The State of Washington's Emergency Cloud Seeding Program (February - June, 1977)

A Brief Report Prepared by the
Cloud Physics Group, University of Washington
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JULY 1977
Snow showers from shallow cumulus clouds over the Cascade Mountains. This photograph was taken a half an hour after the clouds were seeded with Dry Ice (see Section 3).
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SECTION 1

ORIGINS AND SCOPE OF THE PROGRAM

During the period September 1, 1976, through January, 1977, precipitation in Washington State was the lowest on record (Figure 1). This drought posed a serious threat to water supplies for agriculture, power production, fisheries, and domestic purposes, and threatened the economic base and general well-being of the State.

Following a recommendation from the Senate Committee on Agriculture, and as one step toward attempting to relieve the many problems raised by the drought, the Legislature of the State of Washington passed an Emergency Cloud Seeding Bill on February 18, 1977 (Senate Bill No. 2561). This Bill called for the Department of Natural Resources to enter into a Contract with the University of Washington's Cloud Physics Group to conduct a program of emergency cloud seeding.

A contract between the Department of Natural Resources and the University of Washington was signed on February 25, 1977. This contract required the University of Washington to carry out a program of airborne operational cloud seeding in an attempt to increase snowpack in the Cascade Mountains and precipitation in critical areas of Eastern Washington. However, in a letter dated March 7, 1977, the Department of Natural Resources asked the University of Washington to place the highest priority on increasing snowpack across the Cascade Mountains, with the intent of maximizing subsequent spring and summer

* Some additional cloud seeding projects were carried out by public utility companies and private organizations under the general authorization of this Bill but these are not discussed in this Report.
Figure 1. Cumulative precipitation measurements for (a) Seattle and (b) Wenatchee for the period September through May.
runoff into the reservoirs on the Yakima, Naches and Tieton Rivers. Consequently, the majority of the seeding was carried out just west of the Cascade Crest in an area extending from about Mt. Rainier to Skykomish (Fig. 2), although during the first week of the program some seeding was carried out in the Yakima Valley.
Figure 2. Area (shaded) in which the majority of the cloud seeding was carried out.
SECTION 2
OPERATION OF THE PROGRAM

In order to eliminate the many uncertainties associated with ground-based seeding, all of the seeding in this program was carried out from aircraft.

During the period February 28 to May 6 a DC-3 aircraft (leased from Aero-Dyne Inc.) was used. This aircraft was equipped with a device for crushing and dispensing Dry Ice (i.e., solid carbon dioxide) at variable rates and a unit for dispersing ammonium nitrate at controlled rates. The ammonium nitrate was to be used for seeding "warm clouds" (i.e., clouds situated beneath the 0°C level) in Eastern Washington but, as mentioned in Section 1, this part of the program was curtailed early on in favor of seeding "cold clouds" over the Cascades with Dry Ice.

After May 6 the University of Washington's B-23 Cloud Physics Research Aircraft (Fig. 3) became available and it was used for the remainder of the Cloud Seeding Program. This aircraft is equipped with an extensive array of instruments for seeding clouds and for measuring the effects of cloud seeding on clouds and precipitation.

A listing of all the flights carried out in the Cloud Seeding Program is contained in Table 1*.

During each flight a scientist aboard the aircraft assessed the potential for precipitation augmentation by cloud seeding, decided upon the exact flight route during which seeding would be carried

* More detailed documentation on each flight is on file at the University of Washington.
Figure 3. The University of Washington's B-23 Cloud Physics Research Aircraft.
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**TOTAL 9.4 tons 225 gals**
out, and determined the rate of dispersal of the seeding material. The effects of the seeding were documented, wherever possible, through visual observations, photography and (when the B-23 was used) by direct measurements.
SECTION 3
EVALUATION OF THE PROGRAM

Determination of the precise effects of cloud seeding on precipitation is a very difficult task, even for experimental research programs specifically designed for this purpose (see, for example, Weather and Climate Modification: Problems and Progress, National Academy of Sciences, 1973). The State of Washington's Emergency Cloud Seeding Program was not an experimental research program but an operational program in which the prime task was to seed as much as possible in an effort to increase precipitation. Consequently, the program was neither designed nor operated in such a way as to provide a scientific evaluation of the effects of the seeding on precipitation. Nevertheless, as described below, some information was gained on the effects of the seeding.

