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Artificial Rainfall Produced by Seeding with Liquid Carbon Dioxide at Miyake and Mikura Islands, Japan

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Cloud seeding experiments using liquid carbon dioxide were carried out on 26 and 27 February 2012 near Miyake Island in the Izu Islands south of Tokyo, Japan. Convective clouds developed 0.5 to 1 h after the seeding near Miyake and Mikura Islands and reached heights of 3000 m and 4000 m on 26 and 27 February, respectively. Artificial convective clouds accompanied by rain, *i.e.*, virga were observed, and rain was recognized by eye around Miyake and Mikura Islands on 27 February; we presume that the amount of rain increased on the mountainous part of the island. Consistent with cloud trajectories estimated from weather data, the artificial cloud was recognized as radar echoes later on 27 February east of Mikura Island as a chain of clouds at 3000 to 5000 m elevation. We found that seeding with liquid carbon dioxide within convective clouds near their bases is feasible when the air temperature is below −5℃. The practicality of liquid carbon dioxide seeding is supported by the results of this study, and we believe the spread of the technique.

Key words: artificial rainfall, aircraft seeding, convective cloud, liquid carbon dioxide, Miyake and Mikura Islands

1. Introduction

The occurrence of a global water crisis during the 21st century is predicted. Because the demand for water continues to increase as the population increases, even in regions where the water supply is currently adequate, the demand may eventually outpace the supply. Droughts and other water-related problems also are increasing in frequency as a result of abnormal weather and global warming. Water deficits are an especially urgent problem in countries in arid or desert areas. Effective techniques for producing artificial rainfall are being sought to help meet the world's water needs, forestall desertification, and possibly even restore arid lands and deserts.

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 small amounts of rainfall, and they are not without environmental and economic problems. A seeding technique using liquid carbon dioxide (LCD), invented by Prof. Norihiko Fukuta (1988a, b), was tested and shown to be effective at Fukuoka on 2 February 1999 and in numerous 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 the LCD seeding technique in experiments at Miyake Island (34°7.4′ N, 139°31.3′ E) and Mikura Island (33°52.5′ N, 139°36.1′ E) in the Izu Islands, Japan (Miyake and Mikura hereafter). These islands are south of Tokyo and have very small populations, particularly during the suitable cold season when the experiments were conducted.

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2. Principles of the LCD Rainfall Technique

LCD seeding is done by aircraft, which spreads LCD near the base of a cloud in a layer of supercooled humid air mass at temperatures below zero. The LCD, at −90℃, instantaneously produces ice crystals (10^{13} particles per 1 g CO_2) (Fukuta, 1988a, b; Fukuta *et al.*, 2000), which collect ambient water vapor and grow to the point of 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) the ice crystals supercool in the clouds, reach to the cloud tops and disperse vertically and horizontally.

In addition, the natural updraft in the cloud is augmented by latent heat from the formation of ice crystals. High-humidity air masses are drawn into the cloud from below, 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 the cloud is improved when stable air layer lies above it, suppressing vertical convection and promoting its lateral spread. These convective clouds expand by three dimensions of longitudinal, lateral and vertical components. Ice crystals produced by LCD grow actively for up to an hour mainly after seeding, and the artificial rainfall that they induce continues for several hours.

3. Experimental Methods

The seeding experiments were conducted on 26 and 27 February 2012, dates that were chosen two days beforehand based on the weather map, weather forecast, and meteorological data. The locations of Oshima, Miyake, Mikura and Hachijo Islands are shown in Fig. 1. The flight routes around Miyake and Mikura are shown in Fig. 2. The aircraft used was a Beechcraft operated by Diamond Air Service (Fig. 3a).

On 26 February, the aircraft was flown from Nagoya to the west side of Miyake, where LCD was seeded, and then to Oshima Island (Oshima hereafter). On 27 February, the aircraft flew from Oshima to Miyake, where LCD was seeded about 5 km west of Miyake, and then returned to Nagoya. The wind direction, wind speed, air temperature, and flight speed were monitored by the aircraft's instruments, and the aircraft position (Fig. 2) was monitored by our computer using GPS.

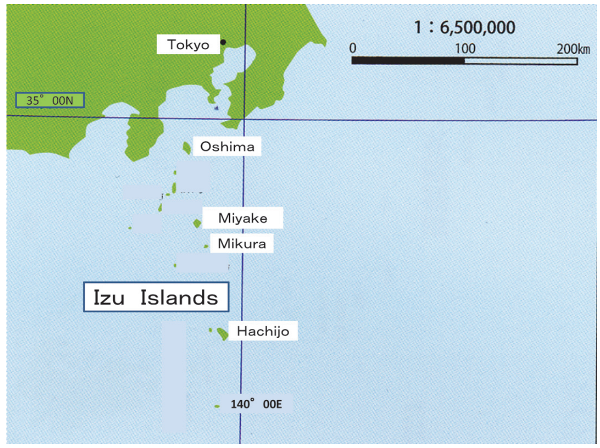

Fig. 1. Map of Oshima, Miyake, Mikura and Hachijo Islands in the Izu Islands, Tokyo.

The LCD was emitted from a nozzle on the bottom of the aircraft at the rate of 5–6 g/s. 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 in Figs. 3b–3h). 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.

4. Results and Discussion

4.1 Meteorological Data

Weather maps for the two seeding dates are shown in Fig. 4. A winter-type pressure pattern was present with the west high-east low type. On 26 February, the radar showed high clouds due to an outbreak of cold air in the Tokai and Kanto areas of Japan, consisting of mixed stratiform clouds with bands of convective clouds. On 27 February, there were no high clouds with rain around Miyake and Mikura. A slow-moving continental anticyclone was changing to a travelling anticyclone, slightly disrupting the winter-type pressure pattern. The cold air outbreak produced mixed stratiform and convective clouds (cumulus and stratocumulus). There were no well-developed convective clouds around the experiment area.

