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REPEATABILITY OF STRONG RESPONSES IN PRECIPITATION MANAGEMENT

by

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ABSTRACT

Reported evaluations of 49 cloud-seeding projects, 35 of them randomized, yielded nearly 80 data sets categorized according to expected responses based on cloud-physics concepts. The median response in the 31 sets of cumulus congestus with tops between -10 C and -20 C was + 90%, all increases except one nil; the median response of 11 sets of cumulonimbus with tops colder than -35 C was -30%, all decreases except one nil. Other sets were smaller and mostly less consistent. Hypothetical explanations are offered, and it is concluded that, even without full theoretical understanding, cloud seeders are able to achieve consistent results in the field.

1. INTRODUCTION

All of the published weather modification evaluations of which we are aware relate either to individual projects (e.g. Crow *et al.*, 1979) or to small groups of projects selected for their relevance to some particular aspect of weather modification or cloud physics (e.g., Neyman *et al.*, 1965, 1968; Smith, 1970; Grant & Elliott, 1974; Dennis *et al.*., 1974; Vardiman and Moore, 1978). Most of the latter selections have adduced evidence from weather modification operations relating to a concept such as static or dynamic seeding (e.g. Silverman, 1984) or to a computational theory such as particle growth by collision or vapor deposition (Cooper, 1984). No publication appearing within the past quarter-century that we are aware of has attempted a comprehensive summary of weather modification reports. The purpose of the present article is to give some preliminary results of our attempt at a comprehensive survey.

In reviewing articles and reports assembled for a World Atlas of Precipitation Management Projects (Todd and Howell, 1985), we found that some projects were confined mainly to one climatically preferred cloud type, and some others classified the responses to seeding according to cloud type or according to conditions for which the predominant cloud type could be inferred. From among the reports in hand up to a certain date, we selected all the randomized scientific experiments, a total of 35, considering them to have been carefully conducted and to have produced reasonably reliable data. To these we added three projects that had been evaluated on the basis of clearly differentiated visual effects not requiring statistical evaluation, and 11 evaluated by other nonrandom (mostly target/control) procedures. We catalogued and mapped this total of 49 projects to see if there was consistency of reported response according to cloud type among projects, across geographic diversity, over the seasons.

2. THE CLOUD TYPE CLASSIFICATION

The classes of clouds reported on here are those for which we have previously arrived at expectations of seeding response based on a combination of empirical evidence and concepts rooted in our interpretation of theoretical and experimental studies of cloud physics (Todd and Howell, 1982). These classes are:

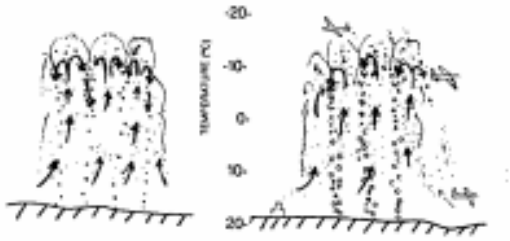


Fig. 1a. Cumulus congestus with tops -10 C to -20 C

2.1 *Convective clouds*

Cumulus congestus with cloud-top temperatures -10 C to -20 C and bases mostly 15 C to 0 C (Fig. 1a). The term Cu cong specifies clouds with hard-appearing tops, usually multi-turretted.

Depending on what meteorological data are available, these clouds are recognizable by radar echo tops at a height corresponding to the the stated temperature range; by runs of the Great Plains Cumulus Model (GPCM) based on the best available selection of aerological sounding(s); or by airplane observations of cloud-top heights or temperatures.

A subclass may be designated within this class for events with conditions suitable for strong dynamic response to seeding. This subclass may be recognized when the GPCM at 1.5 km radius indicates a cloud-top height increase of at least 500 m using the model specifications suitable for a seeded cloud.

Cumulonimbus with cloud-top temperatures colder than -35 C (Fig. 1b). The term Cb specifies a cloud of great vertical extent the top of which appears soft and usually spreads out as an anvil.

