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Evaluation of cloud base height measurements from ceilometer CL31 and MODIS satellite over Ahmedabad, India

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Abstract

Clouds play a tangible role in the Earth's atmosphere and in particular, the cloud base height (CBH) which is linked to cloud type is one of the important characteristic to describe the influence of clouds on the environment. In present study, CBH observations from ceilometer CL31 have been extensively studied during May 2013 to January 2015 over Ahmedabad (23.03° N, 72.54° E), India. A detail comparison has been performed with the use of ground-based CBH measurements from ceilometer CL31 and CBH retrieved from MODIS (Moderate Resolution Imaging Spectroradiometer) onboard Aqua and Terra satellite. Some interesting features of cloud dynamics viz. strong downdraft and updraft have been observed over Ahmedabad which revealed different cloud characteristics during monsoon and post-monsoon periods. CBH shows seasonal variation during Indian summer monsoon and post-monsoon period. Results indicate that ceilometer is one of the excellent instruments to precisely detect low and mid-level clouds and MODIS satellite provides accurate retrieval of high-level clouds over this region. The CBH algorithm used for MODIS satellite is also able to capture the low-level clouds.

1 Introduction

Cloud, a visible mass of tiny water droplets or frozen ice crystals, is one of the most crucial parameters for weather and climate prediction. Kiehl and Trenberth (1997) showed the importance of clouds on the global energy budget. Accurate information of cloud cover is essential for better understating of the climate system (Fontana et al., 2013). Randall et al. (1984) observed that 4 % increase in the cloud cover with stratocumulus can compensate the global warming due to CO_2 doubling. The types of low level clouds and their development are governed by meteorological conditions especially in the atmospheric boundary layer such as vertical stability (Norris, 1998). Koren et al. (2010) discussed that aerosols affect clouds which contribute to climate change. Andrejczuk

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et al. (2014) found that cloud albedo may increase as a result of the seeding, if enough aerosols are delivered into the cloud. Kokhanovsky et al. (2007) discussed that the global cloud top height is near to 6 km. Li and Min (2010) showed the impact of mineral dust on tropical clouds which is dependable on rain type. Varikoden et al. (2011) studied cloud base height (CBH) over Thiruvananthapuram during different seasons and found diurnal and seasonal variations except rainy days. Zhang et al. (2010) deployed AMF (ARM Mobile Facility) for radiosonde in Shouxian, China and showed that the diurnal variation in upper-level clouds thickness is larger than low-level clouds over this region.

Space based instruments are widely used to detect clouds globally at high spatial and temporal resolution. Various scientific studies have been performed to retrieve clouds information which needs further evaluation with ground observations. In night time, CBH can be retrieved accurately using Visible Infrared Imaging Radiometer Suite (VIIRS) algorithms (Hutchison et al., 2006). Meerkotter and Zinner (2007) used an adiabatic algorithm to find CBH from satellite data for convective cloud. Weisz (2007) suggested various algorithms and methods to measure cloud height from space borne instruments. The ability to determine the cloud top/bottom height is still limited due to the nature of infrared-based passive measurements from satellites (Kim et al., 2011). Bhat and Kumar (2015) used precipitation radar measurement to detect vertical structure of cumulonimbus and convective clouds over south Asian region. Gu et al. (2011) used Scale Invariant Features Transform (SIFT) algorithm to detect clouds from MODIS satellite without manual interference.

Lidars have been widely used for both atmospheric boundary layer structure and cloud-base detection (Mariucci et al., 2007; Albrecht et al., 1990). Liu et al. (2015) used two ceilometers (CL31, CL51) and whole-sky infrared cloud-measuring system (WSIRCMS) and found significant differences in CBH due to retrieval algorithm or measurement principle. The Cloud-Aerosol Lidar and Pathfinder Satellite Observations (CALIPSO) observations are used to understand the global clouds distribution, cloud statics and the effect of clouds on the radiation budget (Rasmussen et al., 2002; Wu

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et al., 2011; Winker et al., 2003). Pal et al. (1992) demonstrated an algorithm to retrieve cloud top height and CBH from Nd: YAG Lidar. Duynkerke and Teixeira (2001) determined cloud cover with stratocumulus using observations obtained from the Regional Experiment of International Satellite Cloud Climatology (ISCCP-FIRE1) Project. Clothiaux et al. (2000) used multiple active remote sensors like Belfort or Vaisala ceilometer and a micro pulse Lidar to find CBH.

