Planned and Inadvertent Weather Modification Research at the Cloud and Aerosol Research Group at the University of Washington: 1963-2005

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Abstract: We present many of the contributions of the Cloud and Aerosol Research Group over the past 40 years, clustered by topics, and in chronological order, beginning with the establishment of the Cloud Physics Laboratory (later renamed the Cloud and Aerosol Research Group). We confine ourselves for this *Book of Achievements* to brief reviews of those studies most directly relevant to the field of weather modification, including anthropogenic aerosol measurements that impact clouds and precipitation development, cloud seeding trials with dry ice and silver iodide, and the discovery of inadvertent production of ice in moderately supercooled clouds by aircraft. Lastly, we enumerate the reanalyses of and commentaries on published cloud seeding literature that began in 1978, the latter two subjects the particular province of Award winners, *Peter V. Hobbs* and *Arthur L. Rangno.* We dedicate this paper to the memory of *Peter V. Hobbs*.

1. Introduction

For more than 40 years *Peter Victor Hobbs* was the mentor, leader, editor par excellence, and colleague for the Cloud and Aerosol Research Group (CARG, University of Washington, Seattle, USA). He succumbed to cancer recently while still deeply engaged in the atmospheric sciences that he so enjoyed and so influenced. Our intentions as the authors of this article are to compose a manuscript meant to encapsulate his and his Group's contributions to the field of planned and inadvertent weather modification, a field in which those contributions were numerous and had wide impact.

There is no better way to preface a discussion of the extensive and far-reaching research in planned and inadvertent weather modification of *Peter V. Hobbs*, *Arthur Rangno,* and CARG than to quote from the citation accompanying the UAE Prize for Excellence in Weather Modification (2005). *Hobbs* and *Rangno* received this honor "in recognition of their conscientious application of physical principles to weather modification."

"They brought to attention three major cloud processes which also influence the results of cloud seeding: the role of dust from remote regions of the world, the role of cloud condensation nuclei released by paper mills and similar sources, and the modification of aerosol by cloud cycling. The Cascades Project was a leading experiment in its day for combining in situ observations, remote sensing, and cloud modeling for assessing the precipitation enhancement potential in orographically induced clouds. Their re-analyses of other projects, even if still controversial, brought into focus the need and benefits of independent evaluation.

"As one of the supporting letters said: '*Peter Hobbs* and *Arthur Rangno's* research on weather modification set some much-needed higher standards in the science of weather modification that persist today. Their research in cloud physics and cloud dynamics were the pioneering works that many of us adopted in our research work in attempting to assess impacts of cloud seeding on precipitation reaching the ground.'

"Their proposals to conduct further evaluations of advertent and inadvertent weather modification processes and findings can be expected to provide yet other unexpected stimuli to the quest for understanding and improving cloud seeding experiments."

This paper describes the formation and the accomplishments of CARG, led by *Peter V. Hobbs*, below in the areas of aerosols and their effects on clouds, cloud seeding experimentation, inadvertent cloud seeding by aircraft, and the long period of commentaries and reanalyses by the team of *Hobbs* and *Rangno* over the past 30 years.

2. The founding of the University of Washington's Cloud Physics Laboratory (1963), later renamed the Cloud and Aerosol Research Group

Professor *Phil Church*, founder of the University of Washington's Department of Atmospheric Sciences, recognized the critical role of experimental cloud physics and wrote a successful proposal to the National Science Foundation that allowed him to hire a new faculty member. After consultation with *Peter V. Hobbs'* dissertation supervisor, *Sir B. John Mason*, *Church*

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offered *Hobbs* a faculty position at the University of Washington, the role of Co-Principal Investigator on his grant, and an empty classroom for a laboratory.

3. Aerosols and their effects on clouds

3.1 *Hobbs'* first graduate students arrived and research in ice and aerosol physics began both in the laboratory and in the field. Their research focused on cloud-forming aerosols (1964–1968).

The newly organized Lab branched out to conduct its first field program headquartered on a rocky ledge of the upper slopes of Mount Olympus (WA, USA). Here a small, cloud-shrouded research station, built during the International Geophysics Year, was chained to a rock facing winter's Pacific gales. Outside in a mixed phase cloud, *Hobbs* made one of his early discoveries with his student, *James Dye*. With knowledge of the number of ice nuclei as a function of temperature, and a primitive estimate of the concentration of ice crystals present in the cloud he was immersed in at that moment, *Hobbs* exclaimed, "There are too many ice crystals!" Later, *Hobbs* (*1969*) reported these anomalous occurrences and defined the phenomenon of "ice multiplication." He made the significant point that the ratio of ice particle concentrations to the expected ice nuclei concentrations based on *Fletcher (1962) decreases* as the cloud top temperature decreases, approaching a value of unity for cloud top temperatures of about -25°C. This finding helped to organize and understand the emerging phenomenon of higher ice particle concentrations than those that would be expected from *Fletcher's* summary ice nucleus curve that was beginning to be reported around the world (e.g., *Koenig 1963; Mossop 1967*). *Hobbs* pointed to drop fragmentation upon freezing and mechanical fracture of delicate ice particles, the likely dependence on the type of ice particle, and the drop size distribution as likely players in the ice multiplication phenomenon.

Later from this same lofty perch, *Hobbs* and *Radke* made their earliest cloud and aerosol interaction observations, witnessing the changes in the cloud condensation nuclei (CCN) spectra as upwind fair weather cumulus first ingests the upwind aerosol and then releases the cloud-processed aerosol as the cloud evaporates (*Radke and Hobbs 1969*). Surprisingly, these cloud-processed aerosols now had rather different nucleating properties, suggesting an evolutionary process where both CCN number and efficiency have been altered by time and cloud interactions.

These initial, in-cloud mountaintop observations had a lasting impact on the Lab's development. The group was at the weather's whim while waiting for favorable conditions to bring the desired clouds to their location. The solution to this inefficiency was obvious: acquire an instrumented aircraft! Initially the University of Washington resisted acquiring an "Air Force" and

Figure 1. The Douglas B-23 Dragon. This old warrior, stronger cousin to the C-47 and DC-3, survived WWII, Hollywood filmmakers, an onslaught of scientists and students, and more than 1300 research missions in bad weather before retiring to a USAF museum.

Figure 2. The Convair C-131A, 1950's airliner, CV-240, later converted to medical evacuation, "Samaritan." Like the B-23, it was sturdy and amenable to modification. Sadly, it was driven from the air by its thirst for high-octane leaded gasoline.

