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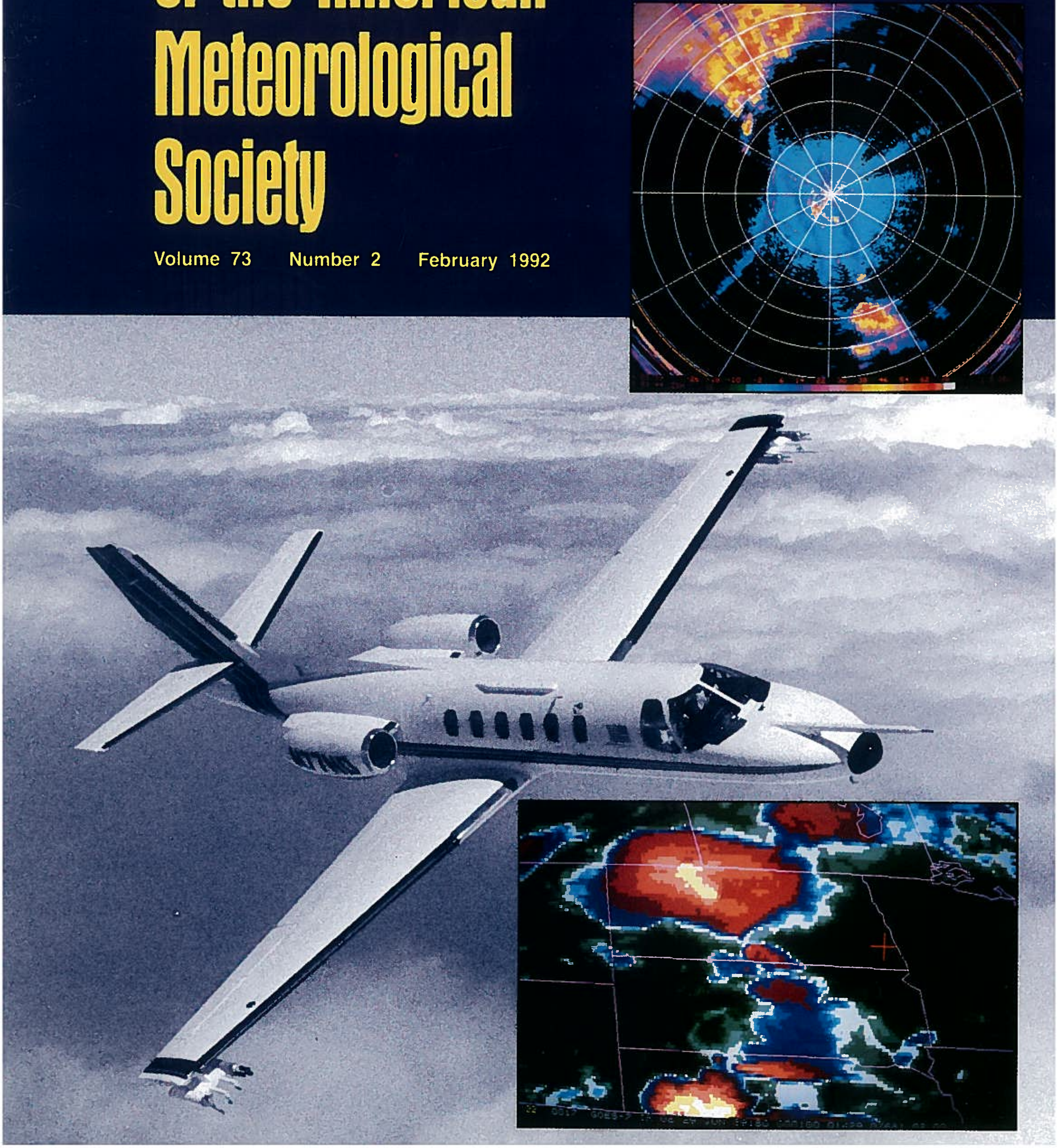

Cover: Upper left-hand panel shows a cloud-to-ground lightning flash that occurred in a deep "hot tower" on 18 January 1989 in Darwin. Upper right-hand panel shows a branching in-cloud discharge near the base of a stratiform anvil cloud. MIT radar radome is in the foreground. Lower right-hand panel shows the MIT radar and antenna system, which was located at Koolpinyah, about 50 km east of Darwin. Lower left-hand panel shows a vertical cross section of a thunderstorm observed by the MIT radar near Darwin on 5 December 1989 with reflectivity tops near 18 km AGL. (Please see article by Rutledge et al, p. 3.)

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The North Dakota Thunderstorm Project: A Cooperative Study of High Plains Thunderstorms

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Abstract

The North Dakota Thunderstorm Project was conducted in the Bismarck, North Dakota, area from 12 June through 22 July 1989. The project deployed Doppler radars, cloud physics aircraft, and supporting instrumentation to study a variety of aspects of convective clouds. These included transport and dispersion; entrainment; cloud-ice initiation and evolution; storm structure, dynamics, and kinematics; atmospheric chemistry; and electrification.

Of primary interest were tracer experiments that identified and tracked specific regions within evolving clouds as a means of investigating the transport, dispersion, and activation of ice-nucleating agents as well as studying basic transport and entrainment processes. Tracers included sulfur hexafluoride (SF_6), carbon monoxide, ozone, radar chaff, and silver iodide.

Doppler radars were used to perform studies of all scales of convection, from first-echo cases to a mesoscale convective system. An especially interesting dual-Doppler study of two splitting thunderstorms has resulted.

The objectives of the various project experiments and the specific facilities employed are described. Project highlights and some preliminary results are also presented.

1. Introduction

The North Dakota Thunderstorm Project (NDTP) was conducted on the northern High Plains in the vicinity of Bismarck, North Dakota, from 12 June through 22 July 1989. The project brought together significant resources to study many of the dynamic and microphysical characteristics of northern Great Plains convection. Much of the Dakotas, especially the western portions, relies almost exclusively on thunderstorms for timely growing-season precipitation. Irrigation is generally not practical in these largely agricultural regions, except for those few areas fortunate enough to be near the Missouri River or its major tributaries. Crop hail damage is also a major problem, with some areas experiencing losses exceeding 10% annually (Changnon 1977). Consequently, these agricultural areas live and die by the thunderstorm.

County-sponsored operational cloud seeding for precipitation enhancement and hail suppression has been ongoing for more than 30 years in North Dakota (Rose 1986). Aircraft directed from radar-equipped operations centers seed feeder clouds in flanking lines with glaciogenic nuclei (Boe et al. 1990). The North Dakota Atmospheric Resource Board (ARB) manages the operational program and has been an active participant in the NOAA Federal–State Cooperative Program in Atmospheric Modification Research (NOAA/AMP) since that program's inception in 1980. A physical chain-of-events approach has been adopted in the North Dakota research, emphasizing field experiments and numerical modeling to follow the seeding agent and various tracers (sulfur hexafluoride, radar chaff) into supercooled cloud, and to study the resulting microphysical effects (Stith et al. 1986; Stith and Benner 1987; Stith and Politovich 1989; Stith et al. 1990).

The core program for the NDTP included one aircraft for release of tracer and seeding agents, two cloud-physics/tracer-detection aircraft, two C-band Doppler radars, and a circularly polarized X-band Doppler radar. A NOAA WP-3D aircraft provided an additional airborne X-band Doppler radar, greatly increasing the workable project area. The NSF provided two additional aircraft for cloud physics and atmospheric chemistry work, and also supported atmospheric electricity studies, numerical cloud modeling, hail sensor development, and student participation in the field.

Primary project sponsors were NOAA/AMP and the

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+++NOAA/ERL National Severe Storms Laboratory, Norman, OK.

