Artificial rainfall experiment by seeding of liquid carbon dioxide above the Izu Islands of Tokyo on December 15-16 in 2013

Taichi MAKI^{a, c, †}, Osamu MORITA^b, Yoshinori SUZUKI^c, Kenji WAKIMIZU^d and Koji NISHIYAMA^e

^aJapan International Research Center for Agricultural Sciences, 1-1 Ohwashi, Tsukuba, Ibaraki, 305-8686, Japan

^bOffice for a Sustainable Future, Fukuoka University, 8-19-1 Nanakuma, Minamiku, Fukuoka, 814-0180, Japan

^cProfessor Emeritus, Kyushu University, 6-10-1 Hakozaki, Higashiku, Fukuoka, 812-8581, Japan

^dFaculty of Agriculture, Kyushu University, 6-10-1 Hakozaki, Higashiku, Fukuoka, 812-8581, Japan

^eFaculty of Engineering, Kyushu University, 744 Motoooka, Nishiku, Fukuoka, 819-0395, Japan

Abstract

An artificial rainfall technique of liquid carbon dioxide (LCD) was used in experiments operated on Nii, Miyake and Mikura Islands in the Izu Islands of Tokyo in Japan on December 15-16, 2013. On Dec. 15, rain particles or graupel pellets struck the aircraft front window and virga or rain was observed under a cloud from the aircraft on the east leeward-side of the seeded area under the condition of thin cloud of 760 m in depth until 30 minutes. On Dec. 16, rain or graupel struck the aircraft front window at 15 minutes after seeding and virga or rain under the cloud was observed at 37 minutes after the seeding under the condition of a thinner cloud of 610 m in depth. On Dec. 15, rain was recognized along the route of the seeding and a line-type trail of cloud disappeared was visibly recognized with an average width of 2 km. The development and disappearance of clouds were evaluated using satellite images near Mikura Island. On Dec. 16, a cloud developed immediately after the seeding and a line-type cloud running in the NNE-SSW direction was recognized on the satellite image. The cloud developed decreased in scale due to rain and the cloud disappeared was also recognized on a satellite image near Nii Island. On Dec. 15, an analysis showed the existence of following local effects of the seeding; the development of clouds at 700 hPa level higher than the seeding height, the appearance of rain at 850 hPa level around the seeding height, rainfall (virga) and a drastic increase in relative humidity at 925 hPa level lower than the seeding height, and finally the occurrence of artificial rains that were clarified by the upper weather maps based on meso scale model (MSM). The artificial rainfall experiments were succeeded.

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

1. Introduction

It has been predicted that the 21st century will suffer a water crisis. The water demand continues to increase as the population increases even in regions where the water supply has been adequate, and the demand may outpace the supply. This is an especially urgent problem in countries that have arid land or desert areas. Droughts and other water-related problems are increasing in frequency as an instance of abnormal weather due to global warming. Water deficits are already extant or expected to occur around the world. New and effective techniques for producing artificial rainfall are being sought to correspond the world's water needs. It is hoped that an effective technique will also protect against drought and desertification, green deserts and supply for various industries (Maki *et al.*, 2008; 2011; 2012).

There are several existing methods for producing rainfall. There is the seeding of dry ice, seeding of silver iodide, and the scattering of liquids such as pure water or salt water, and so on. However, these methods present a small amount of water and economic

problems for these methods and environmental problem for silver iodide. An artificial rainfall technique of liquid carbon dioxide (LCD) was invented by Fukuta (1988), and it was proven successful at Fukuoka on Feb. 2, 1999 as the first effective rainfall production method. Several rainfall investigations confirmed the LCD method's property and efficiency on Feb. 2 and Oct. 27, 1999 (Fukuta *et al.*, 2000; Wakimizu *et al.*, 2002), Feb. 4 and Nov. 7, 2006, Jan. 8 and 17, 2007, Jan. 24, 2009, and other experiment results included (Maki *et al.*, 2011; 2012). The experimental results on Feb. 27, 2012 and Mar. 14, 2013 around the Izu Islands were shown in the papers (Maki *et al.*, 2013a, b; 2014a, b, c). They are mainly actual experimental results on LCD seeding.

In the present study, the LCD technique was used in experiments operated near Nii Island (34° 22.6' N 139° 15.4' E), Miyake Island (34° 7.4' N 139° 31.3' E) and Mikura Island (33° 52.5' N 139° 36.1' E) of the Izu Islands of Tokyo in Japan. These islands are south of Japan's capital, and they have very small populations as a suitable period in which the experiments were conducted particularly during the cold season in winter. The main objects of this paper are to determine how differences in meteorological and topographical conditions above the ocean have direct and indirect effects due to LCD seeding, including the topography of small islands through 3 experiments performed in the same area.

Received; October 27, 2015.

Accepted; May 11, 2016.

