Variations in the cloud-base height over the central Himalayas during GVAX: association with the monsoon rainfall

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We present the measurements of cloud-base height variations over Aryabhatta Research Institute of Observational Science, Nainital (79.45°E, 29.37°N, 1958 m amsl) obtained from Vaisala Ceilometer, during the nearly year-long Ganges Valley Aerosol Experiment (GVAX). The cloud-base measurements are analysed in conjunction with collocated measurements of rainfall, to study the possible contributions from different cloud types to the observed monsoonal rainfall during June to September 2011. The summer monsoon of 2011 was a normal monsoon year with total accumulated rainfall of 1035.8 mm during June–September with a maximum during July (367.0 mm) and minimum during September (222.3 mm). The annual mean monsoon rainfall over Nainital is 1440 ± 430 mm. The total rainfall measured during other months (October 2011–March 2012) was only 9% of that observed during the summer monsoon. The first cloud-base height varied from about 31 m above ground level (AGL) to a maximum of 7.6 km AGL during the summer monsoon period of 2011. It is found that about 70% of the total rain is observed only when the first cloud-base height varies between surface and 2 km AGL, indicating that most of the rainfall at high altitude stations such as Nainital is associated with stratiform low-level clouds. However, about 25% of the total rainfall is being contributed by clouds between 2 and 6 km. The occurrences of high-altitude cumulus clouds are observed to be only 2–4%. This study is an attempt to fill a major gap of measurements over the topographically complex and observationally sparse northern Indian region providing the evaluation data for atmospheric models and therefore, have implications towards the better predictions of monsoon rainfall and the weather components over this region.

Keywords: Ceilometer, central Himalaya, cloud-base, GVAX, monsoon.

Introduction

INDIAN summer monsoon or popularly known as south-west monsoon (May to September) is the most anticipated atmospheric phenomenon occurring over the South Asian region. In the context of synoptic weather, monsoon influences the Indian agriculture, in a great deal, and therefore, economy as well as the air quality for the large population of this region[1,2]. Extensive rainfall and formation of clouds significantly perturb the atmospheric photochemistry and earth's radiation budget[3,4]. The cloud height, structure and distribution provide vital information for understanding the radiation balance and energy budget of the earth–atmosphere system[5] and thus need to be determined accurately. Despite the aforementioned importance, cloud formation and prediction of resulting rainfall remains highly uncertain[6].

The rapidly increasing anthropogenic emissions, particularly of aerosols in the climate change scenario, are anticipated to influence the monsoonal rainfall in an uncertain manner[7–9]. However, a synoptic picture on the spatial and seasonal variability of the vertical structure of precipitation over India and adjoining oceans based on long-term measurements has been provided by Saikranthi *et al.*[10]. In order to reduce these uncertainties, the collocated measurements of cloud variations and rainfall over a network of observation sites are highly desirable. These datasets will be invaluable to evaluate the performance of the chemistry transport and climate models which are

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being utilized to simulate the impacts of emissions and climate change on the cloud formations and rainfall[11].

Cloud-base height can act as an indicator of cloud type such as stratiform or boundary layer clouds[12], mid-altitude and high-altitude clouds. Unfortunately, the collocated measurements of cloud height variations and rainfall are much limited over the Indian region and impose a major gap[13]. However, such measurements at other locations over globe are available to some extent and utilized for other objectives such as estimating mixed layer height[14–17]. Ceilometer measurements have also been utilized for aerosol retrievals, comparison of the data with radio acoustic sounding systems and Lidar data, implication of mixing height for air pollution[18,19]. In light of these conditions and various other meteorologically important region, to study and understand the cloud aerosol interaction, a major field campaign called as the Ganges Valley Aerosol Experiment (GVAX) was conducted at ARIES, in a potential Indo-US collaboration involving primarily Aryabhatta Research Institute of Observational Sciences, Nainital; Indian Institute of Science, Bengaluru and Argonne National Laboratory, USA, during June 2011–March 2012. The campaign aimed towards understanding the aerosol–cloud–climate interactions and dynamics in the lower atmosphere. Under this campaign a spectrum of state-of-art instrumentation was utilized for making the measurements on aerosol properties, clouds, wind and vertical profiling of the atmospheric parameters.