These clouds are recognizable by radar echo tops in the appropriate height range; by GPCM runs in the known or credibly inferrable presence of mesosystems (e.g. target precipitation 20 mm or more); or airplane observations.

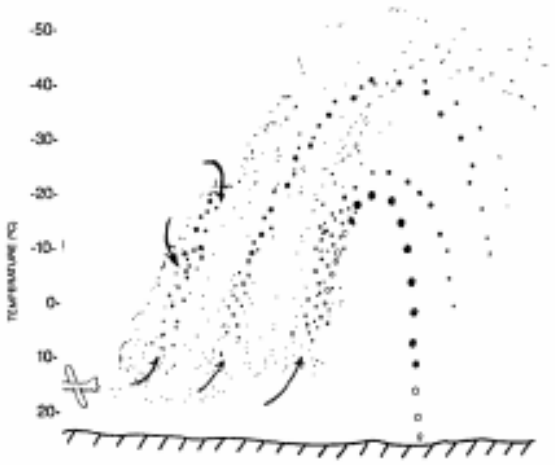


Fig. 1b. Cumulonimbus with warm bases, and tops colder than -35 C

2.2 *Stratiform clouds*

Shallow stratiform clouds without natural precipitation, with at least part of the layer supercooled (Fig. 2a).

This class is recognizable by cloud cover having no radar echo, by aerological indication of saturation below an inversion in the temperature range -5 C to -15 C, or by aircraft observation, all without reported precipitation at the ground in the absence of seeding.

Deep stratiform clouds, at least part of the layer supercooled. This cloud typically produces natural drizzle or fine rain when cloud-top temperatures are -10 C to -20 C (Fig. 2b).

This class is recognizable by weak radar echoes in the form of layers at appropriate altitudes, by aerological indication of saturation of the appropriate depth beneath an inversion in the appropriate temperature range, or by aircraft observation, all with reported drizzle or light rain at the ground in the absence of seeding.

Nimbostratus cloud, usually in connection with a warm front. This class is characterized by a deep stratiformcloud with natural precipitation in the form of light to moderate rain, sleet, or snow (Fig 2c).

This class is recognizable by radar echoes in a more or less continuous layer, sometimes multiple layers, with a bright band near the freezing level, or by aerological indication of a deep saturated layer, usually stable in parts. It is usually associated with an active warm front and with more or less widespread light to moderate rain, sleet, or snow at the ground.



Fig. 2a. Shallow supercooled stratus

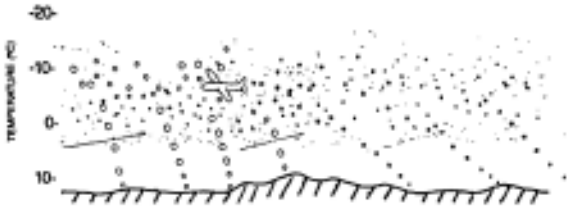


Fig. 2b. Deeper stratiform clouds, at least partly supercooled

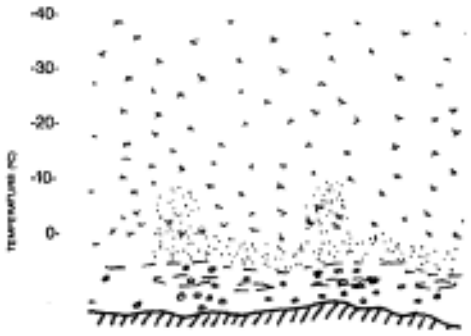


Fig. 2c. Nimbostratus with some regions of supercooled water

2.3 *Orographic clouds*

Stratus clouds, at least partly supercooled, being orographically lifted, not producing natural precipitation (Fig. 3a). This class is recognizable by the absence of radar echo or precipitation at the ground in combination with stratus cloud observed from mountains or aircraft or inferred by aerological data indicating saturation below an inversion.

Nimbostratus being orographically lifted (Fig. 3b).

