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Verification and Correction of Cloud Base and Top Height Retrievals from Ka–band Cloud Radar in Boseong, Korea

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ABSTRACT

In this study, cloud base height (CBH) and cloud top height (CTH) observed by the Ka-band (33.44 GHz) cloud radar at the Boseong National Center for Intensive Observation of Severe Weather during fall 2013 (September–November) were verified and corrected. For comparative verification, CBH and CTH were obtained using a ceilometer (CL51) and the Communication, Ocean and Meteorological Satellite (COMS). During rainfall, the CBH and CTH observed by the cloud radar were lower than observed by the ceilometer and COMS because of signal attenuation due to raindrops, and this difference increased with rainfall intensity. During dry periods, however, the CBH and CTH observed by the cloud radar, ceilometer, and COMS were similar. Thin and low-density clouds were observed more effectively by the cloud radar compared with the ceilometer and COMS. In cases of rainfall or missing cloud radar data, the ceilometer and COMS data were proven effective in correcting or compensating the cloud radar data. These corrected cloud data were used to classify cloud types, which revealed that low clouds occurred most frequently.

Key words: cloud radar, ceilometer, satellite retrieval, cloud base height, cloud top height, cloud type

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1. Introduction

Clouds are important in influencing the energy balance, weather, and climate because they absorb and reflect radiant energy from the Sun and Earth's surface. By identifying the mechanisms of cloud formation and development, and obtaining information on meteorological phenomena in advance, the ability to predict high-impact weather events could be improved significantly. Understanding the microphysical processes of clouds has particular importance for the prediction of the development of precipitation and the estimation of its amount. For these purposes, quantitative and detailed observations of clouds are necessary, but the spatial characteristics of clouds impose many constraints on obtaining such data.

Many studies have observed clouds using diverse equipment. In the case of satellites and ceilometers, the upper and lower boundaries of clouds are detected, which makes it difficult to identify their internal characteristics and to collect three-dimensional cloud data (Zhong et al., 2011). The method of obtaining measurements of meteorological parameters and cloud-particle shapes by direct sampling of clouds using aircraft provides reliable data on the microphysical processes and thermodynamic structure of clouds, but it is costly and only provides instantaneous data (Aydin and Singh, 2004; Yum et al., 2004). Therefore, the observation of clouds using a radar system is more effective in obtaining three-dimensional and continuous data on atmospheric particles. Generally, rainfall radars are designed specifically for observations of precipitation particles and thus, they are limited for measuring cloud particles that are relatively smaller (Sakurai et al., 2012).

To detect smaller hydrometeors, cloud radars may be used. Since these radars use shorter wavelengths than precipitation radars, they are referred to as short-wavelength millimeter wave radar. Rayleigh scattering occurs when the particle size is significantly smaller than the wavelength and scattering strength is proportional to the biquadrate of the wave. As a result, cloud radars have high sensitivities for cloud size hydrometeors (Moran et al., 1998, Kollias et al., 2007a). They typically have high spatial resolution due to the

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narrow beam width and small sidelobes.

Previous studies using cloud radar data include analyses of the mechanisms of cloud formation and development prior to the development of precipitation phenomena (Kobayashi et al., 2011; Sakurai et al., 2012), and cloud climatology based on long-term data (Kollias et al., 2007b). Furthermore, research has been conducted to improve numerical model predictions by verifying and improving cloud radar data or through parameterization and data assimilation (Mace et al., 1998; Hogan and Illingworth, 2000; Ahlgrimm and Forbes, 2014). Moreover, other studies have considered the microphysical characteristics of clouds such as the liquid water content and size distribution of rain droplets (O'Connor et al., 2005; Zhong et al., 2012) and the classification of ice crystal forms in clouds (Aydin and Singh, 2004). Such studies using cloud radar have been conducted widely throughout the world and a network has been formed through the Atmospheric Radiation Measurement (ARM) program (Stokes and Schwartz, 1994). In the ARM program, non-precipitation and weakly precipitating clouds have been observed since 1996 using a vertically pointing Ka-band millimeter-wave cloud radar (Moran et al., 1998) and a W-band ARM cloud radar (Widener and Mead, 2004). Xi et al. (2010) obtained cloud fraction data using millimeter-wave cloud radar (MMCR), light detection and ranging (LiDAR) and ceilometer data observed at the North Slope of Alaska ARM site for 10 years from 1998 to 2008 and observed their influence on radiative forcing. In Europe, the Cloudnet program has utilized observations by ground-based remote sensing instruments (cloud radar, ceilometer, and microwave radiometer) to study clouds for about 15 years (Illingworth et al., 2007).

The National Institute of Meteorological Sciences of Korea installed a Ka-band cloud radar system at the National Center for Intensive Observation of Severe Weather (NCIO) at Boseong in April 2013. It is expected that analysis of the microphysical characteristics of clouds based on the cloud radar data will promote understanding of cloud processes and improve numerical model predictions. However, before such research can be performed, verification and quality control of the cloud radar data must be completed.

The results of comparative analyses of reflectivity, liquid water content, and cloud height, obtained in previous studies from cloud radar and other instruments (e.g., satellites, LiDAR, and micro rain radar), have shown that highly diverse and good quality data can be obtained by linking and combining multiple sources (Syrett et al., 1995; Hollars et al., 2004; O'Connor et al., 2005; Kneifel et al., 2011).

In particular, cloud base height (CBH) and cloud top height (CTH) are important parameters in the formation and development processes of clouds, and it is therefore necessary to compare these data to check whether cloud radars are effective in detecting cloud boundaries. Clothiaux et al. (2000) objectively determined the hydrometeor height distribution using active remote sensing at the Cloud and Radiation Testbed ARM site in Oklahoma and at the Tropical West Pacific site in Darwin, Australia. Cloud boundaries were determined from the returned radar signal using the cloud mask algorithm by Clothiaux et al. (1995). A LiDAR and ceilometer were utilized to detect optically thin clouds and to aid with clutter removal. To evaluate the accuracy of ARM MMCR and GMS-5 satellite data over Manus Island, Hollars et al. (2004) compared the cloud top heights calculated from each piece of equipment according to the type of cloud and precipitation. Oh et al. (2014) performed a comparative analysis of CTHs observed by cloud radar and sensors onboard the Communication, Ocean, and Meteorological Satellite (COMS). They established that cloud radar was useful in detecting the CTH in the absence of precipitation. However, during periods of rainfall, the CTHs obtained by the cloud radar tended to be lower than reality and thus, the expectation was that the radar-derived CTHs could be corrected using COMS data. However, because that study focused solely on the upper boundary of the cloud and analyzed only one case, it was determined that additional analyses were required.

