Redistribution of Snowfall across a Mountain Range by Artificial Seeding: A Case Study

Abstract. *Clouds over the western slopes of the Cascade Mountains were artificially seeded to reduce the riming and fall speeds of snow crystals and to divert snowfall across the crest. Aircraft observations showed that the clouds were glaciated by the seeding. The crystal habits and the degrees of riming of snow crystals reaching the target area were modified. Snowfall rates decreased at the crest and simultaneously increased 20 kilometers east of the crest.*

Most of the work that has been carried out on the artificial seeding of clouds has been designed to either increase or decrease precipitation in a particular locality. However, in certain situations, cloud seeding offers the potential for the controlled redistribution of precipitation which, if it could be carried out reliably, would be of great value in many areas of the world. We are studying the feasibility of redistributing snowfall across the crest of the Cascade Mountains of Washington by seeding with artificial ice nuclei. Results obtained in this area should be applicable to many other mountain ranges.

The theoretical basis for this project has been given by Hobbs *et al.* (*1*). Briefly, the argument is as follows. Solid precipitation particles which develop in winter clouds over the Cascade Mountains are often heavily rimed (that is, covered with frozen cloud droplets) which shows that they have passed through clouds containing large numbers of supercooled droplets. Rimed ice particles have fall speeds of a few meters per second, and most of them reach the ground on the windward side of the Cascades. Riming can be reduced, or eliminated, by overseeding with artificial ice nuclei or with solid carbon dioxide which causes large numbers of ice particles to form in the clouds. Since unrimed ice crystals have fall speeds of only about 0.5 m sec^{-1}, their trajectories as they fall toward the ground are less steep than those of rimed particles and thus they are carried for greater distances downwind and may reach the ground on the leeward side of the mountain. Detailed calculations indicate that, under typical winter conditions in the Cascade Mountains, rimed snow crystals which reach the ground about 30 km west of the Cascade crest would reach the surface about 30 km east of the crest if riming were eliminated by artificial seeding.

To test the above ideas a series of field experiments (called the "Cascade Project") are being carried out (*2*). Prior to seeding, (i) airborne measurements are made of the properties of the clouds over the Cascade Mountains between Seattle and Ellensburg; (ii) snow crystals are collected and the rates of precipitation are measured at several ground stations straddling the mountains; and (iii) rawinsondes are launched upwind of the Cascades to obtain vertical profiles of wind, temperature, and humidity. These measurements are radioed back to the University of Washington where they are used as input data in a numerical model which predicts where artificial seeding should be carried out to redistribute snowfall across the mountains. Seeding from the aircraft, with either silver iodide pyrotechnics or solid carbon dioxide, is then carried out at the specified location for a short period of time (usually about 1 hour). After seeding, the research aircraft obtains measurements in the clouds downwind of the seeded area to document any changes in their structure. Measurements and observations at the ground stations are continued during and after seeding in order to detect any changes in the nature and intensity of the precipitation across the mountain. Our theoretical model is considered to be confirmed if, during the predicted period-of-effect (PPE) due to artificial seeding, changes occur in the clouds and precipitation on the ground in the target area which are of the kind to be expected from the seeding (for example, reduction in the liquid water content and an increase in the concentration of ice particles in the seeded clouds, the appearance of new and virtually unrimed ice crystals at the ground stations which can be traced back to the seeded clouds, and decreases in the precipitation rates on the windward side of the mountain and corresponding increases in the precipitation rates on the leeward slopes).

We describe below a case study conducted on 31 January 1972, in which artificial seeding was carried out and many of the predicted effects of seeding, which have been listed above, were observed. A more detailed description of the measurements obtained on this occasion will be presented elsewhere (*3*).

