Artificial rainfall experiment by seeding liquid carbon dioxide above the Izu Islands of Tokyo on March 14 in 2013

Taichi MAKI *****,[†], Osamu MORITA **, Yoshinori SUZUKI ***, Kenji WAKIMIZU **** and Koji NISHIYAMA *****

* Japan International Research Center for Agricultural Sciences, 1–1 Ohwashi, Tsukuba, Ibaraki, 305–8686, Japan

** Office for a Sustainable Future, Fukuoka University, 8–19–1 Nanakuma, Jonanku, Fukuoka, 814–0180, Japan

*** Professor Emeritus, Kyushu University, 6–10–1 Hakozaki, Higashiku, Fukuoka, 812–8581, Japan

**** Faculty of Agriculture, Kyushu University, 6–10–1 Hakozaki, Higashiku, Fukuoka, 812–8581, Japan

***** Faculty of Engineering, Kyushu University, 744 Motooka, Nishiku, Fukuoka, 819–0395, Japan

Abstract

Experiments of cloud seeding using liquid carbon dioxide (LCD) were carried out on March 14, 2013 near Miyake Island and Mikura Island in the Izu Islands, Tokyo, Japan. Convective clouds near the islands developed 0.5 to 1 h after the seeding. Artificial convective clouds accompanied by rain stream, *i.e.*, virga, were observed, and rain was seen around the islands. Photos from aircraft and satellite images revealed trails and holes of disappeared clouds about 1 h and 2 h later, respectively. Within 1 h, the amount of precipitation was presumed to be about 0.1 million tons, with the precipitation intensity of 1 mm/h, based on a disappeared area $2 \text{ km} \times 50 \text{ km}$, constituting the first direct effect. Within 2 h, the total amount of precipitation from the disappeared cloud was presumed to be 1.8 million tons, based on a disappeared cloud area of diameter 50 km, constituting the secondary indirect effect. The main objective is whether the experiment of artificial rain is a success or not in a meteorological condition. Other objectives were shown successfully by photos taken of virga and the disappeared cloud, and by a satellite image based on the combination of convective cloud and the air temperature inversion layer. We found that LCD seeding at about 5 g/s within convective clouds near their bases is feasible when the air temperature is below 0°C , *i.e.*, suitable around -5°C . The excellence of LCD seeding technique is supported by the results of this study, and we believe this technique will spread worldwide.

Key words: Artificial rainfall, Aircraft seeding, Convective cloud, Liquid carbon dioxide (LCD), Miyake and Mikura Islands.

1. Introduction

A global water crisis is predicted for the 21st century. Because the demand for water continues to increase as the population grows, even in regions where the water supply is currently adequate, the demand may eventually outpace the supply. Droughts and other water problems are increasing in frequency as a result

of abnormal weather and global warming. Water deficits are an especially urgent problem in countries with arid or desert climates. Researchers are attempting to find effective techniques for inducing artificial rainfall to help meet the world's water needs, protect against desertification and develop arid lands.

Existing methods for producing rainfall involve seeding clouds with fine particles or liquids, *i.e.*, silver iodide, dry ice and water. However, these methods produce only small amounts of rainfall, and they have environmental and economical problems. A seeding technique using liquid carbon dioxide (LCD), invented by Fukuta (1988a, b), was tested and shown to be effective at Fukuoka on February 2, 1999 and in nu-

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[†] Corresponding Author: maki@affrc.go.jp

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merous later trials (Fukuta *et al.*, 2000; Wakimizu *et al.*, 2002; Nagata *et al.*, 2005; Nishiyama *et al.*, 2005; Ota *et al.*, 2005; Maki *et al.*, 2008, 2011, 2012).

The present study used an LCD seeding technique in experiments near Miyake Island (34°7.4'N, 139°31.3'E) and Mikura Island (33°2.5'N, 139°36.1') in the Izu Islands, Tokyo, Japan. These islands are south of metropolitan Tokyo and have small populations during the suitable cold period, when the experiments were conducted.

The induction of artificial rainfall by LCD seeding followed a different type of rainfall system as the experiment at the same area of Miyake and Mikura Islands conducted in February 26–27, 2012 (Maki *et al.*, 2013a, b, 2014), approximately one year earlier. One of our research objectives was to show the successful result of this experiment and the other was to compare the two cases of experiments done on Feb. 26–27, 2012 and Mar. 14, 2013, with the differences in the development of convective and stratus clouds, in the action of the inversion layer and in the effect of topography.