This study was conducted to verify and correct CBHs and CTHs obtained by the cloud radar at Boseong NCIO in the fall (September–November) of 2013. For comparative verification, CBHs and CTHs observed by a ceilometer and COMS were used, and the effectiveness of the cloud radar data was examined by consideration of the occurrence of precipitation, rainfall rate, and cloud thickness and density. Based on these results, a method for the correction of radar-derived CBH and CTH is proposed and, additionally, the characteristics of the occurrence of cloud types examined.

2. Data and method

2.1. *Ka-band cloud radar*

The Ka-band cloud radar used in this study is installed at the Boseong NCIO and operated by the National Institute of Meteorological Sciences of Korea. Boseong NCIO is located on the southern coast of Korea (34.76°N, 127.21°E), and equipped with a variety of meteorological observational instruments (ceilometers, optical rain gauge, micro rain radar, particle size velocity disdrometer, global navigation satellite system, and wind profiler) in addition to the cloud radar. The cloud radar transmits 33.44 GHz pulses in the Ka-band, and it is used for observations of precipitable clouds, non-precipitable clouds, and low precipitation. By transmitting horizontal waves and receiving both horizontal and vertical waves, the cloud radar produces reflectivity, radial velocity, spectrum width, linear depolarization ratio, and signal-to-noise ratio data. It is designed to observe clouds of up to 15-km in height with a resolution of 15 m. Additional details of its characteristics are provided in Table 1.

Clouds were defined using the co-polar vertical reflectivity obtained by the cloud radar from September to November 2013 (Fig. 1a). Overall, 6.27% of the cloud radar data were missing (12.64% in September, 2.96% in October, and 3.33% in November) because of a variety of reasons including the suspension of observations (from 7 to 8 October 2013) because of strong winds. To eliminate ground clutter, noise, and non-cloud echoes, clouds were defined as echoes with

Table 1. Characteristics of the Ka-band cloud radar at the Boseong NCIO.

Variarles	Value
Frequency (GHz)	33.44
Wave length (mm)	8.97
Antenna type	Cassegrain
Antenna gain (dB)	51
Beam width (°)	0.42
Peak power (kW)	20
Average power (W)	5.7
Pulse width (ns)	200
Pulse repetition frequency (Hz)	Dual (2500 or 3333)
Minimum detectable signal (dBm)	−104
Dynamic range (dB)	70
Reflectivity detection range (dBZ)	$-50 \sim 30$
Detection ability	< -30 dBZ at 5 km
Mode	Transmit horizontally; receive horizontally and vertically

reflectivity values of greater than −30 dBZ and thicknesses of greater than 1.5 km. The reflectivity threshold of −30 dBZ has been reported previously as the minimum value of radar reflectivity for cirrus clouds (Brown et al., 1995), and the thickness threshold of 1.5 km was determined based on the average thickness of cirrus clouds observed by LiDAR (Fuller et al., 1988; Kent and Schaffner, 1988). In addition, to remove non-meteorological echo, like that generated by insects, which appears with reflectivity values lower than −30 dBZ and at heights of less than 2 km, the hydrometeor boundaries were determined using the threshold of reflectivity of −30 dBZ and a signal to noise ratio (SNR) of 5 dB. Although not shown in this paper, when these thresholds were set to a reflectivity lower than −30 dBZ and an SNR lower than 5 dB, it was hard to detect the boundaries accurately due to the influence of the noise generated on the ground: and when it was set to values greater than the thresholds, the top height was estimated lower and the base height greater. The CBHs and CTHs were defined as the lowest and highest altitudes of the clouds, respectively (Fig. 1b). Multi-layer clouds were considered as single entities and cloud thicknesses were defined as the difference between the CBH and CTH.

2.2. *Ceilometer and COMS*

For comparative analysis, clouds were defined using a ceilometer and COMS from September to November 2013. The CBHs were observed using a Vaisala CL51 ceilometer, which uses LiDAR technology to transmit pulsed waves vertically and receive backscattered signals reflected by cloud drops. This ceilometer has a range of 13 km with a 10-m resolution for cloud detection. The CTHs were obtained using the COMS meteorological data processing system, which simultaneously employs single-channel and radiation-ratio methods (METRI/KMA, 2009). The single-channel method calculates the cloud top temperature by converting the brightness temperature of COMS to cloud top pressure. When this method is employed, the cloud top pressures of semi-transparent clouds are calculated to be higher than their actual values. Therefore, this is corrected using the radiation-ratio method. The radiation-ratio method involves applying the brightness temperatures of the water vapor (6.75 μm) and infrared-1 channels to obtain the cloud top pressure. The temporal resolution of the CTHs observed by COMS is 15 min and the spatial resolution is 4 km. In this study, the data at 00 min were extracted and used and were analyzed using the grid data (34.76°N, 127.21°E) nearest to Boseong Center. The results of these two methods were compared to select the optimum cloud top pressure, from which CTHs were calculated using the hypsometric equation.

In this study, targets for which CBHs and CTHs were observed by both the ceilometer and COMS were defined as clouds. Furthermore, cases for which the cloud radar data contained missing values were excluded from further analysis. The CBHs and CTHs obtained using the ceilometer–COMS data were compared with the cloud radar data.

3. Comparative verification of cloud radar data

3.1. *Comparison of cloud base and top height formations*

3.1.1. *Average cloud base and top heights*

Table 2 shows the CBHs, CTHs, and cloud thicknesses observed by the cloud radar and ceilometer–COMS. The difference between the average CBH and CTH based on the observations from the cloud radar (363 cases) and ceilometer–COMS (510 cases), showed that the cloud-radar-derived CBH and CTH were higher by 0.75 and 0.36 km, respectively, and that the radar-derived average cloud thickness was 0.39 km smaller. However, for the 285 cases in which the clouds were observed simultaneously by the cloud radar and ceilometer–COMS, it was found that the radar-derived CBH and CTH was 0.11 km higher and 0.73 km lower, respectively, and that the radar-derived cloud thickness was 0.84 km smaller. These cases showed only slight differences between

Table 2. Mean values of CBH, CTH, and cloud thickness observed by cloud radar (CR) and ceilometer–COMS (CC) of total, simultaneous, and sole (CR or CC) cases.