Figure 3. The Convair CV-580 propjet carried researchers into the jet age, higher altitudes, the Arctic, Equatorial Pacific, and Africa before being doomed by declining budgets and shifting priorities.

the Lab settled for renting a large single-engine aircraft, piloted by *Robert Spurling*, to continue observations of natural and anthropogenic CCN sources. In 1970, the University decided it needed its own aircraft, and cloud and airborne research took center stage at the University of Washington. The three aircraft that provided the airborne measurements described in this paper over the ensuing 30 years is shown in Figures 1-3.

Effective use of a meteorological research aircraft requires that the aircraft crews are aware of their position within the hemispheric panorama of the sky. This was provided on each of the aircraft by a 360° viewing dome, large enough for head and camera on the top of the fuselage. *Rangno* and others made exceptional use of this perspective to watch the evolving character of the individual natural life cycle of clouds and the artificial modification of the cloudscape. Confident visual and instrumental identification of the treated clouds "before and after" cloud physics proved critical to the rapid progress in developing physical assessment tools for CARG's weather modification studies.

3.2 Aerosols and their effects on clouds: airborne studies

In the course of the early airborne work CARG found a number of unexpectedly large CCN sources. Several of these sources were observed, on occasion, to rapidly initiate precipitation in low-lying stratocumulus. Teaming with the Washington State Climatologist (*Hobbs et al. 1970a*) report that the CCN sources appeared to be the cause of higher precipitation downstream relative to background values. This apparent case of inadvertent weather modification naturally sparked interest within and outside the Lab (e.g., *Elliott and Ramsey 1970)* regarding the reality of such changes and the mechanism involved; simply increasing the CCN concentration at cloud base seemed unlikely to have produced significant precipitation increases. However, *Eagan et al.* (*1974*) found, surprisingly, that downwind from a large Kraft paper mill in western Washington that higher concentrations of CCN particles produced by the mill were, in fact, associated with clouds having a *broader* droplet spectra than those clouds outside of the plume. They attributed this to the large sizes of some of the CCN emitted in the plume. Later, *Hindman et al.* (*1977*), following up on this finding, calculated that the concentrations of very large CCN were too low to have altered precipitation efficiently.

Eagan et al. (1974) also sampled the effect of forest fires on cloud structure and found the opposite effect. Forest fires emitted as many as $6x10^{10}$ CCN per gram of wood and debris consumed and CCN concentrations were still about 10-20 times higher than background CCN about 40 km downwind from the fire. Correspondingly, droplet concentrations in small cumulus clouds were two to five times higher than in similar clouds outside of the smoke plume. Considerably narrower drop size distributions were observed in smoke-laden clouds compared with natural clouds in the vicinity. The large size tail of the droplet spectra in adjacent clouds was generally 20-25 μm diameter, while in the smoky clouds it was only about 15 μm.

3.3 *Hobbs and Locatelli* (*1970*) reported on ice nucleus measurements at three sites in Washington State.

Hobbs and Locatelli found that ice nuclei are higher in urban regions and lower in rural and coastal locations except when the wind at the rural and coastal locations is from urban areas.

3.4 *Hobbs et al. (1980)* found a land version of the shiptrack in coal-fired power plants emitting plumes into marine stratus clouds.

Hobbs et al. found that the emissions of coal-fired electric power plants had different effects depending on the type of cloud present. When the sulfur-laden plumes were ingested into low stratiform clouds, such as stratus and stratocumulus clouds forming in clean, maritime conditions, the plumes from the power plant produced a long-lived, high droplet concentration region that infected the clouds for many kilometers downwind, a phenomenon similar to that observed with ship tracks. On the other hand, when convective clouds were present, the plume produced a much less detectable signature on droplet concentrations and on the drop size distribution; they were little changed from the natural variations observed.

3.5 *Bowdle et al.* (*1985*) reported on the aerosol background conditions in the High Plains of the United States in the context of the High Plains Experiment cloud seeding studies.

Bowdle et al. found that relatively large aerosol particles (>10 μm diameter) were in concentrations high enough to serve roles in the formation of rain and to be tracked by radar for the purpose of measuring wind flow. They also reported that aerosol concentrations could range from "maritime" (very low) to "continental" in a region located thousands of kilometers from the nearest ocean. They also found that ice nuclei can vary drastically over periods as short as a day and reached their highest concentrations in a dust storm.

3.6 *Hegg et al. (1984)* reported on the rapid

modification of pristine maritime air masses as they penetrate inland.

Hegg et al. reported on the time required for purely maritime air to be modified by moderate sources of air pollution in western Washington State and found that an equilibrium developed on the order of 100-200 kilometers of travel inland, and in about 5-15 hours. These distance and time scales showed that overall modification of pristine air masses and their clouds was relatively rapid compared with some assumptions made concerning the stability of air masses in long-range transport situations.

Rangno and Hobbs (1988, hereafter RH88) reported that the temperature of initial ice formation *decreased* as the cloud droplet concentrations increased in such air mass transformations across Washington State, apparently due to the decreasing size of the largest cloud drops caused by both increasing drop concentrations and rising cloud bases.

3.7 From 1989-2000, CARG turned again to inadvertent weather modification and began a long collaboration with *Michael D. King* (NASA, Goddard) to investigate the complex optical properties of clouds under the influence of admixtures of anthropogenic aerosols.

Cloud and aerosol interactions have long been suspected as agents of climate change. *Gunn and Phillips (1957), Squires (1958)*, and *Twomey et al.* (*1984*) suggested that pollution-derived CCN could increase average cloud droplet numbers, decrease their mean size, and deter precipitation. These effects in turn would increase the short-wave reflectance of the earth, thus tending to cool the planet. *Hobbs* (*1993*) noted that estimates of such cooling effects are similar in strength to greenhouse warming effects, but opposite in sign.

Aerosol pollution in the Arctic has a variety of climate impacts. Arctic haze alters clouds in a manner that exactly mirrors those observed when ship exhaust aerosols mix upward into clean marine stratus clouds to form long-lived "ship tracks" (*Conover 1966; Radke et al. 1989; King et al. 1993*) (Figure 4). Droplet concentration increases, the optically effective droplet radius decreases, drizzle halts or is decreased, and longwave (LW) cloud emissivity increases (*e.g., Ferek et al. 2000*).

The ice pack thickness and open water fractions of the Arctic Ocean have long been suspected of being sensitive to polar cloud and surface albedo feedback mechanisms, but until recently the sensitivity of the radiation balance to cloud microphysics was thought to be modest (*Curry and Ebert 1992*). However, *Stone* (*1997*) has demonstrated unexpectedly strong links, which seasonally control surface temperature (Ts) namely, low cloudiness, the near-surface temperature inversions, and longwave downwelling (LWD) radiation. Given that some 70% of the total radiation received annually in the Arctic is LWD (*Maykut and Church 1973*), such sensitivity should perhaps not be entirely a surprise. However, recently *Garrett et al.* (*2002*) have shown a strong link between arctic haze pollution, arctic cloud microphysics, and LWD. The aerosol-induced changes in cloud microphysics are such that LW cloud emissivity can be substantially increased.