[†] Present affiliation: Research Faculty of Agriculture, Hokkaido University

[†] Corresponding Author: makitm@kra.biglobe.ne.jp

DOI: 10.2480/agrmet.D-15-00025

2. Materials and Methods

2.1 Experimental Methods

The flight routes of Beechcraft 200T twin-engine aircraft operated by Diamond Air Service, INC on Dec. 15 and 16 are shown in Fig. 1. The aircraft took off Prefectural Nagoya Airport at 10:48 on Dec. 15, seeded LCD around the west of Mikura Island (Mikura) at 11:20-11:57, observed meteorological conditions around the south of Mikura, passed over Mikura and Miyake Island (Miyake) and landed on Oshima Airport at 12:54. On Dec. 16, the aircraft took off Oshima Airport at 9:35, seeded around the east of Nii Island (Nii) at 9:56-10:14, observed around the leeward side of east of Nii and landed on Nagoya Airport at 11:22.

In order to be compared with 2 previous experiments performed on Feb. 27, 2012 and Mar. 14, 2013, the seeding and meteorological observations were carried out far to the west and south of Mikura on Dec. 15 and north of Miyake, *i.e.*, the east of Nii on Dec. 16 because of the position of the proper clouds for seeding. The meteorological elements of air temperature, wind direction and wind speed were observed by instruments in the aircraft as necessary, *i.e.*, at the cloud top, bottom and so on.

The vertical profiles of air temperature were observed on the flight routes during an elevating period of aircraft from Nagoya (around 35°N, 137°E), Aichi to Hamamatsu (around 34.5°N, 138°E), Shizuoka on Dec. 15 and from Izu Oshima to Nii Islands on Dec. 16.

2.2 A General Weather Condition

The surface weather maps around the seeding time with 12:00 Dec. 15 and 16, 2013 are shown in Fig. 2. There was the strong high of 1048 hPa on the Continent on Dec. 15-16 and the low of 984 hPa on Dec. 15 and 972 hPa on Dec. 16 on the east of Hokkaido. A winter-type pressure pattern of west high=east low type was prevalent. The isobar line of north to south was found around Miyake. The weather types of 2 days were pretty similar as a pattern. Then NW-WNW winds as winter monsoon were blowing at the lower layer around the seeding height of about 1400 m and also NW-WNW winds as westerlies at the upper layer on Dec. 15, but on Dec. 16, S-SW winds were blowing around the seeding height and NWN-NW winds as westerlies at the upper layer.

2.3 Observation Condition

On Dec. 15, the first seeding time was 11:28:08-11:32:23 about 4 minutes (min), the second 11:34:30-11:39:20 about 5 min and the third 11:48:05-11:57:24 about 9 min, and seeding time was 18 min 24 second (s) in 11:28-11:57. The seeding cloud moved to SE by NW wind direction around the seeding height and to ESE by WNW wind direction at the higher air layer. The seeding rate of LCD was 4.0 g/s and total seeding weight was 4.42 kg. The observation time around the south of Mikura was 1 hour (h) 9 min in 11:28-12:47.

On Dec. 16, the first seeding time was 9:56:37-10:00:59, about 4 min included intermission 15 s and seeding height was 1370 m, the second was 10:02:58-10:07:50, about 5 min, and seeding

Fig. 1. Flight routes of aircraft and seeding orders (No.1-3) on Dec. 15 and 16, 2013. ①-③ is seeding order.

Fig. 2. Surface weather maps at 12:00 Dec. 15 and 12:00 Dec. 16, 2013.

Fig. 3. Vertical profile of air temperature from Nagoya to Hamamatsu areas on Dec. 15, 2013.

height 1460 m and the third was 10:09:58-10:13:54, about 4 min and seeding height 1480 m. The seeding rate was 3.3 g/s and total seeding weight 2.52 kg. The seeding time was 12 min 55 s in 9:56-10:14. The observation time around the east of Nii was 40 min in 9:56-10:36.

3. Results and Discussion

3.1 Vertical Profile of Air Temperature

The vertical profile of air temperature observed from Nagoya, Aichi to Hamamatsu, Shizuoka is shown in Fig. 3 on Dec. 15. The air temperature decreased with the gradient of 0.73°C per 100 m

from the ground surface to the height of 2740 m. The air temperature decreased gradually with a mean of dry ($1.0^{\circ}\text{C}/100\text{m}$) and wet ($0.5^{\circ}\text{C}/100\text{m}$) lapse rates. The inversion layer was recognized from 2740 m to 3740 m with the depth of just 1000 m and the temperature difference of -11°C to -7°C , *i.e.*, the temperature lapse rate of $0.40^{\circ}\text{C}/100\text{ m}$, and then the air temperature decreased again with $0.63^{\circ}\text{C}/100\text{ m}$ from 3740 m to 5330 m of observed height. That is, there was the inversion layer with $0.4^{\circ}\text{C}/100\text{ m}$ between 2 layers with the lapse rate about $0.7^{\circ}\text{C}/100\text{ m}$.

The inversion layer was obtained at Nagoya-Hamamatsu on Dec. 15, but not observed near Miyake because of seeding proce-

ture. The seeding experiment was done near Miyake and the observed data were analyzed as an inversion layer seemed to be existed. Around the seeding height 1370 m of upper air layer, the temperature lapse rate near Miyake was similar to that near Nago-ya-Hamamatsu.

