National Severe Storms Laboratory

Annual Report FY 1988

U.S. Department of Commerce
National Oceanic and Atmospheric Administration
Environmental Research Laboratories

COVER.

Top Left: Rotating cumulonimbus and associated anvil near Nunn, CO, at 2004 MDT on 7 July 1987.

Top Right: Lightning over the 48 contiguous states as observed by the Demonstration National Lightning Detection Network.

Bottom Left: Infrared satellite imagery of a mesoscale convective system over south Texas at 0600 UCT on 3 June 1988.

Bottom Right: Intracloud lightning on the base of anvil near Lake Texhoma, OK, just prior to the release of an M-CLASS sounding on 28 May 1987.

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CONTENTS

The NSSL Mission

The National Severe Storms Laboratory conducts a broad program of research to develop basic understanding of severe weather phenomena, including the large and mesoscale environments that evolve and interact to produce intense storms. The focus is upon observational and theoretical studies of hazardous, middle latitude weather phenomena such as tornadoes, hailstorms, lightning, windstorms, floods, and blizzards. Sophisticated numerical models are often employed as research tools. The Laboratory's research projects provide sound scientific foundations upon which improvements to NOAA's weather and climate forecasting services may be built. NSSL participates in field programs and special projects, usually in coordination with other ERL components, the National Weather Service, and other agencies, intended to demonstrate or improve capabilities to detect, forecast, and warn of hazardous weather events.

FOREWORD

The National Severe Storms Laboratory (NSSL) develops means for improving weather forecasting through studies of storm processes, numerical and conceptual modeling of storm phenomena, and applications of new remote-sensing technologies in the severe weather environment. Recent studies have drawn heavily on observations gathered by Doppler radar, the NOAA P-3 research aircraft, and lightning-mapping systems. The work at NSSL, probably the most substantial precursor of the major national initiative NEXRAD, continues to support that program, and a major effort in the Laboratory is directed toward operational implementation of an effective national weather radar network for the late 1980s and beyond. Through numerous relationships with other government agencies and universities, NSSL constitutes a resource for severe-storm data examined by researchers around the country and overseas. NSSL directly participates in many research projects outside Oklahoma; for example, during FY 1988 NSSL staff participated in the Terminal Doppler Weather Radar field project at Stapleton International Airport, and wind shear studies in eastern Colorado. The Laboratory utilized the NOAA P-3 research aircraft and NOAA satellites to study the destabilization of polar air masses over the Gulf of Mexico early in calendar year 1988. This research is part of a new effort to study larger-scale phenomena and circulations of importance to operational weather forecasting.

Midway through FY 1988, reorganizations within the Environmental Research Laboratories led to the formation of a Mesoscale Research Division (MRD) of NSSL, situated in Boulder, Colorado. Research in the new division gives heavy emphasis to studies of mesoscale convective systems (MCSs) based on data gathered during field programs. Integration of observations from the P-3 aircraft, satellite, ground-based radars, and lightning strike networks contributes substantially to the MRD research effort.

During coming years increasing emphasis will be given to the expansion of research to include larger scales of meteorological phenomena, and to the incorporation of modern research workstations, wind profilers, and digital satellite data into both case study analyses and the development of conceptual and numerical models. The blending of data from diverse and asynchronous observing systems (e.g., Doppler radar, wind profilers, and satellites) must be accomplished if work is to progress rapidly in these areas. A plan of action to bring edge-of-the art capabilities for computing, data synthesis, and analysis to the Laboratory during the remainder of this decade has been developed and implementation begun.

Tornadic Studies

Vertical wind shear is a key parameter for tornado forecasting. However, the exact types of shear profiles that favor the development of mesocyclones in thunderstorms have not been recognized until recently. Theory developed at NSSL has demonstrated that a storm has a helical structure (cyclonic updraft, anticyclonic downdraft) when the low-level storm-relative environmental winds are greater than 7 m s^{-1} and veer markedly (more than 30° per kilometer) with height or, equivalently, when the low-level environmental vorticity is large, nearly horizontal and mostly streamwise in a reference frame that moves with the storm. The helical structure results from the near coincidence of streamlines and vortex lines. Thus, in updrafts (downdrafts), vortex lines are tilted upward (downward). A theoretical formula for the correlation coefficient between vertical velocity and vertical vorticity at each level is the basis of a simple nowcast model that predicts whether a storm will develop a mesocyclone, on the basis of the storm's observed or anticipated motion and a nearby sounding. For practical nowcasting use, the correlation coefficient is averaged over an appropriate layer, usually the lowest 300 mb, and presented as a function of all feasible storm motions (Fig.1). Case studies indicate that a threshold value for the coefficient for mesocyclones is roughly 0.5. Results so far have been encouraging although they illustrate the difficulties of tornado forecasting. On days when widespread tornado outbreaks occur, favorable mesocyclone conditions persist for many hours over a large area for a considerable range of storm motions. Local outbreaks or isolated tornadoes are often associated with rapidly changing situations where the threat for tornadoes is confined to a small area for a short time and storm motion may be extremely critical. Such situations may not be detected even inside mesoscale sounding networks. Measurements of low-level winds by remote sensors such as Doppler radars and profilers may be used to update the model and improve chances of detecting a threat area. The model is currently being tested by comparing its predictions with results obtained from a three-dimensional numerical cloud model. In the future, a data set of tornado proximity soundings and observed storm motions will be constructed from NSSL archives and used to generate verification statistics for the model. Conclusions from these studies will suggest ways to improve the model.

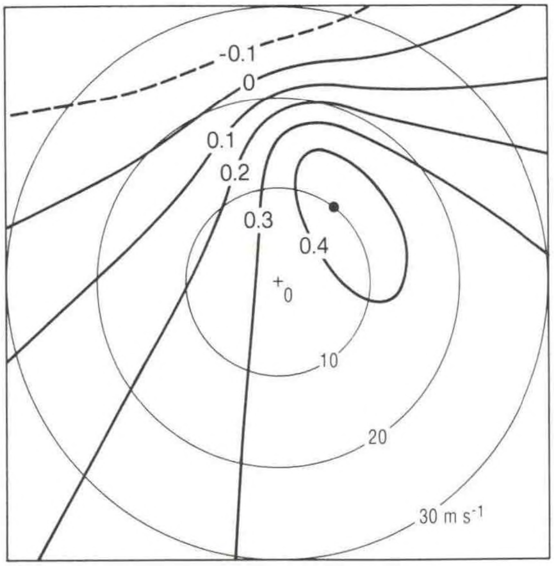

Fig. 1. Contours of average correlation coefficient over lowest 150 mb plotted on a polar diagram with storm speed as the radial coordinate and storm direction as the azimuthal coordinate. Large dot marks observed storm motion from 220° at 10 m s^{-1}. Even though an F3 tornado is on the ground 65 km west of the station, the correlation coefficient is not especially high (<0.5). This sounding may not be very representative of the tornado environment because later soundings from the same station showed dramatic increases in low-level shear and correlation coefficient.

For the past 20 years, Doppler radars have provided direct evidence that the supercell thunderstorm contains a rotating updraft. Multiple Doppler radar studies have documented the evolution of vorticity within supercell storms, but data collection typically has started too late to document the process by which updraft rotation was initiated. An exception occurred on 6 June 1979 during SESAME when data collection started early enough in the Agawam, Oklahoma, storm for the initiation process to be identified. As in numerically modeled supercell storms, a middle-altitude vortex couplet formed on the lateral flanks of the Agawam storm's strong updraft, with cyclonic vorticity on the right flank (looking in direction of storm motion) and anticyclonic vorticity on the left flank. In response to storm-relative environmental winds, the precipitation downdraft reached the ground on the updraft's left side and cold air began to spread out beneath the updraft. The expanding air produced two significant effects: (a) the updraft slowly started to weaken by ingesting the colder air, and (b) convergence developed on the updraft's right flank between the cold air and environmental flow approaching the storm from the right. Low pressure at the center of the middle-altitude cyclonic vortex favored the formation of a new updraft along that portion of the convergence line directly beneath the vortex. The developing updraft entrained the surrounding cyclonic vorticity and concentrated it into a rotating updraft at middle altitudes--marking the beginning of the storm's supercell stage. As the initiating updraft died and the rotating updraft developed, the temporal and spatial integration of hydrometeors from the two updrafts produced a unicellular radar reflectivity pattern that started to move to the right in a continuous manner. Existing numerical models do not reproduce the evolution of successive updrafts. Because of coarse spatial resolution, numerical models depict both the precipitation and updraft propagation processes as continuously varying. A cooperative study is under way with the University of Oklahoma to use a fine-resolution numerical model to produce more realistic rotation initiation and discrete updraft evolution. The resulting synergism between observed and simulated data fields should lead to greater insights about severe thunderstorm processes.

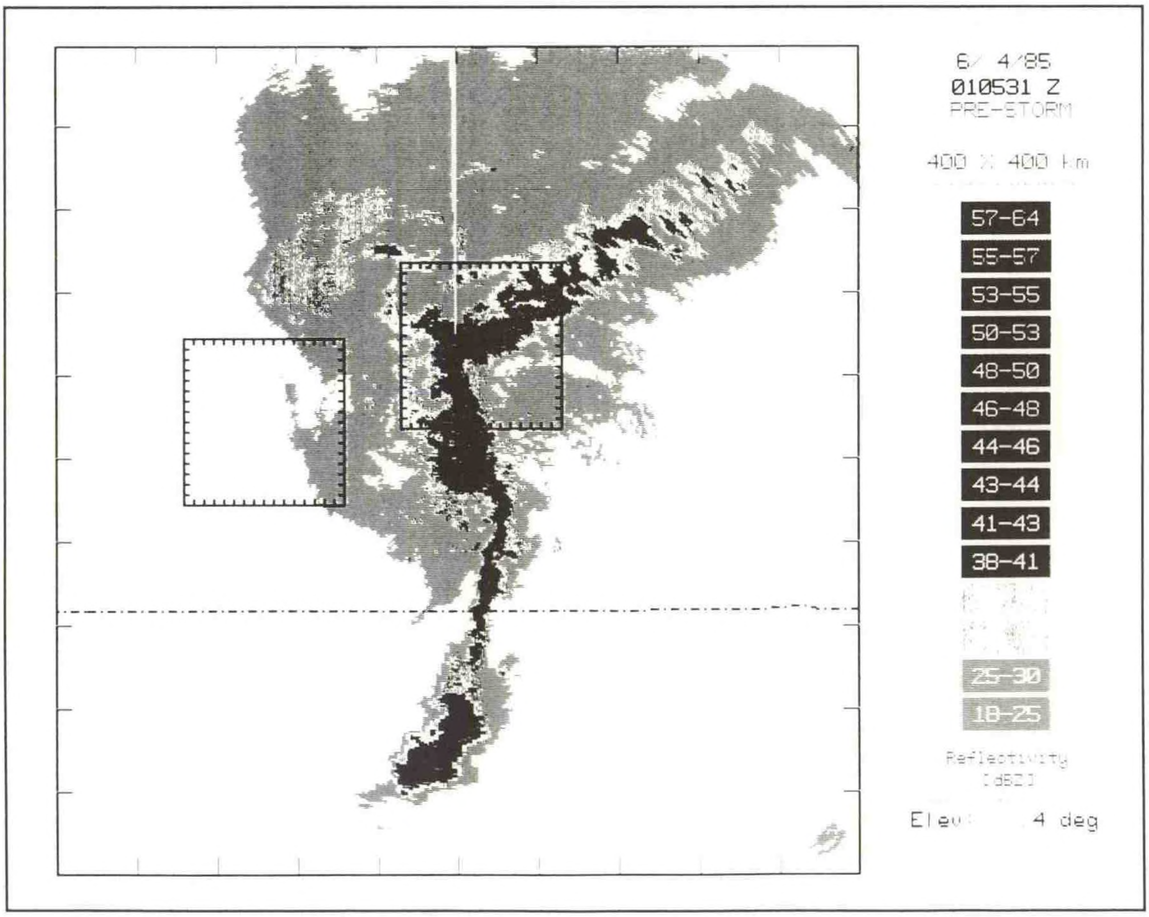

Fig. 2. Low-level reflectivity map from the Wichita WSR-57 radar showing the precipitation structure of the 3-4 June PRE-STORM mesoscale convective system. The locations of the two NCAR C-band Doppler radars and the connecting baseline are shown. The two squares are 80 x 80 km dual-Doppler analysis domains.

PRE-STORM Analyses

Many of the research projects within NSSL/MRD continued to focus on the analysis and interpretation of observational data collected during the OK-PRE-STORM (Oklahoma-Kansas Preliminary Regional Experiment for STORM-Central) project conducted in 1985. The analysis in FY 1988 was facilitated by the development of extensive software for processing and display of the data sets from various sources such as profilers, P-3 airborne Doppler radar, conventional and supplementary soundings, digitized NWS radar, ground-based Doppler radar, surface mesonetwork, and lightning ground strike detectors. Principal accomplishments were the following:

- Completed the documentation of the precipitation and kinematic structure of an MCS that occurred on 4 June 1985 near the Kansas dual-Doppler radars (Figs. 2, 3).

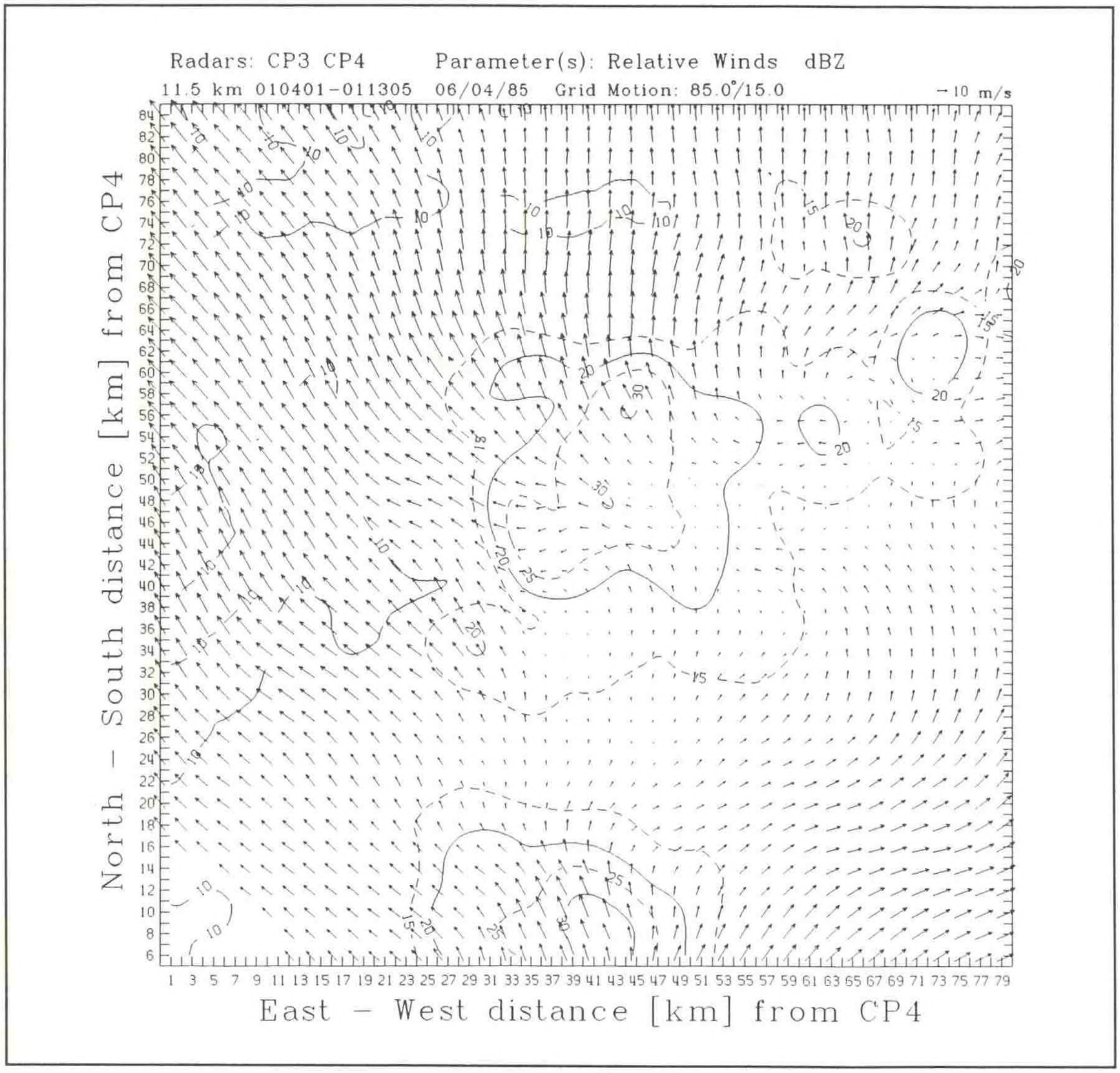

Fig. 3. Doppler-derived air motion and reflectivity fields for 11.5 km height in the northeast domain (80 x 80 km) of Fig. 2. Reflectivity contours are in dBZ; the length of a 10 m s^{-1} vector is one grid length (arrow in upper right corner). The flow pattern reveals strong divergence from the apex of the line echo wave pattern of Fig. 2.

