



23        **Abstract.** Using the vertical velocity ( $w$ ) observed by a Ka-band millimeter wave cloud radar (MMCR)  
24 at Wuhan, we investigate the evolution of convective boundary layer height (CBLH) based on a specified  
25 threshold of vertical velocity variance ( $\sigma_w^2$ ). The CBLHs from the MMCR  $w$  in the selected durations are  
26 compared with those estimated by the lidar range corrected signal (RCS) and radiosonde temperature based  
27 on different algorithms, showing good agreement with each other. Although these algorithms are on basis of  
28 different dynamic and thermodynamic effects, the diurnal evolution of CBLH from MMCR is generally  
29 consistent with that from lidar, except for a few hours post-sunrise and pre-sunset due to the influence of  
30 aerosol residual layer on the lidar RCS. Meanwhile, the CBLH from MMCR shows less variation in  
31 occurrence of sand and dust, and swifter response of thick clouds, relative to that from lidar. In this case,  
32  $\sigma_w^2$  of the MMCR  $w$  identifies the CBLH based on dynamic effect, which can accurately capture the  
33 diurnal evolution of CBLH compared with that from the change of long time-mixing aerosol concentration.  
34 The monthly and seasonal features of CBLH at Wuhan is revealed via the MMCR measurement. Hence,  
35 considering that the MMCR is capable of continuous observation in various weather conditions, the MMCR  
36  $w$  with high resolution can be applied to monitoring the evolution of CBLH in different atmospheric  
37 conditions, which is helpful for improving our comprehensive understanding of CBL and dynamic processes  
38 in CBL.

39

## 40 1. Introduction

41        The planetary boundary layer (PBL) is located in the lower part of the troposphere, and is where the  
42 air-land (or air-sea) interaction takes place, thus the PBL is directly impacted by the surface forcings (Stull,  
43 1988). Owing to the combined effects of friction, evaporation and transpiration, heat transfer, and pollutant  
44 emission, the PBL is characterized by complex dynamical processes, with the prominent turbulence features  
45 of vorticity and compressibility (Bernardini et al., 2012; Schneider, 2008). The height of PBL varies with

46 local time, ranging generally from a few tens of meters to a few kilometers at mid latitudes. Since the PBL  
47 regulates the exchange of momentum, moisture and mass between the ground and the free atmosphere  
48 (Mahrt, 1999; Holtslag and Nieuwstadt, 1986), the structure of PBL is an important input variable in  
49 numerical weather-prediction and climate models (Edwards et al., 2020).

50 The convective boundary layer (CBL) is a type of PBL driven primarily by convection, and the CBL  
51 height (CBLH) has a distinct daily cycle. Convective sources include heat transfer from the ground surface  
52 warmed by solar radiation, and radiative cooling-induced air sinking from the cloud top, thus the evolution  
53 of CBL is mainly dominated by surface sensible heat, which is significantly influenced by weather  
54 conditions, such as clouds, and humidity near the surface (Kwon et al., 2022; Ribeiro et al., 2018; Zhang et  
55 al. 2014). On a clear day, the CBLH rises after sunrise and reaches its maximum in the afternoon (LeMone  
56 et al., 2010; Grossman and Robert, 2005; Yates et al., 2001). When the CBL collapses after sunset, most of  
57 aerosol particles within the CBL are deposited into the nocturnal stable PBL due to the rapid weakening of  
58 convectively driven turbulence, and some particles are transformed into an aerosol residual layer. The  
59 residual layer descends gradually due to the sinking effect until it is mixed with the CBL driven by the next  
60 day's post-sunrise convection (Blay-Carreras et al., 2014; Heus et al., 2010; Tennekes and Driedonks, 1981).  
61 At the CBL top, moisture, aerosols and other chemical substances can be entrained to the free atmosphere,  
62 leading to an entrainment transition zone between the CBL and the free atmosphere (Franck et al., 2021; Liu  
63 et al., 2021; Brooks and Fowler, 2007). Hence, the CBL has an influence not only on the dispersion of  
64 surface emissions and pollutants (Kong and Yi, 2015; Pal et al., 2015; Stull, 1988), but also on the weather  
65 processes above it through the entrainment process (Guo et al., 2017; Brooks and Fowler, 2007; Neggers et  
66 al., 2004).

67 The observations of in situ radiosonde and remote sensing are extensively used to estimate the CBLH  
68 and its seasonal features. Radiosonde can obtain high-precision meteorological parameters, such as

69 temperature, humidity, horizontal wind and pressure, providing the possibility of estimating CBLH through  
70 various algorithms (Seidel et al., 2010; Seibert, 2000). Typically, the vertical gradients of potential  
71 temperature and water vapor (including relative humidity and specific humidity) are used to determine the  
72 CBLH (Zhang et al., 2022; Guo et al., 2021; Dang et al., 2019; Liu and Liang, 2010; Seidel et al., 2010).  
73 Additionally, the CBL top can be evaluated using the profiles of refractivity and bulk Richardson number  
74 derived from the temperature, pressure, vapor pressure and horizontal wind data (Burgos-Cuevas et al., 2021;  
75 Guo et al., 2016; Zhang et al., 2014; Seidel et al., 2012; Basha and Ratnam, 2009). These retrieval  
76 algorithms provide insights into the features of CBL from the perspective of energy exchange, mass  
77 transport, turbulent motion and effect on radio propagation. Even so, radiosonde faces a severe limitation in  
78 capturing the clear development of CBL due to its conventional release schedule, which typically occurs  
79 only twice a day.

80 In contrast to radiosonde, ground-based remote sensing offers high-temporal resolution in observational  
81 profiles, which is essential to investigate the diurnal evolution of CBL. Wind profile radar can measure the  
82 atmospheric wind speed and direction by analyzing the Doppler shift of the backscattered waves of multiple  
83 beams (Liu et al., 2019; Singh et al., 2016; Seibert, 2000). The electromagnetic beams are reflected back due  
84 mainly to the atmospheric refractive index change caused by the non-uniform vertical structure of the  
85 atmosphere, such as vertical gradients in temperature, humidity, and turbulence, thus received echo and  
86 retrieved wind from radar contain the information related to the atmospheric vertical structure. In this way,  
87 several parameters from the wind profile radar measurement, such as signal-to-noise ratio, Doppler spectral  
88 width, and refractive index structure constant, are utilized to retrieve the CBLH for every 30-60 minutes  
89 based on their vertical gradients or chosen thresholds (Burgos-Cuevas et al., 2023; Bianco et al., 2022;  
90 Solanki et al., 2021; Allabakash et al., 2017; Sandeep et al., 2014). Nevertheless, previous studies showed  
91 that the top of CBL derived from the radar observation may be influenced by strong residual layer and

92 shallow or large entrainment zone (Sandeep et al., 2014; Bianco and Wilczak, 2002).

93 Lidar is regarded as a powerful detection equipment for capturing the CBL development due to its high  
94 sensitivity to echo signals from various atmospheric components. Its relatively short operating wavelength  
95 allows it to receive echoes backscattered not only from aerosol and cloud particles, but also from  
96 atmospheric molecules. Nevertheless, since Rayleigh scattering of atmospheric molecules is much weaker  
97 than Mie scattering of aerosol particles, the profile of lidar backscatter coefficient or range corrected signal  
98 (RCS) from aerosols is applied to determining the CBLH by tracing the height where the aerosol  
99 concentration sharply decreases with height. Accordingly, many techniques have been developed to identify  
100 the extreme value of RCS gradient (Liu et al., 2021; Su et al., 2020; Dang et al., 2019; Yang et al., 2017;  
101 Granados-Muñoz et al., 2012). As a simplified low-power lidar, ceilometer is initially designed to measure  
102 the height of cloud base, thus similarly, the backscatter profile in the ceilometer observation can be  
103 employed in the CBL investigation (Zhang et al., 2022; Schween et al., 2014; Van Der Kamp and McKendry,  
104 2010). However, due to the incapability of lasers to penetrate clouds, the CBLH may be contaminated and  
105 even misinterpreted by clouds within the CBL in the lidar and ceilometer measurements (Schween et al.,  
106 2014).

107 With the advances in atmospheric sounding technology, the vertical velocity from Doppler lidar provides  
108 a direct estimation of CBLH, which can reduce the impact of strong aerosol concentration within the  
109 residual layer on the retrieved CBLH (Burgos-Cuevas et al., 2023; Dewani et al., 2023; Huang et al., 2017;  
110 Schween et al., 2014; Barlow et al., 2011). At the initial stage of CBL formation in the morning and the  
111 rapid decline stage of CBL in the late afternoon (Dewani et al., 2023; Manninen et al., 2018; Schween et al.,  
112 2014; Barlow et al., 2011), aerosol particles in the residual layer may cause the CBLH to be overestimated  
113 several hundred meters. This discrepancy is due to aerosols from a long time-mixing process rather than the  
114 current situation of convectively driven turbulence (Burgos-Cuevas et al., 2023; Schween et al., 2014;

115 Pearson et al., 2010). When utilizing Doppler lidar data, a specified threshold of vertical velocity variance is  
116 used to define the height of CBL top. This method has been validated by comparison with the radiosonde  
117 observation (Dang et al., 2019; Li et al. 2017; Granados-Muñoz et al., 2012), and the sensitivity of threshold  
118 has been discussed across different sites (de Arruda et al., 2018; Manninen et al., 2018; Schween et al., 2014;  
119 Barlow et al., 2011; Pearson et al., 2010). A disadvantage of lidar is that it has a large blind range and  
120 incapability to penetrate clouds, thus because of that, it is valuable to utilize microwave cloud radar that  
121 offers good low altitude coverage and superior performance in cloud penetration. In the cloud observation, a  
122 weak echo layer always exists near the surface, from which the vertical velocity can be retrieved. However,  
123 there are few reports utilizing vertical velocity obtained from Doppler cloud radar for the CBL  
124 investigations.

