High Resolution Doppler Observations of Clouds with the Millimeter-wave CPR FALCON-I

TAKANO Toshiaki[1], YAMAGUCHI Jun[2], ABE Hideji[1], SUZUKI Yohei[1], MORIYA Shusuke[1], NISHINO Daichi[1], KAWAMURA Yohei[1], NAKANISHI Yuji[3], and TAKAMURA Tamio[3]
[1]*Graduate School of Engineering, Chiba University; Inage, Chiba 263-8522, Japan, takano@faculty.chiba-u.jp*
[2]*Japan Aerospace Exploration Agency*
[3]*Center for Environmental Remote Sensing, Chiba University*

Abstract

High resolution Doppler Observations of clouds have been done with the millimeter-wave cloud profiling radar (CPR) FALCON-I developed at Chiba University. FALCON-I operated at 95 GHz has a high spatial resolution of 15 m in the ranging direction and of 0.2° in the perpendicular directions. Precise observations of melting layers at the bottom of clouds reveal that rain drops whose diameters would be around 1 mm are generated and accelerated up to 7 m/s downward in quite thin layer of about 200 m. Doppler Observations of interior of cumulonimbus suggest existence of small structures of about 1 km in which abrupt up and downward flow occurs. These results will be useful to investigate characteristics of clouds in various places and oceans in order to make global model of atmosphere.

Keywords : Cloud Profiling Radar, Millimeter Wave Radar, Cloud Properties, Height Distribution of Clouds, Structure of melting layer, dynamics of interior clouds, Global Model of Atmosphere.

1. Introduction

It is getting more important to know the global environment and the global change of climate for the human beings. It is necessary to know balance of solar energy coming to the Earth and cycle of water for the comprehension and to solve severe problems such as the greenhouse warming, the drying, the ozone holes and so on. One of the most significant features to know them is cloud. Information on 3-dimensional structures of clouds, sizes and distribution of cloud particles, dependence on size of optical characteristics of cloud particles, motions of particles in clouds, and so on are all desirable to determine the role of clouds.

Fig.1. Cloud profiling radar FALCON-I. It has two 1-m diameter antennas which transmit and receive radio waves at 95 GHz.

Observations of clouds with radars would be the most powerful method to derive the information because of the following advantages: a) radio waves do not suffer from heavy extinction such as visible light, and consequently can investigate the interior of clouds, b) the radar technique, which is an active sensing method, has great advantage to investigate interior structures of clouds to passive methods such as total power observations of irradiance of clouds, c) Doppler measurements of clouds is applicable only to radio frequency waves.

We have originally designed and developed a cloud profiling radar at 95GHz. We adopt a frequency-modulated continuous wave (FM-CW) radar rather than a pulse radar because the former can easily achieve more sensitive and high-resolution system than the latter. Whole view of the developed radar, which is named "FALCON-I" is shown in Fig.1 and its parameters and performance of are summarized in Table 1. Detail of FALCON-I is described in the papers [1]-[4].

Table 1. Parameters and performance of FALCON-I.

Antenna Diameter	1 m × 2
Frequency	94.79 GHz
Output Power	0.5 W (+27 dBm)
Beam Width	0.18 degree
Range Resolution	15 m
Direction of Antennas	Zenith
Polarization	1 Linear
Temporal Resolution	1 msec (Typical)
Sensiutivity (at 5 km)	-32 dBZ (Typical)
Doppler Velocity Range	±3.2 m/sec (Typ)

2. Observations with FALCON-I

Using FALCON-I, we observed clouds in various regions, at Chiba (Fig.2), at cape Hedo in Okinawa (Fig.3), and oceans on board MIRAI (Fig.4): a Japanese scientific research vessel operated by Japan Agency for Marine-Earth Science and Technology (JAMSTEC). FACLON-I is a mobile facility which is able to operate through the internet connection with the commercial power supply of about 100V 15A. During these observations, FALCON-I worked stable and well and showed good performance [5]-[7].

3. Observations of cumulonimbus

3-1. Reflectivity profiles

We continuously observed clouds in summer 2010 at Chiba University. High resolution Doppler Observations of clouds have been obtained as well as reflectivity profiles for several large cumulonimbus during the period.

Fig.5. shows time-height diagram of reflectivity for a cumulonimbus on July 25, 2010. The anvil of the cumulonimbus began to be seen around 9:30 UT (18:30 JST) from about 12 km in height and gradually came down to lower height. The main part of the cumulonimbus was shown in 10:40-11:20 UT at 4-9 km in height. Abrupt increase of observed reflectivity by going lower height is shown at 4 km. This increase of reflectivity should be caused with growth of diameters of raindrops in the melting layer. At lower frequency, for example, X-band (10 GHz) observations, strong enhancement of reflectivity called "bright band is usually recognized in the melting layer. At 95 GHz, however, bright enhancement cannot be seen but abrupt increase of reflectivity is only seen.