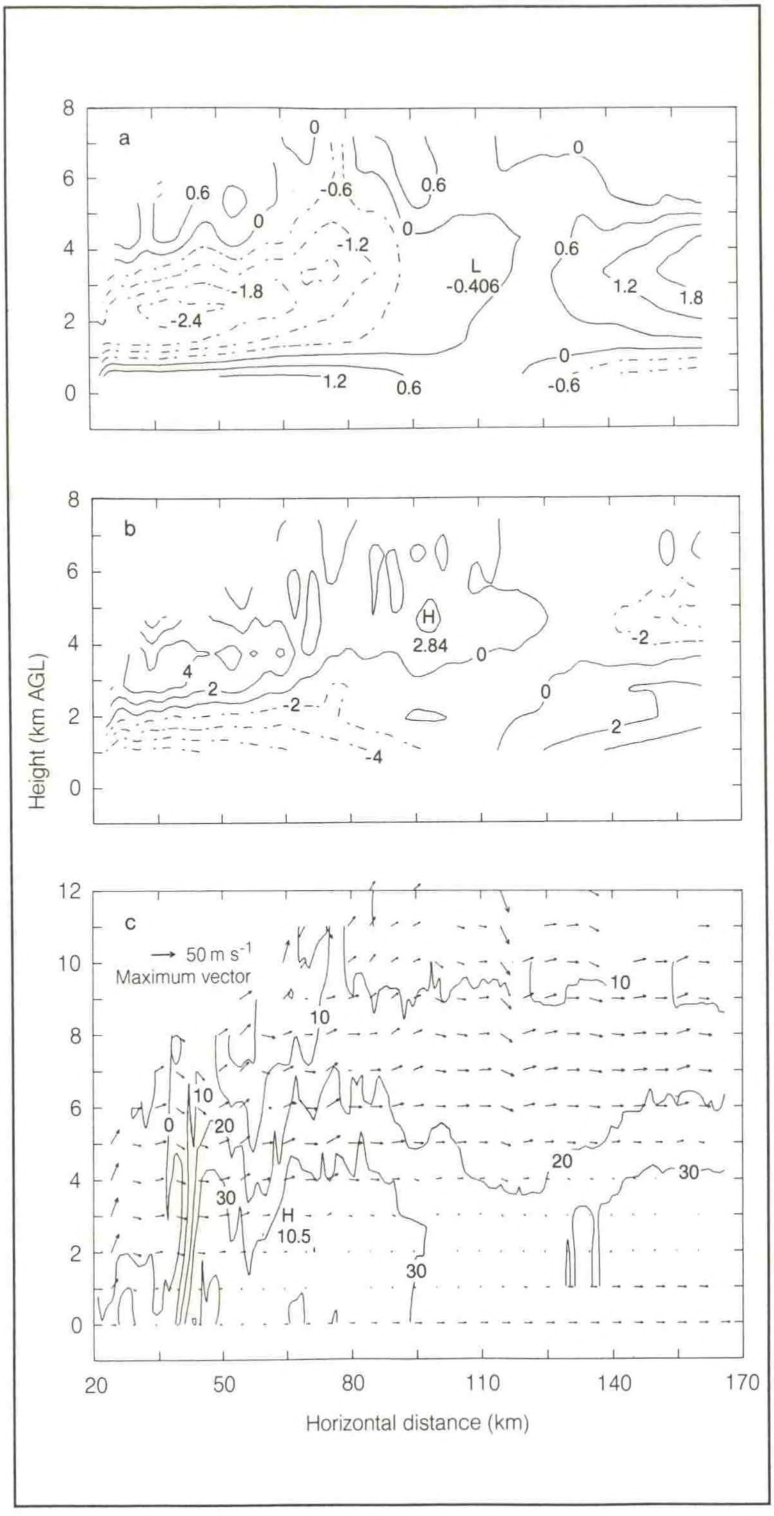

Fig. 4. Vertical planes at 0426 UTC for 11 June 1985, PRE-STORM squall line perpendicular to squall line of (a) perturbation pressure (mb); (b) temperature anomaly (deg); (c) wind and reflectivity. Pressure and buoyancy are deviations from a horizontal average.

- Completed the classification of all PRE-STORM convective systems from their radar structure.

- Completed the documentation of the evolution of the kinematic structure of a single-cell thunderstorm into a convective line, using P-3 airborne Doppler radar data coupled with ground-based Doppler radar data.

- Began the study of the detailed dryline structure using aircraft data.

- Completed the documentation of the structure of a residual cyclonic, warm-core circulation associated with a dissipating MCS.

A major emphasis during FY 1989 at NSSL/MRD will be on continued analysis of PRE-STORM observational data. A diagnostic analysis technique, called dynamic retrieval, will be developed to further elucidate the dynamics of the airflow associated with the 4 June MCS, based on the Doppler-derived three-dimensional wind fields. MRD staff will begin a study of the relationships between cloud-to-ground lightning strike distributions and polarity of the strikes to the mesoscale precipitation structure and three-dimensional airflow in the 4 June MCS observed during PRE-STORM. We will continue the investigation of the relationships between the types of convective activity and the propagation of convective systems and the synoptic and mesoscale environments.

The 10-11 June 1985 PRE-STORM squall line is being analyzed in order to further understand squall line structure and evolution. Emphasis is being placed on two separate mechanisms believed to be responsible for the decay of the system. First, the environment became less favorable to convection with the formation of a nocturnal inversion and veering of the low-level jet. Second, characteristics of the vertical circulation about a horizontal axis parallel to the squall line are being studied to determine the role of internal dynamics. Assuming two-dimensionality, vertical cross sections of wind and reflectivity fields have been obtained along with retrieved perturbation pressure and buoyancy (Fig. 4). Examination of these fields reveals features such as a stagnant flow regime toward the rear of the system that corresponds to warm temperature anomalies and low perturbation pressure. Near the surface, a cold high-pressure anomaly was present in the convective region. Changes in space and time of these fields are being analyzed. Future work will be to compare results obtained by using the two-dimensional assumption and a three-dimensional assumption.

Two MCSs developed over the central plains in and near the PRE-STORM observing network on 23-24 June 1985. Mesoscale outflows from these two systems collided in central Kansas at 0430 UTC on 24 June. Special soundings taken behind the outflow boundaries indicated a stable atmosphere; however, a sounding taken south of the area of outflow collision sampled a conditionally unstable atmosphere in which lifting of 90 mb was needed to release the instability. The PRE-STORM forecast team monitored this situation using conventional data and special surface mesonetwork and sounding data. They issued a forecast update at 0500 UTC on 24 June that anticipated new convective development in the conditionally unstable atmosphere near the area of outflow collision. As the outflows moved southward, surface convergence increased near the area of outflow collision, yet no new development of deep convection occurred.

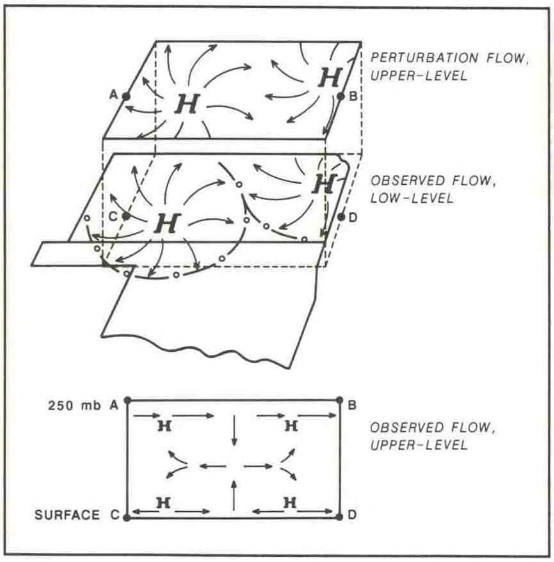

Fig. 5. (Top) Hypothesized mesoscale circulations showing observed low-level colliding outflows and the perturbation upper-level converging anticyclonic outflows. (Bottom) Hypothesized vertical circulations driven by the convergence of both the low-level and upper-level outflows in a vertical cross-section specified by points A, B, C, and D.

The PRE-STORM upper-air soundings were used to compute divergence and vertical velocity, by means of the line integral method at various times and locations, during the development and decay of the two MCSs. The presence of strong rising motion in the lower troposphere near the zone of outflow collision at 0430 on 24 June suggests that the outflows were significantly affecting storm development and system propagation. However, at 0900 UTC while strong rising motion is found below 800 mb, there is strong sinking motion between 800 mb and 400 mb. It is hypothesized that this mesoscale downdraft occurred between the two mesoscale convective systems as their upper-level outflows converged (Fig. 5). This layer of sinking air may have helped maintain a capping inversion at the top of a deepening moist layer and apparently was sufficient to inhibit development of new convection even in the face of strong low-level forcing. The case illustrates the simultaneous development of mesoscale circulations that appear to be acting in opposition to each other during the initiation of new storms. It further illustrates the complexity of the mesoscale and shows why it is often hard to anticipate the evolution of convective storm systems.

Observations collected during the PRE-STORM experiment are being used to study the evolution and structure of the MCS that occurred on 6-7 May 1985. The system began as a squall line that developed in response to an advancing lower tropospheric shortwave. An extensive area of stratiform precipitation with an embedded mesoscale vortex formed behind the squall line. Other storm features included a low-level inflow jet, a mesoscale updraft, a mesoscale downdraft, and a middle-level rear inflow jet (Fig. 6). Two source regions were found for the mesoscale downdraft. Some air parcels, particularly those at low levels in the northern sections of the downdraft, began at middle levels (4 km) in the prestorm environment. The bulk of the downdraft air originated in a deep, broad confluent zone on the storm's rear. The descending rear-inflow air, depending on location, extended from 1 km AGL to the upper troposphere and concentrated in a jet that passed to the south of the vortex. The distribution of vertical vorticity within the MCS was closely tied to the rear inflow. Maximum vorticity ($25 \times 10^{-5}\ s^{-1}$) existed at middle levels of the storm where convergence was large but also at lower levels where the mesoscale downdraft dominated. The buildup of low-level vorticity is attributed to a

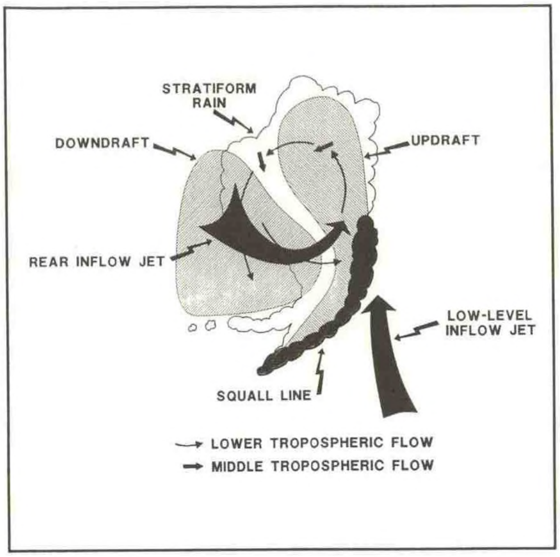

Fig. 6. Schematic summarization showing the location of the low-level jet, the middle-level rear-inflow jet, and the principal middle-level updraft and downdraft regions in the 6-7 May 1985 MCS. Scalloped areas represent precipitation.

downward transport of vorticity and to the baroclinic generation of vorticity in the rear inflow. Little vorticity was found in the overlying convective outflow layer.

A three-volume set of Technical Memoranda was completed during 1988. It describes the daily operations, and provides a summary and catalog of the data collected by NWS and research radars and research aircraft during PRE-STORM. Numerous requests for data, consultation, and analysis software were received by NSSL in Boulder and Norman from interested scientists at various research institutions, among them, NCAR, NASA, other ERL labs, the Nanjing Institute and many universities around the United States.

Four-Dimensional Data Assimilation

Since late 1986, NSSL has started work on the assimilation of mesoscale data into nonhydrostatic prediction models. The approach used is based on the principle of adjoint modeling, a methodology that was developed during the 1970s in the field of optimum control. Intuitively, the method can be thought of as a process of fitting models to observations; i.e., the initial state, boundary conditions, and intrinsic parameters of a deterministic model are adjusted such that the subsequent model evolution fits the observations in some distance-dependent sense such as a least-squares fit. This approach has two main advantages over traditional approaches:

(1) The final analyzed state is absolutely consistent with the model dynamics.
(2) The sensitivity of the model to input parameters is a natural by-product of the process.

The disadvantage is the demand on computational resources. As the approach is now configured, the assimilation of data using larger-scale prediction models indicates that the equivalent of 10-15 model integrations is necessary to find the optimal state. This precludes operational implementation at the present time, but the solution to 4-dimensional data assimilation (4DDA) using this strategy is manageable in the research environment. Our modeling work is nearing completion, and we expect to do 4DDA experiments in several areas:

(1) 4DDA near middle-latitude frontal zones.
(2) 4DDA on the meso alpha scale using data from PRE-STORM.
(3) 4DDA on convective storm environments.

Item (3) will undoubtedly be the most challenging, and items (1) and (2) will be attempted first in order to determine strengths and weaknesses of the 4DDA approach. In item (1) we will be simulating the Doppler observations in and around frontal systems; in (2) we will be examining the ability to combine conventional wind and Profiler-derived winds on the larger mesoscale. Finally, we will address the problems associated with latent heat release in convective systems.

Calculation of the derivative properties of the wind field is an essential step in utilization of wind data. As a part of a continuing program in the study of objective analysis of meteorological fields, a theoretical examination of the procedures for wind field derivative estimation has been carried out. Previous work in this area led to the conclusion that estimating kinematic (i.e., first derivative) properties of the wind directly from the data by means of line integral techniques gave much better estimates of those properties than the standard technique of mapping the wind data onto a regular grid and then estimating derivatives through

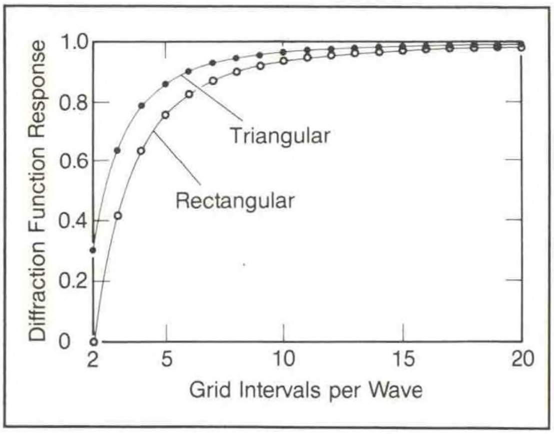

Fig. 7. Quality of derivative estimates obtained using the traditional ("rectangular") method and the line integral ("triangular") approach. The information gain associated with the triangular approach was modeled by means of an effective sampling interval that is 3/4 that of the rectangular grid spacing.

finite differencing on that grid. In this study, the underlying reasons for that improvement have been brought out, further underscoring the value of the line integral approach. In addition, a more efficient algorithm for doing the line integral estimates has been developed. The theory suggests that using the line integral method is most likely to be of importance in the range of wavelengths roughly 6 to 12 times the sampling frequency, and is of special value when the sampling is done at irregular spacing. The improvement in derivative estimation increases with decreasing wavelength (Fig. 7). Future work in this area will concern the effects of instrument and sampling errors on diagnostic fields.

