Artificial rainfall experiment involving seeding of liquid carbon dioxide at Karatsu in Saga

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Abstract

The purposes of this research were to increase artificial rainfall and evaluate the area affected by artificial rainfall. The experiment involved the seeding of liquid carbon dioxide at a height of 2500 m with a seeding rate of 11.1 g/s for 6 min around Karatsu, Saga, Japan on Dec. 26, 2013. The height of the cloud increased significantly, and a virga was observed under the cloud bottom at 2100 m at 30 min after the seeding. The cloud top of the previous seeding cloud was at 3350 m, the cloud bottom was at 2100 m, and the cloud depth was 1250 m. The cloud top after 30 min was at 3500 m, the cloud bottom was at 2100 m, the cloud depth was 1400 m, and the depth had increased by 150 m. The wind direction and speed around the seeding time at 3050 m were WSW and 13.9 m/s, respectively. At 1 h after the seeding, artificial clouds around Fukutsu and Munakata were clearly recognized, and after 1 h 30 min the clouds were around Kitakyushu. The final distance affected by artificial clouds was over 100 km after 2 h. The artificial rainfall (precipitation) amounts at Munakata, Yahata, and Shimoneseki were estimated to be 1.0, 1.0, and 0.5 mm, respectively. The amounts of artificial and natural rainfall or water resources were both estimated to be 0.15 million tons each after 2 h. The estimation of artificial rainfall by radar echo and the surface rainfall agreed well with each other. The artificial rainfall was observed at a target region and the amount of rainfall ultimately increased.

Key words: Aircraft seeding, Artificial rainfall, Convective cloud or stratocumulus, Liquid carbon dioxide (LCD), Saga and Fukuoka.

1. Introduction

It has already been more than 70 years since the first scientific rainfall experiments. There are several existing methods for producing rainfall, namely the seeding of silver iodide, the seeding of dry ice, the scattering of liquids such as pure water or salt water, and others. However, these methods only produce small amounts of water, and they are very costly, and in the case of silver iodide, can cause environmental problems. An artificial rainfall technique using liquid carbon dioxide (LCD) was invented by Fukuta (1988), and it was proven successful in Fukuoka on Feb. 2, 1999, when it produced its first artificial rainfall, and on Oct. 27, 1999, when it produced its second rainfall (Fukuta et al., 2000; Wakimizu et al., 2002). After then, this method produced no successful results for several years; however, successful results were observed in Feb. and Nov. 2006, Jan. 2007, and Jan. 24, 2009 (Maki et al., 2012). Recently, successful results were observed on Feb. 27, 2012, and Mar. 14, May 28, Dec. 15–16 and Dec. 27, 2013. The present experiments were done 3 times over the ocean near Miyake Island (I.) and Mikura I., part of the Izu Islands, and 1 time over land at Saijo in Shikoku, as an example of complex terrain. This experimental result is similar to the example at Saijo on Dec. 27, 2013. We are interested as an evaluation of the topographic effects of inland mountains (Maki et al., 2013; 2014; 2015b; 2016) and inland terrain (Maki et al., 2015a). The distances artificially affected by LCD seeding were over 100 km (W-E direction) around Miyake I. and Mikura I. in the Izu Islands (Maki et al., 2013; 2014), and near 100 km at Saijo, Ehime to the east of Sugao, Tokushima and at Nii I. to the east of Mikura I. (Maki et al., 2015a; 2016). In the present study, the LCD technique was used in experiments conducted in the Karatsu, Saga, and Fukuoka regions in Japan on Dec. 26, 2013.

The main purposes of this research were to increase artificial rainfall and evaluate the area affected by artificial rainfall. Transferring rain water resources in the air from a wet area with a large amount of snow or rain to a dry area with a small amount of snow or rain can be very useful. Throughout the world, there are many regions that contain areas with opposite rain and water characteristics in close proximity to one another. The LCD technique can be used in such regions.

In Japan, there is a region on the Japan Sea side that receives large amounts of rain and frequent heavy snow in winter. On the other hand, there is a considerably dry area nearby on the Pacific Ocean side that receives small amounts of snow and rain in winter. If it were possible to transfer snow and rain from the Japan Sea side to the Pacific Ocean side in the air, the heavy snow in the mountainous area on the Japan Sea side would decrease, thus
decreasing the amount of snow damage there and decreasing the likelihood of flooding, and water resources would be increased on the Pacific Ocean side. This paper is an experimental case study of such an in-air transfer of water resources. It is now important to accumulate the experiment cases.