On the morning of 31 January 1972,

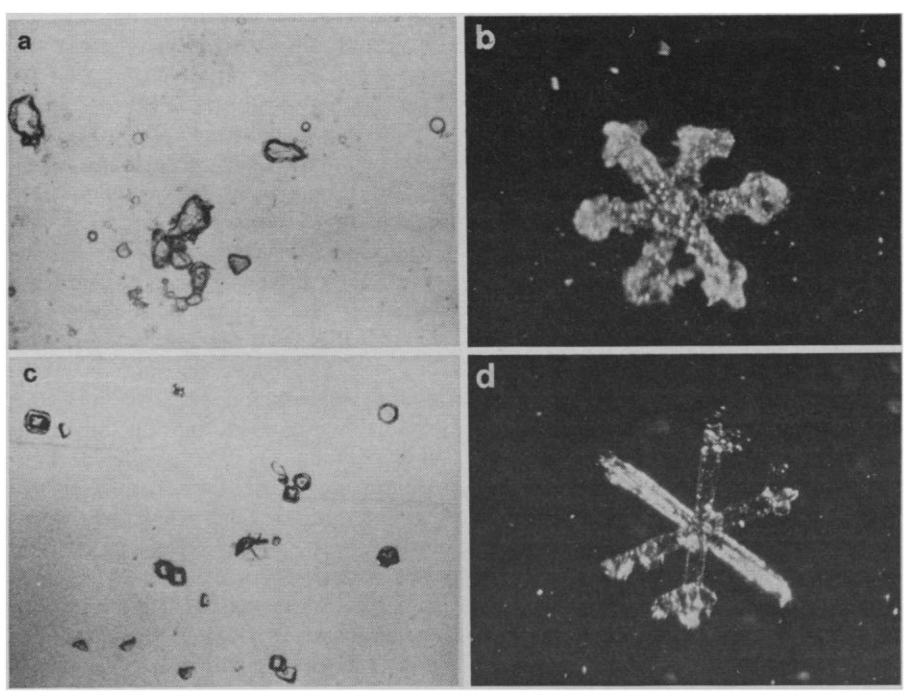

Fig. 1. (a) Small supercooled cloud droplets and ice particles collected from the aircraft while flying over the western slopes of the Cascades prior to seeding (× 27.5). (b) Rimed stellar crystal collected on the ground at Hyak prior to seeding (× 27.5). (c) Unrimed ice crystals collected from the aircraft over the western slopes of the Cascades after seeding (× 27.5). (d) Unrimed stellar crystal collected on the ground at Hyak after seeding (× 27.5).

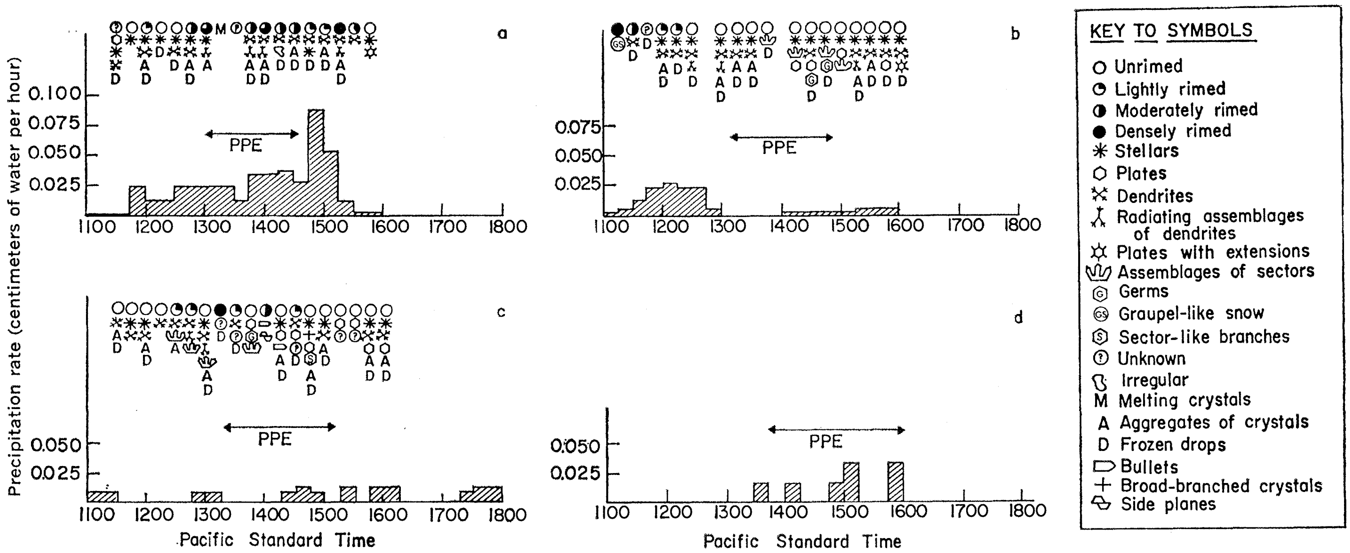

Fig. 2. Snow crystal types, degree of riming, and precipitation rates at (a) Alpental, (b) Hyak, (c) Keechelus Dam, and (d) Kachess Dam on 31 January 1972. The arrows indicate the PPE of seeding at each ground station.

the airflow was generally westerly and layered stratus and stratocumulus clouds extended across the Cascade Mountains. The bases of these clouds were near 0.9 km (−5°C) on the western slopes and at about 2 km (−10°C) over the crest, and their tops were near 2.9 km (−16°C). A layer of altocumulus clouds extended from 3 to 3.6 km, and around 6 km there were thin cirrus clouds.