2. Materials and Methods

2.1 Principles of the LCD rainfall technique

LCD seeding is done by aircraft, which spreads LCD near the base or bottom of a cloud in the layer of supercooled humid air mass at temperatures below zero. The LCD at -90°C instantaneously produces ice crystals with 10^{13} particles per 1 gCO₂ (Fukuta, 1988a, b; Fukuta *et al.*, 2000), which collect ambient water vapor and grow to ice crystals or rain particles, thereby producing snow or rain.

This procedure exerts its effects through two processes: (1) air masses with these new ice crystals rise because of the release of heat of condensation, and expand in twin cylindrical vortexes as they reach the top of the cloud, and (2) supercooling clouds with ice crystals rise up in humid air masses, reach the top of the cloud and grow vertically and horizontally.

In addition, the natural updraft in the cloud is increased by the latent heat from the formation of ice crystals. The artificial clouds entered from below rise into higher-humidity air masses, causing the cloud to grow. Eventually, snowflakes or rain droplets grow large enough to fall to the ground as snow or rain.

The development of clouds is improved when a stable inversion air layer of vertical air temperature profile lies above them, suppressing vertical convection and promoting their lateral spread. These convective

Fig. 1. Locations of Oshima, Miyake and Mikura Islands and the flight route during a seeding time of liquid carbon dioxide on March 14, 2013. Seeding lines of Series 1 (1-1, 1-2, 1-3) and Series 2 (2-1, 2-2, 2-3) are shown in the left figure.

clouds expand in three dimensions, with longitudinal, lateral and vertical components. Ice crystals produced by LCD grow actively for up to one hour (1 h) mainly after seeding, and the artificial snowfall or rainfall that they induce continues for several hours.

2.2 Experimental Methods

A Beechcraft 200T twin-engine aircraft operated by Diamond Air Service, INC carried out the experiment of seeding of LCD on March 14, 2013, a date that was chosen two days beforehand based on the weather map, weather forecast, and meteorological data. The locations of Oshima, Miyake and Mikura Islands (Oshima, Miyake and Mikura hereafter) and the flight route during the LCD seeding on March 14, 2013 are shown in Fig. 1. The seeding lines of the upper level of the north area, about 10 km from Miyake (Series 1) and the upper level of northeast area, about 20 km from Mikura (Series 2) are shown in the left of Fig.1.

On March 14, the aircraft was flown from Nagoya to Miyake, where LCD was seeded around Miyake and Mikura, and then flown to Oshima. The wind direction, wind speed, air temperature and flight speed were monitored by the aircraft's instruments, and the aircraft

position (Fig. 1) was monitored by our computer using GPS.

The LCD was emitted from a nozzle on the bottom of the aircraft at the seeding rate of about 5 g/s, and the seeding was undertaken in two series, each about a 10-minute operation. The total weight of CO₂ was 6.7 kg in about 20 minutes at a seeding rate of about 5 g/s. The seeding areas were about 10 km north of Miyake and about 20 km north east of Mikura. To evaluate the effects of the seeding, we flew around Miyake and Mikura for 1 h, observing rain phenomena and taking photos (examples are shown after in Figs. 4(A)–4(D)). We used surface meteorological data, radar data and satellite data issued by the Japan Meteorological Agency (JMA) to model the development and movement of clouds affected by the LCD seeding.

3. Experiment results and discussion

3.1 Meteorological data

Fig. 2 shows a surface weather map at 12:00 on the seeding date of March 14, 2013. A winter-type pressure pattern of west high=east low type was prevalent. A continental anticyclone was changed to a travelling

Fig. 2. Surface weather map at 12:00 JST March 14, 2013 (Japan Meteorological Agency; JMA).

anticyclone moving at 30 km/h. There was a cold front near Miyake and a stratocumulus convective cloud. A rainy area with high clouds passed over Miyake at 12:00, but did not still pass over Mikura. By the visual observation from aircraft, there were mixed stratiform and convective clouds, but no high clouds with rain were present around Miyake and Mikura from 13:30 to 14:30, which was the seeding period on March 14.

