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Study on the satellite and ground based aerosol measurements over Himalayan region

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Abstract

In this study, the evaluation of satellite retrievals with ground based aerosol measurements and a case study on hygroscopic aerosol transport is discussed. Latest aerosol product levels 1B and 2 (version 4.10) of Cloud-Aerosol LiDAR and Infrared Pathfinder Satellite Observations (CALIPSO) are evaluated with its earlier versions at a regional scale. A marked improvement is observed in the surface detection and tropospheric aerosol classification over the complex mountainous terrain in the latest version. A typical case on the measurements from ground-based sensors, in conjunction with CALIPSO, and reanalysis products is also discussed.

1. Introduction

The anthropogenic sources can alter the climate on regional as well as on global scales [1, 2]. The understanding on their variability over a region may improve the in-situ knowledge of the processes such as the radiation balance, cloud formation, precipitation etc. Rising concerns on climate change demand better insight of the physical and optical properties of aerosols by means of ground and satellite based measurements such as LiDAR, AErosol RObotic NETwork (AERONET), and CALIPSO. The improved understanding on the relationships between ground based and space borne observations is also essential in formulating the reliable current and future predictions [3, 4]. Moreover, the space borne measurements and retrieval algorithms are to be improved from time to time.

Past studies have proven that satellites are the best tool for broader understanding of aerosol parameters on a global scale, however, satellite measurements possess some uncertainties, especially, on the local scale which can be quantified through their assessment with the ground based measurements [5]. Further, the regional climate, particularly, in the mountain regions is being greatly affected due to deleterious anthropogenic interventions. The preliminary assessment of climate change with impact studies have also been reported [6, 7]. Considering the aforementioned facts, an attempt is made to evaluate the latest version of satellite aerosol retrievals from CALIPSO with its earlier version and compared with the ground truth to be useful at the regional scale studies and better understanding the nature of the aerosols.

2. Study region

The observational site [8], Manora Peak (29.36° N, 79.46°E, 1939 amsl) in the Nainital region of Uttarakhand is surrounded by the southern slopes of central Himalayas. This pristine site often influenced by the transport of the pollutants from Indo-Gangetic plains which are towards south as well as from the long range [9-11]. Thus provides a natural laboratory for transport of pollutants and the background measurements of the aerosol parameters.

3. Data and methodology

The CALIPSO satellite is operational since April 2006 and is equipped with a dual wavelength (532 and 1064 nm) polarization LiDAR system referred as Cloud and Aerosol LiDAR with Orthogonal Polarization (CALIOP) for providing the long term database of global aerosol vertical profiles [12]. The researchers worldwide are utilizing the CALIPSO products to a great extent in order to understand the impact of aerosols and clouds on the Earth's radiation budget. To evaluate the CALIPSO/CALIOP product versions (ver. 4.10 and ver. 3.xx) and for further studies, we identified three closest satellite overpasses (within ~80 km distance from the observation site) coinciding with the ground observations: 30 March 2012 (08:06 UTC), 9 December 2010 (20:43 UTC) and 10 November 2011 (20:42 UTC).

The 6-hourly ERA-Interim reanalysis product, are produced from the available atmospheric observations and dynamic models [13], and we utilize it to understand the prevailing meteorological conditions over the site during the period of study.

