INITIAL RESULTS FROM THE 1989 CLOUD SEEDING EXPERIMENT IN ILLINOIS

Robert R. Czys, Stanley A. Changnon, Mary Schoen Petersen
Robert W. Scott, and Nancy E. Westcott

Illinois State Water Survey
Atmospheric Sciences Division
2204 Griffith Drive
Champaign, IL 61820 - 7495

ABSTRACT. Some early results from the 1989 cloud seeding experiment conducted in Illinois are reported in this paper. This exploratory field project was designed to achieve four primary objectives: 1) to obtain data on the largest possible sample of clouds (treated and natural); 2) to test some of the early physical steps of the dynamic seeding hypothesis; 3) to provide data for the development of analytical tools for discerning seeding effects; and 4) to improve basic knowledge about natural cloud and precipitation processes in the Midwest. The treatment randomization was based on "floating" experimental units, initially defined by a single cumulus congestus. Analysis of predictor variables revealed significant differences between the AgI and sand treated clouds at the time of treatment in many aspects that might govern future cloud growth. A Seedability Index composed of criteria physically consistent with the dynamic seeding hypothesis is described which was developed as an initial approach to addressing the problem of the bad draw revealed by the predictor variable analysis. The temporal series of the empirically-defined Seedability Index revealed that seedable conditions did not remain constant over the course of the field experiment and that even the seedable conditions for pairs of experimental units obtained on the same day were not always comparable. These findings illustrate the large inherent natural variability which has come into play in other cloud seeding experiments, and has frustrated efforts to randomly select two populations of clouds having sufficient similarity in individual characteristics to allow valid comparisons.

1. INTRODUCTION

Preliminary results of exploratory cloud seeding experimentation to increase rainfall conducted in Illinois during the summer of 1989 are the subject of this paper. This field experiment was conducted as part of the Precipitation Augmentation for Crops Experiment (PACE) which was begun by the Illinois State Water Survey in 1978. PACE has continuously addressed two fundamental questions relating to precipitation enhancement in Illinois: 1) can it be accomplished, and 2) is it worth doing?

An organized long-term project to investigate these two questions was initiated by the State of Illinois for several reasons. First, research simulating the effects of precipitation enhancement in Illinois suggested that marked benefits could occur, principally to agriculture, in the form of increased and stabilized crop yields (Huff and Changnon 1972). Secondly, a series of operational cloud seeding projects developed in the Midwest during the 1970s with local agricultural backing raised fundamental questions in the agricultural sector, as to whether cloud seeding could change rainfall and what the effects might be (Changnon and Hsu 1981). Third, results of inadvertent weather modification studies in Illinois, and from cloud seeding research in other locations, coupled with major technological advances in weather radar and cloud physics aircraft instrumentation were encouraging factors for improved field research. Additionally, some success in modifying clouds believed to be similar to those in Illinois had been achieved in Florida and the Dakotas (Changnon 1980).

PACE was designed with two major components: meteorological studies, and weather impact studies (see Changnon et al. 1991 for a comprehensive description of the design of PACE). The meteorological components of PACE addressed five areas of activity including: 1) design and evaluation of experimentation, 2) cloud studies, 3) precipitation studies, 4) synoptic weather analyses including predictor variables and covariates, and 5) modification and seeding hypotheses development. PACE was designed as a three phase effort. Phase 1 was an assessment of historical data and existing results and did not involve seeding trials (Ackerman et al. 1978). Information relevant to precipitation modification in the Midwest was studied and interpreted in order to make a decision about the potential for rain modification in the Midwest and what modification hypothesis should be followed. By 1985, the results of the Phase 1 assessment indicated the potential for success from experimental cloud treatments under the dynamic seeding hypotheses (Woodley 1970). In assessing potential seeding materials including silver iodide (AgI) and dry ice, we chose to use AgI flares to best target the updraft regions of midwestern clouds, a necessity within the framework of the dynamic seeding hypotheses.