125 In present study, we estimate the CBLH based on the vertical velocity from a Ka-band millimeter wave  
126 cloud radar (MMCR) at Wuhan, and compared this result with that derived from the lidar RCS by three  
127 algorithms, and from radiosonde data by two algorithms. These algorithms are on basis of different dynamic  
128 and thermodynamic effects, respectively, thus the comparison enhances our comprehensive understanding of  
129 CBL and retrieval algorithms. Then, the general features of monthly and seasonal mean CBLHs are studied  
130 by using the MMCR observation with high-temporal resolution. In section 2, the MMCR, lidar and their  
131 data are briefly described. In Section 3, we discuss the methods that are used to identify the CBL top from  
132 the MMCR, lidar and radiosonde measurements. In section 4, we present four examples of CBLH diurnal  
133 evolution in different seasons by comparing the CBL tops retrieved from the MMCR and lidar  
134 measurements, and then investigate the monthly and seasonal mean CBLHs over Wuhan in Section 5.  
135 Section 6 provides a summary.

136

## 137 **2. Instruments and Data**

138 In this study, the CBLH derived from the MMCR measurements is compared with that from the lidar  
139 measurements. The Ka-band MMCR and lidar are situated at the Atmospheric Remote Sensing Observatory  
140 (ARSO) in Wuhan University (WHU, 30.5°N, 114.4°E). Wuhan, an inland megacity in central China, is  
141 located in the east of Jiangnan Plain, with a resident population of over 12 million. The climate of the city is  
142 humid, dominated by the subtropical monsoon, which is characterized by abundant precipitation and four  
143 distinct seasons (Guo et al., 2023). Due to heavy traffic and industrial activities, large amounts of aerosols  
144 are emitted from the industrialized metropolis. Sandstorms from the northwest often pass through Wuhan,  
145 especially in spring. These sandstorms cause the remarkable variation in the spatial distribution and  
146 concentration of aerosols. Frequent sand and dust activity along with cloudy weather poses significant  
147 challenges for the Ka-band MMCR and lidar in accurately capturing the CBL evolution.

## 148 **2.1 Ka-Band Radar**

149 The WHU-CW MMCR established by the ARSO adopted a continuous wave (CW) system, and is a  
150 Ka-band frequency-modulated continuous wave (FMCW) Doppler radar. The MMCR is installed in WHU,  
151 as shown in Figure 1. The radar system transmits a mean power of 50 W at operating frequency of 35.035  
152 GHz through 0.38° width beam formed by a Cassegrain antenna with 1.5 m diameter. Backscatter echoes  
153 from aerosol and cloud particles are received by the other same Cassegrain antenna, and then are sent to the  
154 signal processing subsystem to obtain the radial distribution of parameters that represent the characteristics  
155 and motion of particles, such as reflectivity factor, Doppler velocity, and Doppler spectrum width. Because  
156 of almost continuous transmitting and receiving, FMCW radar has generally a much higher mean power  
157 relative to pulse radar, which improves the capacity of MMCR to detect weak echo targets. Meanwhile, by  
158 modulating and demodulating the continuous wave, the FMCW radar measurement has an adjustable range  
159 and time resolution. In non-precipitation, the MMCR measurement has a temporal resolution of 0.26 s and a  
160 maximum measurable velocity of 4.30 m s<sup>-1</sup> without aliasing effect, which are adjusted to be 0.104 s and

161 10.75 m s<sup>-1</sup> in precipitation as the size and falling speed of hydrometeors increase (Mao et al., 2023),  
162 respectively. The MMCR observation has been applied to the investigations of cloud and precipitation over  
163 Wuhan in previous works (Fang et al., 2023; Mao et al., 2023).

164 The MMCR has a maximum detectable distance of about 30 km and a sensitivity of -30 dBZ at the  
165 distance of 10 km. In the MMCR measurement, there are weak echoes generally less than -40 dBz within a  
166 few kilometers above the surface. The weak echoes near the surface are attributed to the backscattering of  
167 small insects and aerial plankton in some studies (Franck et al., 2021; Chandra et al., 2010; Achtemeier,  
168 1991), and are also suggested to come from the scattering of dust particles in other studies (Görsdorf et al.,  
169 2015; Clothiaux et al, 2000; Moran et al., 1998). Considering that the size of large dust particles, plant  
170 aerosol particles, and aerosol particles from combustion can be much larger than 10 μm, it is possible for the  
171 large aerosol particles to cause these weak echoes observed by MMCR. The servo-mechanical subsystem  
172 conducts the MMCR to work in specified directional mode or scanning mode. In 2020, the MMCR was  
173 operated in the vertical pointing mode, and the observation is recorded with a vertical resolution of 30 m. In  
174 this study, we attempt to explore the CBL evolution at Wuhan from the Ka-band MMCR observation in  
175 2020.

## 176 **2.2 Polarization Lidar**

177 The WHU-PL polarization lidar developed by the ARSO is also located in WHU, about 0.5 km from the  
178 Ka-band MMCR. The lidar telescope is 70 m above sea level, which is about 30 m higher than the MMCR  
179 antenna. Expanded laser beam overlaps with the full view field of the receiving telescope at a height of 0.3  
180 km, thus this height is the low limit of lidar detection. The lidar data has a temporal resolution of 1 min, and  
181 the same vertical resolution of 30 m as the MMCR data. In this study, we regard the height of MMCR  
182 antenna as a baseline, and then the initial height of lidar data is set at 0.33 km.

183 The lidar system consists of transmitting subsystem receiving subsystem and information processing



184 subsystem. The lidar vertically emits the laser pulses of 120 mJ at operating wavelength of 532 nm with a  
185 repetition rate of 20 Hz by a frequency-doubled Nd: YAG laser. The output polarized laser beam has a fine  
186 polarization purity with depolarization ratio less than 1:10000 by using a Brewster polarizer. Light  
187 backscattered by aerosol and cloud particles and atmospheric molecules is collected by a telescope with 0.3  
188 m diameter. After separated through an interference filter with 0.3 nm bandwidth centered at 532 nm, the  
189 elastically backscattered light is incident on a polarization beam splitter prism, and then the two-channel  
190 polarized light are focused onto two photomultiplier tubes (PMTs), respectively. The signals from the two  
191 PMTs are transferred to a personal computer (PC)-controlled two-channel transient digitizer, which can  
192 obtain the echo signal intensity and volume depolarization ratio through the PC processing. Backscatter  
193 coefficient is retrieved based on the backward iteration algorithm under the condition of a given lidar ratio  
194 proposed by Fernald and Klett (Fernald, 1984; Klett, 1981), and then the RCS is derived from the  
195 backscatter coefficient (Freudenthaler et al., 2009; Immler and Schrems, 2003). The lidar configuration and  
196 depolarization comparison with the measurement from the cloud-aerosol lidar and infrared pathfinder  
197 satellite observation (CALIPSO) were in detail described in the early study (Kong and Yi, 2015).

198

### 199 **3. Methodology**

200 Given that the CBLH is estimated from instruments that retrieve different variables, the algorithms that  
201 are utilized to make such estimations are also based on different principles, which are explained in the  
202 following subsections.

#### 203 **3.1 Gradient, Variance and Wavelet Transformation Methods**

204 In the lidar observation, the CBLH is derived from the RCS, which is approximately proportional to the  
205 aerosol concentration (Kong and Yi, 2015; Lewis et al., 2013; Pal et al., 2010; Emeis et al., 2008). Generally,  
206 aerosols are well-mixed within the CBL due to the convectively driven turbulence, and its concentration

207 decays sharply over the CBL top. Hence, the gradient (Grd) method is often utilized to investigate the  
208 CBLH by identifying the strongest or minimum gradient of RCS. The wavelet covariance transformation  
209 (WCT) method, with a chosen Harr wavelet function, estimates the CBL top by investigating the correlation  
210 of the RCS variation with a step function (Zhang et al., 2021; Angelini and Gobbi, 2014; Pal et al., 2010;  
211 Baars et al., 2008; Brooks, 2003). Essentially, the WCT method can be considered as a smooth enhancement  
212 of Grd method, which may be less affected by noise than the Grd method (Davis et al., 2000; Baars et al. al.,  
213 2008).

214 On the other hand, because of the entrainment process, there is a frequent exchange of matter and energy  
215 between the CBL and the free atmosphere, causing the dramatic variation of aerosol concentration or lidar  
216 RCS on small time scales around the CBL top (Zhang et al., 2018; Kong and Yi, 2015). In this case, the  
217 variance (Var) method is used to determine the CBL top by identifying the maximum variance of RCS  
218 during a relatively long period (Lammert and Bösenberg, 2006; Martucci et al., 2004; Piironen and Eloranta,  
219 1995). We estimate the CBLH from the lidar RCS in a period of 30 min by using the three methods, for  
220 instance, the CBLH at 12:00 LT (the same below) is calculated based on the RCS data from 11:45 to 12:15.

### 221 **3.2 Threshold Method**

222 The variance ( $\sigma_w^2$ ) of vertical velocity ( $w$ ) is representative of the level of turbulent activity, thus a  
223 threshold of  $\sigma_w^2$  is applied to determining the CBLH in the Doppler lidar measurement. The threshold is  
224 chosen to be  $0.04 \text{ m}^2 \text{ s}^{-2}$  in the regions with weak turbulence (Tucker et al., 2009),  $0.3 \text{ m}^2 \text{ s}^{-2}$  in a tropical  
225 rainforest (Pearson et al., 2010), and  $0.4 \text{ m}^2 \text{ s}^{-2}$  in the regions with central European climate (Schween et al.,  
226 2014; Träumner et al., 2011), while the thresholds of  $0.1$  and  $0.2 \text{ m}^2 \text{ s}^{-2}$  are selected in the urban landscapes  
227 since the retrieved CBLH is not heavily dependent on the given thresholds (Burgos-Cuevas et al., 2023;  
228 Huang et al. 2017; Barlow et al., 2011). Similarly, the threshold method is also used to determine a CBLH  
229 from the more than 6000  $w$  profiles in the MMCR measurement during a period of 30 min.