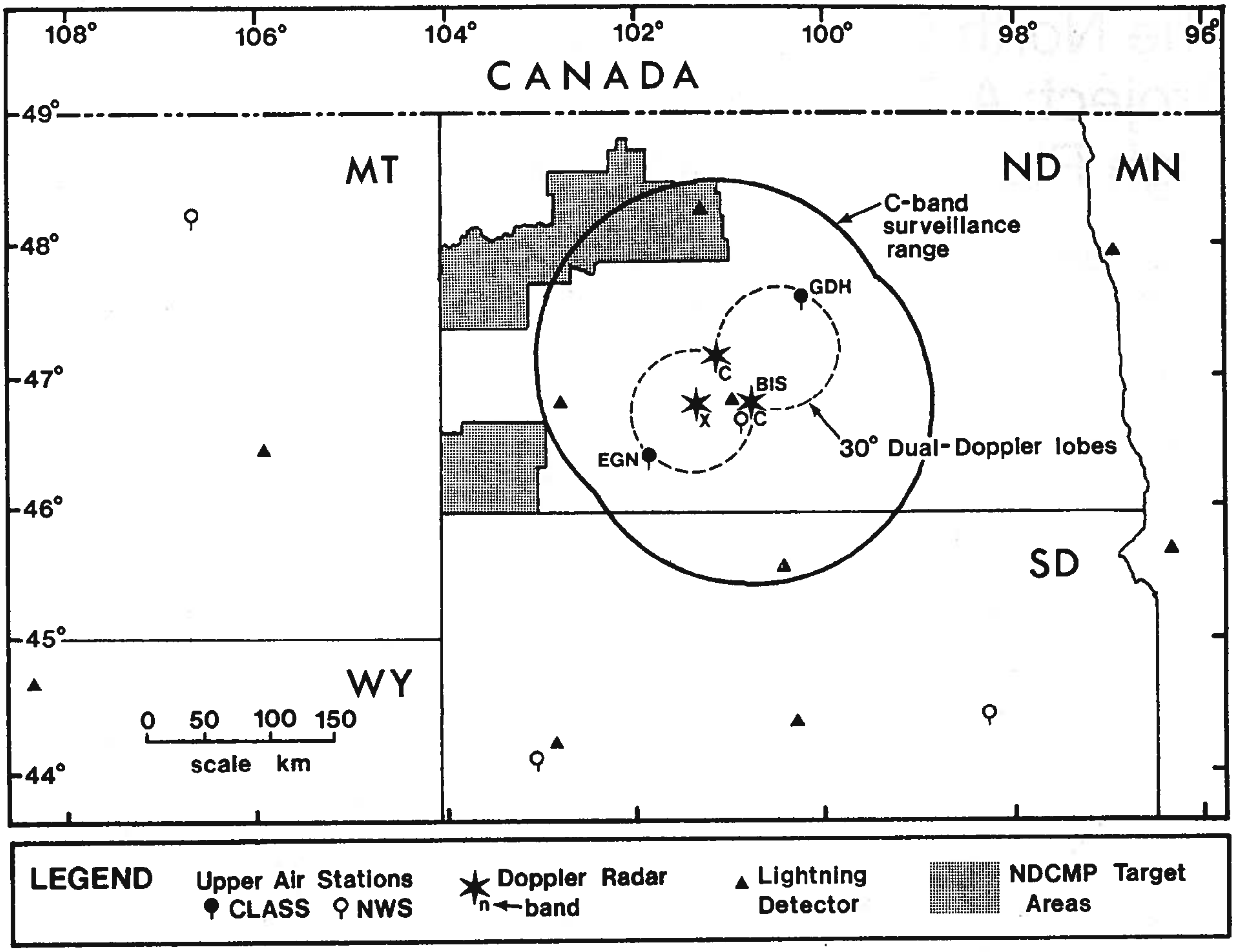

FIG. 1. The North Dakota Thunderstorm Project operations area. Stippled areas denote counties participating in the North Dakota Cloud Modification Project, an operational program attempting hail suppression and rainfall enhancement.

state of North Dakota, but many other agencies also contributed. NOAA's National Severe Storms Laboratory funded the field presence of an experienced Doppler radar meteorologist. The U.S. Bureau of Reclamation provided a tristatic Doppler acoustic sounder and personnel to assist with ground-based tracer experiments. The North Dakota Army National Guard provided support facilities for the NOAA WP-3D aircraft, and the Air National Guard lent the services of a special chaff-release aircraft on two occasions. The Bismarck NWS Forecast Office (NWSFO) assisted with the continuous recording of their WSR-74C radar data for surveillance/backup purposes. The National Center for Atmospheric Research (NCAR) funded the field presence of a senior scientist, who developed and supervised the photographic aspects of the program.

Figure 1 shows the NDTP operations area and locations of observing systems. Thirty scientists from 15 institutions participated in the field program. The project combined the instrumented aircraft with the surface-based Doppler radar network and other supporting instrumentation in coordinated studies of meteorological processes. The primary research area was central North Dakota, separate from the operational cloud-seeding program in the western end of the state, thus avoiding potential airspace conflicts. This separation also greatly increased the number of untreated clouds that passed through the Doppler network, and enabled all multiple-aircraft case studies to be conducted within the airspace controlled by a single Air Route Traffic Control Center (ARTCC). All six project aircraft were based in Bismarck, which optimized communications and aircraft coordination.

2. Background

The most recent intensive convective storm research on the northern Great Plains prior to the NDTP was the 1981 Cooperative Convective Precipitation Experiment (CCOPE) conducted in eastern Montana

(Knight 1982). When the CCOPE field effort occurred, the NOAA Federal–State Cooperative Program in Atmospheric Modification Research (initially known as the Weather Modification Program) had been in place just one year, with North Dakota and Utah being the charter states. The following year, Illinois and Nevada joined the program, which was conceived to better understand the physical processes in clouds, particularly those being treated with glaciogenic nuclei.

The North Dakota investigations began by examining the assumptions long made in that state's operational cloud-seeding program, which focuses on hail suppression and rainfall enhancement in convective clouds. This review suggested that obtaining measurements to verify the first steps in the chain of seeding events should have the highest priority.

The questions to be addressed first related to the primary mode of treatment of North Dakota clouds, and included the testing of seeding agents, evaluation of targeting methods, and estimations of the microphysical impacts of glaciogenic seeding (e.g., Miller et al. 1983; Stith 1983). Specific questions posed were: a) After glaciogenic nuclei are released at cloud base, how consistently do they fill the appropriate supercooled cloud regions? b) Are the expected amounts of ice crystals actually being produced by the agent? c) What influence do these artificially generated ice particles have on the hail and rain processes? These questions had not previously been addressed in detail, and the processes had not been documented in vigorous convective clouds. The early studies also included assessment and redevelopment of the conceptual models in use.

The SF_6 technique provides a new tool to better document the initial activation of the ice in the cloud, and assists interpreting the aircraft measurements.

Well-maintained, carefully monitored acoustical ice-nucleus counters can provide qualitative estimates of AgI nuclei concentrations in clear air (Super 1974; Heimbach and Stone 1984; Super et al. 1988). However, such estimates become more difficult in precipitating clouds because of activation and scavenging of the nuclei. In addition, more quantitative estimates of nuclei concentrations are often desired. One solution is to track not the AgI itself, but rather a simultaneously released inert tracer having a dispersion rate and terminal velocity similar to the AgI seeding plume. A suitable gaseous tracer is sulfur hexafluoride (SF_6), which exists in low natural concentrations and is insoluble in water (Stith et al. 1986). Recent developments in tracer technology have made it possible to detect SF_6 in parts per trillion in near-real time (Benner and Lamb 1985).

Once ice has been nucleated, it grows and falls away from the tracer plume, typically after about 10 to 50 min, depending upon the cloud-ice growth environment. The SF_6 tracer helps quantify nuclei concentrations only in the initial ice activation region, and may aid in identifying situations when there is persistent activation of AgI nuclei in the treatment plume. Comparisons of SF_6 plumes in similar seeded and unseeded clouds also may help identify conditions conducive to the generation of aircraft-produced ice particles (APIPS).

The application of SF_6 tracer techniques to study transport, dispersion, and the activation of ice nuclei in convective clouds was begun in 1984, and revised and reapplied during subsequent field investigations in 1985 and 1987 (e.g., Stith et al. 1990). In the course of these early field experiments, the required release rates were determined and the methodology to optimize the frequency of plume detection was refined (Stith and Benner 1987).

The SF_6 technique provides a new tool to better document the initial activation of the ice in the cloud, and assists interpreting the aircraft measurements. However, the aircraft cannot sample enough of the cloud to map the full extent of the treatment plume. The remote-sensing capability afforded by Doppler radar and other new radar techniques described below were used to sample larger cloud volumes in the NDTP.

3. Conceptual models and research objectives

a. The physical chain of events

Both the rainfall enhancement and hail suppression concepts employed in North Dakota's operational cloud-seeding program postulate that cloud precipitation efficiencies suffer from a deficiency of ice nuclei active at temperatures of −10°C and higher. The precipitation process within the continental clouds of this region is most often dependent upon ice-phase processes. For cumulus congestus or larger clouds having sustained updrafts of a few meters per second, appreciable supercooled liquid water, and low ice-particle concentrations (less than a few per liter), it is hypothesized that well-timed, well-targeted seeding with glaciogenic nuclei will greatly accelerate precipitation development.

Precipitation increases are expected from isolated cumulus congestus; for congestus developing on the flanks of mature cumulonimbus, a hail suppression effect is also ultimately intended. In the latter case, the chain of events is considerably more complex. The hail-suppression seeding concepts are summarized as follows.

1) Energy transfer: When qualifying cumulus congestus developing on the flanks of mature storms are seeded, ice development initiates at an earlier stage in each treated feeder cloud's life time. The associated latent heat release adds buoyancy, strengthening the feeder-cloud updraft rather than later invigorating that of the hail-producing mature cell.

2) Premature rainout: The earlier nucleation of supercooled liquid water (SLW) in growing feeder clouds accelerates hydrometeor growth significantly. This allows many hydrometeors to grow large enough to fall from the lesser updrafts of the feeder cloud prior to the feeder cloud's merger with the main updraft, where larger particles are easily sustained and would continue to grow.

3) Updraft loading: Premature rainout may not always occur; hydrometeors developing in the feeder cloud may still reside within it when merger occurs. The hydrometeors within the feeder cloud are nevertheless larger and more numerous than would naturally be the case. When cloud merger occurs, the main updraft thus becomes burdened and slowed by the additional mass, making it more difficult to support the development of larger hailstones.