Methodology

GVAX campaign

GVAX was an extensive field campaign covering detailed measurements of aerosol properties, meteorological parameters, clouds, radiation and atmospheric soundings over ARIES, Nainital (http://www.arm.gov/sites/amf/pgh/) during the period from June 2011 to March 2012 (ref. 20). The campaign was aimed at understanding of aerosols and cloud processes and their implications towards radiation changes. Major objectives of the campaign were to study and understand the impact of increasing concentration of the aerosol on the Indian summer monsoon, role of evolution of atmospheric boundary layer over Ganges, in vertical distribution of aerosol and the cloud microphysics. The state-of-art instruments for the measurements of aerosol, radiation, cloud, rainfall, and vertical profiling of various parameters were deployed at site and measurements were made for nearly a year. Aerosol observing system for aerosol properties, boundary layer Lidar, Doppler Lidar, high frequency radiometers, ceilometer, sky imager and many more instruments were operated for the measurements of meteorological parameters. In addition, for vertical profiling of meteorological parameters, 4–5 radiosonde were launched every day from the site. The site chosen for such studies has its strategic importance as it lies in the central Himalayan foothills and appropriate for studying the transport of pollutants from continents and long ranges. More details about the campaign, objectives and instrumentation can be found in ref. 20. The preliminary analysis of aerosol properties and their radiative impacts over Nainital has been presented recently[21–23].

Observation site and general meteorology

The observation site Manora Peak, ARIES (79.45°E, 29.37°N, 1958 m amsl) near the city of Nainital is a high altitude station located in the central Himalayas[24]. Geographical and topographical representation is given in Figure 1. The site is reasonably away from any direct influences of anthropogenic emissions and has been suggested to be a better regional representative of the northern Indian region[25,26]. Solar radiation over Nainital is observed to be most intense during spring/pre-monsoon and the site receives maximum rainfall during summer/monsoon (June–September). The minimum temperature in winter occasionally reaches about 1°C or less and maximum temperature is about 12°C. The atmospheric pressure varies between 790 and 810 mb, gradually increases from monsoon to winter and then slightly decreases towards spring. The monthly mean temperature remains nearly steady (~21°C) between June and September, with a gradual decrease thereafter to a minimum value of ~6°C in January. The RH is greater than 90% during the summer monsoon and decreases to about 60–40% in the rest of the period, Synoptic winds are generally westerly and north-westerly during the winter which changes to south-westerly and south easterly during the summer monsoon bringing moist and cleaner marine air masses. In general, the wind speed varies between 2 and 6 m s^{-1} with an average of ~2 m s^{-1} most of the time. Spring and autumn months generally receive polluted air masses from the

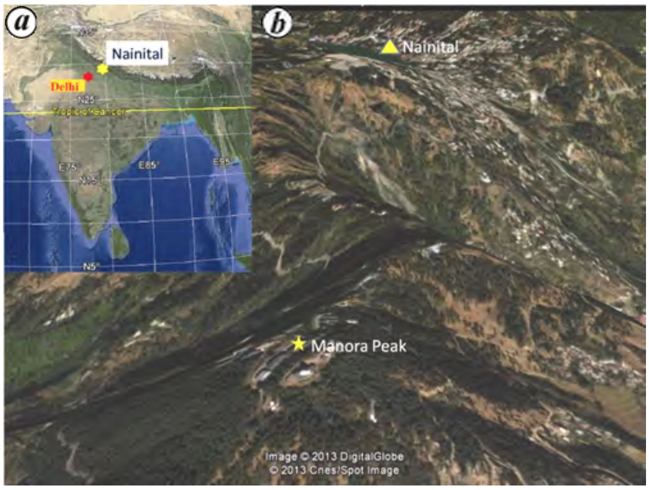

Figure 1. ***a***, Geographical location (marked by yellow star) of observation site at Nainital and nearest megacity Delhi (marked by red star). ***b***, The topography around observation site Manora Peak and Nainital.