230 Figure 2 presents the distribution of  $w$  from the Ka-band MMCR observation and RCS (in arbitrary  
231 unit) from the lidar measurement on 15 August 2020. The day is 3 days later than the rainy day of 12 August.  
232 By taking observations for a period of 30 min from 11:45 to 12:15, we calculate the mean  $w$  and RCS, and  
233 estimate the position of CBL top by means of different algorithms, which are shown in Figure 3. From the  
234 lidar RCS, the CBLH is 1.35 km in the Grd and WCT methods, and 1.32 km in the Var method. In the  
235 MMCR observation,  $\sigma_w^2$  has a clear downward trend with increasing height, with the values of about 1.36  
236  $\text{m}^2 \text{s}^{-2}$  from the near ground to 0.15  $\text{m}^2 \text{s}^{-2}$  at 1.47 km, and then maintains slight fluctuations around the value  
237 of 0.15  $\text{m}^2 \text{s}^{-2}$  to higher altitudes. For a specified threshold of 0.3  $\text{m}^2 \text{s}^{-2}$ , the CBL top is identified at the  
238 height of 1.35 km, which is in agreement with the lidar results.

239 It can be noted from Figures 3d and 3f that the CBLHs in the mean RCS profile are around the position  
240 with the most rapid change, while the CBLH retrieved from the MMCR  $\sigma_w^2$  is not related to the vertical  
241 variation of mean  $w$ .  $\sigma_w^2$  indicates the turbulence level under the current condition, whereas, RCS tends to  
242 reflect the variation in the concentration of long time-mixing aerosol particles caused by dynamic effects  
243 (Kotthaus et al., 2023). Hence, the threshold method is a dynamical algorithm, which is more effective in  
244 capturing the dynamic changes within the CBL compared to the aerosol concentration algorithm based on  
245 the lidar RCS. In this way, the MMCR observes the high-temporal resolution data of  $w$ , making it available  
246 for analyzing diurnal evolution of CBL in different months and seasons. However, based on earlier studies,  
247 the selected threshold values are subject to change across the different regions (Burgos-Cuevas et al., 2023;  
248 Schween et al., 2014; Pearson et al., 2010; Tucker et al., 2009).

249 In Figure 3e,  $\sigma_w^2$  decreases quickly from 0.4  $\text{m}^2 \text{s}^{-2}$  at 1.29 km to 0.15  $\text{m}^2 \text{s}^{-2}$  at 1.47 km, indicating that  
250 the CBH top at noon is less sensitive to the selected threshold within 0.15-0.4  $\text{m}^2 \text{s}^{-2}$ . Figure 4 depicts the  
251 CBLHs on 15 August 2020 at the thresholds from 0.2 to 0.45  $\text{m}^2 \text{s}^{-2}$ . Nevertheless, the CBLH from 09:30 to  
252 17:30 remains relatively stable with little change at the different thresholds, and the discrepancy among

253 these thresholds arises mainly in the initial growing and final decaying stages of CBL.

254  $\sigma_w^2$  of MMCR  $w$  determines the CBL top from the perspective of dynamic effect, and the CBLH can  
255 be estimated from the temperature data based on the thermodynamic effect. Here, we compare the CBLH  
256 derived from the MMCR  $w$  with that from the radiosonde data. Radiosonde is typically launched in  
257 Wuhan at 08:00 and 20:00. Given that the sun has set by 20:00, we present the comparison at 08:00. The  
258 radiosonde data are provided by University of Wyoming from the website at  
259 <https://weather.uwyo.edu/upperair/buffraob.shtml>. The vertical resolution of radiosonde data in Wuhan was  
260 approximately 0.5-1.0 km before June 2021, and then was improved to a range of tens to hundreds of meters  
261 at higher altitudes. Therefore, we select the high-resolution data in the days without precipitation for our  
262 analysis.

263 We estimate the CBLH from the radiosonde data by using the methods of potential temperature ( $\theta$ )  
264 gradient and bulk Richardson number ( $Ri$ ) threshold. The potential temperature gradient ( $Grd_\theta$ ) is  
265 calculated at two adjacent heights in the radiosonde data, and the CBLH is determined by the maximum  
266 gradient in the profile of  $Grd_\theta$  (Seidel et al., 2010). The bulk Richardson number is expressed (Zhang et al.,  
267 2014; Seibert et al., 2000), as follows,

$$268 \quad Ri(z) = \frac{(g/\theta_{vs})(\theta_{zs} - \theta_{vs})z}{(u_z - u_s)^2 + (v_z - v_s)^2 + (bu_*^2)} \quad (1)$$

269 where  $g$  is the acceleration due to gravity;  $z$  is the height;  $\theta_v$  is the virtual potential temperature;  $u_*$  is  
270 the surface friction velocity;  $u$  and  $v$  are the zonal and meridional wind components, respectively; and  
271  $b$  is a constant, which is usually set to zero due to the fact that friction velocity is much weaker compared  
272 with the horizontal wind (Seidel et al., 2012). The subscripts of  $z$  and  $s$  denote the parameters at  $z$   
273 height and surface level, respectively. In the profile of  $Ri$ , the CBLH is identified when  $Ri$  firstly crosses  
274 a threshold value upward from the ground, and the threshold is typically taken as 0.25 in early studies (Guo

275 et al., 2021; Seibert et al., 2000), which is chosen in the analysis.

276 Figure 5 shows the comparisons of CBLHs derived from the MMCR and radiosonde measurements at  
277 8:00 on 21 and 25, July 2021, respectively. On 21, for a threshold of  $\sigma_w^2=0.3 \text{ m}^2 \text{ s}^{-2}$ , the CBLH of 0.39 km  
278 from the MMCR  $w$  is in agreement with that of 0.40 km from the radiosonde  $Grd_\theta$ , which are slightly  
279 larger than that of 0.34 km from the radiosonde  $Ri$ . In contrast to this, on 25, the CBLH is 0.57 km from  
280 the MMCR  $w$ , which is consistent with that of 0.59 km from the radiosonde  $Ri$ , but is slightly higher than  
281 that of 0.45 km from the radiosonde  $Grd_\theta$ . Nevertheless, in the whole, the results from all the three  
282 methods roughly agree with each other.

283 Figure 6 displays the scatterplot of CBLHs identified by the MMCR  $w$ , and the radiosonde  $Grd_\theta$   
284 and  $Ri$  at 8:00 on the clear days in June and July 2021. The different variables and algorithms are used in  
285 the three methods, thus there are some differences of CBLHs derived from these methods, as shown in  
286 Figure 6. The CBLH from  $\sigma_w^2$  of MMCR  $w$  has the correlation coefficients of 0.83 and 0.81 with that  
287 from the radiosonde  $Grd_\theta$  and  $Ri$ , respectively, which are highly consistent with the correlation  
288 coefficient of 0.83 from the radiosonde  $Grd_\theta$  and  $Ri$ . These results support the threshold of  $\sigma_w^2 = 0.3 \text{ m}^2$   
289  $\text{s}^{-2}$  applied to the CBLH estimation in Wuhan. In following analysis, we take  $0.3 \text{ m}^2 \text{ s}^{-2}$  as the threshold to  
290 determine the CBLH in the MMCR observation.

291 It can be noted that the comparison focuses solely on the CBLH at 8:00 rather than the diurnal evolution  
292 of CBLH, owing to the lack of radiosonde observation. Consequently, we analyze the diurnal evolution of  
293 CBLH derived from the MMCR and lidar measurements.

294

#### 295 4. Case Investigation and Comparison

296 Figure 7 presents the CBLH evolution on 15 August 2020 from the lidar RCS based on the Grd, Var and  
297 WCT methods, and the comparison with that obtained from the MMCR  $\sigma_w^2$ , together with the distribution

298 of MMCR reflectivity factor in the range of 10-15 km. As shown in Figure 7c, due to the influence of  
299 aerosol residual layer, the CBLH from the lidar RCS fluctuates from about 1.56 km at 06:00 down to 1.17  
300 km at 09:30, however, with the sunrise at 05:50, the CBL top derived from the MMCR  $\sigma_w^2$  gradually rises  
301 from about 0.09 km at 06:00 to 1.17 km at 09:30. It is interesting that the CBLH from the lidar RCS  
302 variance drops at 07:30 and then shows a change similar to that from the MMCR  $\sigma_w^2$ . Both the variances of  
303  $w$  and RCS represent the deviation degree of their small time scale values relative to their 30 min-mean  
304 values, which may be responsible for the similar results. When the CBL ascends gradually and mixes with  
305 the residual layer, the CBLHs in the lidar and MMCR observations are consistent with each other between  
306 09:30 and 17:00, including a slight drop at 12:30 and 14:30 (from the gradient and variance of RCS). The  
307 maximum height of CBL is about 1.71 km at 14:00 and 15:00 based on  $\sigma_w^2$  and the RCS gradient and  
308 variance.