Some Examples of the Effects of the Seeding

The purpose of seeding clouds with Dry Ice is to increase the concentrations of ice particles in the clouds above those which would occur naturally. These ice particles may then increase rapidly in size to produce precipitation. Dry Ice is very effective in increasing ice particle concentrations in clouds, since one pound of Dry Ice dropped into a "cold cloud" produces about one hundred million million small ice particles!

The effects of Dry Ice seeding on the appearance and structure of clouds (as distinct from its effects on precipitation at the ground) are relatively easy to document. We describe a few cases below which clearly demonstrate that clouds over the Cascade
Mountains were modified by the seeding which we carried out.

We start first with a series of photographs which illustrate the effects of artificial seeding. On March 15, fairly shallow, non-precipitating, cumulus clouds with bases around 8,000 ft and tops at about 12,000 ft (-14°C) were encountered near Packwood (Fig. 4). The well-defined, "hard" appearance of these clouds is characteristic of fairly young, growing clouds which contain supercooled liquid water droplets (that is, cloud droplets in the liquid phase even though the temperature is below 0°C) but few ice particles. The main cloud shown in Fig. 4(a) (and on the left in Fig. 4b) was seeded with 10 lbs of Dry Ice at 1430 PST. Ten minutes later the appearance of this cloud had not changed very much (Fig. 5). It was therefore seeded with a further 45 lbs of Dry Ice (dispersed into four separate turrets of the cloud). By 1450 PST the cloud had changed dramatically (Fig. 6); it was now far more ill-defined and fuzzy looking, a sure indication that it contained numerous ice particles. Fig. 7, taken 5 mins later, shows a turret growing out of the seeded cloud. This illustrates an additional benefit of artificial seeding which can occur under certain conditions, namely, an increase in the buoyancy (and therefore the height) of a convective cloud. The increase in buoyancy is produced by the latent heat released during the formation of the ice particles by the Dry Ice. The final photographs in this series (Fig. 8 and Frontispiece) show snow showers which fell from the cloud 30 mins after it was first seeded. The new turret produced by the seeding is clearly visible in these photographs.
Figure 4. Non-precipitating cumulus clouds near Packwood at 1427 PST on March 15, 1977. Note the "hard" looking appearance of the clouds indicating that they contained little ice.
Figure 5. Same clouds as in Figure 4 at 1440 PST, 10 mins. after seeding with 10 lbs. of Dry Ice.
Figure 6. Close ups of the seeded clouds at 1450 PST after seeding with a total of 55 lbs of Dry Ice. Note the ill-defined, ragged appearance of the cloud indicating the presence of numerous ice particles.
Figure 7. 25 minutes after seeding started. Note the growing turret from the seeded cloud.
Figure 8. Snow showers from the seeded cloud at 1500 PST (half an hour after seeding started).
We turn now to more quantitative information on the effects of artificial seeding on cloud structure which can be obtained from a suitably instrumented aircraft such as the University of Washington's B-23. Two case studies are described below.

On May 18, 1977, cumulus clouds over the Snoqualmie Pass area reached an altitude of 14,000 ft (-8°C) and were embedded in a lower deck of stratus clouds with tops at 10,000 ft and bases between 5,000 and 7,000 ft. Within the field of view of the aircraft, natural precipitation was virtually non-existent throughout the period of the flight. The cumulus clouds were penetrated in a horizontal traverse at about 1,000 ft above the top of the stratus deck while Dry Ice was dispersed. The clouds were then repenetrated to determine the effects of the seeding.

