13B.2 CIRRIFORM CLOUD OBSERVATION IN THE TROPICS BY VHF WIND PROFILER AND 95-GHz CLOUD RADAR

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1. Introduction

Cirriform clouds (cirrus, cirrostratus, cirrocumulus) existing in the upper part of the troposphere consist almost entirely of ice particles, and play a significant role in regulating the radiation balance of the earth-atmosphere system (Liou, 1986). Therefore, knowing of microphysical properties and dynamical processes related to them is important for parameterizing effects of cirriform clouds in numerical models. Particle falling velocity is one of crucial factors that determine lifetime of cirriform clouds, because it determines evaporation of cloud particles through sedimentation. The most unknown factor for observing correct particle falling velocity is vertical air velocity (hereafter Vair). Because means to directly observe Vair is limited, Vair is computed indirectly in most of the previous observations. Wind profiler operated at VHF frequency (VHF wind profiler), which directly observes vertical profiles of winds by receiving echoes from fluctuations of refractive index, is a useful instrument to directly observe Vair in and around cirriform clouds. In this extended abstract, it is shown that a combination of VHF wind profiler and millimeter-wave cloud profiling radar is a key tool to observe particle falling velocity in tropical cirriform clouds.

2. DATA AND ANALYSIS METHOD

The Equatorial Atmosphere Radar (hereafter EAR) is a wind profiler operated at VHF frequency (47 MHz; radar wavelength of 6.38 m). The EAR has been operated at Equatorial Atmosphere Observatory, Kototabang, West Sumatra, Indonesia (0.2 degrees south, 100.32 degrees east, 865 m above mean sea level). For the system description of the EAR, see Fukao et al. (2003). During a period we focus on (14-15 November 2005), the EAR is operated by two observation modes; a standard mode to observe vertical and horizontal winds and an additional observation mode to steer radar beams only to the vertical direction, which contributes to an improvement of the estimation accuracy and data rate of Vair (hereafter vertical wind mode). We used Vair derived from the vertical wind mode. The vertical wind mode during 14-15 November 2005 is the same as used during 5-9 May 2004, except that a number of coherent integrations (Ncoh) and FFT points (NFFT) are changed to 64 and 1024, respectively (see Table 1 of Yamamoto et al. (2007)). For details of the vertical wind mode, see Yamamoto et al. (2007).

A 95-GHz cloud profiling radar (hereafter cloud radar) developed by National Institute of Information and Communications Technology (NICT), Japan observed radar reflectivity factor (hereafter Ze) and Doppler velocity by receiving echoes from cloud particles. The cloud radar was temporarily operated at the Equatorial Atmosphere Observatory for the cirrus observation campaign. Doppler...
velocity was observed by pulse-pair method. For the system description of the cloud radar, see Horie et al. (2000).

Doppler velocity observed by the cloud radar (hereafter Vair+Z) is a sum of Vair and reflectivity-weighted particle falling velocity (hereafter VZ; see Houze (1993) for its definition). Therefore VZ is computed by subtracting Vair observed by the EAR from Vair+Z. Vertical profiles of Vair and VZ are computed every 3 minutes, and further smoothed by 12-minute running average to reduce fluctuations in time. Vertical resolution used in data analysis is 150 m.

To investigate horizontal distribution of cumulus activity, equivalent blackbody brightness temperature (hereafter TB) observed by IR-1 (10.3-11.3 μm) channel of the weather satellite (MTSAT-1R) is used. Cloud-top altitudes were inferred by TB and vertical profile of temperature observed by radiosondes launched at the observation site during October-November 2005. TB is generally higher than real temperature at cloud top because clouds are not regarded as perfect black bodies (Sherwood et al., 2004); it means that cloud-top altitudes inferred from TB are generally lower than real cloud top, and indicate lowest altitudes where cloud top can exist.