Kotarba (2009) evaluated MODIS (Moderate Resolution Imaging Spectroradiometer) derived cloud amount data with visual surface observations over Poland region. Forsythe et al. (2000) compared cloud information retrieved from GOES-8 geostationary satellite with surface observation. Stefan (2014) used both ceilometer and satellite data to detect clouds and found that low-level clouds are better capture by ceilometer and for high-level clouds satellite provide better information. Albrecht et al. (1990) used sodar, ceilometer and microwave radiometer all together to estimate cloud thickness. Kassianov et al. (2005) estimated CBH from hemispherical surface observations and validated against micropulse Lidar (MPL) observations.

Recently, Physical Research Laboratory (PRL) installed ceilometer CL31 over Ahmedabad, India. The objective of this study is to evaluate the performance of satellite derived cloud features with this ground based cloud measurements. Detail investigations of cloud base retrieved from MODIS satellite is compared with ceilometer measurements during 2013 to 2015.

2 Data used

2.1 Ground observations from ceilometer

The ceilometer Lidar set up at PRL, Ahmedabad (23.03° N, 72.54° E, 55 m a.m.s.l.; Fig. 1) consist of a vertically pointing laser and a receiver at the same location. Ceilometer CL31 employs pulsed diode laser InGaAs (Indium Gallium Arsenide) Lidar technology. The transmitter is an InGaAs pulsed laser diode, operating at a wavelength

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of 910 nm (±10 nm) with the peak power of 11 W typically. The receiving unit is a Silicon Avalanche photodiode with an interference filter having center wavelength at 915 nm and surface diameter is 0.5 mm. Receiver bandwidth is 3 MHz and 80 % of transmissivity at 913 nm. The focal length of the optical system is 300 mm with lens diameter of 96 mm. The model CL31 has the maximum reportable cloud base detection range of 7500 m above the surface with the reporting interval of minimum 2 s to maximum 120 s. It can be used in the temperature range of −40 to +60 °C. The technical specifications of the system are provided in Table 1. The single lens eye-safe Lidar ceilometer reported CBH at three layers and vertical visibility at lower altitudes regularly. To obtain the height of cloud base, a laser pulse is sent through the atmosphere. This light pulse is scattered by aerosol particle. A component of this scattered light is received back by Lidar receiver. The received backscattered profile are used to detect CBH. "CL view" software is used here for data handling and visualization purposes.

2.2 MODIS retrieved clouds

The MODIS is a scientific instrument launched by NASA (National Aeronautics and Space Administration) into the Earth's orbit on board two satellites Terra in 1999 and Aqua in 2002. It uses 36 spectral bands between wavelength of 0.41 and 14.2 µm (Xiong et al., 2004) and scans a cross-track swath of 2330 km. These bands are divided into four separate focal plane assemblies viz. Visible, Near Infrared, Short-Wave Infrared, Mid-Wave Infrared, and Long-Wave Infrared. MODIS provides measurements of large-scale global dynamics, including cloud cover, radiation budget and the process occurring in the lower atmosphere at 5 km spatial resolution. The cloud detection algorithm is mainly based on the multispectral analysis of clouds. Reflectance and radiation of clouds are different from the earth's surface in Visible and Infrared band spectrum. Following five bands viz. CH1 (0.620–0.670 µm), CH2 (0.841–0.876 µm), CH26 (1.360–1.390 µm), CH29 (8.400–8.700 µm) and CH31 (10.780–11.280 µm) band in near infrared/visible and thermal infrared are used for cloud spectrum (Gu et al., 2011).

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2.3 Methodology

The present study focuses on the most important features of temporal variability of cloudiness over Ahmedabad during May 2013 to January 2015, using cloud data retrieved from MODIS satellite, in conjunction with cloud observations from ceilometer. The location map of Ahmedabad region and a photograph of the Ceilometer CL31 are shown in Fig. 1. The ceilometer data set contains three consecutive heights of multi-layer clouds and backscatter coefficients (Martucci et al., 2007, 2010). The MODIS satellite products MOD06_L2 (Hirsch et al., 2010) contain the data from the Terra satellite, and the "MYD06_L2" files contain data from the Aqua satellite platform are used in this study. The day time passes of MODIS satellite over Ahmedabad region are only used in this study. For comparison purposes, MODIS satellite data are used directly if lies within 0.1° radius from in situ locations. Ceilometer data has very high temporal frequency, because of this suitability ceilometer data exist near MODIS pass are used for comparison purposes.