northern Indian region including the Indo-Gangetic Plain[27]. The variations in meteorological parameters, surface-based measurements of trace gases and aerosols, vertical profiling of aerosol with LIDAR observations as well as the meteorological parameter with balloon-soundings have been reported elsewhere[24,26,28–30]. There have not been any attempts so far towards the measurement of the cloud base heights, their variations and association with the monsoonal rainfall, which is being presented in this article using Vaisala Ceilometer.

Ceilometer, sky imager and methodology

The measurements of cloud base height variations, indicating the cloud types basically low, mid and high (that includes stratiform or boundary layer clouds or occasional cumulonimbus, etc.), have been made at Nainital using a Vaisala Ceilometer (VCEIL) as a part of the ARM mobile facility (AMF1). VCEIL is a self-contained, ground-based, active remote-sensing device designed to measure cloud-base height to a maximum of 7.6 km and potential backscatter signals by aerosols[31–33]. It transmits near-infrared pulses of light (905 nm) and the receiver telescope detects the light scattered back by clouds and precipitation, in the vertical at every 15 m and at a time resolution of 16 s. Table 1 gives the technical specifications of Vaisala Ceilometer Model CT25K (2004). However, to ensure the sky conditions, a sky imager was also operational at site, that corroborated the ceilometer measurements.

Total Sky Imager is an automatic colour sky imager system that provides real-time display of daytime sky conditions. At many sites, the accurate determination of sky conditions is a highly desirable parameter yet rarely attainable goal. Traditionally, meteorological observers (human) used to report the sky conditions, resulting in considerable discrepancies from subjective observations. Sky imager replaces the need for these human observers under all weather conditions. This self-contained system automatically processes the images internally and keeps the record. The cloud base measurements using ceilometer and sky cover using sky imager are recorded and data archived during monsoon months is analysed, for identifying and assigning the cloud type. Ceilometer and sky imager generated data are averaged for 10 min and utilized for this study. Daily cloud base heights (CBH) have been obtained for a total number of 102 days during monsoon months and subjected for further analysis to generate the cloud statistics, in terms of the percentage occurrences under various altitude ranges such as below 2000 m, 2000–4000 m, 4000–6000 m and above 6000 m. Based on the above selection criteria of CBH, various types of clouds are classified and the contribution of particular type of cloud to the accumulated rainfall, during the period of observation have been assigned. Some case studies have also been carried out using the corresponding 10-min average values for sky cover and cloud base.

Table 1. Technical specifications of the Ceilometer employed at Nainital during the GVAX campaign

Range	7.5 km
Range resolution	15 m
Wavelength	905 nm @ 25°C
Transmitter	Pulsed mode energy 1.6 micro watts ± 5% indium gallium arsenide
Receiver	Silicon APD response @ 905 nm = 65 Amps/Watt 50% Pass = 35 nm @ 890–925 nm
Field of view	Divergence = ± 0.66 m Radian
Optics	Focal length 377 mm, lens diameter 145 mm, transmittance 96% lens, window 98%
Size	672 × 308 × 244 mm (without stand)

Results and discussions

In order to understand the general feature of monsoonal rainfall distribution over Indian region, Figure 2 is provided with the spatial distribution of rain rate (mm/hr) obtained from the Tropical Rainfall Measuring Mission (TRMM) Online Visualization and Analysis System (TOVAS) for June–September 2011. The rain rate values of 0.5 mm/h and above are evidently seen over the northern Indian region. Notably, the rain rates are observed to be significantly higher over the Himalayas and foothills as compared to the Indo-Gangetic basin, highlighting the spatial heterogeneity in the rainfall distribution. It indicates that mountains play an important role in blocking the south-westerly moist air and hence lifting the moisture