Since in the Arctic the bases of clouds are likely to be warmer than the Arctic surface much of the year (*e.g., Hobbs and Rangno 1998*), a pollution-aerosol modulated increase in LW emissivity can produce remarkable heating at the surface, especially during the Arctic winter. This largely neglected term in the global radiation budget thus becomes another aspect of inadvertent weather modification that should tend to heat the planet.

Garrett and Hobbs (1995) found, in analogy to the effects of ship tracks described above, that huge plumes of air pollution from continents can travel several thousands of kilometers over the oceans where they can have a similar direct and indirect effect as do ship tracks on the radiation balance by reducing drop sizes and inhibiting drizzle formation.

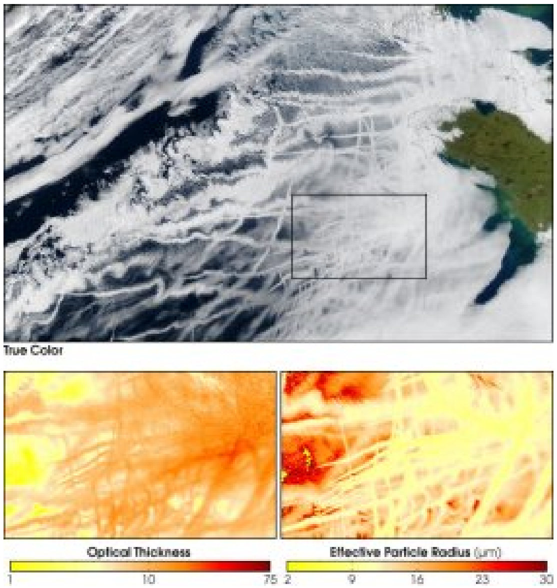

Figure 4. An exceptional number of ship tracks permeate shallow maritime clouds in the Atlantic Ocean. (Images courtesy of NASA.)

In studies of biomass burning on clouds in Brazil, *Reid et al.* (*1999*) found the unexpected result that the regional haze and smoke are so widespread and thick that narrow droplet spectra and small effective radii (r_e) of small-to-moderate cumulus clouds outside of active fires are similar to that in cumulus clouds over fires. Further, they found that the haze-infected clouds of Brazil are similar in microstructure to clouds off the Atlantic seaboard of the United States.

Finally, in summarizing the findings of the Monterey, CA area ship track experiment conducted in 1994, *Hobbs et al. (2000)* reported that the cause of ship tracks is not heat nor water vapor emitted by ships, but rather particle emissions, particularly those associated with low-grade fuel oil.

3.8 Super-large raindrops were encountered by *Hobbs and Rangno* (*2004*) and with them, implications for hygroscopic seeding of smoke-filled continental clouds rich in liquid water content.

Hobbs and *Rangno* found "super-large" raindrops of about 1 cm diameter falling from clouds in two markedly different microstructural situations (Figure 5). One, in the Marshall Islands, was in a very pristine aerosol environment similar to a situation in Hawaii in which giant raindrops were found (*Beard et al. 1986*).

However, in the second situation, giant drops were encountered while the aircraft was "orbiting" and preparing to take smoke samples below the base of and near a fire-enhanced "pyro-cumulus" congestus cloud. The tops of this pyro-cumulus were estimated by eye to be near the freezing level. In this pyro-cumulus, the clouds contained some ashes, high cloud droplet concentrations ($\geq$900 cm^{-3}), and high liquid water content, about 3 g m^{-3} near the freezing level, estimated from other cloud penetrations at that top height on this day.

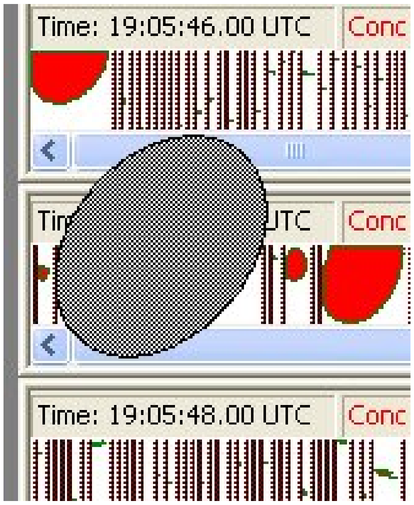

Figure 5. The drop whose maximum dimension was 10.1 mm as determined by a convex-hull–ellipse fit algorithm (*Wilson et al. 2006*). The drop, among several of extraordinary size, fell from a pyro-cumulus congestus cloud over a fire in Brazil (*Hobbs and Rangno 2004*).

The giant drops that fell from this cloud are interpreted as strong indications of the response that highly polluted clouds might have to the introduction of giant hygroscopic or "mechanical" collectors (such as ash particles may have been). This finding supported the speculations of "ash seeding" by *Andreae et al.* (*2004*).

4. Cloud Seeding Experimentation

In 1970, *Hobbs* and his group are asked by the US Bureau of Reclamation to reorganize one of their pilot cloud seeding programs whose execution is becoming increasingly problematic. The Cascade Project is born.

4.1 *Hobbs et al.* (*1973*) and *Fraser et al.* (*1973*) formulated the theoretical and physical basis for a cloud seeding experiment designed to shift snowfall from the west side to the east side of the Cascade Mountains of Washington State.

In these two companion papers, *Fraser et al.* laid out the airflow and fallout of solid precipitation over an idealized mountain range and then adapted it to the terrain profile presented by the Cascades. *Hobbs et al.* then calculated the trajectories of individual particles based on model projections of condensate, riming, and aggregation. *Hobbs et al.* concluded that increases in ice-particle concentrations ranging between 1 and 100 per liter are sufficient to cause precipitation to be shifted to the lee side of the Cascades.

4.2 Results of the *Hobbs*-led Cascade Mountains glaciogenic cloud-seeding experiments (1970-1973) reached the journals.

From 1969 to 1974 CARG carried the Cascade Project to determine the structure of winter clouds and precipitation over the Washington Cascade Mountains, and what the effects of artificial seeding with silver iodide and dry ice were on the clouds and precipitation in this region. The motivation for this project was the possibility that, by decreasing the riming on snow particles falling close to the Cascade crest, additional snow could carry over to the east side of the crest where it would increase the snow pack used for summer crop irrigation in eastern Washington.

