The North Dakota Tracer Experiment: Tracer Applications in a Cooperative Thunderstorm Research Program

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Abstract

Radar chaff and sulfur hexafluoride gas were used in the North Dakota Tracer Experiment to tag air parcels which were subsequently tracked through actively growing convective clouds and sampled by cloud physics aircraft and Doppler radars. The scope and objectives for this cooperative thunderstorm research program conducted in south-central North Dakota during June and July 1993 are presented. The project organization and resulting data base are summarized, and the course of analysis efforts charted.

1. INTRODUCTION

Western North Dakota is one of the permanent high hail incidence areas in the upper Great Plains and midwestern United States. Changnon (1984) attributed the high hail incidence to synoptic scale factors including high frequencies of cyclone and cold front passage in the summer. This makes the region of interest contrast to the location of other recent major hailstorm studies (the Black Hills of South Dakota, northeast Colorado, or central Alberta) where orographic factors play a prominent role. North Dakota suffers the highest dollar loss due to crop damage by hail of any state (Changnon 1977), and the southwestern corner of North Dakota has historically had among the highest crop-hail insurance loss costs in the United States.

Interest in hail suppression and rainfall augmentation has driven operational weather modification efforts in North Dakota for over three decades (Rose 1986, Boe 1992). From the early 1950's to the present, convective clouds have been treated with glaciogenic nuclei each June, July, and August. While the first efforts were undertaken with ground-based generators, seeding since 1961 has been exclusively airborne. Nuclei have been released within updrafts at cloud base and within supercooled updrafts by direct penetration. Numerous evaluations have been conducted of the impacts on rainfall (Eddy and Cooter 1979, Schaffner *et al.* 1983, Johnson 1985) and on hail damage (Butchbaker 1970, Smith *et al.* 1987, Johnson *et al.* 1989), and of possible combined effects (Smith *et al.* 1992). All of these evaluations suggest positive results, providing the sponsoring counties ample encouragement for continuing the program.

Still, lack of complete understanding of the physical effects of the seeding fueled speculation as to the cause of the perceived effects. The need to explore and document these processes was recognized, and in 1978 the National Oceanic and Atmospheric Administration's (NOAA's) Federal-State Cooperative Program in Weather Modification Research, now known as the NOAA Atmospheric Modification Program (NOAA/AMP) was born (Reinking 1985). Through this initial funding, the North Dakota Atmospheric Resource Board (ARB) began to coordinate efforts aimed at addressing the uncertainties of their operational seeding program, starting with the transport of seeding agent from the release aircraft into updrafts encountered below rain-free cloud bases. Early on it was decided that a "chain of events" approach would be taken, in which each step in the seeding process would be identified and experimentally examined to test the operational methodology. The data collection efforts began with instrumented aircraft, radars, and other equipment sampling clouds in a brief 1984 field program. Follow-on investigations were conducted in 1985, and on significantly larger scales in 1987, 1989 (the North Dakota Thunderstorm Project, Boe *et al.* 1992), and most recently, the 1993 North Dakota Tracer Experiment, reported herein. This paper examines the objectives of the North Dakota efforts, the approach employed, and provides an overview of the data base assembled through the 1993 field effort.

2. OBJECTIVES

The goals and objectives of the North Dakota program are summarized in Tables 1 and 2. In general, the short-term goals are those which appear fairly straightforward and on which specific efforts are already in progress; the long-term goals those which are predicated on the completion of the short-term goals.

Table 1. Long-Term Goals	
1.	Determine and quantify the physical processes that lead to the development of rainfall in northern Great Plains convective clouds.
2.	Determine the physical processes which result in the production of hail, and develop means to predict hail formation *a priori.*
3.	Improve the understanding and predictability of weather hazards, including damaging winds and cloud-to-ground lightning, on the northern Great Plains.
4.	Determine the feasibility of significantly altering the hail and precipitation formation processes towards improved agricultural productivity.

The more numerous short-term objectives listed in Table 2 are in most cases considerably more specific, but none are trivial. To date significant progress has been made in addressing Short-Term Goals (1), (2), (3), and (8). Additional progress has been made with Short-Term Goals (5) and (6). A single season's cloud-to-ground lightning data have been examined in the course of initial attempts to address (7). While some progress has been made towards goals (4) and (9), much work remains with these objectives. Data which will allow (10) and (11) to begin to be addressed have been collected during the NDTE field effort.

3. FACILITIES

Facilities employed in the NDTE are summarized in Table 3; locations for most are shown in Fig. 1. All aircraft, the C-band Doppler radar, and the project Operations Center were based at the Bismarck Airport. The X-band radar was deployed ~50 km west of the Operations Center (see Fig. 1).

Regional surface weather data were recorded by the *North Dakota Agricultural Weather Network* (NDAWN, Enz *et al.* 1992), operated by North Dakota State University and UND Aerospace. A 900-member statewide volunteer network (not shown) is maintained by the ARB which records daily precipitation and reports hail.

Atmospheric aerosols were sampled from the operations center, and aerosol samples collected aloft by the Citation were processed immediately after each flight, affording some quantitative feel for ice nucleus and cloud condensation nucleus concentrations.

