

# THE GREAT LAKES PROJECT

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## 1. Introduction

Winter lake storms in the Great Lakes region form in early winter when the first cold air outbreaks sweep across the still unfrozen lakes. The continental cold air is usually well mixed and nearly dry adiabatic in its vertical structure within the boundary layer; at the 1500 to 2000 m level it is topped by an inversion. On moving from land across the warm lake the air is picking up moisture and forms clouds which may precipitate a large amount of snow over Buffalo and the downwind shore areas as the storm persists. It is these snowfalls which often paralyze traffic and the activities of civilization; it is therefore desirable that their effects are modified beneficially.

## 2. Numerical mesoscale model

The flow of air is subjected to several influences which have been most clearly illuminated in a mesoscale numerical model developed by Lavoie<sup>1</sup>. Lavoie postulates a 3-layer model consisting of a shallow surface layer in which the transfer of heat and momentum from the surface takes place and a middle layer for which the potential temperature is constant. This layer is topped by an upper stable layer; the boundary between the two layers being characterized by a temperature inversion. The equation of motion for the middle (mixed) layer can be written<sup>2</sup>:

$$\frac{d\vec{V}}{dt} = -f\vec{K} \times \vec{V} + \frac{g}{\theta_L} [\theta_L - \theta_g] \nabla H + \frac{gH}{2\theta_L} \nabla \theta_L - \frac{\theta_L}{\theta_g} \left( \frac{1}{p} \nabla P \right) - \frac{C_D}{H} |\vec{V}| \vec{V} \quad (1)$$

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where the notation is as follows

- $\vec{V}$  = horizontal vector wind
- $f$  = Coriolis parameter
- $\vec{K}$  = unit vector vertically upward
- $\theta_L$  = potential temperature of mixed layer (a function of x and y only).
- $\theta_\zeta$  = potential temperature of unmodified air above the inversion (constant)
- $H$  = inversion height
- $g$  = acceleration of gravity
- $\rho$  = density
- $P$  = pressure
- $C_D$  = surface drag coefficient

A physical interpretation of the various terms in the equation can readily be given. The first term on the right is the Coriolis force, and the last term is the frictional drag due to surface roughness. The remaining three terms together make up the horizontal pressure gradient force. When written in this form, they show the three pressure components that are important in the lake-effect problem.

$$\frac{\theta_L}{\theta_\zeta} \left( \frac{1}{\rho} \nabla P \right) \zeta \quad (2)$$

is the large-scale pressure gradient imposed above the layer of surface influence.

$$\frac{g}{\theta_L} [\theta_L - \theta_\zeta] \nabla H \quad (3)$$

is the component of pressure gradient due to the varying depth of the mixed layer. For typical temperature stratification, negative slope of the inversion (inversion height decreasing downwind) provides a positive acceleration

$$\frac{gH}{2\theta_L} \nabla \theta_L \quad (4)$$

is the pressure gradient component due to horizontal temperature gradient in the mixed layer. Increasing temperature downwind leads to acceleration.

Early in the field experiments it became very clear that the project required a thorough study of the whole gamut of lake snow storms. As such we consider those snowstorms which are confined to the layer below the 500 mb level, in most cases even below the 700 mb level. For these systems momentum, heat and nuclei transferred upward influence materially their life history. It was necessary to develop and employ entirely new methods for the mesoscale analysis of these cloud systems using airborne sensors, radar, doppler radars, and fixed and mobile surface stations. The analysis systems include ESSA satellites, an ESSA DC-6 aircraft and its doppler navigational system, as well as instrumentation for inflight measurements of Aitken, cloud condensation nuclei, new applications of infrared remote temperature measurements for cloud surveillance when flying above or in clouds; while at the surface formvar replica of snow crystals and snow samples for neutron activation silver analyses are collected for the documentation of the seeding effect.

Subsequently highlights of the results of two seasons of field experimentation are reported.

