IMPLICATIONS FROM THE NORTH DAKOTA TRACER EXPERIMENT OF 1993 FOR THE GLACIOGENIC SEEDING OF SUPERCOOLED CONVECTIVE CLOUDS TO SUPPRESS HAIL

By Mark Bloomer and Andy Detwiler

During the summer of 1993, a study of thunderstorm and hail development, known as the North Dakota Tracer Experiment (NDTE), was conducted in the Bismarck, North Dakota region. The primary objective of this study was to examine airflow and hydrometeor transport through convective storms. The focus was on the development of flanking line cumulus clouds upwind of a primary thunderstorm cell, and on the airflow through and around these flanking line cumuli. One specific goal of the study was to determine if a mechanism existed for the transport of hail embryos between flanking line cells and the main cell and, if it did, what the nature of this mechanism might be. A second goal was to study the transport of simulated seeding material released according to procedures followed by the North Dakota Atmospheric Resource Board (NDARB) in their successful hail suppression work in western North Dakota. (See, e.g., Smith *et al.*, 1996.)

The NDTE study was designed to test the fundamental hypothesis upon which NDARB hail suppression treatments are based. This is that hail formation begins in the small cumulus clouds that comprise the flanking line of a convective storm. Within the cumulus clouds of a flanking line, frozen hydrometeors begin as tiny ice crystals which grow into graupel through a combination of riming and droplet evaporation-ice deposition. After the graupel grows to between one and two millimeters in diameter it is transported into the stronger updraft environment of the main cell where it may grow into hail. This transport might occur by some combination of two different processes. Either the flanking-line cell might grow to become the main cell in a multi-cellular storm, or it might merge into a pre-existing main cell in a super-cellular storm. (See, e.g., Krauss and Marwitz, 1984.) Many have suggested (e.g., Foote and Frank, 1983; Vasiloff *et al.*, 1986) that there is a continuum of storm structures between these two extremes. Vasiloff *et al.* (1986), for example, hypothesize that the main distinction between the two extremes is the distance at which new cells are triggered over the outflow boundary and the speed with which the new cells merge into the main storm structure. If the flanking cells form far enough away and fully develop before merging into the main storm, then the storm appears to be multicellular. If the flanking cells form near the main storm and merge before they fully develop, then the storm appears to be single-cellular.

Observationally, it has been difficult to observe transport of embryos from flanking cells (e.g., Musil *et al.*, 1986; Musil and Smith, 1989; Miller *et al.*, 1990) . Even so, the flanking line environment of a convective storm is believed by many to be necessary for the beginning stages of hail growth because updraft velocities in the main cell are generally too strong for prolonged growth at the low terminal velocities of ice particles in their early stages of development.

The procedure for examining air and precipitation particle flow through the flanking line cumuli during the NDTE involved the use of tracer materials including chaff composed of fine metallic fibers and the gaseous sulfur hexaflouride (SF_6). These materials were released at the bases of the flanking line cumuli by an aircraft in a manner similar to that in which silver iodide is released during hail suppression operations. The chaff cloud then was traced by radar and the SF_6 could be detected by instrumentation aboard research aircraft sampling in upper portions of both the flanking cumuli and the main storm. A National Oceanic and Atmospheric Administration (NOAA) circularly-polarized X-band radar system (NOAA-C) was able to distinguish between chaff and precipitation because the return from the linear chaff fibers was depolarized while that from the more spherically-symmetric precipitation particles was not. (See Martner *et al.*, 1992, for more discussion of this technique.)

A preliminary examination of results from two convective storm studies on 9 July 1993 is shown here to illustrate the nature of the air flow through flanking line cumulus clouds. (See Bloomer, 1995, for more details.) Two tracer experiments took place on this day. Both involved the release of chaff and SF_6 in updrafts at the bases of lines of cumuli flanking thunderstorms producing marble-size hail. In the first study the cells of the flanking line ceased their vigorous growth shortly after tracer release. Material released at cloud base (~10°C) did not rise above the freezing level, nor become incorporated into the main storm. The main storm was observed to contain mushy marble-sized hail and reflectivities approaching 60 dBZ during instrumented aircraft penetration at the -3°C level.