4) Reduction in water vapor (fuel) supply: Thunderstorms commonly feed on moist air in the boundary layer, often from the southeastern or southern flank. Premature rainout, as hypothesized in 2) above, results in rainfall developing from what would have been rain-free cloud base. The precipitation and accompanying cool outflow may partially restrict the low-level moisture flux into the storm, ultimately lessening the updraft speeds.

These hail-suppression concepts rely on complex and often poorly documented processes, and so are subject to constant review and revision as the physical chain of events involved becomes better understood. The concept of beneficial competition of hail embryos within the main updraft as discussed by Dennis (1980) is not considered to play a significant role in the North Dakota hail-suppression process. Instead, the treatment seeks to modify the suspected hail embryo source regions rather than treat the main updraft directly.

b. Objectives

A major goal of the NDTP was to obtain better experimental evidence concerning the various concepts just outlined. However, the objectives of the NDTP were numerous and varied, to take full advantage of atmospheric conditions ranging from clear air to severe storms. Of the 19 different experiments conducted, the first five comprised the core and focal point of this field effort. Each of these five experiments was conceived and designed to improve the knowledge of the chain of events that produce rain and hail, and offer prospects of modifying the process—from release of seeding agent through the transport, dispersion, nucleation, and precipitation development. The multiagency sponsorship of the program also begat a variety of other investigations in storm dynamics, cloud physics, radar meteorology, and atmospheric chemistry and electricity. The objectives can be loosely categorized as either clear-air, small-cloud, or mature-storm objectives.

1) CLEAR-AIR OBJECTIVES

- Study the evolution of ground-released tracer plumes during convective conditions typified by strong insolation. The tracers used included SF_6 or X-band radar chaff.
- Study the development and evolution of clear-air radar echoes associated with horizontal rolls in the boundary layer.

2) SMALL-CLOUD OBJECTIVES (CU MED TO CUCG)

- Investigate the dominant transport, dispersion, and mixing processes within Great Plains cumulus.
- Determine whether glaciogenic seeding agents can be reliably targeted in supercooled cumulus and, if so, under what conditions.
- Verify that seeding produces increases in ice crystal concentrations of magnitude sufficient to influence the precipitation process.
- Study early radar echoes using very high-resolution radar sector volume scans coordinated with photogrammetry of cumulus developing through about 20 dBZ.

3) MATURE-STORM OBJECTIVES

- Document storm development through satellite and photographic investigations.
- Investigate the development of initial ice particles and subsequent hailstone embryos.
- Relate internal storm motions to precipitation development.
- Relate cloud electrification to microphysical and dynamic development.
- Study transport by thunderstorms of natural trace gases such as ozone (O_3) and carbon monoxide (CO).
- Evaluate and improve the utility of numerical cloud models for describing the microphysical and dynamic chain of events.

It was understood that this ambitious array of objectives would not be fully attained through data-collec-

TABLE 1. Key facilities deployed in the NDTP.

Surface and upper air

Facility	Source	Location	Data Type
PAM stations (2)	NCAR	Elgin, Goodrich	Surface obs
Acoustic sounder	USBR	Bismarck	Boundary-layer winds
CLASS stations (2)	NCAR	Elgin, Goodrich	Soundings

Ground-based radars

Facility	Source	Location	Data Type
CP-3	NCAR	Bismarck	C-band reflectivity, Doppler winds
CP-4	NCAR	Center	C-band reflectivity, Doppler winds
NOAA-C	NOAA/WPL	New Salem	X-band reflectivity, Doppler winds, CDR

Aircraft

Facility	Source	Location	Data Type
WP-3D	NOAA/OAO	Bismarck	X-band Doppler radar, cloud physics, chemistry
Citation	UND	Bismarck	Cloud physics, SF_6 detection
King Air	U. Wyoming	Bismarck	Cloud physics, SF_6 detection, chaff release
T-28	SDSM&T	Bismarck	Cloud physics, SF_6 detection
Duke	WMI	Bismarck	Release aircraft: SF_6 tracer, silver iodide, fluorescent beads
Sabreliner	NCAR	Bismarck	Cloud physics, chemistry

tion efforts of the NDTP, but continued progress in most of these areas was anticipated.

4. Project facilities

Table 1 summarizes key project facilities. The NCAR MOCCA operations center (Wilson et al. 1988) served as NDTP operations center at the Bismarck airport. The ARB's McIDAS workstation provided visual and infrared imagery from the GOES satellite. Satellite data were archived during most NDTP operations; rapid-scan support was obtained on several occasions. A receiving station for the National Lightning Detection Network (NLDN) was also in place at the operations center. Upper-air data were collected routinely from two NCAR Cross-chain LORAN Atmospheric Sounding Stations (CLASS) located at Goodrich and Elgin, North Dakota. Serial soundings were obtained from these sites when requested by the operations director. Daily 0000 and 1200 UTC soundings from the Bismarck WSFO provided additional upper-air data.

A Research Experience for Undergraduates (REU) grant from NSF allowed 10 university students to gain research experience in the field, and provided additional personnel required for a variety of project duties (Orville and Knight 1992). The NCAR Cray computer was used to run a two-dimensional numerical cloud model each morning for forecasting purposes (Kopp

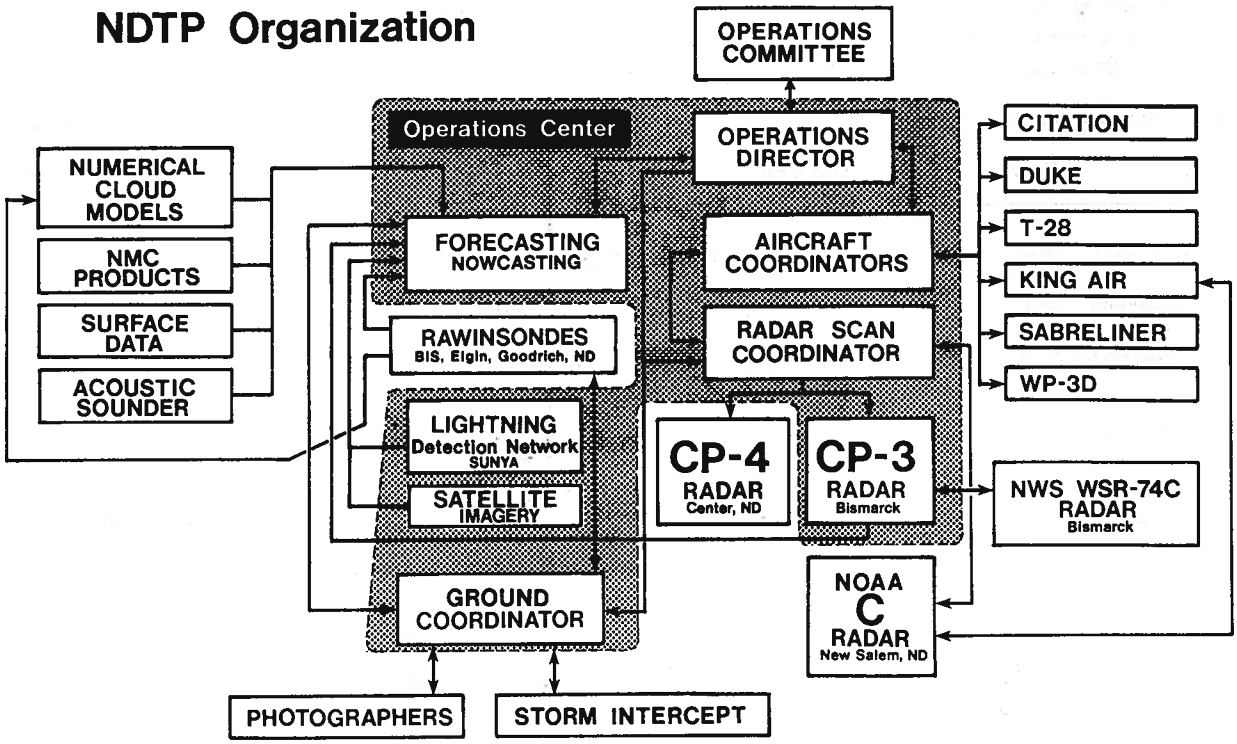

FIG. 2. NDTP organizational diagram. Facilities and personnel at the operations center are within the shaded portion.

and Orville 1990). Experimental hailstone-sensing devices developed by undergraduate students at three universities were deployed by storm intercept teams whenever the opportunity arose. Other facilities included hand-held, 35-mm and 16-mm time-lapse cameras. The Bismarck NWSFO WSR-74C weather radar was videotaped while operating in a continuous scanning PPI mode to provide backup radar surveillance. The organization of the project and the general lines of communication are illustrated in Fig. 2.

