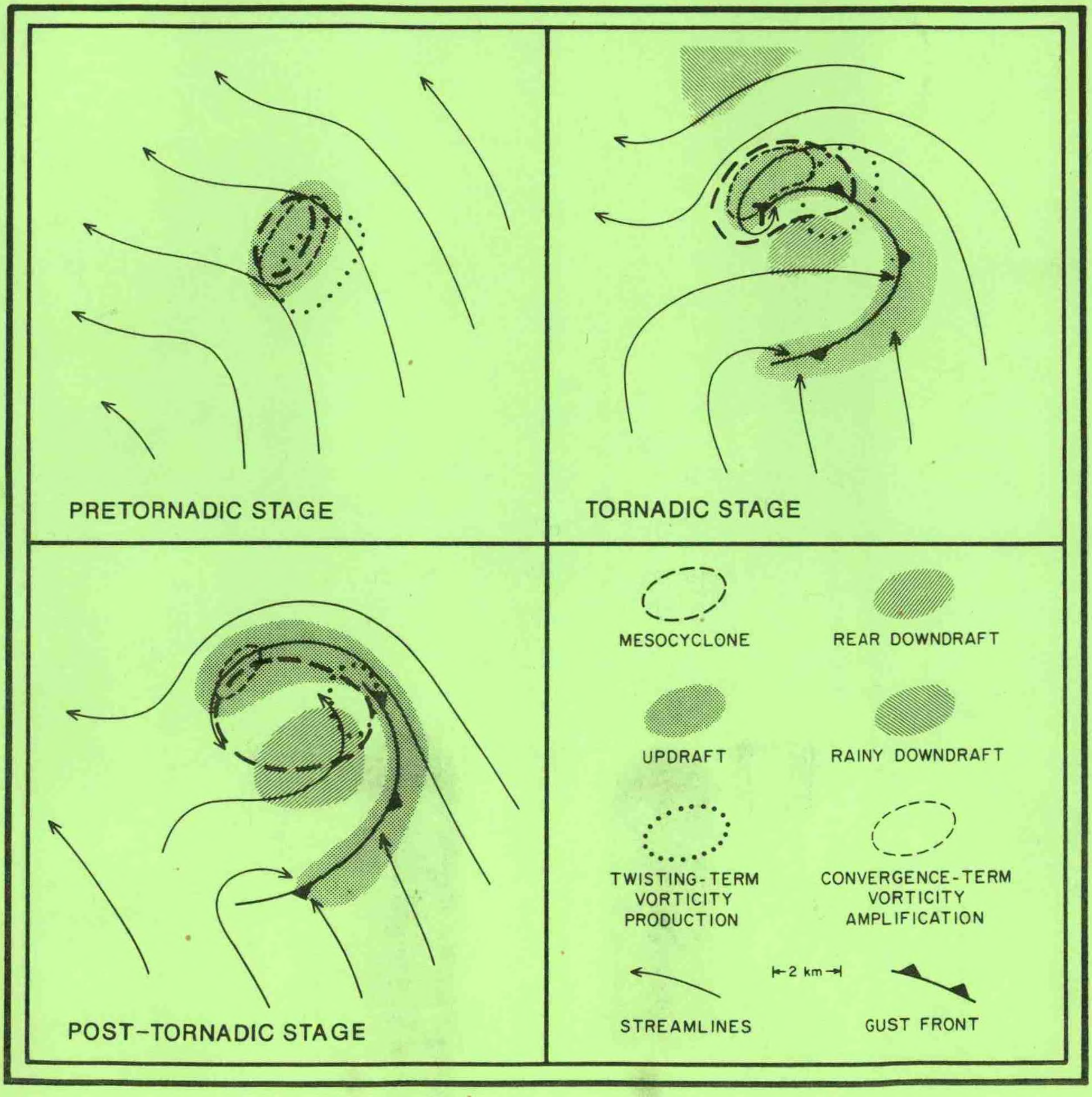
National Severe Storms Laboratory
ANNUAL REPORT FY 85



UNITED STATES DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
Environmental Research Laboratories

COVER

Pictorial summary of principal wind flow characteristics at low levels in vicinity of mesocyclones for (a) pretornadic, (b) tornadic, and (c) post-tornadic stages of development. Storm motion is toward the upper right. Tornado location is indicated by T in (b).