2.4 Cloud Base Height detection algorithm

For water clouds, CBH is measured using Cloud Top Height (CTH) and Cloud Geometrical Thickness (CGT; Meerkotter and Bugliaro, 2009). CGT is derived from two parameters, Liquid Water Path (LWP) which is obtained from the Cloud Optical Thickness (t) and cloud effective radius (reff; $\mathrm{g\,m^{-2}}$) and liquid water content (LWC), where LWC is the integration of cloud size distribution over droplet size and has units of $\mathrm{g\,m^{-3}}$ (Hutchison, 2002). The value of LWC varies according to the types of cloud.

$$\mathrm{CBH} = \mathrm{CTH} - \mathrm{CGT} \tag{1}$$

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where,

$$CGT = \frac{LWP}{LWC}, \quad (2)$$

$$LWP = \frac{2 \times t \times \text{reff}}{3}. \quad (3)$$

Here, t is cloud optical depth and reff is cloud droplet effective radius.

The value of LWC varies between about 0.03–0.45 $g\,m^{-3}$ (Hess et al., 1998; Rosenfeld and lensky, 1998). This algorithm of CBH is restricted to day-time data only, because the cloud optical thickness and effective radius are available only in sunlit regions of the Earth (Hutchison, 2002).

3 Results and discussions

This study investigates cloud analysis over Ahmedabad region using ceilometer measurements and MODIS satellite retrieved cloud parameters. The scanning frequency of MODIS satellite above Ahmedabad region is twice per day, whereas, ceilometer provides ~ 100 % monthly coverage at high temporal resolution. The number of observations was 379 days during 2013 to 2015. Figure 2 shows the sample vertical backscattering profile for different days and times. In Fig. 2a, the maximum backscattering is seen at 7220 m on 6 June 2013 at 02:00:02 IST which shows the availability of high level clouds. Figure 2b shows detection of multi-layer clouds in which low-level and mid-level clouds appear together. The peak backscattering is at 4000 m, which provides us information about mid-level cloud as found in Fig. 2c. In Fig. 2d, the maximum backscattering is seen at 2000 m, which gives low-level clouds information.

Figure 3a shows the detection of multi-layer clouds using ceilometers instrument. In this figure, both the intensity and back scattering profile and three layers of clouds with a corresponding height of 384, 1800 and 2000 m are seen at 15:29:50 IST. Figure 3b shows multi-layer clouds detection for 2 August 2014. The strong updraft and downdraft can be seen in lower panel of Fig. 3b. Continuous updraft and downdraft can be found from 1 km height to 3 km height till 18:00 IST. Strong downdraft was seen from 13:44 to 13:51 IST with the velocity of 2.1 m s^{-1}, and strong updraft was observed from 16:36 to 16:51 IST with the velocity of 1.8 m s^{-1}. On 22 July 2013 from 03:00 to 04:00 IST, ceilometer detected multi-layer cloud which move with almost constant velocity (figure not shown). At 03:21 IST, the corresponding backscatter profile in which maximum backscattering seen at 320 and 3520 m which provides information about low-level and mid-level clouds. Similarly, on 25 July 2015 (01:00 to 02:00 IST) and 1 August 2015 (16:00 to 18:00 IST), low-level clouds appear at 1 to 0.86 km respectively and second layer of cloud (CBH2) is seen from the backscattering at 3.5 to 3.13 km respectively. These investigations from continuous CBH measurements at high temporal resolution (every 2 s) show that ceilometer is able to capture the multi-layer clouds, which may be an important input for various meteorological applications. With the use of very high temporal resolution CBH observations from ceilometers, CBH shows an updraft over Ahmedabad region on 1 January 2015 between 14:00 to 16:00 IST. Ceilometer also captured the two-layer low-clouds at 201 and 1316 m on 25 July 2013 and corresponding backscatter values show peak at same heights. The ceilometers detect three layers of clouds on 30 October 2014 at 22:40 IST and shows the capability of instrument to measure multi-layer clouds. From these experiences to detect multi-layer clouds at different altitudes, we can state that ceilometer provides better information of the low and mid-level clouds. Recently, Stefan et al. (2014) have used similar ground based instrument to study cloud cover over Măgurele, Romania and compared with MODIS satellite. These results infer that ceilometer observed low- and mid-level clouds are very precise and high-level clouds can be accurately detected by satellite. The comparison has been made between Ceilometer and MODIS satellite in Fig. 4, which shows the cloud cover over Ahmedabad region for three different days.