Objective analysis has been carried to a new level of development by the discovery that objective analysis by weighted sums can be reformatted as an approximation of discrete data by an analytic approximation using the weighting function as a basis for the analysis. Once this is done using a Gaussian weighting function, derivatives of the approximation can be computed as combinations of weighted sums of data values and position vectors of the observation sites. These derivatives possess the same spectral band limitations as the original approximation, and hence they do not suffer from the accumulation of diffraction noise that is inherent in the finite difference approximation of derivatives. The analytic approximation scheme has been carried a step further by optimization. The fact that the analytic approximation of discrete data can be evaluated at any set of points, including the data points themselves, renders this approach amenable to optimization through least squares. The results are continuous approximations of meteorological fields that are sampled by a discrete set of observations, and the values of the approximations at the observation sites are exactly equal to the observations themselves. The optimized analytical approximation scheme resembles somewhat the optimal interpolation scheme described by Gandin, but differs from it on one important feature. Optimal interpolation uses a poorly determined autocorrelation function from climatological data to fit the observations, whereas no such climatological assumption is contained in the optimized analytic approximation. How well this scheme works is demonstrated in Fig. 8 in which an analysis on a personal computer is presented of upper-air conditions preceding the Big Thompson flash flood on the morning of 31 July 1976. The first panel (Fig. 8a) is a composite analysis of the 700-500 mb layer showing mean height contours and the divergence of Q field. The analysis of the forcing field indicates that the Front Range and Palmer Ridge areas of Colorado were in the center of an area with an increasingly stormy outlook. The second panel (Fig. 8b) shows an excessive amount of moisture at 850 mb east and northeast of the Front Range area that is associated with a polar front as indicated by a trough in the height field and temperature gradient to the northeast. Both panels taken together indicate a high potential for flash floods since they indicate increasing instability during the day, plenty of low-level moisture as fuel for convection, and a bent-back ridge that would have tended to steer convection from the plains toward the Front Range. An analysis such as that presented in Fig. 8b indicates the utility of the optimized analytic approximation that can generate smoothed diagnostic analyses involving various orders of derivatives in real time for forecasters in the field.

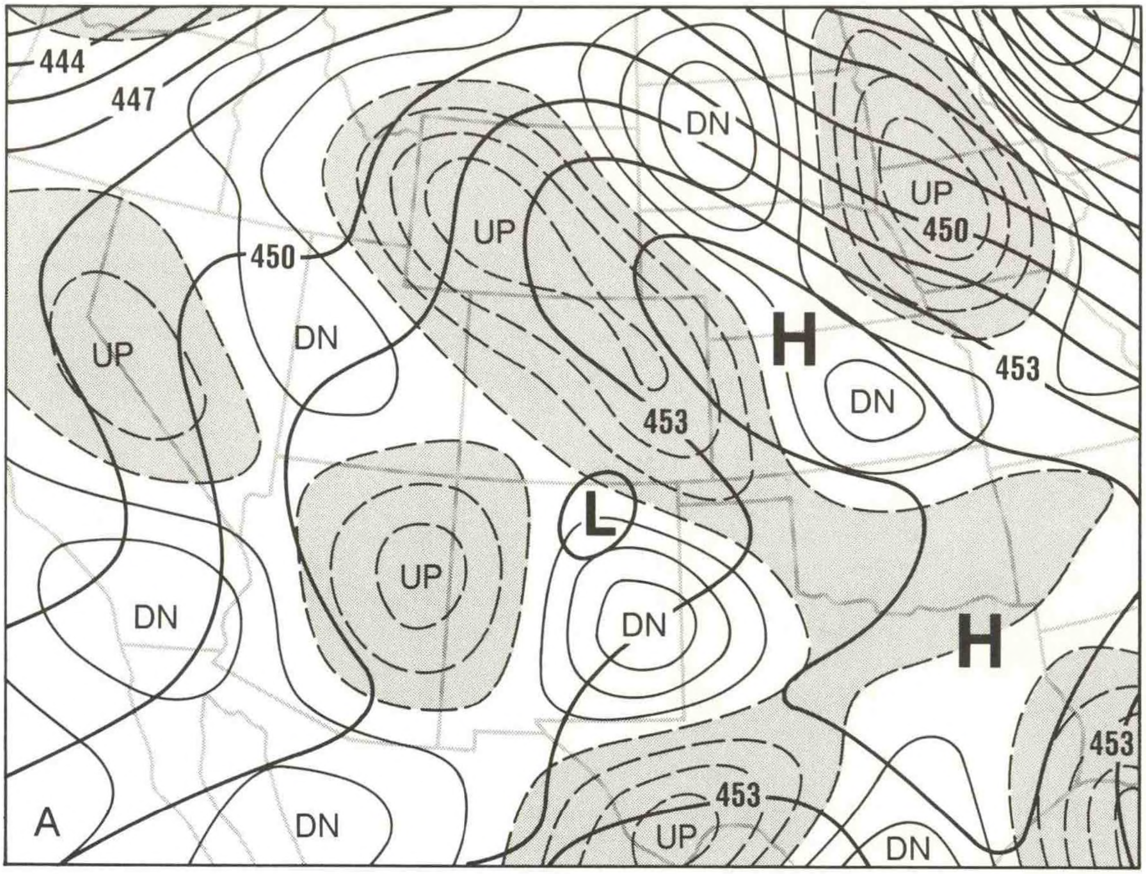

Fig. 8. Analyses at 1200 UTC on 31 July 1976. (A) Composite analysis for the 700-500 mb layer. The contours that represent divergence of the Q-vector are in units of $5 \times 10^{-15} mb^{-1} s^{-3}$: Upward forcing (UP) that is part of an increasing potential for stormy weather is indicated by shaded negative areas in the dashed contours; downward forcing (DN) associated with clearing is indicated by the thin, solid contours. Thick contours represent mean layer heights at 15-m increments.

MCC Climatologies and Mean Features

Mesoscale convective complexes (MCCs) are of sufficient scale, and occur frequently enough in the warm season, to inject feedback to the synoptic scale. The maintenance of an annual summary of these storm systems keeps the community informed on their interannual variability, and provides researchers a quick reference to the times and places of occurrence. A climatology of MCCs has been kept since their identification in 1978. The summary for the 1986 warm season has been completed, and 58 MCCs were identified--one less than the total for 1985. 1985 and 1986 were the most active MCC seasons to date, with nearly 50 percent more MCCs than the usual number expected. MCCs of these two years compare well in total number and temporal characteristics, but differ in geographical and seasonal distributions. Normally, peak MCC activity occurs in May and June. The frequency distribution for 1985 maximizes in May and June, but a midsummer maximum characterizes the 1986 distribution. Geographically, nearly 40

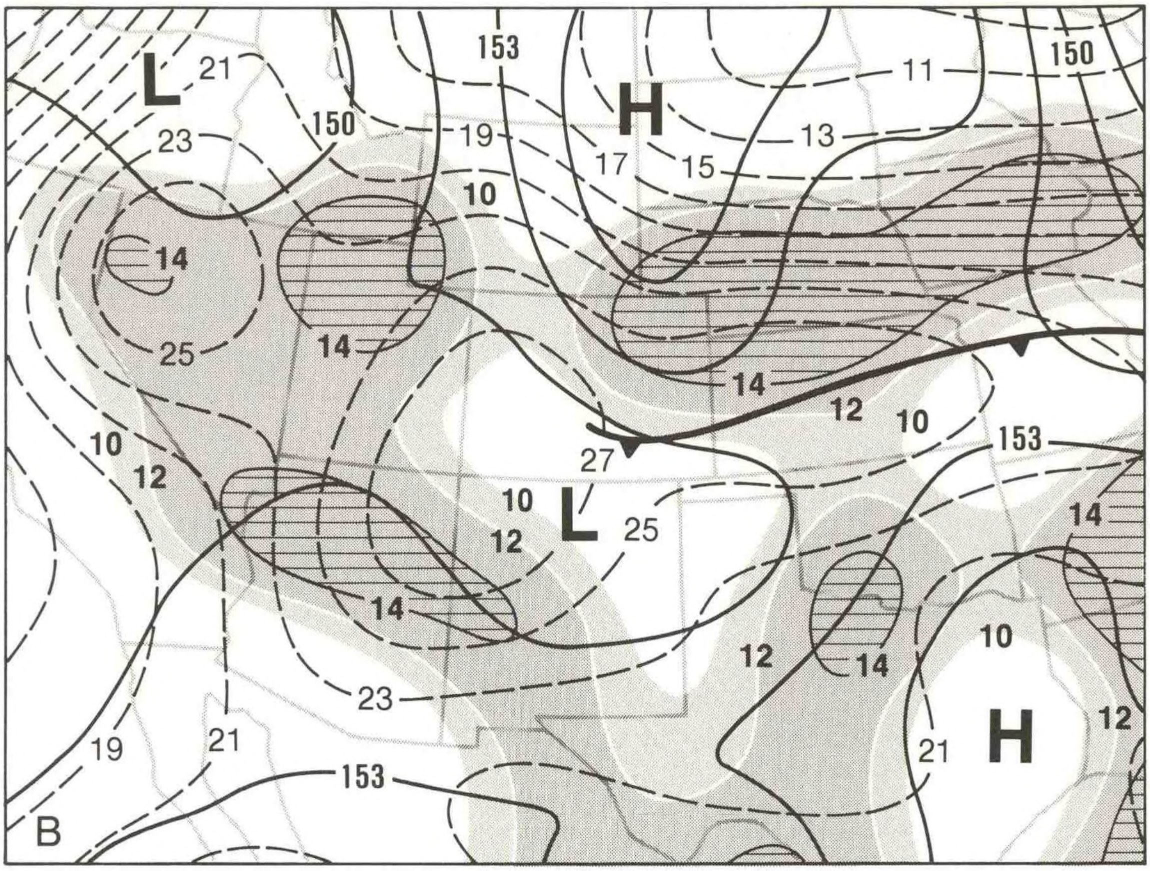

Fig. 8 (B). Composite analysis at 850 mb. Dew point temperatures are shaded and hatched: light, ≥10°C; dark, ≥12°C; and hatched, ≥14°C. Solid contours represent 850-mb heights in decameters; dashed con tours are isotherms in °C. The position of the polar front that pushed into Colorado is indicated by standard notation.

percent of the MCCs in 1985 matured over eastern Kansas and Missouri (Fig. 9a). In contrast, MCCs in 1986 favored a more northerly track over eastern Nebraska and Iowa (Fig. 9b). This comparison is interesting in that 1986 was the first year of the recent drought in the southeastern United States. The tendency for more northerly MCC tracks in 1986 may have been associated with the rapid onset of the subtropical high over the eastern United States. During 1986, the ridge abruptly shifted from low latitudes in late May to its summertime position of 1 June, and during the first two weeks of June no MCCs were observed. In contrast, during 1985 the northward progression of the subtropical high was noted to be relatively gradual from mid-May to 1 July, and during that period many MCCs were observed in the south-central Plains. Although more than the average number of MCCs occurred in 1986, the seasonal and geographical distributions were very atypical. During FY 1989, MCCs of 1987 and 1988 will be tabulated, and the association of reduced convective activity with the continuing drought conditions, noted during the last few years, will be followed.

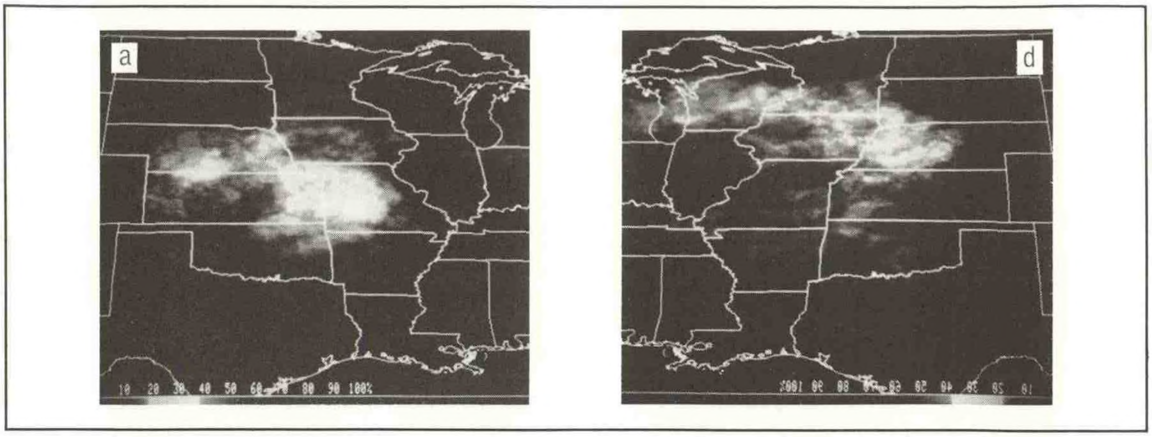

Fig. 9. Fixed-area composite of infrared satellite images of each MCC at the time of maximum extent during (a) 1985 and (b) 1986, expressed as a fraction of the total number of images composited.

Modeling Studies

An analysis of the sensitivity of modeled thermal and microphysical processes in a thunderstorm to the microphysical parameterization method has recently been completed. A three-dimensional kinematic cloud model calculates temperature and water substance fields in a thunderstorm observed by Doppler radars. The precipitation cycle, deduced from model output, is characterized by a balance of condensation, rain and graupel/hail accretion of cloud, rain freezing, graupel/hail melting, and sedimentation and advection of precipitation including recycling (Fig. 10). The largest differences between model solutions are traced to a major change of the predominant precipitation accretion mechanism. Latent heating due to the presence of ice is localized and of secondary importance to condensation of vapor to cloud in the main updraft region. These findings provide a basis for refining cloud models and mesoscale subgrid convective parameterizations.

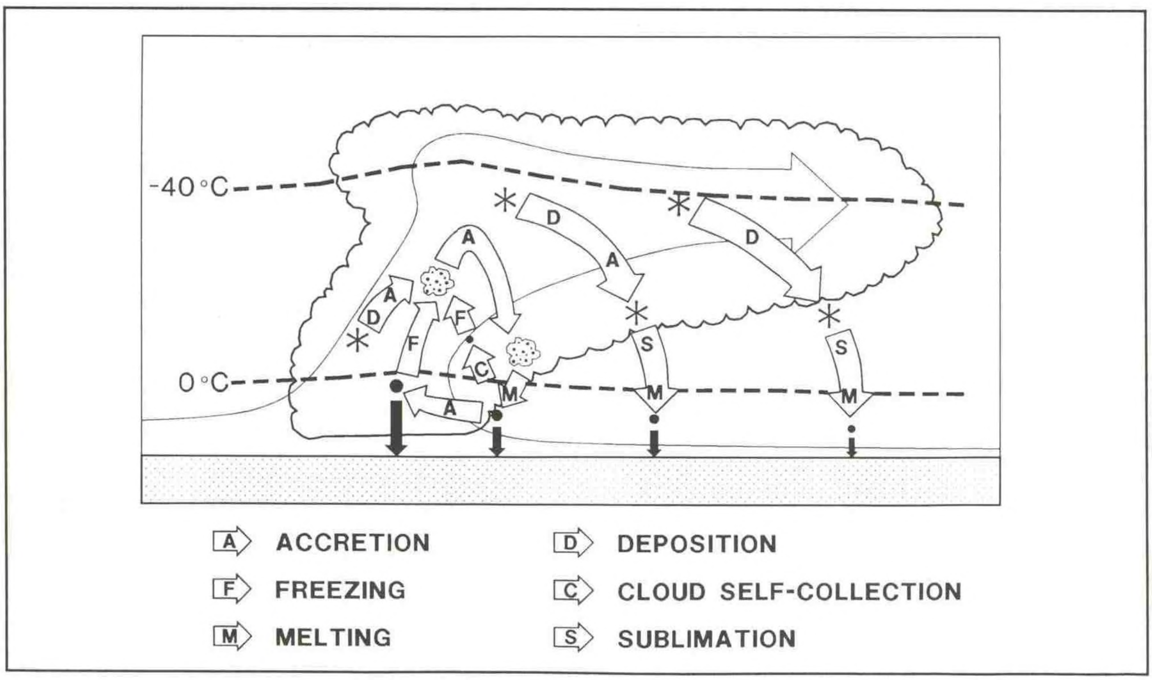

Fig. 10. The precipitation cycle in a thunderstorm, deduced from cloud model output.

