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Aerosol characteristics in the UTLS region: A satellite-based study over north India

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HIGHLIGHTS

- CALIPSO-derived aerosol profiles are analyzed in the UTLS region over north India.
- An aerosol layer of about 2 km depth is identified in the vicinity of tropopause.
- Aerosols in UTLS region are anisotropic (non-spherical) in nature.
- Enhanced aerosol layer is associated with tropospheric convection through modulation of tropopause.

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ABSTRACT

Vertical profiles of aerosol backscatter coefficient and depolarization ratio, obtained from the Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite, were studied in the upper troposphere and lower stratosphere (UTLS) region over North India (21–30° N and 72–90° E), covering the highly polluted Indo-Gangetic Plain (IGP) for one-year period from December 2011 to November 2012. An enhanced aerosol layer was observed between 15 and 18 km altitude, in the vicinity of tropopause, with a broad layer depth of about 2 km. The aerosol layer showed strong seasonal, monthly as well as day and night time variability, with a peak value of backscatter coefficient during monsoon season ($\sim$5.54 $\times$ 10^{-3} sr^{-1} in September). The corresponding depolarization ratio indicates anisotropic (non-spherical) nature of particles. The aerosol layer was found to be highly linked with the variability in tropopause height, showing a positive correlation between tropopause height and the height of maximum backscatter coefficient (correlation coefficient of 0.8). However, it was found to be negatively correlated with the integrated backscatter coefficient (IBC), with a correlation coefficient of 0.3. We further analyzed outgoing long-wave radiation (OLR) data during the study period to investigate the link between the observed enhanced aerosol layer in the UTLS region and prevailing deep convective activities over the study region. Low values of OLR during monsoon (about 214 W m^{-2}) indicate the occurrence of deep convection over this region, which may cause a large-scale circulation-driven vertical transport of boundary-layer pollution into the atmosphere of UTLS region. Results may have potential implications for better understanding and assessing the chemical and radiative impacts of these aerosols in the tropical UTLS region.

1. Introduction

Atmospheric aerosols are ubiquitous in the Earth's lower atmosphere and exist in both troposphere and the stratosphere globally, but they are highly variable in their number concentration, composition and various properties (Pöschl, 2005). They interact both directly and indirectly with the Earth's radiation budget, and thereby affecting the climate system (IPCC, 2007). The properties of tropospheric aerosols have a large spatial and temporal variability because of their uneven distribution of widespread sources and the short residence time in the atmosphere. However, stratospheric aerosols are quite different from the tropospheric aerosols because unlike tropospheric aerosols that can produce regional and

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seasonal effects on the climate system, stratospheric aerosols can produce long-term global effects due to their long residence time in the stratosphere (Ramachandran and Jayaraman, 2003). Generally, aerosols in the stratosphere originate from volcanic effluvia, and have been studied by many researchers (Haywood et al., 2010; Vernier et al., 2011a; He et al., 2014). However, stratospheric aerosol layers have also been observed during volcanically quiescent period (Thomason et al., 2008), which is strongly dependent on input from the troposphere in the absence of any major volcanic eruption.

The vertical distribution of particulates in the Upper Troposphere and Lower Stratosphere (UTLS) region over the tropics gained considerable interest due to its role in the dehydration of tropospheric air entering in the tropical lower stratosphere (Jensen et al., 1996) as well as their potential to influence the radiation budget of the Earth-atmosphere system (Hartmann et al., 2001). On an average, tropospheric convection is very strong in the tropical region. The Asian summer monsoon system is mainly characterized by deep convective activity, and causes transport of boundary layer constituents such as aerosols, water vapor, and other precursor gases which have their sources on the earth surface into the upper troposphere region through tropospheric convection (Randel et al., 2010; Fadnavis et al., 2013). The tropopause layer is generally recognized to control the entry of tropospheric air into the stratosphere (Devara et al., 1997; Fueglistaler et al., 2009). However, the tropospheric convection offers an alternative pathway that bypasses the tropopause region and allows these constituents to enter into the lower stratosphere (Randel et al., 2010). This transport can also have significant influence on the chemical processes in the stratosphere, and thus can control stratospheric ozone chemistry and climate system (Vernier et al., 2009). Few studies on stratospheric aerosol characteristics have been carried out on global basis (Thomason et al., 2007; Vernier et al., 2009). However, such studies are limited to regional scale, which may have some impact on regional atmospheric phenomenon, like monsoon activities (Gettelman et al., 2004; Inoue and Takahashi, 2009; Randel et al., 2010).