The B-23 seeded stratocumulus and cumulus clouds upwind of the crest at a location where it was calculated that the ice crystals created by seeding would fall out on ground observers in the target area. The time that the seeding-created plume of ice crystals (Figure 6) would reach the observers on the ground was predicted by the aircrew. On many of these occasions the riming on the snow particles falling on the target area decreased, the crystal type changed (i.e., graupel was replaced by unrimed stellar and dendritic ice crystals), and the number of freezing nuclei in the snowfall increased. The silver content in the snow also increased. Concurrent with the changes observed in the target area, the aircraft measured increased concentration of ice crystals in the seeded clouds. Some ground stations also measured increases in snowfall during the seeding effect.

It was determined that under the right conditions (westerly airflow producing relatively simple orographic clouds), snowfall across the Cascade Mountains can be successfully redistributed by artificial seeding from aircraft.

Several detailed reports were published in 1975 about the Cascade Project. These are enumerated below.

4.3 *Hobbs and Radke* (*1973*) demonstrated that redistributing snowfall was possible in a field trial by overseeding an orographic cloud layer that caused a reduction in riming and increased the concentration of ice particles.

In this benchmark case study, all of the physical linkages for this experiment were documented: from the moment of seeding, to the crystals that were produced, to their arrival on the ground, a unique event. The smaller, slower falling, and more numerous ice particles in the seeded plume were carried farther downstream before they could reach the surface. In typically disinterested prose, *Hobbs* and *Radke* end their paper by pointing out that in spite of the stunning success they are reporting, there have also been many failed attempts doing the same thing on other occasions.

4.4 *Hobbs and Weiss* (*1975*) reported on the results of using a vertically pointed, Dopplerized radar for the detection of changes in the fall speeds of precipitation particles before, during, and after seeding plumes pass overhead.

This was the first time that a vertically pointed radar was used to look at the growth processes of precipitation and cloud seeding signatures simultaneously. *Hobbs* and *Weiss* documented the passage of seeding plumes that passed overhead and found that the ice particle fall speeds were markedly reduced.

4.5 *Hobbs* (*1975a*), in Part I of a three-part series on the Cascade Project, reported on the many aspects of the natural orographic precipitation in the Cascades.

The major findings included the change from unrimed to rimed ice particles following frontal passages, that maximum ice-particle concentrations were often much higher than can be explained by ice nuclei concentrations, that the growth of particles was fastest in the last kilometer of fall, and that snow particles reaching the ground began to fall from as close as 10 km to as much as 100 km upwind.

Figure 6. Supercooled stratocumulus seeding during the CASCADE Project often produced spectacular ice crystal optics such as these parhelia and subsun.

In Part II, *Hobbs and Radke* (*1975*) detailed the methods and experimental techniques used and presented tabular data obtained in these unique seeding trials.

In Part III, *Hobbs* (*1975b*) described the results of several of the seeding trials in detail. In these extensively analyzed case studies, all or nearly all of the physical linkages are documented with radar and ground measurements from the natural cloud's initial state to the final state reached after seeding as described in Part I above.

4.6 *Hobbs et al.* (*1980*) reported on the extensive studies of natural clouds near Miles City, Montana, as a part of the High Plains Experiment (HIPLEX).

Ninety-three cumulus clouds with supercooled tops that were grouped into three broad categories formed the basis for findings reported for natural clouds in HIPLEX: small cumulus, cumulus complexes including cumulonimbus clouds, and embedded cumulus clouds with attendant stratiform layers. Small cumulus clouds had generally narrow drop spectra and little ice (<1 per liter), embedded clouds had somewhat more ice (generally 1-10 l^{-1}) and more liquid water content, and complexes of cumulus clouds have appreciable ice (>10 per liter) and the highest liquid water content (in separate regions). Droplet spectra were broadest in complexes and in embedded cumulus clouds. Liquid water content was as high as several grams per cubic meter in updrafts in complexes.

The major findings were that “maritime” droplet conditions often occur, and these situations help contribute to ice multiplication in these clouds, that ice concentrations generally increase with time, that most of the ice is located in downdrafts, and that cloud lifetime determines whether a cloud produces rain.

Hobbs and Politovich (1980) in a related study concluded from their comparisons of natural and seeded clouds that the seeding of small and embedded cumulus clouds offer the best targets for enhancing precipitation.

4.7 *Hobbs et al.* (*1981*) reported on a unique method of detecting cloud seeding signatures in layer clouds.

This benchmark experiment described what may be the only way in which cloud-seeding effects can be reliably assessed in a rapid manner. In these experiments, an aircraft was used to seed with dry ice in lines perpendicular to the wind and upstream of a vertically pointed, millimeter wavelength radar. The aircraft, measuring winds at the release level, cloud properties, and calculating the growth and fallout times of crystals nucleated by artificial seeding, was able to pinpoint when a “seeding line” would pass overhead of the radar (Figure 7). While the *Hobbs et al.* experiment was not randomized, it demonstrated how powerful such an experiment could be in a randomized setting. Many experiments could be accomplished in a few hours or less when stratiform cloud decks are likely to be relatively constant in microphysical properties. Variability of clouds had long been a bugaboo of seeding experiments with longer time units.

The experimental technique described by *Hobbs et al.* was subsequently adopted as a method of detecting seeding effects in the large Sierra Cooperative Pilot Project.

4.8 *Locatelli et al.* (*1983*) reported on a unique cloud seeding experiment that compared the results of natural seeding of a slightly supercooled stratocumulus layer by fallstreaks from a higher, separate layer with seeding by dry ice.

Locatelli et al. found that the precipitation rate at the ground was highest (about 0.10 mm h^{-1}) in the portions of the stratocumulus where dendrites in a fallstreak from an altocumulus layer were naturally rimed in and fell out of the stratocumulus deck. The seeded region of the stratocumulus deck produced higher precipitation rates (0.01 to 0.03 mm h^{-1}) than the non-seeded region not affected by fallstreaks (0.01 mm h^{-1}). However, they calculated that glaciating a lower stratocumulus layer via seeding would inadvertently *decrease* precipitation when the lower layer had been providing riming for ice crystals falling into it.

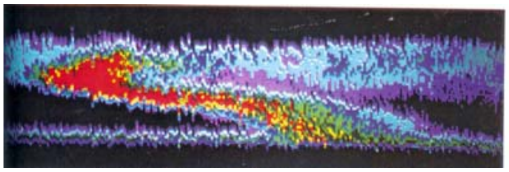

Figure 7. A 0.8-mm wavelength vertically pointed radar return about 40 minutes after the seeding of a thin and largely nonprecipitating altocumulus layer at 2.5 km above sea level (echo movement is toward the left). The heart of the seeded region is shown by the echo in red. The width of the echo head is about 1 km.