### 3. Lake Storm of 15 and 16 November 1969

A classical case of a lake storm occurred on 15 and 16 November 1969. The cloud pattern as seen from the ESSA satellite with the outlines of Lake Erie, Ontario, Michigan and Huron marked is shown in Fig. 1. Note the white cloud band which extends almost the whole length of Lake Erie. It persisted with little variation over more than 12 hours, precipitating during this time 12 - 15 inches of snow on the Buffalo metropolitan area. Fig. 2 shows radar contours which were drawn at about the same time as the satellite picture from the image on the picture tube of the WSR-57 radar of the Buffalo Weather Bureau. The lines are 0, 6, 12, 18 db attenuation. This means that within the 12 db contour line the heaviest precipitation fell. It should be considered that due to the earth's curvature the echo strength, particularly toward the West, has decreased faster than should be expected from the storm picture of Fig. 1. Fig. 3 shows the increase of inversion height which was computed using the Lavoie model with initial conditions entered as they prevailed in Dayton, Ohio. Here the inversion level was at 1500 meters, the winds in the boundary layer were about 230° and 30 kts, and above the boundary layer 270° and 30 kts. The temperature difference between lake and land was 15°C. Over Buffalo nine hours later the inversion was at 660 mb and the winds veered from 200°, 24 kts at the surface to 260° and 35 kts on top of the boundary layer. The satellite picture, Fig. 1, shows quite convincingly the wind shear from



Fig. 1. Lake Snowstorm over Lake Erie as seen from ESSA Satellite on 15 November 1969. Outlines of lakes are dotted, arrow points to North.

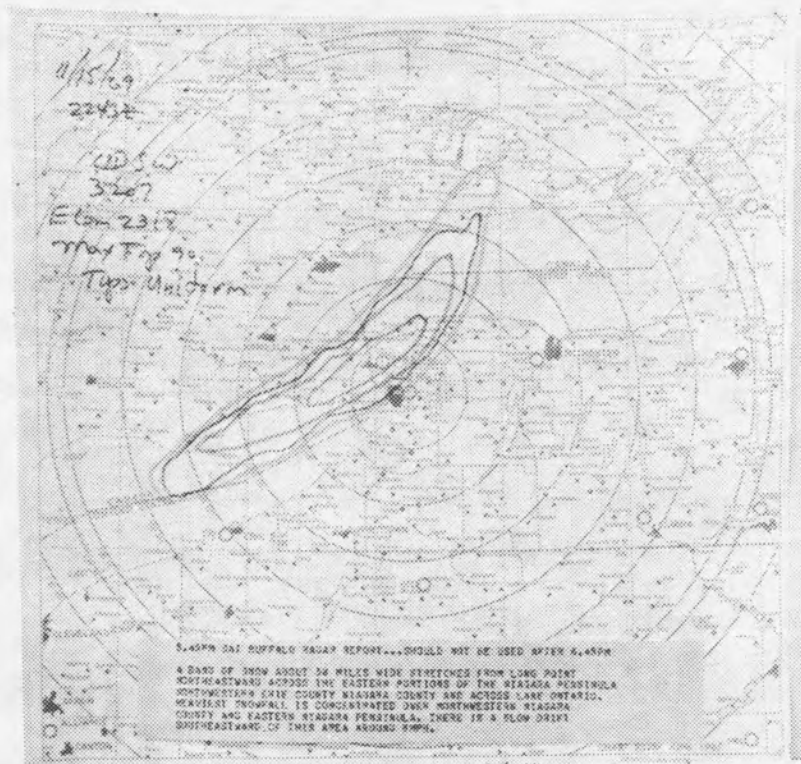


Fig. 2 Radar contours of PPI echo of Lake Erie snowstorm as observed on the WSR-57 10 cm radar of the Buffalo Weather Bureau.



SSW to WSW with altitude; the clouds in the beginning are low and arranged with the low level flow while towards the Buffalo lake end, as the cloud height increases, the tops follow the upper level wind.

Comparison of Figs. 2 and 3 indicate that the most intensive radar echo was located where the modified boundary layer was deepest, permitting the convective clouds to grow largest and to produce precipitation most efficiently. Fig. 4 gives a cross-section along the storm axis showing the computed inversion height increase and the strength of the radar echo. Note that the most intensive echo occurs downwind of the highest inversion level. This should be expected as the heaviest snowfall should occur downwind from the deepest clouds.