309 One can note from the reflectivity factor distribution in Figure 7b that cirrus clouds occur from 17:00,  
310 develop rapidly into the thick clouds at about 11-14.4 km at 17:30, and then dissipate quickly after 17:30. In  
311 the MMCR observation, the CBLH shows an obvious reduction between 17:30 and 18:30, and then a lift as  
312 the clouds dissipates rapidly. Earlier studies from the Doppler lidar  $w$  investigated the complex influence  
313 of low-level clouds on the CBL and turbulence. The cloud-top radiative cooling drives top-down convective  
314 mixing, leading to the increasement of  $\sigma_w^2$  (Hogan et al., 2009; Harvey et al., 2013; Manninen et al., 2018).  
315 Whereas, during the warm season, the magnitude of  $\sigma_w^2$  from the lidar  $w$  is large on clear-sky days and  
316 decreases on cloud-topped days, and the intensity of turbulence reduces with an increase in the cloud  
317 fraction within the CBL, except in the cloud layer that exceeds 90% of the CBL thickness (Dewani et al.,  
318 2023). Here, the cirrus clouds are above 11 km, thus the cloud-top driven convective mixing has little impact  
319 on the low atmosphere, however, the thick clouds cool the surface by attenuating solar radiation, which can  
320 weaken the surface-driven convective mixing. Therefore, the thick cirrus makes a large contribution to the

321 evident reduction of CBLH. The phenomenon of CBLH reduction also arises in the lidar RCS, especially  
322 from the RCS variance, but with a time lag due to the influence of a long time-mixing process on the aerosol  
323 distribution (Burgos-Cuevas et al., 2023; Schween et al., 2014). After the sunset at 19:05, the CBLH  
324 retrieved by  $\sigma_w^2$  drops quickly to 0.27 km at 20:00 from 1.47 km at 19:00, while the top of aerosol residual  
325 layer (or horizontally migrating aerosol layer) identified by the lidar stays at a far higher level, especially  
326 from the RCS gradient and WCT.

327 Next, we select the observations on 31 January, 12 November, and 19 March 2020 to compare the CBLH  
328 evolutions. The three days, without clouds and precipitation, are chosen as the representative in different  
329 seasons. Figure 8 shows the CBLHs on 31 January derived from the four methods above, which are overlaid  
330 on the MMCR  $w$  and  $\sigma_w^2$  and the lidar RCS, respectively. January is the coldest month of the year, and  
331 on 31 January, the minimum (maximum) temperature is  $-5$  °C ( $4$  °C) recorded in the weather forecast.  
332 Owing to the convection inhibited largely by the frigid surface and air,  $\sigma_w^2$  shows that the CBLH develops  
333 very slowly upward to 0.3 km at 11:30 from 0.12 km at 07:30 as the sun rises at 07:15. Thereafter, the top of  
334 CBL escalates quickly to 0.9 km at 13:30, and reaches the maximum height of 0.99 km at 14:30, and during  
335 this period, the CBLH from the lidar RCS experiences a similarly rapid uplift, and attains the peak of 1.2 km  
336 at 14:00 from the RCS gradient and variance, and 1.14 km at 14:30 from the RCS WCT. In addition, it can  
337 be seen from Figure 8d that all the CBLHs from the lidar RCS are slightly larger than those from the  
338 MMCR  $\sigma_w^2$ , which may be attributed to the long time-mixing aerosols and wet surface in winter. After  
339 14:30, the CBLH from  $\sigma_w^2$  descends gradually, and approaches the ground at 17:30 prior to the sunset at  
340 17:57, while at the sunset, the CBL top from the RCS is at 0.8-0.9 km due to the long time-mixing  
341 processes.

342 Figure 9 presents the CBLHs determined from the MMCR and lidar observations on 12 November 2020.  
343 With the sunset on this day in late autumn, the CBLH identified from  $\sigma_w^2$  displays a little fluctuation until

344 10:30. After then, the CBL is rapidly developed to 0.51 km at 11:30, and mixes fully with the residual layer  
345 retrieved from the lidar RCS, thus the CBL tops have approximately the same evolution between the MMCR  
346 and lidar observations from 11:30 to 17:30, with the maximum values of about 0.75-0.78 km at 15:00 and  
347 16:00. As the sun goes down at 17:27, the CBL from  $\sigma_w^2$  rapidly shrinks close to the ground at 18:00, and  
348 aerosol particles left in the air form a residual layer, similar to the two cases above.

349 Figure 10 depicts the CBLH variations in the MMCR and lidar observations on 19 March 2020, together  
350 with the depolarization ratio from the lidar. In spring, sand and dust with different intensities from the  
351 northwest of China pass frequently through Wuhan. On this day, there is a fine sand and dust layer mostly  
352 above 1.8 km, with the depolarization ratios of about 0.08-0.12 in Figure 10c, which can also be noted from  
353 the distribution of  $w$  in the MMCR observation. Meanwhile, another sand and dust layer with the larger  
354 depolarization ratios of about 0.14-0.16 passes through Wuhan from about 14:00, and mixes with the lower  
355 part of the first sand and dust layer. In this situation, the MMCR observation indicates that the CBL starts to  
356 develop gently upward from the sunrise, and the upward trend of CBLH is also presented in the lidar  
357 measurement, but at higher altitudes. At 09:30, the CBLH is about 0.48 km in both the MMCR and lidar  
358 observations, and then rises steadily to 1.32 km at 16:00 and 16:30, showing a good agreement between the  
359 two observations. Subsequently, the CBLH from  $\sigma_w^2$  undergoes two rapid declines. One occurs from 1.2  
360 km at 17:00 to 0.51 km at 18:00, which is probably related to the sand and dust deposition in addition to the  
361 diminished radiation in the late afternoon, and the other arises after the sunset. However, because of the  
362 effect of sand and dust, the CBLH from the lidar RCS increases slightly from 1.32 km at 16:30 to about 1.38  
363 km at 18:00 and 18:30, and then decreases gradually with time.

364 The CBLH is identified by the spatial and temporal variation of aerosol concentration from the lidar  
365 measurement and by the temporal change of  $w$  from the MMCR observation. The four examples  
366 demonstrate that except for the periods with the influence of aerosol residual layer, particularly during the



367 few hours after sunrise and before sunset, the MMCR CBLHs are generally in agreement with the lidar  
368 CBLHs. The residual layer causes a higher CBLH estimated by the lidar RCS than by the MMCR  $\sigma_w$   
369 because  $\sigma_w^2$  is less contaminated by the residual layer relative to the aerosol concentration. Additionally,  
370 the CBLH estimated by  $\sigma_w^2$  shows a rapid response to thick high-level clouds and less influence by the  
371 long-range transport of sand and dust. Hence, the MMCR observation can accurately retrieve the CBLH and  
372 capture its diurnal evolution, especially for the CBL in the blind range of lidar.

373

## 374 **5. Monthly and Seasonal Mean CBLHs**

375 To reveal the general characteristics of CBLH diurnal evolution in different months and seasons, we  
376 calculate the monthly and seasonal mean CBLHs by using the MMCR  $\sigma_w$  on these days without  
377 precipitation in 2020. We consider that winter covers the months of December, January and February, while  
378 March, April and May are spring, June, July and August are summer and the rest is autumn.

379 Figure 11 illustrates the averaged CBLHs with the standard deviations superimposed on the mean  $\sigma_w^2$   
380 in each month and season. As the spot of direct sunlight slowly moves northward, the mean variance  
381 gradually increases from January to July, and then decreases gradually from August to December, moreover,  
382 the coverage height and time duration of its large values show an analogous monthly variation. In this case,  
383 the peak height of CBL ascends steadily from 0.66 km in January to 1.47 (1.44) km in July (August), and  
384 subsequently, descends gradually to the lowest height of 0.42 km in December. Additionally, at Wuhan, the  
385 plum rain starts in June and prevails in July. As shown in Figure 11, the CBLH in July has the largest  
386 standard deviation (between 13:00 and 19:00), which is possibly attributable to the cloudy and rainy weather  
387 besides the strongest radiation.

388 As for seasonal variation, as we expected, the mean  $\sigma_w^2$  is the strongest in summer and the weakest in  
389 winter. Interestingly, the variance is significantly larger in spring than in autumn. Not only the maximum

390 CBLH of 1.14 km at 13:30 in spring is much higher than that of about 0.66 km at 13:30 and 14:00 in autumn,  
391 but also the mean  $\sigma_w^2$  of 0.42  $\text{m}^2 \text{s}^{-2}$  in the CBL during spring is stronger than that of 0.35  $\text{m}^2 \text{s}^{-2}$  during  
392 autumn. The maximum height of CBL is 1.29 km at 14:30 and 15:00 in summer, and about 0.6 km at 14:30  
393 in winter. In summer, the CBLH displays a feature of quick descent near twilight, and in autumn, the CBL  
394 shows a wider envelope with an earlier development and a later dissipation relative to that in winter though  
395 their maximum CBLHs are almost the same. In previous studies, based on the threshold of  $\sigma_w^2$  from the  
396 Doppler lidar measurement in Mexico City (19.3° N, 99.1° E), the CBLH is higher in spring and summer,  
397 and lower in winter, while the maximum CBLH of about 1.5 km occurs in May, which is because the CBLH  
398 is suppressed to some extent by increased cloud cover in the rainy season between June and September  
399 (Burgos-Cuevas et al., 2021). However, the CBLH retrieved from the ceilometer backscatter data is  
400 obviously larger than that from the threshold of  $\sigma_w^2$  (Burgos-Cuevas et al., 2021; Tang et al., 2016).  
401 Similarly, in the estimation of CBLH from the lidar RCS over Wuhan and Granada (37.18° N, 3.60° E), the  
402 maximum values of seasonal mean CBLHs in all the seasons are larger than those in our results although the  
403 gradual ascent of CBLH from winter and autumn to spring and summer is consistent with that in our results  
404 (Kong and Yi, 2015; Granados-Muñoz et al., 2012).

405

## 406 **6. Summary**

407 In this study, we estimate the CBLH from the profile of  $w$  in the Ka-MMCR observation by using a  
408 threshold of  $\sigma_w^2$ . The CBLH from MMCR is compared with that from the lidar RCS by utilizing the  
409 gradient, variance and wavelet methods, and from radiosonde data by using the methods of  $\theta$  gradient and  
410  $Ri$ , which demonstrates the general agreement of CBLH estimation based on different dynamic and  
411 thermodynamic effects. Then, we investigate the diurnal evolution of monthly and seasonal mean CBLHs  
412 based on the MMCR observation.