2. Materials and Methods

2.1 General Weather Conditions

The surface weather map at 9:00 on Dec. 26, 2013 is shown in Fig. 1. A strong anticyclone of 1060 hPa was on the Asian continent, and a traveling anticyclone of 1026 hPa passed Honshu on the Pacific Ocean. A cyclone of 1016 hPa was moving east on the Japan Sea east of the Korean Peninsula, and a cyclone of 1016 hPa broke out south of Kyushu. The pressure gradient was small at Nagasaki, Saga, and Fukuoka. It was in a transition stage to the winter-type pattern due to a trough around the seedling time. At this time, line-type clouds were flowing in from the southern area of the Korean Peninsula to the Tsushima Channel and Genkainada. The clouds were relatively thin convective stratuscumulus clouds.

An emagram, an adiabatic diagram of Fukuoka at 9:00 Dec. 26 is shown in Fig. 2(A). An appearance of clouds could be discerned on the emagram. The first, higher cloud layer was found at 5200–5500 m and the second, lower cloud layer was found at 1600–3050 m with both layers have a width of 1500–3500 m (Fig. 2(B)). At 1500 m (about 850 hPa), the wind direction was WSW, the wind speed was 6.2 m/s, the air temperature was 1°C and the relative humidity was 94%; at 2500 m (750 hPa), those same respective parameters were WSW, 17.5 m/s, −4°C and 100%; at 3000 m (700 hPa), they were SW or SSW, 20.1 m/s, −6.7°C and 100%; and at 5600 m (500 hPa), they were W, 27.8 m/s, −19.1°C and 89%. These were reference values measured at Fukuoka, 40 km from the experiment area and 5 hours (h) before the experiment time.

2.2 Experimental Methods

A Cessna aircraft operated by SGC Saga Aviation Co., LTD and loaded with a 10-kg gas cylinder of LCD permitted by the Ministry of Land, Infrastructure, Transport and Tourism took off from Saga Airport at 12:30. The wind direction, wind speed and air temperature were observed at 12:32–12:38 on the way to the experiment area. The LCD was seeded at 13:35–13:45 in the northern area of Karatsu City as shown in Fig. 3 (Google map template); i.e., the first round (square No. 1 in map) (33°30’N, 129°59’E to 33°35’N, 129°58’E) was performed

![Fig. 1. Surface weather map at 9:00 JST on Dec. 26, 2013. (Japan Meteorological Agency)](image1)

![Fig. 2. (A) Emagram; adiabatic diagram at Fukuoka at 9:00 JST on Dec. 26, 2013. (Japan Meteorological Agency) and (B) vertical profile of cloud layer.](image2)
from 13:35–13:37 at 2440 m in height, the second round (No. 2) (33°35′N, 129°56′E to 33°30′N, 129°59′E) from 13:39–13:41 at 2590 m, and the third round (No. 3) (33°30′N, 129°59′E to 33°31′N, 130°05′E) from 13:42–13:44 at 2590 m. Arrows 1–3 show the seeding order. Photos of the clouds were taken, and a virga was observed by eye for about 30 minutes (min) after the seeding. The aircraft left the observation region at 14:16 and landed at Saga Airport at 14:28.

3. Results and Discussion

3.1 Observational Status of Meteorological Elements and Clouds in Experiment

The seeding of LCD took place in the transitional period to the winter-type pressure pattern as shown by the effect of the trough from 13:30 to 15:30 on Dec. 26, 2013. The cloud top of the second lower layer observed from the aircraft was at 2750–3350 m, but the cloud bottom could not be observed.

The profiles of the air temperature observed by the aircraft from Saga to Karatsu are shown in Fig. 4. The air temperature at the height of 460 m at 12:33 was 4°C near Saga, and at 3350 m at 12:58 it was −9°C near Karatsu, and the profile showed a linear relation. A cloud layer was estimated to be present from 1520 to 1830 m because of the isothermal layer.