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3.1 Comparison of cloud heights from Ceilometer and MODIS

In this section, the cloud top height retrieved from passive remote sensor viz. MODIS and active remote sensor viz. Ceilometer (Naud et al., 2003) are compared for cloud detection (Fig. 5). Firstly in last section, for comparing the accuracy of the ceilometer retrievals, the CBHs derived from the active remote sensor Ceilometer are presented. Ceilometer has confirmed its ability to operate throughout the year, taking continuous measurements of the lowest CBH as found by Costa-Surós et al. (2013). The cloud detection from MODIS and ceilometer are compared to show the difference between the passive remote sensor and the active remote sensor. Ceilometer can detect three cloud layers simultaneously. As found in Table 2, the different measurements are used for comparison between satellite and ceilometer. Figure 5a shows that on 20 July 2013 between 14:00 to 15:00 IST, the CBH is 1 km. At 14:40 IST the ceilometer detect clouds at 786 m and MODIS at 11 250 m that indicates that MODIS provides the information about high level cirrus cloud and ceilometer provide the information about low level cloud. Figure 5b shows that cloud moved with almost constant velocity from 14:20 to 14:30 IST on 25 July 2014 and CBH detected by ceilometer is 1920 m. Cloud top height from MODIS satellite is 4250 m which shows the mid-level clouds and by applying algorithm CBH is calculated as 2200 m. So, the difference between base height measured by ceilometer and MODIS is $\sim$ 130 m. Multilayer clouds appear in Fig. 5c by ceilometer from 02:00 to 04:00 IST. It shows the beauty of this instrument to detect the three layers of clouds and MODIS provides CTH at 3400 m. Here, CBH algorithm for MODIS satellite is not applicable due to non-availability of cloud optical thickness and effective radius. Figure 5d shows that on 1 January 2015 from 14:00 to 16:00 IST multi-layered clouds appeared with the height of around 1 km and layer 2 appeared at around 1.5 km for first 15 min. The continuous updraft of cloud from 1 to 2 km till 16:00 IST was observed. At common point (at 14:25 IST), the CBH by ceilometer is 1097 m and CTH provided by MODIS is 2000 m and from the algorithm CBH is calculated as 1093 m, which is almost same as CBH measured by ceilometer. Therefore, it can be concluded

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that for low level clouds this algorithm is fine. The cloud cover for monsoon and post monsoon periods during 2014 was also studied and found the variation of CBH with rain and without rain.

3.2 Cloud characteristics during Monsoon

3.2.1 Rainy clouds

On 5 September 2014 from 11:00 to 12:00 IST ceilometer detected low level clouds which move with almost constant velocity. At 11:55 IST, the ceilometer detects the CBH at 820 m, which show the availability of low level clouds and MODIS detect CTH is 4250 m provide information about mid-level clouds. On that day, rainfall amount was reported as 21 mm shown in Fig. 6a.

3.2.2 Heavy rain

On 30 July 2014, low level clouds were detected which move with almost constant velocity. At 11:35 IST, CBH measured by ceilometer is 400 m and CTH retrieved by MODIS is 10 900 m, which provides information on high level cloud. On that day, rainfall amount was 207 mm which is the maximum, as shown in Fig. 6b.

3.2.3 Non-rainy clouds

On 15 September 2014 from 10:00 to 11:00 IST, cloud over the Ahmedabad region from ceilometer is shown in Fig. 6c. It detects CBH 900 m, which is low level clouds and CTH retrieve from MODIS satellite is 1250 m.

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3.3 Cloud characteristics during Post-Monsoon

3.3.1 Rainy clouds

On 15 November 2014 strong updraft and downdraft have been observed. Clouds moved downward with velocity of 14.79 $\mathrm{m\,s^{-1}}$ from 16:51 to 16:56 IST and move upward with velocity of 15.13 $\mathrm{m\,s^{-1}}$ from 17:08 to 17:15 IST as shown in Fig. 7a.

3.3.2 Non-rainy clouds

Figure 7b shows that on 30 October 2014 from 02:00 to 03:00 IST high level cloud is detected from ceilometer over the Ahmedabad region. Between 02:26 to 02:41 IST, ceilometer shows clear sky and cloud top height detected by MODIS is 9000 m. Higher level clouds are much better detected in the satellite data than in ceilometer due to power limitation, it can detect maximum up to 7.5 km.