3.2 Seeding of LCD near Miyake and Mikura Islands

Series 1: The seeding area was about 10 km north of Miyake in the direction of WNW to ESE and the reverse, ESE to WNW, at two passes of three minutes each, and a final pass of SW to NE taking four minutes, producing a path like the symbol $\neq$. The seeding order is shown on the left of Fig. 1.

The first seeding time was from 13:29 to 13:46. The seeding height in the cloud was 1070 m or 3500 ft, the air temperature was -2.0 to -1.0°C , the wind direction was NE and wind speed was 15.4 m/s. The height of the cloud top was 1940 m, the air temperature 0.6°C , wind direction WSW and wind speed 9.1 m/s. The height of the cloud bottom was 580 m, 2.3°C , E and 17.0 m/s. The thickness of cloud was rather thin at 1360 m.

Series 2: The second seeding area was about 20 km

north of Mikura. The seeding of LCD was done in the direction of NW to SE and the reverse, SE to NW, for two passes of three minutes each, and a final pass of SW to NE as taking four minutes, producing a path like the symbol $\neq$ (Fig. 1).

The second seeding time was from 14:03 to 14:22. The height of the seeding cloud was 1070 m, -2.0 to -1.0°C , NE and 15.4 m/s. The height of the cloud top was 2060 m, -1.0°C , W and 7.7 m/s. The height of the cloud bottom was 670 m, 5.0°C , ENE and 20.6 m/s. The thickness of the cloud was 1390 m.

It was initially thought that the cloud thickness of about 1400 m might be thin for the seeding.

An inversion layer was recognized at the height from 1200 to 2200 m, and was significantly present at the level of 2000 to 2200 m, as shown in Fig. 3. This was significantly different from the case on February 26–27, 2012 (Maki *et al.*, 2013a, b, 2014). Clouds can develop quickly by the original upstream in a natural cloud and by the artificial upstream mainly based on latent heat of condensation. As the affection in an early time is strong to the cloud because of many ice crystals, the clouds develop strongly and can pass the thin inversion layer of second lower level at about 1400 m.

Freezing 1 g/m³ of supercooled water generates a thermal buoyancy of 0.34°C . As we are considering a

Fig. 3. Vertical profile of air temperature with inversion layer around Miyake Island on March 14, 2013.

10 m^3 or larger air mass by the reaction by LCD seeding, the buoyancy of 3.4°C (K) could overcome by comparing with the air temperature difference of 3.0°C (K) based on -3°C at 1200 m and 0°C at 1400 m. Consequently, the artificial convective cloud could easily pass the second lower inversion.

There were no separate clouds around 1400 m and clouds continuously appeared in the level by visual observation from aircraft. As the cloud was pressed down by the inversion, the cloud development was almost stopped at the thick inversion layer of the first higher level at 2000–2200 m. However, if the upstream is stronger, the cloud can rise up a little throughout the inversion. Such a cloud can be seen in the right side of Fig. 4(D). However, there was no topographical effect of the mountain because of the artificial effect of clouds above the sea.

The cloud (middle line) in Fig. 4(A) showed artificial clouds developing with entrainment and two parallel lines of slightly lower or hollowing down clouds by

a downward moving air mass cooled at both borders of the artificial cloud. The development degree at the center cloud of 2-side-borders was smaller than that on Feb. 27, 2012 (Maki *et al.*, 2013a, b), however, the inversion powerfully increased the efficiency of artificial raining. The cloud development based on the inversion layer is significant on Mar. 14, 2013, *i.e.*, the inversion layer is an important phenomenon for inducing artificial rainfall because of the upstream in the cloud and developing cloud stop around the top of inversion layer. The cloud develops in three dimensions, *i.e.*, in the vertical direction as well as in the horizontal plane. This cloud development for three dimensions is fundamentally significant reason for increase of precipitation amount as water resources.

The amount of rain produced presumably by the artificial rainfall was observed 1 mm on Feb. 27, 2012 at the sloped north point of 139 m elevation in Mikura by Tokyo Water Disaster Prevention Information System (Maki *et al.*, 2014). As the rain and cloud hole were

Fig. 4. Photos of developing cloud (A) after about 0.5 h of first seeding around 14:30, virga with rain under developing clouds (B) after about 0.5 h of second seeding around 15:00 and disappeared clouds ((C) and (D)) after 1–1.5 h of second seeding around 15:30–16:00 by the LCD seeding near Mikura Island on March 14, 2013.

found above the sea in this case on Mar. 14, 2013, the amount of rain was not on Miyake and Mikura, *i.e.*, the topographical effect of the mountain is nothing in this case.