The wind direction was WSW, the wind speed 13.9 m/s (50.0 km/h) and the air temperature −6°C at 3050 m at 12:48. The wind direction and air temperature agreed with the values of the emagram at 9:00, but the wind speed was considerably low. The air temperature at the cloud top at 3350 m was −9°C at 12:58, but at the cloud top near the seeding area it was −6°C and −5°C at 13:15 and 13:27, respectively. The first layer of higher clouds was recognized, and a virga with snow and rain was observed by eye at 14:09 and 14:13 at the level of 2100 m with an air temperature of −2°C. The second, lower cloud layer was located from 2100 m to 3350 m. As the cloud top of the convective clouds (stratocumulus) varied widely from 2750–3350 m, the mean height of the cloud top was 3050 m. Moreover, there was the third, lowest cloud layer, but the level of the cloud bottom was not clear. Fig. 5(A) shows the clouds just after seeding and Fig. 5(B) shows the clouds after 30 min. The virga was observed obscurely between the second and third cloud layers in the middle of Fig. 5(B). The difference between the 2 photos was mainly based on the virga.

3.2 Development of Clouds after Seeding and Evaluation of Clouds by Radar

The seeding was done at the lower level (not at the bottom) of the second, lower cloud under a temperature of −4°C in the northern area of Karatsu. The seeding was done 1 time at 2440 m and 2 times at 2590 m in a higher density cloud for a total of 6 min from 13:35–13:45 with a seeding rate of LCD of 11.1 g/s and a total mass of 4.0 kg. The first seeding was from SSE to
NNW, the second from NNW to SSE, and the third from WSW to ENE at 10-km distances between each seeding run (Fig. 3). The cloud bottom of the second, lower cloud layer was estimated to be about 2100 m from the observation of the virga, and the cloud depth was 1250 m.

The seeded cloud moved in the ENE direction due to a WSW wind and became enlarged after seeding, and the height of the cloud top was at about 3500 m according to aircraft observation at 13:50 after about 30 min of seeding. The cloud depth increased by 150 m from 1250 m to 1400 m. If the mean cloud top was used, the depth increased to 450 m. Even though the humidity profile vertically continued in Fig. 2(A), the cloud layer was separated into the second, lower seeded cloud and the third, lowest cloud in Fig. 2(B). The height of the third layer was estimated to be 1500–2000 m based on the observation height of the virga by eye at 2100 m and the emagram, and no cloud layer was estimated to be 100 m in width (Fig. 2(B)).

The Japan Meteorological Agency shows a radar echo around the Kyushu region as shown in Figs. 6(A)–(H): (A) 13:40, (B) 14:20, (C) 14:30, (D) 14:40, (E) 14:50, (F) 15:00, (G) 15:10 and (H) 15:20. The radar rain intensity was classified as 1, 5, 10 and 20 mm/h in Fig. 6(D). Radar echoes were occasionally observed at heights of 5200–5500 m, 2100–3350 m, 2100–3500 m after seeding, and 1500–2000 m (Fig. 6(A)–(H)). No cloud was found in a radar image taken at 13:40 (Fig. 6(A)) around the seeding area, Karatsu. The cloud could not be detected on radar due to its low height and density. In any case, LCD was seeded in the cloud at 2100–3350 m as mentioned above. Even though the cloud developed was active, it did not appear on the radar. The virga was observed under the seeded cloud around Itoshima P. There was still no echo at 14:20 (Fig. 6(B)) to the west of Shikanoshima I. (33 km to the leeward side of the seeded area; distance shown hereafter).

A small cloud image appeared on the radar to the east of Shikanoshima I. to the north of Hakata Bay (Genkai I and Aino I., 42 km) at 14:30 (Fig. 6(C)). These clouds seemed to be mainly natural clouds that had moved in from the west even if the seeding had partially affected them. Radar echoes around Fukutsu City to Munakata City (Shingu Town, 50 km, Koga City, 52 km) were clearly recognized at 14:40 (Fig. 6(D)). These echoes after 1 h around 50–52 km were almost consistent with the distance that the cloud would have traveled with a wind speed of 13.9 m/s (50 km/h). This distance is based on the evaluation of the wind direction (WSW), wind speed (13.9 m/s), time (1 h), distance (52 km) and height (3000 m). The echoes were assumed to be an artificial cloud with a precipitation intensity of almost 0–1 mm/h. At 14:50 (Fig. 6(E), 58 km), the cloud echoes were significantly wide and moved inland. Moreover, at 15:00 (Fig. 6(F), 67 km), the echoes had become comparatively wider. At 15:10 (Fig. 6(G), 75 km), the cloud echoes were observed near Nakama City and Noogata City, and they then moved from Nakama to Kitakyushu City.