During the second experiment, however, the flanking cells continued to grow after tracer release and the tracers did become drawn into an updraft. Evidence that the tracer elements were drawn into an updraft is shown by radar observations of the chaff. The chaff was initially deposited at the base of a flanking line cumulus cloud by an aircraft at 18:54 (Fig 1). The flanking cells contained little precipitation at this time and the echo at low levels adjacent to the main storm is entirely due to chaff. After the chaff was deposited, radar showed it being drawn toward the main cell of the convective system at 18:56 (Fig 2). As it approached the main storm the chaff became drawn into an updraft. By following the maximum in the circular depolarization ratio (CDR, depolarized returned power divided by total.returned power) the chaff was observed to enter an updraft at 19:00. Fig 3 shows the chaff being drawn upward and toward the main convective system.

An aircraft penetration of this updraft at the 6 km (-15°C) level at 1855 UT detected SF_6 and revealed a sharply defined updraft. (Fig 4 and 5). Vertical velocities within this updraft region ranged between 10 and 14 m s^{-1}. The presence of this updraft offered evidence that a transport mechanism from the base of the flanking line cells upward and toward the main cell existed. The updraft region penetrated was that of a cell which had begun as a flanking line cell but was merging with the main

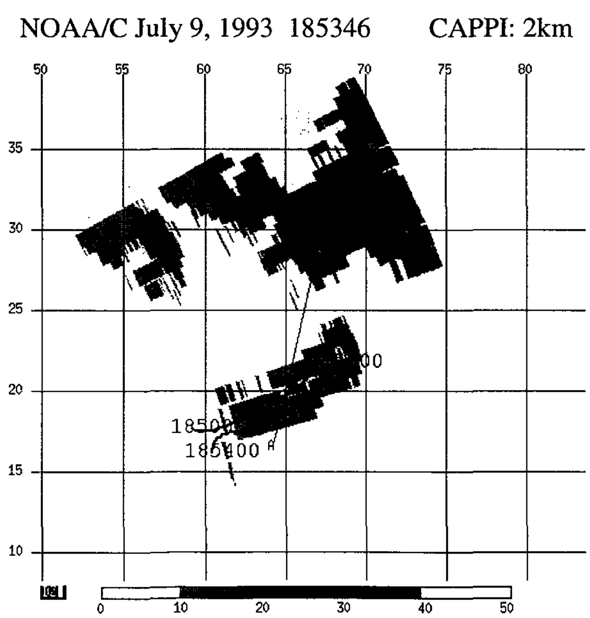

Figure 1a: Equivalent X-band radar reflectivity of a sector of the storm region at the 2 km MSL level at 1854 CDT just at the end of the tracer release period. The oval-shaped reflectivity pattern centered near 20 km N, 65 km E from the NOAA/C radar is due to chaff. The track of the chaff-release aircraft is shown using a dark line, with times indicated at 1-min intervals. Grid labeled in km from the radar site.