Phase 2 of PACE began in 1986 and is still in progress. The first efforts involved designing initial experimental seeding trials. The principal elements of field projects conducted in Illinois during the summers of 1986 and 1989 included an operational forecasting effort, the use of meteorological and seeding aircraft, weather radars, and special soundings involving the NCAR/CLASS system. Unfortunately, the 1986 sampling was limited to 23 clouds due to the lack of daytime cloud activity during the July-August operational period. However, the results encouraged further testing of the seeding hypothesis by field experimentation.

2. THE 1989 FIELD PROJECT

The field experiment conducted in Illinois during 1989 studied natural cloud behavior and cloud reactions to AgI seeding. Operations began on 8 May and ended on 11 August, and were divided into two periods. Period 1 (8 May - 31 May) was devoted to monitoring the conversion of water-to-ice in clouds treated with either AgI or sand. Period 2 (1 June - 7 August) was devoted to studies of reactions of clouds and cloud systems to seeding. The study area of the field project included central Illinois as shown in Fig. 1.

2.1 Facilities

The plane used for cloud physics and cloud seeding was a twin engine Beechcraft Baron leased from Colorado International Corporation. The aircraft was used to make in-cloud measurements of cumulus congestus as they reached the -8 to -15°C levels, and to simultaneously release cloud treatment flares (some AgI, some placebos of sand) according to a predetermined randomization scheme. The airplane was equipped to measure Rosemont and reverse-flow temperature, cooled-mirror dew point, pressure, vertical winds, Johnson-Williams hot-wire liquid water content, FSSP cloud droplets spectra, and precipitation-size particles by 2DC and 2DP imaging. The airplane also carried a rack containing 200 pyrotechnic flares for cloud treatments.

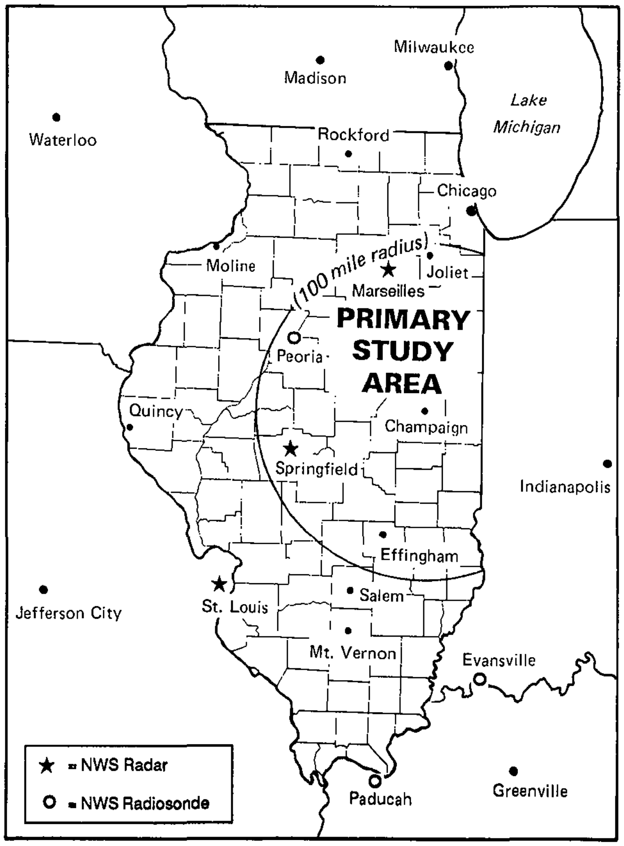


Figure 1. Study Area for the 1989 PACE field project.

A T-28 aircraft of South Dakota School of Mines and Technology and staff participated in the project in May. The aircraft was intended to be used to monitor water-to-ice conversions at constant temperatures as a cloud evolved. Being armored, the aircraft could penetrate into cloud regions containing hail and severe turbulence, and thus, provided in-cloud data from more mature and potentially severe cloud stages.