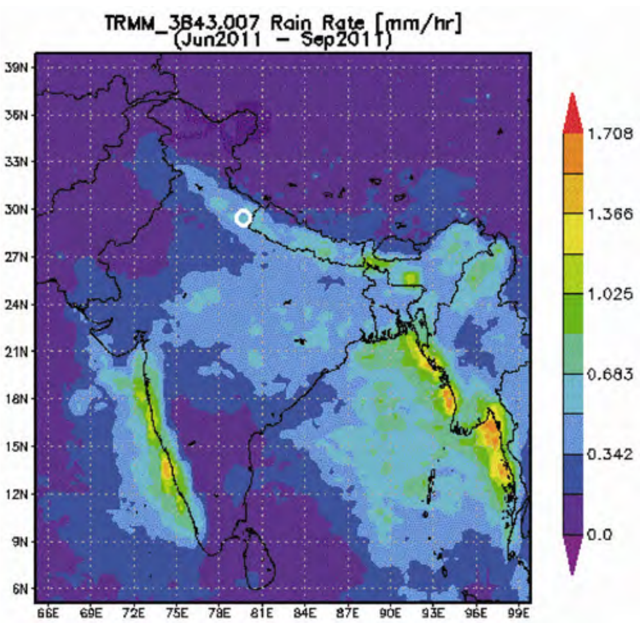

Figure 2. Distribution of rain rate (mm/h) during June–September 2011 over Indian region obtained from Tropical Rainfall Measuring Mission. The location of observation site Nainital is shown by a white circle.

and clouds along the mountain slopes may result in intermittent and persistent rains in the Himalayas during monsoon.

Rainfall variability during GVAX period

Figure 3 *a* shows the time series of daily total rainfall measured from rain gauge in the automatic weather station deployed at Nainital, during GVAX period from June 2011 to March 2012. The monthly accumulated rainfall and maximum daily total rainfall values for monsoon season are given in Table 2. The summer monsoon period is distinguished by heavy rainfall during June–September 2011 with monthly total rain varying from 222.3 mm (September) to 367.0 mm (July). The rainfall observed in winter season (December to February) is mainly resulting from western disturbances arising quite frequently. The maximum daily rainfall observed in winter is about 8 mm on 1 January 2012 and about 16 mm, on 7 March 2012 in spring. Figure 3 *b* shows the variations in daily rainfall during the summer monsoon months. The maximum daily rainfall varies from 34.4 to 79.3 mm. The rainfall received during all the months other than summer monsoon, i.e. October 2011 to March 2012, comprise of about 9% of the total rainfall received during the period of study. The rainfall in these months are generally associated with the local convective processes[33] while wintertime rainfall are associated with the western disturbances[34].

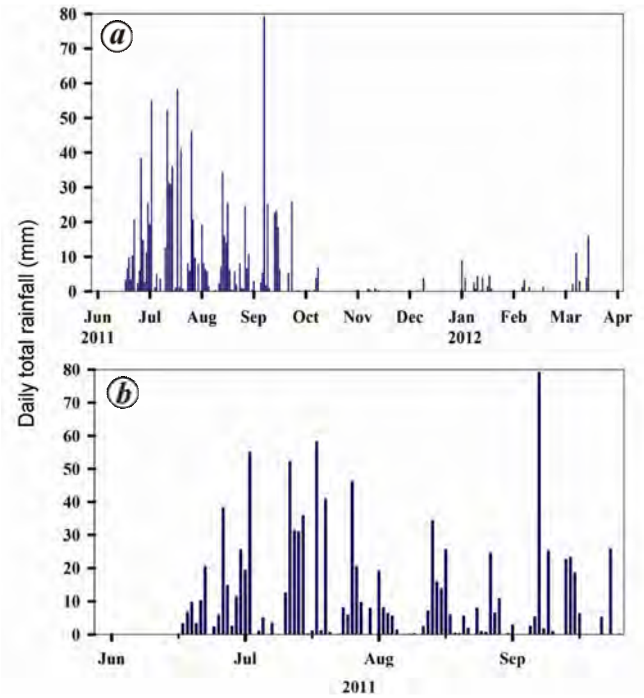

Figure 3. ***a***, The time series of daily total measured rainfall (mm) over Nainital during the GVAX period: June 2011 to March 2012. ***b***, Daily total rainfall during the summer monsoon period of June to September 2011.