NATIONAL SEVERE STORMS LABORATORY

ANNUAL REPORT - FISCAL YEAR 1985

October 1, 1984 - September 30, 1985

National Severe Storms Laboratory
1313 Halley Circle
Norman, Oklahoma 73069
March 1986

UNITED STATES DEPARTMENT OF COMMERCE

Malcolm Baldrige, Secretary

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

Anthony J. Calio, Administrator

Environmental Research Laboratories

Vernon E. Derr, Director

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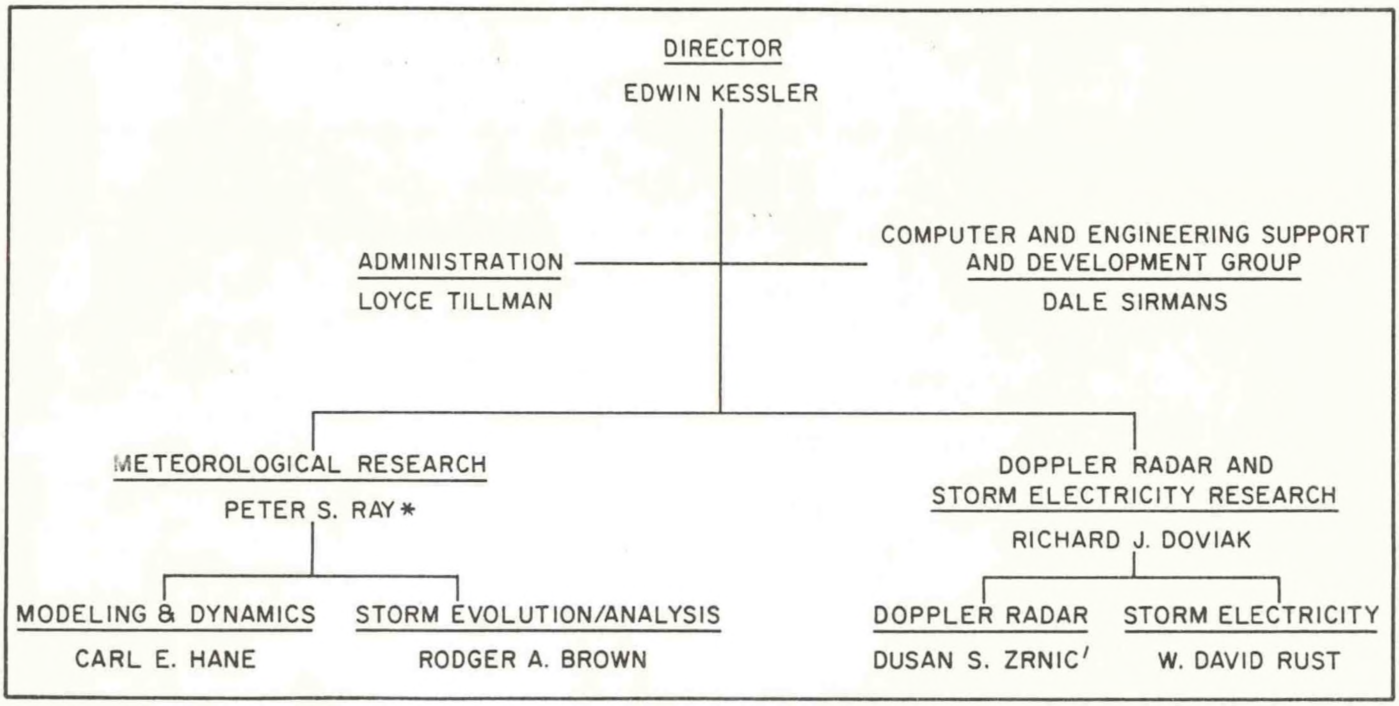
NATIONAL SEVERE STORMS LABORATORY