4. Assessment of CALIOP product versions

CALIPSO mission announced the release of its level 1B ver. 4.00 data product in November 2014 and, level 1B and 2 ver. 4.10 during November 2016, however, the two differ only in the ancillary data sets used for computations. In comparison to the earlier ver. 3.xx (3.01 and 3.02), the quality in ver. 4.10 releases is enhanced with the inclusion of the updated digital elevation map (DEM) from CloudSat and high-quality Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) product [14]. Study on a global scale has reported that the mean relative deviations (MRDs) [11] in the total attenuated backscatter ($\beta'_{532,total}(r)$) provided in ver. 4.xx (4.00 and 4.10), tends to be positive in comparison to the preceding ver. 3.xx products, however, deviations are higher for night as compared to the day time observations [15]. In order to assess the latest data product quantitatively at regional scale, the retrieved CALIPSO overpasses within ~80 km are used for comparative study as presented in **Table 1**. For the days mentioned in the table, $\beta'_{532,total}(r)$ values are higher in level-1B ver. 4.xx than ver. 3.xx, and the relative mean bias and MRD is highest in ver. 4.10 than ver. 3.xx and ver. 4.00 products. Increasing the DEM resolution from 30 to 15 arc seconds in ver.4.10, an enhancement in the surface detectability is also seen. For the number of detected surfaces, the MRDs between ver. 4.10 and other versions are found to be ~1.25 % (30 March 2012) during day-time, and during night-time, it is ~ 2.42 % (10 November 2011) and ~ 2.53 % (9 December 2010).

Table 1. Statistical comparison on different versions of CALIPSO level-1B product.

	Total Attenuated Backscatter 532, $\beta'_{532,total}(r)$			
	Mean bias (Mm^{-1}sr^{-1})		**MRD** (%)	
	v4.1-v3	**v4.1-v4.0**	**(v4.1-v3)/v3**	**(v4.1-v4.0)/v4.0**
30 Mar 2012 (Day)	0.71	0.04	7.1	0.34
10 Nov 2011 (Night)	0.39	0.02	7.8	0.39
9 Dec 2010 (Night)	0.12	0.04	1.6	0.52

A vertical profile of $\beta'_{532,total}(r)$ for a single overpass necessarily may not represent the aerosol subtype. Therefore, to classify the aerosol subtype in the troposphere up to 8 km with 30 m vertical and 333 m horizontal resolutions [16], CALIOP level-2 VFM product ver. 4.10 are examined over ver.3.xx as shown in **Figure 1(a and b)**. The VFM product ver. 4.10 basically identifies the seven major tropospheric aerosol types represented by color codes (**Figure 1(b)**) in contrast to the six aerosol classifications in ver. 3.xx (**Figure 1(a)**). The inclusion of 'dusty marine' in ver. 4.10 is to distinguish it from the clean marine aerosol, and is applicable for the cases where the marine aerosols are contaminated with dust and anthropogenic pollution. The changes in the nomenclatures from 'polluted continental' and 'smoke' in ver. 3.xx to 'polluted continental/smoke' and 'elevated smoke', respectively in ver. 4.10 are to overcome the misclassification observed under certain circumstances as reported in earlier studies [17]. In **Figure 1(b)** particularly between (29.89°N, 80.07°E) and (17.33°N, 77.03°E), the actual transitions between aerosol types is accurately reflected in ver. 4.10. The improvements can be attributed to the major changes in the retrieval algorithms used in ver. 4.10 for tropospheric aerosols subtyping.

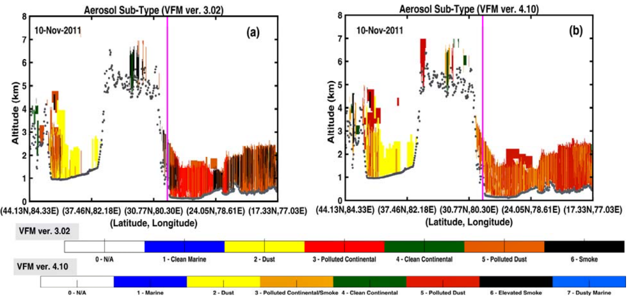

Figure 1. CALIOP VFM profiles obtained from CALIPSO (a) version 3.02, and (b) version 4.10 for 10 November 2011 (20:38:35 – 20:46:01 UTC).

5. AERONET measurements

In coincidence to the CALIPSO overpass days, the diurnal variations in the AERONET [18] measured aerosol optical depth (AOD) at 500 nm, temporal variation of AE in the wavelength band of 440 - 870 nm, angstrom exponent (AE) along with columnar water vapor content derived from 935 nm channel are studied and presented in **Figure 2(a-c)**. The AE is an indicator of average aerosol concentrations which are broadly distributed between fine (AE > 1) and coarse (AE ≤ 1) mode particles. AE > 1.5 is an indication of intensive fine mode aerosols. However, both modes of aerosols coexist but with the seasonal dominance of the one over the other (**Figure 3**).