4 Conclusions

For the first time, cloud characteristics have been produced over Ahmedabad for the total cloudiness as a physical parameter, using observations from ceilometer CL31 and MODIS satellite. The study of cloud types and cloud cover fraction (total cloudiness) at Ahmedabad during May 2013–January 2015 has shown the following findings: (1) some strong downdraft and updraft have been found. Clouds moved downward with velocity of 14.8 $\mathrm{m\,s^{-1}}$ and upward with velocity of 15.1 $\mathrm{m\,s^{-1}}$ on 15 November 2014. (2) CBH shows variations during south-west monsoon and post monsoon period. (3) The ground measured cloudiness due to low-level and mid-level clouds are obviously higher than the one determined by satellite. Overall, ceilometer provides information, up to three layers of clouds which is not possible to detect from MODIS satellite. Satellite only provides the cloud top height, moreover satellite give information about cloud height twice in a day when it passes over the Ahmedabad region, but ceilometer pro-

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vide regular (high temporal frequency) and real time information. The low level cloud is not accurately detected by satellite as shown in the observation table, whereas satellite provides information about high level cloud. The high-level clouds are accurately captured by satellite data compared to ceilometer measurements due to the power limitation of ceilometer because of that it can measure up to 7.5 km. The comparison of the cloud cover from satellite observation with the one from ground based observation suggests that, the low and mid-level cloud is much better and accurately detected by the ceilometer CL31 ground based instrument than the satellite and satellite provide better information about high level cloud. Also, it is important to note here that the CBH algorithm is valid for low level cloud but mostly fails due to the absence of cloud optical thickness and effective radius. Finally, the cloud detection can be obtained by the combination of ground based observations and satellite observations which can be used for further weather modeling purposes which need accurate cloud information to initialize the numerical model.

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Table 1. Technical specification of ceilometer CL31.

Property	Dexcription/Value
Laser source	Indium Gallium Arsenide (InGaAs) Diode Laser
Center wavelength	910 ± 10 nm at 25 °C (77 °F)
Operating Mode	Pulsed
Energy	1.2 µW s ± 20 % (factory adjustment)
Width, 50 %	110 ns typical
Repetition rate	10.0 kHz
Average power	12.0 mW
Max Irradiance	760 W cm^{-2} measured with 7 mm aperture
Laser classification	Classified as Class 1M laser device
Beam divergence	±0.4 mrad × ±0.7 mrad
Receiver Detector	Silicon Avalanche Photodiode (APD)

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Table 2. Comparison between ceilometer and MODIS satellite measured clouds.

S. No.	Date/Time	Ceilometer Data Height (m)	MODIS Data CTH (m)	MODIS Data CBH (m)
1	1 Jan 2015 14:25	1097.3	2000.0	1093.4
2	20 Jul 2014 20:40	1078.9	250.0	NA
3	21 Jul 2014 02:15	1911.1	NA	NA
4	25 Jul 2014 13:45	685.8	3100.0	NA
5	26 Jul 2014 02:35	2487.2	3400.0	NA
6	25 Jul 2014 14:25	1920.0	4250.0	1955.5
7	30 Jul 2014 11:35	440.0	10 900.0	NA
8	5 Sep 2014 11:55	630.0	4250.0	NA
9	15 Sep 2014 10:55	1680.0	1250.0	NA
10	20 Jul 2013 14:40	786.4	11 250.0	NA
11	21 Jul 2013 02:50	7141.5	13 700.0	NA
12	21 Jul 2013 13:45	896.1	750.0	NA
13	22 Jul 2013 01:45	429.8	14 100.0	NA

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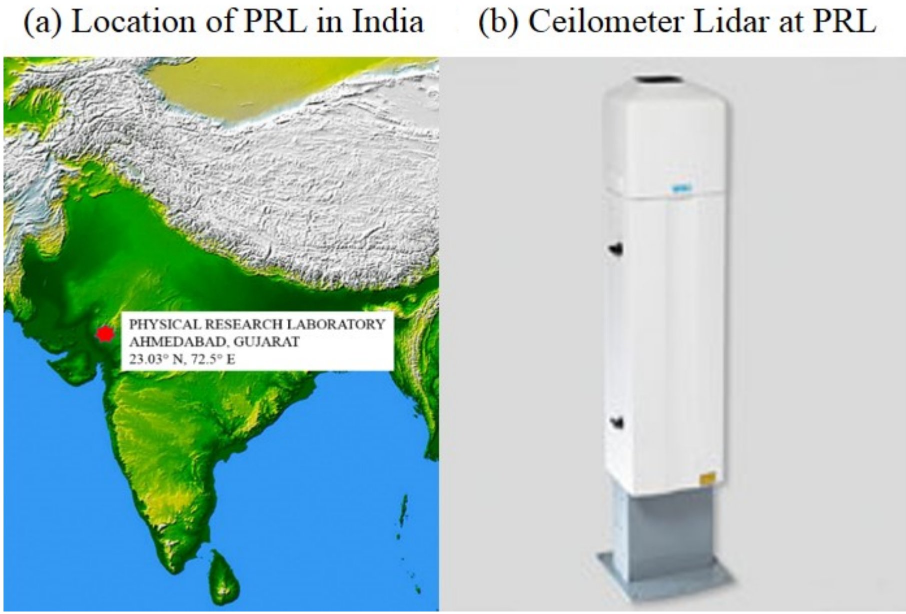