Table 2. Short-Term Goals	
1.	Determine the cloud-scale transport, dispersion, entrainment, and mixing processes in High Plains cumulus and cumulonimbus.
2.	Determine whether glaciogenic seeding agents, as applied in the ongoing county-sponsored operational cloud seeding project, reach and fill the targeted (supercooled) portion of the treated cloud.
3.	Determine the dominant primary ice initiation mechanism(s) in Northern High Plains cumuliform clouds.
4.	Determine what concentrations of artificial ice nuclei are required to significantly influence the precipitation process.
5.	Employ appropriate cloud models to simulate seeded and non-seeded cloud conditions, and compare the results of the simulations to: a) observations of similar real clouds, and b) the expected cloud behavior based on the seeding conceptual model.
6.	Apply *in situ* aircraft, tracer, radar, and other data to verify various aspects of the cloud models.
7.	Examine the effects of seeding on cloud-to-ground lightning production in and out of operational seeding target areas.
8.	Conduct preliminary assessments of benefits accrued from seeding in North Dakota.
9.	Determine the relation of cloud transport, glaciation and precipitation processes to cloud structure, organization, and life cycle using radar, satellite, aircraft, and other observations in conjunction with numerical simulations.
10.	Characterize northern Great Plains atmospheric aerosols (cloud condensation nuclei and ice nuclei) which influence cloud processes near the surface and aloft.
11.	Identify the conditions and circumstances under which warm-cloud precipitation processes are important in northern Great Plains convective clouds.

This and previous field efforts in North Dakota have combined radar measurements with *in situ* aircraft sampling in building a foundation of knowledge on the

TABLE 3. NDTE Facilities		
AIRCRAFT	Agency	Function
Cessna Citation II	UND	Cloud physics, tracer detection
North AmericanT-28	SDSMT	Cloud physics, tracer detection
Beechcraft Duke	WMI	Tracer release
RADARS		
X-Band Doppler Radar	NOAA/ETL	TRACIR, radar reflectivity, Doppler velocity
C-Band Doppler Radar	UND	Radar reflectivity, Doppler velocity
SUPPLEMENTAL		
CLASS Mobile Sounding System	NCAR	Proximity soundings
McIDAS	ARB	Satellite imagery display, archival
National Lightning Detection Network	ARB	Cloud-to-ground lightning detection
Forecasting Workstation	AES	Upper air forecasting, analysis
Aerosol Sampling Equipment	CSU	IN and CCN measurement
Numerical Modeling Workstation - SD	SDSMT	Predictive numerical cloud modeling
Numerical Modeling Workstation GCE	NASA/GSFC	Predictive numerical cloud modeling
North Dakota Ag. Weather Network	UND/NDSU	Regional weather observations
ND Cooperative Raingauge Network	ARB	Daily rain and hail reporting

AES - Atmospheric Environment Service, Winnipeg, Manitoba, Canada
ARB - North Dakota Atmospheric Resource Board, Bismarck, North Dakota
CSU - Colorado State University, Fort Collins, Colorado
NASA/GSFC - National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, Maryland
NCAR - National Center for Atmospheric Research, Boulder, Colorado
NDSU - North Dakota State University, Fargo, North Dakota
NOAA/ETL - National Oceanic and Atmospheric Administration, Environmental Technologies Laboratories, Boulder, CO
UND - University of North Dakota, Grand Forks, North Dakota
WMI - Weather Modification, Inc., Fargo, North Dakota

cloud scale. These modest field programs have remained focussed on the specific objectives of the ND/AMP. The North Dakota PI's remain dedicated to this concept, sometimes termed "medium-sized science", in which the goals always remain in sight, and the scale of the field programs never becomes so large that focus is lost or that conflicting demands for the data collection resources dilute the effort.

Part of this approach includes the belief that documentation of natural processes will ultimately allow the verification of the effects of cloud seeding efforts. That is, the most direct means of demonstrating the efficacy of the technology will be through physical measurements of the storms themselves, and ***not solely by statistical evaluations***. This approach allows verification of targeting of the seeding agent, while enabling more to be learned about cloud processes. Thus, inconsistencies in the seeding conceptual model can be identified and corrected.

Some improvements over earlier North Dakota field programs included simultaneous release of radar chaff and SF_6 from the *same* aircraft, aircraft tracking by GPS (global positioning system) rather than FAA flight tracks, real-time downlinking of aircraft positions directly to the operations center, and real-time display of the Duke tracer release aircraft position relative to the Citation tracer detection aircraft *within the cockpit of the detection aircraft*. Another very important addition was the sampling of atmospheric aerosols which are believed to play a critical role in the determination of storm precipitation efficiency (Stith *et al.* 1992). The NDTE also employed a mobile Cross-chain Loran Atmospheric Sounding System (CLASS) to obtain soundings in the vicinity of the subject cloud complexes.