413 Although the RCS is proportional to aerosol concentration and  $w$  represents the vertical motion of  
414 aerosol particles, the comparison of four examples in different seasons indicates that the diurnal evolution of  
415 CBLH from the MMCR  $w$  is consistent with those from the lidar RCS, except for the initial growth and  
416 final decay phases. The discrepancy can mainly be attributed to the aerosol residual layer and the lidar blind  
417 range. The influence of residual layer on the lidar RCS generally causes an overestimation of CBLH,  
418 meanwhile, it is impossible for lidar to capture the CBL top within its large blind range. In addition, the  
419 CBLH in the MMCR observation shows less contamination by the long-range transport of sand and dust,  
420 and thick high-level clouds due to the rapid response of aerosol  $w$  relative to its concentration. In this case,  
421 the MMCR observation can capture the diurnal evolution of CBLH.

422 Using the profile of  $w$  from the MMCR observation on these days without precipitation in 2020, we  
423 investigate the diurnal evolution of monthly and seasonal mean CBLHs. The maximum value of monthly  
424 mean CBLH increases gradually from 0.66 km in January to 1.47 (1.44) km in July (August), and then  
425 decreases to the lowest height of 0.42 km in December. As for the seasonal behavior, the mean CBLH has  
426 the maximum heights of 1.29 km at 14:30 and 15:00 in summer, 1.14 km at 13:30 in spring, 0.66 km at  
427 13:30 and 14:00 in autumn, and 0.6 km at 14:30 in winter. In addition, the statistical standard deviations are  
428 monthly-dependent, indicating that the CBLH is not only mainly regulated by the surface heating associated  
429 with solar radiation, but also significantly affected by weather conditions, such as humidity and clouds.  
430 Therefore, since the Ka-band MMCR is a powerful instrument for observing clouds and weak precipitation,  
431 the full-time MMCR observation with low blind height can obtain the entire diurnal evolution of CBLH,  
432 which helps us gain an insight into CBL features and also provides important input variables for weather  
433 prediction and climate models.

434

435

436 **Code availability.** Software code to obtain the results is available upon request from the corresponding  
437 author.

438 **Data availability.** All data used are available upon request from the corresponding author.

439 **Author contributions.** KH and FY conceptualized this study. ZZ and KH completed the analysis and the  
440 manuscript. WC, FL, JZ, YJ, and FY discussed the results and finalized the manuscript.

441 **Competing interests.** The authors declare that they have no conflict of interest.

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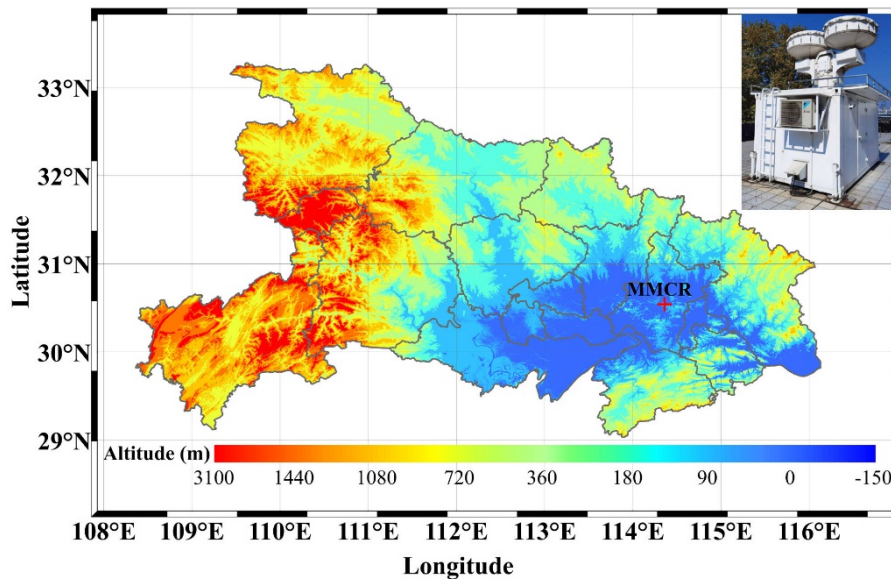
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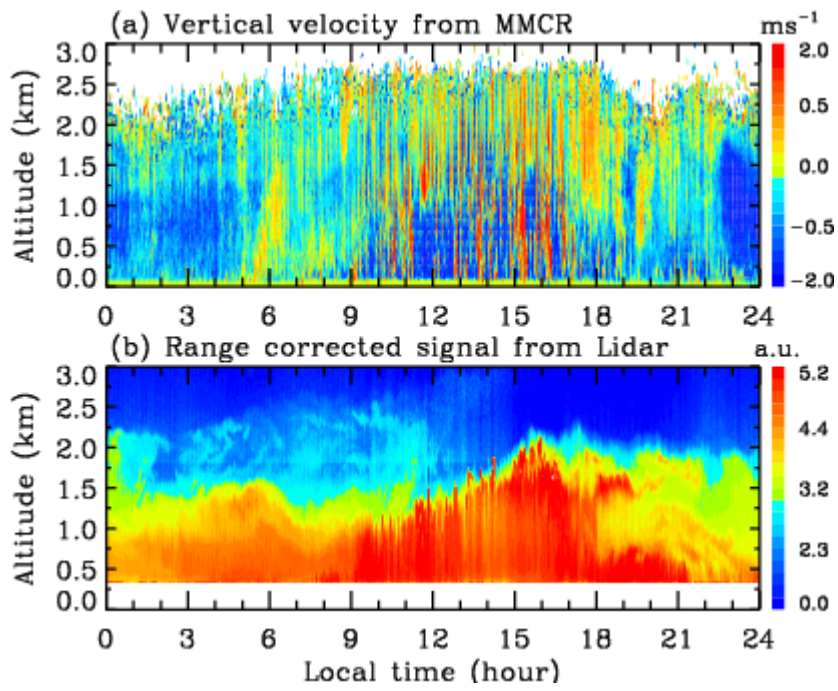


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696 **Figure 1.** Topographic elevation map of Hubei Province and Ka-band MMCR located in Wuhan University

697 (30.54°N, 114.36°E). The red crisscross denotes the site of MMCR.





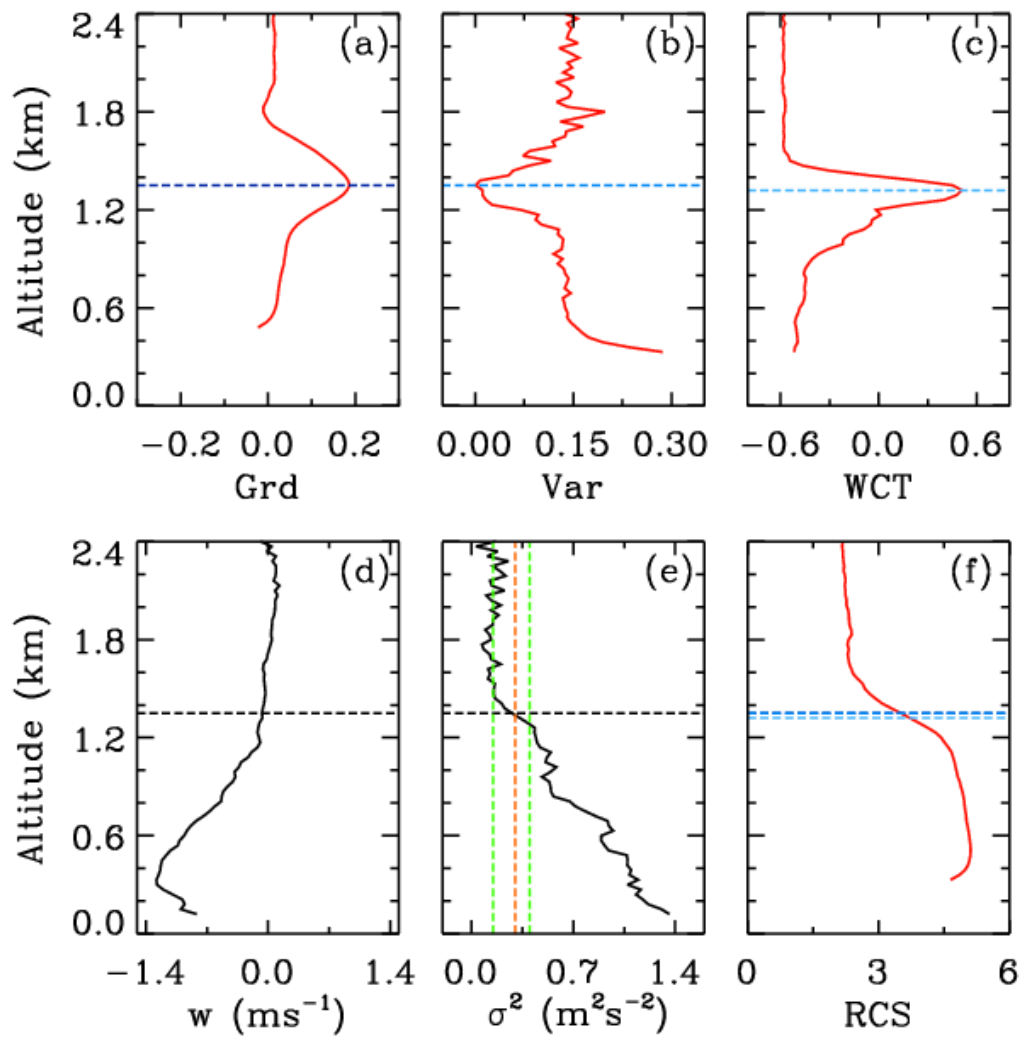
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**Figure 2.** Time-height section of (a) vertical velocity from MMCR and (b) RCS from lidar on 15 August