Table 2. The monthly total rainfall (mm) and maximum daily total rainfall (mm) observed at Nainital during GVAX period

Months	Total rainfall (mm)	Maximum daily rainfall (mm)
June*	230.4*	55.0*
July	367.0	58.3
August	216.1	34.4
September	222.3	79.3
June–September 2011	1035.8	79.3
October 2011–March 2012	96.2	16.0

*Observations were not available for all the days but only from 15 to 30 June.

Cloud base height, rainfall and sky opacity measurements

In order to understand the association between cloud base height and rainfall over the site, we have taken three different cases of rainfall events, comprising of rainfall in the morning of 28 July 2011 (M28J), evening of 8 September 2011 (E8S) and rainfall whole day for 17 August 2011 (F17A). To corroborate the ceilometer measurements, the sky opacity measurements are also made. Figure 4 depicts the 10-min averaged measurements of cloud base height, rainfall and sky opacity. For M28J and E8S, the rainfall takes place up to 4 h with rain rate of 60 mm/h, during both the events only first cloud base height measurement of less than 500 m are observed. During the M28J event, we observed about 14 mm of rain in the afternoon hours, the opacity fluctuating between 70% and 99%, and the clouds present contributing significantly to the rainfall. It indicates frequent arrival of a new cloud mass that is being blocked by mountain systems and resulting into rain. It is also observed that after a heavy spell of rain sky is either clear for few hours or covered with the clouds which are non-precipitating or the residual of the dissipated rain clouds. The F17A rainfall event is observed during all day with rain rate of less than 2 mm/h, the ceilometer observation indicates multilayer clouds during 0000 to 1400 h in the height range from near surface to about 2 km. In E8S, however, opacity cannot be monitored in the absence of sunlight, but the rainfall is again well synchronized with low cloud base.

First cloud-base height and multi-layered cloud statistics

Figure 5 depicts 10-min averaged time series of cloud base height over the site during June 2011 to March 2012. First cloud-base height observed during the monsoon months of 2011 ranges between 31 and 7604.76 m, above ground level (AGL). It is evident from the figure that during monsoon months the first cloud base is densely

Table 3. Percentage contributions of cloud-base heights from different altitude ranges over Nainital during summer monsoon months of 2011

	Percentage occurrences				
Month	Min–600 m	600–2000 m	2000–4000 m	4000–6000 m	6000 m–Max
June	49.06	21.87	16.88	9.8	2.39
July	51.43	20.42	17.89	8.26	2
August	52.23	22.89	16.33	6.36	2.19
September	56.65	12.97	16.01	9.49	4.89