Many meteorological phenomena important to severe storms contain sharp spatial gradients (e.g., storm outflows, fronts, cloud boundaries). Numerical modeling efforts have traditionally encountered problems in dealing with such boundaries, including the generation of spurious oscillations and the numerical diffusion of the boundary itself. A collaborative effort with the Oklahoma University School of Meteorology has been undertaken to apply a numerical method that is new to the atmospheric sciences within a cloud scale model. The method has its roots in astrophysics and is known as the piecewise parabolic method (PPM). Various advection tests were successfully carried out to verify the ability of the method to move scalar perturbations in fixed wind fields without changes in amplitude, phase, and edge gradients. Following these tests, a two-dimensional dry thermal model was formulated on the basis of PPM, and the time-dependent calculations were compared with results of a state-of-the art finite difference model. The PPM results were superior to the finite difference results in several respects including the ability to preserve sharp gradients in the fluid. In the future, the PPM-based model will be made to run more efficiently and will be expanded to include moisture.

An understanding of the physical relationships of microphysical and electrification processes in thunderstorms to concomitant dynamical evolution is fundamental to interpretations of measured storm properties. The effects of precipitation-based charge separation mechanisms on the evolution of space charge and the electric field in New Mexico mountain thunderstorms is studied with the aid of a three-dimensional kinematic cloud model that includes conservation equations for space charge on cloud droplets, rain, cloud ice, snow, and graupel. Assimilation of three-dimensional, time-dependent Doppler airflow fields facilitates numerical forecasts of temperature, water substance, space charge, and electric fields. Model output for the 31 July 1984 case (Fig. 11) shows a classical positive-over-negative-charge dipole with vertical electric fields approaching values associated with lightning. These output variables are verified with in situ aircraft, free balloon, radar reflectivity, and surface field mill measurements. The important task of verifying cloud models is thus carried forward in a new and more quantitative direction. This work sets the stage for studies of the electrification of severe High Plains storms.

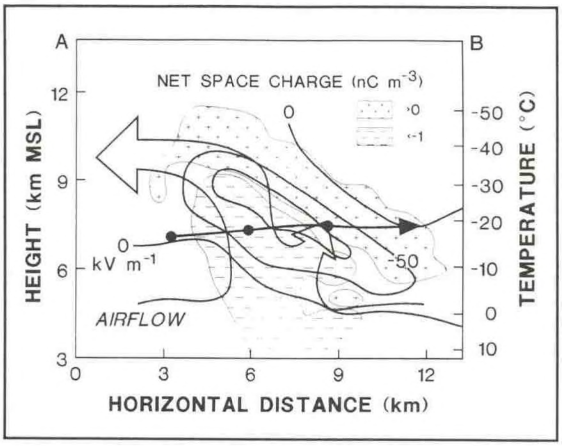

Fig. 11. Modeled electrical structure of the 31 July 1984 New Mexico mountain thunderstorm at 1152 MST. Regions contain negative (-) or positive (+) net space charge. Dashed contours represent vertical electric field (kV m^{-1}). The heavy solid line indicates the penetration path of the NCAR-NOAA sailplane.

Improved knowledge and quantification of the mechanisms responsible for organization and persistence of MCSs provide the basis for better forecasts. The effects of diabatic heat and moisture sources/sinks on the solenoidal generation of vorticity in the 7 May 1985 PRE-STORM MCS is being investigated with a three-dimensional time-dependent kinematic mesoscale model. An objective gridded airflow analysis of radiosonde data is inserted into the model as proxy for dynamically simulated flow to provide time-evolving mesoscale heat and water substance fields. The thermodynamic sounding data are used both for time-dependent model lateral boundary conditions and verification of model forecasts. A refined version of this mesoscale analysis and modeling system will ultimately assist in the meteorological assessment of profiler network data being planned for FY 1990 and beyond.

TAMEX Analysis

Data collected by the P-3 aircraft during the Taiwan Area Mesoscale Experiment (TAMEX) are being analyzed to determine the structure and kinematics of mature oceanic MCSs (Fig. 12). Analysis of the vertical velocity data collected during penetrations of cumulonimbus clouds by the P-3 aircraft have been summarized in the form of log-probability plots of updraft and downdraft core sizes and strengths as a function of altitude. The results indicate the relative weakness of oceanic convective updrafts and downdrafts compared with continental thunderstorms. This weakness in updraft strength is consistent with the observed profiles of radar reflectivity and cloud water content, and indicates the large role that warm rain processes play in oceanic convection. Water loading is also of primary importance in driving convective-scale downdrafts and in reducing updraft buoyancy from what would be expected from parcel theory.

Future research will focus on the kinematics of one well-organized system observed by airborne Doppler radar. Emphasis will be placed on understanding the precipitation structure in terms of the observed air motions.

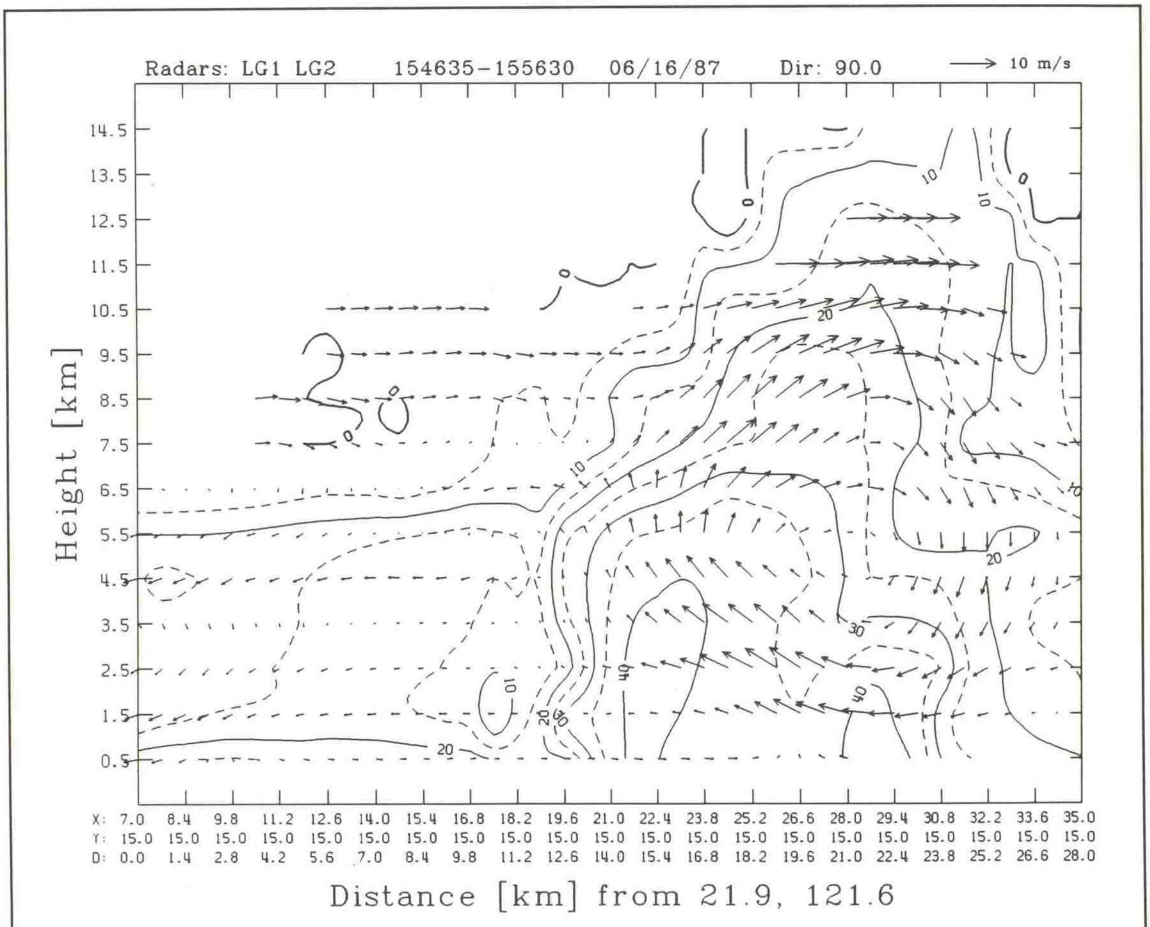

Fig. 12. East-West vertical cross section of relative wind vectors and radar reflectivity (dBZ) through a stationary oceanic convective line observed by airborne Doppler radar during the TAMEX project. Strong convergence above a height of about 1.5-2.5 km occurred to the west of the strong reflectivity in spite of the lack of a well-defined low-level density current.

Convective Storms and Mesoscale Systems Over Mexico

Examination of the convective climatology of Mexico has begun, primarily utilizing satellite data. These studies are being pursued in collaboration with ERL/ESG scientists. It is hypothesized that convective events over Mexico, particularly those organized on the mesoscale, represent important components of the summertime monsoon flow regime that influences the weather and climate of much of the western United States from June through September. Initial efforts have documented the high frequency of thunderstorm events over Mexico (2 to 3 times greater than indicated in climatological charts) and the repetitive character of MCSs over certain geographical regions (Fig. 13). This study will help in determining whether field studies of subtropical convective systems could contribute substantially to our understanding of mesoscale precipitation systems. Regardless, it is envisaged that these studies will lead to better understanding of the sources of convective instability over the western United States and eventually to improved NOAA forecast services.

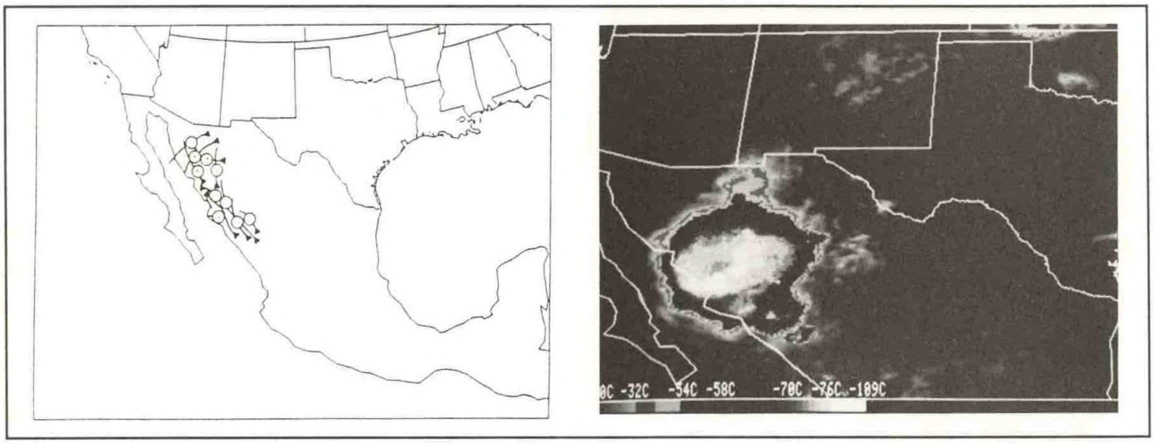

Fig. 13. Sample tracks of typical MCSs over northwestern Mexico, and an IR satellite image that captures one of these weather systems.

GUFMEX

It is generally accepted that the Gulf of Mexico is the primary source of water vapor for both general precipitation and severe storms in the central United States, yet there have been relatively few investigations of the details of moisture transport from the Gulf, or the modification processes that occur when continental air plunges southward over this body of water. An especially difficult forecast problem exists in the late winter and early spring when cold air masses move into the Gulf, undergo modification, and subsequently return to the continent. The return flow can consist of several different air masses: the modified continental air, continental tropical air from Mexico, and tropical air from the southern reaches of the Gulf or from the Caribbean. These returns have been associated with some of the most intense storm outbreaks (e.g., Mississippi Delta outbreak, 3-4 April outbreak, Palm Sunday 1965 tornadoes), making the outlook of great public importance. Because of these forecast problems and their potential effect on the populace, a modest field program was planned and executed during the winter-spring of 1988.

The field experiment, GUFMEX, was conducted over the Gulf of Mexico to gather data on two phenomena: air mass modification over the Loop Current (the persistent warm gyre in the eastern Gulf), and return flow characteristics of the modified polar air returning to the southern shores of the United States. The experiment took place between 20 February and 2 April 1988. Six-hourly radiosondes, special Cross-chain LORAN Atmospheric Sounding System (CLASS) soundings, and three P-3 flights including dropwindsondes and Airborne Expendable Bathythermograph (AXBT) measurements were accomplished. Figure 14 is a

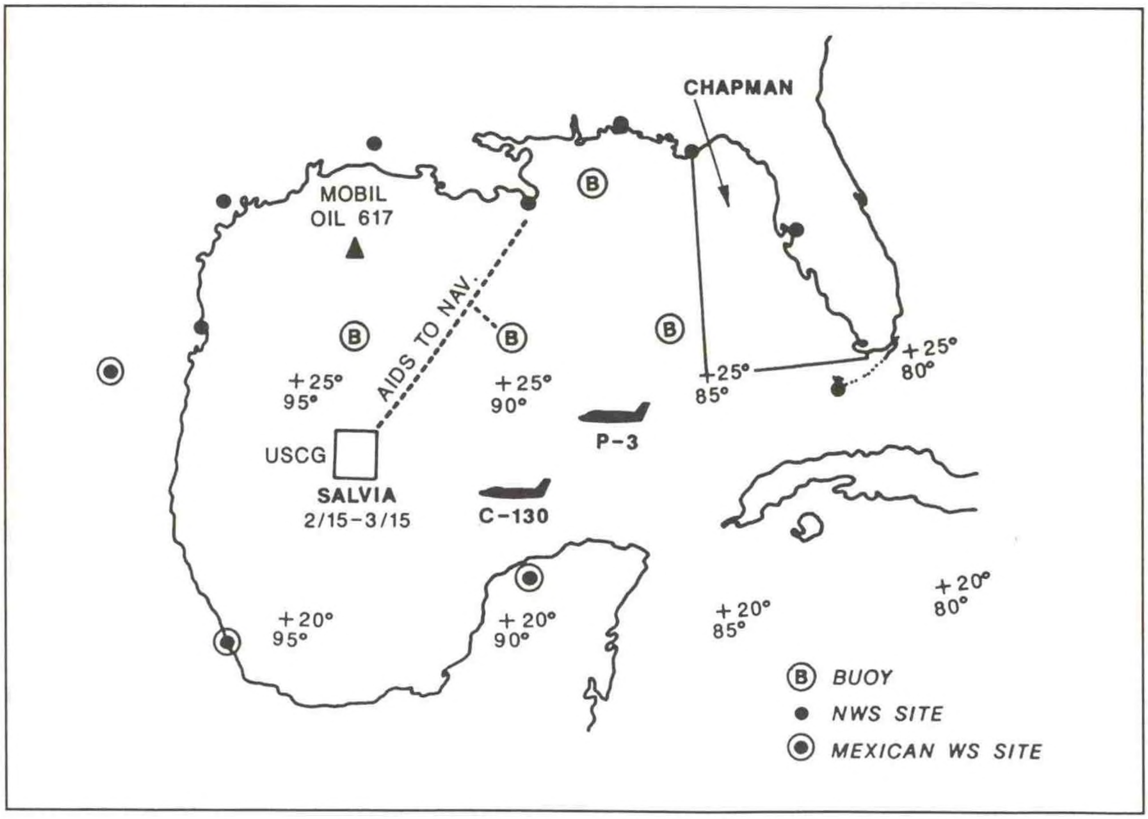

Fig. 14. Observational platforms used during the field phase of project GUFMEX.

display of the observation systems deployed during the experiment. Seven return flow events occurred during the field phase of GUFMEX, and special data were collected during five of the events.

Research has been under way in the following areas:

- Climatological study of return flows from the Gulf of Mexico over the past 10 years.
- A study of the operational prediction models' performances in return flow situations.
- Validation of NWP models' boundary layer packages in return flow episodes.
- Validation of satellite derived products in return flow episodes.
- Analysis of 15 years of buoy data over the Gulf, and evaluation of fluxes during extreme cold outbreaks.
- Computation of air trajectories over the Gulf for some 1988 data periods, in collaboration with the ERL Air Resources Laboratory, using available synoptic data.

The collection and formatting of data sets is well under way at both NSSL and the Cooperative Institute for Meteorological Satellite Studies (University of Wisconsin), and scientists in the larger community of meteorology are encouraged to share these data.

Gust Front Algorithm for the Terminal Doppler Weather Radar (TDWR)

In 1984, the development of an algorithm for automatic detection of gust fronts using Doppler spectral moments began at NSSL. Wind shears and turbulence associated with gust fronts are potentially hazardous to landing and departing aircraft. Because of this, the detection of gust fronts in the airport environment is an integral part of the Federal Aviation Administration's Terminal Doppler Weather Radar (TDWR) system.

