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Atmospheric Measurement Techniques

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 most important characteristics to describe the influence of clouds on the environment. In the present study, CBH observations from Ceilometer CL31 were extensively studied during May 2013 to January 2015 over Ahmedabad (23.03° N, 72.54° E), India. A detailed 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. CBH retrieved from MODIS is ∼ 1.955 and ∼ 1.093 km on 25 July 2014 and 1 January 2015 respectively, which matches well with ceilometer-measured CBH (∼ 1.92 and ∼ 1.097 km). 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 the Indian summer monsoon and post-monsoon period. Results indicate that the ceilometer is an excellent instrument to precisely detect low- and mid-level clouds, and the MODIS satellite provides accurate retrieval of high-level clouds over this region. The CBH algorithm used for the MODIS satellite is also able to capture the low-level clouds.

1 Introduction

Clouds, visible masses of tiny water droplets or frozen ice crystals, are one of the most crucial parameters for weather and climate prediction (Bauer et al., 2011; Errico et al., 2007; Shah et al., 2010). 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 a 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 contributes to climate change. Andrejczuk 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 (CTH) is near to 6000 m. 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 (8.4° N, 76.9° E), India, during different seasons and found diurnal and seasonal variations except rainy days. Zhang et al. (2010) deployed AMF (ARM Mobile Facility) for radiosondes in Shouxian, China, and showed that the diurnal variation in upper-level clouds thickness is larger than that of 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 informa-

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tion on clouds, which needs further evaluation with ground observations. At nighttime, CBH can be retrieved accurately using Visible Infrared Imaging Radiometer Suite algorithms (Hutchison et al., 2006). Meerkötter and Zinner (2007) used an adiabatic algorithm to find CBH from satellite data for convective clouds. 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 the south Asian region. Gu et al. (2011) used the Scale Invariant Feature Transform algorithm to detect clouds from the MODIS (Moderate Resolution Imaging Spectroradiometer) 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 a whole-sky infrared cloud-measuring system and found significant differences in CBH due to the retrieval algorithm or measurement principle. Cloud-Aerosol Lidar and Pathfinder Satellite 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 et al., 2011; Winker et al., 2003). Pal et al. (1992) demonstrated an algorithm to retrieve CTH and CBH from Nd YAG (neodymium-doped yttrium aluminium garnet) lidar. Duynkerke and Teixeira (2001) determined cloud cover with stratocumulus using observations obtained from the Regional Experiment of International Satellite Cloud Climatology Project. Clothiaux et al. (2000) used multiple active remote sensors like the Belfort or Vaisala Ceilometer and a micro-pulse lidar to find CBH.

Kotarba (2009) evaluated MODIS-derived cloud amount data with visual surface observations over the Poland region. Forsythe et al. (2000) compared cloud information retrieved from GOES-8 geostationary satellite with surface observation. Stefan et al. (2014) used both ceilometer and satellite data to detect clouds and found that low-level clouds are better captured by the ceilometer, and for high-level clouds, satellites provide better information. Albrecht et al. (1990) used a sodar, ceilometer, and microwave radiometer all together to estimate cloud thickness. Kassianov et al. (2005) estimated CBH from hemispherical surface observations and validated these against micro-pulse 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 these ground-based cloud measurements. Detailed investigations of cloud base retrieved from the MODIS satellite are compared with ceilometer measurements during the years 2013 to 2015. Brief details about ceilometer observations and MODIS data are discussed in Sect. 2. The methodology and results are discussed in Sects. 3 and 4 respectively. Conclusions of the paper are given in Sect. 5.

Table 1. Technical specification of Ceilometer CL31.

Property	Description/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 µWs ±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 $\times$ ±0.7 mrad
Receiver detector	Silicon avalanche photodiode

2 Data used

2.1 Ground observations by the ceilometer

The ceilometer lidar set up at PRL, Ahmedabad (23.03° N, 72.54° E; 55 m a.m.s.l.; Fig. 1), consists 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 of 910 nm (±10 nm), typically with a peak power of 11 W. The receiving unit is a silicon avalanche photodiode with an interference filter with a center wavelength of 915 nm and a surface diameter of 0.5 mm. The receiver bandwidth is 3 MHz and 80 % of transmissivity at 913 nm. The focal length of the optical system is 300 mm with a 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 a minimum 2 s to a 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 the cloud base, a laser pulse is sent through the atmosphere. This light pulse is scattered by aerosol particles. A component of this scattered light is received back by the lidar receiver. The received backscattered profile is used to detect the CBH. CL View is an interface software which is a graphical presentation program for cloud height and backscatter profile information. CL view software is used here for data handling and visualization purposes.