	Total cases		Simultaneous cases		Sole cases	
	CR (363 cases)	CC (510 cases)	CR (285 cases)	CC (285 cases)	CR (78 cases)	CC (225 cases)
CBH (km)	2.99	2.24	2.43	2.32	5.04	2.13
CTH (km)	6.92	6.56	6.75	7.48	7.54	5.38
Thickness (km)	3.93	4.32	4.32	5.16	2.50	3.25

the data obtained by the cloud radar and ceilometer–COMS. Conversely, when the CBH and CTH were observed by either the cloud radar or ceilometer–COMS, the differences in the data were relatively more significant. For instance, observations by the cloud radar (78 cases) showed average CBHs and CTHs of 5.04 and 7.54 km, respectively, indicating mainly high clouds with thicknesses of about 2.5 km. However, observations by ceilometer–COMS (225 cases) showed average CBHs and CTHs of 2.13 and 5.38 km, respectively, indicating mainly low clouds with thicknesses of 3.25 km. Although the average CBHs and CTHs were similar when cloud observations were made concurrently by the cloud radar and ceilometer–COMS, there were differences between the frequencies of occurrence determined for varying altitudes. The frequency of occurrence of CBH decreased gradually from the surface to the altitude of 10 km in the ceilometer observations, whereas the frequency of occurrence was concentrated below the altitude of 1 km in the cloud radar observations (Fig. 2a). Excluding the fact that the frequency of occurrence of clouds with top heights of 2–3 km was higher in the cloud radar observations, similar distributions were observed at most altitudes (Fig. 2b).

3.1.2. *Precipitation events*

In order to analyze the reason for the differences between the cloud radar and ceilometer–COMS data, the CBHs and

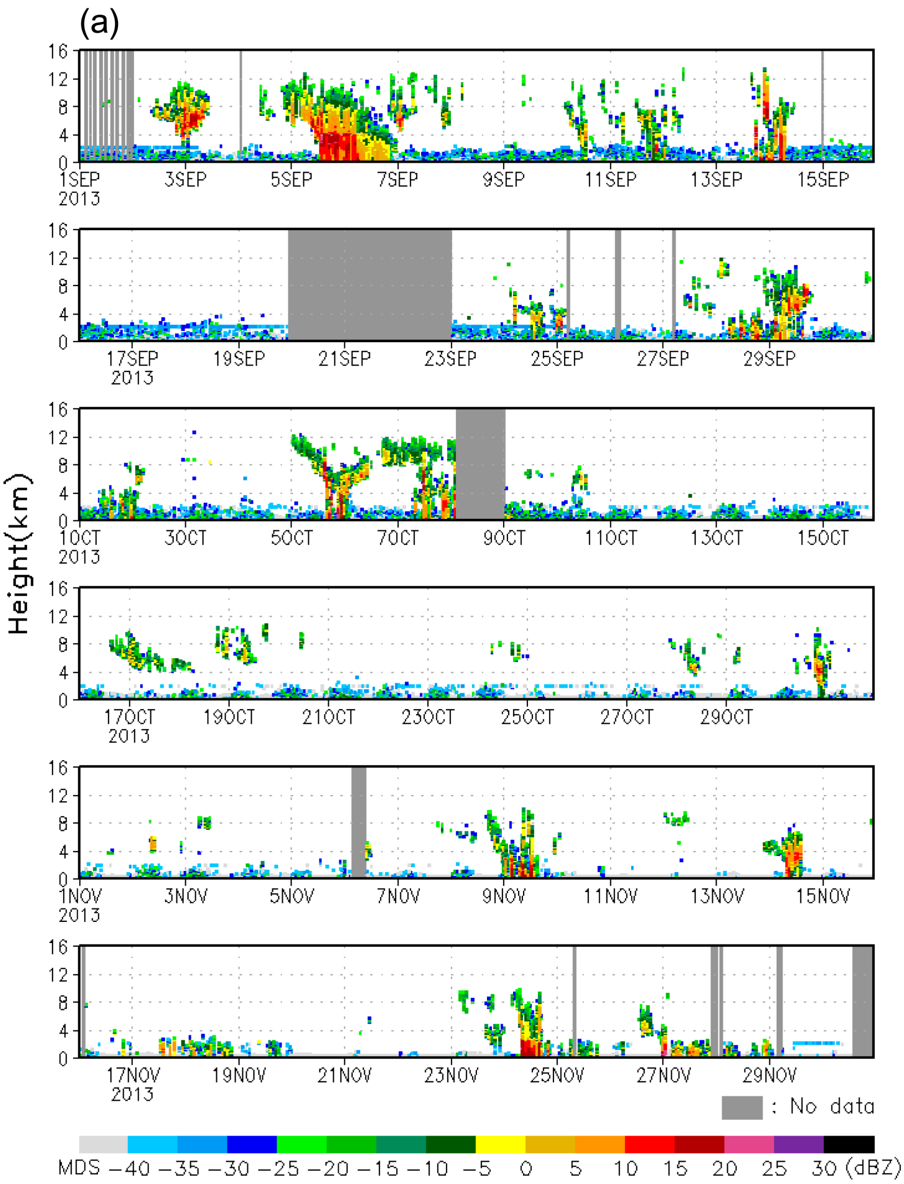

Fig. 1. (a) Time-height cross section of reflectivity (units: dB*Z*) observed by cloud radar from September to November 2013 and (b) cloud base (crosses) and top (circles) heights (units: km) observed by cloud radar (CR; blue) and ceilometer-COMS (Ceil; red). The gray and green shading indicates missing values and rainfall cases, respectively. MDS means minimum detectable signal.