An air mass with rain under a treated cloud, *i.e.*, virga, was found at the west side of Mikura, as is clearly shown in the photo of Fig. 4(B) around 15:00. The cloud layer from 2000 to 600 m was presumed to be almost liquid water. The cloud disappeared as the trace of the aircraft into the artificial rain; its width was about 2 km (1–3 km) and the flight length was 50 km for about twenty minutes. The disappearance formed a kind of trench as shown in the photos of Figs. 4(C) and 4(D) after 1–1.5 h by second seeding around 15:30–16:00. We can see the other trench from the disappearing cloud in the distance.

3.3 Horizontal and vertical meteorological variations by the LCD seeding

Fig. 5 shows the surface weather maps of air pressure and rain intensity at (A) 12:00 and (B) 15:00 on March 14, 2013. There was a small local cyclone around Tokai and Shinshu Districts and the air pressure in the center of cyclone increased from 1015 to 1017 hPa at 12:00 to 15:00. Around Miyake and Mikura,

there was rain at 12:00, but not at 15:00, and the air pressure was increased about 2 hPa. The artificial effect could not always be found at 15:00 because of the small scale of the local action.

Fig. 6 shows a latitudinal or north-south cross section at the seeding area of 34.0°N at (A) 12:00 and (B) 15:00, and a longitudinal cross section at the seeding area of 139.25°E at (C) 12:00 and (D) 15:00. On the latitudinal cross section at the seeding area of 34.0°N at 139.25°E of the seeding point at 12:00, the wind direction was NE and the wind speed was strong, 15 to 18 m/s, at heights of about 100 and 1000 m above sea level on the level of air pressure 1000 and 900 hPa. The surface hourly wind direction was NE and the speed was 11.0, 9.3, 10.9, 8.7 m/s from 12:00 to 15:00 at the Miyake Observatory. At the height of about 1500 m, at 850 hPa, the wind was calm. The wind was W, 5 m/s at about 2000 m, at 800 hPa and W to WSW, 20 m/s at about 3000 m at 700 hPa. The wind shear or wind variation was significantly large.

At the height of 900 hPa, the wind speed was 8 and 10 m/s at 12:00 and 15:00, respectively. The wind did not change much at pressures less than 700 hPa, *i.e.*, about 3000 m above sea level. At 12:00, there was a

Fig. 5. Surface weather maps of air pressure and rain intensity at (A) 12:00 and (B) 15:00 March 14, 2013 (JMA).

Fig. 6. Latitudinal cross section at the seeding area of 34.0°N at (A) 12:00 and (B) 15:00, and longitudinal cross section at the seeding area of 139.25°E at (C) 12:00 and (D) 15:00 March 14, 2013 (JMA).

sharp dry area in the center of the 700 hPa pressure gradient on $34\text{--}35^{\circ}\text{N}$. From the level of 800 to 600 hPa, it became increasingly drier, from a relative humidity (RH) over 90% at 800 hPa to 80–20% at higher altitudes, and it was even drier at 500 hPa out of Fig. 6. Air temperatures at 850 hPa decreased from 3 to 1°C during the period of 12:00 to 15:00.

On the longitudinal cross section at the seeding area of 139.25°E (Fig. 6(C)), the seeding area was located on the border of a humid area of the south (RH over 90%) at 12:00. At 15:00 (Fig. 6(D)), the humidity had decreased drastically to 60% at the seeding point of 34.0°N at 700 hPa, and to 15% at 600 hPa. On the other hand, from 1070 m (seeding height about 900 hPa) to 2000 m, where the inversion layer (Fig. 3) became prominent, there was a saturated humidity layer over 90% in the east-west direction, and clouds could clearly develop. The air temperature at the seeding height at 900 hPa changed from 4.5 to 2.0°C between 12:00 and 15:00. The wind speed did not change between 12:00 and 15:00 except for a slight increase at 900 hPa. In this elevation, a relationship was not clear-

ly found between the effects of artificial seeding and meteorological change.