On Dec. 16, the profile around the inversion layer near Miyake was not observed, but the air temperature around the average seeding height of about 1400 m (1000 to 1700 m) increased 2.0°C higher than that on Dec. 15.

3.2 Seeding Situation and Weather Condition

On Dec. 15, LCD was seeded around 40 km west from Mikura Island with the seeding distance of 30 km for approximately north-south (N-S) direction. The height of cloud top was 1830 m with air temperature -6°C, wind direction WNW and wind speed 20.6 m/s. The height of cloud bottom was 1070 m with air temperature -1°C and winds not observed. The depth of cloud was thin 760 m and the density of cloud was low. The seeding cloud was wide stratocumulus. The seeding height of three times was 1370 m with air temperature -3°C, wind direction NW and wind speed 18.0 m/s.

On Dec. 16, LCD was seeded around 40 km north from Miyake Island with the seeding distance of 30 km for NNE-SSW direction. The height of cloud top was 1680 m with air temperature -4°C and winds not observed. The height of cloud bottom was 1070 m, air temperature 3°C and winds not observed. The depth of cloud

was very thin 610 m and density of cloud was slight higher than on Dec. 15. The seeding cloud was narrow but pretty developed stratocumulus was spread over wide area.

Meteorological elements were that air temperature was -1°C, wind direction E and wind speed 1.3 m/s for the first seeding, -3°C, S and 6.2 m/s for the second and -3°C, SW and 8.7 m/s for the third. The average seeding height was 1440 m, mean wind direction southern and mean wind speed 5.4 m/s.

The differences of wind direction and wind speed on Dec. 15 and 16 were based on topographic phenomena, *i.e.*, the wind came from west sea area with smooth surface on Dec. 15, but the wind was affected by the Izu Peninsula and Izu Oshima Island on Dec. 16.

3.3 Evaluation of Rain Particles and Virga

On Dec. 15, rain particles or graupel pellets that struck the aircraft front window around 12:00 at about 20 min after the middle of the seeding time at the east leeward side of the seeded area in the seeded cloud chased by the aircraft. This phenomenon is the first principal of artificial rainfall. Seeding technique is based on two processes: (1) air masses with new ice crystals rise due to the released latent heat of condensation and expand in twin cylindrical vortexes as they reach 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.

A cloud containing rain or graupel, *i.e.*, a virga was observed

Fig. 4. (A) Virga shown on the middle area in the photo and (B) disappeared area of cloud with 2-3 km width along the line of LCD seeding by the aircraft on Dec. 15, 2013, and (C) developing cloud seen from high elevation and (D) virga shown on a little left in the photo near Nii Island on Dec. 16, 2013.

from the aircraft window around 12:10, about 30 min after the middle of the seeding time, under the seeded cloud at the east leeward side of the seeded area, and photos were taken, as shown in Fig. 4(A). This phenomenon is the second principal of artificial rainfall. The area of cloud disappeared or no cloud trail as a line-type was found around 12:30-13:00 until 0.5-1 h after the seeding as shown in Fig. 4(B). This is the third principal of artificial rainfall. The width of the cloud disappeared was estimated to be an average of 2 km with a range from 1-3 km.

The development of the cloud and line-type cloud disappeared on Dec. 15 is similar to the phenomenon observed on Mar. 14, 2013 (Maki *et al.*, 2014b, c), but not to that observed on Feb. 26-27, 2012 (Maki *et al.*, 2013a, b).

On Dec. 16, the rain particles or graupel pellets that struck the aircraft front window were observed around 10:05 about 15 min after the seeding and the cloud with rain, *i.e.*, virga was observed from the aircraft window around 10:27 about 37 min after seeding at the north leeward side of the seeded area. The cloud that developing around the seeding cloud is shown in Fig. 4(C) and the virga was found under the cloud shown in Fig. 4(D). The width of the NNW-SSE line-type cloud disappeared was narrow, however, the seeded cloud developed quickly. No line-type cloud disappeared like that seen on Dec. 15 was observed by aircraft in a short observation period. The development and disappearance of the cloud are described after.

3.4 Evaluation of Cloud by Satellite Infrared and Visible Images on Dec. 15

The experiment was evaluated using satellite infrared images, the images obtained at 11:30, 12:00, 12:30, 13:00, 13:30 and

14:00 on Dec. 15 are shown in Fig. 5-1. At 11:30 (Fig. 5-1(A)), no clouds were clearly found west of Miyake and Mikura, but a slight thin cloud was found in the area SE of Mikura. As the seeding time was 11:28-11:57, so no effect could be expected to be seen at 11:30. Low level clouds were present from south of Isewan and Atsumi Peninsula to Enshunada, and reached as far as Miyake and Mikura. Then, these clouds developed and were significantly denser at 12:00 in the white oval in Fig. 5-1(B). Considering the movement of clouds over time and based on their position, *i.e.*, their movement around Miyake and Mikura, and on the winds, the effect of LCD seeding seemed to be apparent in the enhancement of these clouds at 20-30 min after the first seeding. The seeding effect seemed to continue, but the clouds became a little thinner in areas west and east of Miyake and Mikura from 12:30 to 13:00. The clouds were rather denser at 13:30 and 14:00 in these same areas. This suggested that the clouds developed quickly as a result of the seeding of LCD, the clouds disappeared first like a line-type 0.5-1 h after the seeding, and second the area of cloud disappeared became wider on the east side of Mikura for a time. A good example of this phenomenon was recognized on Mar. 14, 2013 (Maki *et al.*, 2014b, c). The natural clouds that were found near Mikura and Miyake from 13:30 to 14:00 and moved from the west to the east side seemed to be intensified by the artificial clouds. Clouds on the east side of Mikura were observed in this case and the development of the clouds due to topographical features may have occurred around the leeward sides of both islands (Seto *et al.*, 2011; Maki *et al.*, 2013a, b).