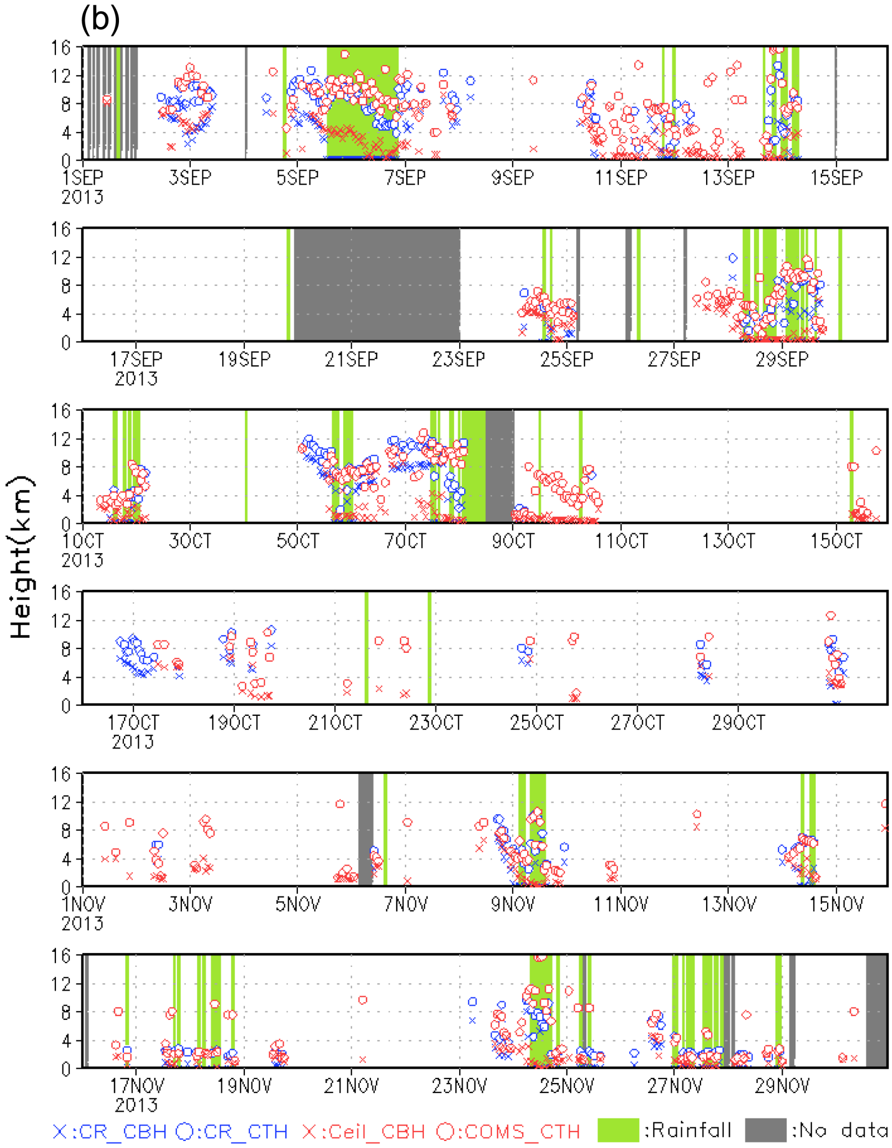

Fig. 1. (Continued.)

CTHs were compared based on whether precipitation had been present (Fig. 3). The cases in which rainfall was detected by the micro rain radar at the Boseong NCIO were defined as precipitation cases (125 cases), and the remainder defined as non-precipitation cases (160 cases). The CBHs obtained by the cloud radar were either similar to or higher than the values obtained by the ceilometer in non-precipitation cases (Fig. 3a). However, in precipitation cases, the CBHs observed by the cloud radar were similar to ground level, and for this reason, the frequency of low CBH was shown to be high in the cloud radar data, as shown in Fig. 2a. For the precipitation cases, the CTHs derived by cloud radar were similar to or lower than observed by COMS (Fig. 3b).

These results can be explained based on the observational characteristics of cloud radar. First, cloud radar transmits signals from the ground, and is thus influenced by meteorological phenomena occurring in the lower atmosphere. Figure 4a shows that similar CBHs were observed by the cloud radar and ceilometer before the occurrence of precipitation. However, in the precipitation cases, cloud radar reflectivity was even observed at the surface due to the raindrops. The bottom boundaries of the cloud radar reflectivity that appeared during rainfall can be explained by the hydrometeor boundaries, which have a different meaning to the CTHs. Therefore, during rainfall, the CTHs of the cloud radar need to be compensated using other ground observation data. Another characteristic of the cloud radar is that it uses short-wavelength signals to detect small cloud particles and therefore, signal attenuation occurs due to the large raindrops. This phenomenon was confirmed by the fact that the CTHs observed by the cloud radar were lower than observed by COMS in the precipitation cases (Fig. 4b).

The impact of precipitation could change depending on rainfall intensity. The differences between the CBHs and

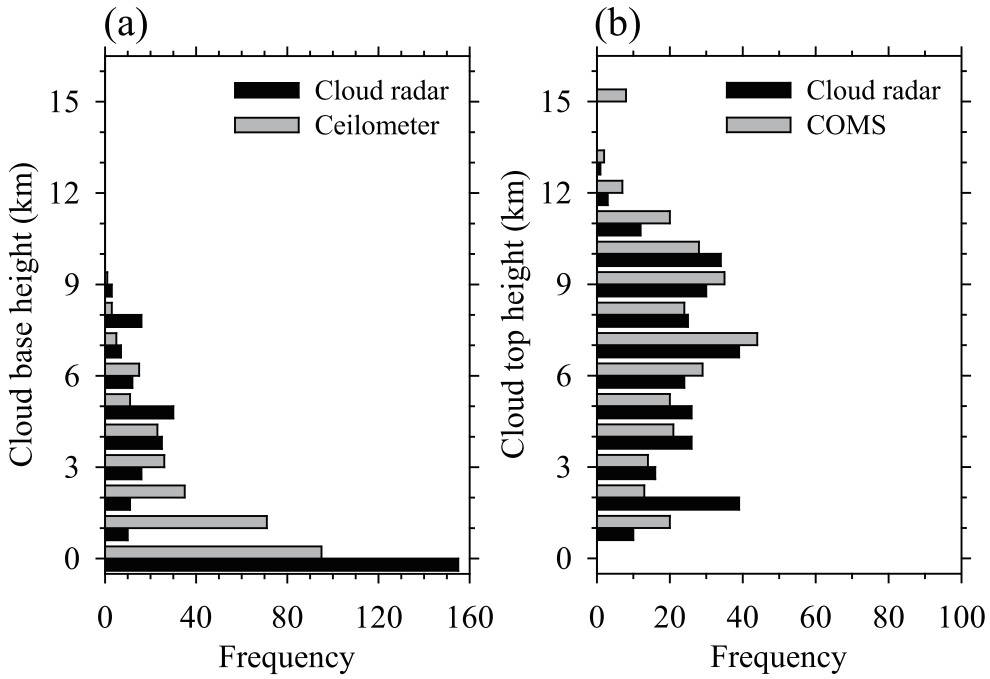

Fig. 2. Frequency of occurrence of cloud (a) base and (b) top heights observed by cloud radar (black) and ceilometer–COMS (gray).

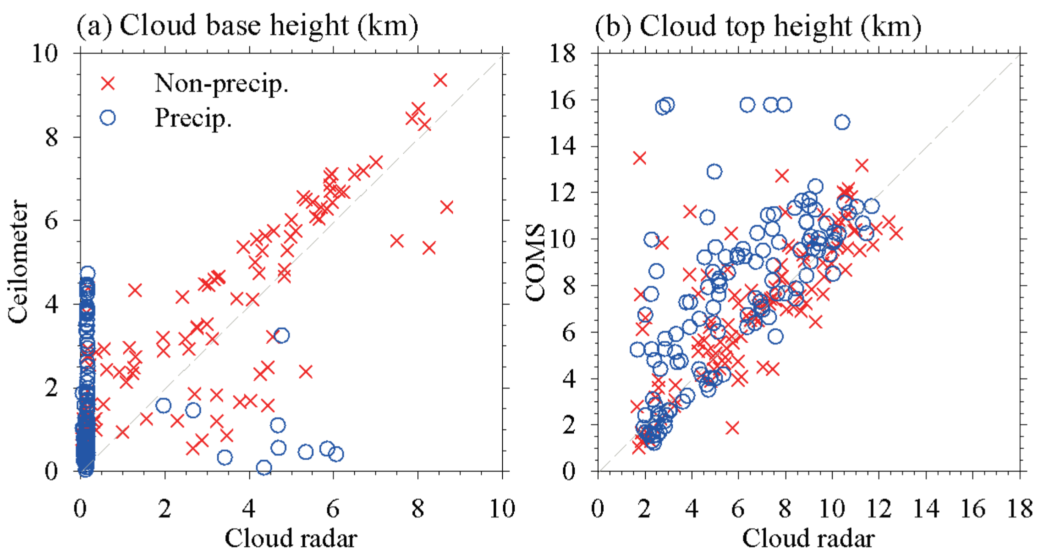

Fig. 3. Scatter plots of cloud (a) base and (b) top heights (km) observed by cloud radar and ceilometer–COMS. The crosses and circles indicate non-precipitation and precipitation cases, respectively.