5. Inadvertent cloud seeding: The production of ice particles by an aircraft in moderately supercooled clouds

This benchmark discovery by *Rangno and Hobbs* (*1983,* hereafter *RH83*) that ice particles in concentrations of hundreds per liter could be produced by an aircraft flying in supercooled clouds as warm as -8°C came as a shock to the airborne research community. Many in that community had been repenetrating supercooled clouds with aircraft in the High Plains Experiment and in the Cooperative Convective Precipitation Experiment in the United States; it was possible that their work had been compromised. In fact, the paper was so controversial it was rejected twice! (*B. Silverman*, co-chief editor, *J. Clim. Appl. Meteor.,* personal communications, 1982.) The paper was accepted only after a third submission when more corroborating evidence was developed, including photographic evidence from another journal of an ice canal in altocumulus clouds produced by a jet (*J. Locatelli,* personal communication, 1982).

Within a few months of the publication of *RH83, Rangno and Hobbs (1984),* while flying the aircraft in a quiescent layer of wintertime supercooled, “fair-weather” stratus cloud in eastern Washington near an airport, intercepted high concentrations of rather uniformly sized ice particles in a very localized region of the cloud. A subsequent investigation placed a turboprop aircraft very near this spot.

The *Rangno* and *Hobbs* articles in 1983 and 1984 launched a number of workers in various universities and laboratories (*e.g., Foster and Hallett 1993*) into a flurry of studies to try to confirm the *Rangno* and *Hobbs* findings and their cause. It was soon verified that ice particles could indeed be produced in moderately supercooled clouds by other kinds of aircraft, not just the University of Washington’s B-23. The most thorough confirmatory studies were carried out by *Woodley et al. (1991, 2003).*

The impact of the *Rangno* and *Hobbs*

findings can be appreciated in the *Woodley et al. (2003)* article that began, "Considerable progress has been made in documenting and explaining the existence of aircraft-produced ice particles (APIPs) since they were first brought to the attention of the scientific community by *Rangno and Hobbs (1983, 1984)."*

This discovery changed the way that supercooled clouds were sampled by aircraft when they repenetrate clouds for the sake of life cycle studies. In turn, it meant that some past studies of supercooled natural clouds that had been repenetrated by an aircraft were likely contaminated by APIPs. Researchers now must be careful that their aircraft do not produce APIPs when sampling supercooled clouds (Figure 8).

Figure 8. A canal of ice crystals produced by a long aircraft traverse rends a supercooled layer of altocumulus clouds over Seattle, Washington, USA.

It is also likely that some randomly chosen control clouds in cumulus cloud seeding experiments that were sampled by aircraft were inadvertently seeded with APIPs. For example, in the Florida Area Cumulus Experiment II 1973 season, the supercooled cloud turrets randomly selected as control clouds against which the seeded clouds were to be compared, were flown through with a four propeller C-130 aircraft, an aircraft associated with APIPs.

Recently, holes in clouds caused by APIPs have been detected in satellite imagery over the southern United States (*Sealls 2004*).

The *RH83* findings also demonstrated that cloud seeding can take place without having to use chemicals since it is presently believed that this effect is caused by a large drop in temperature associated with the expansion of air at the tips of the propellers (e. g., Woodley et al 2003).

6. Reanalyses and commentaries on cloud seeding

6.1 Following the successful completion of the Cascade Project, *Hobbs* offered his personal views on weather modification in *Sax et al. (1975).*

Hobbs, asked to offer his personal viewpoint on weather modification by *Sax et al.,* expressed optimism about the future of weather modification and reflected on the conclusions of the National Academy of Sciences (NAS) Panel on Weather Modification (1973) of which he took part. He noted that evidence was mounting that snowfall can be increased on a determinate basis in orographic clouds and that in one "well-designed" cumulus cloud seeding experiment, increases in rainfall had been documented.

Hobbs emphasized that significant further progress would depend on the best theoretical models available for describing the cloud systems to be experimented upon, comprehensive physical evaluations, and carefully designed randomized statistical experiments.

6.2 The reanalysis of the Skagit cloud-seeding project in 1978.

The Skagit Project (*Hastay and Gladwell 1969,* hereafter *HG69*) was deemed to be one of the better designed nonrandomized cloud seeding projects (*NAS 1973*), and one that showed extremely encouraging results. The probability that the increases in runoff reported in two consecutive seasons of seeding (the duration of this project) were due to chance could be rejected at p=0.01. The Skagit Project was also cited by *NAS (1973)* as having produced strong evidence that orographic precipitation had been increased due to cloud seeding.

Undaunted by these assessments, *Hobbs and Rangno (1978),* in the context of a design of their own cloud seeding experiment in the Cascade Mountains of Washington State, looked closer at the two-season Skagit experiment as reported by *HG69* to see what they could learn from it.

The re-examination of the Skagit Project brought out the unexpected facts that the same seeding effects reported for the target river were also seen over wide "side-wind" and upwind watersheds in Washington State. These findings indicated that the original authors had been misled by a Type I statistical error ("lucky draw") in their post-facto selection of control runoffs.

It was learned from this reanalysis that it is possible, even when having extremely high historical correlations between target and control river runoffs (in this case, r=0.98), that such correlations can nevertheless be upset during unusual weather regimes. Also, it emphasized the crucial need to declare control variables in advance of seeding experiments, which was not done in this case.

6.3 The Wolf Creek Pass randomized cloud seeding experiment in southwest Colorado was reanalyzed by *Rangno (1979).*

This experiment was the third of three stunning randomized cloud seeding successes reported by scientists at Colorado State University in the late 1960s and early 1970s.

In the Wolf Creek Pass experiment, randomized by entire winter seasons, the goal was to see if cloud seeding could produce measurable increases in runoff in three target rivers draining from Wolf Creek Pass. The answer appeared to be an unequivocal "Yes" when post-experiment analyses yielded probabilities of 0.01 that the large increases found for the target river runoffs for each of the three seeded seasons were due to chance (*Morel-Seytoux and Saheli 1973*). As in the case of the Skagit Project, the target and control runoffs used were extremely well correlated in the pre-experiment historical period (r=0.97).

Not convinced by these findings, *Rangno* undertook his first "deconstruction" of a cloud seeding experiment (begun in 1975) by reanalyzing this one. The reanalysis demonstrated that a wide area of southwest Colorado, southern Utah, northeast Arizona, and northern New Mexico exhibited similar or larger "increases" in precipitation and runoff in the seeded seasons, as did the three target rivers when measured against the same controls used by the experimenters. This meant that a Type I statistical error or "lucky draw" had occurred and caused the misperception of a seeding effect by the experimenters.

This paper also reinforced the need to declare control variables in advance of cloud seeding experiments which was not done in this experiment.

Evidence was also presented in this paper that some of the fundamental assumptions made by the experimenters about the meteorology of their three experiments were flawed.

