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# LiDAR observations of the vertical distribution of aerosols in free troposphere: Comparison with CALIPSO level-2 data over the central Himalayas

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## HIGHLIGHTS

- Yearlong LiDAR observation and aerosol layers over the central Himalayas.
- Comparison and validation of CALIPSO aerosol backscatter with LiDAR data.
- Strong variability in vertical profiles of aerosol extinction coefficient.

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## ABSTRACT

This study elucidates the seasonality in aerosol vertical profiles acquired using LiDAR measurements and compares it with the CALIPSO level-2 data products over central Himalayas. A detailed analysis on the vertical distribution of aerosols over the central Himalayan region is carried out during different seasons. We present intermittent observations that were made over Manora Peak (29.36° N, 79.45° E, 1951 m, AMSL) Nainital, during March 2012 to May 2013 amounting to a total of 360 h of LiDAR operation, out of which 57 suitable cases were subjected to further analysis. Aerosol loading in the vertical column was found to be highest with 3.40 $(\mathrm{Mm\ sr})^{-1}$ at 3.3 km during the spring and summer seasons (MAMJ-2012), and the lowest with 0.48 $(\mathrm{Mm\ sr})^{-1}$ at 2.5 km, during winter season (DJF 2012–13). The aerosol layer reaches to the maximum altitude of 5.6 km in the period of MAMJ-2012 and a minimum at 2.8 km in the winter (DJF). The highest value (124 $\mathrm{Mm}^{-1}$) of extinction coefficient is found at 3.3 km, during MAMJ-2012 and minimum (7 $\mathrm{Mm}^{-1}$) at 2.5 km during the winter season. A comparison of ground based LiDAR observations with the CALIPSO satellite derived aerosol backscatter profiles has been carried out for 37 suitable cases. To determine the LiDAR ratio, AOD measurements from MODIS were used as constrain. The mean percent bias for different seasons is found to be $+18 \pm 42\%$, $+22 \pm 28\%$, $+32 \pm 36\%$ and $+18 \pm 51\%$ for MAMJ-2012, SON-2012, DJF-2012–13 and MAM-2013 respectively.



## 1. Introduction

Aerosols play a vital role in the earth's radiation budget, cloud formation and climate change. The measurements of vertical distribution of aerosol are critical to assess the radiative impact of aerosol on the surface and atmosphere (Liu et al., 2012; Kaufman et al., 1997; Pelon et al., 2008). In addition, aerosols influence the lifetime and microphysical properties of clouds, precipitation rates, and tropospheric photochemistry (Towmey, 1977; IPCC, 2001). Due to the presence of distinct aerosol layers, the columnar properties can be entirely different from the surface properties of aerosol (Ramanathan et al., 2001). Considering such an importance, numerous efforts were made from ground based and space borne observations to study aerosol distribution and properties, along with model simulations around the globe, but such studies are very limited over the Indian region particularly those having the information on the vertical distribution of aerosol. Over the Indian regions, satellite based observations have demonstrated very high pollution loadings in terms of aerosol optical depth (AOD), particularly over the Indo-Gangetic Plain (IGP) region. Although integrated columnar properties of aerosols over the central Himalayas have been studied extensively (Sagar et al., 2004; Guleria et al., 2012) but a very limited study on vertical profile exists over

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Himalayan region (Ramana et al., 2004; Hegde et al., 2009, Srivastava et al., 2011a). The study of aerosol vertical distribution is essential in many aspects such as radiative transfer calculations, vertical mixing in the lower troposphere in order to understand aerosol variability and aerosol–cloud interaction. Two recent studies on vertical distribution of aerosol have been reported in the adjoining IGP region by Komppula et al. (2012) and Misra et al. (2012), but results of these studies cannot be implemented over complex terrains such as the Himalayas. Therefore, in this study we attempt to reveal the loading in vertical column, and analyzed a total of 57 night observations in order to understand day-to-day and seasonal variability in the vertical distribution of aerosols over Manora Peak, which is a high altitude regional representative site in central Himalayas (Kumar et al., 2010).

Further, a comparison of the satellite (CALIPSO) retrieved vertical profiles over the central Himalayas with ground based measurement is being studied, as satellite observations provide time constrained observations of aerosol vertical distributions but ground based LiDAR can give information on the evolution of the distribution over a location. Thus, with the aid of a composite study on satellite, ground based observations and transport models; one can extricate the temporal, spatial distribution and the evolution of aerosol on a regional to global scale (Ansmann, 2006). Studies on comparison of CALIPSO data with ground based observations have been reported in several research articles (Mamouri et al., 2009; Pappalardo et al., 2010; Tesche et al., 2013) indicating the utility and importance of the satellite observations and comparison with ground truth at different locations over the globe. Vertical aerosol distribution with CALIPSO measurements over Delhi has been studied by Srivastava et al. (2012) during winter and summer season. However, due to sparsity of the ground-based observations, such comparison with the satellite data is still severely lacking over Himalayan region. This comparison study over such a complex terrain would enable the CALIPSO satellite retrievals to be used with greater confidence over the Himalayas and the adjoining IGP region. This study will also assist in quantifying the impact of pollution on the climate and hydrological cycle of the Himalayas.