Given that the cloud development continued until 15:10 (Fig. 6(G)), it is likely, based on the former experiments, that a good environment was present for the artificial development of ice crystals in natural clouds. Thus, a large amount of precipitation was produced. The fact that the rainfall continued for over 1 h 30 min was also consistent with the experimental results (Maki et al., 2013; 2014; 2015a, b; 2016). However, the echoes had almost disappeared at 15:20 (Fig. 6(H), 83 km) south of Kitakyushu. Also, the cloud north of Kitakyushu, i.e., the artificial cloud continued to develop to a distance of 90 km at 15:30.

There was a particularly interesting cloud at 15:00 (Fig. 6(F)). As the seeding was done north of Karatsu and the wind direction was WSW (red arrow), the artificial low altitude clouds (red oval area) moved in the WSW-ENE or SW-NE direction, and the wind direction and the direction of motion (red arrow and long axis direction of red oval) were the same. However, there were 2 lines of narrow clouds that originated naturally south of Iki I. at 14:30 and east of Iki I. at 15:00. These natural clouds (yellow oval area) extended in the SW-NE or SSW-NNE direction (yellow arrow), and these natural high-altitude clouds themselves moved in the WSW-ENE direction (white arrow). The artificial and natural cloud areas are shown as red and yellow oval areas in Fig. 6(G).

These clouds extending in the SW-NE direction originated naturally at 14:50 (Fig. 6(E)), combined with the WSW-ENE artificial cloud, and moved slightly inland. Two layer (row) clouds seemed to be wider and more significant by the accumulation of each row cloud. However, two combined clouds could be separated based on the different heights of clouds in the second,
lower layer and third, lowest layer. The east side cloud became a generally high-intensity cloud due to the combination of natural and artificial layers. The artificial cloud developed in the upper direction as an upstream cloud observed on radar at 14:50–15:00. The principle of cloud development was the upstream in the convective cloud and self-upstream produced by condensation latent heat combined in the connective cloud.

The rain cloud area moved from Onga Town and Nakama to Kitakyushu at 15:10 and then suddenly disappeared at 15:20 due to their consumption as rain. The clouds around the cloud bottom rapidly decreased after 15:10 or 15:20 (Fig. 6H). The clouds almost disappeared with only a small part remained. There was a dry air mass from the continent at 4000 m in the upper layer (Fig. 2). As the cloud produced by evaporation from the Tsushima Channel and Genkainada was low in height and shallow, almost all rainfall occurred from almost the same height and at the same time. Consequently, the cloud seemed to be drastically decreased around the Kitakyushu area due to rainfall.

The low cloud height and shallow cloud depth seem to be the topographical effects of a 500-m high mountain in the NW-SE.
direction in the northeastern area of Munakata and western area of Okagaki Town. As downward stream passed through to Onga over the low land west of Kitakyushu, it is thought that the cloud disappeared and the area dried up due to a rain shadow desert climate on the leeward side. These phenomena were interesting in that the properties of the development and disappearance of clouds were similar in Seto et al. (2011) and Maki et al. (2013; 2014; 2015a).

One of the purposes of this experiment was to transfer clouds or rain from the Japan Sea side to the Seto Inland Sea side, but the wind direction was not suitable for this experiment because the seeded cloud moved in the WSW-ENE direction rather than NW-SE. However, this result was a useful example of the evaluation of artificial rainfall.

The wind speed was 13.9 m/s (50.0 km/h) around the 3000-m level at 13:00 immediately before the seeding, and the distances moved in Figs. 6(G) and (H) were 75 km in 1 h 30 min and 83 km in 1 h 40 min, respectively. Thus, the time, distance, direction and speed all agreed. The speed at which the cloud moved in the SW-NE direction from Iki I. to Genkainada was 60 km/h, i.e., the height and speed of the natural cloud were higher than those of the artificial cloud. The precipitation estimated by radar echo was 1 mm/h in the surrounding area and 2 mm/h in the stronger precipitation area shown in Fig. 6.

The artificial cloud in the red oval area was evaluated. The main area of precipitation was estimated to be 50 km × 20 km, and the amounts of rainfall were 0.2 and 0.3 million tons on the 1 and 1.5 mm/h expected intensities in Fig. 6 (radar echo), respectively. The artificial precipitation shown in Fig. 6(F) (red oval) was estimated to be 0.15 million tons, and the natural (yellow) and artificial (red) precipitation shown in Fig. 6(F) (black oval) was 0.3 million tons.