On the other hand, the clouds were also evaluated using satellite visible images for comparison with infrared images as shown

Fig. 5-1. Satellite infrared images of the seeding area at 11:30, 12:00, 12:30, 13:00, 13:30 and 14:00 on Dec. 15, 2013.

Fig. 5-2. Satellite visible images of the seeding area from 11:00 to 13:30 on Dec. 15, 2013.

in Fig. 5-2, and these images showed almost nothing west and east of Miyake and Mikura at 11:00 (no figure) and 11:30 on Dec. 15. Clouds were found on the west side but not on the east side at 12:00, about 20-30 min after the first seeding. Clouds were continuously found on the west of Mikura from 12:30 to 14:00 and slightly found on the east of Mikura from 12:30 to 13:30. These clouds on the west side at 12:00 and on the east side of Mikura from 12:30 to 13:30 seemed to be the artificial rain clouds affected by the seeding due to the time, their position, the wind direction and the wind speed. The time of the appearance of the clouds on the east side of Mikura showed a reasonable correspondence to what would be expected for the seeded clouds, because no clouds were observed at 12:00 and the clouds appeared from 12:30 to 13:30, and the height at which the clouds appeared also fit with expectations. The clouds were clearly shown in the visible image, but lower than those shown in the infrared image for thin clouds.

3.5 Evaluation of Cloud by Satellite Terra and Satellite Aqua on Dec. 15

The satellite true color images of Terra at 9:35 and Aqua at 12:55 on Dec. 15 detected by NASA, USA are shown in Figs. 5-3 (A), (B). Although the image in Fig. 5-3 (A) was composited by 9:35 and 11:15, the time 9:35 was used because that image was the main image of the seeding area. As the image in Fig. 5-3 (B) was composited by 12:50 and 12:55, the time 12:55 composited was used because that corresponded to the main image.

Before seeding at 9:30, a wide cloud was recognized west of Miyake and Mikura, however, there were no clouds east of them (Fig. 5-3 (A)). This cloud west of Mikura was seeded with LCD at 11:28-11:57, a thin and wide cloud around Miyake and Mikura (Fig. 5-3 (B)) were observed at 12:55, 1 h after the last seeding. This cloud was moved to the east from the west by an upper wind from the WNW at 20.6 m/s around a height of 1800 to 1900 m.

There were wide striped clouds west and east of Miyake and Mikura (black oval area, Fig. 5-3 (B)). However, an abnormal cloud gap with an area of clouds that had almost disappeared, compared with the clouds in the circumference area (white circle area, Fig. 5-3 (B)) was recognized as a slight cloud area having a rather wide hole near the east-side of Mikura. This may have been the track of the cloud that disappeared due to artificial rainfall as a rain dropped from artificial cloud. The experimental example was that a first straight line of cloud disappeared changed to a second circle of the area of cloud disappeared with 50 km in diameter (Maki *et al.*, 2014b, c).

3.6 Evaluation of Cloud by Satellite Infrared and Visible Images on Dec. 16

The satellite infrared images taken from 10:00 to 16:00 on Dec. 16 are shown in Fig. 5-4. As the seeding period was from 9:56-10:14 at a height of 1440 m, there was a thin line-type cloud at 10:00 in the area labeled (a) (Fig. 5-4 (A)) not affected by the seeding running in the NNE-SSW direction near Nii. The cloud developed quickly after 10:00 due to LCD seeding. The cloud was visible and could be identified by eye until 10:30 north east of Nii in the area labeled (b) (Fig. 5-4 (B)) due to a southern wind that was measured by the aircraft observation passing over the cloud at a high altitude. It was likely that these developing clouds were affected by the artificial seeding as indicated by the seeding time (10:03-10:14), the height at which the cloud appeared by the upstream induced by the seeding, the wind direction (S-SW) and the wind speed (6.2-8.7 m/s). After 10:30, the clouds moved to the east of Nii and were visibly recognized as a clearly developed clouds running in the NNE-SSW direction. However, there was not sufficient time to observe the cloud as it disappeared due to the limit of the flight time and the aircraft left the area at 10:36 to go back to Nagoya. The development of the cloud on satellite

Fig. 5-3. Satellite images of Terra (A) at 9:35 and Aqua (B) at 12:55 on Dec. 15, 2013.

images (cloud in the area labeled (b) in Fig. 5-4(B)) continued from 10:30 to 11:30 east of Nii as an effect of the seeding. This occurred, as described above, due to the time and winds. The cloud started to diffuse at 12:00 and decreased in density at 12:30. At 13:00, the cloud shown on the infrared images disappeared around the northern area of the east side of Nii (NE area), but it was still found at 13:30-14:00 east of Nii. After 14:30, the cloud became a thinner narrow cloud to the east of Nii. Finally the cloud disappeared at 16:00 except for a remainder of the NNW-SSE cloud far-southeast direction from Mikura.

