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Enhancement of precipitation by liquid carbon dioxide seeding

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Abstract. A precipitation augmentation experiment based on a new airborne liquid carbon dioxide (LC) seeding at low level of supercooled convective clouds was carried out in Northern Kyushu, Japan. It is inferred that the new seeding method consisting of LOLEPSHIN contributed to the growth of artificially formed ice particles with horizontal spreading of cloud volume through the artificially induced dynamic and microphysical processes consisting of two fundamental processes, RETHIT and FILAS. In addition, it was found that dynamical interaction between the seeded and the adjacent natural cumuli was important factor in the formation of the secondary cumulus. In this study, based on these observed facts, the process for enhancing water resources by LC seeding method was investigated. As a result, LC seeding operation will lead to two significant effects; (1) the conversion of large amount of inactive cloud volume into valuable precipitation for water resources by LC seeding, (2) the additional contribution of secondary formed cumulus to precipitation enhancement.

1 Introduction

It was discovered that the introduction of dry ice (Schaefer, 1946) or silver iodide (Vonnegut, 1947) into supercooled clouds existing below 0° leads to the conversion of supercooled liquid water into ice. Since the discoveries, many trials for an increase in precipitation have been carried out all over the world. However, these methods lead to serious situation that individual ice particle cannot grow into enough size to induce precipitation due to the generation of too many ice particles in low temperature by heterogeneous nucleation according to Garvey (1975) in case of AgI method, and due to no time for individual ice particle to grow into enough size to fall out in case of dry ice method, as pointed out by Fukuta (1999). To solve the above-mentioned problems, a new seeding method was suggested by Fukuta (1996). The method consists of the generation of ice particles by homogeneous nucleation using liquid carbon dioxide (LC) and the subsequent more effective growth for ice particles without competition process.

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In our study, using small aircraft, the new LC seeding method was applied to supercooled convective clouds formed in the Northern Kyushu twice in 1999. These seeding operations led to the formation of artificial radar echoes with a unique mushroom shape due to micro-physical and dynamical interaction. In addition, the formation of vertical motion due to the intrusion of cold gust fonts from the artificially induced cumuli into ambient warm air seems to have caused the subsequent formation of the secondary radar echoes. In this paper, considering the combination of the first and secondary seeding effects induced by seeding operation on 27 October 1999, the process for enhancing precipitation will be discussed on the basis of the hypothesis of the new LC seeding method.

2 New seeding method using liquid carbon dioxide

2.1 Seeding method

The injection of LC materials into supercooled clouds causes strong evaporative cooling reaching $-90°$ as shown in Fukuta (1988) and the subsequent generation of approximately 10^{13} ice particles per gram of LC materials by homogeneous nucleation. The number of artificially formed ice particles keeps approximately constant after the injection of LC materials during the ascent of an artificially formed thermal. No competition process for limited supercooled liquid water among ice particles occurs in the thermal. Therefore, the conservation of ice particles in the thermal provides an important advantage for effective growth of ice particles. From this point of view, LC seeding method is still more advantageous than AgI seeding method, which causes competition process for the limited amount of supercooled liquid

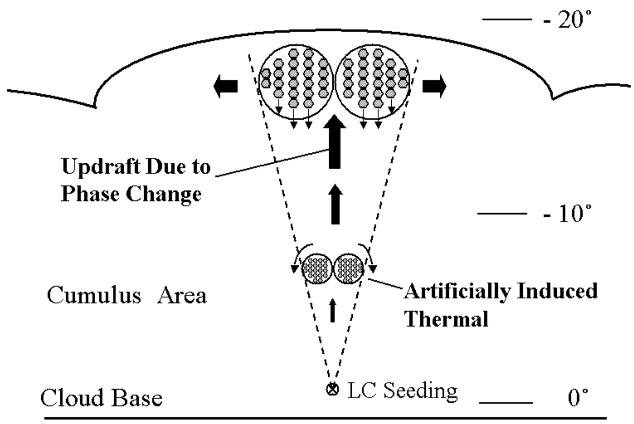

Fig. 1. RETHIT process.