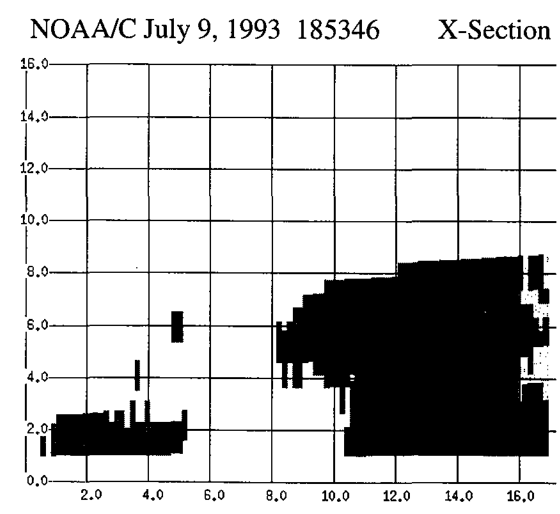

Figure 1b: Vertical cross-section of equivalent radar reflectivity along the line A-B indicated in Fig. 1a. The chaff is seen at the left, near 2 km MSL. The main storm is seen to the right with peak reflectivities exceeding 40 dBZ, and probably reduced by effects of attenuation. The isolated radar echoes at 6 km and 4 km, over the chaff, are from 2 additional research aircraft penetrating echo-free flanking-line turrets over the area of tracer release. Grid labeled in km from the radar site. (Figures 1-3 provided by Dave Priegnitz, SDSM&T.)

body of the storm and perhaps growing into a new main cell. Further aircraft penetrations of the updraft at the 6 km level could not be attempted as it subsequently merged into the main storm and reflectivities were too high for safe operation of the aircraft employed. A more-heavily-armored aircraft-penetrating below through both the flanking line and main storm at the 3.5 km level did not encounter SF_6 but did encounter mm-size graupel in the flanking cells and marble-size hail in the main storm region.

One goal of this study of thunderstorm transport processes is to increase knowledge of storm processes in a way which will help develop improved strategies for hail suppression. Specific interest is in using glaciogenic seeding agents to increase the number of hail embryos in flanking line convective cells. This concept is based on the hypothesis that a greater number of embryos will increase the competition for available supercooled water in a main cell updraft. This, in turn, may cause individual hailstones to grow less large which will increase the chances that they melt before they reach the ground and reduce damage at the ground.

If a glaciogenic seeding agent, such as silver iodide, had been released at the base of the flanking line cells in place of the tracer materials employed on this day and if the seeding produced no dynamic effect, the seeding agent would have followed the same path as was observed for the tracers. In the first storm, none of the agent would have risen above the freezing level. There could have been no microphysical or dynamical effects. In the second storm it would have been drawn into the updraft and carried to high levels in a cell very closely flanking the main storm, but remained below the freezing level elsewhere. In the latter case, the updraft was so strong, between 10 and 14 m/s, that any ice crystals which the agent might have induced to form would likely have been carried aloft into the upper reaches of the storm cloud before growing large enough to overcome the strength of the updraft. Upper-level downdrafts may later have brought ice particles from aloft back to mid- and lower levels of the cloud where they might have interacted with cloud water in an adjacent updraft and become embryos for hail. However, the concept of seeding in order to generate increased concentrations of mm-size ice particles at

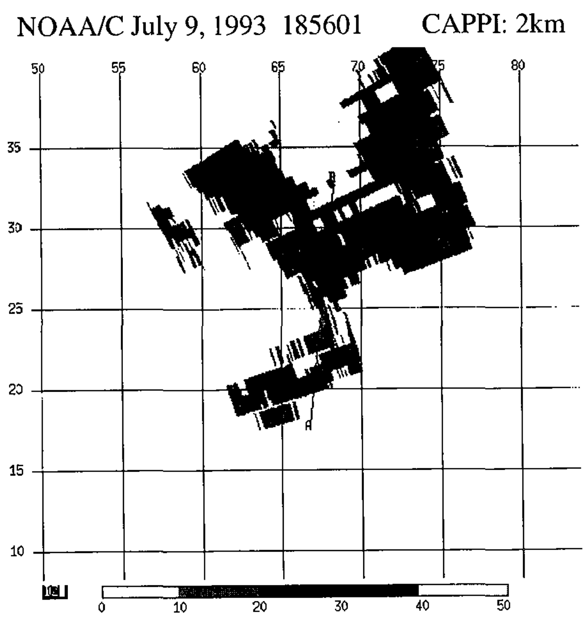

Figure 2a: As in Fig. 1a, but for time 1856 CDT. The chaff loop is being drawn in toward the main storm.