At the lowest level of 1000 hPa near the surface, the RH decreased from 80 to 70% between 12:00 and 15:00. At the surface, the hourly RH was 87, 85, 86, 71% from 12:00 to 15:00, and the hourly air temperature was 9.5 , 9.6 , 8.9 and 9.5°C . There was 0.0 h of sunshine and 0.0 mm of precipitation as drizzle.

The air temperature at the lowest level of 1000 hPa near the surface decreased from 10 to 8°C between 12:00 and 15:00. At 700 hPa, the air temperature decreased from -2°C to -3°C from 12:00 to 15:00 and reached -5°C at 18:00. At 700 hPa, the RH decreased from 90 to 60% between 12:00 and 15:00. Around the north of the seeding area ($34\text{--}35^{\circ}\text{N}$), there was a dry upper layer. By 18:00 the lower altitudes had dried up as well. The air temperature was 0°C at 900 hPa, the RH was 90%, and a stratus cloud was present. The RH was 70% at 800 hPa and was 20% at 700 hPa as a fine weather region.

Fig. 7 shows the upper-level weather maps of height, air temperature, humidity (over 90%), wind direction

and isotach as a mesoscale forecast model (MSM) at the height of 850 hPa (about 1500 m above the sea level) at (A) 12:00 and (B) 15:00 on March 14, 2013. According to the MSM, there were few changes from 12:00 to 15:00 in the wind direction (NNE), wind speed (10 m/s) and humidity (over 90%) because of the small local area of seeding, but the air temperature decreased slightly, from 2 to 0°C. It is possible to be changed by the cooling of LCD seeding. From 15:00 to 18:00, the air temperature changed from 0 to -2°C, i.e., it is also possible to be changed by the seeding, and the wind direction changed from NNE to NE while the wind speed (about 10 m/s) remained unchanged. The effect of seeding at the height of 850 hPa was not

found so clearly, as similar effects as at the heights of 700, 925 and 975 hPa.

Fig. 8 shows the upper-level weather maps of height, air temperature, wind direction and wind speed at the height of 850 hPa at (A) 12:00 and (B) 15:00 near Miyake on March 14, 2013. It was interesting in that there was a warm region around Shinshu and Tokai Districts. This was related to the local cyclone on the surface shown in Fig. 5.

At a height of 1465 m from 12:00 to 15:00, the wind direction remained relatively constant at NNE and wind speed at 10 m/s, but the air temperature changed from 2 to 0°C. No artificial effect on the numerals in Fig. 8 could be seen because of the small scale of the

Fig. 7. Upper level weather maps of height, air temperature, humidity (over 90%), wind direction and isotach at the height of 850 hPa (about 1500 m above sea level) at (A) 12:00 and (B) 15:00 March 14, 2013 (JMA).

Fig. 8. Upper level weather maps of height, air temperature, wind direction and wind speed at the height of 850 hPa (about 1500 m above sea level) at (A) 12:00 and (B) 15:00 March 14, 2013 (JMA).

seeding. Moreover, no artificial effect was found in the meteorological data observed at 18:00, again because of the small scale of the operation.

3.4 Artificial drastic changes of clouds by the LCD seeding

Fig. 9 shows the satellite cloud images of the appearance covered with cloud at 14:00, the disappearance of clouds at 15:00, 16:00, 16:30 and 17:00, and the recovery of clouds at 17:30 near Miyake and Mikura Islands. A characteristic and active effect on the clouds is shown in Fig. 9.

The first seeding was done near the NE area of Miyake and the second seeding was near the NE area of Mikura or the SE area of Miyake. In the first seeding, the seeding cloud started by the wind of NE with 15.4 m/s at 1070 m, then reached to the higher level of cloud top by the wind of WSW with 9.1 m/s at 1940 m, and snow particle fell down by the wind of NE with 15.4 m/s at 1070 m, and rain passed at the lower level of cloud bottom by the wind of E with 17.0 m/s at 1360 m. In the second seeding, the seeding cloud started by the wind of NE with 15.4 m/s at 1070 m, then reached to the higher level of cloud top by the wind of

W with 7.7 m/s at 2060 m, and snow particles fell down by the wind of NE with 15.4 m/s at 1070 m, and rain passed at the lower level of cloud bottom by the wind of ENE with 20.6 m/s at 670 m. Artificial rain first appeared around the western area of Miyake and Mikura, and a disappeared cloud area was found around the area. The disappeared cloud area moved finally to the eastern area of the islands by the westerly wind of the westerlies as shown in Fig. 9.