4.2 LCD Seeding Near Miyake

Seeding on 26 February was done in three bursts lasting about 2, 2, and 4 min. The seeding took place northwest of Miyake at a height of 1830 m (6000 ft),

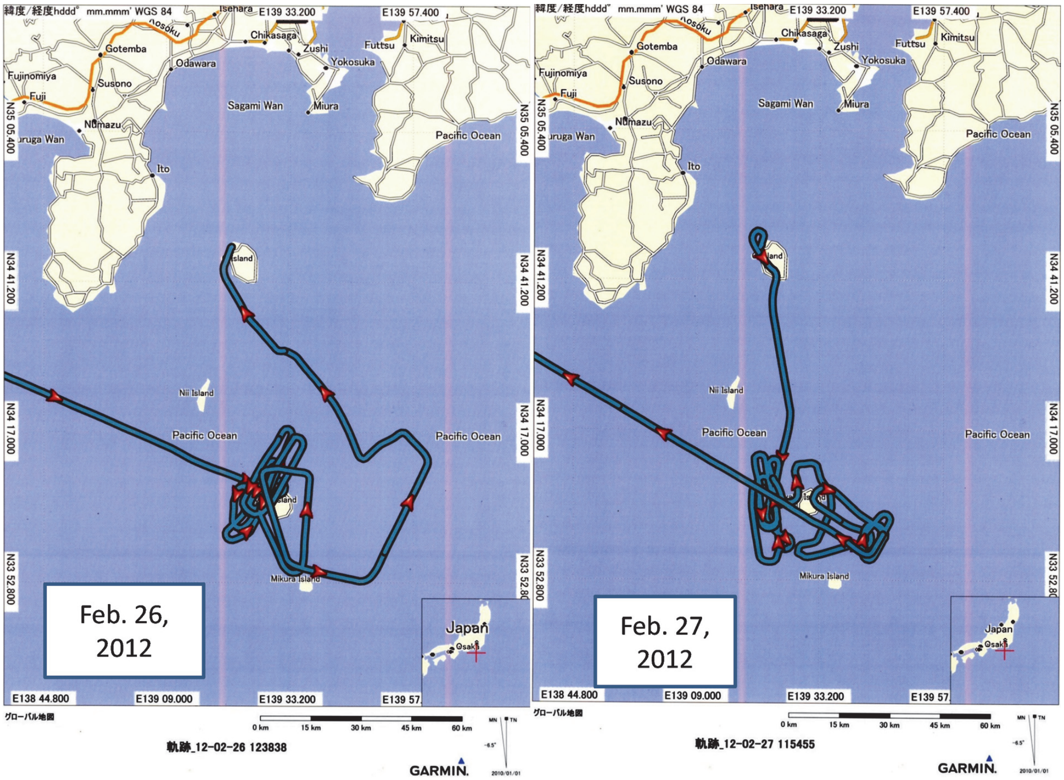

Fig. 2. Map of the northern Izu Islands showing flight routes during seeding experiments. Seeding was done directly northwest of Miyake on 26 February and about 5 km west of Miyake on 27 February 2012.

where the wind direction was W, the wind speed was 10.8 m/s (21 kt), and the air temperature was −3℃. There were three cloud layers; the top of the middle layer was at 2830 m and −8℃, the bottom of the middle layer was at 2290 m, and the bottom of the lowest layer was at 940 m and 3.5℃. The thickness of the cloud was thus 1890 m. In the high air layer at 2740 m, the wind direction and speed were WNW and 11.3 m/s.

The flight speed during the seeding was 283 km/h (78.7 m/s), and the seeding direction was from SSW to NNE.

Seeding 1: time, 11:13:42–11:15:20; position, 34° 05.20′ N, 139°27.74′ E

Seeding 2: time, 11:19:42–11:21:35; position, 34° 05.83′ N, 139°27.91′ E

Seeding 3: time, 11:27:09–11:31:09; position, 34° 05.72′ N, 139°27.89′ E

Seeding on 27 February was done in four bursts lasting about 2, 3, 2, and 2 min. The seeding took place about 5 km west of Miyake. LCD was seeded from south to north at a flight speed of 304 km/h (84.4 m/s). The seeding height, near the base of the main cloud layer, was 2130 m for the first seeding and 2290 m for the next three seedings. There were two layers of cloud. The base of the main cloud layer was at 1830 m and its top was at 2960 m for a total thickness of 1130 m. The second cloud layer was sparse and located at about 1000 m. The wind direction was SW and the wind speed was 8.2 m/s at 2130–2290 m (mean 2210 m) for all seedings, and the air temperature was −4℃ at 2134 m for the first seeding and −5.5℃ at 2290 m for the next three seedings. The wind direction and speed were W and 8.7 m/s at 3050 m and WNW and 18.5 m/s at 3660 m.