3.3 Precise Analysis of Artificial Rainfall by X Band MP Radar

Images from X band MP radar (Ministry of Land, Infrastructure, Transport and Tourism) detected by 4 radar antennas near Fukuoka are shown in Figs. 7(A)–(H). The radar rain intensity is 1, 5, 10 and 20 mm/h as shown in Fig. 7(A). A local thin rain cloud can be precisely detected. There was no radar echo at 13:40 nor at 14:20 around the ENE area of the seeding (Figs. 7(A), (B)). Although no echo can be seen clearly in Fig. 6(C), Fig. 7(C) shows 2 lines of clouds on Genkainada from north of Itoshima P. to north of Hakata Bay at 14:30. As these were natural and artificial clouds (Fig. 7(C)), the west cloud running SW-NE or SSW-NNE and the northeast cloud were natural clouds, and the southeast cloud running WSW-ENE was believed to be an artificial cloud based on the differences in the cloud and wind directions. The cloud in the WSW-ENE direction from north of Shikanoshima I. to west of Fukutsu P. seemed to be an artificial cloud.

At 14:40 (Fig. 7(D)), the cloud area increased and the area of 1–5 mm/h intensity became wider. The cloud area southeast of Oshima I. was a natural cloud as evidenced by its SW-N direction based on the direction of two-line clouds south of Iki I. (Fig. 6(D)). On the other hand, the main cloud over the west side seashore and the surrounding clouds on sea and land were likely to be artificial clouds, as shown by the time and distance calculations and the WSW-ENE direction. The clouds northeast of Shikanoshima I. seemed to be a combination of natural and artificial clouds which were connected in Fig. 7(E) based on the difference in the cloud directions. These radar images are good examples that can be evaluated using precise detection data.

At 14:50 (Fig. 7(E)), the cloud area became enlarged as a result of cloud development. A narrow continual cloud in the WSW-ENE direction was determined to be an artificial cloud based on the direction, time, and distance mentioned above; i.e., the clouds from the northeast of Shikanoshima I. to the northwest of Wakamatsu P. and the clouds on the sea seemed to be artificial clouds. The distance of this distribution was fairly long at 40 km. The information on cloud movement in terms of time and distance, and the amount of rainfall were consistent with other experiments (Maki, et al., 2013; 2014; 2015a, b, 2016).

That is, in general, there is a period when the snow and/or rain particles fall from a higher cloud and the ice crystal particles circulate up and down in the clouds. These particles increase as time passes. There is a time lag, as these particles grow at each height by different growing processes. Thus, the rain continues for a long time, which is a significant characteristic of LCD seeding and makes it useful for producing a large amount of rain and water resources. The stronger rain at the intensity of 5–10 mm/h in Fig. 7(E) occurred on a considerably wide area around the seashore of Okagaki Town. However, the cloud over the eastern inland area was a natural cloud; i.e., a round echo (cloud) on Sarakura Mountain (622 m) presumably developed as a topographic cloud grown by the upstream process due to the mountain, and on the leeward side no cloud area appeared by the consumption of clouds as rain.

At 15:00 (Fig. 7(F)), the cloud area increased, and the artificial cloud area became wider and longer in the WSW-ENE direction as well. However, the east inland cloud was a natural cloud continuing from 14:50. These clouds were partially recognized over a certain area, but not a wide area. These clouds could be separated into a natural cloud with a SW-NE or SSW-NNE direction at 5200–5500 m, a natural cloud and an artificial cloud produced by seeding with a WSW-ENE direction at 2100–3350 m (after 3500 m), and a natural cloud and an artificial cloud with a WSW-ENE direction at 1500–2000 m (Figs. 6 and 7).

At 15:10 (Fig. 7(G)), there were clouds from the seashore to the inland areas. The seashore clouds in the WSW-ENE direction seemed to be mainly artificial clouds (red oval area), the inland clouds were both natural and artificial clouds (yellow oval area), and the clouds further inland at Kiku P. were natural clouds. However, at 15:20 (Fig. 7(H)), the artificial clouds moved further in the ENE direction, and the northern clouds in the oval area were both natural and artificial clouds as shown in Fig. 7(G). Fig. 7(G) clearly shows the differences between the artificial and natural clouds. But in Figs. 7(F) and 7(H), these clouds were not well separated because their echoes connected to each other.