CTHs obtained by the cloud radar and ceilometer–COMS and the micro rain radar at 200 m at varying rainfall rates were examined (Fig. 5). The results showed that at higher rainfall rates, CTHs observed by the cloud radar were lower than COMS (Fig. 5b). Generally, the CBHs observed by the cloud radar were lower than the ceilometer, but the difference decreased as the rainfall rate increased (Fig. 5a). This can be attributed to the ceilometer also being a ground-based instrument. In cases of heavy precipitation (>30 mm h^{-1}), the CBHs observed by the ceilometer were close to the ground, as was the case for the cloud radar.

3.1.3. *Cloud thickness and density*

Even in the non-precipitation cases, there were differences between the CBHs and CTHs observed by the cloud radar and ceilometer–COMS (Fig. 3). In order to determine the cause, the differences between the CBHs and CTHs observed by the cloud radar and ceilometer–COMS were exam-

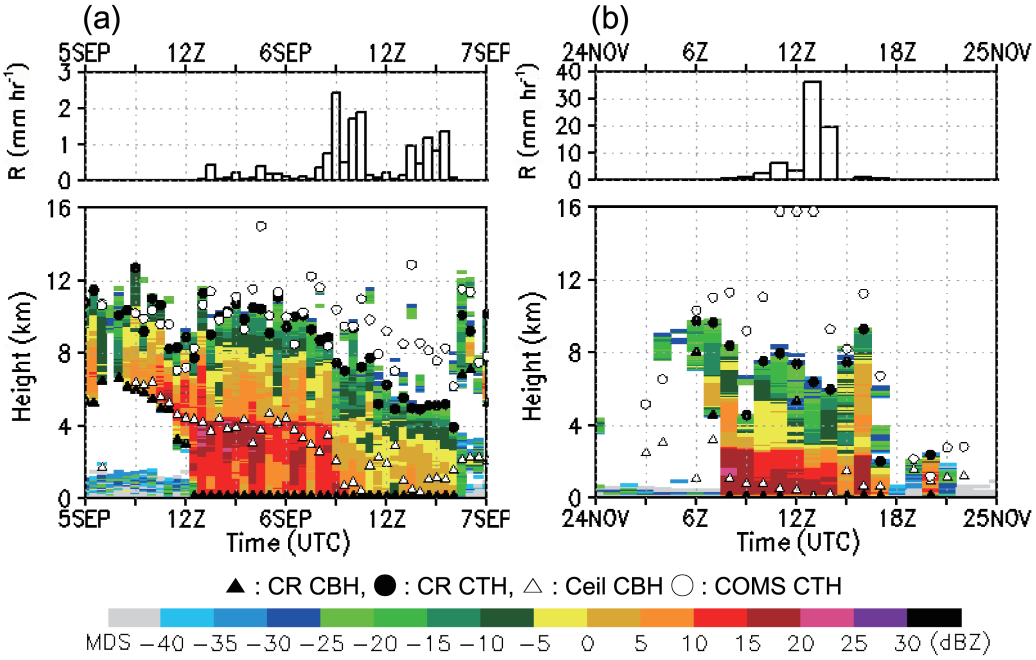

Fig. 4. Time-series of hourly rainfall rate (R; units: mm h^{-1}) observed by MRR (upper panels) and time–height cross sections of reflectivity (units: dB*Z*) and cloud base (triangles) and top (circles) height (lower panels) observed by cloud radar (CR) and ceilometer–COMS (Ceil) pn (a) 5–6 September 2013 and (b) 24 November 2013.

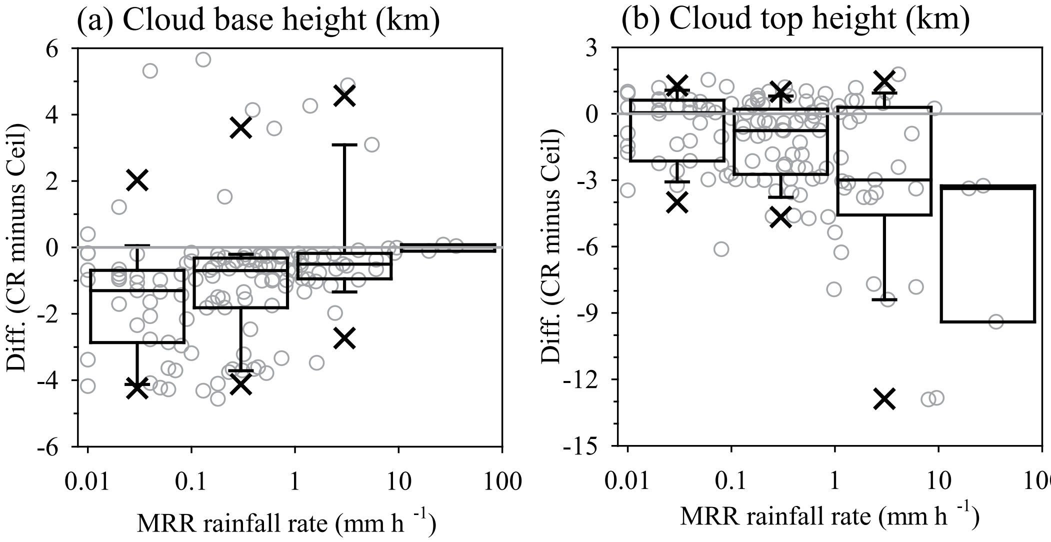

Fig. 5. Scatter plots and box plots of rainfall rate (units: mm h^{-1}) observed by MRR versus differences of cloud (a) base and (b) top heights (units: km) between cloud radar (CR) and ceilometer–COMS (Ceil). Boxes denote the 25th and 75th percentile positions, and the lines inside the box show the median; the whiskers denote the 10th and 90th percentile; outliers are indicated by the 5th and 95th percentile positions.

ined according to cloud thickness (Fig. 6). Cloud thickness was calculated using the cloud radar data. When the cloud was thick, the CBH and CTH values were relatively similar between the cloud radar and ceilometer–COMS, but there were significant differences for thin cloud.