Two radars were involved in the 1989 PACE field program: the CHILL radar and the Illinois State Water Survey's HOT radar. Both radars transmit at 10-cm wavelength with a beam width of 1° for the CHILL and 1.5° for the HOT. Further details on the facilities used are available elsewhere (Changnon et al. 1991).

2.2 Design

The field project was designed to achieve two primary objectives: 1) to obtain data on the largest possible sample of clouds (treated and natural); and 2) to address early steps of dynamic seeding hypothesis by focusing on initial cloud reactions. Operational procedures were designed around five weather, cloud, and facility readiness situations. The five experiments were of two general classes, either 1) the collection of data about natural cloud and precipitation processes by the project aircraft and/or radar when seeding was inappropriate for various reasons, or 2) the randomized treatment of clouds (using AgI or placebos) under three experimental variations that differed according to available cloud sizes and/or equipment.

Under the second class, there were two top priority experiments. Missions in the first experiment involved randomized treatment of cumulus congestus clouds expected to reach at least 30,000 feet (9145 meters) in height. This experiment was referred to as the "large cloud experiment." Clouds in this experiment were cumulus congestus towers either forming individually or in association with a larger, sustaining cloud system. The "large cloud experiment" included simultaneous collection of radar and aircraft data on treated clouds.

The second experiment, titled the "small cloud experiment", involved randomized treatment of cumulus congestus clouds which were growing above approximately 20,000 feet (6095 m), but not surpassing 30,000 feet (9145 meters) in height. These were typically cumulus congestus towers growing individually. The "small cloud experiment" included simultaneous collection of radar and aircraft data on treated clouds. We followed all of the operation procedures of the "large cloud experiment" in the "small cloud experiment", except "small" clouds were penetrated at least once after treatment in order to obtain a limited amount of direct measurements of seeding agent effect on in-cloud conditions. Initial results of randomized treatments in the "large cloud experiment" are the subject of this paper.

2.3 Randomization

Although the use of randomization in cloud seeding experiments has been questioned, it has been used in PACE because we consider it to be an essential means of gathering trustworthy data when people are involved in making critical analytical choices and assessments. The treatment randomization was based on "floating" experimental units, initially defined by a single congestus cloud or a group of congestus clouds behaving as an entity (see Fig. 2).

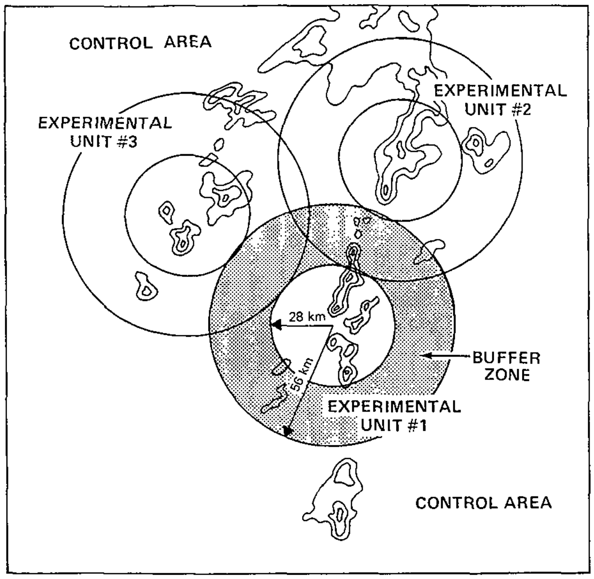


Figure 2. Illustration of experimental unit geometry.

The concept of a "floating" experimental unit was adapted from that used in cloud seeding operations in West Texas (Rosenfeld and Woodley 1989). The radius of each unit where treatments were delivered was set at 28 kilometers from an initial cloud treatment point, and each unit typically swept out an oblate-shaped area during its lifetime. All clouds in the unit received the same seeding material, and the design allowed selection of up to 4 units during any operational period of up to 3 hours. An annular buffer area of 28 km around the treatment area was maintained to address concerns over physical and chemical interactions between units.