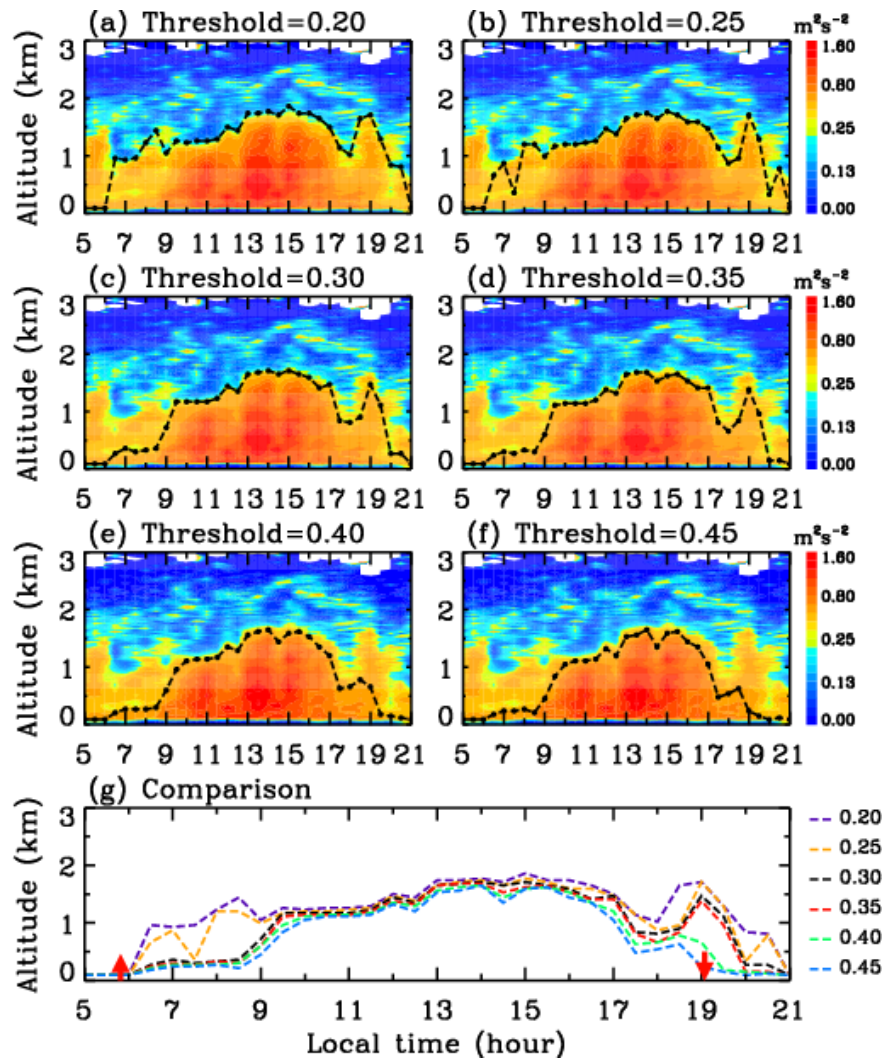
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702 **Figure 3.** Profiles of (a) RCS gradient, (b) variance, (c) WCT and (f) RCS from lidar, and (d) vertical  
 703 vertical velocity and (e) its variance from MMCR between 12:15 and 12:45 LT on 15 August 2020. In these panels,  
 704 the horizontal lines in different colors represent the CBLH determined by different methods. In Panel 3e, the  
 705 orange vertical line denotes the selected threshold of  $0.3 \text{ m}^2 \text{ s}^{-2}$ , and the two green vertical lines correspond  
 706 to the variances of  $0.15$  and  $0.4 \text{ m}^2 \text{ s}^{-2}$ , respectively.



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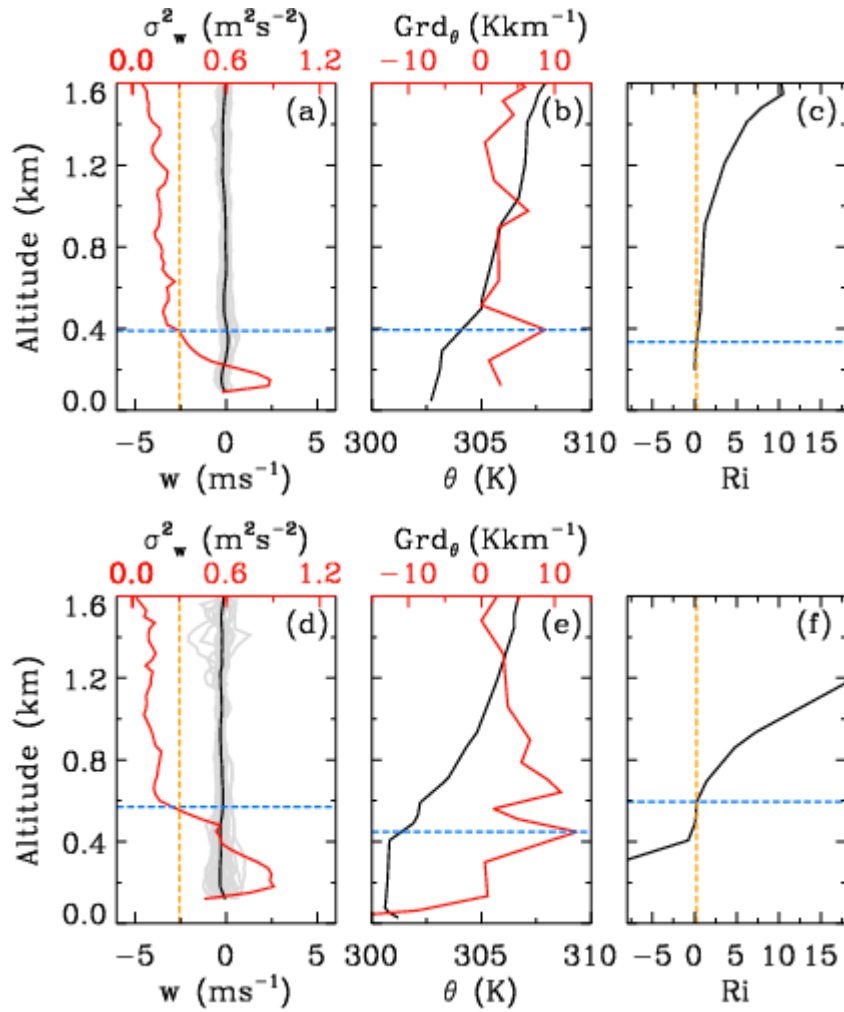
708 **Figure 4.** CBLHs derived from thresholds of (a) 0.2, (b) 0.25, (c) 0.3, (d) 0.35, (e) 0.4 and (f) 0.45  $m^2 s^{-2}$

709 superimposed over vertical velocity variance (color shading) from MMCR on 15 August 2020, and (g) their

710 comparison. In Panel 4g, the two red arrows denote the time of sunrise and sunset at 05:50 and 19:05,

711 respectively.

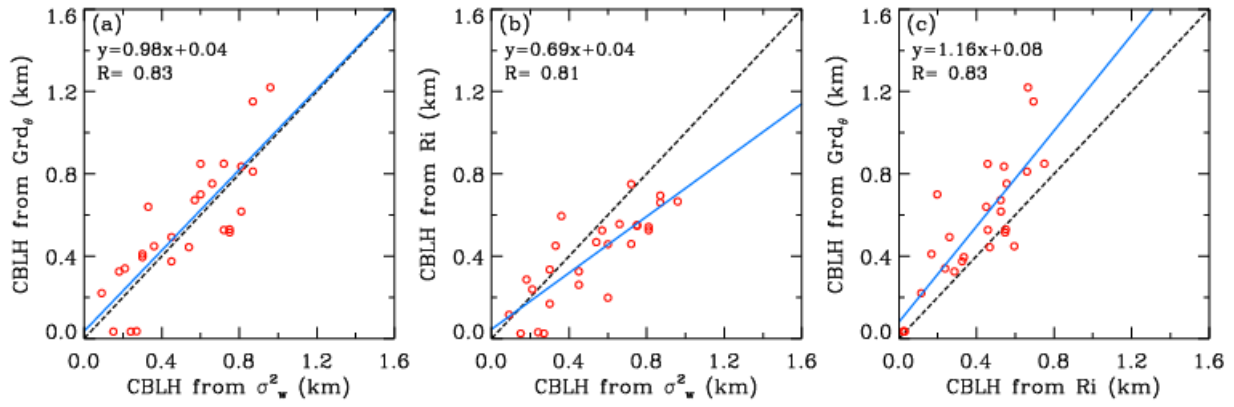
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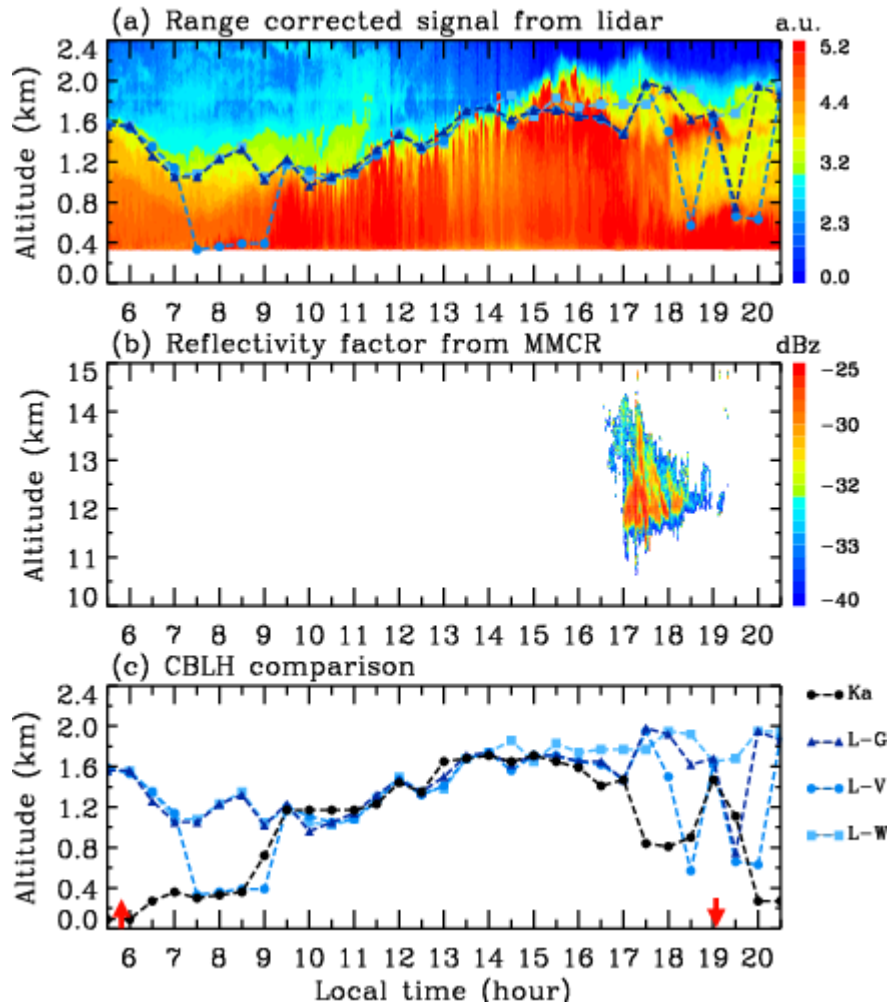
714 **Figure 5.** Comparison of CBLHs estimated by (a, d) threshold of  $\sigma_w^2=0.3 \text{ m}^2 \text{ s}^{-2}$  from MMCR, and (b, e)  
 715 maximum gradient of  $\theta$  and (c, f) threshold of  $Ri=0.25$  from radiosonde data at 08:00 on (upper) 21 and  
 716 (lower) 25 July 2021. In the panels 5a and 5d, the gray and black lines denote (lower horizontal axis)  $w$  and its  
 717 mean value from MMCR, respectively, and the red and yellow lines denote (upper horizontal axis)  $\sigma_w^2$  and the  
 718 threshold of  $\sigma_w^2=0.3 \text{ m}^2 \text{ s}^{-2}$ , respectively. In the panels 5b and 5e, the black and red lines denote (lower  
 719 horizontal axis)  $\theta$  and (upper horizontal axis) its gradient from radiosonde, respectively. In the panels 5c and  
 720 5f, the black and yellow lines denote  $Ri$  and the threshold of  $Ri=0.25$  from radiosonde data, respectively.  
 721 The blue horizontal line represents the position of identified CBL top.