## 2. Site description

The observation site Manora Peak (29.36° N, 79.45° E), 1951 m above mean sea level (AMSL), is situated at an aerial distance of about 2 km from the City of Nainital, in the North India as shown in Fig. 1. Observations are being made at the peak of the mountain with steep slopes on the east and west sides. To the south of the peak, mountains gradually decrease in altitude and merge into a small city called Haldwani, whereas in the North and North-East higher altitude mountains create complex topography. Overall image of site reveals the complex terrain of the central Himalayas. The site is free from any major local source of aerosol or anthropogenic activities, hence, considered to be pristine (Sagar et al., 2004), but due to complex topography it has got a local boundary layer (LBL) different from the planetary boundary layer (PBL). The extensive measurements of the LBL height during different seasons over this site are not available. However, the model simulated average planetary boundary layer height at a nearby low altitude site Pantnagar, does not evolve above 1.5 km, except in the spring season when the average PBL or mixed layer height goes up to 4 km

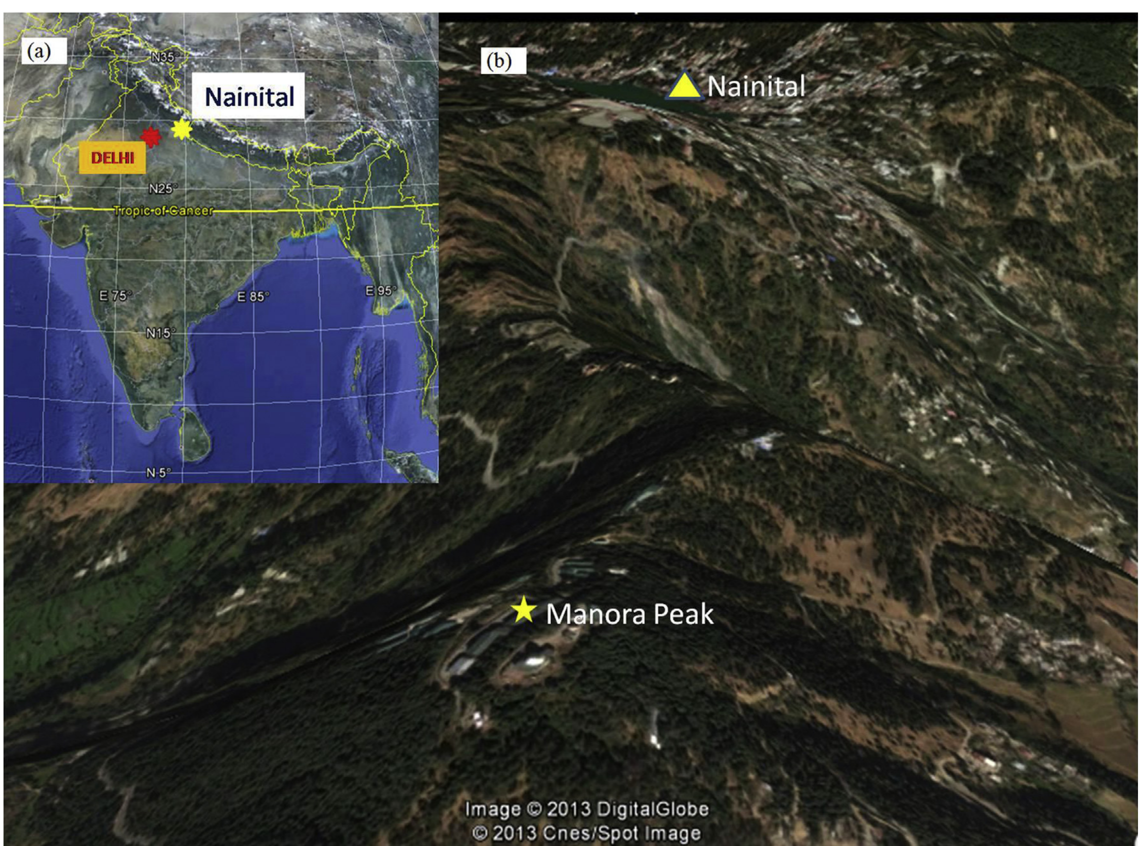


**Fig. 1.** (a) Geographical location (marked by yellow star) of observation site at Nainital and nearest megacity Delhi (marked by red star), on the map of India (b) The topography around observation site Manora Peak, and the city of Nainital, in the Google earth imagery. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)