The experiments were designed to gather detailed microphysical information (*in situ* aircraft sampling), afford in-cloud tracing capability (SF_6 detection), reveal detailed cloud structure (radar reflectivity data) and internal cloud motions (Doppler velocity data, sometimes coordinated dual-Doppler scanning), and provide cloud-scale transport information. The dual-circularly-polarized NOAA radar can differentiate between echoes resulting from chaff and meteorological echoes through the use of the circular depolarization ratio (CDR), a technique dubbed TRACIR, for TRacking of Air with CIrcularly-polarized Radar (Moninger and Kropfli 1987, Martner and Kropfli 1989, Martner *et al.* 1992).

4. INFRASTRUCTURE

Research efforts were directed from an Operations Center collocated with the UND Doppler radar at the Bismarck Airport. The UND radar was controlled from the Operations Center through a fiber-optic link to the radar van. In addition to the radar reflectivity and Doppler velocity displays, the Operations Center contained the ARB's McIDAS workstation; the NLDN lightning display station; VHF and FM radio links to project aircraft and the NOAA radar, respectively; direct radio downlinks from the project aircraft; and an AES workstation with software for a variety of forecasting/nowcasting tasks, including sounding analysis.

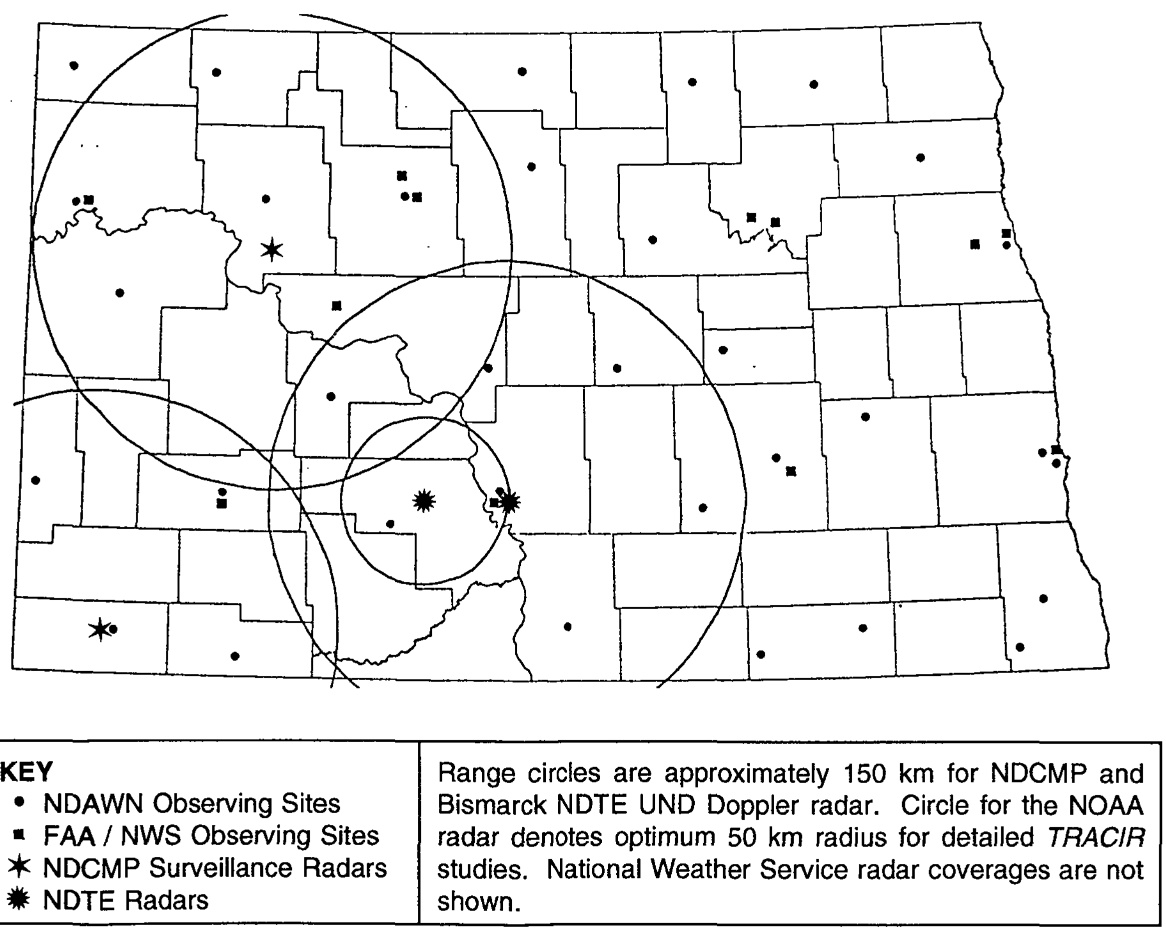

Figure 1. The NDTE facilities and supporting data collection sites.

A numerical modeling workstation which accessed an NCAR Cray supercomputer to run the SDSMT two-dimensional, time-dependent cloud model (*e.g.* Kopp and Orville 1994); and another which accessed either the UND Aerospace Cray or the Goddard Space Flight Center Cray (depending on which was affording better speed) to run the NASA Goddard Cumulus Ensemble (GCE) cloud model (Stith and Scala 1993) did so through Internet connections via the North Dakota University System.

Aircraft positions reported by on board GPS receivers were telemetered to the Operations Center, processed into the radar data stream, and displayed in real-time on the PPI's as they were refreshed. For continuity, a series of past positions was displayed for each aircraft, creating a "tail" behind each aircraft plotted.