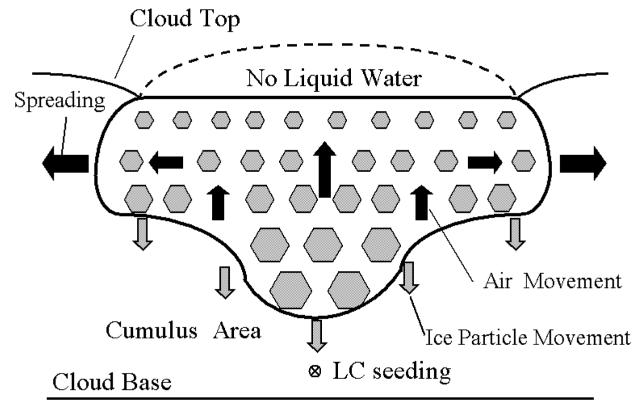

Fig. 2. FILAS process.

water among too many ice particles because the number of ice particles continues to increase during the ascent of artificially induced thermal containing AgI particles, as pointed out by Fukuta (1981). In addition, in order to enhance the efficiency of seeding, seeding operation by an aircraft is designed to be carried out at a low supercooled portion near 0° in a young developing cumulus so that ice particles can spend a relatively long time for the growth in the thermal. The reason is that it takes enough time for ice particles to grow effectively into enough size to fall out within a limited lifetime of a cumulus. The method is called "Low Level Penetration Seeding of Homogeneous Ice Nucleant (LOLEPSHIN)" as suggested by Fukuta (1999).

2.2 Expected direct seeding effects

Two processes induced by LC seeding were shown by Fukuta (1996) and Fukuta (1998). The first process is called RETHIT, which means Roll-up Expansion of Twin Horizontal Ice Crystal Thermal. On the other hand, the second process is called FILAS, which means Falling-growth Induced Lateral Air Spreading. In the first RETHIT process (see Fig. 1), ice particles forms instantaneously by homogeneous nucleation after LC seeding at a low altitude slightly less than 0° and the resultant artificially induced thermal starts to go up with latent heat release due to phase change of vapor into ice. The thermal takes the shape of the two-dimensional twin cylinders perpendicular to flight path and continues to go upward, with expanding its volume at a constant vertical angle because of the continuous supply of buoyant energy generated by the latent heat release and the associated turbulent diffusion. The ice particles can grow into enough size to fall out and to be detected by meteorological radar with no or little competition among ice particles until the thermal arrives at the cloud top.

In the second FILAS process (see Fig. 2), after the thermal reaches a stable layer, the falling ice particles move horizontally toward the both sides of the thermal due to lateral spreading. Then, the horizontally moving and falling ice particles cause artificial secondary upward motion in mature stage of the cumulus by the latent heat release due to phase change of vapor and the cloud volume continues to expand horizontally due to the existence of the stable layer around the cloud top until all of the available liquid cloud water for the ice particles in the cumulus is converted into ice. In this stage, the ice particles continue to grow further by consuming additionally formed liquid cloud water by the secondary upward motion.

2.3 Expected secondary seeding effects

The above-mentioned FILAS process corresponding to dissipating stage develops cold downdraft due to melting and evaporation of falling and horizontally spreading ice particles. As the downdraft air approaches the surface, it diverges and forms a gust front, which consists of relatively cold air to ambient air and is characterized by roll structure at it leading edge as shown by Wakimoto (1982). In addition, Purdom (1982) showed that significant convergence along the leading edge was primary mechanism for the formation of new cumulus. Particularly, the collision of two gust fronts between two neighboring clouds led to explosive growth of new cloud as shown in Purdom (1976). Considering artificially induced cumulus is formed by seeding operation using LC around active natural cumuli, the collision of a gust front from artificially induced cumulus in the FILAS stage with the other one from the adjacent natural cumulus in dissipating stage will lead to the formation of new cloud between both cumuli as discussed in Sect. 4.

3 Summary of LC seeding experiment

This section will give the summary of the second experiment applied to the supercooled convective cloud in a post-frontal weather condition in northern Kyushu, Japan, on 27 October in 1999 in order to suggest the optimum design of seeding operation using LC for enhancing precipitation in the next section. Detailed descriptions of the seeding results are given in Wakimizu et al. (2002).