Although the natural clouds in the inland area gradually decreased, the echo in Fig. 7(H) was clearly wider than that in Fig. 6(H) at the same time, 15:20, and the efficiency of the echo evaluation was higher. But, both the artificial and natural clouds decreased and the radar echo in Fig. 7(H) had almost disappeared at 15:30.
Fig. 7. Variations of radar echoes based on XRAIN, MP radar by X band at (A) 13:40, (B) 14:20, (C) 14:30, (D) 14:40, (E) 14:50, (F) 15:00, (G) 15:10 and (H) 15:20 on Dec. 26, 2013. The radar rain intensity is classified as 1, 5, 10, and 20 mm/h as shown in (A). (Ministry of Land, Infrastructure, Transport and Tourism)
The future objective is for snow and rain to be transferred in the air from the Japan Sea side to the Pacific Ocean side, but in this case the snow and rain were transferred from the Genkaiinada side to the Seto Inland Sea side. The general radar image lasted until 15:20, the X band MP radar image lasted until 15:30, and their effective areas were 90 km and 100 km, respectively. This artificial rainfall affected an area 100 km leeward. The experimental period occurred before a winter-type pressure pattern emerged, and so the width, length and depth of the clouds were small. If the experiment was performed when the typical pattern was of the west high = east low type, a major increase in rainfall could occur because large amounts of cumulus clouds come from the Japan Sea side continuously. We hope that in the future, this research will be useful in decreasing heavy snow and heavy rain and protecting against related disasters.

3.4 Artificial Precipitation and Water Resources

The amounts of daily precipitation (AMeDAS, surface rainfall) at different locations were as follows: Fukuoka (37 km leeward from seeding area), 2.0 mm; Munakata (62 km), 2.5 mm; Iizuka (68 km), 2.0 mm; Yahata (90 km), 2.0 mm; and Shimonoseki (103 km), 0.5 mm. The amounts of hourly precipitation were as follows: Fukuoka and Iizuka at 16:00 (rain time 15:00–16:00), 1.0 mm, and at 17:00, 0.5 mm, Munakata at 15:00, 0.5 mm, at 16:00, 1.5 mm, at 18:00, 0.5 mm, and at Yahata at 16:00, 2.0 mm. These rainfall amounts show that the artificial rain intensity was under 5 mm/h because the cloud moved for a short time due to wind, and that the artificial cloud area affected by the seeding was under 50 km, but the affected area was made rather wider by wind.

The seeding was done at 13:40, and the peak of precipitation occurred 1 h 30 min later (15:10). Figs. 6 and 7 (G, H) show these phenomena. The cloud had almost disappeared after 15:20 (Fig. 6(H)), but a vapor echo on MP radar was evaluated in the air as rain at 15:20 (Fig. 7(H)) and 15:30 (no figure). The precipitation at 15:00–17:00 was presumably artificial rainfall because there was almost no other evidence of rainfall at any other time and/or place.

A precipitation amount of 1.0 mm (about half, as in the oval scale in Fig. 6(F)) of 2.0 or 2.5 mm at Munakata and Yahata was supposed to be due to artificial rainfall based on the time (1–2 h after seeding, rainfall time 15:00–17:00) and place (leeward side, except Fukuoka and Iizuka not leeward), direction (WSW-ENE), distance (Munakata 62 km; Yahata, 90 km; Shimonoseki, 103 km), wind direction of WSW, wind speed of 13.9 m/s and height of 3000 m. A 0.5 mm amount of precipitation at Shimonoseki was presumably artificial rainfall because it was located at the end of the leeward side, lasted until 17:00, and was the only rainfall in that day. The artificial rainfall spread over a 100-km distance. The distances artificially affected by LCD seeding were over 100 km around Miyake I. and Mikura I., the Izu Islands (Maki et al., 2013; 2014), and near 100 km at Saijo, Ehime, to east of Sugao, Tokushima, and at Nii I. to east of Mikura I. (Maki et al., 2015a; 2016).