Seeding 1: time, 09:58:23–10:00:39; position, 33° 59.94′ N, 139°25.15′ E

Seeding 2: time, 10:06:10–10:09:00; position, 34° 03.26′ N, 139°24.82′ E

Seeding 3: time, 10:15:06–10:17:06; position, 34° 03.17′ N, 139°24.79′ E

Seeding 4: time, 10:24:45–10:26:46; position, 34°

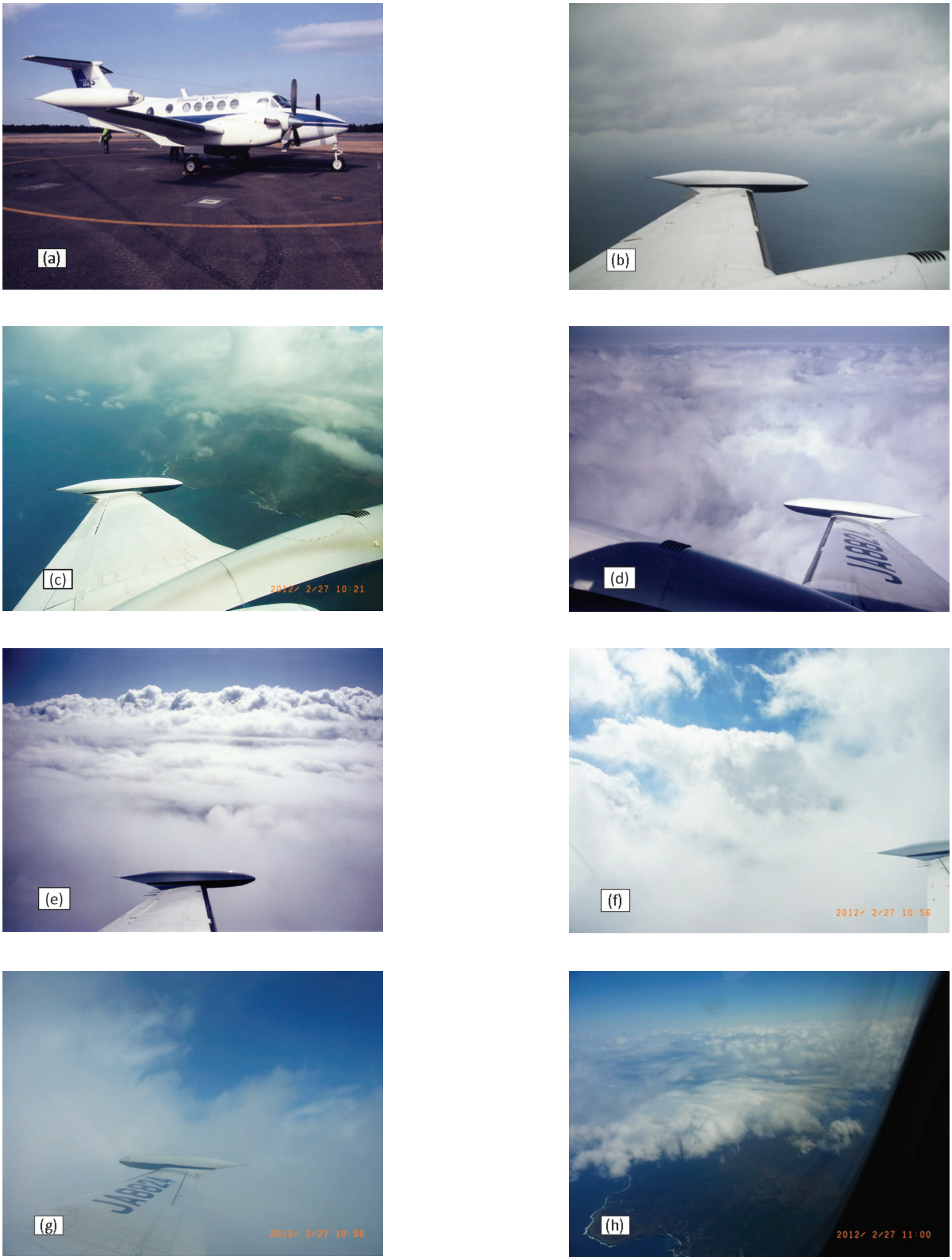

Fig. 3. Photographs of (a) Beechcraft aircraft operated by Diamond Air Service; (b) bottom cloud before LCD seeding on 26 February 2012; (c) cloud during seeding over Miyake at 10:21 on 27 February; (d) developing cloud just after seeding at 10:30 on 27 February; (e) developed cloud by seeding at 11:10 on 27 February; (f) entering into the developed cloud with rain or virga on 27 February; (g) passing through the developed cloud with rain or virga on 27 February; (h) developed cloud over Miyake 0.5–1 h after seeding on 27 February.

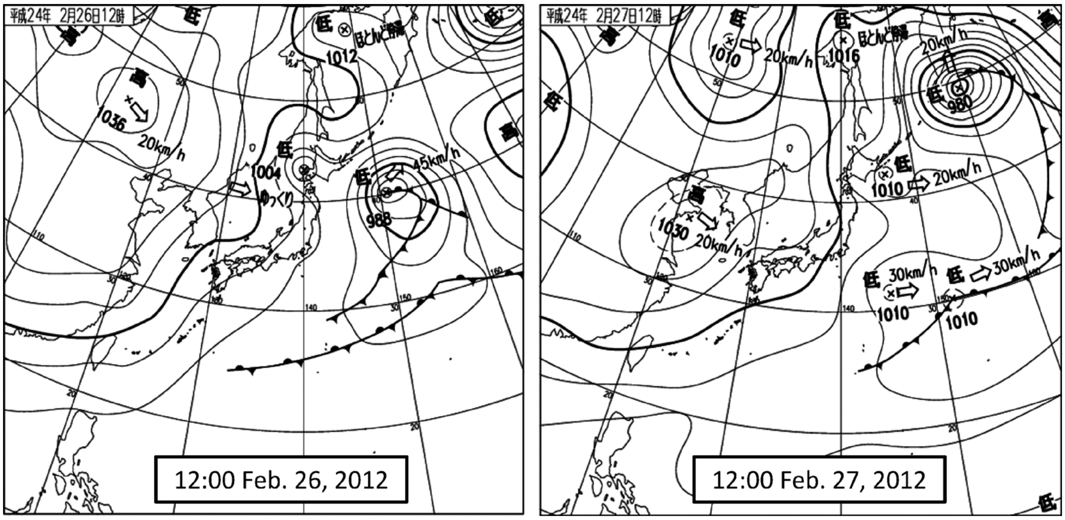

Fig. 4. JMA regional surface weather maps around Miyake and Mikura for 12:00 on 26 and 27 February 2012.