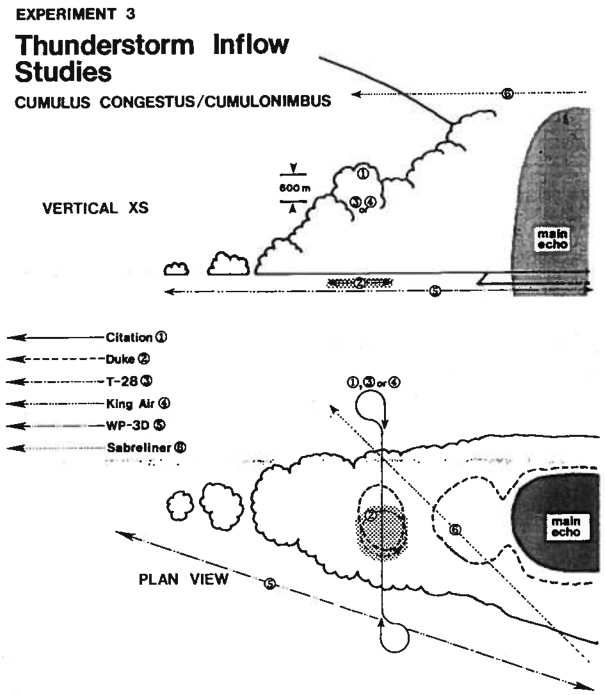

FIG. 3. Sample schematic for experiment 3, thunderstorm inflow studies. Planned aircraft flight paths relative to the subject cloud are denoted by numbered arrows.

5. Operations procedures

The objective(s) and methodology for each experiment were predefined in the NDTP operations plan. Experimental design summaries were composited with listings of facilities requirements and schematic diagrams to provide a quick reference guide for use in the field. Table 2 and Fig. 3 give an example of one such experimental plan; in the interest of brevity, the other plans are not presented here.

Table 3 summarizes the 19 different experiments attempted in the NDTP and the number of attempts for each (the topic of each is indicated in parentheses). The number of attempts made at each experiment varied widely, owing to the variability of the convective storms during the project period. Particularly disappointing was that few mature storms with associated feeder-cloud systems occurred within the dual-Doppler coverage area. There were numerous mature-storm investigations, as evidenced by the number of

TABLE 2. Example of the experimental designs set forth in the NDTP field operations plan.

Experiment 3: Feeder cloud–cloud-base treatment (AgI/SF_6), thunderstorm inflow studies (Reference Illustration: Fig. 3).

Summary:	Treatment below rain-free cloud base by the Duke. Subsequent sampling of treated cloud mass by Citation, King Air, and T-28, and in the storm anvil by the Sabreliner.
Aircraft:	Duke; one or more of Citation, King Air, T-28; (Sabreliner), (WP-3D)
Radar:	CP-3, CP-4, (WSR-74C), (NOAA-C), (WP-3D) Coverage: Dual-Doppler, good or better. Resolution: <2.5 min, <0.5 km
Treatments:	SF_6 with or without AgI•AgCl
Objective:	Track upward transport by convection of injected and natural tracers. These studies are relevant to cloud-base seeding as employed in the operational cloud seeding program. Natural tracers will include O_3, moisture, and CO.
Methodology:	Sustained release of tracer will take place beneath the rain-free cloud base below developing cumulus congestus in the flanking line. Release of SF_6, with or without AgI, will continue for 15 min. Cloud tops should exceed the –10°C level at the time release begins. The Duke will then remain at cloud base to monitor conditions there, or stand off to videotape the cloud if subcloud conditions become unsafe. For SF_6 releases, the King Air will make sampling passes beginning at 600 m above the Duke release altitude. The T-28 will operate at about the –10°C level, while the Citation will operate from at least 600 m above the T-28 on up to the top of the feeder cloud. Passes will be made across the flanking line, except that the T-28 will proceed generally along the line. Doppler radar scans will be made in the sector-scan mode to cover at least the relevant part of the cloud shown in Fig. 3.

studies classified as Experiment 6, and these cases have provided some of the most interesting data from the NDTP. However, many occurred far from Bismarck. This limited the number of project facilities that could be brought to bear and compromised the ability to conduct some of the experiments as planned. This was largely a consequence of the continuing drought in North Dakota; during June and July 1989, Bismarck received only 49% of the normal precipitation.

6. Highlights and preliminary results

a. Tracer studies

The NDTP placed emphasis on studies of transport, dispersion, entrainment, and mixing processes using tracers to improve knowledge of where seeding material or trace gases are likely to go when in or near convective clouds. Both in situ and remote sensing methods were used in the tracer experiments discussed in section 2a. Natural gaseous tracers such as O_3, CO, or total water content were also used to follow the evolution of clear air and cloud regions. The availability of fast-response analyzers for these gases makes real-time airborne measurements on the scale of individual cumuliform turrets possible. Total water content and specific entropy have been used in a similar manner in some thermodynamic techniques (e.g., Paluch 1979), but it is often difficult to measure water vapor adequately for this approach. Radar chaff was also used as a tracer in the NDTP.

With a single, brief, high-volume release of a tracer such as SF_6, it is possible to fix the time and location of the treatment so that the treated region can subsequently be unambiguously identified by sampling passes through the cloud, and a time history can then be constructed. Several types of tracer experiments were conducted in the NDTP. For example, releasing tracer at cloud base allows the history of the cloud-base air and its interaction with other regions of the cloud and the environment to be studied (experiments 3, 4, 5; see Stith and Politovich 1989). Releasing tracer just above a growing turret allows the entrainment of clear air into the cloud to be investigated (experiment 15; see Stith 1990).

The SF_6 tracer was also used in the NDTP to investigate the activation of AgI aerosols to form ice particles (experiments 1, 5). Since the release rates of the aerosol and SF_6 are known, the measured concentration of SF_6 can be used to estimate the AgI concen-

TABLE 3. Summary of experiments conducted.

Experiment number	Number of attempts	Experimental Description
1	9	Feeder cloud: Midcloud treatment with SF_6 (Ice initiation in feeder cells)
2	1	Feeder cloud: Midcloud treatment with chaff (Ice initiation/evolution in feeder cells)
3	5	Feeder cloud: Cloud-base treatment with SF_6 (Thunderstorm inflow studies)
4	3	Feeder cloud: Cloud-base treatment with chaff (Thunderstorm inflow studies)
5	3	Cumulus congestus: Cloud-base treatment with SF_6 (Vertical transport/ice initiation/early storm electrification)
6	16	Mature-storm studies (Dynamics, electrification, chemistry)
7	8	Cumulus humilis/mediocris: Midcloud treatment with SF_6 (Transport/dispersion studies)
8	2	Doppler time-series studies
9	5	Clear-air, early-morning tracking of honey bees (Foraging habits)
10	10	Surface tracer release, prestorm and early storm (Transport and dispersion/ice-initiation studies)
11	7	Doppler surveillance (Convective initiation, first-echo climatology, storm tracking)
12	13	Pre- and postflight operations radar and lightning studies (Storm electrification)
13	17	First-echo photography (Precipitation initiation)
14	6	Mesoscale convective complexes/systems (Storm development, upscale evolution)
15	4(a), 5(b)	Cumulus congestus: Treatment with chaff (a) or SF_6 (b) at cloud top or around periphery.
16	2	Feeder cloud: Midcloud treatment with fluorescent particles (Hailstone embryo sources and evolution)
17	2	Boundary-layer rolls (Structure, evolution)
18	5	Radar VAD/acoustic sounder intercomparison
19	6	Miscellaneous experiments

tration (Stith et al. 1990), at least until nucleation and scavenging removes the particles. This normally provides adequate time to investigate the initiation of ice particles by the aerosol. This technique is an improvement over more direct measurements of AgI ice nuclei, because the SF_6 concentration can be measured in situ with a response time of less than 1 s. Initial comparisons of the ice formation rates observed in treated clouds with laboratory and theoretical results show good agreement (DeMott 1990; Stith et al. 1990).

Much of the operational cloud seeding in North Dakota involves AgI releases of several minutes duration at the cloud base. One objective was to assess the ice-production effectiveness of this method (experiments 3, 5). After release, the agent must be transported by the cloud to supercooled regions aloft, mix with a significant cloud volume, and produce sufficient ice to influence the precipitation process. Previous work (Stith et al. 1986, 1990; Kopp 1988) suggested that some large clouds are likely to transport the agent rapidly through the cloud to supercooled regions without mixing over any appreciable cloud volume. However, smaller clouds having top temperatures greater than about −18°C often mix the agent through a larger portion of their supercooled volume.

Figure 4 shows an example of measurements made in one of these smaller clouds on 7 July 1989. In this case, a small convective system was sampled near its top after being treated with AgI and SF_6 in the updraft at cloud base for about 15 min. The clear correlation between the tracer and ice particle concentrations suggests that the numbers of ice particles produced in the cloud were related to the numbers of AgI nuclei available. This is expected because more nuclei should produce greater concentrations of ice particles.

However, this does not always occur. At slightly warmer levels (–8° to –10°C) in a case examined by Stith et al. (1990), cloudy air in downdrafts that had been exposed to lower temperatures before being sampled contained greater ice concentrations than air arriving at the observation level in updrafts, even though the concentrations of tracer (and, by inference, AgI) were greater in the updraft regions. Knowing the history of the previously cooled air and the amounts of AgI agent in the updraft and downdraft regions provided the insight necessary for interpreting the in situ ice measurements.

A second tracer approach used the TRACIR (tracking air with circular-polarized radar) remote sensing technique developed by Moninger and Kropfli (1987; see also Martner and Kropfli 1989). The technique uses dual-polarization radar to measure the location and concentration of microwave chaff fibers within clouds and precipitation, as well as in clear air. The circular depolarization ratio (CDR) of chaff is much greater than that of cloud hydrometeors. TRACIR exploits this difference to detect the chaff even though its reflectivity is often much weaker than that of the surrounding hydrometeors.