The objective of modifying this type of storms is to redistribute the snow fall further downwind without affecting the total precipitation. The physical concept is to artificially increase the number of snow crystals through seeding so that riming is eliminated and only non-rimed crystals precipitate. For the fall velocity of rimed and non-rimed snowflakes one may apply expressions which were derived by Magono<sup>3</sup> in taking into account the effect of two types of aerodynamic drag: one caused by the air flowing around the snowflake and one caused by the air flowing through the open structure of the flake. He arrives at the following expressions:

$$u = 132 \sqrt{\frac{r}{0.40 + 0.63r}} \quad \text{non-rimed flakes} \quad (5)$$

$$u = 194 \sqrt{\frac{r}{0.45 + 0.60r}} \quad \text{rimed flakes} \quad (6)$$

where  $r$  in cm and  $u$  in cm/sec. Proper seeding will not only convert rimed into non-rimed snowflakes but it will also decrease their radius due to their greater number. The fall velocity of the artificially modified snowflakes will consequently decrease and they will be carried further downwind and away from their natural target.

#### 4. Case study December 7, 1968

We have so far established that we have the capability to materially affect the snow crystal concentration over large areas. Fig. 5 shows an area of 1000 km<sup>2</sup> which was modified on December 7, 1968 through seeding with 2400 g AgI, and Fig. 6 indicates the variation in the concentration of ice crystals as the seeded area moved over the observation site. Fig. 6 indicates local time vs concentration of snow

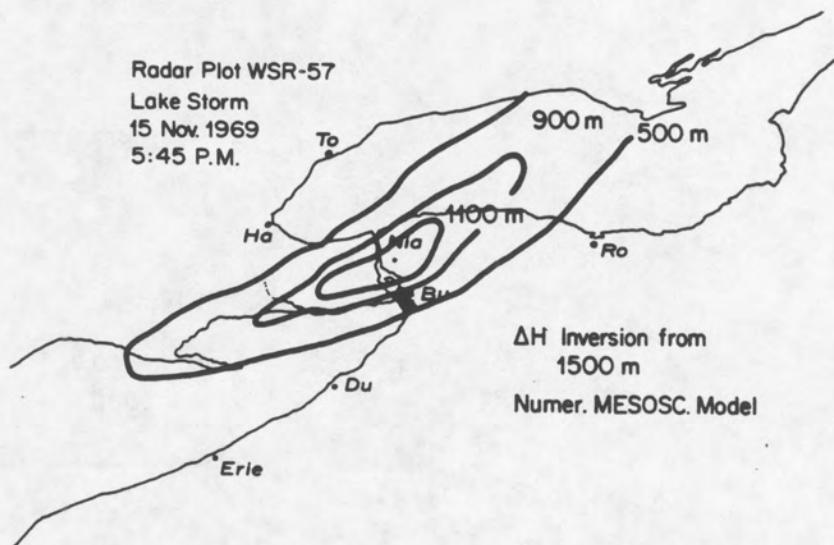


Fig. 3 Contour lines of increase of inversion height over initial value (1500 m) taken from Dayton, Ohio, morning radiosonde. Contour lines have been computed from meso-scale model following equation (1).