Within the Operations Center, activities were coordinated by an Operations Director (OD), aided by an Assistant Operations Director (AOD). Three persons served as OD on a continuous nine-day rotation, wherein each individual would be free from duty for three days, then became the AOD for three days, and finally the OD for three days. In that manner, the AOD always became the OD prior to having days off, ensuring continuity in the day-to-day conduct of data collection efforts.

Storm intercept activities and the mobile CLASS team were directed by the Intercept Coordinator, with input from the OD. All project aircraft were directed by the Aircraft Coordinator. During operations, nowcasting was handled by a team from the ARB and the Atmospheric Environment Service (AES) Prairie Weather Centre, Winnipeg, Canada. When dual-Doppler sampling of a subject cloud was appropriate, coordinated scanning by project radars was directed by the Radar Coordinator, always an experienced Doppler radar meteorologist. A Research Experience for Undergraduates (REU) program, sponsored by the National Science Foundation (NSF), allowed students from universities nationwide to participate in the NDTE field effort (*e.g.* Orville and Knight 1992). On a rotating basis, the students served on storm intercept and the mobile CLASS teams. They ran a one-dimensional cloud model daily, served as assistants to the forecasters and radar coordinator, and worked with the research aircraft crews, flying on board the UND Citation when circumstances allowed. Without the REU students, the program could not have been conducted as it was.

5. DATA COLLECTION

Fourteen discrete experimental designs were set forth in the *NDTE Field Operations Plan.* At least one attempt was made at conducting every experimental design except one. Designs were explicitly expressed in the field operations plan document by number, title, and a discussion of the experimental procedure. Required facilities were also listed, and reference illustrations provided where applicable. The design for Experiment One is presented herein as Figs. 2 and 3. Other designs are presented in the *NDTE Field Operations Plan.*

Experiments were designed to address the following hypotheses which reflect various aspects of the conceptual model for hydrometeor development:

26 *Experimental Designs*

Experiment 1

TRANSPORT AND HYDROMETEOR EVOLUTION IN FEEDER CLOUDS

Mid-cloud Treatment

Reference Illustration: Fig. 4.1.

	Summary:	A volume of air in an individual tower in the flanking line of a mature storm will be tagged with tracer(s) and (on about one-third of the cases) seeding agent during a single pass at mid-cloud. Treatment may include any combination of the following: (a) SF_6, (b) **X-band chaff**, (c) **AgI-AgCl aerosol**, and (d) **fluorescent particles** (FP). Subsequent sampling of treated cloud turret and neighboring cells will be done by aircraft and radar, with collection of hailstones at the ground in case (d). The T-28 will penetrate at mid-cloud levels (around -8°C), in cells evolving into/merging with the mature (main) cell, while the Citation penetrates the same cell near cloud top. A subsequent treatment pass (or passes) will be flown by the Duke, at intervals of approximately ten minutes or so, depending on the time required for the treatment aircraft to return to the cloud. Aircraft penetrations will continue until the subject cloud (1) grows too intense to safely penetrate, (2) dissipates, or (3) evolves so that the original cloud volume can no longer be identified.
Facilities:	Aircraft:	Duke and Citation or T-28, or all three.
	Radar:	Both preferred, can be done with either radar alone when circumstances preclude using both due to range or storm position.
	Surface:	Mobile CLASS, Storm Intercept Teams (especially for FP/hail experiments.)

Figure 2. *Description for NDTE Experiment 1 as it appeared in the Field Operations Plan. The schematic for Experiment 1 is shown in Figure 3.*