6.4 *Hobbs and Rangno (1979),* following up on the weaknesses in the physical linkages underlying the Wolf Creek Pass cloud seeding experiment, showed that the three physical cornerstones of the acclaimed Climax, Colorado daily randomized cloud seeding experiments were also invalid.

The two sets of daily randomized cloud seeding experiments at Climax, Colorado, were highly acclaimed as scientific successes (*NAS 1973*). Why? Because there appeared to be strong physical arguments that linked the properties of the clouds in both experiments that were seeded with the statistically significant results that were achieved on the ground on some seeded days. The three physical cornerstones of the experiments in Colorado were:

1. The clouds were often low in ice particle concentrations, and those concentrations, in turn, were well predicted by cloud top temperature.
2. Cloud top temperatures at Climax could be reliably known by knowing what the 500-hPa temperature was (*Grant and Mielke 1967*). These 500-hPa values could be obtained from nearby rawinsonde stations. This allowed the experimenters to "back out" cloud top temperatures from 500-hPa temperatures. They reasoned that stratifications by 500-hPa temperatures (interpolated for Climax from adjacent rawinsonde stations) might reveal differential-seeding effects based on "cloud top" temperatures using the 500-hPa temperatures as proxies. Such stratifications by 500-hPa temperatures indicated that precipitation was being increased by 50–100% when the 500-hPa temperature was $\geq$-20ºC.
3. Precipitation-per-day curves for the *control* days of Climax I and II showed a sharp decrease in amounts per day that began at a 500-hPa temperature of -20°C (e.g., *Grant and Kahan 1974*). The experimenters interpreted this finding as further evidence that cloud tops were near the 500-hPa level. As the "cloud tops" warmed above -20°C, they reasoned, they no longer were efficient producers of precipitation. The sharp roll off demonstrated that the clouds needed artificially introduced ice crystals to increase precipitation efficiency.

Strongly supporting these interpretations by the experimenters was that the precipitation-per-day curves for the *seeded* days in Climax I and II did NOT show a decrease in precipitation-per-day at temperatures above -20°C. They thought this increase was surely due to seeding on those days.

As persuasive as these arguments were, *Hobbs* and *Rangno* (*1979*) showed that all of these cornerstones were illusory. These findings, along with the retraction by *Mielke* (*1979*), provided the downfall of the once-acclaimed Climax randomized cloud seeding experiments, earlier cited by the *NAS* (*1973*) as having "demonstrated" cloud seeding efficacy on a "determinant basis."

6.5 *Rangno and Hobbs* (*1980a*) critiqued the Colorado River Basin Pilot Project analyses of *Elliott et al.* (*1978*).

Elliott et al. (hereafter "*E78*") summarized the results of cloud seeding in the daily randomized Colorado River Basin Pilot Project (CRBPP). The CRBPP was conducted in the same region as the Wolf Creek Pass experiment. *E78* found no statistical difference between precipitation on seeded and non-seeded days as they were selected in the CRBPP. However, in *a* *posteriori* analyses, they found that positive seeding effects may have been achieved in groups of 6-h blocks with cloud tops >-29°C.

Rangno and Hobbs (hereafter *RH80a*) took issue with many of the descriptions of both Climax experiments, on which the CRBPP was based, and the description of the experimental design of the CRBPP made by *E78.* For example, *E78* stated that the Climax I and II experiments "demonstrated the significance of cloud top temperature in relation to the effects of seeding." *E78* was in the unfortunate position of not knowing that in the following year (1979) the experimenters themselves would retract the results of the experiments at Climax (*Mielke 1979; Grant et al. 1979*) and also state that they really did not know what the cloud top temperatures were in their experiment, a point also made by *Rangno* (*1979*).

An important facet of the *E78* paper was to take into account inadvertent, carry-over seeding effects on precipitation from control days that followed a seeded day, a plausible remedial act at first glance since carry-over seeding certainly did occur. However, *RH80a* demonstrated that *E78* had not taken into account the synoptic settings that caused two consecutive days to be randomly drawn in the first place and how heavy natural precipitation was likely to occur at the beginning of any second of two randomly drawn days in a row. For example, *RH80a* showed that a control day followed by a control day also exhibited heavy precipitation in the first 6h of the second experimental day. *E78* had automatically assigned the first 6-h block of a control day that followed a seeded day as also "seeded", thus improving the case for seeded periods while greatly diminishing the control day's precipitation. Further, it was not explained by *E78* why turning off the seeding generators at the end of a seeded day had produced such a large effect on precipitation while having them running during the normal course of the seeding trials in the rest of the experiment had not!

6.6 The lessons learned from the reanalyses of past cloud seeding experiments are summarized by *Hobbs* (*1980*) in Clermont-Ferrand at the third WMO Scientific Conference on Weather Modification.

Hobbs reviewed the recent reanalyses and revelations regarding the Climax and Wolf Creek Pass experiments and observed that the cornerstones on which the credibility of those experiments were built were made of sand. *Hobbs* cautioned that one should accept the results of cloud seeding experiments only if the physical foundations and statistical evaluations have been "independently" (*Hobbs*' emphasis) checked and replicated.

6.7 *Rangno and Hobbs* (*1980b, 1981*) critique "Generalized Criteria for Seeding Winter Orographic Clouds".

Rangno and Hobbs (*1980b*) dissected the meta-study of cloud seeding effects for several projects compiled by *Vardiman and Moore* (*1978,* aka, "Monograph No. 1" from the Bureau of Reclamation). They found several flaws. Skeptical Bureau of Reclamation scientists, working with *Vardiman* and *Moore,* also independently found critical flaws and the paper was retracted (*Rottner et al. 1980, 1981*). The exchanges between *Rangno* and *Hobbs* and *Rottner et al.* were deemed important enough that they were the subject of an editorial by the co-chief editor of *J. Appl. Meteor*. The *Vardiman* and *Moore* paper (hereafter *VM78*) has not since been cited in support of cloud seeding effects to our knowledge. The results from the *VM78* study were praised in *Weather Modification by Cloud Seeding* (*1980*), a book from Academic Press by *Arnett Dennis*, because it was published before the problems with *VM78* were discovered.

6.8 *Rangno* (*1986*) was assigned a topic in an AMS monograph entitled, "Precipitation Enhancement—A Scientific Challenge", edited by *R. R. Braham, Jr.*

In "How good are our conceptual models of orographic cloud seeding?", *Rangno* described the many complexities associated with the execution of the Colorado River Basin Pilot Project (CRBPP), carried out between 1969-1975. The CRBPP was going to be a showcase randomized cloud seeding experiment on simple wintertime orographic clouds, but instead it suffered unexpected cloud complexities and other phenomena, such as barrier-blocked wind regimes, that caused fluctuations in operating criteria that ultimately doomed the experiment.