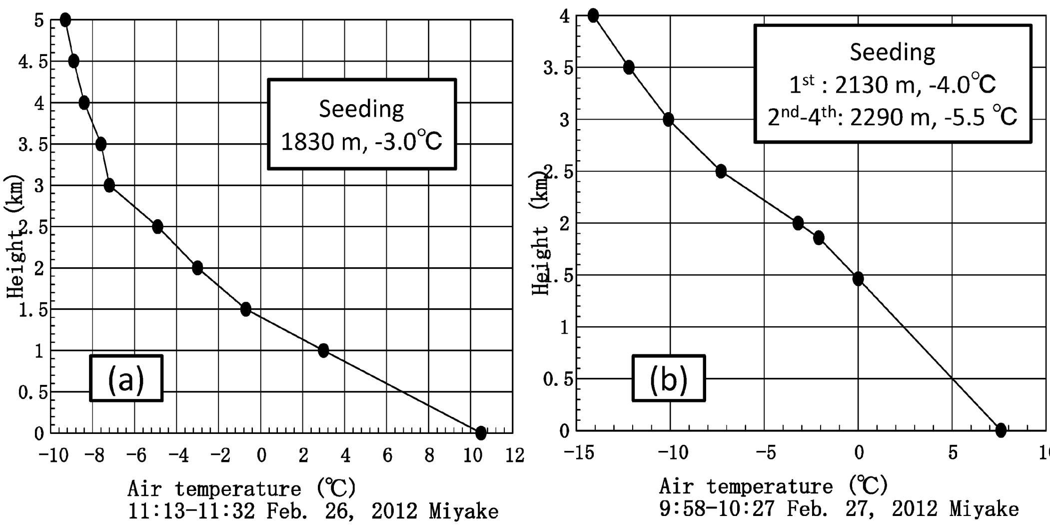

Fig. 5. Vertical profiles of air temperature above Miyake Island on (a) 26 February and (b) 27 February 2012.

11.17′ N, 139°32.75′ E

4.3 Experimental Results for 26 February

There was no inversion layer near Miyake in the vertical air temperature profile for 26 February at the time of the seeding (Fig. 5) in spite of finding near Nagoya. Figure 3b shows the scene of the bottom cloud on 26 February 2012. The convective clouds developing and developed by the seeding on 26 February were similar to the clouds on 27 February shown in Figs. 3c–3e.

4.3.1 Effect of Seeding at Miyake and Mikura on 26 February

On 26 February, there were not new convective clouds over Miyake, because that the seeding place was too close to Miyake. We observed an artificial convective cloud at the east (leeward) region of Miyake. We presume that this cloud produced rainfall in response to the LCD seeding.

Because the wind direction was W at 1800 m and WNW at the top of the clouds, the clouds moved eastward and the artificial convective cloud appeared

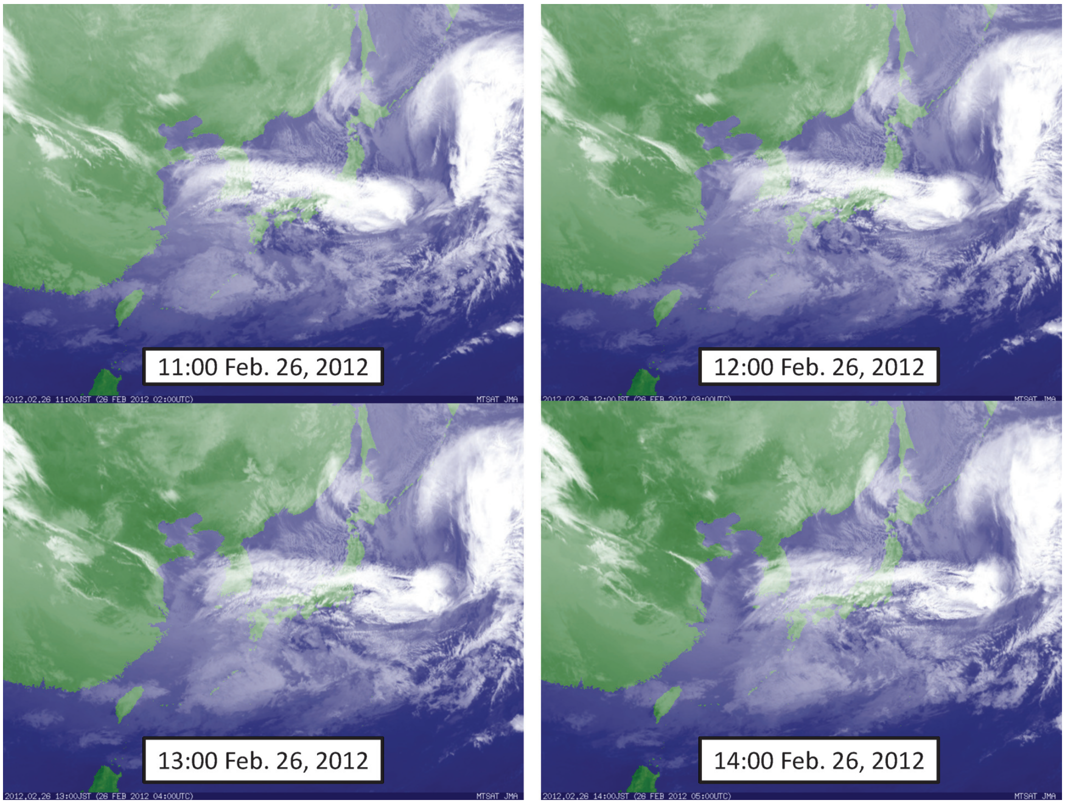

Fig. 6. JMA satellite infrared synoptic cloud images around Miyake, Mikura and Hachijo at 11:00, 12:00, 13:00 and 14:00 on 26 February 2012.