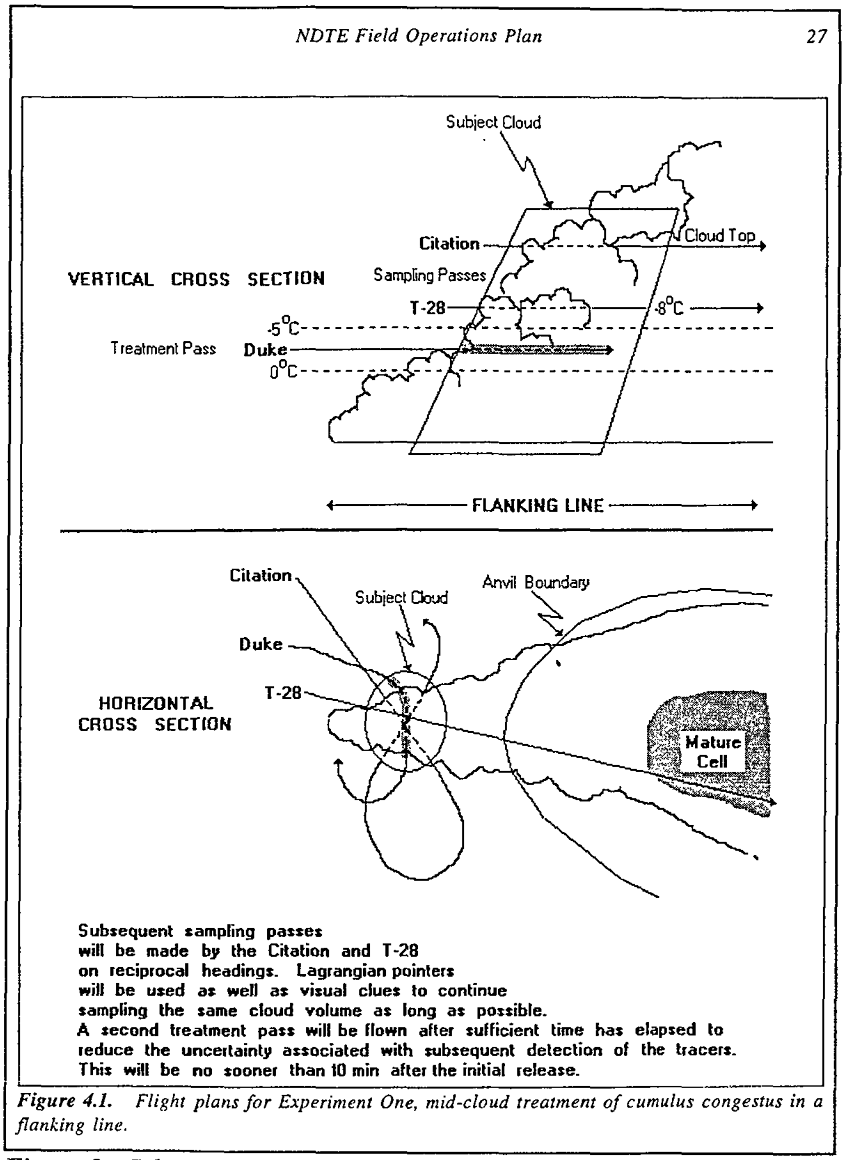

***Figure 3.** Schematic for Experiment 1 as it appeared in the Field Operations Plan.*

1. Transport at mid-levels between feeder cells and adjacent mature cells in a multicell thunderstorm can be a significant source of hailstone embryos.

2. Transport of seeding material upward from the base of a feeder cloud occurs initially in narrower plumes, but by the time the -10°C level is reached, dispersion across the updraft region is substantially complete.

3. The transport time from cloud base to the -10°C level in cumulus congestus is a significant fraction of the lifetimes of most such clouds.

4. Material in updrafts at mid-cloud levels in cumulus congestus disperses across updraft regions fairly rapidly.

5. Cloud-top entrainment occurs mainly by transport of air from above the cloud downward into the cloud periphery, followed by ingestion through the cloud sides.

6. The evolution of ice particles that nucleate and grow in clouds with weak vertical motions (and hence at roughly constant temperature) matches that observed in cloud chamber experiments.

Of the fourteen experimental designs, eleven were based on the sampling of convective clouds. Two of the remaining three were predictive numerical cloud modeling experiments; the other, aerosol sampling, was conducted with or without pre-existing convection.

The forty-day period proved to be extraordinarily active both in terms of convective activity and precipitation. The Bismarck National Weather Service precipitation total for the month of July was 34.9 cm (13.75 inches), the wettest for any month since records had been kept beginning in 1885. The disbenefit to such abundant precipitation from the scientific viewpoint was that often skies were excessively cloudy, and coordination of aircraft on subject storms was more difficult than would have normally been the case.

Clouds within range of the dual-Doppler radar coverage and, depending upon experimental intent, within range of the NOAA radar, were given priority over those in other areas. Clouds outside the primary research area identified above, but within aircraft range (about 150 km of the C-band Doppler radar) were considered for experimental purposes only when no suitable candidates could be found in preferred locations. Feeder cloud studies were accorded the highest priority, and were conducted whenever circumstances allowed. Cumulus congestus experiments were given the next highest priority, with subcloud thermodynamic studies assigned the lowest priority.

The NOAA radar was able to employ the circular depolarization ratio (CDR) signal from chaff (released by the Duke) to track the chaff *within the greater cloud volume.* Chaff was released above cloud tops, at cloud bases (in updrafts), in lines through the mid-cloud regions, and in circles in clear air around the perimeters of the clouds at various altitudes. Quantitative estimates of chaff concentration can be computed in post-processing from the radar reflectivity of the chaff measured by the cross-polarized channel.

The mean Doppler velocity and variance of the Doppler velocity spectrum were also routinely measured and will be useful in studies of turbulence and chaff dispersion rates. In most cases chaff and SF_6 were released simultaneously. The Citation and T-28 subsequently detected the SF_6 while collecting microphysical, thermodynamic, kinematic, and electric field measurements during cloud penetrations. The *in situ* microphysical and tracer measurements complement the large-scale continuous CDR measurements of the chaff. Narrow sector scans centered on the treated cloud maximized the spatial and temporal resolution of the NOAA radar data. Resolution of about 150 m in *x, y,* and *z* dimensions was achieved within a range of 30 km of the radar. Occasional 360° sweeps made by the C-band radar provided surveillance of the storm environment.