The cloud radar observations of thin and high clouds showed higher sensitivity (Fig. 7a). The reason for this can be conjectured based on the observational characteristics of COMS: in the cases of thin and high clouds, the energy emitted from below the cloud is observed by the satellite, which can lead to a higher brightness temperature in the infrared channel than the actual cloud top temperature. However, even with thin clouds, similar CBHs and CTHs were observed by the cloud radar and ceilometer–COMS in some cases (Fig. 6).

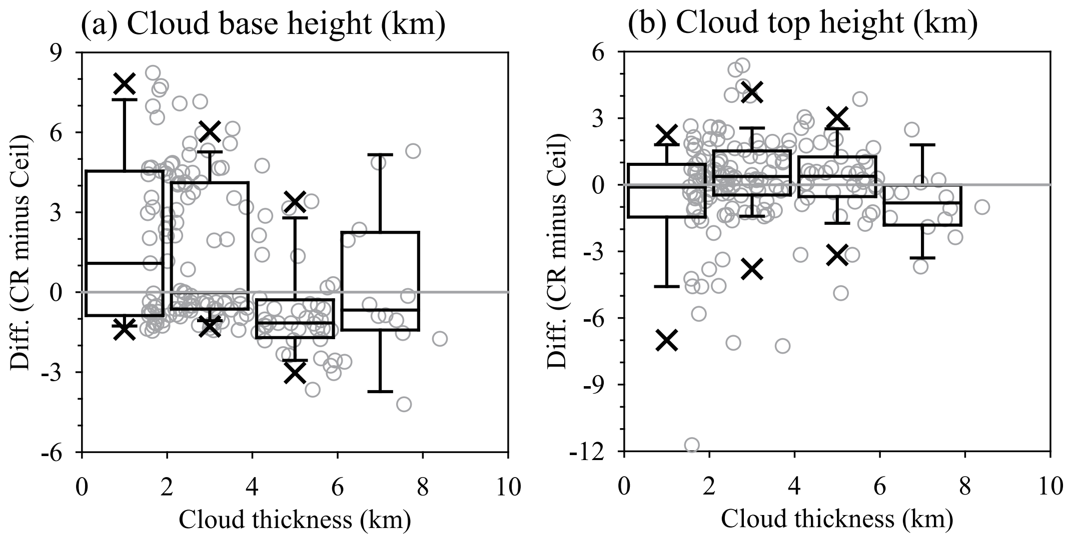

Fig. 6. Scatter plots and box plots of cloud thickness (units: km) versus differences of (a) CBHs and (b) CTHs (units: km) between cloud radar (CR) and ceilometer–COMS (Ceil). Boxes denote the 25th and 75th percentile positions, and the lines inside the box show the median; the whiskers denote the 10th and 90th percentile; outliers are indicated by the 5th and 95th percentile positions.

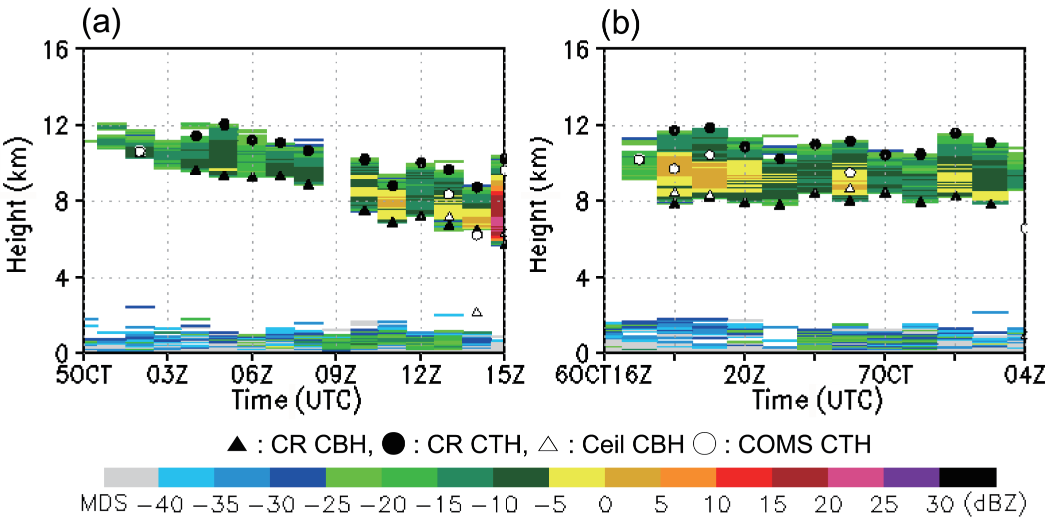

Fig. 7. Time-height cross sections of reflectivity (units: dB*Z*) and cloud base (triangles) and top (circles) height observed by cloud radar (CR) and ceilometer–COMS (Ceil) on (a) 5 (∼1500 UTC) October 2013 and (b) 6 (1600 UTC) to 7 (0300 UTC) October 2013.

Although the clouds were thin in such cases, the cloud radar reflectivity was greater than 0 dB*Z* (Fig. 7b). The reflectivity of the radar is a log of the ratio of the number of water droplets with diameter of 1 mm to the unit volume (1 m^3); therefore, it can be said that it provides information on the density of the cloud particles. Even in the case of thin clouds, if the cloud density is high, they will be observed effectively by ceilometer–COMS.

3.2. *Comparison of cloud types*

CBH and CTH data from the cloud radar and ceilometer–COMS were used to classify the cloud types observed at Boseong NCIO in the fall of 2013, based on the classification method of Kollias et al. (2007b) (Table 3). Using this method, clouds were classified as high, middle, and low depending on their CBHs and CTHs. Additionally, low clouds were subdivided into non-precipitable and precipitable clouds, and then the precipitable clouds subdivided further into shallow and deep precipitable clouds according to their CTHs. The frequency of occurrence during the entire analysis period of clouds observed by the cloud radar was the highest for low clouds (49.59%), followed by middle clouds (31.68%), and high clouds (18.73%), as shown in Fig. 8a. With respect to the monthly data, the aforementioned frequency pattern

Table 2. The classification of cloud types using CBH and CTH (Kollias et al., 2007b).

Cloud type			Height
High			CBH ⩾ 6 km
Middle			2 km ⩽ CBH < 6 km
Low	Non-precipitable		200 m ⩽ CBH < 2 km
	Precipitable	Shallow	CBH < 200 m CTH < 2 km
		Deep	CBH < 200 m CTH ⩾ 2 km

was also observed in September and November, whereas the frequency of occurrence of low clouds was lower than the other two types in October. Similar to the cloud radar data, the ceilometer–COMS data revealed that the frequency of occurrence was highest for low clouds (61.37%), followed by middle clouds (31.18%), and high clouds (7.45%), as shown in Fig. 8b. However, significant differences were found regarding the sub-classifications of low clouds. For instance, deep precipitable clouds were observed mainly by the cloud radar (Fig. 8a), whereas non-precipitable clouds were observed mainly by ceilometer–COMS (Fig. 8b).