Prior to artificial seeding, which started at 1254 hours (all times are Pacific Standard Time), a comprehensive series of airborne and ground measurements were obtained. Between 1153 and 1217 hours the research aircraft traversed from west to east across the Cascades at an altitude of 2.4 km (−13°C). Particles collected in the clouds over the western slopes were predominantly supercooled water droplets from 10 to 35 μm in diameter, but droplets up to 100 μm were also collected (Fig. 1a); the liquid water content in these clouds fluctuated around 0.1 g m^{-3}, occasionally reaching values of 0.25 g m^{-3}. Rimed platelike ice crystals and ice aggregates up to 1300 μm in diameter were also present (Fig. 1a). The predominance of water droplets in the clouds was confirmed by frequent observations of cloud bows, supernumerary bows, and glories (see cover, upper left), which are atmospheric optical phenomena produced by water droplets. At the same altitude over the eastern slopes of the mountains, only ice particles 20 to 150 μm in diameter, with a few up to 400 μm, were collected and the liquid water content was close to zero.

Observers located 2 km to the west of the Cascade crest at Alpental (882 m), at the crest at Hyak (744 m), and 12 km to the east of the crest at Keechelus Dam (744 m), made continuous observations from 1100 through 1600 hours on 31 January 1972. In addition, precipitation rates were measured automatically at other stations throughout the day. A summary of the types of snow particles (*4*), their degree of riming, the precipitation rates at the three manned stations, and the precipitation rates at Kachess Dam, which is located about 27 km east of the crest, throughout the period of measurements is contained in Fig. 2. Prior to artificial seeding, the snow crystal types reaching Alpental consisted primarily of unrimed to moderately rimed dendrites, stellars, and aggregates of these crystals. At Hyak during this period the snow crystals were lightly to densely rimed dendrites, radiating assemblages of dendrites, stellars (Fig. 1b), assemblages of sectors, and aggregates of these crystals.

Model calculations, based on rawinsonde measurements and the observed types of snow crystals, predicted that, in order to cause a redistribution of snowfall across the Cascade crest, seeding with silver iodide should be carried out between heights of 3.3 and 1.5 km in a region located at about 6.6 km southwest of Alpental. The research aircraft flew at an altitude between 3.3 and 3.1 km around a kidney-shaped track located just west of the Cascade crest which encompassed the prescribed seeding location. Nine pyrotechnic units attached to the aircraft, each containing 64 g of silver iodide, were ignited in sequence between 1254 and 1406 hours. During the same period, 24 pyrotechnic units, each containing 40 g of silver iodide, were released from the aircraft at 3-minute intervals. These units fell for a distance of 0.6 km before ignition and then dispersed the silver iodide into the air during the next 0.9 km of fall.

About 18 minutes after artificial seeding commenced, optical effects due to ice crystals in the clouds began to be observed from the aircraft. These included subsuns, pillars, and subparhelia (see cover, upper right and bottom left). Cloud particles collected from the aircraft during the period of seeding contained many small (up to 100 μm) unrimed ice crystals (Fig. 1c), whereas, prior to seeding, the clouds in this area were composed primarily of water droplets (Fig. 1a). Definite increases in the concentration of ice nuclei, attributable to the released silver iodide, were recorded on the aircraft from 1303 to 1405 hours. Sharp fluctuations in the air temperature and dew point, of the order of 2°C in 30 seconds, were measured from the aircraft in the seeded area. The liquid water content also showed much larger fluctuations in this area than had been observed prior to seeding, and the frequency and intensity of the measured air turbulence increased during seeding. These observations indicate that the artificial seeding increased convective activity and also partially glaciated the clouds.

After the completion of seeding the research aircraft flew downwind into the target area which should have been affected by the seeding. The clouds in this area were glaciated, nearly featureless, and consisted almost entirely of unrimed and unaggregated ice particles (thick plates, columns, bullets, and irregular crystals) present in high concentrations. While flying over this area, we observed the unusual paranthelic circle (that is, a white horizontal arc passing through both the antisolar and subsolar points) (see cover, bottom right); this is caused by external reflections in uniformly sized ice crystals. The oblique arcs crossing the paranthelic circle at the antisolar points do not appear to have been previously reported. In clouds sampled just south of the seeded area, supercooled water droplets coexisted with ice particles.

Calculations based on the rawinsonde measurements, the dispersal of the silver iodide, and the trajectories of the solid precipitation particles indicated that the artificial seeding was unlikely to have affected the precipitation reaching Alpental. However, at Hyak and Keechelus Dam there was an excellent chance that most of the crystals reaching the ground would have been affected by the seeding between about 1310 to 1450 and 1315 to 1510 hours, respectively.