It was analyzed about the clouds developed and disappeared. The cloud in area (b) developed from 10:30 to 11:30 (B-D) mainly as an artificial effect of the LCD seeding. The cloud decreased from 12:00 to 13:30 (E-H) because rain particles dropped from the cloud and due to diffusion of the cloud in the air. Three short artificial NNE-SSW clouds (shown after in Fig. 5-6) were included in a part of long natural NNW-SSE cloud. The clouds became weaker from 14:00 to 15:30 (I-K) and finally disappeared at 16:00 (L).

The satellite visible images taken from 9:00 to 12:00 on Dec. 16 are shown in Fig. 5-5. At 9:00 before the seeding, no clouds were found near Miyake, but at 10:00 slight clouds were found around Nii and east of Miyake and Mikura in white oval in Fig. 5-5(B). Clouds appeared north east of Nii as in the infrared images taken at 10:30 and 11:30, and these clouds were estimated to be artificial clouds based on by the time, position and winds. The clouds were still found north east of Nii from 11:30 to 12:00, but they were a little weak at 11:30 and weaker at 12:00. These phenomena show the artificial effects due to the first development of cloud and second disappearance of cloud. Even if the resolution of

the visible image on Dec. 16 was weaker than that of the infrared image and also that of the images on Dec. 15, the artificial cloud was evaluated.

3.7 Evaluation of Cloud by Satellite Terra and Satellite Aqua on Dec. 16

The satellite true color images of Terra at 10:20 and Aqua at 12:45 on Dec. 16 detected by NASA are shown in Figs. 5-6. The figures of Terra in Figs. 5-6(A), (B) were composited at 10:20, 11:55 and 12:00, but the image composited at 10:20 was used as the main image because those from 11:55 and 12:00 were side views. The average time 12:45 composited with 11:55 and 13:35 of Aqua in Figs. 5-6(C), (D) was used, but not 12:00 because of almost out of the region.

On the images shown in Figs. 5-6(A), (B) at 10:20 after seeding of about 20 min, there were bright clouds running NNW-SSE near Nii (arrow (a), Fig. 5-6(A)). Moreover, a thin and spotted cloud (arrow (b), Fig. 5-6(A)) was scattered widely, but this cloud seemed not to be an artificial cloud based on the seeding time and position.

On the other hand, 3 parallel lines of bright clouds running in the NNE-SSW direction were recognized south east area of Nii (Figs. 5-6(A), (B), enlarged figure in (B)), those were located in the chain cloud running in the NNW-SSE direction. The image of Bands 7-2-1 (Fig. 5-6(B)) was shown as slightly clearer than that of true color (Fig. 5-6(A)). The image at 10:20 in Figs. 5-6(A), (B) was taken about 30 min after the first seeding. The clouds were estimated to be artificial clouds produced by 3-time seeding in the NNE-SSW direction (Fig. 1(B)) based on the seeding time (9:56-10:36), seeding direction, seeding position, wind direction and wind speed.

Fig. 5-4. Satellite infrared images of the seeding area from 10:00 to 16:00 on Dec. 16, 2013.

The seeded cloud initially moved in the NE direction due to a SW wind of 8-9 m/s at about 1400 m in altitude and the cloud seemed to move in the SE direction due to a the NW wind of 10-15 m/s at a higher level. The wind direction and wind speed at the seeding height were different from those at the intermediate level of the seeding height and at the westerly wind height of higher layer. The artificial effect of the cloud disappeared was recognized as a gap or decrease in the main cloud running in the NNW-SSE direction far-east of Mikura after 2.5-3 h of seeding as 3 no cloud lines of 3 arrows (Figs. 5-6(C), (D), enlarged figure in (D)). This is probably the track of the cloud that disappeared due

to artificial rainfall; dropping rain from artificial cloud. The image of normalized difference vegetation index (NDVI) (Fig. 5-6(D)) was shown as slightly clearer than that of visible color (Fig. 5-6(C)).

3.8 Changing Pattern of Cloud by Radar Echo

Based on the variation in the clouds displayed by radar echo at 11:00, 12:00, 13:00 and 14:00 on Dec. 15, there were significant clouds in the Niigata area on the Japan Sea side, but nothing at all on the Pacific Ocean side. No changes in the clouds caused by the seeding were observed because the radar detecting is not functional under the level of 2000 m in altitude. However the lower

line-type clouds detected by the satellite existed as shown in Fig. 5-1.