This class is recognizable by the characteristics of Ns described above, the distinction being the presence of orographic lifting with local accentuation of precipitation in the region of lifting, and with light to moderate rain or snow at the ground. Identification may be aided by use of mountain-top observations, presence of light radar echoes, aerological indication of a deep saturated stable layer moving across a mountain barrier, or appropriate aircraft or mountain observations, all together with light to moderate rain or snow at the ground.

Embedded cumulus congestus emerging from a stratus or stratocumulus bed (Fig. 3c).

This class is recognizable by bands of radar echoes approaching and passing an orographic barrier, or by appropriate aircraft observations, together with periodic increases in precipitation rate and changes toward showery character at the ground.



Fig. 3a. Supercooled orographic stratus without natural precipitation

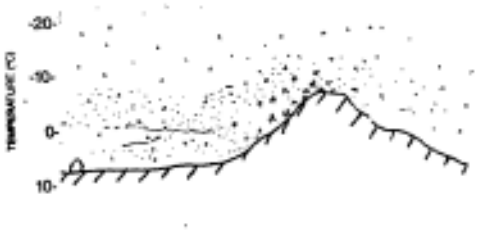


Fig. 3b. Orographic nimbostratus

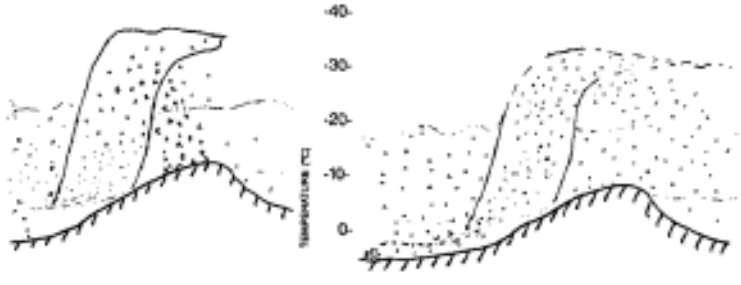


Fig. 3c. Orographic cloud bands with release of embedded cumulonimbus, tops much colder than -20 C

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3. THE DATA BASE

Several projects afforded reports for more than one type of cloud. Furthermore, some authors have reported multiple analyses of their data based on different groupings of events and different statistical approaches. We have done our best, in these cases, to select the data groupings closest to the cloud classifications set forth in the previous section, and to use representative estimates of effect where several were given by the authors. In a few cases, such as Necaxa, we have inferred cloud type from precipitation amounts, interpreting heavy amounts as from Cb and lighter amounts from Cu cong. These selections have resulted in more than 80 data sets tabulated in Table 1.

In classifying the data, no distinction has been made on the basis of targeting of the seeding material because we did not find an adequate documentary basis for doing so. Doubtless targeting was better in some projects than in others and probably contributed to differences among their responses. More we cannot say at this time.