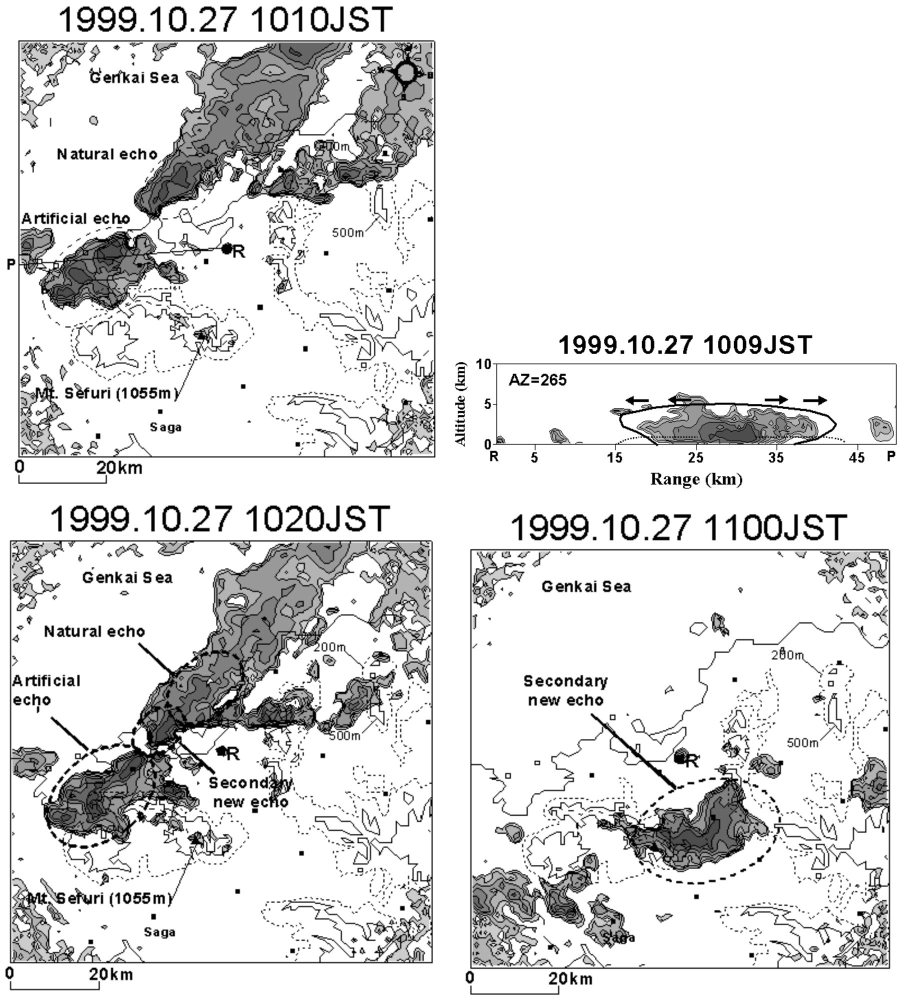

Fig. 3. Evolution of the radar echoes observed by KU radar. The contour lines are depicted at the interval of 5 dBZ from 10 dBZ. (a) PPI at 10:10 JST, (b) RHI at 10:09 JST between $\boldsymbol{R}$ and $\boldsymbol{P}$ in (a), (c) PPI at 10:20 JST, (d) PPI at 11:00 JST. In the Fig. 3b, the image of mushroom type echo generated by FILAS process is depicted, and dotted line indicates inferred gust fronts.

3.1 Direct seeding effect

Since the echo of target cloud seeded at 08:51 JST developed and came into the Kyushu University (KU) radar range after 09:30 JST, images of PPI (plan position indicator) and RHI (range-height indicator) of the seeded target cloud were observed in detail by the KU radar. Here, a part of PPI and RHI pictures observed by KU radar are shown in Fig. 3. The location of KU radar is shown as $\boldsymbol{R}$ in Fig. 3. Around 10:10 JST, the seeded echo of the seeded cloud and the adjacent natural echo located in the northeast side of the seeded echo appear to be in mature stage with a gap of about 10 km between both echoes as confirmed in Fig. 3a. At the time, the seeded echo indicates spreading of the echo area and took a unique mushroom shape with the maximum echo width of 24 km, which was not as remarkable as that of the previous seeding experiment (Fukuta et al., 2000), as shown by the outline of the region consisting of ice particles in the RHI images (Fig. 3b). The above-mentioned results imply artificially formed ice particles could glow into enough size and have enough terminal velocity to be detected by KU radar at a cloud top in FILAS stage followed by RETHIT. Therefore, the new seeding method succeeded in effective conversion of large cloud volume into large amount of precipitation.

3.2 Secondary induced seeding effect

At 10:20 JST, the secondary new echo was formed between artificial and natural echoes as shown in Fig. 3c. After the time, the new echo continued to grow rapidly and, on the contrary, the adjacent artificial and natural echoes weakened rapidly from 10:30 JST and disappeared until 10:40 JST. Consequently, the completely isolated echo could be confirmed as shown in Fig. 3d until the echo went out of the KU radar range at 11:50 JST. It is inferred that the formation of the new echo was attributed to the collision of two divergent gust flows from the artificial cumulus in FILAS stage and natural cumulus in each dissipated stage.