Based on the variation in the clouds displayed by radar echo at 9:30, 10:00, 10:30 and 11:00 on Dec. 16, there was slightly weaker cloud compared to Dec. 15 on the Niigata side, and nothing at all, just as on Dec. 15, on the Pacific Ocean side. There was also no seeding effect on the cloud of higher layer. Consequently no significant convective cloud was found, but a lower line-type cloud was found as mentioned above.

3.9 Evaluation of Seeding Effect on Upper Weather Map of Meso Scale Model (MSM)

The upper weather map (5 km mesh) based on the objective analysis data of Meso Scale Model (MSM) produced by the Japan Meteorological Agency was estimated. The output (5 km mesh) of MSM is initial values of meteorological data at the main observatory that reflects all available observation data, *e.g.*, meteorological data of AMeDAS, radar, satellite, radiosonde, wind profiler, aerological observation, *etc.*, every 3 h. The data of wind direction and wind speed observed at Nagoya, Shizuoka, Katsuura and Hachiojima by a wind profiler were used.

The weather map is useful for the evaluation of local meteorological changes because the scale of an artificial rainfall is mainly

Fig. 5-5. Satellite visible images of the seeding area at 9:00, 10:00, 10:30, 11:00, 11:30 and 12:00 on Dec. 16, 2013.

Fig. 5-6. Satellite images of visible (A) and Bands 7-2-1 (B) by Terra at 10:20 and visible (C) and NDVI (D) by Aqua at 12:45 on Dec. 16, 2013.

Fig. 6. Upper weather maps by a company using meso scale model at the levels of 700 hPa, 850 hPa and 925 hPa at 9:00, 12:00 and 15:00 on Dec. 15, 2013.

Blue (light color) thin line: heights of 700, 850 and 925 hPa levels, red (light) thin line and number: air temperature and blue (dark) flag: wind direction and wind speed.

10 to 100 km. Meteorological data for Miyake Island ($34^{\circ}03' \text{ N}$, $139^{\circ}33' \text{ E}$) were obtained and evaluated. It was shown that LCD seeding has an effect on the local meteorological data around the seeding area.

Figure 6 shows the upper weather maps estimated by a weather information company using the initial data of MSM at 9:00, 12:00 and 15:00 on the levels of 700, 850 and 925 hPa on Dec. 15.

First of all at 700 hPa, the height of isobaric surface (isobaric height), wind direction and wind speed were indicated respectively, at 09:00; 2980 m, WNW and 30 m/s, at 12:00; 2980 m, WNW and 30 m/s, and at 15:00; 2970 m, WNW and 35 m/s.

Next at 850 hPa, isobaric height, wind direction, wind speed and air temperature at 09:00; 1450 m, WNW, 20 m/s and -2°C , at 12:00; 1450 m, WNW, 20 m/s and -3°C , and at 15:00; 1440 m, W-WNW, 20 m/s and -3°C .

The last at 925 hPa, at 09:00; 780 m, W-WNW, 20 m/s and 2°C , at 12:00; 770 m, W-WNW, 20 m/s and 3°C , and at 15:00; 760 m, W-WNW, 20 m/s and 3°C .

At 700 hPa, the isobaric height decreased at 15:00, wind direction did not change, wind speed increased at 15:00. At 850 hPa, the isobaric height decreased at 15:00, wind direction changed to western side at 15:00, wind speed did not change, air temperature decreased a little from 12:00. At 925 hPa, the isobaric height decreased at 12:00 and 15:00 with a time, wind direction and speed did not change, air temperature increased a little from 12:00.

No effect of the seeding on ambient air at about 3000 m (700

hPa) level was found at 12:00 because of too high level for an effect in a time, but the effect seemed to appear 3 h later at 15:00 at Miyake. The air temperature at about 1500 m (850 hPa) level and 750 m (925 hPa) level, and the isobaric height at about 750 m level seemed to be affected by artificial seeding. It was thought that these effects were reasonable results of the changing pattern of weather elements, because of the balance among the seeding height, natural and artificial upstreams and the appearance of virga under the cloud.

Figure 7 shows the upper weather maps estimated by the authors using the initial data of MSM at 9:00, 12:00 and 15:00 at the levels of 700, 850 and 925 hPa on Dec. 15.

First of all at 700 hPa, the height of isobaric surface, wind direction, wind speed, air temperature and relative humidity were indicated respectively, at 09:00; 2990 m, W-WNW, 30 m/s, -5°C and 59 %, at 12:00; 2980 m, WNW, 33 m/s, -7°C and 60 %, and at 15:00; 2970 m, WNW, 34 m/s, -4°C and 61 %.

Next at 850 hPa, at 09:00; 1460 m, WNW, 22 m/s, -2°C and 31 %, at 12:00; 1450 m, W-WNW, 19 m/s, -2°C and 32 %, and at 15:00; 1430 m, W-WNW, 21 m/s, -3°C and 33 %.

The last at 925 hPa, at 09:00; 780 m, WNW, 19 m/s, 2°C and 32 %, at 12:00; 770 m, W-WNW, 19 m/s, 3°C and 41 %, and at 15:00; 760 m, W-WNW, 21 m/s, 3°C and 42 %.