A fairly high cloud covered Miyake at 14:00 as shown in Fig. 9(A). We could find a small cloud hole at 15:00 in Fig. 9(B) and a slightly larger one at 16:00 in Fig. 9(C), which was the combined effect from the lines ($\neq$) to create a hole in the cloud. It was an interesting result to find two holes in the cloud at about 2 h after seeding as shown in Fig. 9(D) at 16:30, and that the diameter of the combined holes of the disappeared cloud area was about 50 km about 2.5 h later, at 17:00, as shown in Fig. 9(E). At 17:30, the artificial effect in the cloud decreased, the original cloud returned to the area (Fig. 9(F)), and this trend continued at 18:00. However, artificial effect continued for a long time of 2.5 h. Such an example was shown in Feb. 24, 2012

Fig. 9. Satellite cloud images of covered cloud at 14:00, of disappeared clouds at 15:00, 16:00, 16:30 and 17:00, and of recovered cloud at 17:30 March 14, 2013 near Miyake and Mikura Islands (JMA).

under the condition of the topographical reason. As the sharp shear in the case effects on the relation between action and reaction with inducing rain and disappearing cloud, it is presumed in this case that such a situation continued for a long time as 2.5 h.

The wind direction near the cloud bottom was easterly, and the wind speed was strong, at 17.0 to 21.0 m/s. The shears of wind direction and wind speed were significantly large at the higher and lower levels. The wind direction at the higher level was westerly by the westerlies, and the wind direction at the seeding height of 1070 m was NE and the wind speed was 15.0 m/s.

Fig. 10 shows the heights of cloud echo top around the Izu Islands at 14:00, 15:00, 16:00 and 17:00 on March 14, 2013. A convective cloud with rain passed over Miyake at 13:20, but the clouds covered Mikura. The cloud passed over Mikura at 13:40 and was gone by 13:50. There was no cloud echo around Miyake and Mikura at 14:00, 15:00 and 16:00. Two high clouds moved from the west area around 16:00 (arrows in Fig. 10(C)). They developed at a height up to 11–13 km above sea level during that period, but their height had decreased to 7–11 km at 16:40. Their height increased

again at 16:50 to 11–13 km and the first (southern) line-type cloud reached Miyake at 17:00, and passed over Miyake and Mikura as shown in Fig. 10(D). It was interesting that the cloud top height of the first cloud line of 11 to 13 km increased by the topographic effect (Maki *et al.*, 2008; Seto *et al.*, 2011; Maki *et al.*, 2012); however, that of the second (northern) one decreased to under 11 km. At 17:10, the first cloud of 9 to 11 km was passing over Mikura; however, the height did not change because of the small variation on the wide-scale range. After passing over the islands, the cloud decreased to 5 to 9 km at 17:30.

It was initially thought that the two lines of clouds had no relationship with the first direct effect of artificial rain. However, the increase of cloud height near Miyake and Mikura was clearly related to the topography of islands' mountains. Moreover, it is possible that some environment changes due to the seeding had a secondary effect on the cloud development, *i.e.*, high humidity, appearance of fog, decrease of air temperature based on the sunshine shadow of the rain cloud, and so on. Further research should explore these issues.

Fig. 11 shows the radar cloud echoes around the Izu

Fig. 10. Heights of cloud echo top around Izu Islands at 14:00, 15:00, 16:00 and 17:00 March 14, 2013 (JMA).

Islands at 14:00, 15:00, 16:00 and 17:00 on March 14, 2013. There were no radar cloud echoes around Miyake and Mikura at 14:00, 15:00 and 16:00, but a slight radar echo was found near the area at 17:00 (Fig. 11(D)). This data corresponds to Fig. 10(D). There were clear chain-type echoes from Hamamatsu to the south, with fairly high precipitation intensity at 14:00 and 17:00, but not at 15:00 and 16:00, except the moving cloud echo shown in Fig. 10(C) and Fig. 11(C).