The effects of the seeding are clearly demonstrated in the measurements of the cloud liquid water content, cloud droplet concentrations, and ice particle concentrations. Fig. 9 shows the measurements obtained in a number of penetrations of one of the seeded cumulus clouds in which a total of 1.7 lbs of Dry Ice was dispersed at a rate of 5 lb per minute. In the first penetration, when the Dry Ice was dispersed (but had not yet affected the cloud), the cloud liquid water content was 2 grams per cubic meter of air and no ice particles were measured (Fig. 9a). In the second pass through the cloud, made about 2 minutes later, ice particles were detected across nearly the entire diameter of the cloud (about 0.7 mile) and their peak concentration was about 75 per liter of air. It can be seen in Fig. 9(b) that at
Figure 9. Measurements of cloud microstructure showing the effects of seeding a cumulus cloud with Dry Ice. (a) Measurements obtained during first horizontal penetration of cloud when seeding was carried out (1403 PST). Repenetrations of seeded cloud at (b) 1405, (c) 1407, and (d) 1409 PST. (See text for discussion.)
the peak ice particle concentration the cloud liquid water content and cloud droplet concentrations were depressed somewhat. This indicates localized overseeding where the ice particles were removing cloud droplets faster than they could be replaced by condensation. Two minutes later (Fig. 9c) the entire diameter of the cloud contained ice particles. It can also be seen from the tabulated data beneath the diagrams in Fig. 9 that the concentrations of precipitation particles in the cloud had increased dramatically within 6 minutes of seeding (from 50 to 3000 per cubic meter of air) and the precipitation rate near cloud base had increased 25 times. A significant snow shower was observed below the base of this cloud about 7 minutes after seeding.

The next cumulus cloud which was selected on this same day (May 18) was seeded with Dry Ice at half the rate of the cloud described above, however, because of its greater diameter, it received about the same total amount of Dry Ice (1.5 lb). Fig. 10 shows that the changes in the structure of this cloud following seeding were similar to those described above. The cloud reached the precipitation stage about 7 minutes after seeding (Fig. 10d). However, two additional facets are apparent in the fifth penetration (Fig. 10e). Firstly, the concentration of precipitation sized particles and the precipitation rate were still increasing, indicating that the peak in precipitation has still not been reached even though the precipitation rate had increased by 250 times in 8 minutes. Secondly, the data reveal a new turret developing on the flank of the seeded cloud. Since about 30% of the diameter of this new turret contained ice particles, it is apparent that it was being seeded by the ice particles produced by the original seeding. Hence, the effects of the seeding were being self-propagated.
Figure 10. Measurements of cloud microstructure showing the effects of seeding a cumulus cloud with Dry Ice. (a) Measurements obtained during first horizontal penetration when seeding was carried out (1413 PST). Repenetrations of seeded cloud at (b) 1415, (c) 1417, (d) 1420, and (e) 1423 PST.
From the in-cloud measurements made on the two seeded cumulus clouds on May 18 (Figs. 9 and 10), we calculate that if the precipitation from these clouds lasted for 30 minutes, and if no evaporation occurred between cloud base and the ground, each of these two relatively small cumulus clouds would have produced the equivalent of about 15 acre feet of water.

Finally, we will illustrate the effects of seeding orographic clouds over the Cascade Mountains. This type of cloud is widespread and common over the Cascades in winter and offers an important potential for increasing snowfall.*

On May 16, 1977, a layer of orographic stratus cloud was present over the western slopes of the Cascades. Seeding commenced at 1211 PDT as the aircraft flew in and out of the cloud tops at about 10,000 ft (-5°C). Dry Ice was dispersed at a rate of 2.5 lbs per minute. A sequence of airborne measurements of cloud liquid water content, cloud droplet concentrations and ice particle concentrations are shown in Figs. 11 and 12. Apart from one region (between the arrows), the measurements shown in Fig. 11 were made in unseeded clouds. It can be seen that in the unseeded regions the liquid water content fluctuated between about 0 and 0.6 grams per cubic meter of air and the ice particle concentrations were very low. However, additional measurements (not shown in Fig. 11) showed that there were very few large (precipitable