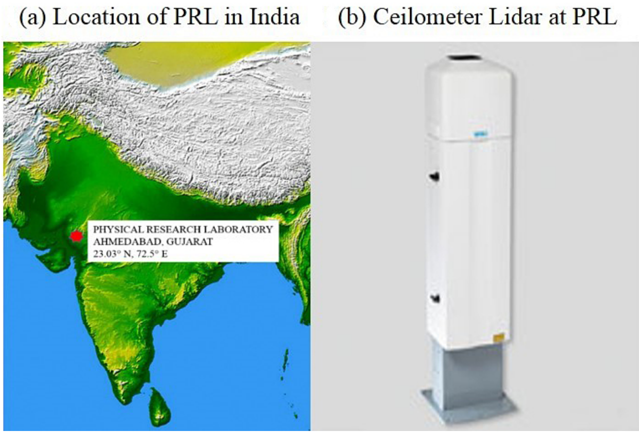

Figure 1. (a) Location of Ahmedabad (23.03° N, 72.54° E; 55 m a.m.s.l.), where Ceilometer CL31 is installed, and **(b)** a photograph of the Vaisala Ceilometer.

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 the year 1999, and Aqua, in the year 2002. It uses 36 spectral bands between wavelengths 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, shortwave infrared, mid-wave infrared, and long-wave infrared. MODIS provides measurements of large-scale global dynamics, including cloud cover, radiation budget, and the processes 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 spectra. The 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) in the near infrared/visible and thermal infrared are used for the cloud spectrum (Gu et al., 2011).

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 the MODIS satellite, in conjunction with cloud observations by the ceilometer. The location map of the Ahmedabad region and a photograph of the Ceilometer CL31 are shown in Fig. 1. The ceilometer data set contains three consecutive heights of multilayer clouds and backscatter coefficients (Martucci et al., 2007, 2010). The MODIS satellite products MOD06_L2 (Hirsch et al., 2011) contain the data from the Terra satellite, and the "MYD06_L2" files contain data from the Aqua satellite platform that are used in this study. Only the daytime passes of the MODIS satellite over the Ahmedabad region are used in this study. For comparison purposes, MODIS satellite data are used directly, if data lie within a 0.1° radius of the in situ location. Ceilometer data have very high temporal frequency; because of this suitability, ceilometer data that lie near the MODIS pass are used for comparison purposes.

CBH detection algorithm

For water clouds, CBH is measured using CTH and cloud geometrical thickness (CGT; Meerkötter 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.

$$\mathrm{CBH} = \mathrm{CTH} - \mathrm{CGT},$$

where

$$\mathrm{CGT} = \frac{\mathrm{LWP}}{\mathrm{LWC}},$$

$$\mathrm{LWP} = \frac{2 \times t \times \mathrm{reff}}{3}.$$

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

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

4 Results and discussions

This study investigates cloud analysis over the Ahmedabad region using ceilometer measurements and MODIS satellite-retrieved cloud parameters. The scanning frequency of MODIS satellite above the Ahmedabad region is twice per day, whereas the ceilometer provides ∼ 100 % monthly coverage at high temporal resolution. The number of observations was 379 days during the years 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 7.22 km on 6 June 2013 at 02:00:02 IST which shows the availability of high-level clouds. Figure 2b shows the detection of multilayer clouds in which low-level and mid-level clouds appear together. The peak backscattering is at 4 km, which provides us information about mid-level clouds, as