As the seeding time was 11:28-11:57, at 700 hPa, the isobaric height decreased at 12:00 and 15:00 with a time, wind direction changed from W-WNW to WNW at 12:00, wind speed increased

Fig. 7. Upper weather maps by the authors using meso scale model at the levels of 700 hPa, 850 hPa and 925 hPa at 9:00, 12:00 and 15:00 on Dec. 15, 2013.

Black thick line and black number: heights of 700, 850 and 925 hPa levels, yellow (light color) thick line and red (light) number: air temperature, blue (light) chain line and purple (light) number: relative humidity, green (light) dotted area: humid area lower than 2°C of dry-wet bulb temperature and blue (dark) arrow: wind direction and wind speed.

3-4 m/s at 12:00 and 15:00, air temperature decreased 2°C at 12:00 and increased 3°C at 15:00 and humidity slightly increased at 12:00 and 15:00. Upper meteorological elements seemed to be affected by the seeding after 30 min because values of wind direction, wind speed and air temperature changed. At 850 hPa, the isobaric height decreased at 12:00 and 15:00 with a time, wind direction changed from WNW to W-WNW at 12:00, wind speed decreased at 12:00 and increased a little at 15:00, air temperature did not change at 12:00 and decreased a little at 15:00, and humidity slightly increased at 12:00 and 15:00. At 925 hPa, the isobaric height decreased at 12:00 and 15:00 with a time, wind direction changed from WNW to W-WNW at 12:00, wind speed increased at 15:00, air temperature increased from 12:00 and humidity drastically increased at 12:00 and continued or slightly increased at 15:00.

Since it takes time for the seeding to affect the clouds and the air mass at lower altitudes, no effect was found in the air temperature, the wind direction and the wind speed because of the short time from seeding to reaction and wide scale phenomenon, but was found in the isobaric height and in the relative humidity, which increased significantly from 32 % to 41 % at 12:00. Even if the variation in isobaric height seemed to be based on a natural inclination, the drastic variation in humidity was mainly caused by the artificial seeding effect. The temperature and humidity increased mainly from 9:00 to 12:00, but the increase in vapor due

to the increase of humidity from 32 to 41% was higher than that which would be caused by the increase in temperature from 2 to 3°C. The vapor increase due to the rain was an effect of the artificial seeding. At 15:00, the seeding may have affected the wind direction, wind speed, air temperature and relative humidity. At the lower level of 925 hPa, the isobaric height decreased with time, the wind direction changed to become westerly, and the wind speed, air temperature and humidity increased. As shown in these data from 12:00 to 15:00, the changes in local meteorological elements seemed to have been the effect of artificial rain, *i.e.*, the virga from the cloud that developed due to the seeding.

These changes were clearly based on the natural upstream in the cloud and the artificial upstream caused by the latent heat of ice crystal condensation above the seeding cloud according to numerical analysis data, and these changes were based on the downstream caused by virga as a visible scene (Fig. 4(B)) under the seeding cloud. Moreover, an important result was that the relative humidity drastically increased. This means that the artificial rainfall from virga caused the increment of humidity at 20-30 min after LCD seeding around a height of 700-800 m under the seeding height.

Consequently at 700 hPa, the decrease in isobaric height and the increase in wind speed agreed with both evaluations of the upper weather maps. At 850 hPa, the decrease in isobaric height also agreed with these evaluations, and the wind direction, wind

speed and air temperature were similar to those in the evaluation although with slight variations in the details. At 925 hPa, the decrease in isobaric height and the change in air temperature were also consistent with each other. However, the relative humidity could not be compared, because humidity data were obtained only in Fig 7. The evaluation using upper weather maps of both figures sufficiently explained the effect of seeding due to the height and time conditions.

The local action of the seeding affected a rather wide area and its changing degree was evaluated. In particular, the accuracy of the meteorological evaluation performed by the authors based on the upper weather maps was fairly high and was useful for estimating the variation due to local artificial action. The MSM numerical evaluation of the artificial effect on natural clouds of the LCD seeding was basically consistent with several experiment results (Maki *et al.*, 2013a, b; 2014a, b, c; 2015a, b). So, this artificial rainfall experiment was also considered to be reasonable by the MSM analysis.

4. Conclusions

The experiment result of artificial rainfall by aircraft seeding of LCD was carried out near Nii, Miyake and Mikura Islands of Izu Islands, Tokyo, Japan from Dec. 15 to 16, 2013 were as follows:

- (1) On Dec. 15, rain particles or graupel pellets struck the aircraft front window about 20 min after LCD seeding and virga or rain was observed under a cloud from the aircraft on the east leeward-side of the seeded area under the condition of thin cloud of 760 m in depth until 30 min.
- (2) On Dec. 16, rain or graupel struck the aircraft front window at 15 min after seeding and virga or rain under the cloud was observed at 37 min after the seeding under the condition of a thinner cloud of 610 m in depth.
- (3) On Dec. 15, rain was recognized along the route of the seeding and a line type-trail of cloud disappeared was visibly recognized with an average width of 2 km. The development and disappearance of clouds were evaluated using satellite images near Mikura Island.
- (4) On Dec. 16, a cloud developed immediately after the seeding and a line-type cloud running in the NNE-SSW direction was recognized on the satellite image. Afterward, the cloud developed decreased in scale due to rain and the cloud disappeared was also recognized on a satellite image near Nii Island.
- (5) On Dec. 15, an analysis showed the existence of the following local effects of the LCD seeding; the development of clouds at 700 hPa (3000 m) level higher than the seeding height, the appearance of rain after 20-30 min at 850 hPa (1500 m) level around the seeding height, rainfall (virga) and a drastic increase in relative humidity at 925 hPa (750 m) level lower than the seeding height, and finally the occurrence of artificial rains that were clarified by the upper weather maps based on meso scale model (MSM).
- (6) The artificial rainfall experiments on Dec. 15-16 were succeeded.

References

- Fukuta, N., 1988: Meteorological Engineering—new method of meteorological control—. *Meteorological Research Note*, **164**, Meteorological Society of Japan, 1-213. (in Japanese)
- Fukuta, N., Wakimizu, K., Nishiyama, K., Suzuki, Y. and Yoshikoshi, H., 2000: Large unique radar echoes in a new, self-enhancing cloud seeding. *Atmospheric Research*, **55**, 271-273.
- Maki, T., Hashimoto, Y., Okushima, R., Mitsuno, T., Noguchi, N., Aoki, M., Isoda, H., Omasa, K., Goto, E., Suzuki, Y., Takatsuji, M., Nonami, H., Hashiguchi, K., Hayakawa, S., Murase, H. and Yamagata, T., 2008: *Promotion of Artificial Rainfall Technique for Countermeasure of Drought and Prevention of Desertification*. Science Council of Japan, 1-28. (in Japanese)
- Maki, T., Suzuki, Y., Wakimizu, K., Tomine, K. and Nishiyama, K., 2011: Artificial Rainfall. In *Encyclopedia of Wind* ed. by T. Maki, H. Niino, T. Nomura, Y. Hayashi and S. Yamakawa, Maruzen Shuppan, Tokyo, pp. 134-135. (in Japanese)
- Maki, T., Suzuki, Y., Wakimizu, K. and Nishiyama, K., 2012: *Artificial Rainfall from countermeasure of drought to water resources*, Gihodo Shuppan, Tokyo, pp.176. (in Japanese)
- Maki, T., Morita, O., Suzuki, Y. and Wakimizu, K., 2013a: Artificial Rainfall Produced by Seeding with Liquid Carbon Dioxide at Miyake and Mikura Islands, Japan. *Journal of Developments in Sustainable Agriculture*, **8**(1), 13-24.
- Maki, T., Morita, O., Suzuki, Y. and Wakimizu, K., 2013b: Artificial rainfall technique based on the aircraft seeding of liquid carbon dioxide near Miyake and Mikura Islands, Tokyo, Japan. *Journal of Agricultural Meteorology*, **69**(3), 147-157.
- Maki, T., Morita, O., Suzuki, Y. and Wakimizu, K., 2014a: Artificial rainfall experiment by the aircraft seeding of liquid carbon dioxide near Miyake and Mikura Islands. *Agriculture and Horticulture*, **89**(1), 9-22. (in Japanese)
- Maki, T., Morita, O., Suzuki, Y., Wakimizu, K. and Nishiyama, K., 2014b: Artificial rainfall experiment by liquid carbon dioxide in March 2013 near Miyake and Mikura Islands in Tokyo. *Journal of Arid Land Studies*, **24**(2), 277-284. (in Japanese)
- Maki, T., Morita, O., Suzuki, Y., Wakimizu, K. and Nishiyama, K., 2014c: Artificial rainfall experiment by seeding liquid carbon dioxide above the Izu Islands of Tokyo on March 14 in 2013. *Journal of Agricultural Meteorology*, **70**(4), 199-211.
- Maki, T., Nishiyama, K., Morita, O., Wakimizu, K. and Suzuki, Y., 2015a: Artificial rainfall experiment by liquid carbon dioxide in December 2013 near Saijo in Ehime. *Journal of Arid Land Studies*, **25**(1), 1-10. (in Japanese)
- Maki, T., Morita, O., Nishiyama, K., Suzuki, Y. and Wakimizu, K., 2015b: An artificial rainfall experiment based on the seeding of liquid carbon dioxide by aircraft on December 27, 2013, at Saijo, Ehime, in the Inland Sea of Japan. *Journal of Agricultural Meteorology*, **71**(4), 245-255.
- Seto, J., Tomine, K., Wakimizu, K. and Nishiyama, K., 2011: Artificial cloud seeding using liquid carbon dioxide: Comparisons of experimental data and numerical analyses. *Journal of Applied Meteorology and Climatology*, **50**, 1417-1431.
- Wakimizu, K., Nishiyama, K., Suzuki, Y., Tomine, K., Yamazaki, M., Ishimaru, A., Ozaki, M., Itano, T., Naito, G. and Fukuta, N., 2002: Low level penetration seeding experiment of liquid carbon dioxide in a convective cloud. *Hydrological Processes*, **16**, 2239-2253.