3. RESULTS

3.1 Weather Satellite Observation

A case in the nighttime between 14 and 15 November 2005 is intensively studied. During the period, cirriform clouds in the outflow region of convective system were observed at the observation site. Figure 1 shows TB from 2050 local standard time (hereafter LT) to 0650 LT. Note that LT is 7 hours earlier than universal time coordinated. After 20 LT, a region with TB of less than 205 K, which indicates that deep cumulus convection with cloud tops of higher than about 14.1 km, developed in the east and north of the observation site (Figures 1a-b). Cloud tops located above 12 km in most of the observation time, and reached to higher than 14 km from 2320LT 14 November to 0100 LT. Echo tops observed by the cloud radar located above 12 km in most of the observation time, and reached to higher than 14 km from 2320LT 14 November to 0100 LT. Echo bottoms located around 8-10 km. Vair+Z generally shows consistent changes with Zc; relatively smaller Vair+Z (and larger Vair+Z in amplitude) was observed for larger Zc (see Figures 2a and b). Because Zc is weighted by backscattering cross section which is proportional to the 6th power of particle effective diameter and hence generally have large values in the dominance of large-sized cloud particles, the observed feature in Vair+Z indicates that cloud particles with larger Zc have larger particle falling velocity. Further, Vair+Z has consistent changes with Vair; Vair+Z of larger than -0.4 m/s (and smaller than 0.4 m/s in amplitude) tends to be found when upward (positive) Vair was observed. For example, this tendency is seen especially around 2140 LT and during 2340-2400 LT 14 November, and during 0240-0340 LT and 0420-0530 LT on 15 November. Further, Vair+Z showed vertically-standing feature in altitude throughout the observation period, while the vertically-standing feature is not seen in Ze. In Section 3.3, a relationship between Vair and Vair+Z is investigated in detail.

3.3 Estimation of particle falling velocity using Doppler velocity observed by cloud profiling radar and vertical air velocity observed by VHF wind profiler

It is shown that direct Vair observation by VHF wind profiler is useful for deriving particle falling velocity. Firstly, relationships between Vair and Vair+Z are examined. Figure 3a shows a scatter plot between Vair and Vair+Z at 7.3-12.2 km, which is an altitude range that the cloud radar had a
good data acquisition rate (higher than about 80%) from 2000 LT 14 November to 0800 LT 15 November 2005. It is clear that \( V_{\text{ar}+Z} \), a sum of \( V_{\text{ar}} \) and \( V_Z \) and was observed by the cloud radar, shows consistent changes with \( V_{\text{ar}} \). Figure 3b shows a scatter plot between \( V_{\text{ar}} \) and \( V_Z (= V_{\text{ar}+Z} - V_{\text{ar}}) \). Variations in \( V_Z \) seem to have significant relationship with \( V_{\text{ar}} \); the correlation coefficient between \( V_{\text{ar}} \) and \( V_Z \) is only -0.01. These variations observed in \( V_Z \) indicate that consistent changes between \( V_{\text{ar}+Z} \) and \( V_{\text{ar}} \) are caused by \( V_{\text{ar}} \) component in \( V_{\text{ar}+Z} \).

\( Z_e \) is used as a proxy of cloud particle size to confirm that computed \( V_Z \) shows a consistent change with cloud particle size. Figure 4a shows a scatter plot between \( V_{\text{ar}+Z} \) and \( Z_e \), both of which were observed by the cloud radar. A negative correlation between \( V_Z \) and \( Z_e \), which indicates that cloud particles with relatively large size have larger falling velocity, is observed as previously shown in Figures 1a and b. However, \( V_{\text{ar}+Z} \) contains large fluctuations for \( Z_e \) due to \( V_{\text{ar}} \) changes in \( V_{\text{ar}+Z} \); the correlation coefficient between \( V_{\text{ar}+Z} \) and \( Z_e \) is -0.46. Figure 4b shows a scatter plot between \( V_Z \) and \( Z_e \). The correlation coefficient between \( V_Z \) and \( Z_e \) is -0.61, and shows a better correlation than between \( V_{\text{ar}+Z} \) and \( Z_e \). This improvement in the correlation coefficient indicates that the poorer correlation between \( V_{\text{ar}+Z} \) and \( Z_e \), as seen in Figure 3b, occurred due to upwelling and downwelling of \( V_{\text{ar}} \). Results shown in this section have demonstrated that \( V_{\text{ar}} \) observation by VHF wind profiler is useful for observing particle falling velocity in cirriform clouds.