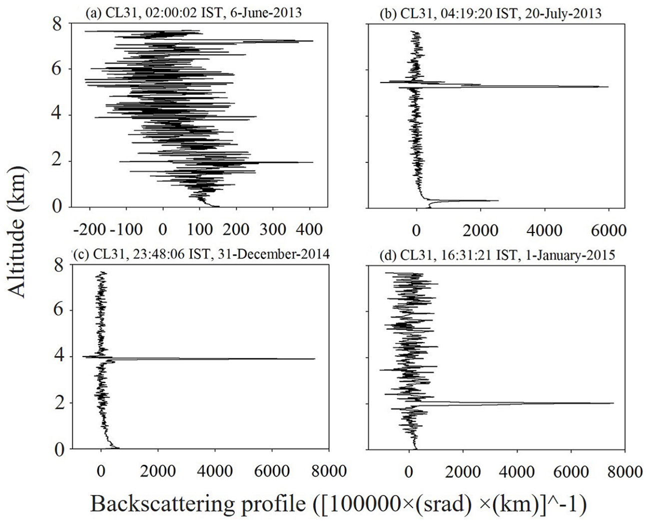

Figure 2. Vertical profile of backscatter data for different days **(a)** 6 June 2013 at 02:00:02 IST, **(b)** 20 July 2013 at 04:19:20 IST, **(c)** 31 December 2014 at 23:48:06 IST, and **(d)** 1 January 2015 at 16:32:21 IST from Ceilometer CL31 over Ahmedabad, India.

found in Fig. 2c. In Fig. 2d, the maximum backscattering is seen at 2 km, which gives information on low-level clouds.

Figure 3a shows the detection of multilayer clouds using the ceilometer instrument. In this figure, both the intensity and back scattering profile and three layers of clouds with a corresponding height of 0.384, 1.8, and 2 km are seen at 15:29:50 IST. Figure 3b shows the detection of multilayer clouds for 2 August 2014. The strong updraft and downdraft can be seen in the 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, the ceilometer detected multilayer clouds, which move with almost constant velocity (figure not shown). At 03:21 IST, the corresponding backscatter profile in which maximum backscattering seen at 320 m and 3.520 km 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 0.860 km respectively and a second layer of clouds (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 the ceilometer is able to capture the multilayer 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 the Ahmedabad region on 1 January 2015 between 14:00 to 16:00 IST. The ceilometer also captured the two-layer low clouds at 0.201 and 1.316 km on 25 July 2013, and corresponding backscatter values show peak at the same heights. The ceilometers detect three layers of clouds on 30 October 2014 at 22:40 IST, and this shows the capability of the instrument to measure multilayer clouds. From these experiences to detect multilayer clouds at different altitudes, we can state that the ceilometer provides better information on the low- and mid-level clouds. Recently, Stefan et al. (2014) used a similar ground-based instrument to study cloud cover over Măgurele, Romania, and compared these with the 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 the satellite. The comparison has been made between the ceilometer and MODIS satellite in Fig. 4, which shows the cloud cover over the Ahmedabad region for 3 different days.

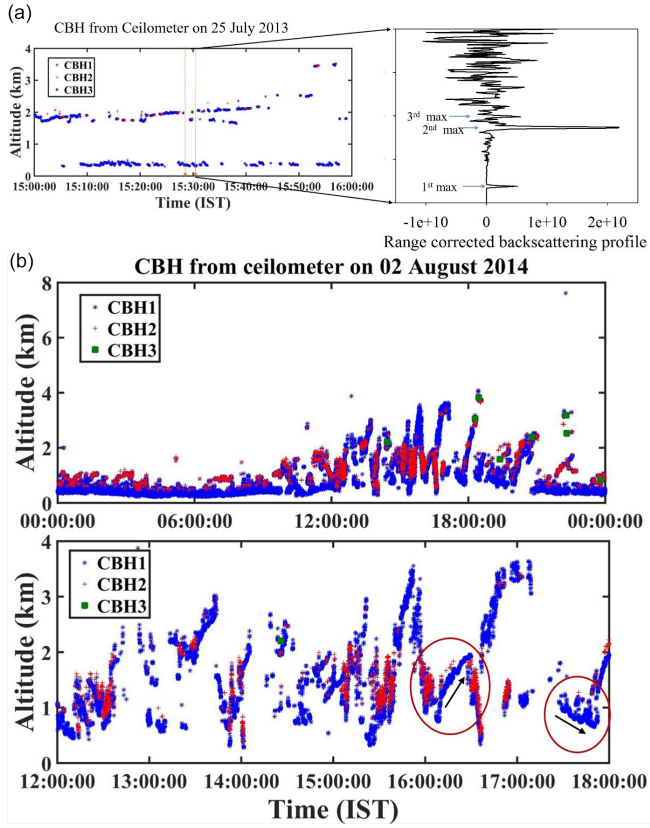

Figure 3. (a) Cloud intensity with range-corrected backscattering profile for multilayer cloud detection on 25 July 2013 at 15:29:50 IST. **(b)** Evolution of three layers of CBH measured by the ceilometer on 2 August 2014 (upper panel) along with strong updraft and downdraft (lower panel) for the same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