Additional objectives that did not compete for resources with the higher priority experiments were also addressed as circumstances allowed. These include radar studies of storm evolution and electrification, which in many respects are natural by-products of the other experiments. Such studies could be conducted with or without aircraft participation, so they were prime candidates for late-day or nocturnal studies. Also included were dual-Doppler radar studies which were conducted when storms of interest passed sufficiently close to the radars, and when aircraft were not engaged in coordinated tracer studies requiring the radars to operate in other modes.

About two-thirds of the NDTE experimental clouds were to have been treated with SF_6, or SF_6 and chaff only (no-seed treatment), and the other third with SF_6 and AgI aerosol as well (seeded treatment). This approach would have allowed comparison of the AgI-treated regions with the non-seeded regions to quantify differences in ice initiation and development. Recent work at the Colorado State University (CSU) Cloud Simulation Laboratory has documented the rates of nucleation and numbers of effective silver iodide nuclei for different water-to-ice conversion mechanisms (DeMott 1990). However, only a few clouds were actually treated with seeding agent, as the record wet July weather made even the appearance of rainfall augmentation activities undesirable after 8 July.

The attempts made to execute each of the fourteen experimental designs appear as Table 4. In addition to the numerical modeling and aerosol sampling experiments (Experiments 9, 10, and 12) conducted almost daily, 62 cases were conducted according to the other experimental designs. Days with multiple experiments of a single type are indicated in Table 4 by parenthetical numbers in the "Dates Conducted" column.

6. ANALYSIS PLANS

Interactions and collaborations are *essential* for the satisfactory completion of analyses. For example, the storm morphology of the 1 July 1993 Bismarck hailstorm (described in Sec. 6.1) is being explored jointly by scientists at UND Aerospace, NSSL, and ETL. Once the morphology is established, studies of ice initiation and subsequent development of rain and hail by researchers at SDSMT, UND, and CSU will be provided a larger scale context. The behaviors of the storm will be examined by numerical modelers at NASA and SDSMT, who will compare their respective predictive models with the field observations.

One of the strengths of the NDTE data base is that specific clouds and cloud systems were sampled simultaneously on the microphysical level, the turret-scale (chaff and SF_6), the storm scale (two Doppler radars, ground-based storm intercept teams), and the synoptic scale, supplemented by proximity upper air soundings and the NDAWN surface weather data. The most complete pictures of the subject storms can only be developed by examining all relevant data, which reaffirms the need for intensive collaboration among individual analysts and agencies/universities.

There are three categories of the NDTE analysis efforts:

*1. **INDIVIDUAL CASE STUDIES,** of experiments like that described below, to elucidate details of the transport, dispersion, ice initiation and hydrometeor evolution processes in the context of the cloud environment and flow fields deduced from the Doppler radar and aircraft observations. The intent will be to obtain a comprehensive description of the cloud under study, and evaluate our understanding of the processes taking place within it, in comparison to the various hypotheses being tested.*

*2. **ANALYSES OF GROUPED EXPERIMENTS,** e.g., all cases of Experiment 1, to assess the implications with respect to the applicable experimental hypotheses. These analyses can include any applicable experiments from the 1989 North Dakota Thunderstorm Project. They can also consider how well the experimental designs worked out in practice, and identify changes that might improve the designs for future projects.*

*3. **NUMERICAL MODELING SIMULATIONS,** in support of the foregoing analysis thrusts. Investigations of cloud processes by modeling have an advantage in that individual components which contribute to specific aspects of cloud development can be isolated more readily.*

Table 4. NDTE Experiments

Aircraft and Radar Experiments

No.	Title[1]	Cloud Class	Treatment Agent(s)[2]	Treatment Location	Dates Conducted
1	Transport and Hydrometeor Evolution in Feeder Clouds	Cb, feeder clouds	Chaff, SF_6, FP	mid-cloud (linear)	22 June, 1 July, 3 July (5), 8 July (2), 15 July, 18 July (2)
2	Transport, Dispersion, and Hydrometeor Evolution in Feeder Clouds	Cb, feeder clouds	Chaff, SF_6	cloud base (orbit)	1 July, 6 July, 9 July (2), 23 July, 27 July
3	Transport, Dispersion, and Hydrometeor Evolution in Cu Cg	TCu	Chaff, SF_6, AgI	cloud base (orbit)	6 July, 27 July
4	Dispersion and Hydrometeor Evolution in CuCg	TCu	Chaff, SF_6, AgI	mid-cloud (linear)	22 June, 25 June, 29 June, 30 June, 1 July (2), 8 July, 27 July
5	Entrainment and Hydrometeor Evolution in CuCg	TCu	Chaff, SF_6	upper cloud (linear)	24 June (3), 25 June, 14 July, 15 July (2), 23 July
6	Entrainment and Hydrometeor Evolution in CuCg	TCu	Chaff, SF_6, AgI	upper cloud edge (orbit)	30 June (2), 22 July (2), 25 July
7	Subcloud thermodynamic Studies	Flanking line	Chaff, SF_6	cloud base	none
8	Anvil Studies	Mature Cb	Search for SF_6, O_3, electricity studies, microphysics		1 July, 3 July, 27 July
11	Thunderstorm Evolution Studies	Cu to Cb	none	N/A	1 July, 9 July (2), 22 July
13	First Echo Development	Cu	none	N/A	1 July, 16 July, 23 July, 25 July
14	Area-Time Integral Studies	Mature Cb	none	N/A	22, 23, 29 June, 1, 8, 15, 16, 21-22, 22-23, 26-27 July

