 2011 are