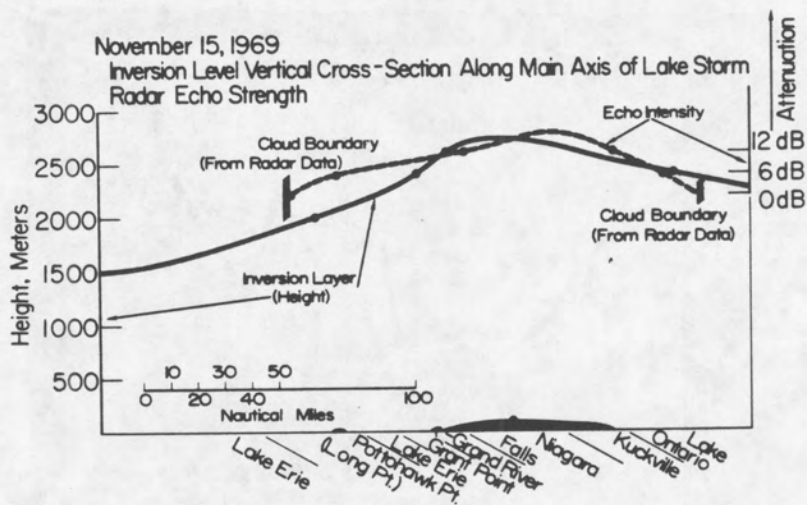


Fig. 4 Increase of inversion height and radar echo strength along storm axis.

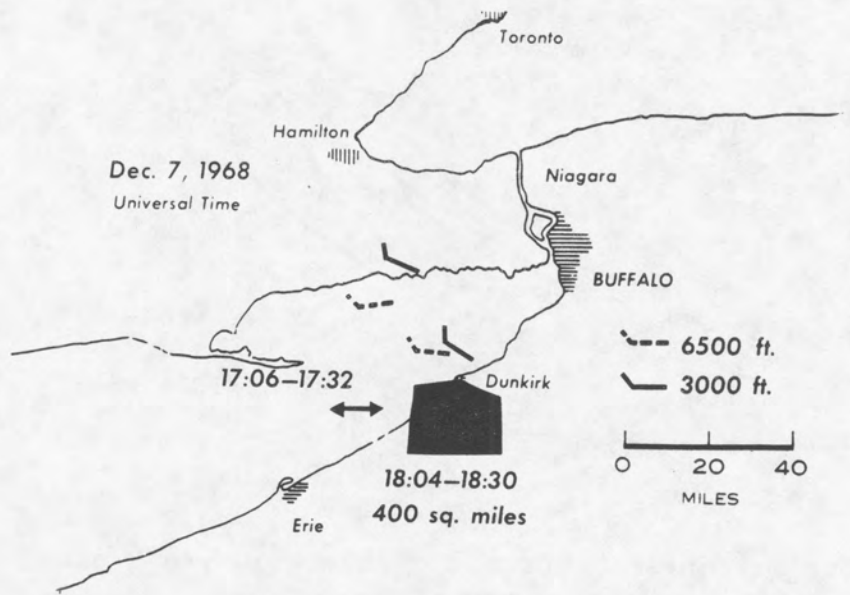


Fig. 5 Location and size of seeded area one hour after seeding began.

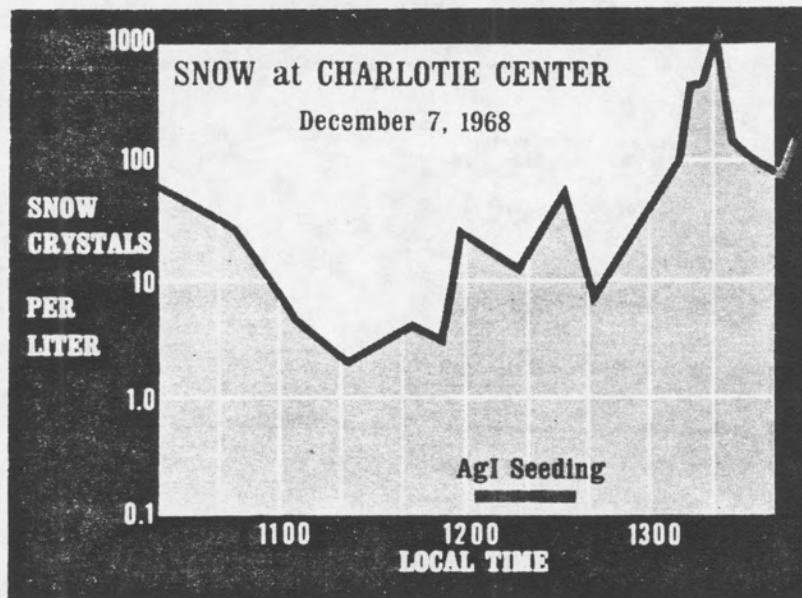


Fig. 6 Snow crystal concentration per liter before and during seeded area moved over observation site.