A 50/50 randomization was set on experimental units rather than randomizing the choice of using AgI or sand by clouds. Balancing was imposed on flights with two or more experimental units to randomly produce at least one AgI and one sand unit for the flight. Separate randomization schedules were used for the "large" and "small" cloud experiment to further maintain balance. The in-flight meteorologist who selected the clouds (and hence the experimental units) was blind as to the type of treatment being applied. All processing and quality control of aircraft, radar and meteorological data was completed prior to releasing information about the type of treatment used in any of the experiment units.

2.4 Flight Procedures

In the large cloud experiment, aircraft and radar operations were launched at the first satellite, radar, and/or visual indication of cumulus initiation. These were days when the morning forecast predicted clouds to be warm-based (preferably around 16°C) and to grow to at least 30,000 ft (9145 m). When the aircraft arrived at a potential seeding area, a candidate cloud was selected to meet the following visual criteria: a) cloud top just passing through 20,000 ft, with potential for reaching 30,000 ft and beyond; b) a cumulus congestus (hard, blocky) appearance; c) be at least 2 kilometers in diameter; and d) show little or no vertical tilt.

A test penetration of a candidate cloud further helped establish whether neighboring clouds could be considered suitable for treatment. In-cloud properties had to include: 1) moderate updrafts, preferably 2 to 4 m s^{-1}, 2) large amounts of supercooled water (about 1 to 6 g m^{-3}), a presence of supercooled drizzle and rain drops in the updrafts; and 4) little or no indication of ice, particularly in the updrafts.

All subsequent clouds in an experimental unit received the same treatment at approximately the -10°C level, as specified by the pre-determined randomization schedule. Treatment flares containing AgI or sand were delivered, with every attempt to release flares only in the updraft regions at a rate of approximately 1 flare every 5 to 10 seconds, or approximately every 500 to 1000 meters of cloud updraft. The aircraft was typically positioned between 1000 and 5000 feet (300 to 1500 m) below the cloud top with the intent to release at least 20 grams of seeding material into the volume of the cloud updraft in the levels of -10 to -3°C.

During these operations, the radars were operated in a sector scanning mode that provided detailed three dimensional portrayal of the echoes approximately once every 4 minutes with 1 or 2, 360° low elevation scans in between sector scans. In the event that 10 or more clouds were treated, a decision was made to either remain with or leave the experimental unit for another. Typically, the experimental unit was abandoned and another one sought with the aid of the radar.

3. PRELIMINARY RESULTS FOR "LARGE" CLOUDS

Initial analysis of the 1989 data has involved three steps. First, was the extensive effort to process, quality control, and digitize the raw data and a large set of derived variables. These included all the various atmospheric synoptic variables determined from soundings and surface data analysis, an assortment of variables determined from the aircraft data as to in-cloud conditions, dosage, and variables determined from the 3-dimensional radar echo measurements, such as echo heights, core size, rate of growth, and maximum reflectivity. Thus far, this endeavor yielded a grand total of 190 predictor and response variables for each of the 71 large clouds in the 1989 sample. Of these 190 variables, 154 were predictor variables and 36 were response variables.

Table 1 presents the number of clouds treated and the treatment material by date and experimental unit number. Of the 71 large clouds penetrated and treated, 4 never developed an echo, even though the radar apparently operated properly. Thus, there were 67 large clouds that echoed, sampled on 9 days from 12 experimental units. The randomization scheme produced a good balance between treatment type by experimental units and clouds. Seven experimental units were treated with silver iodide and six with the placebos (sand). Of these 67 clouds (echo cores), 35 were treated with silver iodide and 32 with sand. Thus, our randomization scheme seems to have worked well numerically, producing an approximate 50/50 split between sand and AgI treated clouds which alternated over the course of the field experiment.