Real-time Numerical Modeling Forecasting Experiments

No.	Title	Model	Computing Facility	Initialization	Dates Forecasts Made
9	Real-Time Two Dimensional Cloud Modeling[3]	SDSM&T 2D-TD	NCAR CRAY Y-MP	BIS NWS, CLASS	22-25, 27, 29-30 June, 1-3, 5-7, 9-10,12-16,18-28, 30 July.
10	Real-Time Predictive Utilization of the Goddard Cumulus Ensemble (GCE) Model[4]	Goddard Cumulus Ensemble	UND CRAY X-MP, or Goddard CRAY Y-MP	NGM forecast soundings	22 June, 24-25 June, 27 June - 3 July, 5-9 July, 12-16 July, 18 July, 20-27 July, 30 July.

Atmospheric Aerosol Measurement Experiment

No.	Title	Equipment	Measurement Locations	Sampling Dates
12	Aerosol Sampling, Surface and Aloft	Continuous flow diffusion chamber, CCN counter	Operations Center at Bismarck Airport, airborne samples collected at altitude by UND Citation	Daily from the Operations Center on 5-23 July. Airborne samples: 6 July, 8 July, 14 July, 18 July (2), 23 July (2)

[1]For complete descriptions of each experimental design, refer to the NDTE Field Operations Plan.
[2]Treatment may have utilized any or all of the listed agents, depending upon cloud size and position relative to the radars. "FP" denotes fluorescent particles (coated polystyrene beads) of approximately 300 μm diameter.
[3]Support provided by the National Science Foundation.
[4]Support provided by NASA Goddard Space Flight Center.

6.1 A Case Day Sample - 1 July 1993

A series of modestly tall (11-12 km) but intense thunderstorms formed in west-central North Dakota during the afternoon of 1 July 1993. These storms moved through the Bismarck area in succession, producing heavy rains and some very damaging hail. The first deep convection occurred west of Bismarck at ~13:00 CDT, when a number of cells developed southwest of the Bismarck operations center. Aircraft began working the cells by 15:00, with a mid-cloud release of chaff and tracer gas as described in Experiment 1. The first storms were sampled by radar and all three project aircraft until after 16:00, when aircraft returned to Bismarck to refuel.

The second storms of the day began as isolated cells which quickly became very intense, exploding along a north-south line west of Bismarck and subsequently moving southeast into the research area. The three largest of these storms all produced mesocyclonic circulations detectable with the UND Doppler radar. At one point distinct mesocyclones were simultaneously observed north of Bismarck, just north of the NOAA radar, and west-southwest of Bismarck! The strongest of these storms tracked directly over south Bismarck, inflicting an estimated $30 million in damages to vehicles, homes, and other property. Though the mesocyclone of the Bismarck storm was unmistakable, no funnels or tornadoes ever developed. This might be attributable to the storm's prolific rain and hail production and associated outflow which repeatedly cut off the spinning up mesocyclone.

The early stages of this storm's development were recorded by the NOAA radar, which was located ~20 km south of the first mesocyclone, and also by the UND radar. Dual-Doppler analyses will be possible for much of the storm's lifetime. A cloud base tracer release (Experiment 2) was conducted beneath a vigorous tower in the flanking line as well, and the cell was located favorably for hail trajectories to be calculated from Doppler analyses. The chaff was quickly carried aloft and toward the higher reflectivity regions of the mature cell (Figs. 4 and 5). As the chaff and SF_6 were transported upward and mixed into the storm, the Citation and T-28 penetrated the cloud, tracking the progression of the SF_6 while documenting the microphysical evolution within the treated volume.

A *third* round of storms of the day formed as a squall line ~100 km northwest of the operations center. An upper wave moved into the state and added some dynamic support to a surface frontal boundary. This line became well organized while still west of the NOAA radar, producing heavy rains and surface winds in excess of 30 m s^{-1} as it passed that radar. The squall line remained intense as it quickly caught up with the isolated storms of round two, absorbing them about 50 km east of Bismarck.

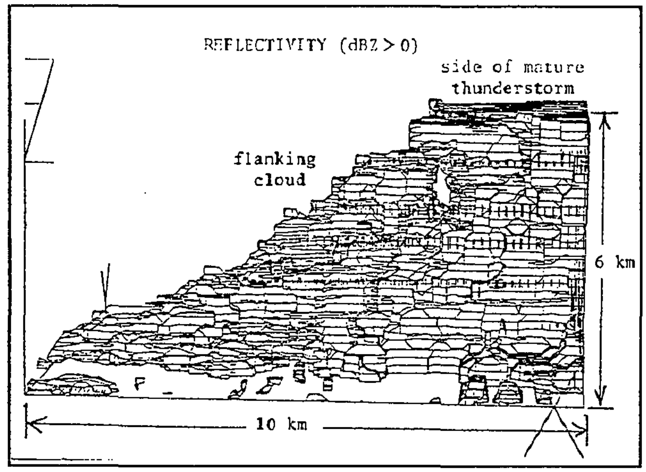

***Figure 4.** Three-dimensional reflectivity reconstruction of thunderstorm flanking line recorded by the NOAA radar at 18:12 CDT, 1 July 1993.*