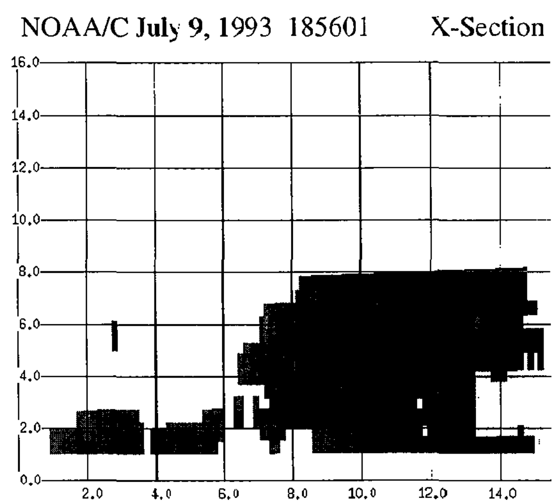

Figure 2b: As in Fig. 1b, but for time 1856 CDT, and along line A-B in Fig. 2a. The chaff can be seen rising at the end of the oval nearest the main storm. The isolated echo near 6 km altitude at 3 km from the left is the uppermost of 3 research aircraft employed in this study.

NOAA/C July 9, 1993 190027 CAPPI: 2km

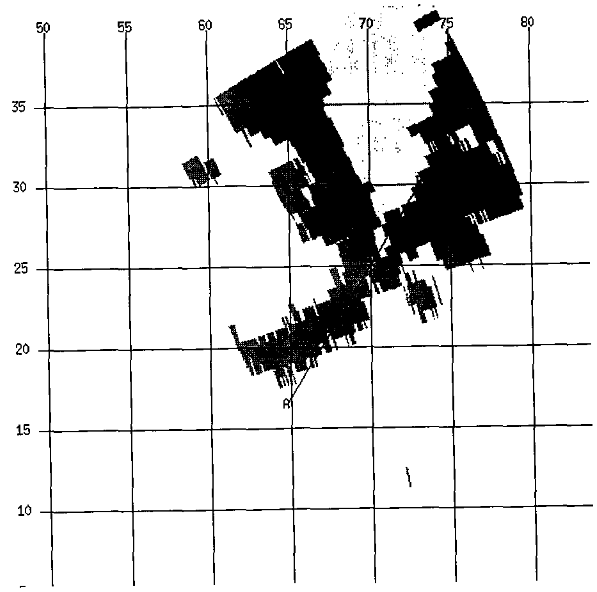

Figure 3a: As in 1a, but for the 1900 CDT. The chaff can be seen merging with the main storm.

NOAA/C July 9, 1993 190027 X-Section

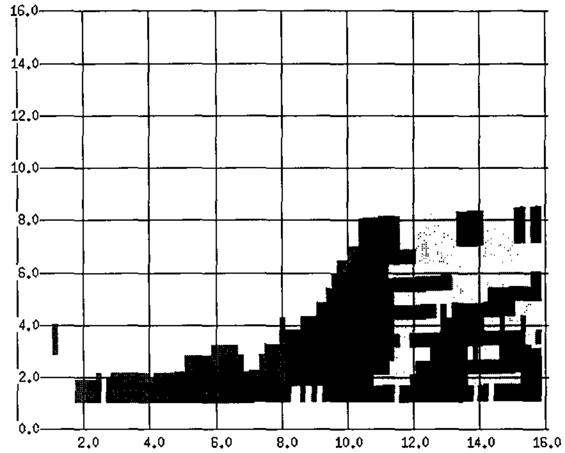

Figure 3b: As in Fig. 1b, but for time 1900 CDT, and along the line A-B in Fig. 3a. The chaff can be seen rising with the main storm. The isolated echo near 4 km altitude at 1 km distance from the left is from the middle of the 3 research aircraft employed in the study.