4.1 Comparison of cloud heights from the ceilometer and MODIS

In this section, the CTH retrieved from the passive remote sensor viz. MODIS and active remote sensor viz. the ceilometer (Naud et al., 2003) are compared for cloud detec-

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

Serial no.	Date/time (IST)	Ceilometer data	MODIS data	
		CBH1 (km)	CTH (km)	CBH (km)
1	1 Jan 2015 14:25	1.097	2.000	1.093
2	20 Jul 2014 20:40	1.079	0.250	NA
3	21 Jul 2014 02:15	1.911	NA	NA
4	25 Jul 2014 13:45	0.685	3.100	NA
5	26 Jul 2014 02:35	2.487	3.400	NA
6	25 Jul 2014 14:25	1.920	4.250	1.955
7	30 Jul 2014 11:35	0.440	10.900	NA
8	5 Sep 2014 11:55	0.630	4.250	NA
9	15 Sep 2014 10:55	1.680	1.250	NA
10	20 Jul 2013 14:40	0.786	11.250	NA
11	21 Jul 2013 02:50	7.142	13.700	NA
12	21 Jul 2013 13:45	0.896	0.750	NA
13	22 Jul 2013 01:45	0.429	14.100	NA

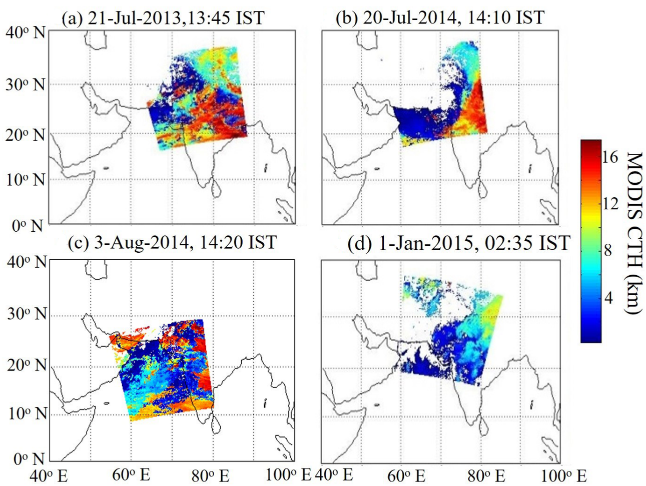

Figure 4. MODIS satellite-retrieved cloud top height for **(a)** 21 July 2013, **(b)** 20 July 2014, **(c)**, 3 August 2014, and **(d)** 1 January 2015 over Ahmedabad, India.

tion (Fig. 5). In the last section, for comparing the accuracy of the ceilometer retrievals, the CBHs derived from the active remote sensor ceilometer are presented. The 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 detections from MODIS and the ceilometer are compared to show the difference between the passive remote sensor and the active remote sensor. The ceilometer can detect three cloud layers simultaneously. As found in Table 2, the different measurements are used for the comparison between the satellite and the 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 detects clouds at 0.786 km and MODIS at 11.25 km. This indicates that MODIS provides the information about high-level cirrus clouds and the ceilometer provides the information about low-level clouds. Figure 5b shows that cloud moved with almost constant velocity from 14:20 to 14:30 IST on 25 July 2014 and the CBH detected by the ceilometer is 1.92 km. The CTH from the MODIS satellite is 4.25 km which shows the mid-level clouds and by applying the algorithm, the CBH is calculated as 2.2 km. So, the difference between the base height measured by the ceilometer and by MODIS is ∼ 130 m. Multilayer clouds appear in Fig. 5c measured by the 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 3.4 km. Here, the CBH algorithm for the MODIS satellite is not applicable due to the non-availability of cloud optical thickness and effective radius. Figure 5d shows that on 1 January 2015 from 14:00 to 16:00 IST, multilayered clouds appeared at a height of around 1 km and the second layer appeared at around 1.5 km for the first 15 min. The continuous updraft of cloud from 1 to 2 km till 16:00 IST was observed. At a common point (at 14:25 IST), the CBH by the ceilometer is 1.097 km and CTH provided by MODIS is 2 m, and from the algorithm, CBH is calculated as 1.093 km, which is almost the same as the CBH measured by the ceilometer. Therefore, it can be concluded that for low-level clouds, this algorithm is fine. The cloud cover for monsoon and post-monsoon periods during the year 2014 was also studied, and the variation of CBH with rain and without rain was found.