Fig.2. FALCON-I installed on a truck in the campus of Chiba University. The container behind the truck is housing of FALCON-I with two Teflon sheet windows on the ceiling for MIRAI observations (see Fig.4).

Fig.3. FALCON-I set in the Cape Hedo Station in Okinawa, Japan, of National Institute for Environmental Studies during the campaign in spring, 2008.

Fig.4(a). Japanese scientific research vessel, MIRAI, operated by Japan Agency for Marine-Earth Science and Technology (JAMSTEC).

Fig.4(b). Container of FALCON-I settled on the upper deck of MIRAI.

3-2. High resolution Doppler observations

Fig.6 shows Doppler spectral diagrams of the cumulonimbus on July 25, 2010 observed with FALCON-I at Chiba University. This cumulonimbus was generated several hours before observations in the northwest direction and moved toward Chiba area. We obtain one Doppler spectral diagram in every minute with 250 ms observations. Because Doppler velocity is derived by measuring phase shift of return signal scattered by objects, there are ambiguities of 2π. This causes that, for example, an echo observed to be 0 m/s may have real vertical velocity of $\pm 6.38 \times n$ m/s, where n is an integer.

We found, first, the anvil of the cumulonimbus around 9:30 UT at about 12 km in height. Vertical velocity of the anvil was about 0 to -1.5 m/s at 10:08 UT, where negative velocity means downward motion of the matter. Such range of small negative velocities is usually observed even for quiet and stable clouds. This fact can be explained that only largest cloud particles would be able to detect with FALCON-I, which have slight downward velocities about 1 m/s. In the lower part of the anvil shown at 10:29 UT, thin up and downward structures were seen projected form the main echo of the cloud. Thin upward cloud of 0 to +1 m/s was revealed at the height of 8.0 km as well as thin downward clouds of -1.5 to -2.5 m/s at 7.3 km and -2 to -3 m/s at 8.3 km. These clouds are as thin as about 100 m in the vertical direction. We can find such thin structures in other temporal data in this cloud and these do not maintain its structure in the next minute data. These facts suggest that these thin structures have also horizontal sizes of about 100 m if we assume the horizontal velocity is 1 to 2 m/s and/or life time of the structure is less than 1 minute.

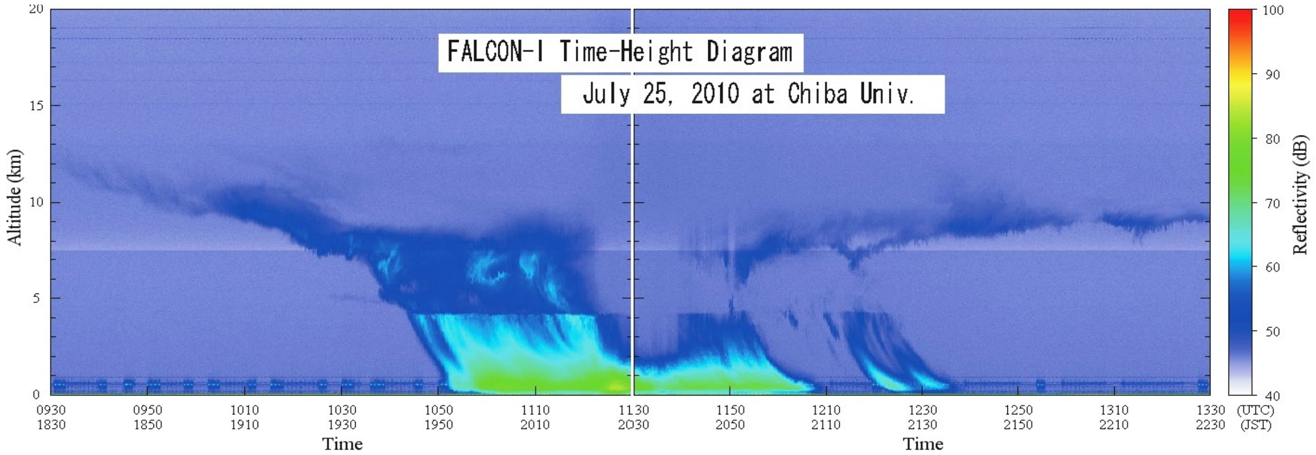

Fig.5. Time-height diagram of reflectivity observed with FALCON-I on July 25, 2010 at Chiba University. The anvil of the cumulonimbus began to be seen around 9:30 UT (18:30 JST) from about 12 km in height and gradually came down to lower height. The main part of the cumulonimbus was shown in 10:40-11:20 UT at 4-9 km in height. Rain started around 10:50. The intensity scale is dB in an arbitrary unit.