The present study aims at understanding vertical distributions of aerosols in the tropical UTLS region over north India using Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) derived aerosol products for one-year period from December 2011 to November 2012. Enhanced aerosol layer was investigated in the UTLS region using CALIPSO derived aerosol vertical profiles to understand its association with tropopause height. To confirm the possible sources of aerosols in the UTLS region, outgoing long-wave radiation (OLR, a proxy for tropospheric convection) data was analyzed during the study period.

2. CALIPSO measurements and data analysis

CALIPSO is a first kind of satellite having vertically down-looking lidar system, known as CALIOP (Cloud–Aerosol Lidar with Orthogonal Polarization) that provides vertical distributions and optical properties of aerosols and clouds globally. It measures elastic laser backscatter at 1064 nm and the parallel and cross-polarized components of the 532 nm return signal, from which the depolarization ratio (a crucial parameter to identify sphericity of particles) can be derived at 532 nm (Hu et al., 2007). CALIPSO identifies aerosol and cloud layer using a threshold technique applied to profiles of attenuated scattering ratio, which is stored as the vertical feature mask (VFM) and atmospheric volume description (AVD) flags (Liu et al., 2009). For aerosol layers, total six aerosol subtypes are identified (e.g. clean marine, dust, polluted continental, clean continental, polluted dust, and smoke), and they determine the extinction-to-backscatter ratio (also known as lidar ratio) based on a look-up table (Omar et al., 2009). Using the lidar ratio (and its uncertainty associated with the identified aerosol subtype), extinction and backscatter profiles are computed with the Hybrid Extinction Retrieval Algorithms, HERA (Young and Vaughan, 2009; Young et al., 2013). The vertical resolution of aerosol products is about 30 m between the surface and 8.2 km altitude, 60 m between 8.2 km and 20.2 km altitude and 180 m for more than 20.2 km altitude in the stratosphere. More details about the instrument and aerosol retrieval processes are given elsewhere (Vaughan et al., 2009; Winker et al., 2013).

We analyzed one-year (December 2011 to November 2012) CALIOP level 2 version 3.1 5 km aerosol profile products, mainly total backscattering coefficient (TBC) and depolarization ratio (DR) on day and night time basis over north India, covering 21–30°N latitude and 72–90°E longitude. A total number of 114 days data were obtained from CALIPSO while passing over the selected region. However, each month is having different number of day's profiles. Accurate night-time calibration of the principal channel at 532 nm is obtained via molecular normalization at stratospheric levels (Powell et al., 2009). As for most lidars, daylight dominates the return signal, and hence reduces the signal-to-noise ratio (SNR), with the consequence that CALIPSO night-time data have superior quality as compared to that of day time data. However, recently, Marenco et al. (2014) verified the airborne aerosol measurements with day time under flight of CALIPSO aerosol products over the Amazon region of Brazil, during the biomass burning season. They observed comparable magnitude of the average extinction coefficient estimated from CALIPSO and aircraft lidar. In another study, Misra et al. (2012) have validated the day time CALIPSO-derived aerosol product with ground based MPLNET-derived backscatter and extinction coefficients over Kanpur, a location in the central Indo-Gangetic Plain (IGP). Further, the validation of CALIPSO data with multi-platform measurements (e.g. ground-based, airborne, satellite) during the day and night time has also been reported in several papers (Mielonen et al., 2009; Pappalardo et al., 2010; Kacenelenbogen et al., 2011; Kim et al., 2013; Omar et al., 2013; Tesche et al., 2013). It should be noted here that the CALIPSO data are available from 2006 onwards; however, in the present study, we presented analysis for particular year as a representative case study, during which no volcanic eruptions deemed violent enough to directly inject particles into the stratosphere.

3. Characteristics of study region

The present study region (21–30°N latitude and 72–90°E longitude) covers major parts of north, north-east and central India, including highly polluted IGP region, which is dominated by the urban/industrial aerosols and demonstrated a significant seasonal variability based on the complex combination of anthropogenic factors mixed with the contribution from natural sources (Srivastava et al., 2012). The study region is surrounded by the Himalayas to the north, which acts as a barrier and accumulates aerosol pollutants over the region (Gautam et al., 2011; Srivastava et al., 2011). Fig. 1 shows MODIS (Moderate Resolution Imaging Spectroradiometer) derived columnar aerosol optical depth (AOD) over India including the region of our interest (shown by a rectangle) during winter (Fig. 1a), summer (Fig. 1b), monsoon (Fig. 1c) and post-monsoon seasons (Fig. 1d) averaged over December 2011 to November 2012. Higher aerosol loading and large spatial heterogeneity were observed over the study region, particularly over IGP region, which is more pronounced during summer (Fig. 1b) and monsoon (Fig. 1c) seasons. During these seasons, impact of dust storm activity from the Thar Desert region over the study region, particularly over IGP in north India can be clearly seen. Further, deep convective activity, associated with the frequent