4.2 Cloud characteristics during monsoon

– Rainy clouds:

on 5 September 2014 from 11:00 to 12:00 IST, the ceilometer detected low-level clouds which move with almost constant velocity. At 11:55 IST, the ceilometer detects the CBH at 0.82 km, which shows the availability of low-level clouds, and MODIS detected CTH as

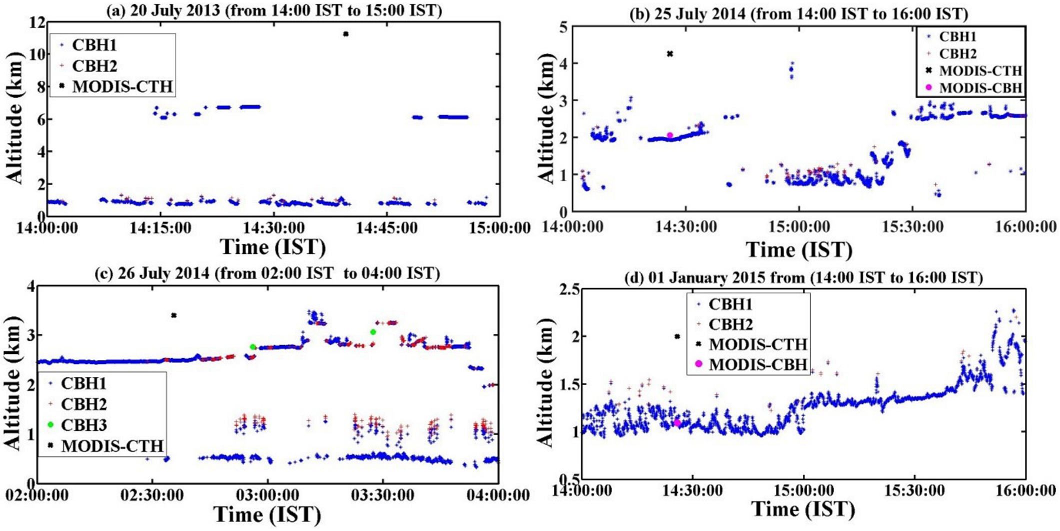

Figure 5. Comparison between cloud top height and CBH derived from MODIS, and base height measured by Ceilometer CL31 over the Ahmedabad region.

4.25 km, which provides information about mid-level clouds. On that day, rainfall amount was reported as 21 mm, shown in Fig. 6a.

– Heavy rain:

on 30 July 2014, low-level clouds were detected which move with almost constant velocity. At 11:35 IST, CBH measured by the ceilometer is 0.4 km and CTH retrieved by MODIS is 10.9 km, which provides information on high-level clouds. On that day, rainfall amount was 207 mm which is the maximum, as shown in Fig. 6b.

– Non-rainy clouds:

on 15 September 2014 from 10:00 to 11:00 IST, cloud over the Ahmedabad region detected by the ceilometer is shown in Fig. 6c. It detects the CBH at 0.9 km, which provides information on low-level clouds, and the CTH retrieved from the MODIS satellite is 1.25 km.

4.3 Cloud characteristics during post-monsoon

– Rainy clouds:

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

– Non-rainy clouds:

Fig. 7b shows that on 30 October 2014 from 02:00 to 03:00 IST high-level clouds are detected by the ceilometer over the Ahmedabad region. Between 02:26 and 02:41 IST, the ceilometer shows clear sky, and the CTH