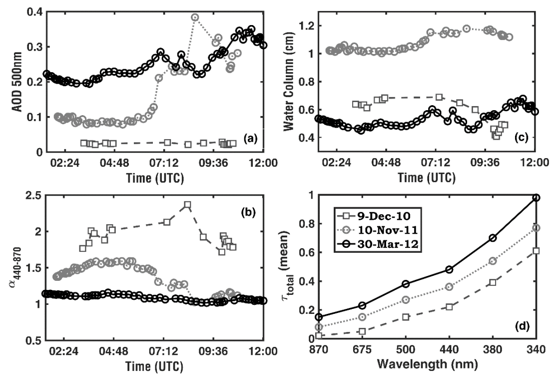

Figure 2. AERONET measured (a) AOD at 500 nm, (b) AE at 440-870 nm, (c) columnar water vapor content, and (d) total aerosol optical thickness in the spectral range from 340 - 870 nm, for 9 December 2010, 10 November 2011 and 30 March 2012.

A strong diurnal variability in the afternoon hours (06:00-08:00 UTC, LT =UTC +05:30 hours) is observed on 30 March 2012 (30M12) and 10 November 2011 (10N11) in AOD and columnar water vapor with an increasing trend that approaches to a maximum thereafter. Since the site is located at the ridge top, therefore enhancement in the

AOD values on these days may be due to the dominance of slope winds, flowing during daytime hours that would have brought the aerosols and the pollutants from the adjoining plains and nearby valleys to the site. The details have been presented elsewhere [11]. Here we are discussing the case of 09 December 2010 (9D10), which may be considered for the intensive transport of fine mode particles marked with the presence of hygroscopic aerosols and have resulted into the formation of clouds with the inflow of moist air.

On 9D10, the AOD values are quite low with peak value of ~0.03 at 09:30 UTC, until then there exists an opposite trend between the AOD and columnar water vapor. The rapid rise in the AE between 08:00 and 09:00 UTC is also seen this day, which surpasses even a maximum of 2. This extremely high AE value indicates the presence of intensive fine mode particles that might have been produced elsewhere and transported to the site by winds. To understand the mechanism behind extremely low AOD and extremely high AE on 9D10, a thorough investigation is also included in the subsequent section. The total optical thickness ($\tau_{total} = \tau_{aerosol} + \tau_{Rayleigh} + \tau_{gaes} + \tau_{cloud}$) typically decreases with increasing wavelengths, and the same is noticeable in **Figure 2(d)**. The total optical thickness variations on 10N11 are also on the higher side, and on 9D10 it is found to be the lowest.

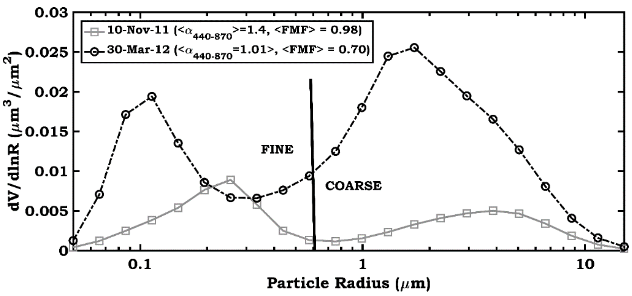

Figure 3. AERONET derived volume particle size distributions for 10 November 2011 and 30 March 2012.

6. An emphasis to the case of 9 December 2010

The aerosol variations are inherently linked with the meteorological parameters such as temperature, humidity, wind speed etc. and the presence of hygroscopic particles at occasions may lead to the formation of clouds as well. In contrast to the episodes of continental and long range transport of aerosols [11], one such case observed on 9D10, is discussed here. The diurnal cycle of AOD at 500 nm (**Figure 2(a)**) does not show any pronounced variability, and AOD values remain low and almost same over the day. However, the AE increases with the advancement of day and reaching to a maximum in the afternoon about 01:00 hour LT, and thereafter a decrease is observed until evening (**Figure 2(b)**). It indicates that the influence of the transport of aerosols mostly of fine and, coarse mode nature is negligible. Hence, the ultra-fine particles of local origine under high humidity conditions seems to be contributing in the formation of localized cloud on the day, which during evening hours dissipates and moisture settles down, thereby, marking a very low water column as shown by **Figure 2(c)**.