Figure 1. (a) Location of Ahmedabad (23°03′ N, 72°40′ E, 55 m a.m.s.l.) where Ceilometer CL31 is installed and **(b)** a photograph of the Vaisala ceilometer instrument.

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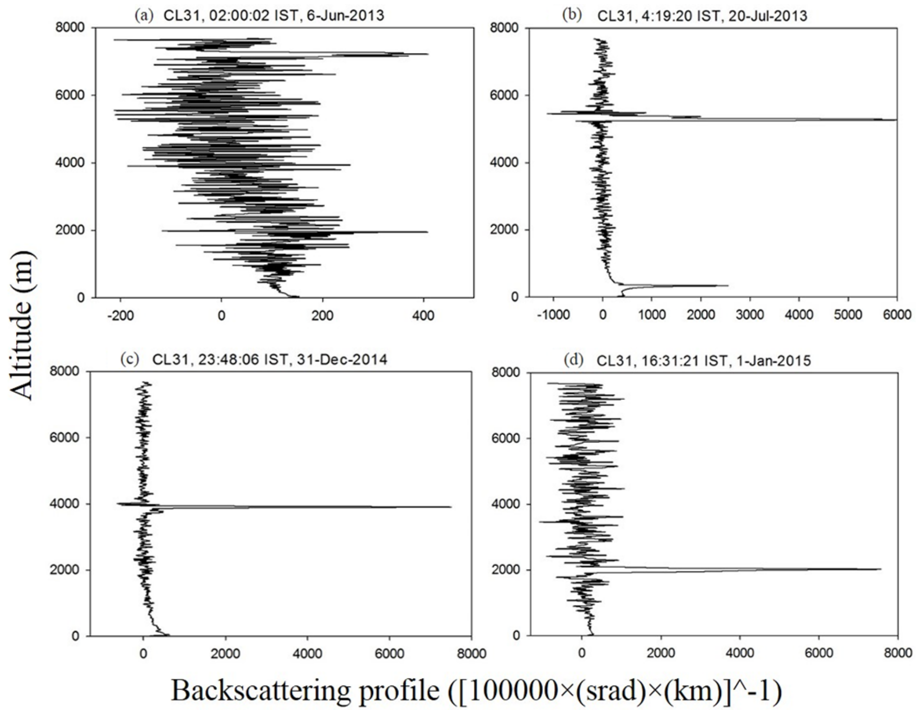

Figure 2. Vertical profile of backscatter data for different days **(a)** 6 June 2013 at 02:00:02 IST, **(b)** 20 July 2013 at 04:19:20 IST, **(c)** 31 December 2014 at 23:48:06 IST, and **(d)** 1 January 2015 at 16:32:21 IST from ceilometer CL31 over Ahmedabad, India.

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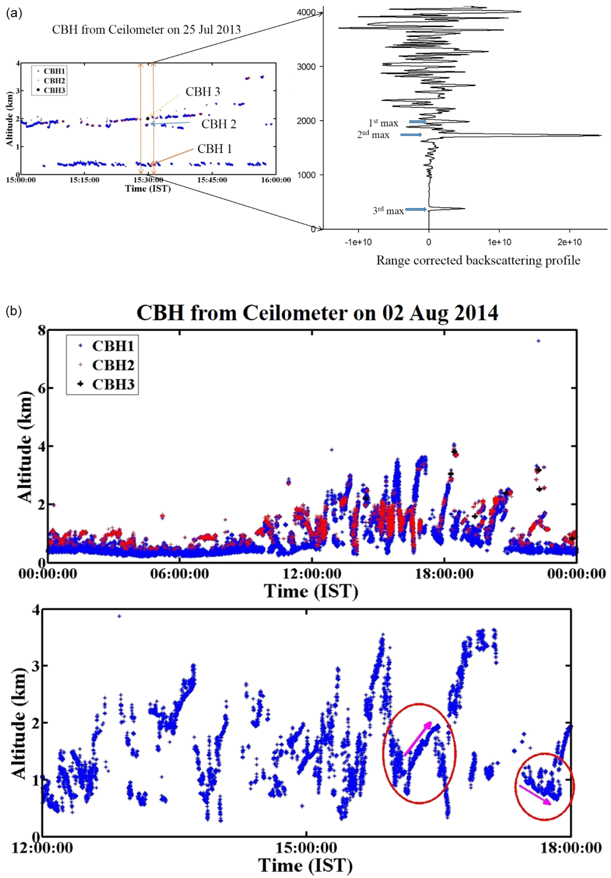