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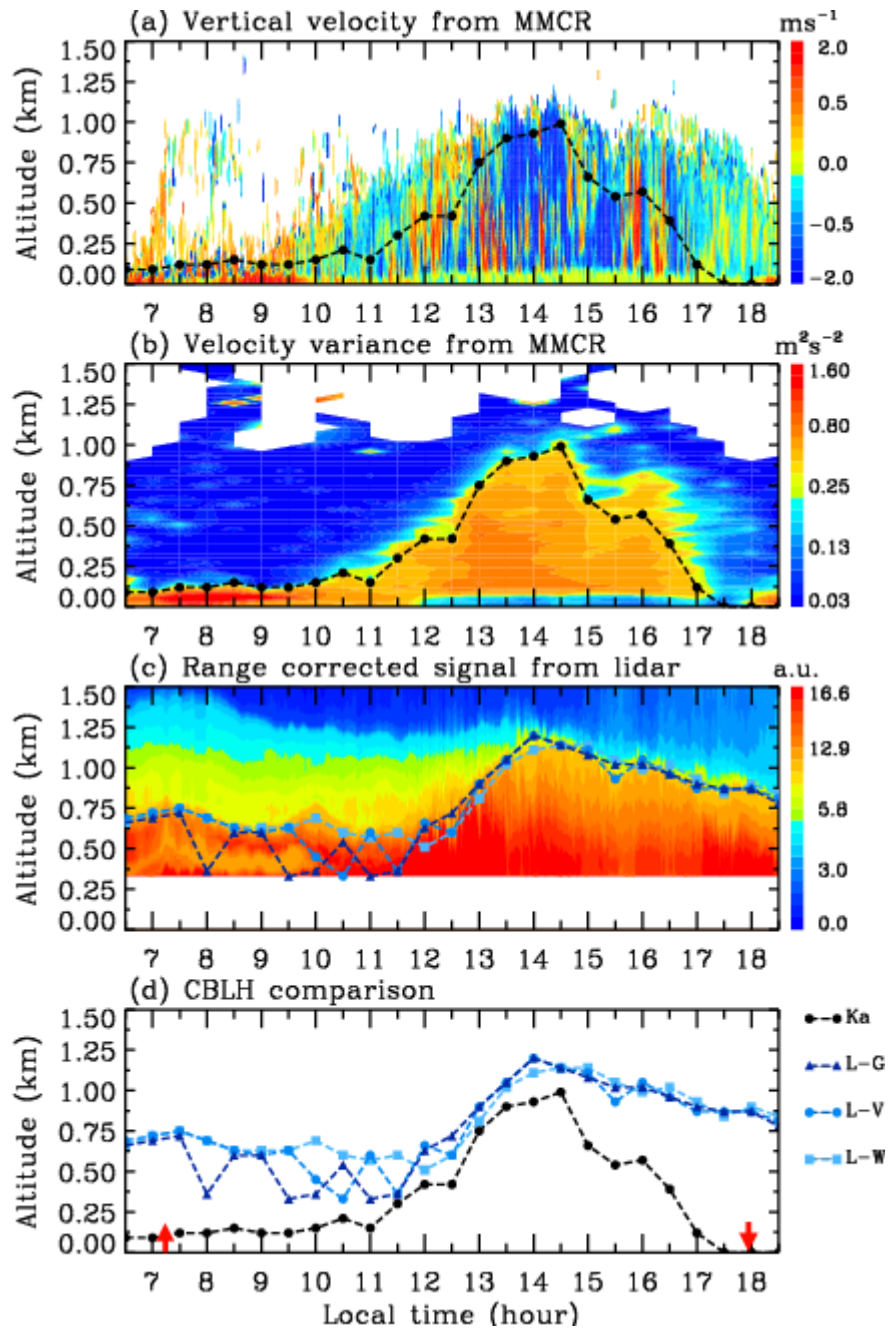
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724 **Figure 6.** Scatterplot of CBLHs derived from (a) threshold of  $\sigma_w^2=0.3 \text{ m}^2 \text{ s}^{-2}$  from MMCR vs. maximum  
 725 gradient of  $\theta$  from radiosonde, (b) threshold of  $\sigma_w^2=0.3 \text{ m}^2 \text{ s}^{-2}$  from MMCR vs. threshold of  $Ri=0.25$  from  
 726 radiosonde, and (c) threshold of  $Ri=0.25$  vs. maximum gradient of  $\theta$  from radiosonde.  
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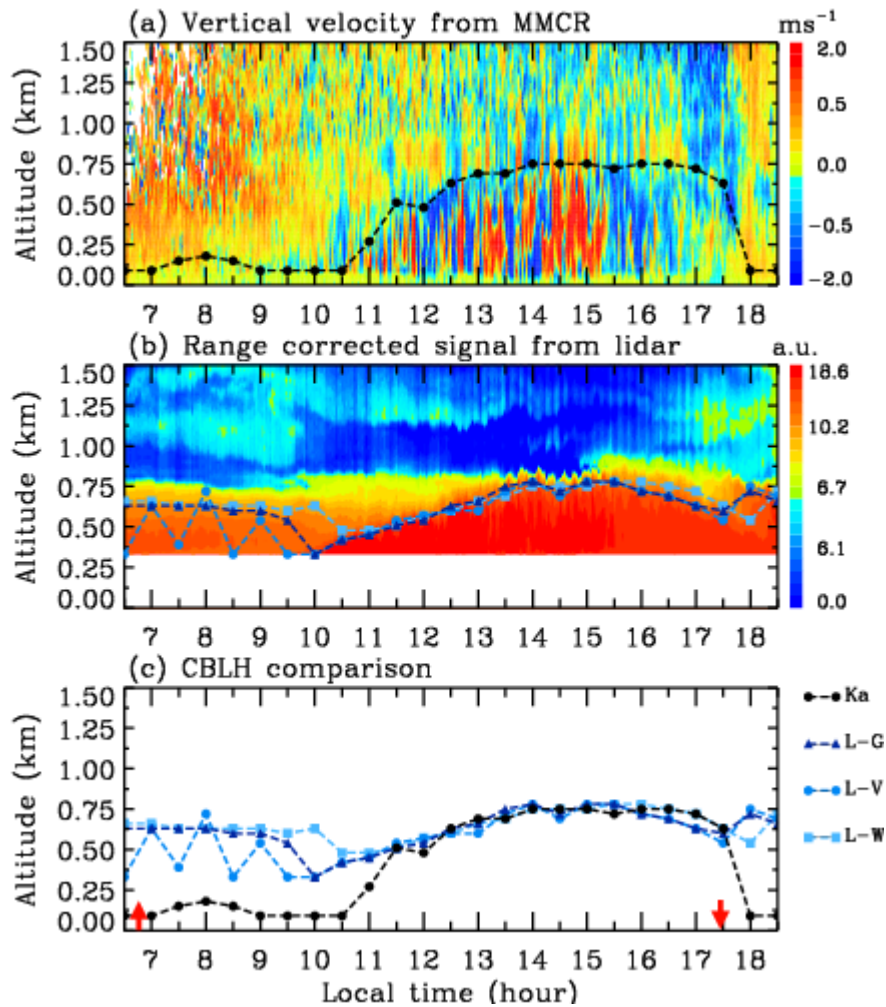
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729 **Figure 7.** (a) Evolution of CBLH derived from RCS gradient, variance and WCT superimposed over lidar  
 730 RCS (color shading) on 15 August 2020, (b) reflectivity factor from MMCR, and (c) comparison of CBLHs  
 731 derived from MMCR and lidar observations. The black dash curve with circle (Ka) denotes the CBLH  
 732 determined by the variance threshold of  $0.3 \text{ m}^2 \text{ s}^{-2}$  in the Ka-band MMCR observation, while the dark blue,  
 733 blue and light blue dash curves with triangle (L-G), circle (L-V) and square (L-W) represent the CBLH  
 734 determined by the gradient, variance and WCT in the lidar measurement, respectively. In Panel 5c, the two  
 735 red arrows denote the time of sunrise and sunset at 05:50 and 19:05, respectively.