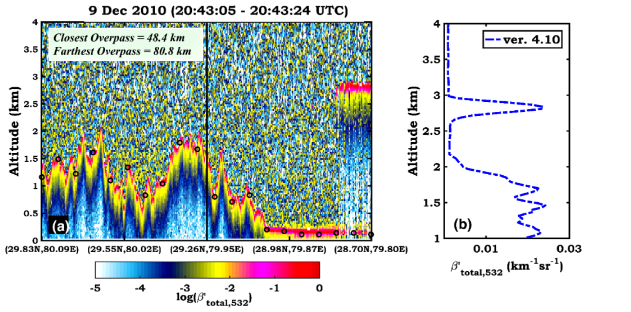

Figure 4. CALIPSO (a) vertical distribution (log scale), and (b) average profile (linear scale) of 532-nm total attenuated backscatter ($\beta'_{532,total}(r)$) for the overpass distance up to 80 km observed on 9 December 2010 during 20:43:05 to 20:43:24 UTC.

The CALIPSO/CALIOP total attenuated backscatter profile (**Figure 4(a** and **b)**) on 9D10 confirms the existence of a thin cloud during midnight (20:43 UTC) at ~3 km altitude in the nearby areas. To check for the diurnal pattern, the meteorological parameters obtained from ERA-Interim data for the closest coordinate (29.5°N, 79.5°E) between 800-400 hPa pressure levels, corresponding to the vertical structure up to about 7 km are analysed and presented in **Figure 5**, which shows the mean and SD of 6-hourly temperature, humidity, wind velocity and cloud water contents for 9D10. ERA-Interim has adopted the meteorological convention for winds with U component positive for eastward wind (West to East) and, V component positive for northward wind (South to North).

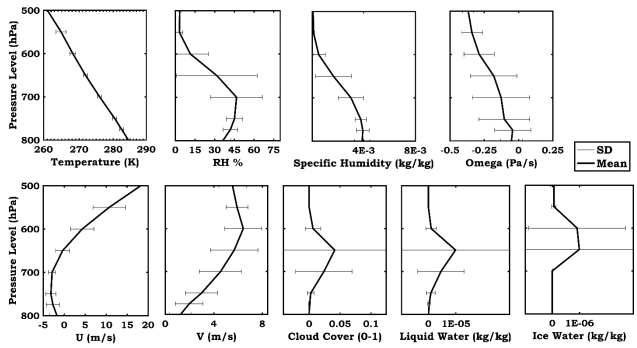

Figure 5. Meteorological conditions on 9 December 2010 derived from ERA-Interim 6-hourly reanalysis product for the coordinate (29.5°N, 79.5°E).

The relative humidity (RH) depicts wide variations between 700-600 hPa (around 3 km to 4.2 km), showing the high and low values of 72.2 % (06:00 UTC) and 0.3% (12:00 UTC), respectively. The negative trend in the vertical velocity (omega) with pressure level on this date confirms the rising motions that have played an important role in the formation of cloud as observed in **Figure 5**, with cloud index and a maxima in liquid water content between 3 and 4 km. Moreover, the zone of uplifts in coincident with the high RH is very favourable for convective cloud development as evident in the vertical profiles of cloud water contents (both liquid and ice).

7. Conclusion

Latest release of CALIPSO aerosol product, with the improved merits, is assessed over Himalayan region and utilized to resolve the aerosol properties at the regional scales. A typical case is discussed in details utilizing the reanalysis data, AERONET products, and satellite measurements. The satellite products assessed over this region may widely be utilized globally by the researchers working on the dynamics and transport of pollutants, to high altitude sites of similar topography.

8. Acknowledgements

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9. References

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