Table 1. Projects included in the present study

Project Name	Cloud Class	Gain/Eval	% eff	Reference	Cases s/n	Agent/Mode	Rate	Months	Years
AUSTRALIA/Darling Downs	Cu cong	+ R/R	+ 178	Smith et al., 1961	(57)	AgI/Air	20	jfmam sd	60-61
AUSTRALIA/Darling Downs	Stratiform	+ R/Rx	− 69	Smith et al., 1961	9x	AgI/Air	20	jfmam sd	60-61
AUSTRALIA/New England	Cu cong	+ P/RX	+ 45	Smith et al., 1963		AgI/Air	20	jfmamjjasond	59-63
AUSTRALIA/New England	Cu cong	+ P/R	+ 180	Bethwaite et al., 1966	12/24	AgI/Air	2	jfmamjjasond	62-65
AUSTRALIA/New So Wales	Cu cong	+ R/R	+ 750	Bethwaite et al., 1966	20/24	AgI/Air	20	jfmamjjasond	62-65
AUSTRALIA/Snowy Mtns	Cu cong	+ P/RX	+ 102	Smith et al., 1964		AgI/Air	20/km	mamjjasond	55-59
AUSTRALIA/Snowy Mtns	Stratiform	+ P/RX	+ 79	Smith et al., 1964		AgI/Air	20/km	mamjjasond	55-59
AUSTRALIA/South	Cu cong	+ P/RX	+ 1	Smith et al., 1966		AgI/Air	20/km.h	jjaso	57-59
AUSTRALIA/South	Stratiform	+ P/RX	− 9	Smith et al., 1966		AgI/Air	20/km.h	jjaso	57-59
AUSTRALIA/Tasmania		+ R/R	− 30	Smith et al., 1979	255	AgI/Air	20	mam	64,66,68,70
AUSTRALIA/Tasmania	St	+ R/R	+ 62	Smith et al., 1979	255	AgI ⊥W	20	mam	64,66,68,70
AUSTRALIA/Tasmania		+ P/RX	+ 30	Smith et al., 1979	41/48	AgI ⊥W	20	mam	64-70
AUSTRALIA/Tasmania	Summer	+ P/RX	− 12	Smith et al., 1979	27/41	AgI/Air	20	jfmamjjasond	64-70
AUSTRALIA/Warragamba	Cu cong	+ P/RX	+ 21	Smith et al., 1964		AgI/Air	20	jfmamjjasond	59-63
AUSTRALIA/Warragamba	Stratiform	+ P/RX	− 28	Smith et al., 1964		AgI/Air	20	jfmamjjasond	59-63
CANADA/Quebec, W	Stratiform	+ R/RX	− 2	Gedson, 1986	45	AgI/Air	20/km	MJJAS	59-63
CHINA/Gudun	Subtropic hi	+ P/RTC	− 17	Yeh et al., 1982	6/8		210	AMJ	75,77,81
CHINA/Gudun	Cu cong	+ R/RTC	+ 70	Yeh et al., 1982	50/51	AgI + Metad	213/old	AMJ	75,77,81
CHINA/Gudun	Stratiform	+ R/RTC	+ 22	Yeh et al., 1982	50/51	AgI + Metad	213/old	AMJ	75,77,81
CHINA/Gudun	Cb	+ R/RTC	− 9	Yeh et al., 1982	50/51	AgI + Metad	213/old	AMJ	75,77,81
ISRAEL/Lake Kinneret	Cu con-21C < top < -15C	+ P/RX	+ 46	Gagin & Neumann, 1981	42x	AgI/Air	62	JFMA OND	61-75
ISRAEL/Lake Kinneret	Cb,top < -26	+ P/RX	− 5	Gagin & Neumann, 1981	87x	AgI/Air	62	JFMA OND	61-75
LIBYA/Tripoli	Cu cong,post-front	+ R/R	+ 805	Davis, 1973	55/55	AgI/Air	175/t	JFMA	71-72
LIBYA/Tripoli, Benghazi	Cu cong,top = -10C	+ R/TC	+ 400	Davis, 1982		AgI/Air	175	JFMA D	80-81
MEXICO/Monterrey	Cu cong,top = -10C	+ R/R	+ 58	Monterrey U. Report		AgI/Grid		SD	66
MEXICO/Necaxa	Cb	+ R/R	− 25	Perez Siliceo, 1970	48/49	AgI/Grid	1.3/h	JJAS	49-72
MEXICO/Necaxa	Cu cong	+ R/R	+ 17	Perez Siliceo, 1970	1219/815	AgI/Grid	1.3/h	JJAS	49-72