Streams of chaff fibers were released at strategic locations in or near clouds, and was tracked by the NOAA-C X-band, dual-polarization Doppler radar located near New Salem, North Dakota (Fig. 1). Preliminary results from two case studies have been reported. Martner (1990) examined the gradual dispersion of chaff in a stratiform cloud, and Martner and Marwitz (1990) investigated the much more rapid dispersion of chaff released at the base of a convective cloud. In the latter case (Fig. 5), reconstruction of the radar data clearly shows the evolution of the chaff-filled volume at various times after chaff release. The chaff rose as rapidly as 10 m s^{-1} from a release circle, in two columns on the southwest side of the cloud, and reached 4 km above cloud base before gradually subsiding. This experiment simulated typical cloud-base seeding operations, and the data provide a dramatic three-dimensional visualization of where seeding agent would most likely have gone. Chaff fiber concentrations computed from the radar's cross-polarized reflectivity measurements also allowed in-cloud dispersion rates to be studied.

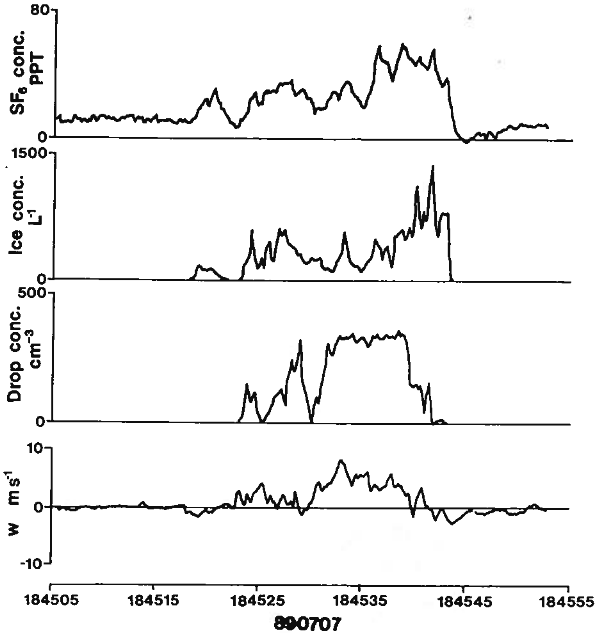

FIG. 4. Tracer, ice particle, and cloud droplet concentrations observed by the UND Citation on 7 July 1989 within a small, treated cumulus are plotted in addition to the vertical wind. Note the strong correlation between tracer (SF_6) and ice particle concentrations.

Ozone was used as a natural tracer as illustrated by a small cumulonimbus (Fig. 6). The O_3 concentrations in the lower to middle regions of the main cell (Fig. 6a) were similar to those found at the most vigorous turret at the top of the cell (Fig. 6b). This indicates little entrainment of the environmental air (which had much lower O_3 concentrations) in this part of the cloud. However, concentrations in the anvil were sometimes similar to and sometimes lower than those observed in the top of the turret, suggesting entrainment had affected some of these regions. One of the objectives of these studies is to relate observations of this type to the large-scale storm kinematics observed by Doppler radar measurements (e.g., Reinking et al. 1990).

Similar results were obtained at lower levels of a severe cell on 28 June 1989. Figure 7 illustrates the results from four passes by the Citation through a developing cell associated with a severe mesoscale convective system (MCS). This cloud exhibited a top-hat profile (i.e., relatively uniform concentrations within the cloud, with sharply lower concentrations at the cloud boundaries). Ozone concentrations in the cloud were similar to those measured near cloud base, and did not change appreciably during upward transport (Alkezweeney et al. 1991). Temperature and liquid water concentration values were near adiabatic, which also suggests an absence of entrainment in the cloud.

No single tracer method will satisfy all of the scientific needs. Observations using natural tracers such as O_3 or water vapor suffer from the natural variability of these gases in the troposphere. With gaseous tracers

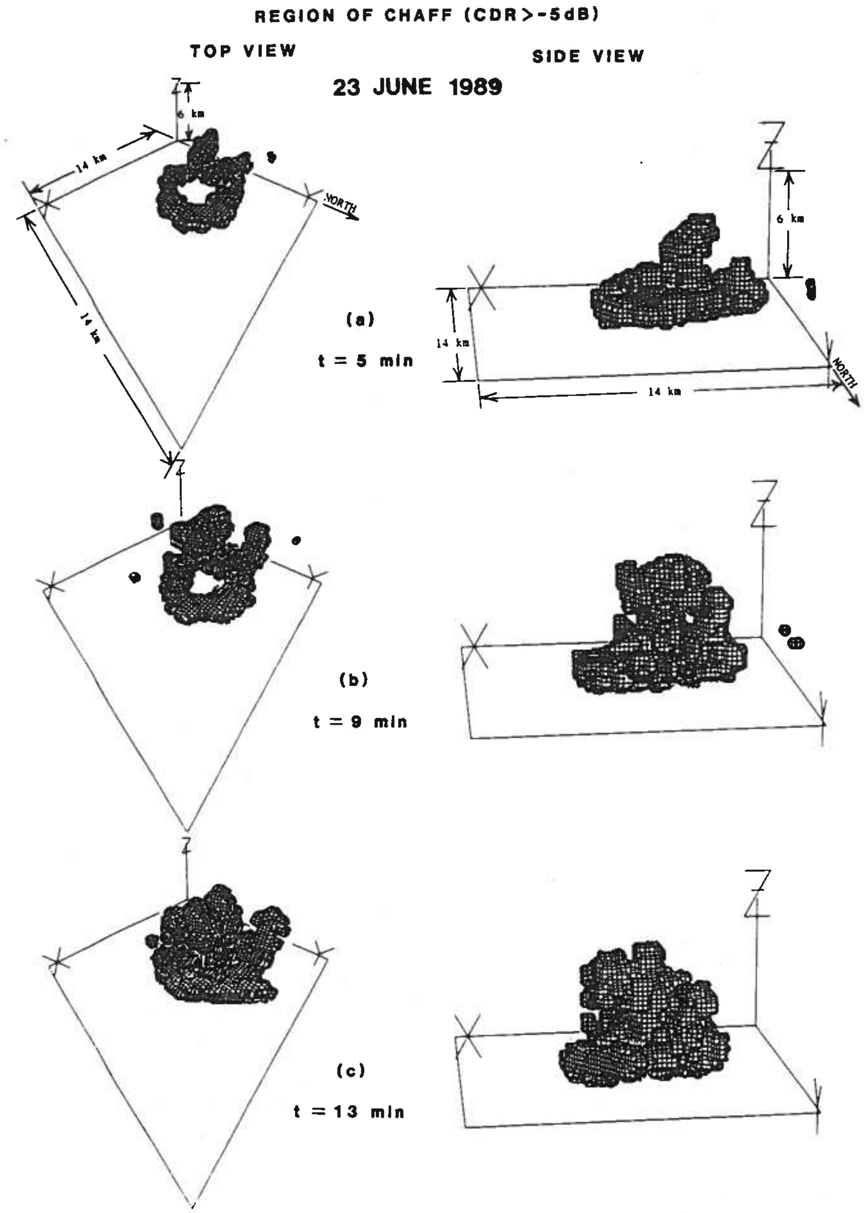

FIG. 5. Perspective views of the region occupied by chaff (CDR > −5 dB) at three time periods after the beginning of the chaff release from just below convective cloud base on 23 June 1989. The view aloft (left) is from a perspective northeast of the cloud, facing southwest. The side view (right) is from the north, facing south (from Martner and Marwitz 1990).

such as SF_6, it is impossible to adequately sample and map the tracer's path through the cloud by in situ methods. The TRACIR technique offers a great improvement in the use of chaff as a tracer, and provides an effective means of sampling the entire cloud volume. However, it is more difficult to compare these radar data with in situ data [e.g., data from Particle Measuring System (PMS) probes] because of navigation requirements and the radar's much larger sampling volume. An experimental approach using a combination of these methods as employed in the NDTP offers a powerful new synergism for the study of convective clouds.

The preliminary results of the tracer studies continue to affirm that when seeding agent is captured by cloud updrafts, it is transported aloft and eventually mixes with the upper cloud region. In most clouds, the seeding plume appears to be transported, ribbon-like, upward through the lower levels of convective clouds, and often does not mix appreciably until reaching the more turbulent upper cloud regions.

b. Mature-storm processes

Mature-storm cases ranged from developing cloud clusters to an MCS (Boe and Johnson 1990). Some preliminary results from these cases are described below.

Meitín and Brown (1990) studied the circulations in storms observed south of Bismarck on 27–28 June. Each storm started with a single radar echo that split into a left-moving portion, which moved nearly perpendicular to the mean wind, and a right-moving portion, which moved essentially with the mean wind. Previous model results and single-Doppler measurements have led Meitín and Brown to postulate a discrete series of interactive events that can lead from a single cell to a split storm pair having the observed anomalous propagation: The initial cell blocks the mean flow, counterrotating vortices develop in the lee, and the main updraft splits. Further dynamic interactions lead to a cyclonically circulating updraft in the right-moving storm, and an anticyclonically circulating updraft in the left-moving storm.