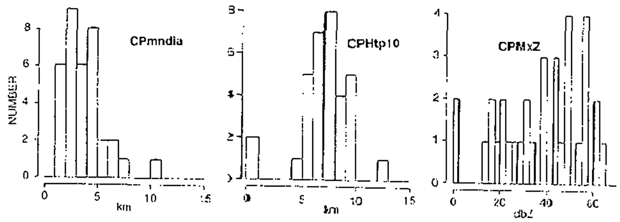
Table 1. Number of clouds treated and the treatment material summarized by date and experimental unit number.

Date	Experimental Unit Number*	Number of Clouds	Treatment Material
May 19	2	4	Sand
June 1	5	4	AgI
June 23	11	7	AgI
June 23	13	7	Sand
July 8	17	5	Sand
July 8	18	7	AgI
July 11	19	7	AgI
July 19	20	3	Sand
July 23	22	10	AgI
July 24	23	5	Sand
July 25	24	8	Sand
July 25	25	4	AgI

* Other numbered units were for other experimental classes.

The next major step in the analysis was to focus attention on the 154 predictor variables and on similarities and differences at the time of treatment between clouds treated with sand and those treated with AgI. Figure 3 shows histograms for three predictor variables which we considered to be fundamental describers of the state of the echo core at the time of treatment. Shown are the AgI and sand populations for the mean diameter of the echo core at treatment (CPmndia), the height of the top (of the 10 dBZ reflectivity) of the echo core at treatment (CPHtp10), and the maximum reflectivity of the echo core at treatment (CPMxZ). Inspection of Fig. 3 reveals that the sand treated clouds had several echo cores that were wider, or taller or more reflective at treatment than AgI treated clouds. These perceived differences are all statistically significant at more than the 0.05 level. Statistically significant differences were also found between sand and AgI treated clouds at first echo (FE). For example, some of the sand clouds changed height from FE to treatment more quickly than AgI treated clouds, and sand clouds also had a few larger accelerations in echo top vertical motion than AgI clouds. However, the height of the top of the first echo, defined by the 10 dBZ contour, was about the same for sand and AgI clouds.

(a) AgI Echo Cores



(b) Sand Echo Cores

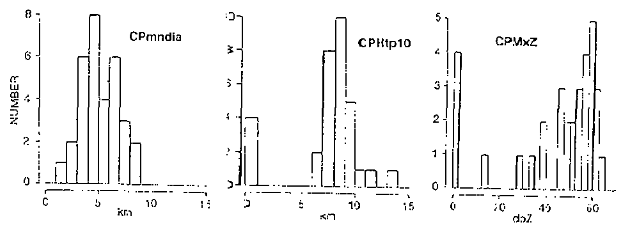


Figure 3. Histograms showing selected fundamental describers of echo core state at treatment.

The important finding of these comparisons was that two populations of clouds, randomly selected, were statistically significantly different from one another (at first echo and treatment) in many physical respects that might govern future cloud growth, despite achieving numerical and temporal balance in cloud selection. In fact, and as shown in Table 1, six of the experimental units (June 23, July 8, July 25) were from the same dates and weather systems. Nevertheless, our sample of 67 clouds, randomly selected, gave us some fairly different clouds in the sand sample than in the AgI sample, reflecting a classic example of the "bad draw." Clearly, any future comparison of the sand and AgI clouds in response variables would provide little useful information as to potential seeding effects unless this bias can be satisfactorily taken into account.

The third stage of the analysis has attempted to address the problem of the bad draw revealed by predictor variable analysis. Our analysis has moved to investigate cloud characteristics before treatment and at treatment so as to define, in various subjective and objective ways, a set of AgI and sand treated clouds that were similar at treatment, and thus comparable.

Our initial and preliminary empirical approach has been to define a set of "seedability" criteria physically consistent with the dynamic seeding hypothesis. From the aircraft, radar, and synoptic based data, 20 variables were selected from the list of 154 predictor variables. Table 2 lists this set of "seedability" criteria and the threshold limits we set to

Table 2. Variables and threshold limits defining the Seedability Index.