SWITZERLAND/Grossver II	Cb hail	− Hs/R	+ 35	Schmid, 1967	145/147	AgI/Grid	25/stm	MJJAS	57-64
USA/ACN Project	Ns	+ R/R	Nil	Hall, 1957	22/13	CO2/Air	1/km	JFMA OND	53-54
USA/Bishop CA	Stratiform orograp	+ P/TC	+ 9	Henderson, 1958		CO2/Air		JFMAMJJASOND	48-58
USA/Bishop CA	Stratiform orograp	+ P/TC	− 4	Henderson, 1958		AgI/Air		JFMAMJJASOND	48-58
USA/Bridger MT	Stratiform orograp	+ Sn/R	+ 50	Super & Heimbuch, 1983		AgI/Grid	30	JFMA ND	69-72
USA/Censare CA	Stratiform orograp	+ Sn/R	+ 25	Rowland, 1973		AgI/Grid	10	JFMA ND	69-70,72-73
USA/Censare CA	Unstable (Cu cong)	+ Sn/R	+ 60	Rowland, 1973		AgI/Grid	10	JFMA	69-70,71-73
USA/Climax I CO	50 kPa < -35C	+ Sn/R	+ 52	Mielke et al., 1983	41/35	AgI/Grid	2	JFMA OND	60-70
USA/Climax I CO	-20C < 50 kPa	+ Sn/R	+ 9	Mielke et al., 1983	68/73	AgI/Grid	2	JFMA OND	60-70
USA/Cald Cu OK	Cu cong	+ R/R	+ 118	Sutherland et al., 1971		AgI/Air	800	JJA	70
USA/Counties, MD	Cb hail	+ P/	+ 48	Boyd, 1972				JJ	71
USA/CRIPP crest CO	Ns -29C < top < -9C	+ Sn/R	+ 166	Elliott et al., 1978	34/40	AgI/Grid	3/km	JFMA ND	70-75
USA/CRIPP crest CO	Ns top < -25C	+ Sn/R	− 49	Elliott et al., 1978	19/14	AgI/Grid	3/km	JFMA ND	70-75
USA/CRIPP crest CO	Embedded convectn	+ Sn/R	− 6	Elliott et al., 1978	66/43	AgI/Grid	3/km	JFMA ND	70-75
USA/CRIPP CO	Cb	+ Sn/R	− 55	Elliott, 1984	14/20	AgI/Grid	3/km	JFMA ND	70-75
USA/FACE I FL	Cu cong	+ R/R	+ 88 !	Woodley et al., 1982	38/36	AgI/Air	60	JJA	70,71,73,75
USA/Hi Plains TX	Cb hail	− H/TC	Nil	Koragan, 1979		AgI/Air		AM,JJASO	70-76
USA/Jemez NM	-18C < top < -10C	+ Sn/R	+ 100	Reyes et al., 1973	(129)	AgI/Grid	7	JFM ND	68-72
USA/Jemez NM	top < -35C	+ Sn/R	− 15	Reyes et al., 1973	(125)	AgI/Grid	7	JFM ND	68-72
USA/Lake Almanor CA	Cu cong	+ S/R	+ 35	Bartlett et al., 1975	30/36	AgI/Grid	8	JFMA ND	62-67
USA/Lake Almanor CA	Ns	+ S/R	− 19	Bartlett et al., 1975	25/27	AgI/Grid	8	JFMA ND	71-74
USA/Lake Erie NY	Cu cong	Move/Vis	Aggr	Holroyd & Jiusto, 1971		AgI/Air	2400	ND	68-69
USA/Muddy Road KS	Cb hail	− H/TC	− 4	Hsu & Chiangron, 1984		AgI/Air	710	AM,JJAS	73-81
USA/NHRE CO	Cb, hailstms	− Hs/R	+ 56	Crow et al., 1979	27/3	AgI/Air	67	JJA	72-74
USA/Northeast	St	− Cld/Visual	Dissip	ashn Kampe et al., 1957	27	CO2/Air	1/km	JFM D	52,54
USA/Northeast	St	− Cld/Visual	Dissip	ashn Kampe et al., 1957	27	AgI/Air	10/km	JFM D	52,54
USA/Park Range CO	50 kPa < -25C	+ Sn/R	− 50	Rhea & Daws, 1970		AgI/Grid,Ai	10	WINTER	'60's
USA/Park Range CO	-20 C < 50 kPa	+ Sn/R	+ 100	Rhea & Daws, 1970		AgI/Grid,Ai	10	WINTER	'60's