Continuous upgrades and improvements to the gust front/wind shift detection algorithm have occurred since its development. Evaluation of the algorithm's performance during the 1987 TDWR experiment in Denver, Colorado, detailed a need for further refinements. The 1988 iteration of algorithm improvements included a sophisticated velocity dealiasing scheme, a technique to mitigate ground-clutter-induced errors, better representation of the gust front, and error checking of wind estimates along with a perpendicular wind estimate as an alternative when uniform wind estimation is not acceptable.

NSSL personnel participated in the 1988 TDWR Operational Testing and Evaluation (OT&E) experiment near Denver during July and August. A preliminary assessment of the current algorithm's performance was completed using data from that experiment. Algorithm products (detections and forecasts) were compared with a truth data base produced by several experienced radar observers. Algorithm performance was measured by the Probability of Detection (POD), the Probability of False Alarm (PFA), and the Probability of Correct Forecast (PCF). The overall POD, for the 1988 TDWR OT&E was 78%; 1105 out of 1426 gust fronts were detected. This result indicates a 20% increase in algorithm effectiveness, compared with 1987 TDWR results. The PFA was reduced from 44% in 1987 to 2.4% in 1988. For 10-minute forecasts and 20-minute forecasts, the PCFs were 95% and 83%, respectively. Ground truth for algorithm wind estimates was derived from surface wind measurements at 38 locations around Denver's Stapleton International Airport. Comparison of algorithm wind estimates with ground truth produced a mean absolute speed difference of 3.0 m s^{-1} and a mean absolute direction difference of 30°.

Experience gained during 1988 suggested additional improvements to the basic radial convergence detection algorithm. Goals for 1989 are to enhance tracking techniques, to add thin-line detection and azimuthal shear detection, and to optimize algorithm thresholds.

National Lightning Network

NSSL continues to have a key role in the Working Group on Lightning Detection Systems in the Office of the Federal Coordinator for Meteorology (OFCM). We wrote a portion of the Preliminary National Plan for Lightning Detection Systems, which was published by the OFCM in June. Furthermore, the NSSL lightning detection network was integrated with two others in an experimental nationwide network (Fig. 15) for a 3-year OFCM program to evaluate applications of this technology to Government needs. Data from the national network are being used in operations by the National Severe Storms Forecast Center and are being processed by the center for distribution to NWS offices as a product on AFOS. Also, NWS will analyze data from the Kansas stations in the NSSL network to investigate using lightning network data to detect local thunderstorms for stations being developed for the Automatic Surface Observing System (ASOS).

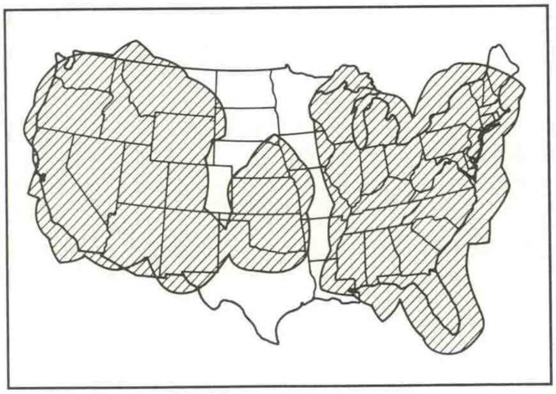

Fig. 15. Coverage of the Demonstration National Lightning Detection Network as of the summer of 1988.

As part of a 3-year project for the OFCM, we completed the first comparative evaluation of the two commercial ground-strike-locating systems now available in the United States. The final report of this evaluation has been accepted by the OFCM, and scientific publication and presentations of the results are under way so that management can make informed decisions on which system is more appropriate for agency needs.

Other studies focused on NWS operations include a collaborative project with the NWS Techniques Development Laboratory (TDL) that examined a lightning strike climatology, particularly relationships with radar reflectivity, forecast model predictors, and storm severity. Previous work by TDL had been successful in using lightning strike data from the Bureau of Land Management to develop forecast products for the western United States. In our recently completed study of storms on the Great Plains, we found for the first time a correlation between storm severity and the occurrence of positive ground flashes. There were also a number of differences from the study of the western United States, including a much stronger relationship between lightning activity and radar reflectivity measured at low elevation angles, a much smaller effect from topography, and a prevalence of nocturnal lightning strike activity over much of Oklahoma. Work continues at TDL to use the results of this study to refine forecasts of thunderstorms and to forecast lightning strike activity.

Lightning and Storm Evolution

The interrelationships between lightning and storm characteristics were analyzed for lightning field changes recorded with the NSSL mobile laboratory as we moved for about an hour in the mesocyclone region of a severe storm that produced a tornado. Upon examining the lightning data, we found that in-cloud (IC) flashes dominated the activity. Intracloud lightning accounted for 95% of all flashes (Fig. 16). We continue to find that most storms, especially severe storms, have a predominance of IC flashes and high IC flash rates.

As part of our collaborative research with several universities and NASA during COHMEX (COoperative Huntsville Meteorological EXperiment), an analysis was also made of NSSL mobile laboratory data on the total lightning activity in a microburst-producing storm. There we found that the IC flashes also dominated the total activity: 110 of the 116 (95%) flashes during the storm's life were intracloud. The analyses, which incorporated dual-polarization Doppler radar data, provide quan-

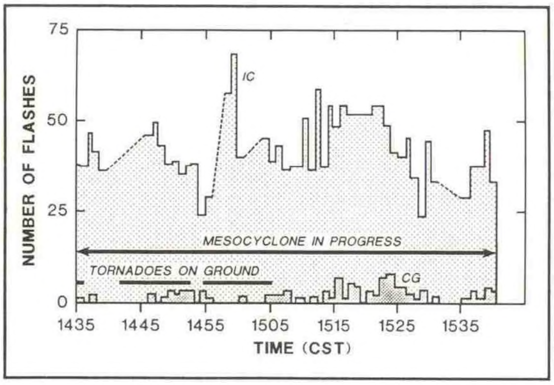

Fig. 16. Total lightning activity and related storm activity during the Altus-Synder tornadic storm, 14 May 1986. The dashed lines on the in-cloud (IC) flash histogram mean no data collected, either because the mobile laboratory was out of the mesocyclone region or tape was being changed on the analog recorder. To maximize the number of cloud-to-ground (CG) flashes counted, data from the NSSL lightning strike locating system are included in the CG flash histogram. The mesocyclone was confirmed from Doppler radar and from visual observations by the mobile laboratory crew.

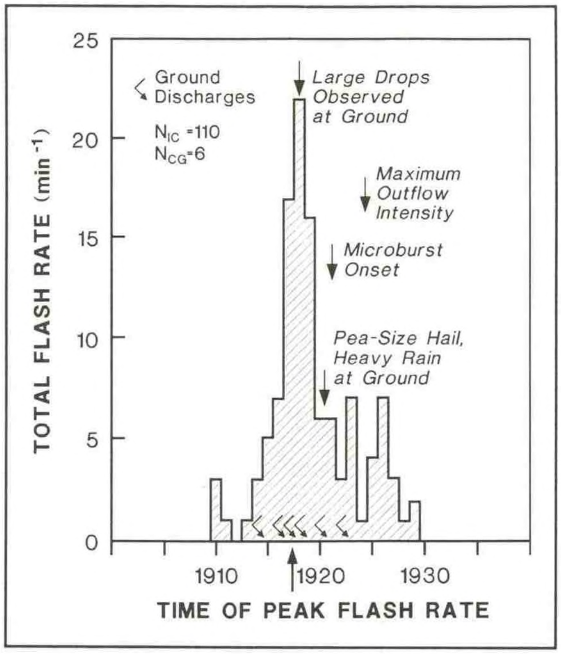

Fig. 17. Total lightning history of the 20 July 1986 wet microburst in Huntsville, AL. N_{IC} and N_{CG} are the respective numbers of intracloud and cloud-to-ground flashes produced during the storm's lifetime. An arrow points to the time of each of the six CG flashes.

titative evidence that there is a signature of the impending microburst in the intracloud flash rate several minutes before the flash occurs (Fig. 17).

Lightning Hazards to Aircraft and Space Vehicles

The problem of lightning hazards to aircraft was addressed starting in 1980 in view of the development of a new generation of aircraft flying "by wire." That is, the aircraft is controlled almost entirely by electronics, and made of nonmetallic, composite materials, and thus is more susceptible to direct or induced effects of lightning. By FY 1987 two research programs (NASA Storm Hazards Program and FAA/USAF Program) completed their inflight measurements. NSSL was involved, to different degrees, in both programs. A key issue still remaining in studying lightning-aircraft interaction was a physical model of lightning initiation (triggering) on aircraft verified by the airborne data. This issue became an objective of the study conducted in FY 88. We proposed a physical model (Fig. 18) that uses the "uncharged leader" concept of Kasemir. It relates processes during lightning attachment to an aircraft to those in negative stepped leaders, positive leaders and continuous current in natural lightning, flashes triggered by wire trailing rockets, and laboratory discharges. The model supported by the airborne data characterizes the lightning initiation as follows: (1) The triggered flash starts with a positive leader with continuous current at the aircraft extremity having the maximum positive electric field. (2) A negative stepped leader starts a few milliseconds later from the extremity with the maximum negative electric field. Two leaders develop in space simultaneously and bidirectionally, and the entire process is governed by the ambient electric field, and the electric circuit that includes capacitances and conductivities of aircraft and leader channels. Applied to natural intracloud lightning, the model helps to connect somewhat fragmentary observations of this phenomenon with ground-based remote sensor data, thus contributing to understanding of the physics of natural lightning initiation and development.

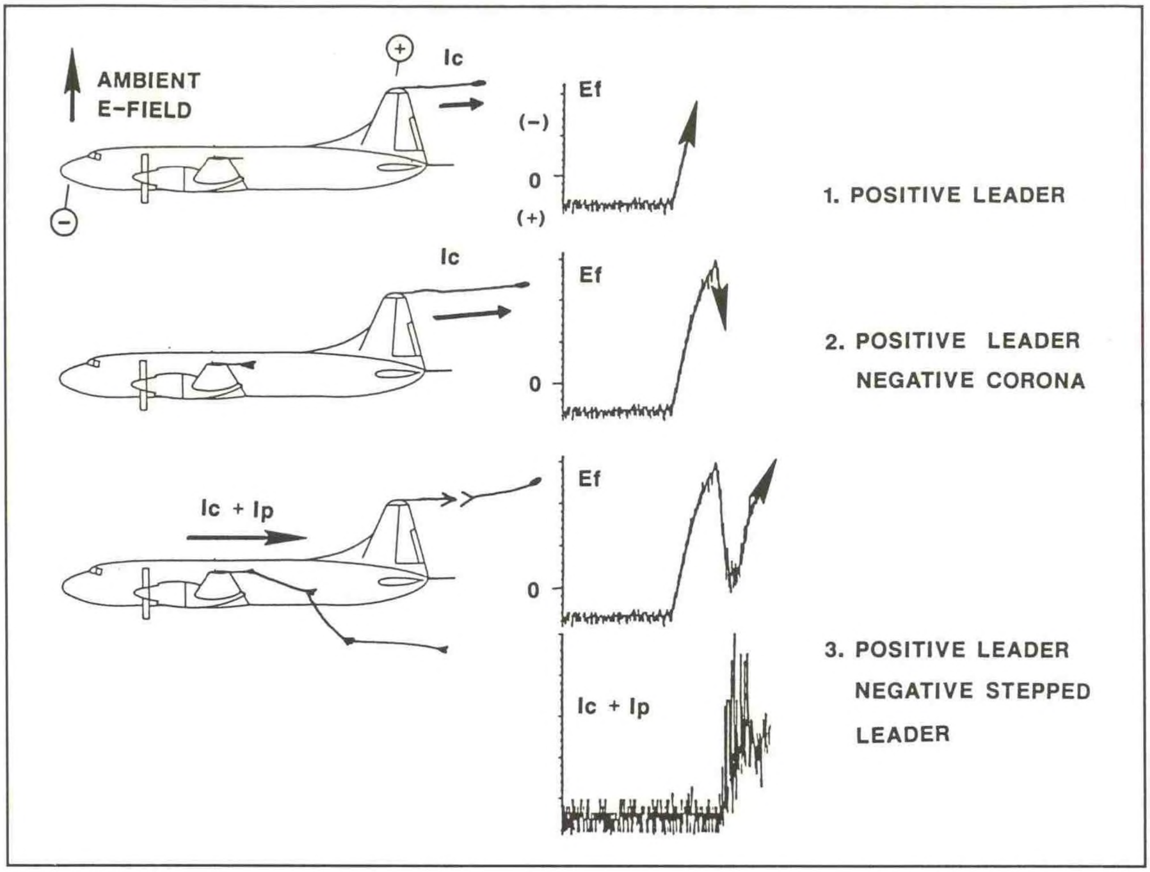

Fig. 18. Conceptual sketches of the processes involved in the initiation of a lightning strike on the FAA CV-580 research airplane. Strike attachment points are the tail boom and the left wing tip. Ef is the local electric field on the upper forward part of the fuselage; Ic and Ip are the continuous and pulse currents, respectively, flowing from nose to tail.

Kennedy Space Center Meteorological Studies

Although several studies have been conducted for the Kennedy Space Center (KSC) region to provide a better understanding of the meteorological context in which lightning occurs in thunderstorms, critical issues remain, providing significant new directions for research. A few years ago, it was shown by NSSL staff that surface winds provide a valuable clue to the subsequent cloud development in summer when clouds are forced by surface heating. As this method was implemented by USAF forecasters, the inadequacy of the small surface network for properly representing a whole cloud's lifetime became very apparent.

Therefore, the surface wind network was expanded, reaching an area of 1600 km^2 in 1987. With this mesoscale network, it has proved possible to follow more storms through their entire life cycle, using the time series of the average surface divergence over the whole network. However, sometimes more than one storm is in the network at a time, causing more complex signals in the surface divergence field. Several new approaches have been developed to address this complexity, such as identifying only the average convergence when it is above a given threshold, or the area of convergence above a given value (Fig. 19).

Although these approaches have appeared to be successful in a few cases, they need to be pursued for more thunderstorms that are well defined

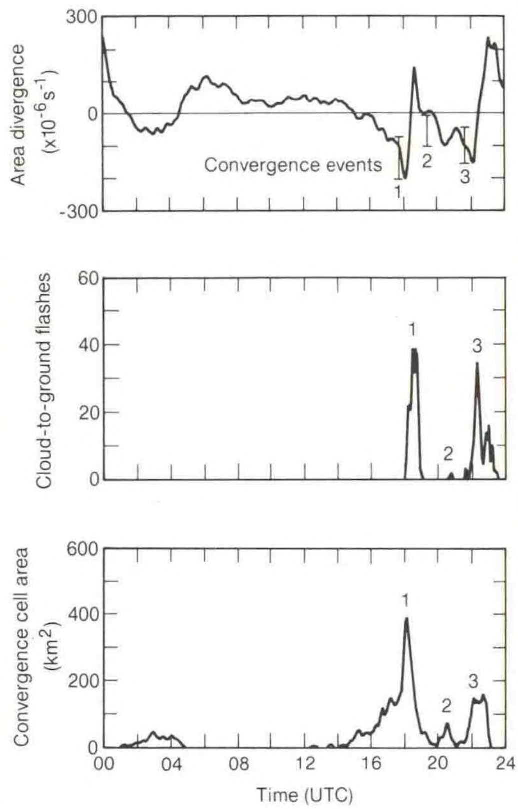

Fig. 19. Time profiles at 5-min intervals on 26 June 1987 in the KSC network of (top) total area divergence, (middle) cloud-to-ground lightning flashes, and (bottom) convergence area exceeding the 600 x $10^{-6}s^{-1}$ contour for three storms (1, 2, 3).

within the mesoscale network (mesonet). Additional research in the next year will use wind information from the larger mesonet combined with radar and cloud-to-ground lightning data to composite the typical storm's wind field relative to flashes, precipitation, and volume-scan radar reflectivity, if such data are available, during various stages of thunderstorm life cycles. This information will be of use to the local forecasters in the KSC area. As the national lightning network becomes a reality, the information will also provide a conceptual model of how these factors are interrelated, for use by others such as the NWS.