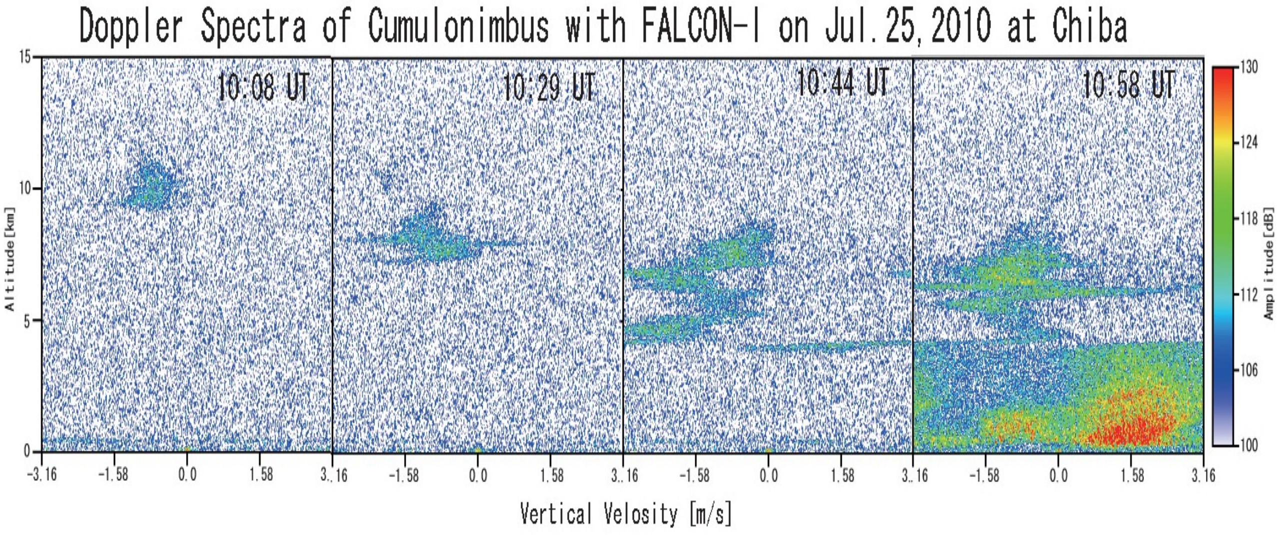

Fig.6. Doppler spectral diagrams of the cumulonimbus shown in Fig.5 observed with FALCON-I on July 25, 2010 at Chiba University. Panels show the velocity structure of matter in the anvil at 10:08 UT, lower part of the anvil at 10:29 UT, at start of the rain at 10:44 UT, and during hevy rain at 10:58 UT.

Rain started at around 10:44 UT as shown in Fig.5 and corresponding Doppler spectral diagram is the third panel in Fig.6. We can see thin line structure of a few hundred meters of vertical width at 4.2 km in height whose vertical velocities are from -0.7 to +3.16 m/s in Doppler diagram at 10:44 UT. It is obvious that this thin line is the echo of the very beginning of precipitation when we look successive spectral diagrams. The real vertical velocities of this line structure should be from -7 to -3.16 m/s instead of from –0.7 to +3.16 m/s, i.e. $2\pi = 6.32$ m/s should be subtracted. The line structure should be connected to the left end of the panel and continued to the bottom of the main body of cumulonimbus. We notice a small velocity gradient in the line structure in the vertical direction: the height of the line is about 3.9 km at the lowest velocity of -7 m/s, and is about 4.2 km at the velocity of -3.16 m/s. The whole structure of the thin line is followings: it starts from about -2 m/s on the bottom of the cumulonimbus at 4.3 km in height, and continues up to -7 m/s at 3.9 km. Turbulent up and down ward motions of ±few m/s also exist in the main body of the cumulonimbus as shown in the Doppler diagrams at 10:44 and 10:58 UT.

3-3. Discussion

Observing frequency ν of FALCON-I is 94.79 GHz which correspond to the wavelength $\lambda = 3.16$ mm. For the wavelength, spherical particles whose diameter D is smaller than about 1 mm scatter the radio wave with Rayleigh scattering region, in which scatter cross section σ is in proportion to ν^4. Particles larger than 1 mm scatter the wave with Mie scattering region, in which σ changes up and down resonating with the particle diameter and converges in its geometric cross section. A rough estimation of the raindrop size distribution N(D) would be in proportion to D^{-3} if we assume total volume of each size is constant. We may, therefore, consider that the most effective diameters of raindrops for scattering the wave of FALCON-I are 1 ±0.5 mm.