USA/Pilot Project ND	Dynam model Cu con	+ Pn/R	+ 73	Dennis et al., 1974	73/21	AgI/Air	10.2	MJJA	69-72
USA/Pilot Project ND	50 kPa < -15C Cb	+ Pn/R	− 50	Dennis et al., 1974	59/26	AgI/Air	10.2	MJJA	69-72
USA/Proj CIRRUS	St	+ Sn/Visual	+ 5	Havens, 1981		CO2/Air	5/km	N	48
USA/Proj CIRRUS	St	+ Sn/Visual	+ 5	Havens, 1981		AgI/Grid		N	48-52
USA/Rapid Project SD	Shower days Cu cong	+ Pn/Rx	+ 180	Dennis & Kascielski, 1969	27 days	AgI	15	MJJA	66-68
USA/Rapid Project SD	Storm days Cb	+ Pn/Rx	− 49	Dennis & Kascielski, 1969	50 days R	AgI/Air			66-68
USA/Sta Barbara CA	Unstable bands	+ R/R	− 30	Elliott et al., 1971		AgI/Grid,Ai	16	JFMA ND	67,68,70,71
USA/Sta Barbara CA	Stable bands	+ R/R	+ 40	Elliott et al., 1971		AgI/Grid,Ai	16	JFMA ND	67,68,70,71
USA/Sta Catalina AZ	Large clds	+ Pn/R	− 30	Battan, 1966	18/16	AgI/Air	100	JAS	61,62,64
USA/Sta Catalina AZ	Small clds	+ Pn/R	Nil	Battan, 1966	18/19	AgI/Air	100	JAS	61,62,64
USA/Sta Clara CA	Cu cong	+ P/TC	+ 13	Dennis et al., 1968		AgI/Grid	25	JFM D	51-63
USA/Sierra Cu CA	Cu cong	+ Rn/Hist	+ 119	Williams & Lehrman, 1970		AgI,CO2/Air		JJA	67-68
USA/Sierra Cu I,II CA	Cu cong	+ R/R	+ visual	Williams & Lehrman, 1970	47/47	AgI/CO2	60	JJA	66-68
USA/Sierra Cu III CA	Cu cong	+ Rn/TC	+ 119	Williams & Lehrman, 1970	7/0	AgI	60	JJA	67-68
USA/SD State	Cb hail	− H/TC	+ 6	Lebsang & Pollett, 1976		AgI/Air		MJJA	72-75
USA/Wasatch UT	Best	+ Sn/R	+ 100	Hill, 1979		AgI/Grid	25	JFMA OND	69-72
USA/Whitetop MD	-40C < top < -20C	+ Pn/R	+ 100	Decker & Schickedanz '67	38/32	AgI/Air	27	JJA	60-64
USA/Whitetop MD	top < -40C	+ Pn/R	− 69	Decker & Schickedanz '67	38/36	AgI/Air	27	JJA	60-64
USA/Wolf Creek Pass CO	Cu cong	+ Sn/R	+ 80	Grant & Elliott, 1974	135/159	AgI/Grid		JFMA ND	64,66,68
USSR/Moldavia	Cb	+ Rn/R	− 50	Zmin, 1980	17/26	Pbl/Rocket		SUMMER	73-75
USSR/Moldavia	Cu cong	+ Rn/R	+ 60	Zmin, 1980	23/26	Pbl/Rocket		SUMMER	73-75
USSR/Krivoi Rog	Multi-cell stms	+ Rn/R	Nil	Komienko 1983		Pbl/Rocket		MJJA	73-78
USSR/Krivoi Rog	Single cells	+ Rn/R	+ 95	Komienko 1983	31/12	Pbl/Rocket		MJJA	73-78
USSR/Krivoi Rog	Cu cong	+ R/Hail	+ 100	Formin et al., 1973	17/99	AgI/Air		MJJA	72-73
USSR/Moldavia	Cb hail	− H/TC	+ 17	Vytchuzhanina		Pbl/Rocket		MJJA	58-63,65-73
USSR/Ukraine	St/Sc	+ Sn/TC	+ 100	Leskov, 1973,-76	16 stan	CO2/Air		JFM	60-72
YUGOSLAVIA/Lazarica	Cb hail	+ H/Hi	+ 8	Curic, 1981		AgI/Rocket	400/stm	MJJAS	67-81
ZIMBABWE/NACSO	Cu con-20C < top < -10C	+ Pn/R	+ 300	McNaughton, 1978	(250)	AgI/Air	20	jfm	73,74,76
ZIMBABWE/	Cu cong -10C < top	+ Pn/R	+ 30	McNaughton, 1978	250	AgI/Air	20	jfm	73,74,76