Motions within the 27–28 June NDTP storms were determined by combining the airborne and ground-based Doppler radar measurements. Middle-altitude reflectivity cores and the horizontal, storm-relative circulations are shown in Figs. 8 and 9. In Fig. 8, storm 1 has already split into a left mover (1L) and a right mover (1R). Within the area of dual-Doppler coverage, anticyclonic vorticity associated with 1L is revealed. The figure also shows counterrotating vortices that resulted in the subsequent split of storm 2. About one-half hour later, storm 2 developed separate precipitation cores with counterrotating circulations (Fig. 9). The coherence of this theory and observations, and the repeatability of the phenomena, suggest that the process may be quite predictable.

Reinking et al. (1990, 1991) examined the very different circulations within a small, rapidly moving, strongly sheared single-cell thunderstorm that occurred on 6 July 1989. Ozone tracer measurements from the cloud and the environment suggest that during its mature stage this storm fed from the lower troposphere, but not primarily from the surface. Storm-relative horizontal winds within the storm system at 3.5 km MSL indicate lateral inflow from a broad feeder-cloud region observed on the south flank. The region of vertical development and transport was manifested as a very tilted cell some 7–8 km in diameter, with peak core reflectivities to 45 dBZ (Fig. 10). No subcloud outflow typical of precipitation-induced downdrafts was observed in this case. Updrafts of over 10 m s^{-1} were measured near storm top (Fig. 6). Subcloud outflow from precipitation-induced downdrafts was weak and confined according to the observations and the model, whereas diffluent outflow through the upper anvil was substantial. A heretofore unobserved, storm-scale, dual-eddy circulation in the lee of the main cell appeared in the anvil when the storm-relative motion was subtracted (Fig. 11); such mixing would likely enhance entrainment and sublimation in the upper troposphere.

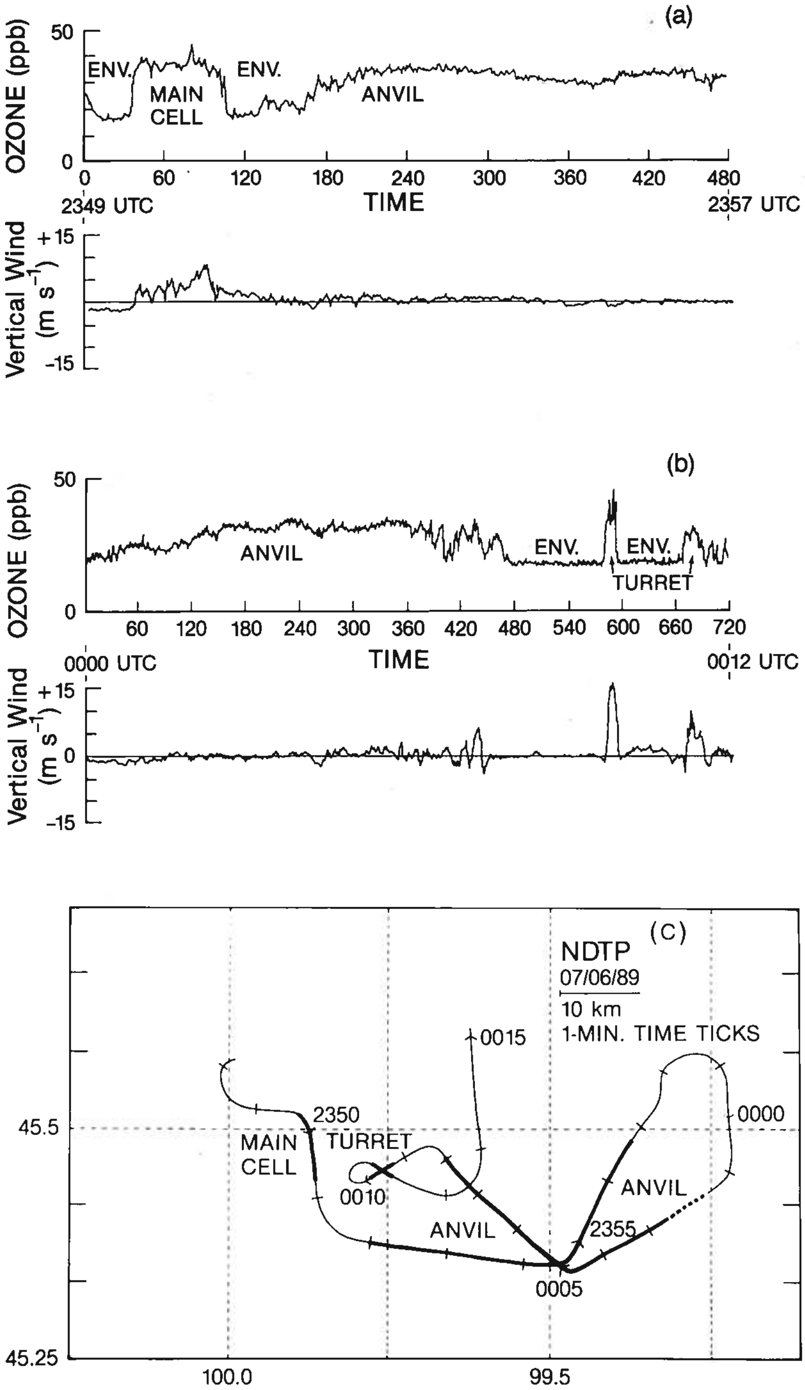

FIG. 6. Vertical wind and ozone concentration observed by the UND Citation on 6 July 1989 at (a) 8.8 km MSL and −33°C, and (b) 9.4 km and −38°C. Time scales in (a) and (b) are in seconds; scales in (c), which show the flight track, are decimal latitude and longitude. All times are UTC (from Reinking et al. 1990).

A two-dimensional cloud model developed by Kopp and Orville (1990) and initialized with the 1200 UTC 6 July 1989 Bismarck (BIS) sounding predicted development of small storms to only 8 km MSL. The observed storm closely fits this prediction scale. The predictive numerical model run was made 5 h prior to storm initiation and 7 h before the mature-storm observations. The salient storm structure and motions observed are very similar to those predicted by the model, except that the modeled storm was vertically and temporally compressed. Although the storm formed in response to surface heating, both the model and radar measurements indicate that the

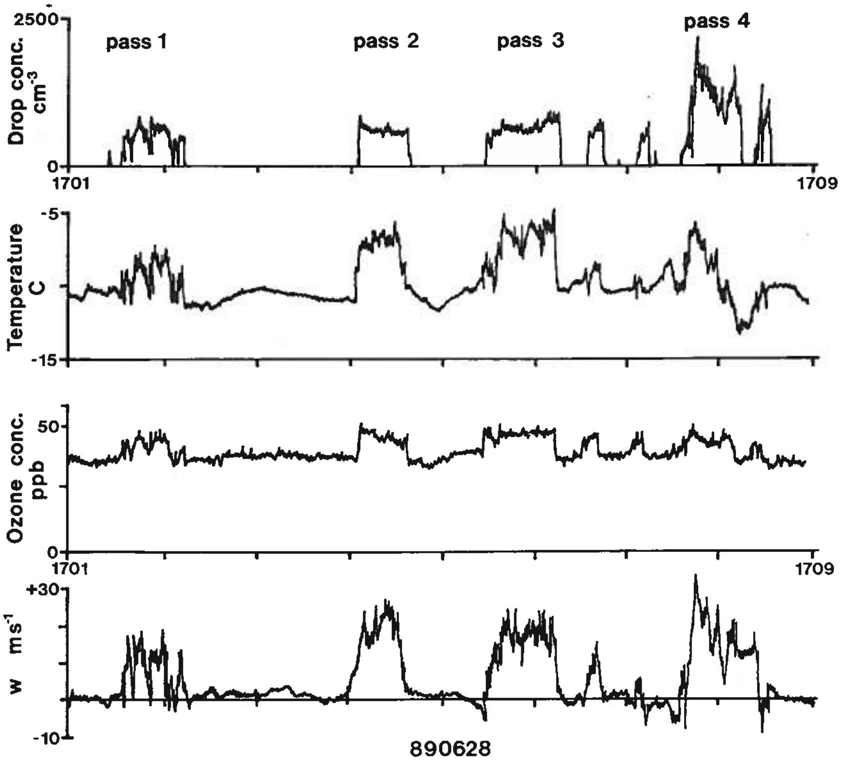

FIG. 7. Cloud droplet and ozone concentrations, temperatures, and vertical winds observed during four passes by the Citation through a very vigorous developing cell on 28 June 1989. The four passes were all made at about 5.5 km MSL.

relative importance of surface feeding diminished during the mature stage as inflow between 3.5 and 6.5 km MSL predominated. The model and in situ measurements support other theories and observations (e.g., Heymsfield and Miller 1988) that hold that storms formed in environments with strong vertical speed shears often have low precipitation efficiencies because a large proportion of the condensate is vented through the anvils. In such cases seeding agents would be most effectively delivered via the flanking feeder field; it is conceivable that seeding for early precipitation development and consequent premature rainout could increase the efficiencies of such storms.

c. Atmospheric electricity studies

Real-time NLDN cloud-to-ground (CG) lightning data were acquired for the project region via satellite downlink. These data were utilized in storm electrification studies, and were used to alert project personnel to the development of significant convective activity outside the radar coverage area or at times when the radars were not operating. Operations were once initiated solely on the basis of detection of lightning at the fringe of the operational area.