6.9 *Rangno and Hobbs* (*1987*) reevaluated the Climax I and II cloud seeding experiments using NOAA-published data. The use of the NOAA data caused a drastic decrease in the snowfall increases reported by the experimenters.

In 1987 the original workers reanalyzed the Climax experiments on several occasions beginning with *Mielke et al.* (*1981*). They reported that they had found new evidence for increases in snowfall produced by cloud seeding, increases they had previously retracted for these experiments (*e.g., Mielke et al. 1979; Grant et al. 1979*).

Rangno and Hobbs (hereafter *RH87*), in what must have been the most basic kind of "replication", went to the National Oceanic and Atmospheric Administration (NOAA) to gather the data for a NOAA recording precipitation gauge located in the middle of the Climax target area, the same data the experimenters said they had used and had highlighted because the measurements were made by an independent organization not affiliated with the experiments.

However, *RH87* found that on many days, neither the precipitation values at the NOAA gauge, the 500-hPa temperatures, nor the 700-hPa winds for the experimental days were the same as those used by the experimenters in their evaluations. When the NOAA values were used, they led to drastically reduced double ratios of 1.14 for Climax I and 1.04 for Climax II, compared with 1.32 and 1.17 respectively, reported for those experiments by *Mielke et al.* (*1981*). *RH87* concluded that the Climax II experiment did not confirm Climax I, a finding also made earlier by *Rhea* (*1983*) on different grounds.

6.10 *Rangno* (*1988*) found that clouds with tops warmer than -10ºC routinely produce rain in Israel.

This finding by *Rangno* (*1988*, hereafter *R88*), given that cloud seeding experimenters at the Hebrew University of Jerusalem (HUJ) had claimed on numerous occasions in the peer-reviewed literature that this did not, and could not occur due to the "continentality" of the clouds in Israel, was stunning and probably not given wide initial credibility.[3] Besides, it was hard to explain how the cloud microstructures reported by *R88* could have been missed by the experimenters, given their routine measurements of cloud top heights for as long as two consecutive rainy seasons (*e.g., Gagin 1980*).

If, in fact, the clouds were precipitating routinely at such relatively high cloud top temperatures (≥-10°C) as reported by *R88*, it meant that they were far more efficient as natural precipitators than was being reported by HUJ investigators over the years. This, in turn, brought into question the primary physical basis for believing that the clouds in Israel had responded dramatically to seeding in two highly acclaimed randomized cloud seeding experiments conducted earlier. For example, the experimenters had reported that seeding in one of these experiments had increased rain by almost 50% over natural rainfall when the tops of clouds were between -12° and -21°C (*e.g., Gagin and Neumann 1981*). This was because such clouds had so few natural ice particles in them and needed "seeding" to precipitate efficiently. However, clouds that naturally precipitate at cloud top temperatures greater than about -10°C are thought to have little "static" seeding potential, the kind of seeding carried out in Israel.

R88's findings, based almost solely on rawinsonde data gathered in Israel in 1986, were corroborated a few years later by aircraft measurements made by scientists from Tel Aviv University (*Levin 1994; Levin et al. 1996*).

Rangno and Hobbs (1988-herafter RH88) also deduced via comparisons with similar "continental" clouds that the clouds of Israel, as described by the cloud seeding experimenters there, are highly anomalous in their ice-forming characteristics. *RH88* offered several reasons why the seeding experimenters' cloud reports were likely in error, such as sampling narrow, isolated, and newly risen turrets too young to have formed much ice or because not enough ice fragments were counted in the reduction of continuous particle film strips that captured ice particles in Formvar. The *RH88* conclusion that something was amiss with the HUJ reports was validated by aircraft measurements a few years later (see above). A perspective on the *Levin et al. (1996)* finding of ice multiplication in the clouds of Israel was offered in *Rangno (2000)*.

6.11 Stimulated by new citations of a 10% increase in precipitation in the Climax experiments, *Rangno and Hobbs* (*1993*) delved further into these experiments.

RH87 had concluded that Climax II did not confirm Climax I as had *Rhea* (*1983*) before them. However, the "double ratios" reported by *RH87* in these experiments were 1.14 and 1.04, respectively. Thus, when these two results are averaged over the entire 10 years of experimentation, it could be (inadvertently) inferred by some, and was, that seeding might have increased precipitation by about 10%. This is because the double ratio over the two experiments was 1.10 (*e.g., Reynolds 1988*).

In a further look at the Climax experiments, *Rangno and Hobbs* (hereafter *RH93*) demonstrated, however, that an extremely large double ratio (1.37) was inadvertently "built in" to the Climax I experiment when the experimenters declared their choice of control stations against which the seeding effects were to be measured. This was done about halfway through the Climax I experiment, and virtually guaranteed a successful outcome.

Once the controls were declared, *RH93* found that there were no further indications of a seeding effect in the remaining half of Climax I (double ratio, 0.99). In the next experiment, Climax II, the double ratio was a statistically insignificant 1.04. Hence, the seeding effect of 14% found for the complete Climax I experiment by *RH87*, was *solely* due to that which

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[3] For example, a short paper that concluded that rain was falling from clouds with slightly supercooled tops as in *R88* was rejected in 1983 (*B. Silverman,* Co-chief Ed., *J. Climate Appl. Meteor*., private communication, 1983).

accompanied the choice of controls at the halfway point of the experiment. No effects due to seeding were seen again for the remaining seven and a half seasons of the two experiments combined (double ratio 1.01)!

Thus, the 10% cloud seeding effect estimated by some researchers for Climax, and surprisingly, also by the *NAS* in 2003, was not real. Rather, it was a spurious effect inadvertently embedded by experimenters when the control stations were selected.

The *RH93* study emphasized again the importance of declaring control stations or other control variables *prior* to the beginning of cloud seeding experiments.

RH93 also found that the meteorological conditions (stability, wind directions, and the great height of the -10°C level) on those days described by the experimenters as having exhibited the greatest seeding effects were, in fact, unfavorable for transport of the seeding agent toward the target area and for nucleation upwind. This *RH93* finding agreed with airborne measurements of silver iodide releases from the ground in the San Juan Mountains of southwest Colorado under similar winter conditions (*Hobbs et al. 1975*).

6.12 *Rangno and Hobbs* (*1995a*) reanalyzed both the Israeli I and II randomized cloud seeding experiments.

This "holistic" review of the two Israeli cloud seeding experiments conducted by HUJ investigators considered several factors: seeding rates, dispersion of the seeding material, cloud microstructure, and whether the results were due to favorable draws on seeded days by examining rain gauge data in neighboring countries as well as in Israel.