crystals. The seeding pulse is indicated from 1206 to 1232 EST (1706 - 1732 UT); during the period when the seeding area moved over the observation site, the concentration of ice crystals increased by a factor of 100. This case illustrates the very effective diffusion mechanism throughout the whole cloud volume as the seeding was accomplished at base level (500 meters) while the seeding effect was observed on cloud top due to the areal glaciation of the upper stratocumulus layer. The total cloud volume affected was about  $300 \text{ km}^3$ . The total number of dispersed nuclei in the temperature interval of the clouds amounted to  $4.8 \times 10^{16}$ , while the total number of liters in the volume modified was  $3 \times 10^{15}$ . This makes 16 nuclei per liter if they were equally distributed.

#### 5. Case study December 6, 1968

The average effect of seeding on the rate and type of precipitation was studied with a network of snow collecting stations whose snow yield was used for silver analysis with neutron activation methods. On December 6, 1968 a lake storm had developed in W-E direction through Dunkirk on the south shore of Lake Erie. Seeding with 2400 g AgI upwind of the storm caused the development of echos north of the natural storm. Silver analyses were obtained from six stations; one received snow directly from a cell which had formed in the seeded path. The silver content of the five stations was about 10 x background while the silver content of the cell which had formed in the seeding plume was 100 x background. ( $2.15 \pm 0.51 \times 10^{-9} \text{ gm Ag/ml}$  versus a background of  $2.09 \pm 0.58 \times 10^{-11} \text{ gm Ag/ml}$ ). Concurrent with this sample was a tenfold decrease of the rate of precipitation. From their analysis Warburton and Owens<sup>4</sup> conclude: "The occurrence of a high silver concentration coupled with a tenfold decrease in snowfall rate indicate that seeding may have caused more diffusional growth with a reduction in riming. The unrimed snow should have a significantly increased fallout time, and this may account for the low snowfall rate (at the station) during this sampling period".

#### 6. Targeting of seeding effect

We have observed that the proper targeting of the seeding effect sometimes presents great difficulties. The storm of December 6, 1968 was seeded in short sequence first with 2400 g AgI pyrotechnics at cloud base and then with 700 lbs dry ice on top. The detailed analysis of the radar echos which developed in both cases following seeding suggests that the AgI seeded areas moved with the upper level wind while the dry ice seeded areas moved with the lower wind. As the



coldest temperature in this cloud system was relatively warm ( $-11.7^{\circ}\text{C}$ ) we may assume that the dry ice due to its greater effectiveness at higher temperatures initiated cell development through release of heat of fusion, the cells moving with the wind at base level, while AgI seeding was just sufficient to stimulate precipitation. The artificial ice crystals ascended in the convective Benard cells and were discharged in the wind direction at cloud tops.

Another interesting case, December 3, 1969 is illustrated in Fig. 7. The figure gives the seeding path of the aircraft at various levels of 1500, 1800, and 2400 m. At the 1500 m level winds were from the NW. The cloud system reached to 2400 m where winds from W to WNW prevailed (see wind barbs along flight path). Subsequently after the seeding the downwind area was explored at the 1800 to 2400 m levels by aircraft for presence of ice crystals and high concentration of freezing nuclei. High counts are indicated in the drawing - they are distributed over a large area whose boundaries are determined by the low level as well as the upper level wind directions. It shall be noted that the entire area was filled with diamond dust. Radar analysis indicated a decrease of echo strength within the seeded area.