The 28 June 1989 MCS that developed over western North Dakota was characterized by the development of individual cells that initially produced a high percentage of positive CGs. Figure 12 shows positive and negative flash density for the entire storm period, which lasted from 2000 UTC 28 June until 0700 UTC 29 June. A total of 2429 CG flashes were recorded by the NLDN during this period, and 995 (41%) had positive polarity.

Helsdon (1990) reported a preliminary analysis of early storm cells in this system. This study of CP-3 radar data and CG lightning data from 1500 to 1612 CDT (2000 to 2112 UTC) examined two storm cells that developed about 55 km apart within 12 min of each other. The first storm produced seven CG discharges, all of positive polarity, during the study period. The second produced 18 CG discharges, all of negative polarity. Table 4 summarizes the character of the radar evolution near –5°C (5 km MSL) and the light-

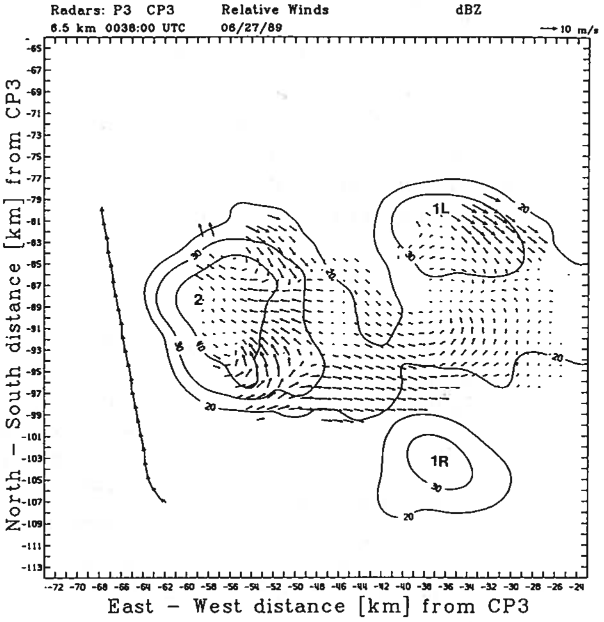

FIG. 8. Middle-altitude reflectivity cores and storm-relative circulations for a splitting thunderstorm observed south of Bismarck on 27 June 1989. Storm 1 has already split into left-moving and right-moving cells (from Meitín and Brown 1990).

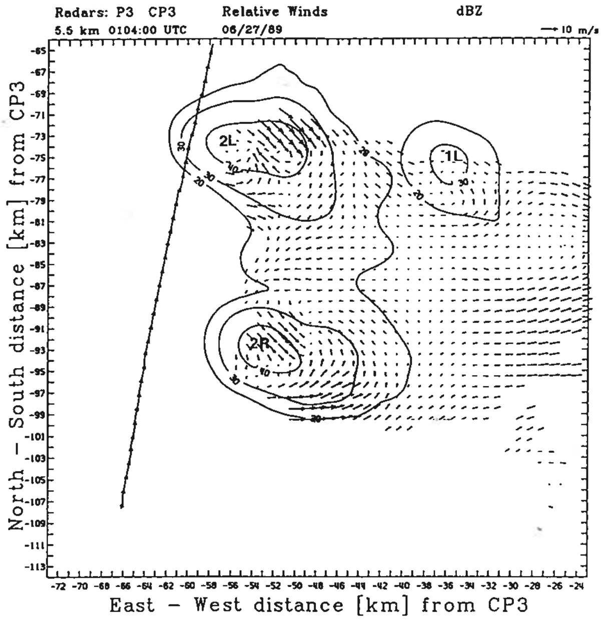

FIG. 9. As in Fig. 8, but about half an hour later. Storm 2 has now also split into separate precipitation cores with counterrotating circulations. For the implications of these observations, see text (from Meitín and Brown 1990).

TABLE 4. Characteristics of two storms on 28 June 1989 from 5 km CAPPI (−5°C) and the National Lightning Detection Network.

1st Cloud	2nd Cloud
Radar Character	**Radar Character**
$Z \leq 25$ dBZ at 151859 CDT $Z > 35$ dBZ at 152243 CDT $Z > 50$ dBZ at 154247 CDT	$Z > 25$ dBZ at 153045 CDT $Z > 35$ dBZ at 153445 CDT $Z > 50$ dBZ at 154127 CDT
$t_{25\text{–}50\ \mathrm{dB}Z}$ 24 min	$t_{25\text{–}50\ \mathrm{dB}Z}$ 11 min
Lightning History	**Lightning History**
2 positive—154407 scan 1 positive—155425 scan 4 positive—160035 scan	11 negative—155425 scan 5 negative—160035 scan 2 negative—160645 scan
25 dBZ to 1st CG 25 min 50 dBZ to 1st CG 1 min	25 dBZ to 1st CG 22 min 50 dBZ to 1st CG 11 min

ning development for these two storms. Although both storms produced low-level radar reflectivities in excess of 55 dBZ, the first one developed this intensity much more slowly than did the second. The CG lightning frequency of the second storm was much greater (average interval between flashes, 25.8 s from 2055 to 2100 UTC) than that of the first. No information is available on intracloud lightning for either of the storms, so the level of total lightning activity remains unknown.

Radar data suggest that the first storm had a greater water content than the second, although there is difficulty in interpreting these data because of the range (130 km) and because for much of the time period the radar only scanned up to 1.5° elevation. However, it does appear that there was a dissimilarity in the microphysical character of these two storms. The electrical implications this might have are under study.

The T-28 and the WP-3D carried electric field mills. This made possible simultaneous in situ measurements of electric fields and cloud kinematic and microphysical evolution. A series of penetrations at 18 000 ft MSL of a growing cumulus congestus was made on 27 June 1989. Figure 13 shows that ice particle development, initiated about 5 min prior to observations of measurable electric field perturbations. An exponential increase in ice particle concentration accompanied a linear increase in electric field strength; three lightning

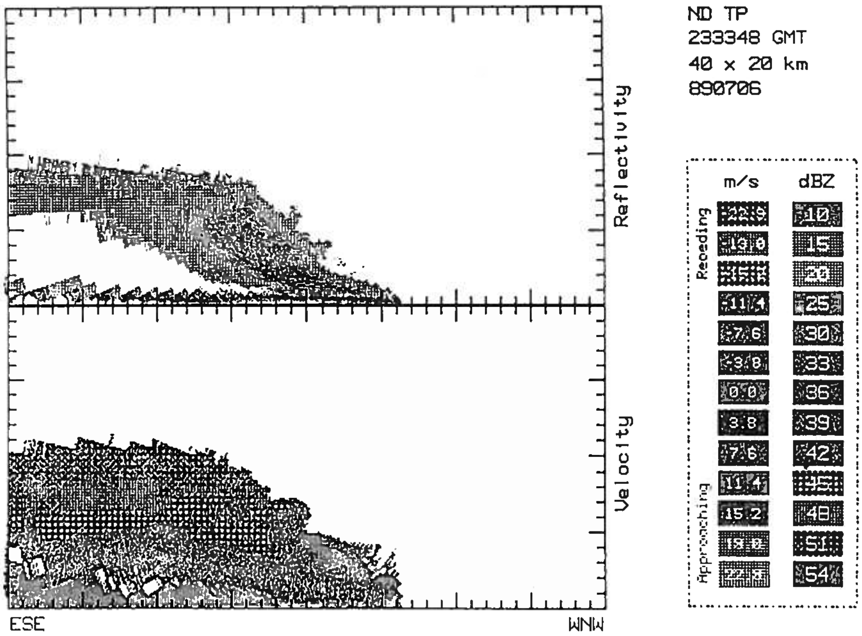

FIG. 10. The circulations and reflectivities of a small, rapidly moving single-cell storm observed by the WP-3D X-band Doppler radar on 6 July 1989 (from Reinking et al. 1990). Ozone measurements indicate this storm did not feed from the surface, and no subcloud storm outflow was observed.