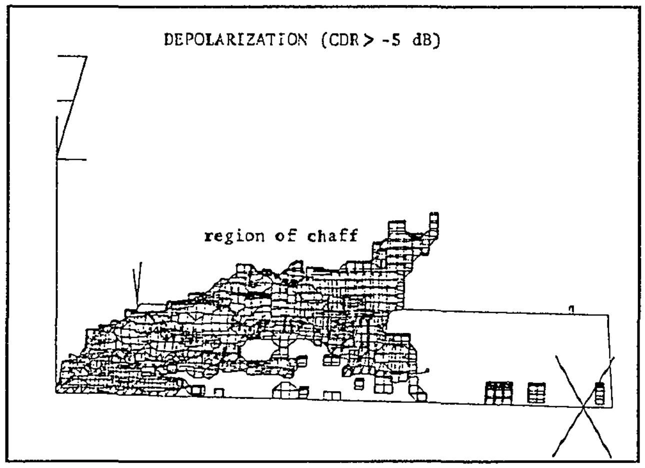

***Figure 5.** The depolarization defines the approximate chaff boundary at 18:12 CDT, 6 min after a chaff-SF_6 release on 1 July 1993.*

Confluence at the base of the updraft on the order of 25 m s^{-1} was recorded as the line approached the operations center.

7. CONCLUSIONS

The success of the NDTE data collection efforts demonstrates that productive, medium-sized field programs remain possible. If core programs are defined and funded with sufficient advance notice, additional scientists with compatible interests are provided the lead time required to bring additional resources to the field, greatly strengthening the overall program-- offering more "bang for the buck".

A year or more is often required before review, revision, and funding occurs.

Real-time aircraft tracking using GPS data telemetered directly to the project operations center is a significant improvement on FAA positioning data, particularly when the nearest FAA radar is well-removed from the project area. Radar skin paints of project aircraft were commonplace, confirming the accuracy of the system. The use of GPS is made even more attractive by FAA regulations which now require considerable paperwork just to request access to the FAA data stream. Such requests must now be routed through the Department of Defense and the Drug Enforcement Agency as well as the FAA, a process which requires a lead time on the order of one year.

The simultaneous use of cloud physics aircraft and Doppler radars in combined chaff/gas tracer experiments affords the cloud microphysics to be examined in the context of cloud-scale motions and structure, particularly if one of the radars is circularly-polarized and capable of TRACIR studies. Radars employed in the NDTE were characterized by beam widths less than 1°, and many cases were within less than 50 km range, so considerable detail was recorded which supports the microphysical data collected by the aircraft.

The transport, dispersion, and mixing within the subject clouds carries strong implications for the behavior of plumes of seeding agent within targeted clouds. In this respect alone, the chaff/SF_6 experiments afford the following opportunities:

1. ***Comparisons of the chaff data with the in situ tracer data.*** Such analyses may reveal the concentration of the tracer in the various parts of each storm. The *in situ* tracer offers the relatively high spatial resolution (~100 m), while the radars provide documentation of essentially the entire cloud volume. This data set affords the first opportunity to apply these techniques used simultaneously.

2. ***Documentation of the in situ microphysics*** (particle size spectra, hydrometeor types and habits) and the dynamics (up- and down-drafts, turbulence, buoyancy) in the tagged regions, at least until cloud growth renders the turrets impenetrable.

3. ***Determination of the destinations of tagged regions***, especially as the tagged regions initially become incorporated into the mature storm cloud volume. The progression of the chaff can be used to continue to follow parcels beyond the point where Citation (and most other aircraft) can continue to safely penetrate the subject clouds (into hail growth regions). This is a first-of-a-kind opportunity to determine the trajectories of the air (and small hydrometeors, to the extent they remain with the parcels) in and near convective storms.

4. ***Integration of the results of (2) and (3) above with larger-scale storm structure*** as determined by analysis of radar reflectivity and Doppler velocity data. Dominant or recurrent storm features may be identifiable, particularly as they relate to ice initiation and hydrometeor development.

5. ***Comparisons of the results of (2), (3), and (4) above with the output of the numerical cloud models*** used during the NDTE in real-time. This will aid in validation of these models. For example, both of these models can produce parcel trajectories for comparison with observed clouds. Mechanisms responsible for observed storm behaviors may also be identified.

6. ***Comparisons of the behavior and hydrometeor development within tagged regions*** also containing AgI with similar tagged but unseeded parcels. In essence this makes use of the limited seeding done in the NDTE as a perturbation tool.

7. ***The in situ measurements present an opportunity to compare measured dispersion rates under a variety of cloud conditions.*** On a number of experimental days multiple encounters with the SF_6 plumes were recorded by both the Citation and T-28. Turbulence on these days ranged from light to severe. Observed tracer gas concentrations can be compared to turbulence measured by the Citation, using the approach used by Weil *et al.* (1993).

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