Positive Cloud-to-Ground Lightning in Stratiform Rain

In 1985, the coverage of the NSSL lightning strike locating network was increased to match the mesoscale target region of the PRE-STORM program. This increased coverage, along with the comprehensive measurements available from other sensors in PRE-STORM, enabled us to begin examining relationships of lightning strikes with other storm properties in MCSs. One result is a study of a squall line on 10-11 June 1985, which was recently completed in collaboration with the University of Oregon. Radar and lightning data for one period in the squall line are shown in Fig. 20. Although flashes lowering positive or negative charge were not restricted to any one region of the storm, there was a tendency for negative ground strikes to occur near or inside convective regions and for positive ground flashes to be more predominant in the stratiform region, well away from convective regions. A comparison of ground flash rates with rainfall rates inferred from radar (Fig. 21) showed that negative ground flash rates appeared to be correlated with rainfall rates in convective regions. Increasing rates of positive ground flashes, on the other hand, appeared to be correlated with increasing stratiform rainfall rates and were probably caused at least partly by the advection of cloud particles and positive charge from convective to stratiform regions. These findings have motivated other ongoing analyses of processes leading to the electrification and growth of the stratiform region: (1) an analysis of a similar system for which we have Doppler radar data, ground strike data, and balloon soundings with electrical and meteorological sensors, (2) a collaborative radar and modeling study of other MCSs, and (3) a study of ground flashes relative to the evolution of MCSs inferred from satellite data.

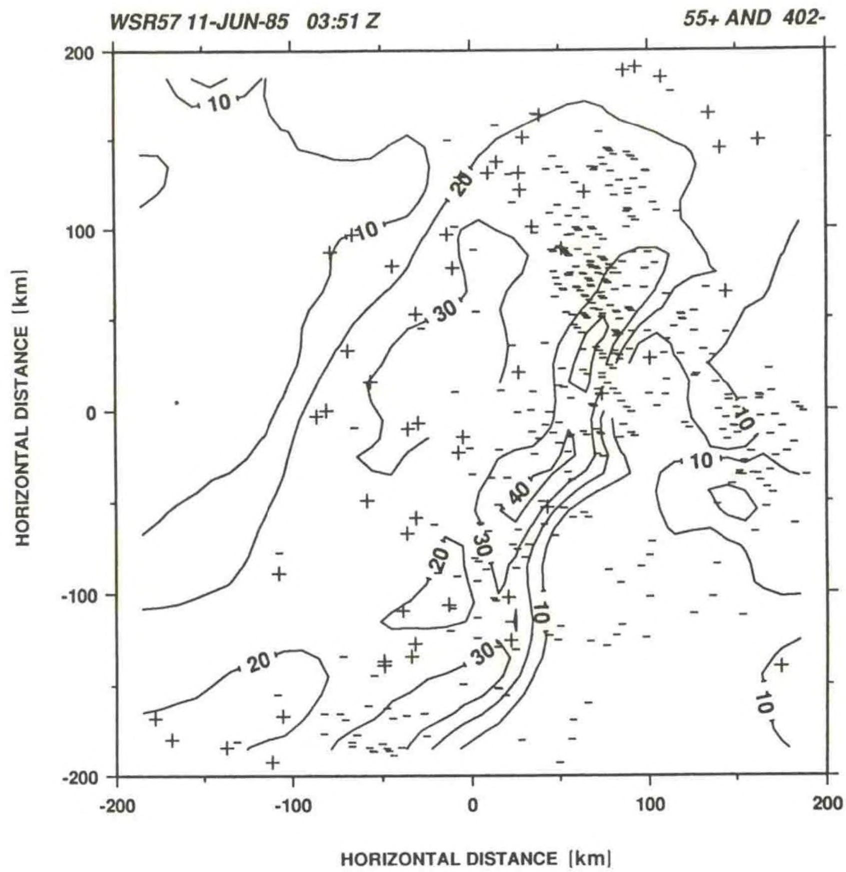

Fig. 20. Lightning strikes superimposed on the low-level reflectivity pattern for 0351 UTC on 11 June 1985 during PRE-STORM. Reflectivity contours, labeled in dBZ, are from a 1° elevation scan of the Wichita WSR-57 radar. The location and polarity of cloud-to-ground strikes for a 30-min period centered on the time of the radar scan are indicated by (-) for negative flashes and (+) for positive flashes.

Lightning Life Cycles in MCCs

A series of four MCCs was observed within the dense mesoscale observing network deployed for the PRE-STORM program. These events on 3-4 June 1985 were within range of the ground-based radar sites and cloud-to-ground lightning direction finders during much of their lifetimes. The occurrence allowed the study of the bulk characteristics of flashes for the major portions of the life cycles of four storms to a degree not possible prior to PRE-STORM in terms of the large geographical extent that was observed.

Preliminary results indicate that each MCC had from 2400 to 9800 flashes as it passed through the PRE-STORM area. Of these flashes, an average of 5 percent were positive, and the rest were negative. The flashes also were classified according to the type of radar echo, convective or stratiform, that was coincident at the time. More than half of the negative flashes (61 percent) were located in convective echoes, and nearly the same amount of positive flashes (59 percent) were in stratiform echoes. The conceptual model of MCC lightning indicates that such storms begin with more negative flashes in convective echoes, and then end with more positive flashes in stratiform echoes.

Further studies will be done in the coming year using the final lightning data set with all corrections applied. Goals will be to identify the exact cor-

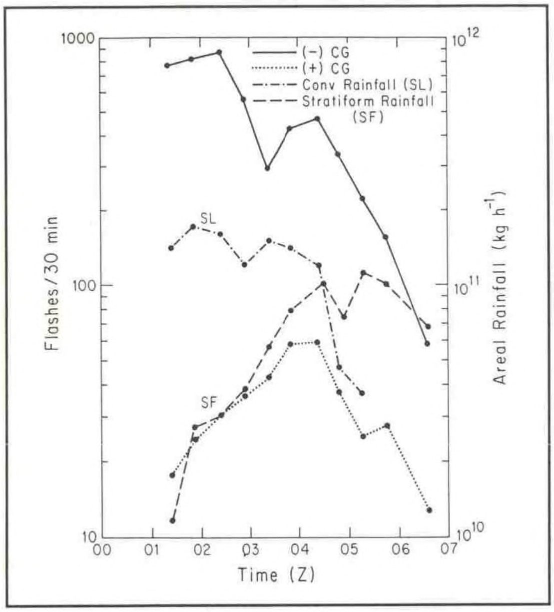

Fig. 21. Radar-inferred areally integrated precipitation for the convective and stratiform regions and 30-min counts of lightning strike activity from 0123 to 0656 UTC on 11 June 1985.

respondence of flashes with radar echo type, and to quantify the portion of the MCC life cycle that was observed with the data set. Additional attention will be paid to the interesting result that the amount of rainfall (derived from radar) in the convective portion of the storm is roughly proportional to the number of flashes in that region, regardless of the stage of the storm's life cycle.

Lightning in Tornadic Storms

Early studies of lightning in tornadic storms found that sferics rates at radio frequencies above 1 MHz usually increased near the time that a tornado occurred. However, there were exceptions, and relationships with storm kinematics were usually not studied. With the availability of Doppler radar data combined with lightning data from ground-strike-mapping networks and other systems, we have begun to study lightning characteristics relative to tornadic storm evolution. In a recent study of a supercell storm that produced a violent tornado near Binger, Oklahoma, we found that intracloud and total flash rates were correlated with the growth of reflectivity at a height of about 8 km and with cyclonic shear in the mesocyclone that produced the tornado. Ground flash rates, on the other hand, were correlated with the dissipation of the mesocyclone.

During FY 1988, we completed analysis of lightning ground strikes relative to the evolution of a second tornadic storm, one that occurred near Edmond, Oklahoma, on 8 May 1986. The relationship of ground flash rates to mesocyclone evolution during the Edmond tornado is similar to that of total flash rates to mesocyclone evolution during the Binger tornado. The two storms differed in several other respects: (1) ground flash rates peaked when the mesocyclone was strongest in the Edmond storm and when it was weakening in the Binger storm; (2) the Edmond storm interacted and merged with other storms; the Binger storm was an isolated supercell storm; and (3) the Edmond tornado was less violent and shorter lived than the Binger tornado. In the Edmond storm, we were also able to examine ground flashes that lowered positive charge, instead of the more common negative charge, and found that positive ground flashes began occurring at about the time when the tornado began. We plan to continue studying other tornadic storms to determine whether lightning data can be used to help real-time diagnosis of tornadic storm evolution.

NEXRAD Research and Development

NSSL has been involved with the NEXRAD program since its conception in the late 1970s. During 1988 the Laboratory continued the long-term cooperative program between the NEXRAD JSPO and NSSL. Besides providing general consulting support in areas of engineering, computing, and program administration, Laboratory staff provided special studies in the following areas:

- Development of operational schemes and algorithms for automatic detection and suppression of radar return through anomalous propagation. Anomalous propagation is a serious problem in radar hydrology. NSSL is in the second phase of this study, and at present staff are developing the necessary signal analysis and processing techniques, which are based on the first-phase theoretical study and data acquired during the 1988 operational program. Preliminary results are encouraging in that the proposed technique will remove 90 to 99 percent of the contamination by anomalous propagation of rainfall depth estimates.

- Development of velocity dealiasing schemes. A technique has been developed that dealiases Doppler velocities by using local continuity and data consistency. This technique has been tested on numerous Doppler radar data sets from clear air, thunderstorms, and severe thunderstorms, with excellent results. One test involved four volume scans that had extreme aliases. Of some 1.2 million velocities in these storms, 0.2 percent were improperly dealiased, and of these, 93 percent were from above 13 km and in the storm-top-divergent region where shears are extreme. Every tornado vortex signature, mesocyclone, gust front, and storm-top-divergent-region signature was preserved, and could be detected by automated algorithms. Our dealiasing scheme is adaptive, and therefore efficient. The method can be implemented for real-time processing on the NEXRAD radars.

- Evaluation of antenna dual polarization utility for NEXRAD. This is the second-phase study of dual polarization for NEXRAD, with emphasis on the utility of the technique of simultaneous dual polarization and rapid Doppler spectral moment measurements. The study shows by both theoretical analysis and real data that the two types of measurements, Doppler and dual polarization, are compatible. It also submits that measurement of dual polarization would enhance the NEXRAD operational capability by providing (1) improved rainfall rate estimates; (2) discrimination between rain and hail, and the potential to categorize hail.

Next year, studies on NEXRAD will include the investigation of circular polarization on reflectivity measurements, continued work on the velocity dealiasing problem, and refinement and improvement of NEXRAD hail, mesocyclone, and storm-tracking algorithms, along with further investigations of the operational benefits of dual polarization.

Data from the quasi-operational DOPLIGHT exercise (conducted in spring 1987) have been examined to identify potential new applications of Doppler radar to forecasts and warnings, and to determine algorithm effectiveness. These examinations have led to work on new approaches to solve problems already handled by existing software and to develop new algorithms to better assist the radar user. In support of better radar input into forecasts, Doppler return from the optically clear air is being used to determine average vertical velocity around the radar, and vertical wind shear in the boundary layer. The vertical shear estimates are used to estimate the likely storm type (if storms do form) and the potential for updraft rotation in longer-lived storms. Changes are being made in the way radar echo cells are identified and tracked, in hopes that the motions of a wide variety of echo types can be automatically followed. The hail identification process is being modified to add Doppler velocity information, particularly storm-top divergence. The original mesocyclone algorithm is being improved by better removal of data artifacts and by comparing output with that of a simulated mesocyclone model initialized with algorithm output parameters.

Retrieval of Thermodynamic Variables From Doppler Radar Data

The diagnostic model for retrieval of pressure and buoyancy was applied to data from two cases during the year. One effort builds on the information already gained from a past analysis of a large Oklahoma squall line that used results of a multiple Doppler analysis and output from a two-dimensional dynamic cloud model. The new effort has revealed that the relationship between the orientation of perturbation pressure gradients across strong updrafts and the orientation of the environmental wind shear vector holds in squall line convective elements as it did in isolated storms analyzed in the past. Additionally, this analysis has shown how a change in the shear produced by flow within the mesoscale system in the locality of an updraft results in an alteration of the pressure gradient orientation across the updraft (Fig. 22). In the future a new analysis of the pressure and buoyancy in the stratiform precipitation region will be accomplished to complete this study that seeks better understanding of MCS structure and evolution.

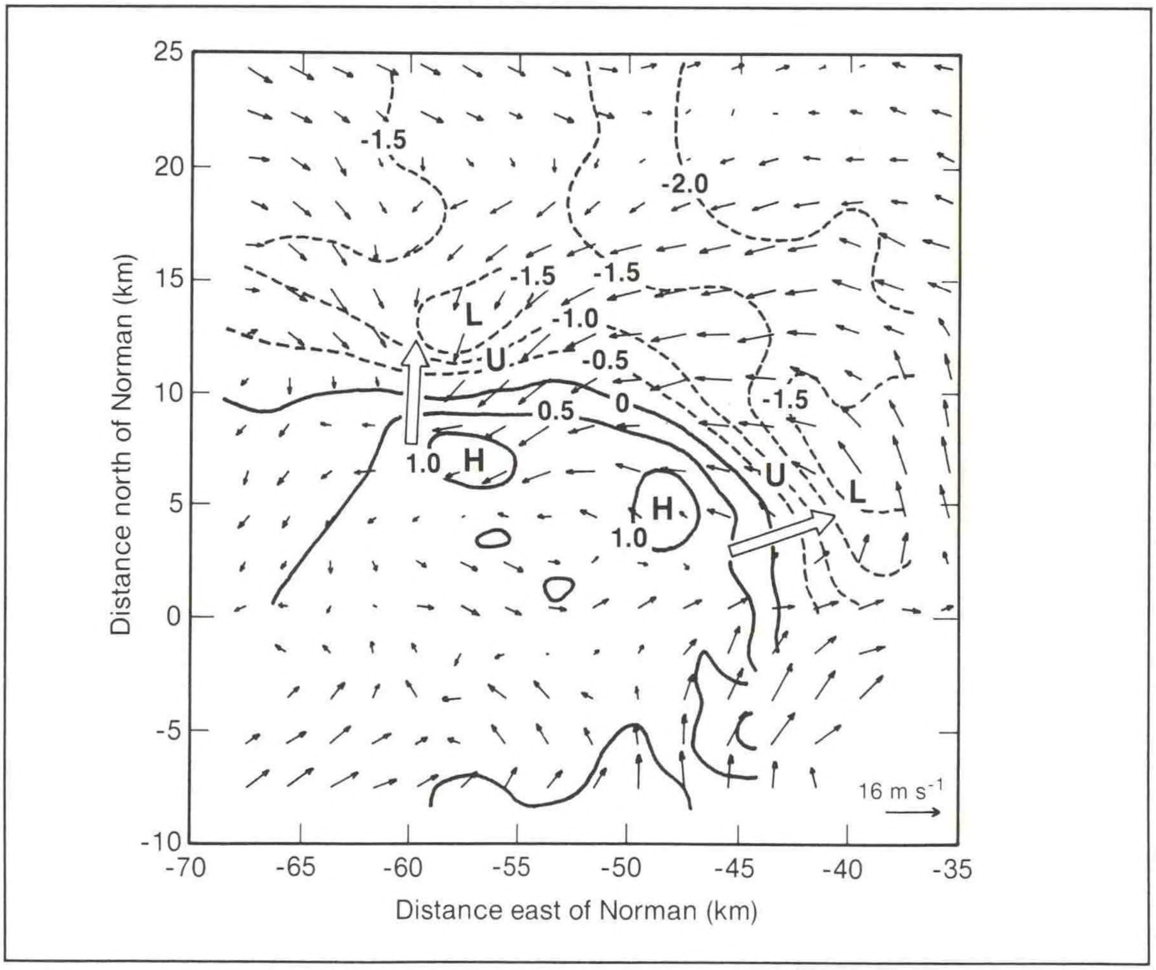

Fig. 22. Airflow and pressure field within the convective region of a squall line on 19 May 1977 at 2034 UTC at z=5.5 km. Contour interval of pressure field is 0.5 mb. Strong updraft locations are indicated by circled U's; locations of maximum high and low perturbation pressure are also shown. Broad arrows indicate orientation of environmental shear vector applicable to each updraft. The westernmost updraft's local environmental shear has been altered by the general airflow within the mesoscale system.