Cases of precipitable and non-precipitable cloud types were also examined (not shown). In the case of precipitable clouds, low clouds were observed mostly by the cloud radar (92.8%) and ceilometer–COMS (76.8%). However, different frequencies of cloud type were observed in the cases of non-precipitable clouds between the cloud radar (middle 46.25% > low 30.63% > high 23.13%) and ceilometer–COMS (low 43.75% > middle 41.25% > high 15.00%). The results of sub-classifying the low clouds showed that, in the event of precipitation, deep precipitable clouds (97.41%) were observed mainly by the cloud radar, whereas the frequency of non-precipitable clouds (94.79%) was highest in the ceilometer–COMS observations. In the event of non-precipitation, the cloud radar did not observe any one particular cloud type more frequently, while non-precipitable clouds (100%) were still observed with high frequency by the ceilometer–COMS.

This could be explained by the fact that, in the event of precipitation, the CBH is observed to be close to ground level by the cloud radar, whereas the CBH observed by ceilometer–COMS is greater than 200 m. However, the CBH observed by the cloud radar is lower than the actual height because of the influence of the precipitation and thus, there is a need for a new set of cloud classification criteria for cases in which the CBH values require correction based on ceilometer–COMS data.

4. Cloud radar data correction and characteristic analysis

Although the cloud radar made high-sensitivity observations in the absence of precipitation, data obtained during the occurrence of precipitation were unreliable. Thus, in cases of

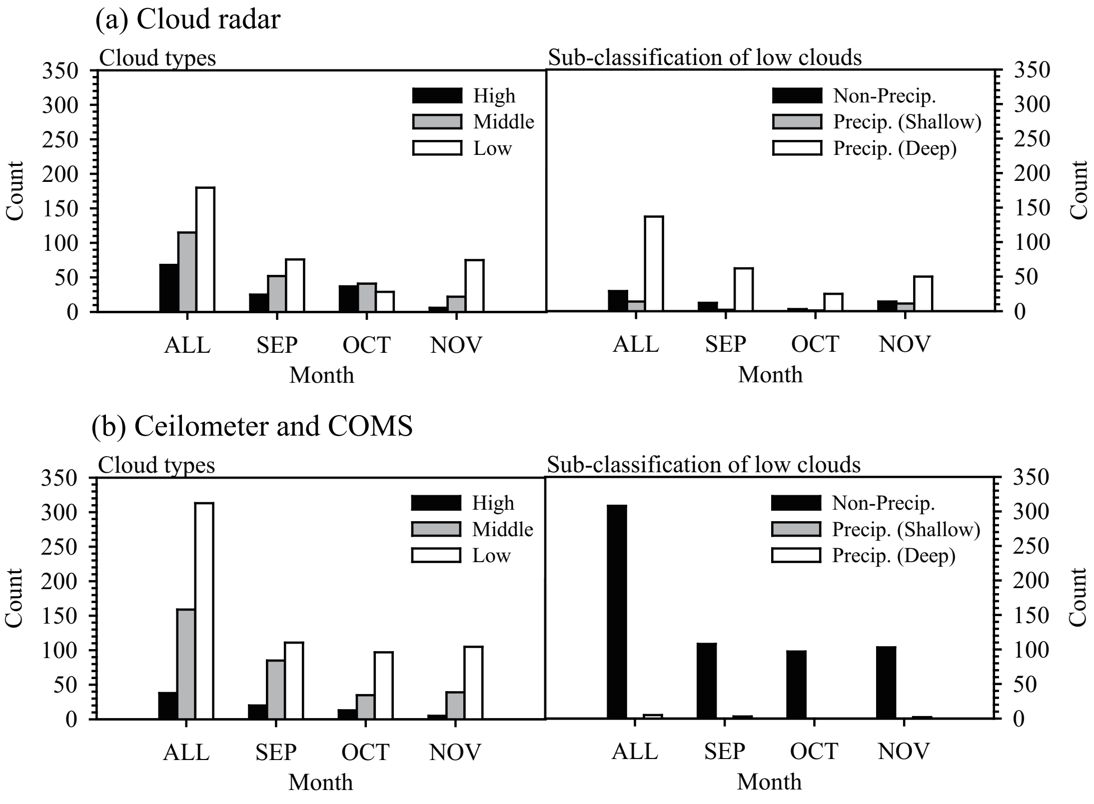

Fig. 8. Occurrence counts of cloud types observed by (a) cloud radar and (b) ceilometer–COMS.