Next, we show the typical difference of the seeding results on Feb. 27, 2012 (Maki *et al.*, 2013 a, b) and on Mar. 14, 2013. The clouds were convective clouds of cumulus and stratocumulus, respectively. By the principles of the LCD rainfall technique in Section 2.1, air masses with these new ice crystals rise because of the release of heat of condensation, and expand in twin cylindrical vortexes as they reach the top of the cloud, and supercooling clouds with ice crystals rise up in humid air masses, reach the top of the cloud and grow vertically and horizontally. As cumulus clouds were included in both cases, a basic reaction by LCD seeding was similar to each other.

On the other hand, the main difference in these cases was the inversion layer. It is very high efficiency if an inversion is observed. As the cloud was pressed down

at the top level of the inversion layer, the cloud became stratus, however, there was a convective cloud of cumulus inside both clouds. The difference of efficiency is based on the vertical activity, which is dependent on various meteorological elements, *i.e.*, air temperature, humidity (vapor density), wind direction, wind speed, and topography, season, etc.

The vertical thickness of the clouds was thick 3000–4000 m, and thin, 1400 m, respectively. Both results could produce rain, but the amount of rain on Feb. 27 was larger than that on Mar. 14. In this paper, two typical interesting results were obtained. The success of experiment is based on application of a useful chance of a good timing.

3.5 Estimation of the amount of rainwater

The amount of precipitation or rain in the first hour was presumed to be about 0.1 million tons with the precipitation intensity of 1 mm/h as a disappeared cloud area of 2 km width and 50 km length, constituting the first direct effect of the seeding. Estimation of rain intensity of 1 mm/h is based on small value as an average amount of water content of a stratus cloud in an air pillow, and 1/2–1/5 of radar echo as 2–5 mm/h on Feb. 27, 2012. As the secondary indirect effect, the total amount of precipitation of the disappeared cloud

Fig. 11. Radar cloud echoes around Izu Islands at 14:00, 15:00, 16:00 and 17:00 March 14, 2013 (JMA).

was presumed to be 2.0 million tons with the precipitation intensity of 1 mm/h based on a 50-km-diameter disappeared cloud area about 2.5 h after seeding. The other estimation was 0.15–1.5 (mean 0.8) million tons as the water content of a stratus cloud is 0.05–0.5 g/m³. The cloud physics estimation was 2.7 million tons as a maximum. Hence, the range of total induced precipitation was from 0.8 to 2.7 million tons, or a round estimation of about 1.8 million tons. The estimated amount of rainfall on March 14, 2013 was relatively larger than that on February 27, 2012 (Maki *et al.*, 2013a, b, 2014) because of high inducing efficiency by the strong inversion layer.

The success of the experiment on March 14, 2013 as a function of the inversion layer (Fig. 3) was shown in photos of the disappeared cloud (Fig. 4) and in satellite images (Fig. 9). The experimental conditions were not perfect, but the induction of artificial rainfall was presumed to be successful and the efficiency of cloud-to-rain conversion was very high.

4. Conclusion

A twin-engine Beechcraft aircraft carried out an experiment using LCD seeding around Miyake and Mikura Islands on March 14, 2013. The results are as follows:

- (1) The experimental conditions were not perfect, but the success of the experiment due to the air temperature inversion layer was shown in photos of disappeared clouds and satellite images. An inversion layer was recognized at 1200 to 2200 m, and particularly at 2000 to 2200 m. The cloud-to-rain conversion efficiency was very high.
- (2) The main difference between the results from March 14, 2013 compared with Feb. 27, 2012 was the inversion layer. The convective cloud was pressed down at the 2200 m level and developed to three dimensions. The disappeared cloud area was found around the west of Miyake and Mikura Islands in the satellite image.
- (3) The amount of precipitation as a first effect of seeding was presumed to be about 0.1 million tons after one hour, with the precipitation intensity of 1 mm/h, based on a disappeared cloud area 2 km wide × 50 km long.
- (4) The total amount of precipitation as a secondary effect of seeding was presumed to be 1.8 million tons by three different estimations.

(5) We found that the seeding of liquid carbon dioxide at about 5 g/s within convective clouds near their cloud bottoms was feasible particularly when an inversion layer appeared and the air temperatures was below 0°C, *i.e.*, around –5°C.

(6) The use of liquid carbon dioxide seeding is supported by the results of this study, and may prove to be a valuable technique to impact water shortages worldwide.

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