The crystal types reaching Alpental did not change significantly throughout the day, but their degree of riming increased from 1300 to 1530 hours (Fig. 2a). Moreover, the precipitation rate was fairly steady at about 0.025 cm of water per hour until 1500 hours when a sharp increase to 0.089 cm per hour occurred. At Hyak, on the other hand, riming was completely absent during and after the PPE of the seeding at this station (Figs. 1d and 2b). Perhaps even more significant, several new crystal types (sectors, plates, and "germs"), which grow at the relatively low supersaturations to be expected in the seeded clouds, fell at Hyak during the PPE and disappeared after the PPE. It was precipitating steadily at Hyak prior to 1300 hours but near the start of the PPE precipitation virtually ceased; at 1400 hours very light precipitation started again. At Keechelus Dam (Fig. 2c) new crystal types (plates, bullets, side planes, and broad-branched crystals) appropriate to low supersaturations also appeared during the PPE and disappeared afterward. Precipitation at Keechelus Dam was light and sporadic throughout the day. Precipitation rates obtained from a recording gauge at Kachess Dam showed that the only precipitation of the day at this station fell during the PPE (Fig. 2d); the rates correspond to moderate drizzle. Measurements between 1100 and 1600 hours of the concentrations of freezing nuclei in the snow which fell at Hyak and Keechelus Dam showed a maximum concentration at 1330 hours at Hyak, and at Keechelus Dam increases in the concentrations of ice nuclei occurred after 1315 hours.

In summary, we have documented a chain of physical events both in the clouds and on the ground which confirm the predicted effects of the artificial seeding. Cloud particles collected from the aircraft and observed optical effects showed conclusively that the seeding promoted glaciation in the clouds upwind and over the target area. Trajectory analysis showed that the effects of seeding should have been observed on the ground at Hyak, Keechelus Dam, and Kachess Dam. At Hyak, riming ceased completely, new crystals appeared, and the precipitation rate decreased dramatically during the PPE. We conclude that this was due to the fact that the bulk of the unrimed ice crystals produced by seeding were carried over the Cascade crest. At Keechelus Dam, situated to the east of the crest, new crystal types which could be traced back to the seeded clouds, appeared during the PPE. At Kachess Dam, situated about 20 km downwind of the crest, the only snowfall of the day fell during the PPE, and we attribute this to the effects of seeding diverting the snowfall across the Cascade crest.

We have obtained results similar to those described above on other occasions during extensive studies over the past 3 years. However, although in most cases seeding has produced observable modifications to the clouds, we have often failed to observe appreciable changes in precipitation within our small target area on the ground. We conclude, therefore, that, although prospects for modifying and redistributing precipitation by cloud seeding across mountain ranges similar to those of the Cascades appear reasonably good, this technique has not yet reached the point where it can be used as a reliable method for the controlled redistribution of precipitation within a small predetermined target area.

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References and Notes

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4. Ice particles are categorized according to the scheme suggested by C. Magono and C. W. Lee, *J. Fac. Sci. Hokkaido Univ. Ser. 7* **2**, 321 (1966).
5. We thank all the members of the Cloud Physics Group at the University of Washington for their valuable help. This work was supported by the Division of Atmospheric Water Resources Management, Department of the Interior, under contract No. 14-06-D-6999 and by the RANN Program of the National Science Foundation (grant GA-27637). Contribution No. 286, Atmospheric Sciences Department, University of Washington.

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Climatic Change on Mars

Abstract. *The equatorial sinuous channels on Mars detected by Mariner 9 point to a past epoch of higher pressures and abundant liquid water. Advective instability of the martian atmosphere permits two stable climates—one close to present conditions, the other at a pressure of the order of 1 bar depending on the quantity of buried volatiles. Variations in the obliquity of Mars, the luminosity of the sun, and the albedo of the polar caps each appear capable of driving the instability between a current ice age and more clement conditions. Obliquity driving alone implies that epochs of much higher and of much lower pressure must have characterized martian history. Climatic change on Mars may have important meteorological, geological, and biological implications.*

Mars is the only known planet with a major atmospheric constituent condensable at typical surface temperatures; they range from 290°K at equatorial noon to a temperature at the cold pole, $T_p \simeq 145°K$ in polar winter—a temperature below the frost point of CO_2, which constitutes over 90 percent of the atmosphere. In a pre–Mariner 9 discussion, one of us (*1*) proposed that Mars is currently in an ice age, that more clement conditions prevailed earlier, and that Mars oscillates between these two climatic states. A time of higher pressures, *P*, higher temperatures, and