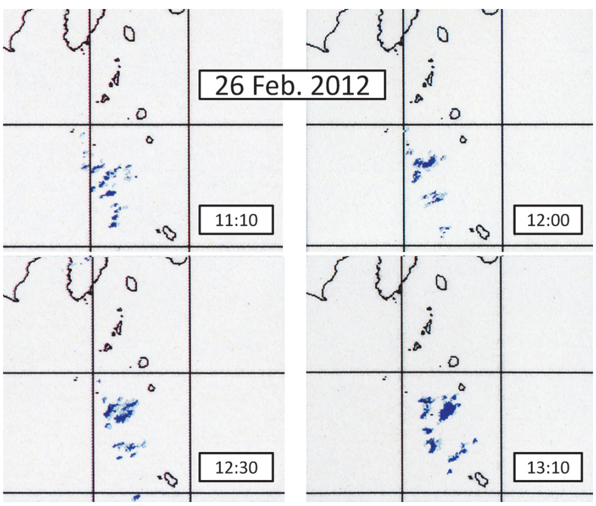

Fig. 7. JMA radar images of cloud echoes around Miyake, Mikura and Hachijo at 11:10, 12:00, 12:30 and 13:10 on 26 February 2012.

0.5 h after the seeding. The arrtificial cloud reached at the height of 2900–3000 m. It was presumed that the rain fell under the cloud and the virga or praecipitatio moved to Mikura by a reverse-direction wind of NE–ENE (0–1400 m, NNE–NE at 9:00 at Hachijo), and that the rainfall could be observed at Mikura on active reaction period.

Regional satellite infrared images from this day are shown in Fig. 6, and more localized radar images are shown in Fig. 7. The development of convective clouds was significant within 1 h of the seeding on the east leeward side of 10 to 20 km from Miyake, reaching a height of 3000 m. Although the LCD seeding succeeded in producing convective clouds, the JMA radar could not detect them because it was limited to elevations above 2000 m, where the artificial cloud was of limited extent and low density. The satellite images showed low-level clouds at Miyake between 11:00 and 13:00, but their resolution was not good enough to distinguish between natural and artificial clouds.

At the surface (height of 12.9 m), the wind was ENE at 3.0 m/s at 11:00, NE at 3.6 m/s at 12:00, and NE at 2.9 m/s at 13:00 in spite of 10.8 m/s at the height of 1830 m because of surface friction of land and sea.

The wind direction at the seeding elevation was W, and the seeded cloud moved east 0.5 h later. There was presumed rainfall under the cloud, which was carried in the form of virga to Mikura by a NNE wind at 1000–1500 m and by NNE and NE winds at 0–1000 m (wind speed was measured at 8–10 m/s at 9:00 at nearby Hachijo Island (33°7.3′ N, 139°46.7′ E, Fig. 1; Hachijo hereafter)). It is presumed that the artificial convective cloud moved toward Mikura and rainfall occurred there, but we were not able to observe conditions under the cloud and we did not see rain from the aircraft during our brief flight time. Clouds were scarce over Mikura before our LCD seeding, but a cloud was observed there after the seeding, which presumably was an artificially stimulated cloud.

At the Mikura Village Office at the south end of the island, it was cloudy and rain was not seen in the daytime on 26 February like shown in Fig. 3h. There are no JMA weather data for Mikura, but rainfall in the mountainous part of Mikura can be significant on days when the island's lowland remains dry, as one of us witnessed during a visit to Mikura in June 2011.

Satellite images showed low clouds at Mikura, but the image resolution was inadequate to distinguish between natural and artificial clouds (Fig. 6). Artificial clouds were seen by witnesses on the mountainous part of Mikura, extending from north to south over a distance greater than the length of Mikura.

The highest point on Mikura, Miyama Mountain, is 851 m high. The base of the artificial cloud and virga that moved to Mikura was almost the same height; thus, it is plausible that the mountainous area of Mikura could have been covered by rain. That scenario would be much like the typical topographic clouds and rain here (Seto *et al*., 2011).

According to the JMA mesoscale forecast model for 12:00 on 26 February near Miyake, winds were estimated as NE at 3.0 m/s at the 925 hPa (727 m) level, WNW at 5.0 m/s at 850 hPa (1423 m), and WNW at 20.0 m/s at 700 hPa (2948 m) (Fig. 8). These estimates show that there was a strong wind shear in the lower troposphere. It is usual for radar echoes to move with the wind at the 700 hPa level; however, the movement of the radar echo in the NW direction at 4.5 m/s is a closer match to conditions at the 850 hPa level on 26 February. The radar image showed no clouds in the area of Miyake at 11:10 before seeding and an artificial cloud after seeding at 12:00, 12:30, and 13:10 (Fig. 7). We first thought that the artificial clouds could develop near SW area of Mikura, but it was not affected by direct artificial cloud based on the investigation about vertical profiles of the air temperature and vapor in spite of necessary of discussion (Fig. 8).

4.3.2 Effect of Seeding at Hachijo on 26 February

The vertical profile at Hachijo at 9:00 on 26 February was shown in Table 1. The wind shear therefore was large at 1400–1900 m. The surface observation data during the seeding experiment were shown in Table 2. Rain as fog or drizzle was recorded from 13:00 to 16:00 at the Hachijo Observatory, located on the leeward side of West Mountain (851 m) at an elevation of 151 m between West and East Mountain (701 m).

The artificial cloud was moved by a NE–NNE wind at 8–11 m/s (35 km/h), moving first to the east of Mikura and then to Hachijo within 3 h of the seeding. It may have had an effect on rain at Hachijo, although this could not be demonstrated.

Some considerations of the relation of rainforest to rainfall on subtropical and temperate islands may be relevant here.

(1) In the subtropical Ogasawara Islands about 1000 km south of Tokyo, cloud forest is absent on Chichi Island (elevation 318 m) but present on Haha Island (elevation 463 m). The difference of rainfall in these islands is based rather on the height of the mountain areas (Maki and Maki, 2012).

(2) The rainforest of Mikura consists of the largest grove of pasania (*Castanopsis cuspidata schottky*) trees in Japan. The annual rainfall is 2953.6 mm at Miyake (elevation 813 m) and 3202.4 mm at Hachijo (854 m), and the peak of Mikura (851 m) is at a similar height in a similar climate. Given these facts, we presume that Mikura gets as much rain as Miyake and Hachijo, possibly more. Unfortunately, there are no JMA data on the rainfall in Mikura.