736

737 **Figure 8.** Distributions of (a) vertical velocity and (b) its variance from MMCR and (c) lidar RCS on 31  
 738 January 2020 with retrieved CBLH, and (d) comparison of CBLHs derived from MMCR and lidar  
 739 observations. The threshold of vertical velocity variance from the MMCR is  $0.3 \text{ m}^2 \text{ s}^{-2}$ . In Panel 6d, the two  
 740 red arrows denote the time of sunrise and sunset at 07:15 and 17:57, respectively.



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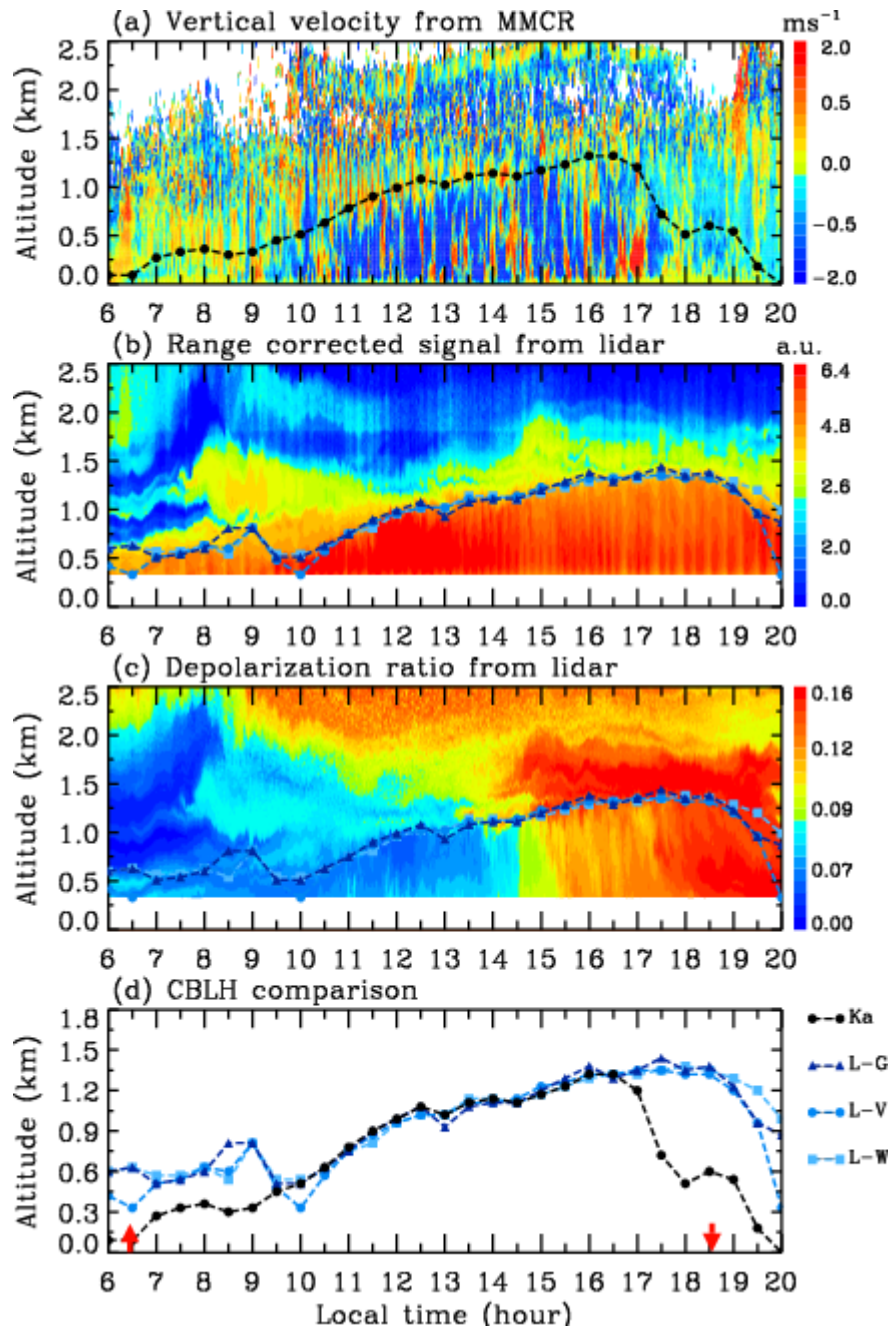
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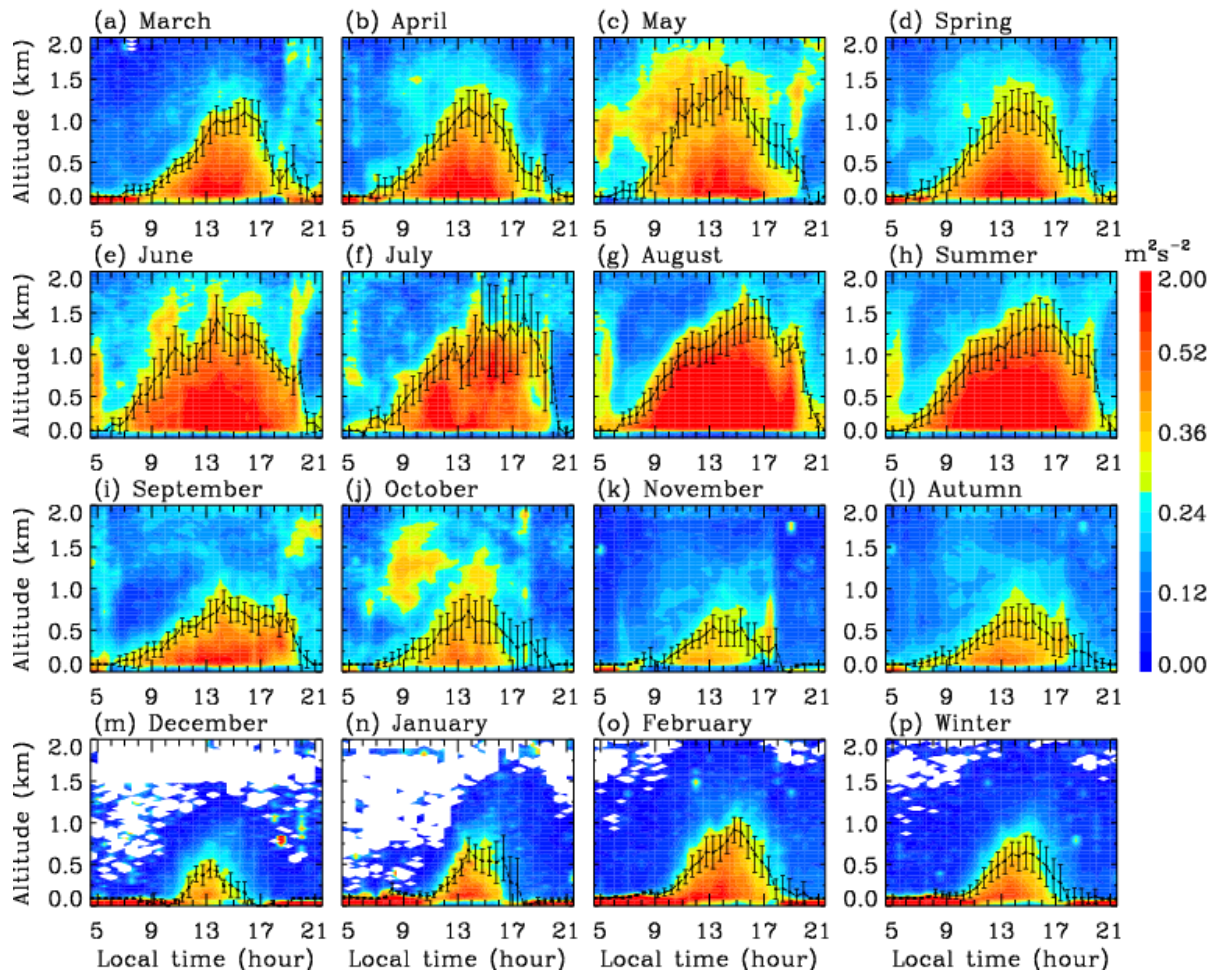
**Figure 9.** Distributions of (a) vertical velocity from MMCR and (b) lidar RCS on 12 November 2020 with retrieved CBLH, and (c) comparison of CBLHs derived from MMCR and lidar observations. The threshold of vertical velocity variance from the MMCR is  $0.3 \text{ m}^2 \text{ s}^{-2}$ . In Panel 7c, the two red arrows denote the time of sunrise and sunset at 06:47 and 17:27, respectively.





746

747 **Figure 10.** Distributions of (a) vertical velocity from MMCR and lidar (b) RCS and (c) depolarization ratio  
 748 on 19 March 2020 with retrieved CBLH, and (d) comparison of CBLHs derived from MMCR and lidar  
 749 observations. The threshold of vertical velocity variance from the MMCR is  $0.3 \text{ m}^2 \text{ s}^{-2}$ . In Panel 8d, the two  
 750 red arrows denote the time of sunrise and sunset at 06:27 and 18:34, respectively.



751

752 **Figure 11.** Monthly and seasonal mean values and statistical standard deviations of CBLH estimated by  
 753 threshold of vertical velocity variance from MMCR. The variance threshold is  $0.3 \text{ m}^2 \text{ s}^{-2}$ , and the color shading  
 754 denotes the variance distribution. The months and seasons are marked above the corresponding panels,  
 755 respectively.