Variable Name	Threshold
Up_Dia	$x \geq 1000$ m
Mean_VW	$2 < x < 8$ m s^{-1}
%_Updraft	$x \geq 33\%$
NBuoy	$-2 \leq x \leq +2$ °C
Buoy_Enh	$x \geq 0.45$ °C
LWCd	$x \geq 0.1$ g m^{-3}
SWC_frac	$x \leq 40\%$
FECPt	$x < 15$ min.
range	$30 \leq x \leq 90$ km
CPMxZ	$x > 20$ dBZ
a_cdp	$-0.02 < x < +0.02$ km min^{-2}
CPFEdZ/dt	$x \geq 0.0$ dBZ min^{-1}
CPmndia	$x \geq 1.0$ km
CPHMxZ	$1 > x \geq 1.5$ km
tccl	$x > 14$°C
pb	$x \geq 3$°C
L	$x \leq 0$
Ri	$x \geq 11$
Dosage 1	$1.5 \leq x \leq 3.5$ flares km^{-1}
Dosage 2	$x \geq 50\%$

derive a "Seedability" Index. As seedability criteria, we chose main updraft diameter (Up_Dia), mean vertical wind (Mean_VW), and percent of cloud with updraft (%_Updraft) as indicators of the organization of a cloud's vertical circulation, reasoning that narrow clouds or clouds with many small updrafts, or clouds with weak updrafts had circulations that were poorly organized, and therefore would not respond too favorably to dynamic seeding. Net buoyancy (NBuoy) was chosen based on the reasoning that if a cloud was either too negatively or too positively buoyant then the forces acting on these clouds may be so large as to not be appreciably modified. Potential buoyancy enhancement (Bouy_Enh) calculated according to the method of Orville and Hubbard (1973) was chosen as an indicator of the potential amount of invigoration from latent heat release due to seeding. The presence of supercooled drizzle or raindrops (LWCd), and the absence of ice expressed as the fraction of the total condensate that was frozen (SWC_frac) were chosen since these are required according to the dynamic seeding hypothesis for release of latent heat and beneficial loading of the updraft. The time from first echo to treatment (FECPt) was selected to include the effect cloud age may have on seedability. Although not directly related to the dynamic seeding hypothesis, distance of the echo from the radar (range) was included as a seedability criteria to limit measurement errors related to spreading of the radar beam. Maximum reflectivity at the time of treatment (CPMxZ) was chosen to include possible effects of intensity on seeding response. The acceleration of cloud top at the time of treatment (a_cdp), defined by the 10 dBZ contour, was chosen since rapid decline or rapid growth may not show appreciable changes in vertical growth that may be due to seeding. The rate of change of maximum reflectivity from first echo to treatment (CPFEdZ/dt), mean echo core diameter (CPmndia), and height of the maximum reflectivity at treatment (CPHMxZ) were included to further insure similar initial cloud conditions for seeding. The temperature of the CCL (tccl), potential buoyancy (pb), coalescence activity index (L), and Richardson Number (Ri) was selected to include similarity in the meteorological setting for the convection. Finally, two dosage criteria were included to account for effects in response that may be related to the amount of seeding material released; Dosage 1 indicates that rate of seeding material release in updraft and Dosage 2 refers to the percentage of the flares that were released in updraft. For each of these 20 variables, threshold values were empirically established, and these are given in the right-hand column of Table 2.

In this analysis based on seedability criteria selected empirically, we had to remove some of the 71 clouds because of a lack of data on the critical variables. Six of the clouds, for various reasons, had no updraft data. One cloud had no updraft data and did not echo. Four clouds had no updraft data and no 2D image data. Three more clouds never echoed, and another four had no 2D image data, resulting in a sample of 53 clouds, 25 treated with silver iodide and 28 with sand.