4.4 Experimental Results for 27 February

An inversion layer was found at Oshima on 27 February, but not around the seeding area near Miyake (Fig. 5). Figures 3c, 3d show the scene of the cloud over Miyake during seeding at 10:21 and the over view of developing cloud on the east side of Miyake just after seeding at 10:30 on 27 February, respectively.

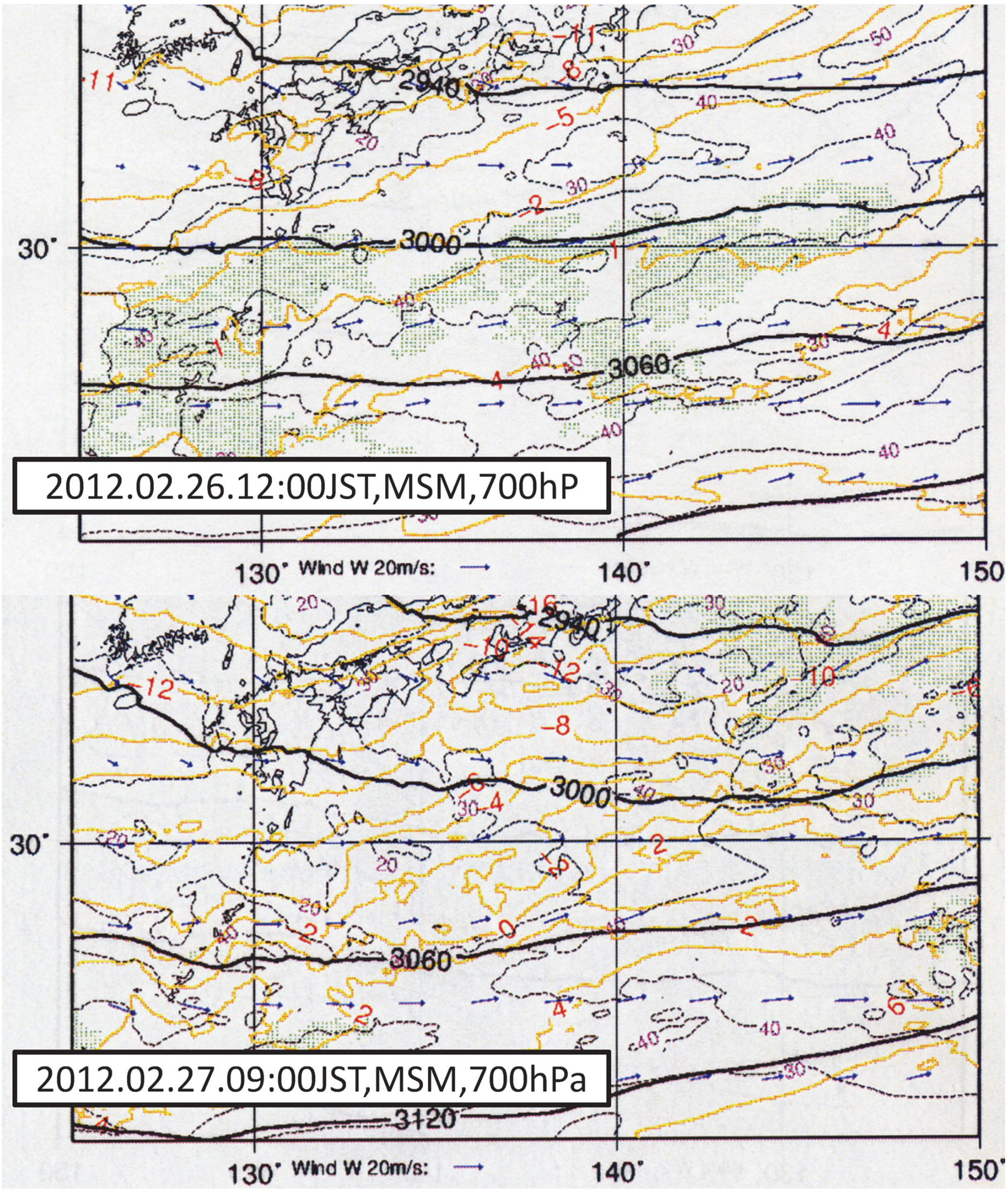

Fig. 8. JMA upper level (700 hPa, about 3000 m) weather maps around Miyake, Mikura and Hachijo on 26 and 27 February 2012.

Figure 3e shows the developed cloud by seeding at 11:10 on 27 February. Figures 3f, 3g show the scenes of inside cloud entering into and passing through the developed cloud with rain or virga, respectively. The cloud over Miyake at an early time after seeding (Fig. 3c) changed to the developed cloud over Miyake 0.5–1 h after seeding (Fig. 3h).

Figure 9 shows the satellite images and Fig. 10 shows the radar images from this day. After seeding with LCD in four bursts between 10:00 and 10:30, a convective cloud developed quickly with a height reaching 3500 m after 0.5 h and 4000 m after 1 h.

4.4.1 Effect of Seeding at Miyake and Mikura on 27 February

The seeded cloud moved ENE over Miyake (Figs. 3c–3e). When the growing convective cloud arrived over the east side of 10 to 20 km from Miyake, it had reached a height of 4000 m. As was the case on 26 February, the JMA radar could not image this cloud.

As the artificial cloud continued to move, we rec-

Table 1. Vertical profile of wind direction, wind speed and air temperature at 9:00 on 26 February 2012.

Height	Wind direction	Wind speed	Air temperature
Surface (1.5, 18.1 m)	NE (18.1 m)	5.1 m/s (18.1 m)	10.2℃ (1.5 m)
700–1400 m	NE–NNE	11–8 m/s	5.1–0.8℃
1900–4100 m	NW–WSW	7–25 m/s	−2.1–12.4℃

Table 2. Variation in wind direction, wind speed and air temperature of surface observation data at 9:00 to 14:00 on 26 February 2012.