* The University of Washington's Cloud Physics Group has carried out an extensive study of the structure of these clouds and their modification by artificial seeding (see the Journal of Applied Meteorology, 14, pg. 783-858, 1975).
Figure 11. In-cloud measurements of liquid water content, droplet concentrations and ice particle concentrations on May 16. The region of cloud seeded was contained between the arrows where the ice particle concentrations increased dramatically.
Figure 12. Continuation of Figure 11. Note the increasing frequency with which regions of the cloud affected by seeding (between arrows) were encountered.
particles) in the unseeded clouds. The first seeded portion of cloud was encountered in the region indicated by the arrows in Fig. 11; it can be seen that in this narrow (1.5 km) region the ice particle concentration increased dramatically. At later times (Fig. 12) regions of the cloud affected by the seeding were encountered with increasing frequency (indicated by the sharp increases in ice particle concentrations); in these regions the concentrations of large precipitable particles were ten to forty times greater than in the unseeded portions of the cloud. By 1600 PDT large areas of the cloud were affected by the seeding and showers of moderate intensity were observed through breaks in the clouds.

It is apparent from the above discussion that significant modifications to cloud structures, and increases in precipitation-sized particles, were produced by the cloud seeding. It is likely that these modifications produced increases in precipitation on the ground, although this cannot be proved scientifically from the data collected in this operational program.
SECTION 4

DROUGHS IN WASHINGTON STATE AND THE POTENTIAL ROLE OF CLOUD SEEDING IN THEIR ALLEVIATION

Precipitation probably has a greater effect on the overall economic well-being of the Pacific Northwest than any other single factor. Eighty-two per cent of the energy supply for the region derives from (relatively cheap and clean) hydroelectric power, the great agricultural areas east of the Cascades are almost entirely dependent upon irrigation, the forests, the salmon runs, and the domestic water supplies are likewise dependent on adequate precipitation.

The relatively low precipitation in Washington in 1976 sent a shudder through the region. What would be the cumulative effects of several years of drought? Since it is impossible to forecast future droughts, we should view the problem on an actuarial basis by looking at the historical precipitation record. Figure 13 shows the precipitation record for Seattle back to 1878 (Seattle has been chosen for illustration, but other sites in the Pacific Northwest show similar trends). It can be seen that the mean annual precipitation has varied from about 39 inches, in the decades 1878-1887 and 1966-1975, to only 27 inches in the decade 1922-1931. The last twenty years have not only been unusually wet relative to previous years, but they show significantly less variation in precipitation amounts from year to year. For example, during the period 1921-1930 there were seven years in which the annual precipitation in Seattle was less than that for 1976. Clearly, viewed strictly from an actuarial basis, the Pacific Northwest should plan for much drier conditions than have been experienced in the last two decades.
Figure 13. Annual Precipitation (vertical lines) and Ten-Year Running Mean Precipitation for Seattle for the period 1880-1976.
Management of the region's water resources is, of course, a complex and multifaceted problem. However, precipitation augmentation by cloud seeding could become an important component in an overall water management strategy. If it were firmly established that cloud seeding was capable of increasing precipitation by a certain amount, cost-benefit studies could be carried out. If these studies show that under certain conditions cloud seeding would be beneficial, operational programs could be set up at key locations (e.g., the watersheds of important rivers, the reservoirs for hydroelectric facilities and city water supplies). Cloud seeding could then be carried out in these critical areas whenever the total precipitation for the time of the year fell below average. In other words, cloud seeding could be carried out as needed in an effort to maintain the precipitation close to the historical average and thereby smooth out the wilder year-to-year fluctuations.

At this juncture we do not know by how much precipitation can be increased by cloud seeding in various regions of Washington State. The Cloud Physics Group at the University of Washington has carried out detailed physical studies of the effects of seeding on winter storms in Western Washington which indicate that it should be possible to increase and redistribute snowfall across the Cascade Mountains (see reference on page 20). However, a statistical study of the effects of seeding on precipitation on the ground has not been carried out.

Now is the time to design and implement a demonstration cloud seeding project in Washington State to determine through both physical
and statistical techniques the effects of seeding on precipitation. Such a project has been proposed by the University of Washington and is now under consideration by the Washington State Department of Commerce and Economic Development.
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