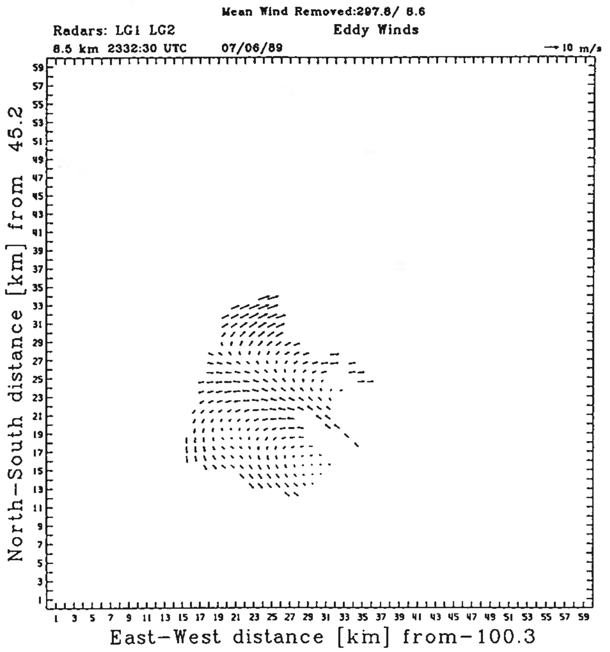

FIG. 11. Diffluent outflow in the upper regions of the 6 July 1989 storm shown in Fig. 10. The observed dual-eddy circulation within the anvil may have been induced by divergence and splitting of the environmental flow beneath the capping inversion (from Reinking et al. 1990).

discharges were noted during the final penetration. This and other cases are currently under investigation.

d. Computer modeling as a forecasting tool

This was the first project that we know of in which a multidimensional, time-dependent cloud model was employed in a forecast mode to supplement the more traditional morning briefing. The 1200 UTC sounding from Bismarck (BIS) was used to specify initial conditions in a two-dimensional, time-dependent cloud model. Equations were numerically integrated using the NCAR Cray X/MP supercomputer. Each morning, in just two to three hours, the model was initialized and run, and the resulting time-height profiles of a few key variables were prepared for the morning briefing. Preliminary results of the forecast test of the model were presented by Kopp and Orville (1990).

Figure 14 is an example of one of the model products shown in the morning briefing, usually given before the day's convection had begun. The day illustrated is 28 June 1989. Cloud development and precipitation fields (horizontal averages across the model domain) are shown for an 8-h period. Rapid growth of cloud top to more than 13 km height was indicated. Other output predicted the maximum vertical velocity to exceed 30 m s^{-1}. Figure 7 includes a graph of vertical velocity recorded in four aircraft passes through an active cell on that date. All passes show strong updrafts, but the final pass indicates an updraft greater than 30 m s^{-1}.

7. Data management

The NDTP database is open to the scientific community. No central data archive is maintained but data are available from the respective principal investigators or the managers of the various facilities. A data inventory is available from either of two sources:

Prof. John H. Hirsch, NDTP Data Manager
Institute of Atmospheric Sciences
South Dakota School of Mines and Technology
501 E. St. Joseph Street
Rapid City, SD 57701-3995

or

Mr. Bruce A. Boe, Director
North Dakota Atmospheric Resource Board
900 East Boulevard Ave.
Bismarck, ND 58505-0850.

Requests for data must be directed to the individual associated with the specific facility, as indicated in the data inventory. Reimbursement for costs of duplicating data may be necessary.

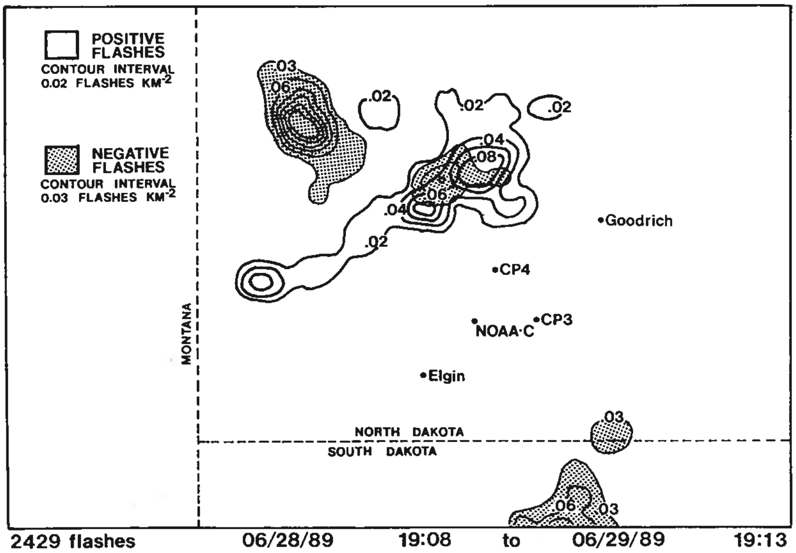

FIG. 12. A contour plot of positive and negative CG flash density for the 28 June 1989 severe-storm outbreak in North Dakota. The lightning activity of interest occurred between 2000 UTC on 28 June and 0700 UTC on 29 June.

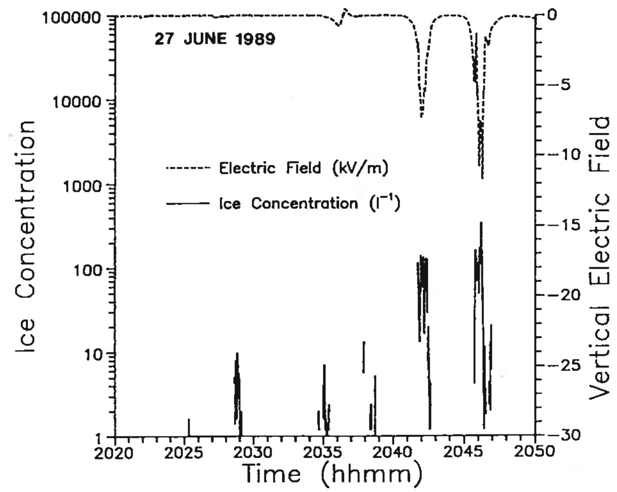

FIG. 13. T-28 observations of ice particle concentrations and electric field strength during penetrations 2 through 7 on 27 June 1989. Altitudes were from 5.5 to 6.0 km MSL; temperatures ranged from −11° to −15°C. Times are UTC.

8. Summary

Originally, 16 NDTP experiments were planned. Three more were added, bringing the total to 19. At least one attempt was made at every experiment. In the six-week period, 129 experiments were conducted (Table 3). Publication of NDTP results is just beginning. The NDTP was truly a cooperative venture, as the state of North Dakota and NOAA worked with the NSF and NCAR to place the required facilities in the field.

The persistence of drought and near-drought conditions on the northern Great Plains in 1989 resulted in fewer opportunities with some scales of clouds than had been anticipated. Few multicell thunderstorms moved through the Doppler network, especially during daylight hours. This especially limited the opportunities for feeder cloud experiments (1–4 and 15); some of these experiments were attempted on clouds that were only marginally suitable.

A return to the field in central North Dakota is therefore planned for the summer of 1992. That effort will further the NDTP investigations, especially those studying ice initiation, transport, dispersion, and hail-embryo development within feeder clouds. One or more Doppler radars and several cloud physics/release aircraft will constitute the majority of facilities. Additional tracer experiments employing SF_6, AgI, and chaff are planned.

Better knowledge of the storm processes that lead to the production of hail and other severe weather will likely result in improved prediction and warnings, and will ultimately allow further definition of hail suppression technology. An improved understanding of the links in the chain of events in convective precipitation development is already being realized.

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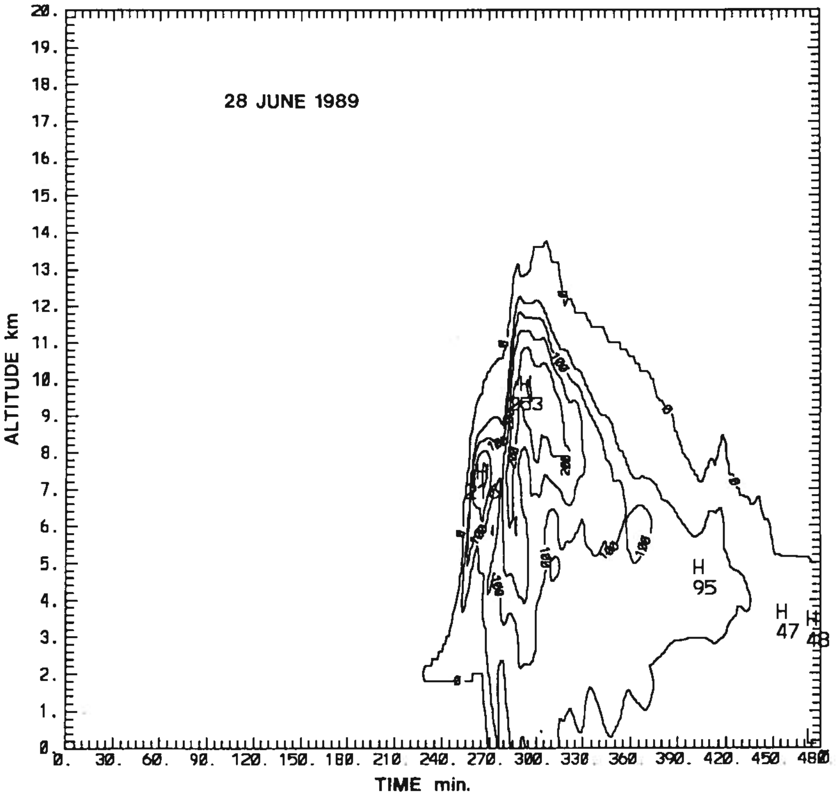

FIG. 14. The time–height profile of the total condensate mixing ratios (horizontal averages) are shown as predicted by the two-dimensional cloud model. These results are for 28 June 1989 and are based on the Bismarck (BIS) 1200 UTC sounding. The abscissa is time in nimutes, and the ordinate is height in km. Total rainfall was predicted to be greater than 3.5 cm, and graupel and hail to 1.25 cm diameter were predicted, the greatest of any project day.

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