4. RESULTS BY CLOUD TYPES

The outcome is that, for:

Cumuliform clouds

From 32 reported Cu cong data sets with tops -10 C to -20 C, 31 reported increases or positive visual effects, the median increase being 90%, and one reported nil result.
From 11 reported Cb data sets with tops colder than -35 C, one reported nil effect and all the others decreases, the median being -30%.
From 8 reported sets of hail-suppression seedings in or around Cb complexes, all but one reported increases, the median being 12%.

Stratiform clouds

From 4 reported shallow St data sets, all reported dissipation with traces of snow.
From 14 reported deeper stratiform data sets (including Ns), 7 were increases, one nil, and 6 decreases, the median being 15%.

Orographic clouds

From 4 reported orographic sets having tops -29 C or warmer, all were increases, the median being 100%.
From 4 reported orographic sets having tops colder than -29 C, three were decreases, the median being -49%.

Unclassified

There remained 7 sets that we were unable to classify with confidence. They split three increases to four decreases, the median being -12%.

5. HYPOTHESES

With further study, more may be learned from these projects about seeding responses. Much statistical information may be gotten from some of the more than 300 additional projects now indexed (Todd and Howell, 1985). More cloud physics observations may be needed to answer many questions about how seeding is producing these effects. We offer some hypotheses to explain the reported results based on a systematic review of the rate that cloud processes can be modified by seeding (Todd and Howell, 1982).

We expect Cu cong clouds with cloud-top temperatures between -10 C and -20 C to respond very positively to seeding applied in any of various ways over a wide range of seeding intensities. Between the undiluted updraft well inside the cloud and the clear air above it, there is an active mixing zone that is energized by evaporation and cooling and contains a variety of micro-environments. Some may be chilled by as much as 6 C below adiabatic cloud temperature. Some have high supersaturation, favorable to droplet freezing.

In this region, seeding is hypothesized to speed up the appearance of an effective concentration of ice particles, for instance by activation of additional ice nuclei in the supersaturated skinaround a newly freezing drop. Conditions are favorable for rapid growth of the new embryos, since water substance is still being supplied to the embryos from the undiluted updraft. If this region remains active for 1000 s or so after seeding, the energetic mixing of ice crystals grown from these embryos with the continuing fresh supply of supercooled water from below causes riming and aggregation to form precipitation. Precipitation growth is further speeded because the newly formed ice embryos are morecollectable than the cloud droplets they replace (Hosler *et al.*, 1957; Hobbs *et al.*, 1974). Furthermore, conversion of liquid cloud droplets into larger frozen masses has a positive effect on the cloud dynamics both by release of the latent heat of fusion and by removal of water substance from the region where evaporative cooling is most actively taking place, thus reducing the loading of the updrafts.

In the Cb, on the other hand, where the flow is up and through the precipitation-freeze-up temperature, there is no opportunity for the seeded portion to mix with a fresh supply of supercooled water. Two cases may be distinguished.

In Cb with slow updrafts, as with most mountain and tropical Cb, there is often sufficient time for seeding to turn all the cloud water to small ice crystals at temperatures where normally larger and fewer crystals would grow, rime up or aggregate, and become effective precipitation.