### 3.5 Comparison of particle falling velocity between the bottom and middle part of cirriform clouds

By improving accuracy in deriving \( V_Z \) using VHF wind profiler, two different relationships between \( V_Z \) and \( Z_e \) were clearly observed between the middle part and the bottom part of the cirriform clouds. Figures 5a and b show scatter plots between \( V_Z \) and \( Z_e \) around bottom part (7.2-10.5 km) and middle part (10.5-12.2 km) of clouds, respectively. Changes of \( V_Z \) for \( Z_e \) in the bottom part are scattering as compared to ones in the middle part of clouds; the correlation coefficient between \( V_Z \) and \( Z_e \) at the bottom part is -0.55, and one at the middle part is -0.83. Because particle size distribution is a factor which determines both \( Z_e \) and \( V_Z \), and particle shape is a factor which causes variability in \( V_Z \), this scattering feature in the bottom part of clouds is explained by larger variability in particle size distribution and particle shape.

Though changes of \( V_Z \) for \( Z_e \) are relatively scattering in the bottom part of clouds, a negative correlation between \( V_Z \) and \( Z_e \) is still observed; a regression line is computed to be \( Z_e = -77.9 \ V_Z - 65.4 \). In the middle part of cloud, changes of \( V_Z \) for \( Z_e \) are relatively large; a regression line is computed to be \( Z_e = -31.9 \ V_Z - 32.2 \). The larger negative slope in the bottom part than in the middle part indicates that relatively large-sized particles with a larger falling velocity dominantly exist in the bottom part of clouds.

### 4. SUMMARY

In the abstract, it has been demonstrated that a combination of VHF wind profiler and millimeter-wave cloud profiling radar is a key tool to observe particle falling velocity in tropical cirriform clouds. By improving the accuracy in deriving particle falling velocity, a clear difference in particle falling velocity between in the bottom and middle part of clouds has been shown. We hope that a capability of VHF wind profiler to observe vertical wind contributes to further understanding of microphysical and dynamical processes in cirriform clouds.

### REFERENCES


Figure 1. Longitude-latitude plots of $T_{BB}$ observed by the IR-1 channel of MTSAT-1R. Contours are plotted with an interval of two hours from 2050 LT 14 to 0650 LT 15 November 2005. Circles in each panel indicate the location of the observation site (0.2 degrees south, 100.32 degrees east, 865 m above mean sea level). Solid curves show coastlines.
Figure 2. Time-altitude plots of (a) $Z_e$, (b) $V_{air+z}$, and (c) $V_{air}$ from 2000 LT 14 to 0800 LT 15 November 2005. Solid contour in panel (c) indicates the region where the cloud radar received echoes from cloud particles.

Figure 3. Scatter plot between (a) $V_{air}$ and $V_{air+z}$, and (b) $V_{air}$ and $V_z$ at 7.2-12.2 km from 2000 LT 14 to 0800 LT 15 November 2005.
Figure 4. Scatter plot between (a) $V_{air+z}$ and $Z_e$, and (b) $V_z$ and $Z_e$ at 7.2-12.2 km from 2000 LT 14 to 0800 LT 15 November 2005.

Figure 5. Scatter plot between (a) $V_z$ and $Z_e$ at 7.2-10.5 km, and (b) $V_z$ and $Z_e$ at 10.5-12.2 km from 2000 LT 14 to 0800 LT 15 November 2005. Broken line in panel (a) and dash-dotted line in panel (b) show regression lines computed in the ranges of 7.2-10.5 km (broken line; $Z_e = -77.9 V_z - 65.4$), and 10.5-12.2 km (dash-dotted line; $Z_e = -31.9 V_z - 32.2$), respectively.