The amount of artificial rainfall was estimated to be 0.15 million tons (m.t.), as mentioned above. This amount could be useful as a water resource. The estimated radar rainfall and surface rainfall amounts agree fairly well with each other. The radar resolution for rain intensity is roughly on the order or 1 mm for an area on the order of 250 m. The surface rainfall data can be evaluated on the order of 0.5 mm for an area on the order of 10 km. The artificial rainfall can be evaluated over an area of 100 km. The artificial rainfall distance between the seeding area and the area of the rainfall was 100 km in this case. As local meteorological variation can be observed over areas on the order of 1 to 100 km, the radar rainfall data and surface rainfall data can generally agree with each other.

There were evaluated that the artificial rainfall was observed at a target region and the amount of precipitation or water resources finally increased in this paper. The amounts of rainfall or water resources were 1.0 m.t. (Feb. 26, 2012) and 0.5 m.t. (Feb. 27, 2012) (Maki et al., 2013), 1.8 m.t. (Mar. 14, 2013) (Maki et al., 2014) and 0.1 m.t. (Dec. 16, 2013) (Maki et al., 2016) around Miyake and Mikura I., and 1.3 m.t. at Saijo, Ehime (Dec. 27, 2013) (Maki et al., 2015a). In the present case (0.15 m.t.), the amount of clouds and the cloud area were not large based on the cloud depth with 3 separated layers, the lower cloud may have been a stratus cloud except for a higher convective cloud around 3000 m in height, and there was no inversion layer and no high mountain terrain, compared with other data.

**Fig. 8.** Variations of clouds based on satellite visible images at (A) 13:30, (B) 14:30 and (C) 15:00 on Dec. 26, 2013. (Japan Meteorological Agency)
3.5 Evaluation of Clouds using Satellite Images

Visible satellite images of high altitude clouds at 13:30 before seeding, at 14:30 after 30 min of seeding, and at 15:00 1 h 20 min after seeding were evaluated. At 13:30 (Fig. 8(A)), there were almost no clouds on the radar around Kitakyushu and north of Hakata Bay. But several line-type clouds were seen from Tsushima I. northeast of Hakata Bay at 14:30 (Fig. 8(B)). As shown in Fig. 6(C) (14:30), mainly natural clouds were evaluated. At 15:00 (Fig. 8(C)), clouds with a SSW-NNE or S-N direction were found around Kitakyushu. The clouds in higher layers with S-N and SSW-NNE directions were not affected by the wind direction, but they showed a wide line-type cloud running in the S-N direction. Clouds which included natural clouds in the SSW-NNE direction and artificial clouds in the WSW-ENE direction under the natural clouds were evaluated at 15:00 (Fig. 6(F)), but the lower artificial clouds could not be recognized clearly because of the shade of the upper clouds.

According to Sections 3.3 and 3.5, the clouds could be divided into the following categories; the highest natural clouds with a direction of S-N or SSW-NNE at around 11000 m, higher natural clouds with a SW-NE or SSW-NNE direction at 5200–5500 m, lower natural and higher artificial clouds with a WSW-ENE direction at 2100–3350 m (after 3500 m), and the lowest natural and lower artificial clouds with a WSW-ENE direction at 1500–2000 m.

4. Conclusions

An artificial rainfall technique of liquid carbon dioxide (LCD) at a height of 2500 m with a seeding rate of 11.1 g/s for 6 min was used in an experiment conducted at Karatsu City in Saga Prefecture in Japan on Dec. 26, 2013.

(1) The height of the cloud increased significantly and a virga was observed under the cloud bottom at 2100 m at 30 min after the seeding.

(2) The cloud top of the previous seeding cloud was at 3350 m, the cloud bottom was at 2100 m, and the cloud depth was 1250 m. The cloud top after 30 min was at 3500 m, the cloud bottom was at 2100 m, the cloud depth was 1400 m, and the depth had increased by 150 m.

(3) The wind direction and speed around the seeding time at 3050 m were WSW and 13.9 m/s, respectively. At 1 h after the seeding, artificial clouds around Fukutsu and Munakata were clearly recognized, and after 1 h 30 min the clouds were around Kitakyushu. The final distance affected by artificial clouds was over 100 km after 2 h.

(4) The artificial rainfall (precipitation) amounts at Munakata, Yahata and Shimonoseki were estimated to be 1.0, 1.0 and 0.5 mm, respectively. The amounts of artificial and natural rainfall or water resources were both estimated to be 0.15 million tons each after 2 h. The estimation of artificial rainfall by radar echo and the surface rainfall agreed well with each other.

(5) The artificial rainfall was observed at a target region and the amount of rainfall ultimately increased.

References