Time	Wind direction	Wind speed	Air temperature	Rain
9:00	NE	5.1 m/s	10.2℃	No
11:00	ENE	4.4 m/s	11.7℃	Yes
12:00	ENE	5.8 m/s	12.7℃	No
13:00	ENE	4.1 m/s	12.5℃	Yes
14:00	NE	3.5 m/s	12.8℃	Yes

ognized rain beneath it and virga at a lower level. The virga reached Mikura around 0.5–1 h after the seeding, moved there by a NNE–NE wind at around 1500 m elevation. We photographed the cloud near Mikura and flew through it (Figs. 3f, 3g), recognizing rain on the windshield as we did so.

However, there was no rain at the Mikura Village Office, as was the case on 26 February, because of its low elevation and position on the leeward side of the island. The presence of rain in the mountainous area of Mikura and its absence in the surrounding lowland area were consistent with the topography and vegetation.

The virga was moved ENE by SW–SSW winds at around 2200 m for 0.5 h, at which time its air mass developed into a higher cloud at Mikura by topographic uplift. This cloud formed a line or chain of clouds running ENE after 11:00 that became high and thick by 11:20. It was clearly visible in radar images (Fig. 10), and the composition radar echoes reached 3000–5000 m after 12:00. This artificial cloud lasted about 3 h and disappeared around 14:00.

We also confirmed that LCD seeding within a convective cloud near its base is successful when the air temperature is below −5℃, consistent with observations in northern Kyushu (Fukuta *et al.*, 2000; Wakimizu *et al.*, 2002; Maki *et al.*, 2011, 2012; Suzuki, 2012).

In order to make clear the movement of the virga, the wind direction and speed are shown. The vertical profile at Hachijo at 9:00 was as follows: Wind W at 4.2 m/s, 10.2℃ near the surface; NNW–N at 3.0–5.0 m/s, 4.2 to −1.5℃ at 700–1500 m; NW–W at 7–29 m/s, −3.7 to −13.2℃ at 2000–4000 m; and winds at higher levels were westerly. The wind direction and wind speed as a time and distance explain the movement of air mass arrived to Hachijo.

According to the mesoscale forecast model at 9:00 near Miyake (Fig. 8), the vertical profile was as follows: Wind W at 4.2 m/s, 10.2℃ at 925 hPa; ESE at 3.0 m/s at 850 hPa; and WSW at 10.0 m/s at 700 hPa. As radar echoes typically move with the wind direction at the 700 hPa level, the moving radar echo corresponding to the artificial cloud chain agreed with the wind direction at 700 hPa.

4.4.2 Effect of Seeding at Hachijo on 27 February

Surface data observed at Hachijo were as follows: Wind W at 3.9 m/s, 9.5℃ at 10:00 (before the seeding); NE at 6.3 m/s, 9.0℃ at 11:00; NE at 10.3 m/s, 8.3 ℃ at 12:00; NE at 10.0 m/s, 8.3℃ at 13:00; and NE at 9.5 m/s, 8.4℃ at 14:00 with 0.0–0.5 mm/h rain (Fig. 11). The rain record from 9:40 to 22:00 on 27 February included rain at a maximum rate of 2.0 mm/h. At 9:00–9:50 a band-type cloud covered Hachijo, but the wind direction abruptly changed from W to NNE–NE

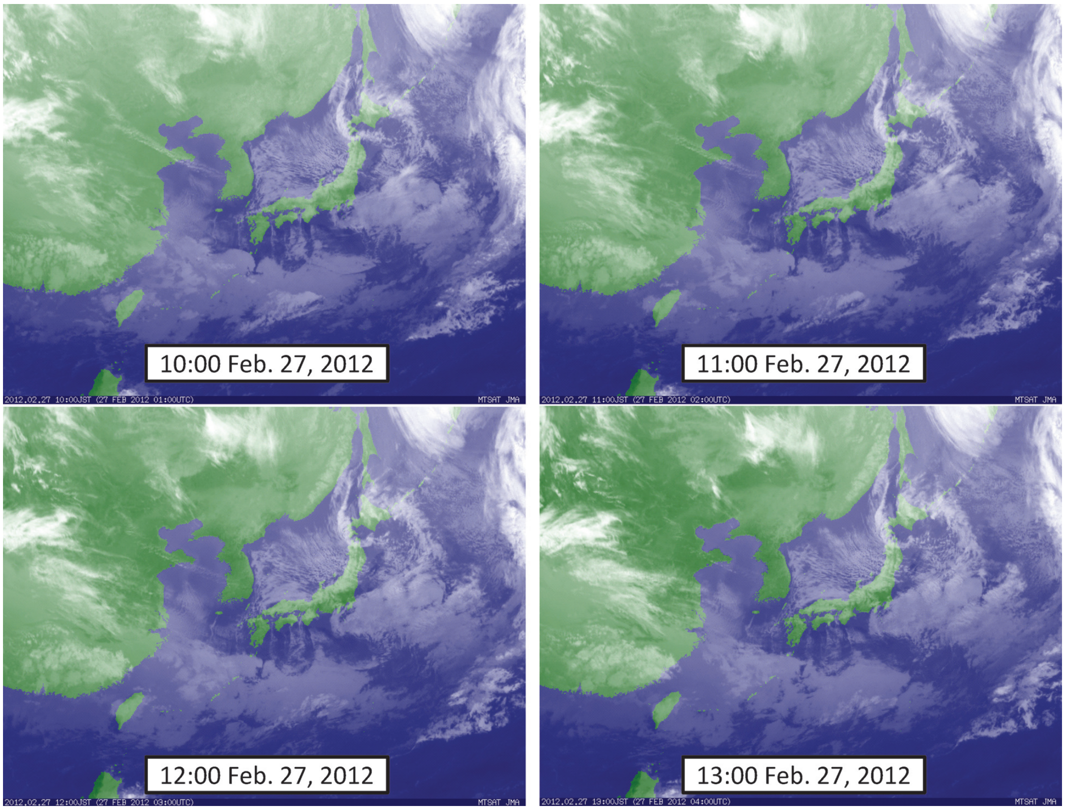

Fig. 9. JMA satellite infrared synoptic cloud images around Miyake, Mikura and Hachijo at 10:00, 11:00, 12:00, and 13:00 on 27 February 2012.