For each cloud, we added the number of times the cloud met a criteria, and then computed the percent criteria met of the total possible 20 criteria. In the event that a value for cloud top acceleration could not be computed, the seedability index was calculated on the basis of 19 criteria. These percentages are an index, indicating for an individual cloud, its tendency towards being "seedable." Thus, any two or more clouds would be considered similarly seedable even though they may not have a one-to-one correspondence in the individual criteria they met. The resulting values for the 53 clouds, plotted in a temporal sequence, appear in Figure 4.

This temporal series of an empirically-derived seedability index reveals two interesting findings. First, there appears to have been a temporal shift in "seedability", at least for the criteria we selected and the threshold values we subjectively established. To the extent our selection of criteria and threshold values are valid, Fig. 4 clearly shows that the seedability of the clouds may have decreased during operations in June and early July (treatment sequence or clouds, 1 thru 41), thereafter leveling off and varying between approximately 70 and 90% (treatment sequence 42 thru 71).

The second important finding revealed in Fig. 4 relates to one of the days (July 8; clouds 23 to 34) that a pair of experimental units were obtained (see Table 1). Comparison of the sand values of seedability index (open circles) to those for AgI (solid circles) reveals considerable difference in the seedability of the two experimental units.

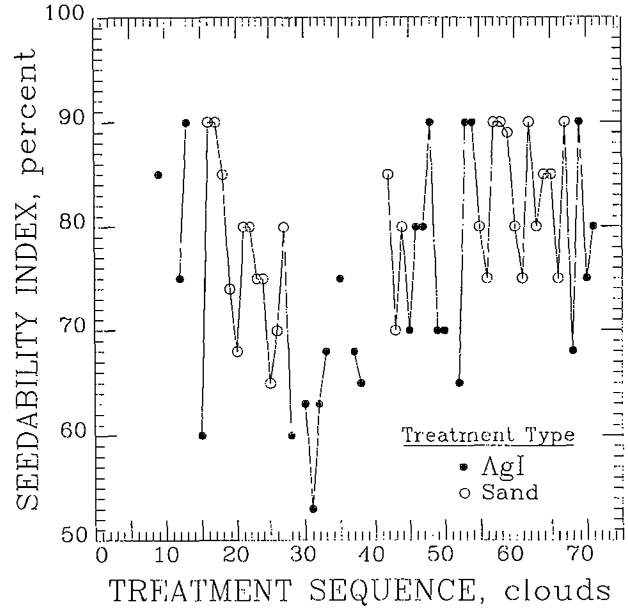


Figure 4. Temporal variation of the Seedability Index. Values of the index are not joined by a solid line if an intervening value was missing.

The clouds in the initial unit on this day received a sand treatment, and the seedability index shows that these clouds may have been more favorable for seeding than were those in the second experimental unit, which was treated with silver iodide. On this day, the experimental units were separated in space by roughly 50 kilometers and in time by less than 40 minutes. This example of in-storm differences in clouds further demonstrates the problem of obtaining comparable samples even within storm periods.

4. DISCUSSION AND CONCLUSION

At this preliminary stage of our analysis, it is too early to make declarations about seeding effects in the 1989 data sample. This must wait development of a satisfactory methodology for selection of comparable clouds based on pre-treatment conditions. However, the findings do illustrate the large inherent natural variability in the conditions of clouds objectively selected on the basis of criteria. The net consequent for the 1989 PACE field experiment was to randomly select two populations of clouds with some very different individual characteristics. Hence, evident is the old dilemma of the "bad draw" as one reminder of why it has been so difficult to avoid some controversial moments in many historical weather modification experiments, even after going to great lengths to carefully randomize selection of clouds for experimentation. The interpretation of the seeding effect in the Illinois sample clouds from 1989, based strictly on all AgI treated clouds versus all sand treated clouds would not indicate a positive seeding effect. However, a careful and detailed analysis of the pre-treatment conditions has revealed that this is not how the evaluation should be pursued.

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