#### 7. Effect of surface seeding

The effective vertical diffusion of the seeding agent was studied on 4 December 1969 by the use of a surface AgI generator on the Canadian shore at Millers Point. It was planned to trace the AgI plume across the lake. Fig. 8 shows the flight path of the aircraft; flight level varied between 300 m and 700 m above water surface. The dots indicate the locations at which the AgI plume was found. During the second traverse near the American shoreline the points were high freezing nuclei counts were intermixed with snow showers which are located on the map. Since these were the only showers over the lake there was little doubt that they were caused by our seeding with one surface generator emitting 1600 g AgI/hour. The showers precipitated about 1 cm of snow per hour; the crystals were sector stars. This was a cloud situation where insufficient natural freezing nuclei existed to release precipitation which could be released artificially. We observed on 25 November 1969 that the aerosol generated by the Buffalo metropolitan area will also release snow showers under such cloud conditions.

#### 8. General Conclusions

We have observed that the lake storm precipitation systems have

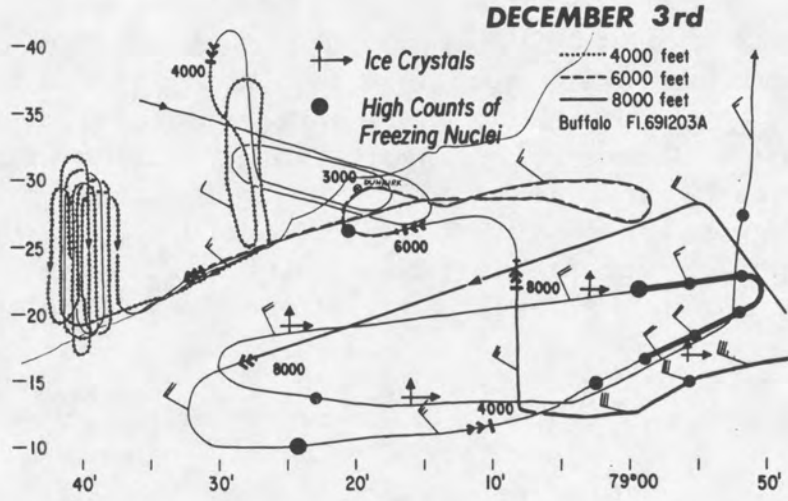


Fig. 7 Seeding path of aircraft on December 3, 1969.

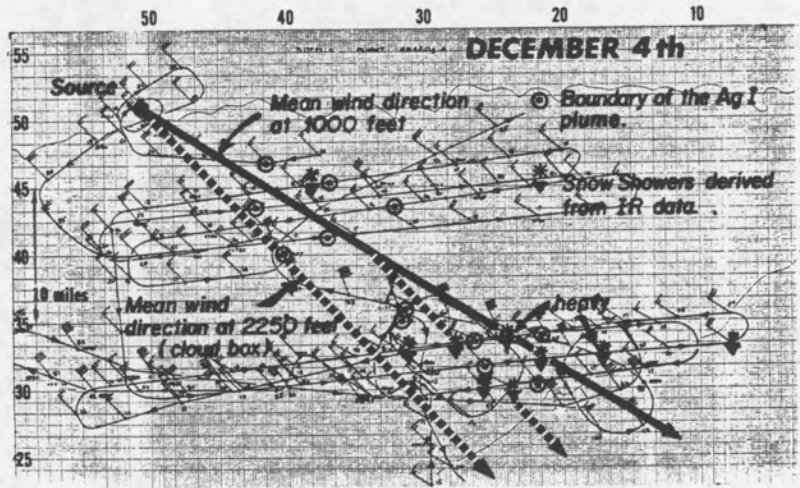


Fig. 8 Record of ground seeding with one AgI burner located on Canadian shore of Lake Erie. The figure contains the flight path for plume surveillance, winds at 300 m (1000 feet) and 700 m (2250 feet) above the water surface, and locations of the plume boundary as well as of snow showers found within the plume.

all a very typical cloud system which consists of a lower convective stratocumulus layer topped by one or sometimes two stratiform stratocumulus layers. They are potential precipitation systems if the entire cloud system is at least 2000 m thick. Type and structure of precipitation then depends on the temperature conditions and - of course - the existing vorticity and transfer of momentum and heat from the surface. Fig. 9 presents three different typical cases which we have experienced and which in our figure are differentiated by temperature only. The figure gives for each case the type of cloud system with approximate temperature boundaries, observations of the type of hydrometeors as well as in form of the international symbol the type of snow fall.