The conclusions reached by *Rangno and Hobbs* (hereafter *RH95a*) were that cloud seeding could not have produced the effects claimed in Israeli I and II for several reasons involving all of the factors listed above. For example, in Israeli II, the wider rainfall analyses of *RH95a* over those of *Gabriel and Rosenfeld* (*1990*, hereafter *GR90*) confirmed that extraordinarily heavy rain fell over a wide area as far north as Beirut, Lebanon and throughout western Jordan when the "North" target area was being seeded. This wider look amplifies the suggestion of a "lucky draw" on seeded days in the Israeli II North target area that was considered, but left unanswered by *GR90*. It also diminished the likelihood that "dust/haze" had interfered with seeding effects in Israeli II and caused decreases in rain in the South target area on seeded days, as concluded by *Rosenfeld and Farbstein* (*1992*). A lot more natural rain fell on control days in the South target area rather than rain having been decreased on seeded days.

6.13 *Gabriel* (*1995*) and *Mielke* (*1995*) offered critiques on the *Rangno and Hobbs'* reanalyses and prior commentaries on the Climax I and II experiments. *Rangno and Hobbs* (*1995b*) replied.

Gabriel, from his reading of the *RH93* evaluations, wondered philosophically whether the Climax experiments were valid (that is, were they executed according to a strict randomization plan that was set up prior to the experiments?). He asked questions of the experimenters and of *RH93*.

RH93 replied that they were only testing whether the experiment was conducted according to the plan the experimenters said they were going to use, and whether their assignments of the meteorological properties of the days were accurate. In both cases, *RH93* concluded that the answers to these questions were "No." And, it was these errors that misled the experimenters both about the precipitation-per-day climatology and whether a seeding effect had occurred.

Mielke (hereafter *M95*) supplied important new information about the Climax experiments. First, he acknowledged that the precipitation data used by the Climax experimenters for the main target gauge was not that of NOAA as the experimenters had asserted several times earlier (e.g., *Mielke et al. 1981*), but were precipitation amounts that were determined by the experimenters themselves from the NOAA recording gauge charts. *M95* defended this new information by making the case that the experimenters' precipitation data were more reliable than the precipitation data evaluated by NOAA personnel in Asheville, North Carolina (where all recording charts were sent in those days).

However, *Rangno and Hobbs* (hereafter *RH95b*) noted that *M95* does not address the bias in the precipitation data found by *RH87* in which the Climax experimenters' values generally aided seeded days. The null hypothesis that the differences were unbiased could be rejected at p=0.001. A further comment about the differences in the independent data acquired by NOAA in the target area in the Climax experiments and the experimenters' precipitation data was made by *Rangno (2000)* when these experiments were discussed by *Bruintjes (1999)*.

6.14 Several commentaries concerning the *Rangno and Hobbs* (*1995a*) reanalysis of the Israeli experiments reached the pages of the *J. Appl. Meteor.* in 1997. *Rangno and Hobbs* (*1997a–e*) replied.

While the debate was vigorous, well-informed and imaginative hypotheses were offered to explain some aspects of the *RH95* findings, none of the several commentaries that followed its publication (*i.e., Rosenfeld 1997; Ben-Zvi 1997; Woodley 1997; Dennis and Orville 1997*) produced solid evidence that countermanded the *RH95* conclusions (*i.e., Rangno and Hobbs 1997a-e*), that the experiments conducted in Israel were compromised by "lucky draws", had unsuitable clouds for seeding purposes, and that inadequate seeding was carried out in Israeli I.

Indeed, the *RH95* conclusions have been reinforced in recent years. *Silverman* (*2001*) found that statistical proof for increases in rainfall in the Israeli experiments was insufficient. *Levin et al.* (*1997*) used a numerical model to test the dispersion characteristics of line seeding by a single aircraft, as was done in Israeli I, and found that it was a largely inadequate technique for seeding convective complexes.

The once-acclaimed cloud seeding experiments in Israel (*e.g., Kerr 1982; Dennis 1989*) were no longer the unique, unambiguous cloud seeding successes that they were once deemed to be. We invite the reader to a careful reading of these "Comments" and "Replies", particularly RH97b.

6.15 *Hobbs* (*2001*) commented on "A Critical Assessment of Glaciogenic Seeding of Convective Clouds for Rainfall Enhancement".

Hobbs, in a few short paragraphs, summarized what the field of weather modification needed to improve its standing as a scientific discipline. He offered important cautions in the acceptance *prima facie* of published cloud seeding results based on raw data that have not been independently checked and analyzed, and reiterated his cautions of 20 years earlier (*Hobbs 1980*) that experiments not only have to have statistical results and observed physical linkages, but also must be duplicated before they should be accepted.

He also believed that the author of the paper he was commenting on had too readily cited positive results from hygroscopic seeding experiments, an act *Hobbs* considered not commensurate with a critical review of cloud seeding that the author purported to have done. *Hobbs* also pointed out the dangers of relying on radar to infer seeding effects on rainfall at the ground, as the author did, and that some of the actual events that occurred in the experiments being described required invoking new hypotheses with complex, undocumented, possible linkages not foreseen in advance of the seeding experiments.

Hobbs finished by criticizing the *AMS Statement* (*1998a*) currently in effect on glaciogenic seeding as misleading to the layperson because it implies more can be done through seeding than most scientists would agree with. He noted, too, the lack of scientific citations in the AMS Statement to support their position (*AMS 1998b*). He also asserted that much of the published literature on cloud seeding would not survive the rigors of the higher standards generally imposed on experimental science.

6.16 *Rangno* (*2006*) provided a viewpoint on the needs of weather modification from the viewpoint of a reanalyst.

Rangno offers a brief review of the recurring problems that he encountered in the reanalyses of six cloud seeding experiments. Recommendations are offered to improve the initial analyses of cloud seeding experiments before they reach the pages of journals. These recommendations include a more demanding review process for manuscripts dealing with cloud seeding results, one that would include local meteorologists familiar with the weather in the region being seeded, the mandatory declaration of controls and their installation (e.g., in upwind mountain ranges) prior to any experiment, and the mandatory presentation of results in a regional context where "lucky draws" would be immediately visible. For the long-term improvement of this field, he also recommends that it be mandatory that commercial cloud seeding projects be randomized. The author observes that if some of the earliest commercial cloud seeding projects had been randomized more than 50 years ago, we would not be having the intense debates over whether cloud seeding works today (*e.g., Garstang et al. 2005*).

7. Summary

In these findings and critiques of published works, the vigor and ideals of science were manifested. Skepticism and questioning our own findings is the foundation for progress in science, for without constantly rethinking our work we might otherwise be the embodiment of the Dark Ages, solidifying ourselves into dogma. Throughout the career of *Peter Hobbs*, and perhaps most so in the domain of weather modification, it has been that questioning and mobility of thought, his repeated emphasis on the standards needed in the domain of weather modification experimentation, that has most represented the ideals of science.

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