NOAA/C July 9, 1993 190027 CAPPI: 2km

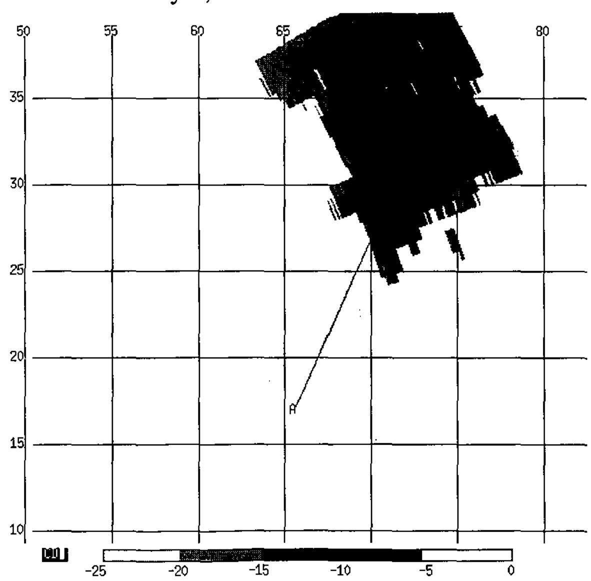

Figure 3c: CDR signature corresponding to the reflectivity pattern presented in Fig. 3a. A value of -10 dB would indicate 10% depolarization. The chaff produces CDR ≥-5 dB at this level and can easily be distinguished from precipitation echo.

NOAA/C July 9, 1993 190027 X-Section

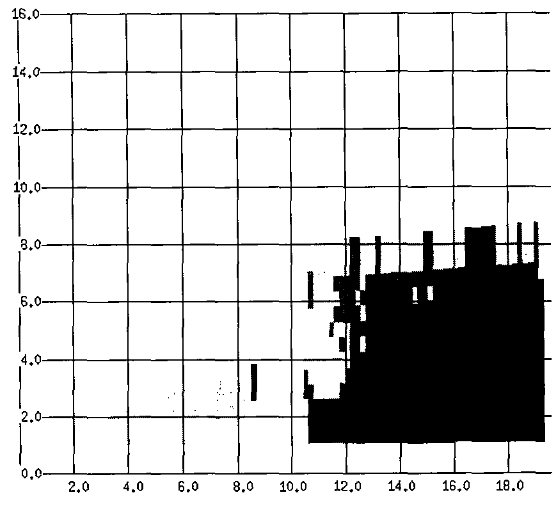

Figure 3d: CDR signature corresponding to the reflectivity pattern presented in Fig. 3b. Chaff can be seen rising above 4 km in this plane.

mid-levels in modest updrafts within flanking cells does not fit the observations described here. It should also be noted that there are no reports from the ground, nor any *in situ* aircraft measurements, indicating that either storm produced damaging hail.

Glaciogenic seeding of flanking cells of storms may be successful in increasing graupel concentrations if the cells which are targeted are seeded early enough and they rise above the freezing level well before they merge into the main storm. The seeding agent which is applied to the storm must have time to form ice crystals within the flanking line cloud, and the ice crystals must have time to grow into mm-size graupel at a rate which is commensurate with long residence time in the increasing updraft in the newly developing flanking cell. The time for flanking line cumulus to grow to cumulonimbus may be no more than several minutes, so early detection and early targeting of newly forming storm cells is important to significantly affect, by seeding, the amount of hail that falls from a storm.

The cases described here show that effective cloud base seeding may only be possible in some selected circumstances, and not in all storms exhibiting flanking line development. Other seeding strategies, such as direct injection into supercooled regions, might be more appropriate when development is rapid, as in the second tracer release discussed here.