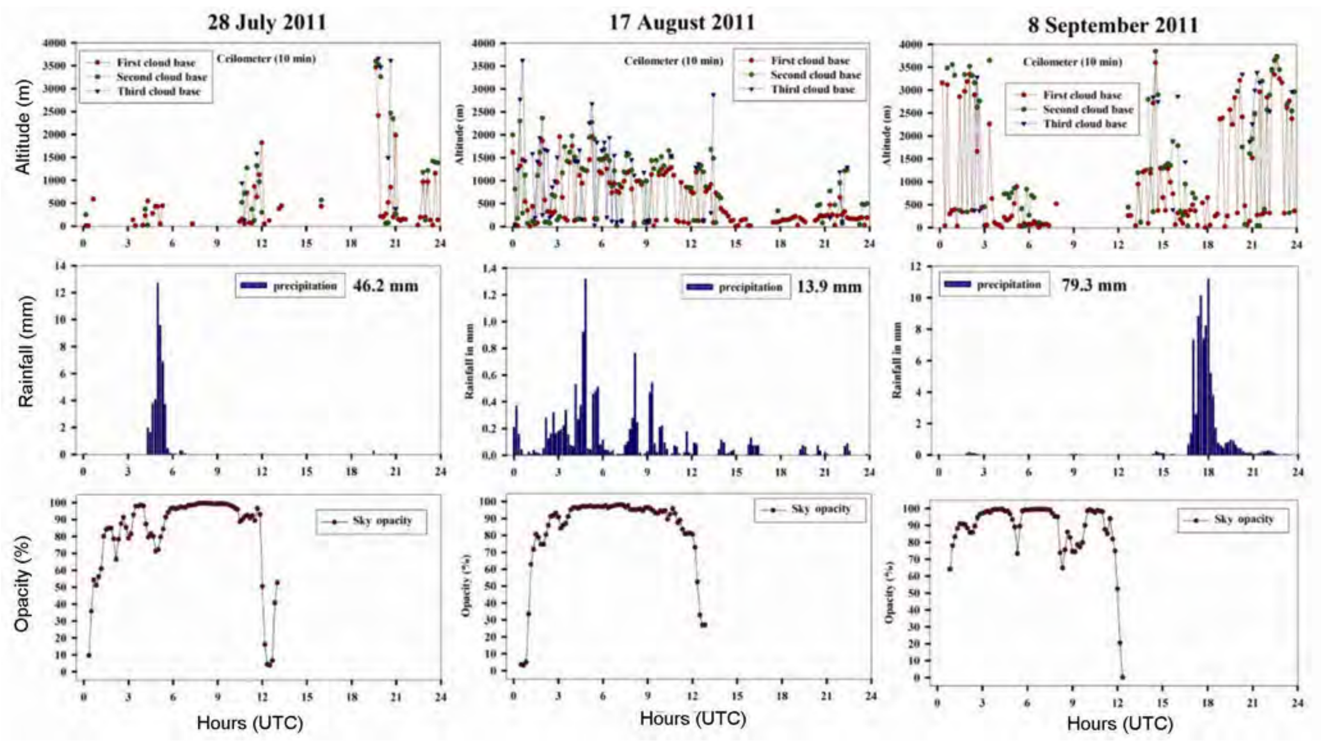

Figure 4. Colocated measurements of cloud base height, rainfall and sky opacity averaged over 10-min duration on three specific days.

populated in the altitude range from surface to about 1 km, and the density decreases from about 1 km to about 4 km. However, a similar trend is observed other than monsoon months, but density of the first CBH at altitudes from 2 to 6 km is significant, indicating the presence of fair weather cumulus as well. Figure 6 shows the distribution on the monthly statistics of multiple cloud bases existing simultaneously as observed with ceilometer every sixteen seconds, confirming the presence of multiple layers of clouds. It is also notable that simultaneous existence of the first and second cloud bases, i.e. a two-layer cloud, is less than 10% and the simultaneous occurrences of three cloud bases, i.e. a very rare three-layer cloud systems is less than 1% of the total observations. In winter and spring seasons when usually western disturbances are active and contribute in rainfall in the north-western and northern high altitude Himalayan region of the country, the occurrences of three layer clouds are found to be negligible[35]. Hence, the clouds observed over the site are generally of the nature of a single cloud base only. Li *et al.*[36] assessed the radiative impacts of single- and multi-layered clouds and found significant cloud radiative effect difference between multi-layered clouds and single-layer clouds. Hence, at our observational site such an effect may not be that significant in radiative impacts whereas a single-layer cloud may be playing a major role.