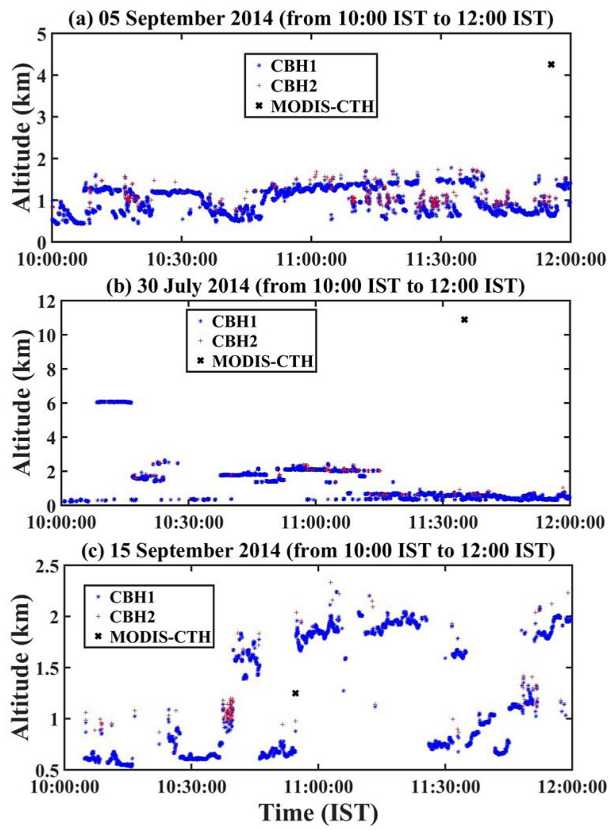

Figure 6. Comparison between cloud top height derived from MODIS, and CBH observed by the ceilometer during the monsoon season over the Ahmedabad region during sample days for **(a)** normal rain, **(b)** heavy rain, and **(c)** no rain cases.

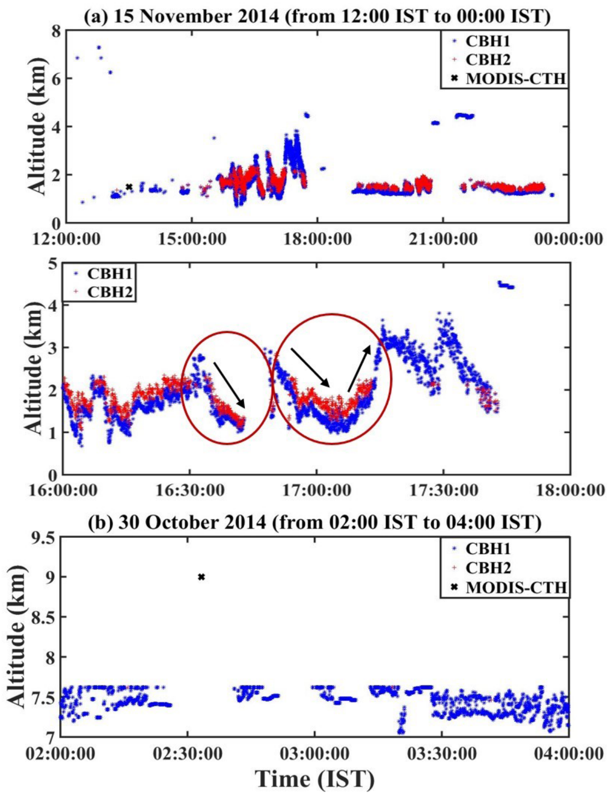

Figure 7. Comparison between cloud top height derived from MODIS, and CBH observed by the ceilometer during the monsoon season over the Ahmedabad region during sample days for **(a)** rain, and **(b)** no rain cases.

detected by MODIS is 9 km. Higher level clouds are much better detected in the satellite data than by the ceilometer due to a power limitation; therefore, the ceilometer can detect a maximum up to 7.5 km.

5 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 the 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 were found. Clouds moved downward at a velocity of 14.8 m s^{-1} and upward at a velocity of 15.1 m s^{-1} on 15 November 2014. (2) CBH shows variations during the southwest monsoon and the post-monsoon period. (3) The ground-measured cloudiness due to low-level and mid-level clouds is obviously higher than the one determined by the satellite. Overall, the ceilometer provides information on up to three layers of clouds, which are not possible to detect by the MODIS satellite. The satellite only provides the CTH; moreover, the satellite gives information about cloud height twice in a day when it passes over the Ahmedabad region, but the ceilometer provides regular (high temporal frequency) and real-time information. The low-level clouds are not accurately detected by the satellite as shown in the observation table, whereas the satellite provides information about high-level clouds. The high-level clouds are accurately captured by satellite data compared to ceilometer measurements due to the power limitation of the ceilometer; because of that it can measure up to 7.5 km. The comparison of the cloud cover from satellite observations with that of the ground-based observations suggests that the low- and mid-level clouds are much better and accurately detected by the Ceilometer CL31 ground-based instrument than the satellite, and the satellite provides better information about high-level clouds. Also, it is important to note here that the CBH algorithm is valid for low-level clouds 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 numerical models.

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