The thin and sharp line structure shown in Fig.6. at 10:44 UT, which is the echo by the beginning of the precipitation, suggests following facts as well as related structures. Rain drops of about 1 mm diameter are rapidly generated in the thin sheet of less than 100m thick in the melting layer at the bottom of the cumulonimbus. They are accelerated from -2 up to -7 m/s during 400 m drop, where this downward velocity corresponds with a usual terminal velocity for 1 mm diameter raindrops. The up and down motions in the anvil and the main body of the cumulonimbus suggest the existence of turbulences of several 100m in size in cumulonimbus

Acknowledgements

The authors thank KOBAYASHI Fumiaki of National Defense Academy for presenting information about cumulonimbus during the collaborative observations in summer 2010. This work was supported with GEOSS (Global Earth Observation System of Systems) by the Japanese Ministry of Education, Culture, Sports Science and Technology (MEXT), and with the Grant-in-Aid for Scientific Research by MEXT #14380241, #18310006 and #20310005. It was also supported with Research Projects for Promoting Technological Seeds by Japan Science and Technology Agency (JST) Innovation Satellite Ibaraki in 2007, 2009, and 2010.

References

1) TAKANO Toshiaki, YAMAGUCHI Jun, ABE Hideji, FUTABA Ken-ichi, YOKOTE Shin-ichi, KAWAMURA Yohei, TAKAMURA Tamio, KUMAGAI Hiroshi, OHNO Yuichi, NAKANISHI Yuji, NAKAJIMA Teruyuki; "Development and Performance of the Millimeter-Wave Cloud Profiling Radar at 95 GHz: Sensitivity and Spatial resolution", IEEJ Trans., FM, Vol.128, No.4, pp.257-262, 2008 (in Japanese), translated to Electronics and Communications in Japan, Vol.93, No.3, 2010.

2) ABE Hideji, YAMAZAKI Fumihiro, YAMAGUCHI Jun, KAWAMURA Yohei, NAKANISHI Yuji, TAKANO Toshiaki, TAKAMURA Tamio, OHNO Yuichi; "Doppler Observations with the Millimeter-Wave Cloud Profiling Radar FALCON-I", IEEJ Trans., FM, Vol.129, No.4, pp.177-182, 2009 (in Japanese).

3) YAMAGUCHI Jun, TAKANO Toshiaki, NAKANISHI Yuji, ABE Hideji, KAWAMURA Yohei, YOKOTE Shin-ichi, KUMAGAI Hiroshi, OHNO Yuichi, HORIE Hiroaki; "Evaluation of Radar Reflectivity (Z) for FMCW Millimeter-Wave Cloud Radar FALCON-I", IEEJ Trans., FM, Vol.129, No.4, pp.183-189, 2009 (in Japanese).

4) YAMAGUCHI Jun, TAKANO Toshiaki, TAKAMURA Tamio, NAKANISHI Yuji, KAWAMURA Yohei, ABE Hideji, HORIE Hiroaki, OHNO Yuichi; "Evaluation of Parallax on the Dual-Antenna 95 GHz MMCR FALCON-I", IEICE Trans, Vol.J92-C, No.12, pp.806-812, 2009 (in Japanese).

5) TAKANO Toshiaki, FUTABA Ken-ichi, ABE Hideji, YAMAGUCHI Jun,HIRAI Akihito, KAWAMURA Youhei, KUMAGAI Hiroshi, OHNO Yuichi, FUJIYOSHI Yasushi, and OKAMOTO Hajime; "Observations of Clouds on MIRAI in the Pacific Ocean with the Millimeter-wave FM-CW Radar at 95GHz", The International Society of Optical Engineering, Vol.6362, No.30, pp.636230・1-8, 2006.

6) G.Pandithurai, T. Takamura, J. Yamaguchi, K. Miyagi, T. Takano, Y. Ishizaka, S. Dipu, A. Shimizu; "Aerosol effect on cloud droplet size as monitored from surface-based remote sensing over East China Sea region, Geophysical Research Lett., VOL.36, L13805, doi:10.1029/2009 GL038451, 2009.

7) J.Suzuki, M.Fujiwara, A.Hamada, Y.Inai, J.Yamaguchi, R.Shirooka, F.Hasebe, T.Takano; "Cloud-Top Height Variability Associated with Equatorial Kelvin Waves in the Tropical Tropopause Layer during the Mirai Indian Ocean Cruise for the Study of the MJO-Convection Onset (MISMO) Campaign", SOLA (Scientific Online Letter on the Atmosphere), Vol.6, pp.097-100, 2010.