Pressure and buoyancy data were also retrieved in a large hailstorm observed in Montana by NCAR during the Cooperative COnvective Precipitation Experiment (CCOPE). The unique aspect of this data set is that an attempt was made to prescribe the velocity field outside the precipitation area by using in situ observations from research aircraft and rawinsondes. Therefore retrieval of pressure and buoyancy could be accomplished in the near environment of the storm including the sub-cloud updraft area and the region around the storm top. In NSSL studies of the data, good agreement in the distribution of pressure in and around the sub-cloud updraft was found between the retrieved field and that obtained using in situ aircraft observations reported by LeMone et al. earlier this year. NSSL also developed the retrieval method as a tool (a) to find the optimal reference frame for calculations of this kind in cases where a steady state must be assumed, and (b) to judge the quality of the analyzed velocity fields in the storm environment. The latter use is very relevant to future efforts to initialize cloud models. In the near future, efforts will continue to assess the quality of the velocity data for this storm and to compare the retrieved results with independent observations. A new effort in collaboration with researchers at the Oklahoma University School of Meteorology will begin in the coming year to look at the problem of predictability of cloud-scale phenomena and initialization of numerical simulations from observations.

Solitary Waves

Solitary atmospheric waves have been targeted as phenomena that are responsible for generating wind shear hazards to aircraft. Furthermore, they could be instrumental in propagating giant waves of elevation (i.e., upward displacements) long distances to where atmospheric conditions are ripe for the initiation of convective storms, as well as being very important in the timing and location of wave-related MCSs.

Thunderstorms in Central Oklahoma, traveling at effective "supersonic" velocities through the atmosphere, were observed to generate large-amplitude single-humped gravity waves (i.e., waves of translation). A modified Mach relation was derived to compute, at various points along the front, the wave speed from measured storm velocity and the convex shape of the wave front. These wave speeds and those directly observed by tracking the wave front positions along lines of energy propagation (i.e., rays) show good agreement. The shape and position of these 100-km and longer wave fronts can be estimated given the direction and speed of the storm, and the single ray direction along which all wavepackets that constitute the generated wave are assumed to propagate. An outstanding problem is the determination of ray direction. It is hypothesized that the direction is controlled in some way by the displacement of air at the wave source, but that it depends upon the value of Scorer's parameter in the upper troposphere where wind curvature is thought to have an important role.

We have completed a thorough analysis on one case to give a quantitative comparison with the nonlinear wave theory of Benjamin Davis-Ono (BDO). The comparison of observation with theory, and an understanding of nonlinear wave properties, should form the bases in determining whether observed gusts and thin lines of reflectivity are solitary waves. Furthermore, this comparison should help resolve some features of our observations that have led other researchers to an alternate interpretation of our data.

We have extended Ono's nonlinear theory for incompressible fluids in a motionless state to one in which a moist unsaturated atmosphere is in sheared flow, and have derived the coefficients for the BDO equation of wave evolution. Critical levels appear to be present in one case studied, and we are determining methods of solutions for this case.

NSSL's Doppler radars have shown the evolution of a sequence of two solitary waves growing out of a longe r wave disturbance. Such evolutionary development is theoretically shown by solution of the BDO equation. On 22 June 1987, thunderstorms in western Oklahoma are hypothesized to have generated a long-wave disturbance that evolved into an undular base (Fig. 23). We have collected dual Doppler data on this event, and NSSL's instrumented tall tower was in operation. This data set is unique in the observation of an atmospheric undular bore.

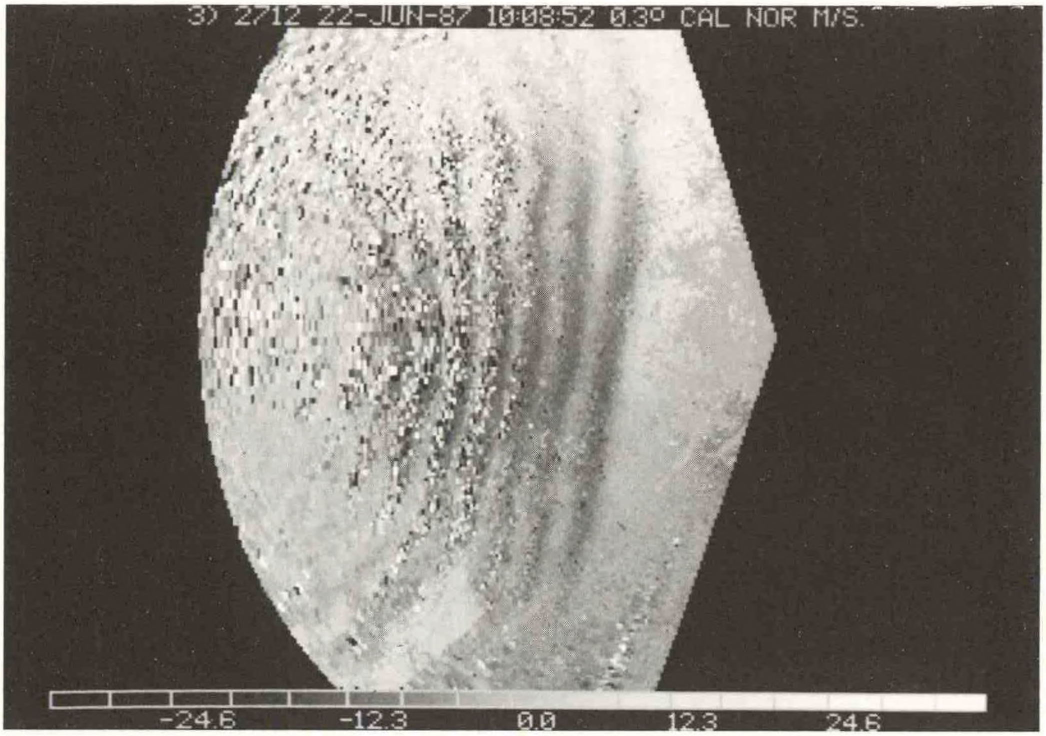

Fig. 23. Train of wave-like perturbations seen in a Doppler velocity field. The perturbations are thought to be an eastward propagating undular bore evolving into an amplitude ordered sequence of solitary waves observed with NSSL's Norman Doppler weather radar. The velocity field is coded with the brightness categories (mm s^{-1}). Radar is at the apex, and surge to the outer edge of the data field is 115 km. El. = 0.3°.

In 1989, activities are planned to obtain solutions to the Taylor Goldstein Equation when critical levels are present and to determine if Scorer's parameter in the upper troposphere acts to guide the direction of gravity waves. Also, we will begin to extend our studies to large-scale events that have gravity waves coupled to storms and squall lines.

Polarization Studies

About 4 years ago, NSSL modified one of its radars to switch the transmitted waves rapidly between horizontal and vertical polarizations. This polarization diversity allows measurements of differential reflectivity, differential propagation constant, and correlation between vertically and horizontally polarized echoes, which provide additional information about precipitation.

We have shown that the differential propagation constant yields a good estimate of liquid water in a rain-hail mixture, and that it can be used together with the differential reflectivity and the reflectivity factor to infer the hail fall rate in a mixture. These conclusions are backed by self-consistency of polarimetric data obtained in storms where mixtures of rain and hail were confirmed on the ground, and by the agreement between theoretical and experimental results (Fig. 24, 25).

We have proposed a method for categorizing hail size on the basis of the value of the correlation coefficient between vertically and horizontally

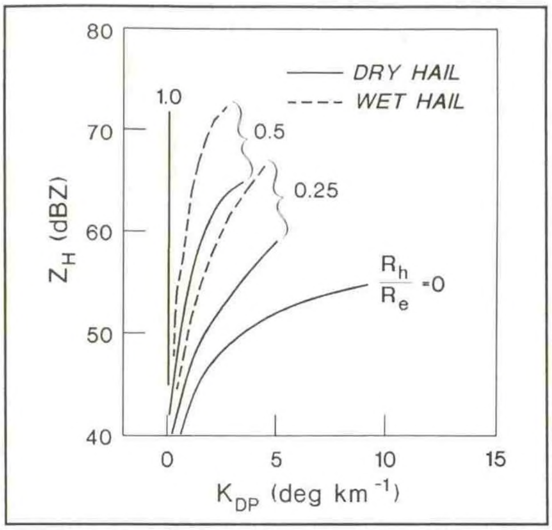

Fig. 24. Theoretical Z_H-K_{DP} curves for fixed proportions of hail and rain in a mixture. R_h is hail rate and R_e is the equivalent total rain-plus-hail rate. Hailstones are assumed to be spherical, to obey the Cheng-English distribution, and to be either dry or very wet (i.e., dielectric constant of water).

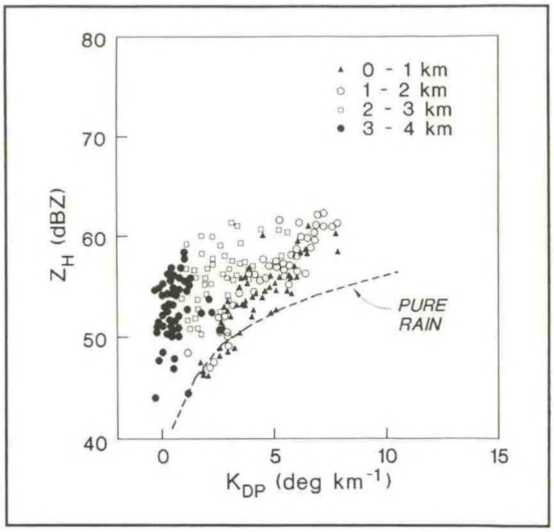

Fig. 25. Data of Z_H, K_{DP} pairs stratified by height and from a storm that produced rain and hail on the ground. Remarkable similarity with theoretical curves suggests a progressively larger amount of hail in the mixture with height, with the result that between 3 and 4 km most of the hydrometeors are frozen.

polarized echoes. The reason for correlation decrease in larger hail sizes rests on the following premises: (1) larger hailstones (4-10 cm in diameter) are roughly irregular, with small or large protuberances; the protuberance-to-diameter ratio is not constant but increases with size; (2) the distribution of sizes, shapes, canting angles, and phase shift upon scattering for hydrometeors consisting of a mixture of rain and hail broadens with increasing hail size, thus decreasing the correlation; (3) oscillations in the differential reflectivity for larger spongy hailstones due to Mie scattering tend to reduce correlation, especially when water phases are mixed. It is premature to speculate on the relative importance of these three mechanisms, yet at least the second one is consistent with data from two hailstorms in that it correctly qualifies hail size.

We intend to enhance the polarimetric capability of the Cimarron radar so that it can collect and process data in real time over the total unambiguous range interval. Analysis of existing data will continue, and the data will be complemented by data from other sources.

Storm Spotter Training

In preparation for the deployment of the NEXRAD radar system during the 1990s, NWS asked NSSL to cooperate in producing training materials on the structure and evolution of severe storms. The first part of this project, the development of an extensive slide program on storm structure (e.g., as in Fig. 26 has been completed. Accompanied by a set of extended captions, the slides are intended for use in training NWS personnel and advanced volunteer storm spotters on fundamental concepts of thunderstorm structure. Particular attention has been paid to the thunderstorm "spectrum," viz., the variety of convective storm types likely to occur, irrespective of geographic location. This work is continuing, and will culminate in a series of three videotapes covering the same topic but using the unique capabilities of videotape for showing cloud motion and wind flow.

NEXRAD and Doppler Training

Also in anticipation of the upcoming NEXRAD implementation, staff of the Norman NWS Forecast Office (WSFO) were given training prior to the spring 1988 severe storm season. The goal of the training was to better prepare the WSFO staff for Doppler interpretation without assistance from NSSL personnel who had been present in the WSFO warning room during the 1987 DOPLIGHT exercise. A training course on Doppler interpretation has been prepared for the NEXRAD Interim Operational Test and Evaluation, Part II (IOT&E II), which will last from January to June of 1989. The course is being taught by NSSL personnel and others to all IOT&E II participants from the three involved Federal agencies prior to the January 1989 startup. Work has also begun on preparation of a series of video tapes that will explain basic Doppler principles and radar-viewed thunderstorm structure. These tapes will be used by NWS as part of a prototype training for all field personnel, prior to formal NEXRAD training.

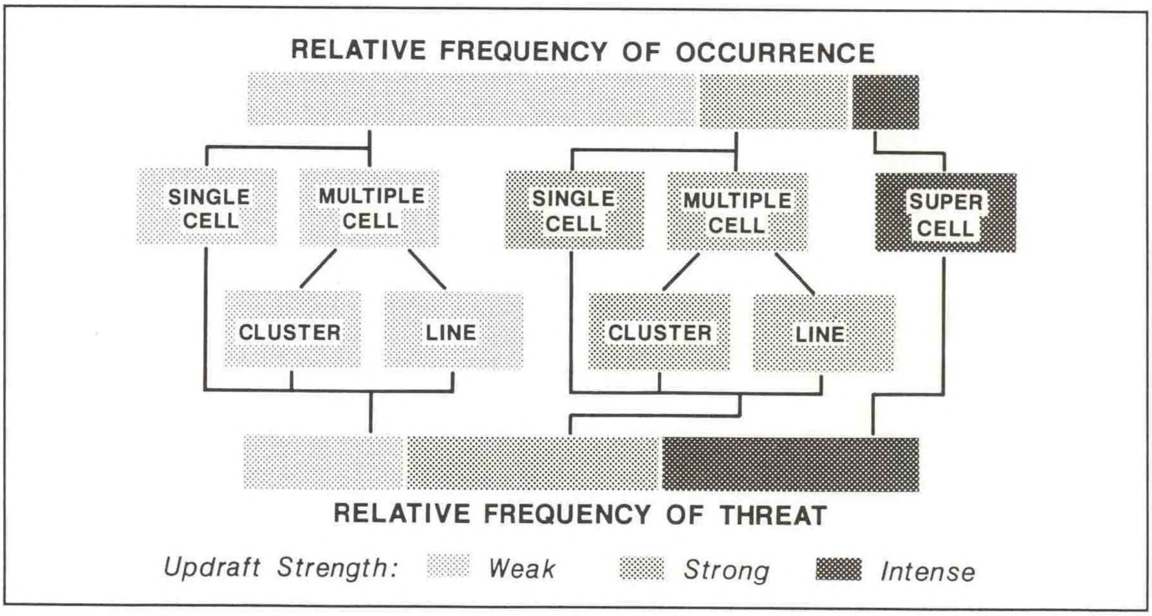

Fig. 26. The thunderstorm spectrum. The relative frequency of occurrence of updrafts with a given strength is not necessarily the same as the relative frequency of threat associated with those updraft strengths; e.g., intense updrafts (supercells) account for only a small fraction of the total number of storms, but create a disproportionate fraction of the threat (i.e., to life and property) because of their intensity.

National Weather Service Interactions

Numerous interactions between NSSL staff and a wide variety of NWS offices and staff took place during the year. NEXRAD planning and development were significant activities undertaken by Laboratory staff and various organizations within NWS, spurred by the installation of the Operational Support Facility (OSF) radar and the imminent first NEXRAD radar at Oklahoma City in 1989. Training, algorithm testing and validation, engineering consultation, and other planning were among the tasks undertaken by NSSL staff in Norman.

NSSL staff also were consulted by several NWS Regions, Forecast Offices, planning groups, and administrative sections as the national lightning network became a reality. The data were available at most NWS sites in the country by late in the year, prompting studies on how to ingest NSSL data into the national network, how to interpret lightning data, and how to use flash information in operations.

In other interactions, the Advanced Storm Spotters Training Program for severe weather was revised jointly by NSSL and NWS staff; results of microburst research were transmitted to aviation interests in NWS by NSSL staff; classes on flash floods were taught by NSSL staff at the NWS Training Center in Kansas City; Laboratory staff participated in national and regional workshops on severe weather and other topics in several locations around the country; and Laboratory staff are involved in an extended project to develop, in conjunction with the NWS Office of Meteorology, several video-based training packages on storm structures and Doppler radar. A number of NSSL personnel members also worked with ESG and Southern Region staff to prepare a research guide for use in NWS Forecast Offices.

Cooperative Institutes

During the year NSSL interacted with three of the joint institutes operated cooperatively by NOAA's Environmental Research Laboratories and universities around the country.