Figure 3. (a) Cloud intensity with range corrected backscattering profile for multi-layer cloud detection on 25 July 2013 at 15:29:50 IST. **(b)** Evolution of three layers CBH measured from Ceilometer on 2 August 2014 (upper panel) along with strong updraft and downdraft (lower panel) for same day.

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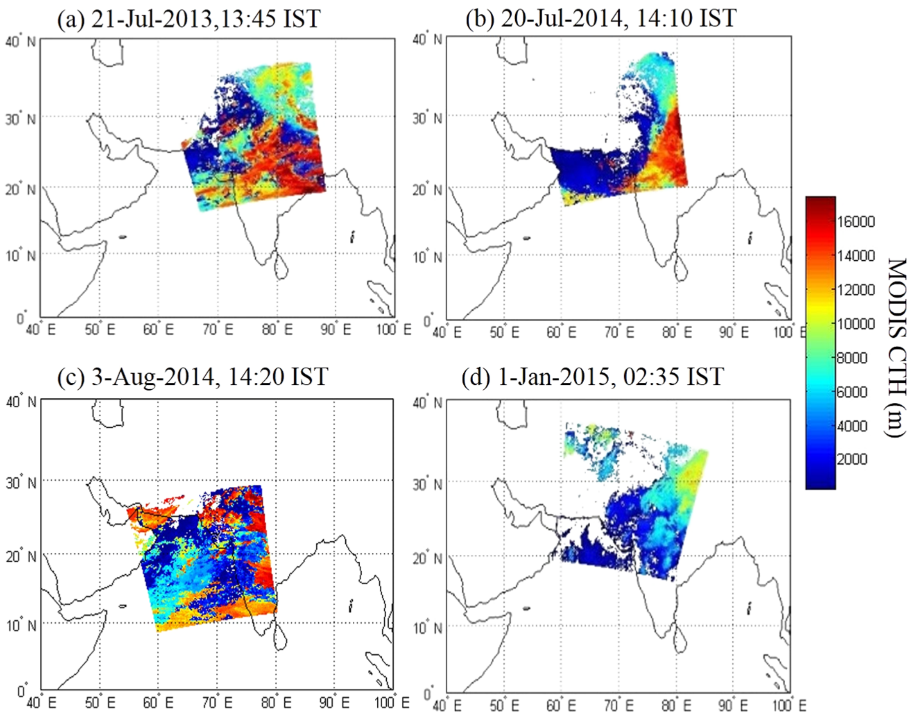

Figure 4. MODIS satellite retrieved cloud top height for **(a)** 21 July 2013, **(b)** 20 July 2014, **(c)** 3 August 2014, and **(d)** 1 January 2015 over Ahmedabad, India.

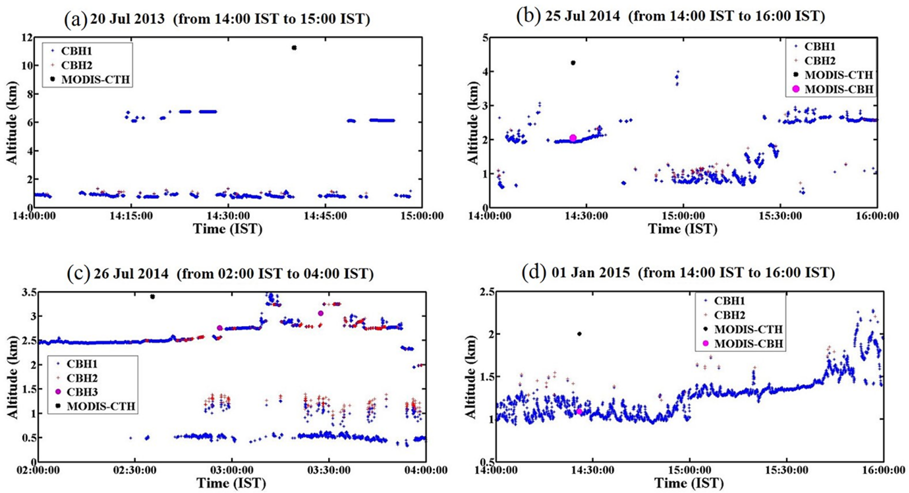

Figure 5. Comparison between Cloud top height and CBH derived from MODIS and measured base height from ceilometer CL31 over Ahmedabad region.