In fast-updraft summer Cb, there is often not enough time for diffusional growth of seeded ice crystals to slow or stop precipitation formation. However, if coalescence was initiating the natural precipitation (normally the case when the cloud base temperature is 10 C or warmer), and if the coalesence had developed drizzle drops that were growing by collision with each other at the level where seeding was effective, then even moderate seeding is likely to freeze all of these, stop this coalesence, and hence inhibit growth of precipitation particles before they became large enough to fall from the anvil without being lost to evaporation.

We note the anomaly that seeding for hail suppression is generally reported to have increased the precipitation. Can this be because seeding to suppress hail has usually been carried out on the feeder clouds as they struggle through the Cu cong stage? If there is sufficient time in the Cu cong cloud top mixing zone, seeding could make more effective precipitation embryos. These may increase precipitaion and reduced hail as many seeders now hypothesize they would.

We expect that seeding of low shallow supercooled stratus will produce very light precipitation, especially where the seeding is light, by conversion of supercooled droplets to crystals growing preferentially in response to their lower vapor pressure.

We expect seeding of deep stratus the upper part of which at least is supercooled to reduce whatever precipitation there may be and displace it downwind by freezing the drizzle drops so that they no longer collect each other butbounce apart when they collide, thus slowing their growth.

The situation of nimbostratus is one of the least understood in terms of the expected effect of cloud seeding and deserves a morecritical analysis of reported outcomes. Perhaps the presence of waves that may produce local convergence and local regions of supercooled water are critical for a seeding effect. If so, we expect that conversion of the supercooled droplets to more collectable snow crystals, if it occurred below the level of nondivergence, would cause a precipitation increase in that region.

We expect light seeding of orographic stratus to produce a positive effect, small quantitatively but perhaps large percentagewise. In some settings, this situation may endure for long periods.

We expect that light to moderate seeding of orographically lifted nimbostratus will increase the precipitation at and to windward of the crest by converting supercooled water produced typically in the lower part of the cloud in the orographic uplift zone (Burhoe, 1948) to snow crystals that are more efficiently collected by the natural snow (Hosler *et al.*, 1957).

Orographic lifting accentuates the release of potential instability. We expect the effect of seeding convective bands will be positive when the embedded cumulus congestus have cloud-top tempertures in the -10 C to -20 C range, negative when cloud-top temperatures are colder than -35 C.

6. SUMMARY

It looks as though:

Seeding Cu cong with cloud tops -10 C to -20 C is a robust way to increase precipitation when the clouds last long enough for the seeding to take effect. The question is, when and where can this increase yield enough added precipitation to effect a meaningful benefit on a given target?

Heavily seeding the main updrafts of Cb with tops colder than -35 C has likely been associated with decreased precipitation enough times to give an appearance of great inconsistency to the outcome of cloud seeding in general. The result may have been a major factor in causing official doubt about seeding as a means of precipitation management, as expressed for example in successive policystatements by the council of the American Meteorological Society (1981, 1984).

Seeding to suppress hail is generally reported to have increased precipitation.

Seeding of nimbostratus with supercooled tops has produced mixed results, with enough reports of decreases on the target to have cast doubt on the usefulness of indiscriminate seeding as a precipitation management tool.

Even in the absence of a broadly accepted set of theories expressing a full understanding of all the cloud-physics and cloud-dynamics processes involved, there is enough empirical evidence, derived from randomized projects and corresponding to reasonble physical explanations, to provide strong support for the effectiveness ofdiscriminate cloud seeding under weather conditions that can be specified, recognized, and treated in the field.

We have presented hypotheses based on our systematic review of cloud physics processes to explain how we think these results have occurred. It will probably be possible to get more information by empirical examination of additional historical projects, and by more detailed analysis of daily results under varying weather conditions, to support or reject these hypotheses.

If these hypotheses are supported by further investigation, they could provide a theoretical underpinning to make precipitation management more reliable and better accepted.

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