Contribution from different altitude ranges

The observed first-cloud base height from ceilometer data has been used to calculate the occurrence statistics of the low-level, middle- and high-altitude clouds (Figure 7). However, time series analysis for an individual typical day during the monsoon and post-monsoon months has also been carried out, but here the overall occurrence

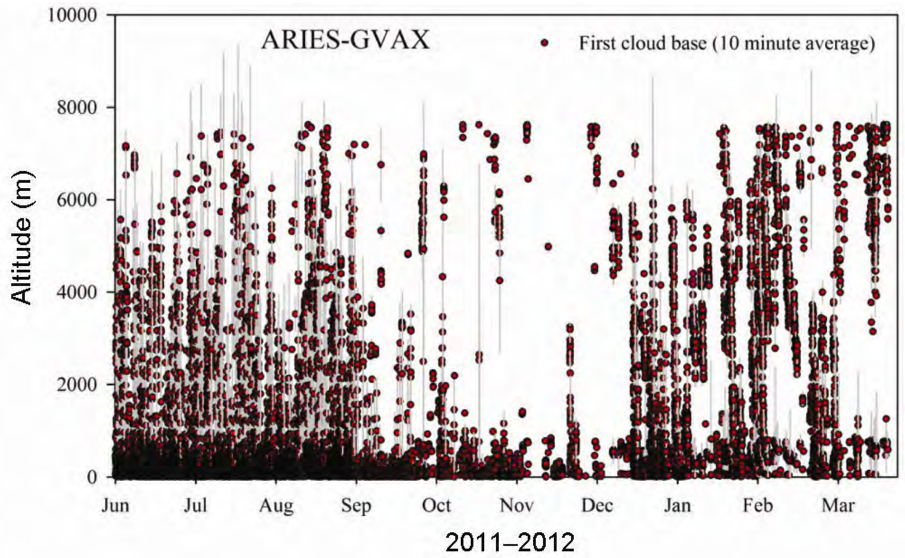

Figure 5. Time series of hourly cloud base height (m) AGL, over Nainital during June 2011 to March 2012. Gaps in the data points indicate that no cloud is present over the site during this period.

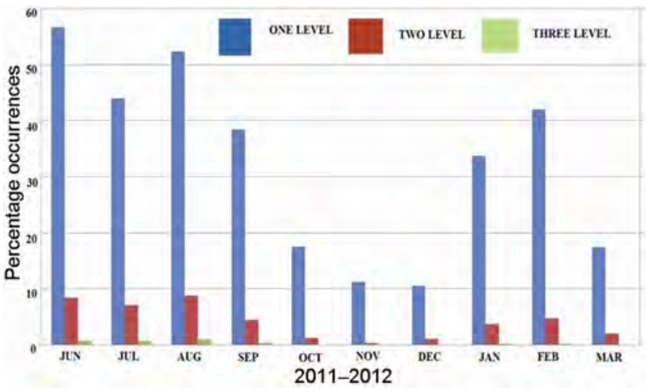

Figure 6. Percentage occurrence of simultaneously observed multiple cloud base height (m, AGL) over Nainital during June 2011 to March 2012.

Table 4. Rainfall contribution by first cloud base height (CB1) observed over different altitude ranges over Nainital during June 2011–March 2012

CB1 range (km)	Rainfall (mm)
CB1 < 0.5	302.186
0.5 < CB1 < 1.0	135.36
1.0 < CB1 < 1.5	71.623
1.5 < CB1 < 2.0	19.8047
2.0 < CB1 < 2.5	46.293
2.5 < CB1 < 3.0	33.197
3.0 < CB1 < 3.5	51.2885
3.5 < CB1 < 4.0	32.0448
4.0 < CB1 < 4.5	18.689
4.5 < CB1 < 5.0	11.4782
5.0 < CB1 < 5.5	11.1028
5.5 < CB1 < 6.0	2.9513
6.0 < CB1 < 6.5	15.5796
6.5 < CB1 < 7.0	2.0272
7.0 < CB1	2.4753