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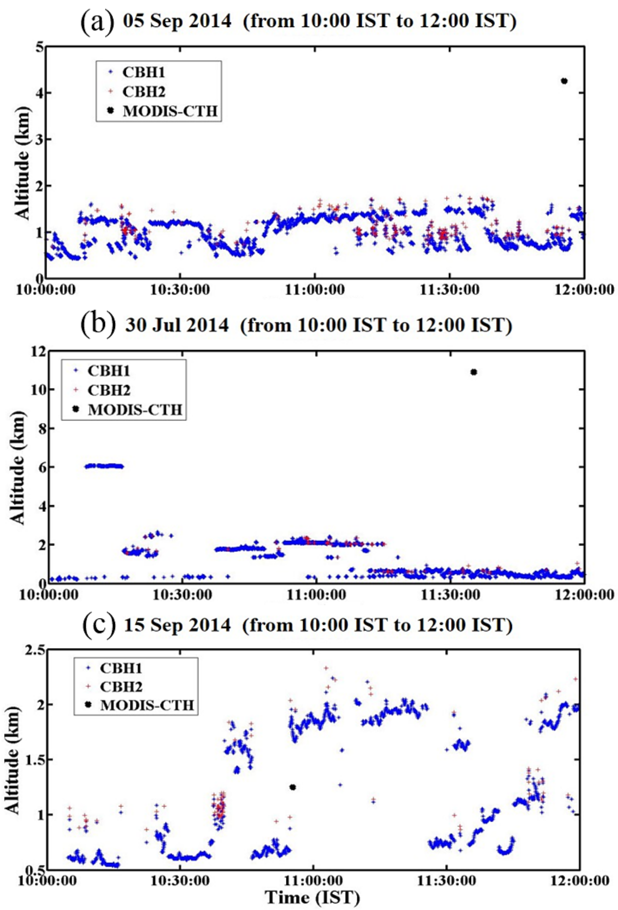

Figure 6. Comparison between cloud top height derived from MODIS, and CBH observed from the ceilometer during monsoon season over Ahmedabad region during sample days for **(a)** normal rain, **(b)** heavy rain, and **(c)** no rain cases.

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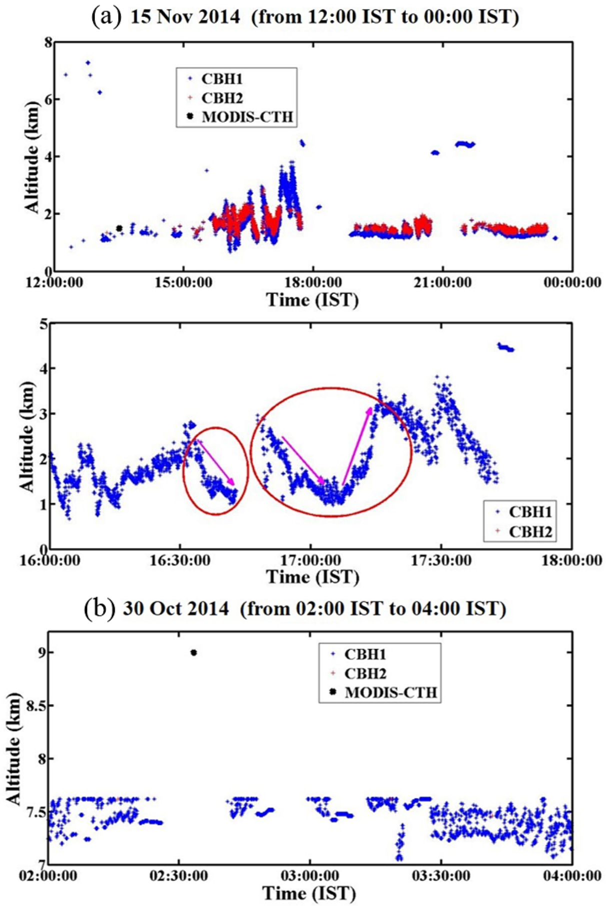

Figure 7. Comparison between cloud top height derived from MODIS, and CBH observed from the ceilometer during monsoon season over Ahmedabad region during sample days for **(a)** rain, and **(b)** no rain cases.

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