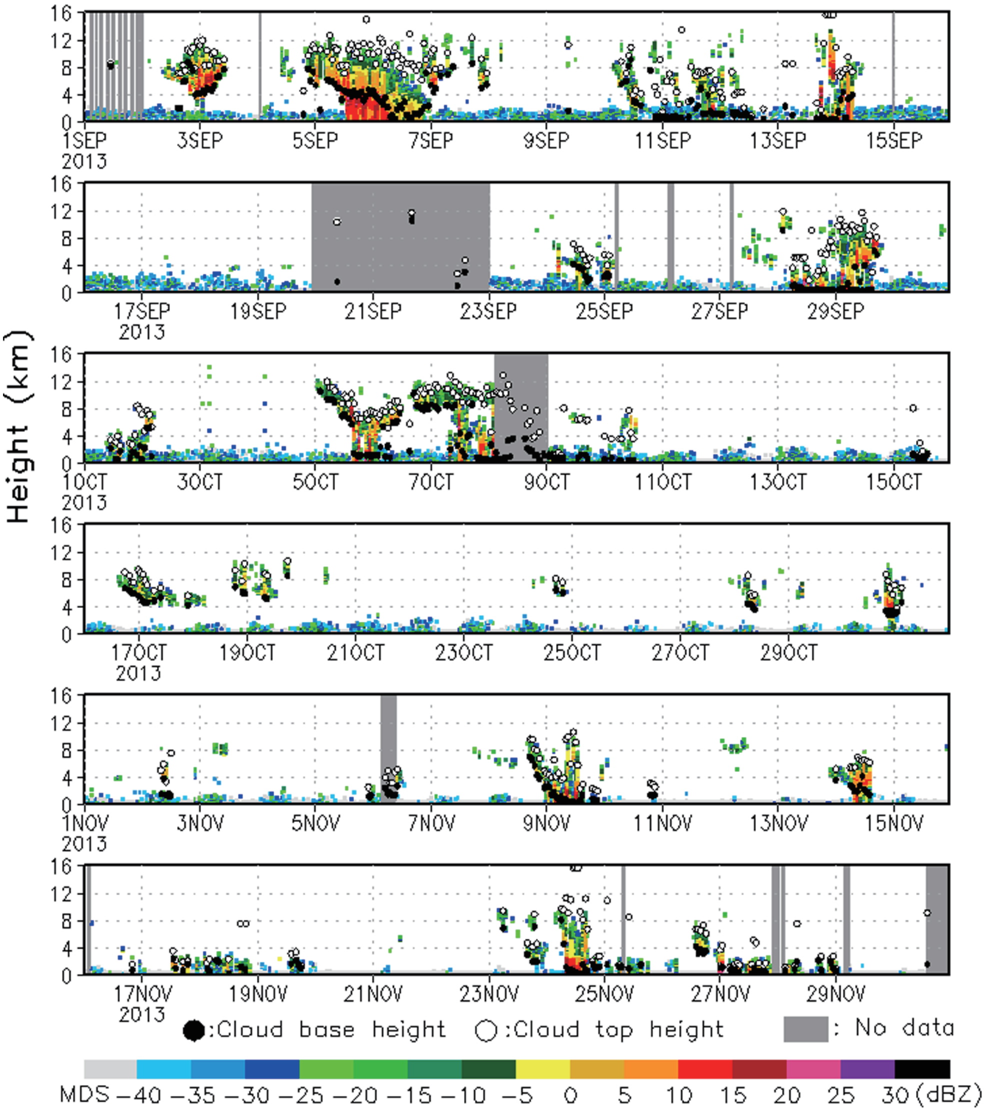

Fig. 9. Time–height cross section of reflectivity (units: dB*Z*) and cloud base and top height using corrected cloud radar data. The gray and green shading indicates missing values and rainfall cases, respectively.

precipitation or missing cloud radar data, the CBH and CTH values obtained from the cloud radar were corrected using ceilometer–COMS data (Fig. 9).

Using the corrected CBH and CTH data, the cloud types were re-classified. Similar to the pre-correction cloud classification results, the cloud types in decreasing order of frequency of occurrence were: low clouds (54.55%) > middle clouds (32.59%) > high clouds (12.86%) (Fig. 10). Data obtained in October showed that the frequency of occurrence of low clouds increased following the correction, which was attributed to the occurrence of low clouds mainly under conditions of strong winds that resulted in missing data values. The result of sub-classifying the low clouds (not shown) was similar to the result obtained from ceilometer–COMS (Fig. 8b). This was thought to be because low clouds occurred most frequently during precipitation events, which meant that cloud radar data were substituted by ceilometer–COMS data. In such cases, the reference value for the CBH (200 m) in the sub-classification of low clouds was changed appropriately to the corrected data. Based on the corrected data, the average CBH of 1.27 km was used during precipitation events for the sub-classification of low clouds, and the results are shown in Fig. 10. The cloud type with the highest frequency of occurrence was deep precipitable clouds, followed by non-precipitable clouds, and shallow precipitable clouds.

5. Summary and conclusions

In this study, the CBHs and CTHs observed by the Ka-band cloud radar at the Boseong NCIO in the fall of 2013 (September–November) were verified and corrected. For the purposes of this study, a cloud was defined as cases in which

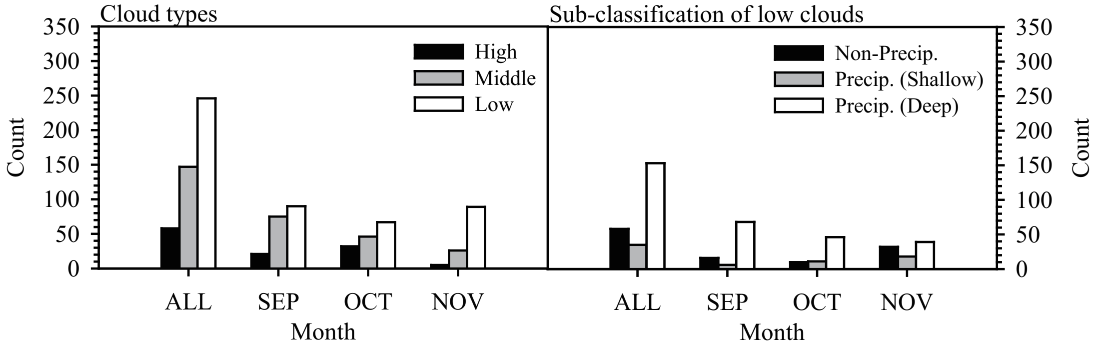

Fig. 10. As in Fig. 8, but using corrected cloud radar data.

the cloud radar observed reflectivity values of greater than −30 dB*Z* and with a thickness of 1.5 km. For comparison, cases in which the CBH observed by the ceilometer and the CTH observed by COMS occurred concurrently were defined as a cloud.

First, the CBH and CTH data obtained by the cloud radar and ceilometer–COMS were compared. In cases of precipitation, the CBHs and CTHs observed by the cloud radar tended to be lower than the actual heights. The reason for this could be explained by the observational characteristics of the cloud radar. Cloud radar is a ground-based observation system, which is affected by meteorological phenomena occurring in the lower levels of the atmosphere. Of particular note, as the cloud radar uses a millimeter-wavelength signal to detect the small cloud particles, signal attenuation occurs in the presence of raindrops. For this reason, the radar-derived CBHs were observed to be closer to the ground, while the CTHs were observed to be lower than the actual heights. In the absence of precipitation, the CBHs and CTHs observed by the cloud radar and ceilometer–COMS were similar. Thin or low-density clouds were observed more effectively by the cloud radar compared with ceilometer–COMS.

The result of classifying the cloud types observed by the cloud radar and ceilometer–COMS showed that the frequency of occurrence was highest for low clouds, followed by middle clouds, and high clouds. Sub-classification of low clouds occurring in precipitation cases showed that deep precipitable clouds were observed mainly by the cloud radar, whereas non-precipitable clouds were observed mainly by ceilometer–COMS. The cloud radar data obtained during the occurrence of precipitation could not be considered reliable. Thus, it was deemed necessary to correct the cloud radar data using the ceilometer–COMS data and to establish new criteria for the sub-classification of cloud in such cases.

Based on these results, for cases of precipitation or missing data, the cloud radar data were corrected using the ceilometer–COMS data and re-classified using the new reference value. The reference value for the CBH (200 m) was changed to 1.27 km for the sub-classification in cases of precipitation.

The results of this study show that cloud radar could effectively provide a description of cloud boundaries in the absence of precipitation. However, cloud radar data are deemed unreliable in the presence of precipitation. In such cases, it is proposed that the radar data be corrected using data obtained from other observational systems such as a ceilometer or satellite. It is expected that future research involving analyses of the liquid water content and rain-rate estimation, with a focus on the microphysical characteristics of clouds, will contribute to the understanding of the mechanisms and characteristics of cloud formation.

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