statistics is presented. Statistical analysis is carried out over a total of 102 days of observations during monsoon and monthly account is presented in Table 3. As evident from Figure 7 (based on the percentage occurrence statistics of the cloud base in different altitude regions) it is observed that, about 52% of the time, first cloud base is confined within the local boundary layer and about 19% of average time during monsoon, the cloud base is found to be located between 600 and 2000 m, indicating that monsoonal stratiform clouds are contributing most to the total rainfall during monsoon months shown in Figure 3 *b*. It is important to mention here that monsoon clouds are basically the result of convective processes already taken place at far distances from the Himalayan region and moves to the north Indian and Himalayan region either with south-westerly of easterly moist winds. Above two cloud bases constitute about 70% of the total cloud base observations, and about 30% of the time clouds are above 2 km. Thus, first two base intervals consisting almost more than 70% of the total rain indicate that most of the rainfall is contributed by stratiform low level clouds and at such a high altitude site percentage occurrence of the clouds above 2000 m is about 20–25. On few occasions about 2–4% of time, high-altitude cumulus clouds are observed. Table 4 provides the amount of rain contributed by the different range of cloud base height.

Conclusions and outlook

Continuous measurements of cloud base height over a mountain peak in the central Himalayas are presented from June 2011 to March 2012, with data obtained using Vaisala Ceilometer. The cloud structure over the site is generally single layer only, with less than 10% cases for

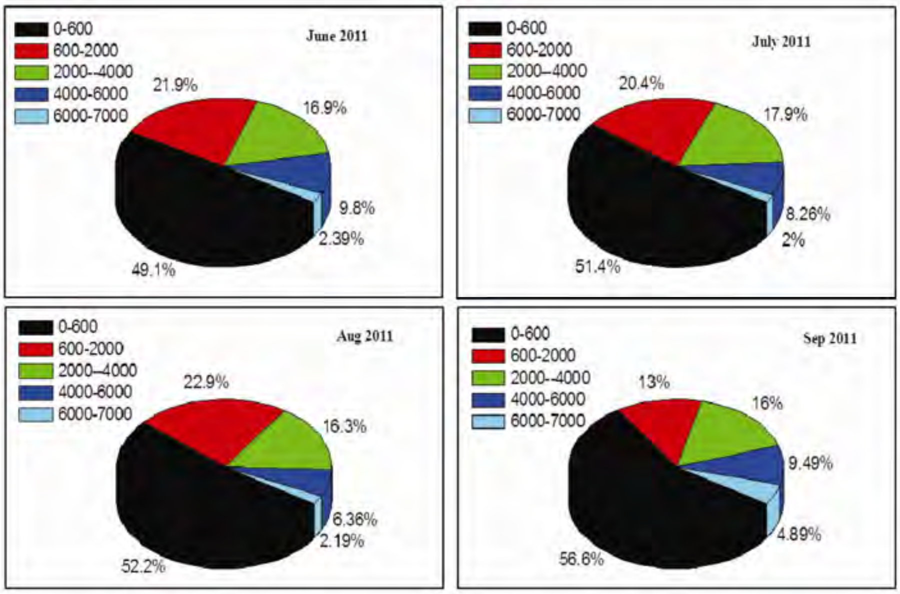

Figure 7. Percentage occurrences of the cloud types based on the cloud height measurements during summer monsoon months of 2011.

two-layer clouds and on few occasions, multilayer. In monsoon the rainfall is mostly contributed by the clouds with base confined to local boundary layer and within 2 km AGL. The results show that during the monsoon season, 70% of the total rainfall is contributed by stratiform low level clouds (or the boundary layer stratus clouds). Rainfall contributed by low clouds is well corroborated by daytime sky image observations. Boundary layer stratus clouds have also been widely recognized as a key component in predicting any potential future climate change[37] and cloud parameterization in climate models needs precise information about cloud parameters, in order to improve the climate prediction. The precise knowledge of cloud layer altitudes is crucial to assess the impact of clouds on climate through radiative interaction[38]; hence this study will play an important role in adapting and optimizing regional climate model over the Himalayan region. However, ceilometers have also been utilized for objectives other than study of cloud altitudes[39,40].

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