Case I. Case I was experienced in six cases during two seasons. With the coldest temperature being  $-12^{\circ}\text{C}$  very little natural precipitation is generated. (The natural background of freezing nuclei is between  $10^{-2}$  and  $10^{-1}$  per liter). The hydrometeors are a few graupel and heavily rimed stellar forms. As the clouds are of sufficient depth and water content seeding with either dry ice or AgI generates a sufficiently large number of ice crystals that snow showers develop. These showers can be moderate to heavy; Fig. 10 shows such heavy snow shower on November 29, 1968, following dry ice seeding at the cloud tops. When flying through the edges of the shower we could observe that large flakes had formed, this was also confirmed by surface observations. These cases have occurred with sufficient frequency and persistence that continuous seeding may precipitate sizable amounts of water or snow. We feel that this is a very important secondary result of this research.

Case II. Case II was experienced on four occasions. The natural concentration of freezing nuclei for the temperature range is now between .1 and 1 nucleus per liter, which is sufficient to initiate precipitation. The shape of the natural hydrometeors in that temperature range is made up of dendritic stars and sector stars, rimed and in flakes. We have noted on two occasions that after upwind seeding with 30 g AgI per minute the intensity of the radar echo decreased in the seeded plume. Observations from the aircraft indicated that the upper stratocumulus deck had been dissipated due to the heavy seeding rate. This circumstance eliminated the function of this layer as releaser cloud or generating cell of precipitating particles. The great number of small ice crystals which had formed due to seeding not only descended slower into the lower convective clouds, but also found less favorable growth conditions due to their slow fall velocity. On a previous occasion one of us had observed<sup>5</sup> when seeding a convective





cloud line that the crystals became discharged left and right of the cloud tops and did not grow into precipitation particles. A similar process may become active here also. We believe that the case of December 3, 1969, Fig. 7 belongs to this category.

Case III. Case III is most interesting as it is essentially the case of the persistent line storms. The concentration of natural freezing nuclei has advanced again by a factor of 10 and is now between 1 and 10 nuclei per liter. The crystals have assumed a different shape, and are now appearing as a spatial aggregate of dendrites or sector stars. These crystals are most effective scavengers of cloud liquid water<sup>6</sup> and they also aggregate easily into flakes. The flakes grow biggest if the basic crystals are spatial dendrites and rimed, smaller flakes form from spatial plate or sector crystals. As the low temperature guarantees abundant natural formation of snow crystals seeding of these storms will indeed increase their concentration and modify shape, riming and aggregation conditions, but it is likely that the rate of precipitation remains unaffected. Similar conditions exist in orographic snowfall seeding experiments<sup>7</sup>. This may explain why in the few cases of such storms the radar echo did not change after seeding in spite of an observed modification of the snow crystal forms. As the storm of December 6 belonged to this category we believe that refined modern analysis methods are necessary to verify the seeding effect - an effect which is the redistribution of the snowfall downwind.

#### 9. Model precipitation process

In Fig. 9 we have indicated the form of precipitation as shower precipitation. This is based upon doppler radar observations of updraft speeds in these cloud systems by the Cornell Aeronautical Laboratory Doppler radar stationed at Dunkirk. Up- and downdraft speeds of several meters have been observed in a Benard cell type arrangement as the line storm moved over the site. This observation indicates that the precipitation process is different from that of single cumulus clouds due to the fact that crystals may be dumped from one cloud into a neighboring cloud. Entrainment conditions particularly are different from those of single clouds.

The microphysics of the development of precipitation has been somewhat idealistically treated under the assumption of a mesoscale average updraft velocity of 20 cm/sec which is well below the fall velocity of even individual crystals.

## 10. Downwind effects

Fig. 1 suggests an interesting downwind effect of the large line storm over Lake Erie. One notices a void in the cloud pattern for a distance of 100 km downwind from the eastern end of the lake. It appears possible that the snowstorm has deposited the moisture influx into the lake and downwind shore areas, so that nothing remains for cloud formation downstream.

## 11. References

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