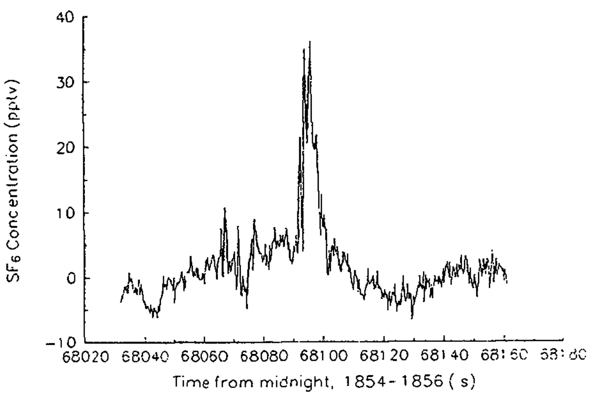

Figure 4. SF_6 mixing ratio during aircraft penetration of flanking cell near 1855 CDT at 6 km MSL (T~ -15°C).

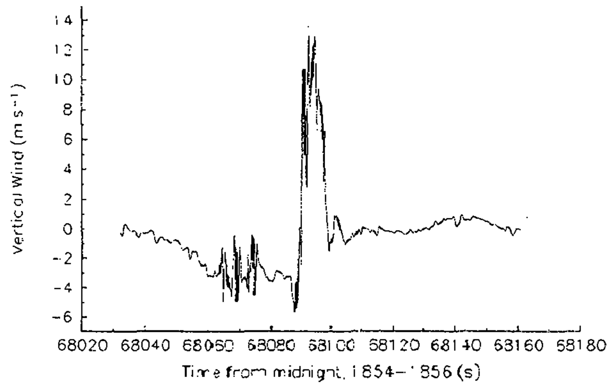

Figure 5. As in Fig. 4, but showing vertical wind. (Figures 4 and 5 provided by Dr. Jeffrey Stith, U. of North Dakota.)

REFERENCES

Bloomer, M. C., 1995. Hail embryo formation and transport in High Plains convective storms. M. S. Thesis, South Dakota School of Mines and Technology, Rapid City, SD. 156 pp.

Foote, G. B., and H. W. Frank, 1983: Case study of a hailstorm in Colorado. Part III: Airflow from triple-Doppler measurements. *J. Atmos. Sci.*, **40**, 686-707.

Krauss, T. W., and J. D. Marwitz, 1984: Precipitation processes within an Alberta supercell hailstorm. *J. Atmos. Sci.*, **41**, 1025-1034.

Martner, B. E., J. D. Marwitz, and R. A. Kropfi, 1992: Radar observations of transport and diffusion in clouds and precipitation using TRACIR. *J. Atmos. Ocean. Tech.*, 9, 226-241.

Miller, L. J., J. D. Tuttle, and G. B. Foote, 1990: Precipitation production in a large Montana hailstorm: Airflow and particle growth trajectories. *J. Atmos. Sci.*, 47, 1619-1646.

Musil, D. J., A. J. Heymsfield and P. L. Smith, 1986: Microphysical characteristics of a well-developed weak echo region in a High

Plains supercell storm. *J. Clim. Appl. Meteor.*, **25**, 1037-1051

Musil, D. J., and P. L. Smith, 1989: Hail growth processes in an Alberta hailstorm. *J. Wea. Mod.*, **21**, 65-72.

Smith, P. L., L. R. Johnson, D. L. Priegnitz, B. A. Boe, and P. W. Mielke, Jr., 1996: An exploratory analysis of crop-hail insurance data for evidence of cloud-seeding effects in North Dakota. (Submitted to *J. Appl. Meteor.*, under review).

Vasiloff, S. V., E. A. Brandes and R. P. Davies-Jones, 1986: An investigation of the transition from multicell to supercell storms. *J. Clim. Appl. Meteor*, **25**, 1022-1036.

Acknowledgments:

Support for this work was provided under NOAA Fed-State Cooperative Agreement NA27RA0178-01 through grants North Dakota Atmospheric Resource Board ARB-IAS-93-1, ARB-IAS-94-1, and ARB-IAS-95-1 and by the National Science Foundation through grant NSF ATM-9221528, and cooperative agreements ATM-9104474 and ATM-9401117. Brooks Martner (NOAA), Jeffrey Stith (U. of North Dakota) and Dave Priegnitz (SDSM&T) assisted with data analysis and interpretation.