The majority of NSSL activities involved the Cooperative Institute for Mesoscale Meteorological Studies (CIMMS) at the University of Oklahoma in Norman. The activities included work by Dr. Hartmut Kapitza, a Post-Doctoral researcher from Germany, to encode a nonhydrostatic, mesoscale research model. Dr. Kapitza's model will be used to explore the use of adjoint method techniques for model initialization and for studies of frontal circulations and the PRE-STORM 7-8 May 1985 convective systems. Dr. J. Kogan, a Russian political refugee, joined CIMMS during the year. He brings strong skills in high-resolution cloud modeling to strengthen the CIMMS mesoscale modeling.

NSSL-MRD scientists in Boulder collaborated with two individuals through the Cooperative Institute for Research in Environmental Sciences (CIRES) of the University of Colorado in Boulder. Dr. Ranjit Passi interacted with MRD to apply mathematical expertise to the problem of proper treatment of the site error and of optimized analyses appropriate to lightning ground strike networks that use direction finder networks. Late in the year, Ms. Lin Li from the People's Republic of China began to use her computer background to apply the theoretical results of their efforts to data from several lightning networks.

Interactions have also begun with the Cooperative Institute for Research in the Atmosphere (CIRA) at Colorado State University, Fort Collins, Colorado. Collaborative research involving studies of the electrical characteristics of MCSs has begun with Professor Steven Rutledge and his students. Additionally, a run of the CSU RAMS model is being used by NSSL scientists to study dryline circulations.

National Environmental Satellite, Data, and Information Service

The NESDIS Satellite Applications Branch, situated at the University of Wisconsin, worked with NSSL scientists in preparing for the GUFMEX experiment early in FY 1988. Both groups, along with NWS-NSSFC and Southern Region meteorologists, are beginning to analyze the data. It is expected that several scientific workshops will be held during the coming year as work progresses.

Computing

NSSL spent a significant portion of its efforts in FY 1988 to improve its computing capabilities. The computer facility has been improved by adding clustering hardware for the VAX computers in Norman, along with a new VAX 11/750 and additional disk drives. A new 6250 bpi tape drive was also added to the PE 3242 computer system to increase the productivity of this system. In addition, 30 new PCs were added along with ETHERNET to create a Local Area Network in Norman (Fig. 27). Graphics hardcopy capabilities increased with the addition of a high-resolution slide camera and high-resolution color printer. Great strides were made in converting seven-track tapes to nine-track and reducing the required amount of tape storage. The computing facilities will continue to expand as one VAX 6210 is added to the Norman facility and another to the Boulder facility. In addition, the PC network will be expanded and a new 6250 tape drive will be added to the PE computer system. Work will begin on building an archive capability for NEXRAD data. Data management will also continue to be improved by adding a catalog and indexing system for all data available at NSSL.

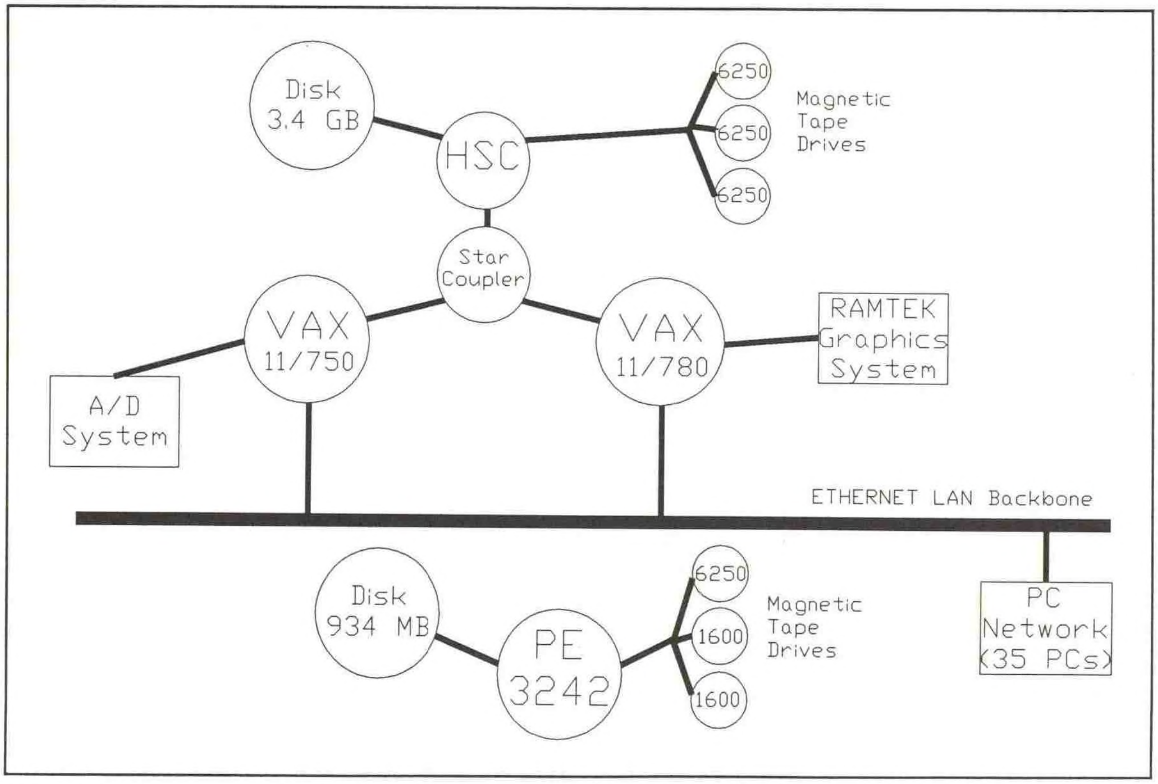

Fig. 27. Configuration of NSSL computing facilities in Norman.

Cimarron Radar

The Cimarron Doppler radar is being upgraded, with the help of FAA funds, to improve data acquisition speed and polarization measurement performance. The Cimarron facilities are also being improved with the addition of a concrete floor in the tower and three-phase power. The antenna has been re-balanced, and the spars have been moved to improve the polarization diversity measurements. An improved AGC has been designed, and a new programmable signal processor has been ordered along with new display and processing capabilities. NSSL will continue with upgrading the Cimarron radar.

Mobile Laboratory

For several years, NSSL has been developing and using a mobile laboratory to obtain observations of storms. With our mobile laboratory (Fig. 28), we record atmospheric electric field, field changes from lightning, return stroke velocity, temperature, pressure, dew point, wind speed and direction, laboratory position, and video images of clouds and lightning. The mobile laboratory has been a key in obtaining new information on aspects of storm electrification, e.g., field changes to compare with high-altitude airplane measurements and ground strike locating networks, electrical aspects of tornadic storms, and positive ground flashes. With the recent addition of mobile balloon launch and tracking, we now can also make specifically located special soundings for forecasts and, after storm formation, obtain vertical profiles of the electric field, thermodynamic parameters, and winds in storms. We completed the initial test of the NCAR Cross-chain LORAN Atmospheric Sounding System (CLASS) in a fully mobile configuration, which we call M-CLASS. The sondes

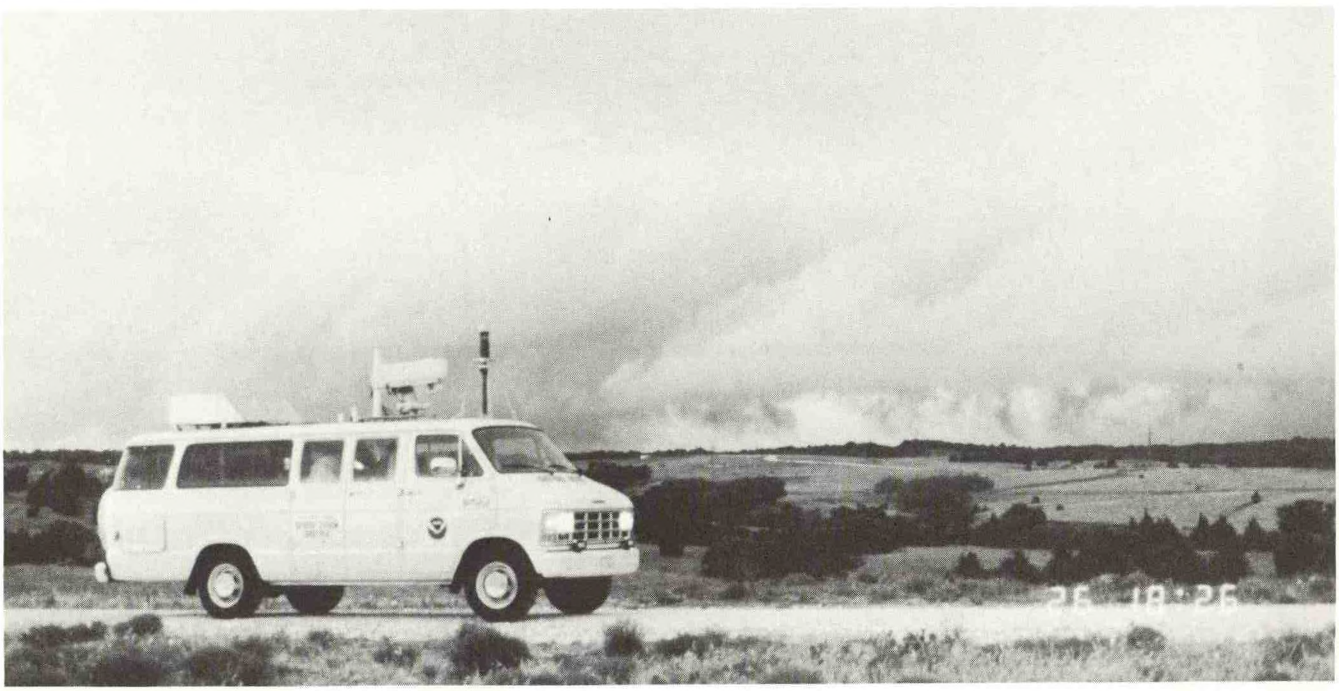

Fig. 28. NSSL mobile laboratory moving into position for balloon launch and other data collection ahead of approaching gust front (roll cloud in background), during DOPLIGHT 87 on 26 May. On the van roof, the aluminum housing aft contains electric field and field change sensors. The two environmental housings (only one on right side visible) house video cameras; the vertical white cylinder on the roof (center) covers 403-MHz antenna for balloon telemetry; the black cylinder with white top contains wind and temperature sensors, respectively. Crew members launched a sounding into the updraft of this storm in northwestern Oklahoma just after passage of the gust front as part of the initial testing of NSSL's mobile CLASS system called M-CLASS.

use LORAN-C navigation signals to allow horizontal winds to be calculated.

The mobile laboratory concept continues to provide data that we could not otherwise obtain except by years of waiting or unrealistically good luck. Our primary strategy for the future is to develop new instrumentation and provide a unique mobile lab facility that we can use to focus on a variety of scientific questions.

Specific plans for next year include the following:

- Develop a new mobile laboratory to provide mobile thermodynamic and wind-sounding capability for use in NOAA and other collaborative research programs.

- Continue evaluation of M-CLASS use in thunderstorm environment to increase data acquisition capabilities.

- Use our mobile laboratory to provide verification data for IOT&E-II as to the occurrence of threatening weather phenomena such as strong winds and large hail.

- Develop and test two new instruments--one to measure the electric field vector in storms, the other to measure the charge and size of precipitation. Both will fly with LORAN-C sondes for obtaining thermodynamic and wind data.

A collaborative test project between NSSL and ERL's Hurricane Research Division in Miami to intercept landfalling hurricanes was implemented during the 1988 hurricane season. The goal was to determine the feasibility of intercepting hurricanes at landfall and to meet limited scientific objectives of obtaining atmospheric sounding and electricity data. There is little information on the atmosphere in the right quadrant of hurricanes, where principal rainbands and severe weather often occur. Our plan was to release soundings in this area at 1-3 hour intervals, depending upon conditions. The initial scientific objectives, although important, were kept simple owing to the expected complexity of intercept. We successfully deployed to Kingsville, Texas, at a site that was free from the hazards of local flooding and storm surge. We launched about 18 sondes, obtaining twice as many soundings of the atmosphere, since we also receive soundings from sondes on the way down after the balloon bursts. The launch times were chosen to match the occurrence of rain bands as well as a preset schedule, an easy option with M-CLASS. We view this first test as a success; results included the following:

- We obtained unique sounding information in rainbands in the right quadrant of hurricane Gilbert and in the attendant severe weather environment.

- We demonstrated that we can intercept and operate safely in a major landfalling hurricane.

- We directly provided NHC forecasters with surface observations through the amateur radio hurricane network, and read them sounding information by telephone.

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MAJOR SEMINARS AT NSSL

2 October 1987	Dr. K. Crawford, Oklahoma City WSFO, presented "On the design of an optimum rain gauge network to support Tulsa's flash flood monitoring system: Implications for the NEXRAD era. Part I - Theoretical background. Part II - Tulsa/NEXRAD results."
21 October 1987	Dr. L. Uccellini, NASA Goddard Space Flight Center, Greenbelt, MD, presented "The utilization of mesoscale models for diagnostic studies of coastal cyclogenesis."
23 October 1987	Dr. H. Bluestein, University of Oklahoma, presented "Results from OU's Severe-Storm Intercept - 1987."
27 October 1987	Dr. D. Jorgensen, NSSL, Boulder, CO, presented a seminar on "Use of airborne Doppler radar in studies of mesoscale convective systems."
12 November 1987	Mr. K. Smith, Department of Atmospheric Sciences, University of Arizona, presented "Tropical squall lines of the Arizona Monsoon."
20 November 1987	Dr. J. Kogan, CIMMS, presented "Three-dimensional numerical model of warm convective cloud that accounts for microphysical processes."
11 December 1987	Dr. J. Flueck, Environmental Sciences Group, ERL, Boulder, CO, presented "A review of some forecast verification procedures - 1884 to the present."
17 March 1988	Dr. W. Moninger, Environmental Sciences Group, ERL, Boulder, CO, presented a seminar on artificial intelligence.
14 April 1988	Dr. R. Zamora, Wave Propagation Laboratory, ERL, Boulder, CO, presented a seminar on "Wind field diagnostic calculations using the Colorado wind profiler network."
25 May 1988	Dr. S. Rutledge, Oregon State University, presented "Observations of positive cloud-to-ground lightning activity in OK-PRE-STORM and possible relationships to storm kinematic structure."
6 June 1988	Dr. A. VanTuyl, NCAR, presented a seminar on "Scale interaction and predictability in a mesoscale model."
7 June 1988	Mr. S. Fredrickson, NSSL, Norman, presented a seminar on "GUFMEX - An instrumentation point of view."
9 June 1988	Dr. R. Bernard presented a seminar on "Boundary-fitted grids and incompressible flow."
8 September 1988	Drs. C. Hane and C. Ziegler, NSSL, Norman, presented a seminar on "The Tenth International Cloud Physics Conference -- Some personal impressions and experiences."
16 September 1988	Dr. M. Weisman, NCAR, presented a seminar on "The structure and evolution of numerically simulated squall lines: The role of vertical wind shear in promoting an optimal squall-line state."
16 September 1988	Dr. J. T. Young, University of Wisconsin, presented a seminar on "McIdas - Current and Future Plans."

MEETINGS HOSTED BY NSSL

1-2 December 1987	NSSL Program Review in Norman.
10-11 December 1987	USAF/Air Weather Service meetings at NSSL-MRD in Boulder concerning Launch Committee Criteria for Kennedy Space Center. Also met on 6 and 20 February 1988.
19 January 1988	PRE-STORM meeting at Fort Collins, CO, co-hosted by NSSL-MRD and Colorado State University.
8-9 February 1988	GUFMEX Project Planning meeting with participants from NSSFC and NWS Southern Region.
18-19 March 1988	TV/Radio Weathercasters Severe Storms Workshop in Norman.
19-22 April 1988	1988 International Aerospace and Ground Conference on Lightning and Static Electricity, hosted by NSSL at the Sheraton Century Center Hotel, Oklahoma City.
25-26 May 1988	Airline Pilots Association Aviation Weather Committee meeting in Norman.
11-12 August 1988	"The Manager Looks at Research Scientists," on-site training course conducted by Dr. John Koning for NSSL in Norman.
15-16 August 1988	"Manager and Secretary Training," on-site training course conducted by J. Hiebert, H. Cook, Y. Henderson, and A. Tafoya for NSSL in Norman.

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