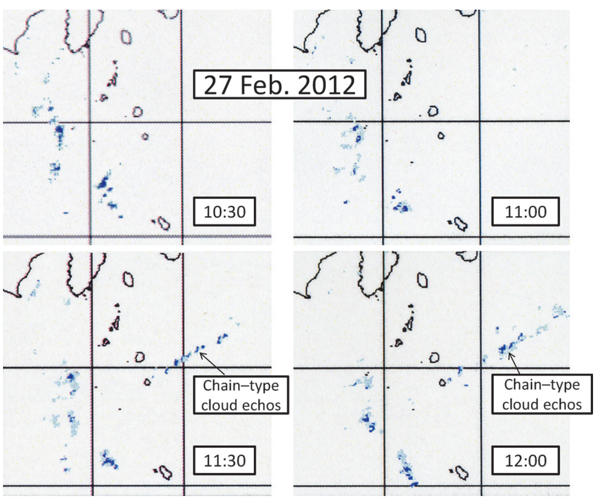

Fig. 10. JMA radar images of cloud echoes around Miyake, Mikura and Hachijo at 10:30, 11:00, 11:30 and 12:00 on 27 February 2012.

at 10:40–10:50 and the cloud dissipated. However, this change of weather occurred at least 1 h earlier than the effects of the LCD seeding could have arrived, based on the wind speed at Hachijo. Therefore, the sudden change was not a direct effect of the LCD seeding, but the possibility of wave transportation should not be ignored.

Miyake is 20 km from Mikura and 100 km from Hachijo. As the artificial rain air mass or virga was mainly at a low elevation, the virga would have been moved by a wind of 10.2–17.3 m/s (50 km/h) at 0–2000 m toward the SW–SSW for 0.5–1 h after the seeding. Although the artificial cloud initially moved to the east side of Miyake, it is possible that the artificial rain air mass or virga arrived with northerly winds at Hachijo and delivered rain there about 3 h later, as the results of 26 February suggest. Although artificial rain may have contributed to the rain observed after 13:00, the rain data at Hachijo are not conclusive as artificial rains based on the falling speed and time of virga considering with wind speed, distance and gravity.

5. Conclusions

(1) The development of a significant artificial convective cloud was visible within 1 h of LCD

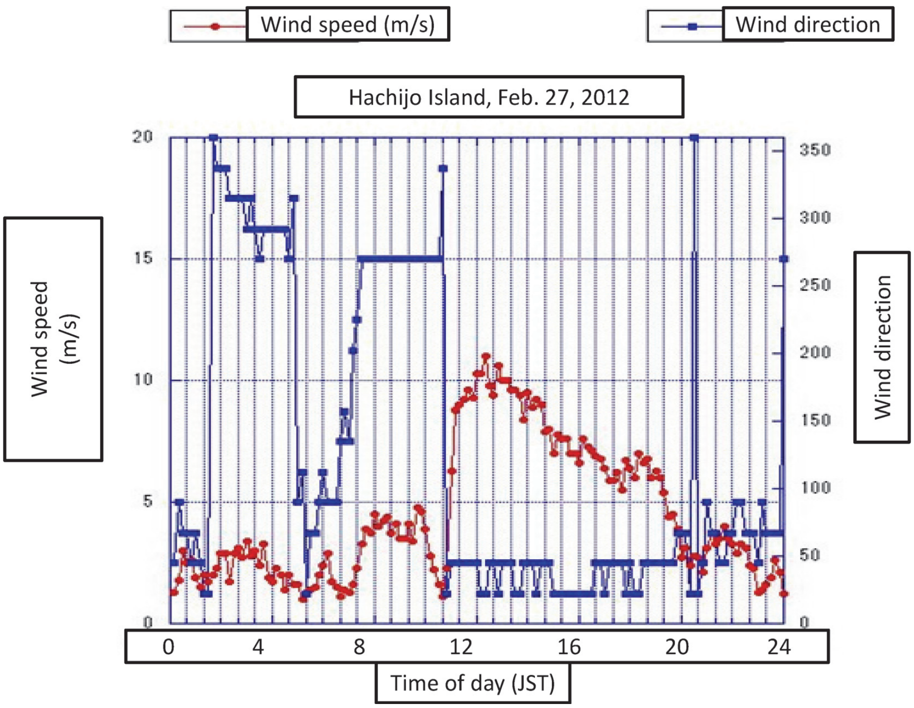

Fig. 11. Wind direction and wind speed at Hachijo on 27 February 2012.

seeding on the east side of Miyake. The cloud reached heights of 3000 m and 4000 m on 26 and 27 February 2012, respectively. However, on both days the direct artificial cloud was too small and too low density to be detected in JMA radar imagery.

(2) No rain was produced at Miyake on 26 February because the cloud passed over the island before rain could develop. On 27 February, an artificial cloud appeared over Miyake and it was possible for rain to have fallen on the mountain.

(3) Artificial clouds appeared within 1 h of seeding on both days at Mikura. The amount of rain presumably increased there in the mountainous area. The artificial clouds were correlated with echoes in JMA radar data on 27 February using the movements of clouds with upper and lower level wind directions. Chain-type cloud echoes were observed reaching 3000–5000 m when the artificial cloud moved to the ENE side of Mikura.

(4) As wind directions differed at upper and lower levels, the movements of cloud and virga were different. Rains were observed at Hachijo 3 to 4 h after the seeding on both days, although they could not be confirmed to be the result of seeding.

(5) LCD seeding was effective when done inside convective clouds near their bases when the air temperature was below −5℃.

Acknowledgements

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