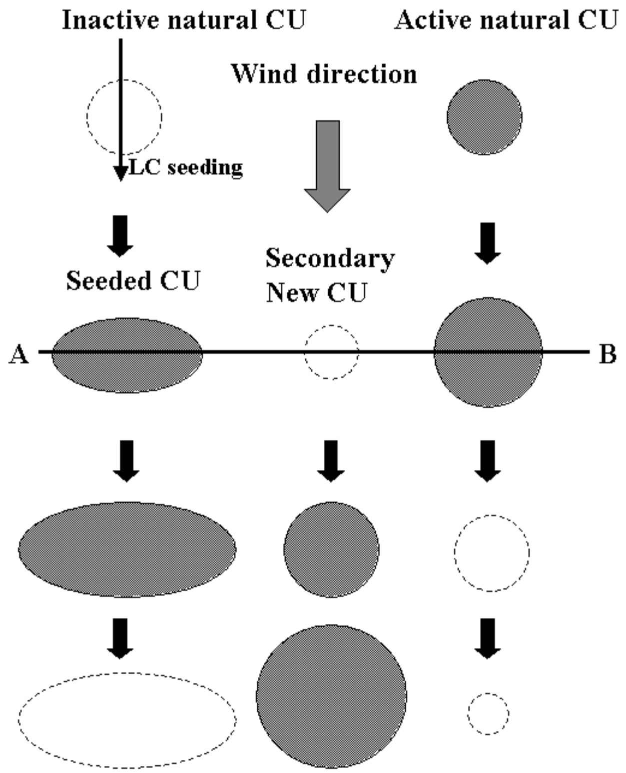

Fig. 4. Development of seeded cumulus and subsequent formation of secondary induced cumulus between seeded and the adjacent natural cumulus. Black colored circles and ellipsoids indicate the existence of precipitation and radar echo. Broken circles and ellipsoids indicate the state of no radar echo (no precipitation).

4 The process of precipitation enhancement

Inactive cumuli as well as precipitating active cumuli may exist in unstable atmosphere. Since inactive cumulus has the possibility of artificial precipitation by LC seeding if it has enough thickness to have significant liquid water in the developing stage, inactive cumulus would be useful as seeding target for enhancing precipitation. As shown in Figs. 4 and 5, after seeding aircraft penetrates inactive cumulus, its cloud volume will spread horizontally as direct effects of LC seeding. After that, dynamical interaction between artificially activated cumulus and the adjacent natural active cumulus in dissipating stage as explained in Sect. 2.3 will lead to the formation and development of secondary new cumulus as indirect effect of LC seeding. Consequently, LC seeding operation will lead to two significant effects; (1) the conversion of large amount of inactive cloud volume into valuable precipitation for water resources by LC seeding, (2) the additional contribution of secondary formed cumulus to precipitation enhancement.

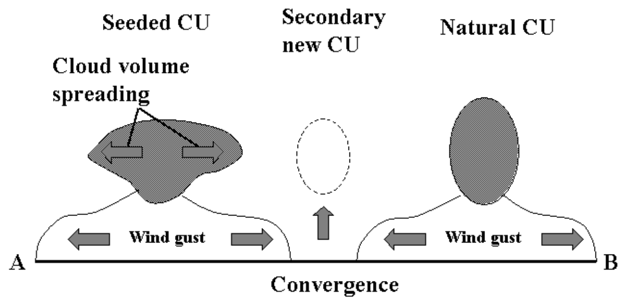

Fig. 5. Vertical cross-section along the line connecting between A and B in Fig. 4

5 Conclusion

A precipitation augmentation experiment based on a new airborne liquid carbon dioxide (LC) seeding at low level of supercooled convective clouds was carried out on 27 October 1999, in Northern Kyushu, Japan. As a result, the seeded echo indicates spreading of the echo area and took a unique mushroom shape with the maximum echo width of 24 km. It is inferred that the echo took a unique shape characterized by the new seeding method (LOLEPSHIN), low-level horizontal penetrations of operational aircraft with seeding LC, because the method is expected to contribute to the growth of artificially formed ice particles with horizontal spreading of cloud volume through the artificially induced dynamic and microphysical processes consisting of two fundamental processes, RETHIT and FILAS. Therefore, the unique echo shape indicates remarkable seeding effect by the new method as could be confirmed by only a single case. In addition, the collision of a gust front from artificially induced cumulus in the FILAS stage with the other one from the adjacent natural cumulus in dissipating stage will lead to the formation and development of new cloud between both cumuli.

These observed facts show that the new method will lead to the effective conversion of large amount of inactive cloud volume into significant precipitation due to horizontal spreading of cloud volume and the generation of new precipitation due to the convective activity of secondary induced cumulus. Therefore, the new method would have enough possibility to enhance significant precipitation for water resources through these processes.

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