FY 1985



* UNTIL 1 AUGUST 1985, WHEN DR. RAY ACCEPTED A PROFESSORSHIP AT FLORIDA STATE UNIVERSITY, TALLAHASSEE

NATIONAL SEVERE STORMS LABORATORY

PERSONNEL STATISTICS

FY 1985

	October 1, 1984		September 30, 1985	
	Full-time	Part-time	Full-time	Part-time
Professional	26	5	24	5
Technical	8	2	9	2
Clerical	5	4	5	4
TOTAL	39	11	38	11

Number of full-time holding doctoral degrees on September 30, 1985: 11

In addition to the above, the Laboratory employs 19 University of Oklahoma (OU) students part time; they are assigned to NSSL staff who are Adjunct Professors at OU. The Cooperative Institute for Mesoscale Meteorological Studies employs nine Graduate Research Assistants, four computer programmers, and three supporting staff funded by NSSL.

NATIONAL SEVERE STORMS LABORATORY

FY 1985 Budget and Funding

NOAA Operations Research and Facilities......................$3,854,580

Support..408,000

Other Agencies: (FY 1985 New Funds)

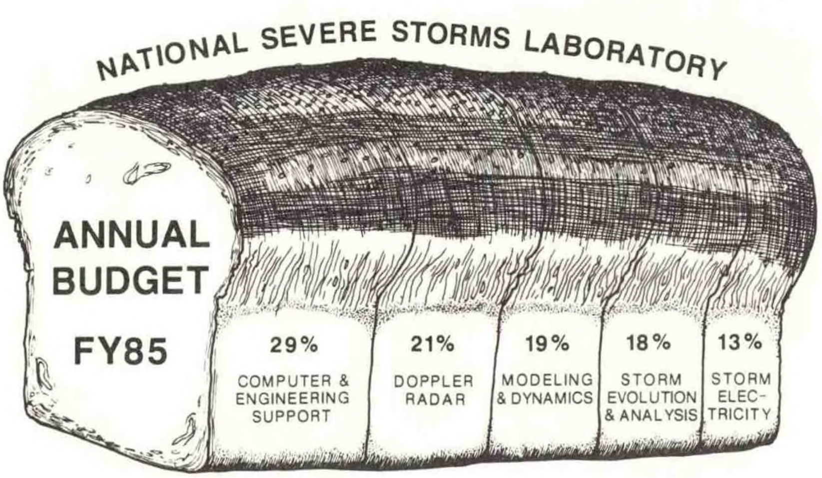
National Science Foundation	$ 15,400
Joint System Program Office, NEXRAD	217,000
Federal Aviation Administration	210,000
National Aeronautics & Space Admin.	173,100
Office of the Federal Coordinator	30,000

Total Other Agencies.................................... 645,500

TOTAL..$4,908,080

Proportional allotment of funds*

Storm Evolution & Analysis	18%
Modeling & Dynamics	19%
Computer & Engineering Support	29%
Storm Electricity	13%
Doppler Radar	21%
	100%



* A portion of administrative costs is included in each percentage.

PROGRAM AREAS

NATIONAL SEVERE STORMS LABORATORY

INTRODUCTION

Edwin Kessler, Director

The Laboratory staff studies severe-storm circulations and the processes through which they develop, and investigates techniques for improved storm detection and prediction, in support of NOAA's operational mission as carried out by the National Weather Service. Our work during 1985 continued in many cases along lines identified in our 1984 Annual Report. Thus:

(1) Results of several investigations provide comprehensive understanding of processes ongoing during developments depicted on the cover of this report. In severe thunderstorms, the rainy downdraft, twisting updraft, surface pressure deficit of mesoscyclones, and rear flank downdraft are manifestations of continuous interactions among fields of wind, pressure, thermal buoyancy, and condensed water load. These interactions have been brilliantly illuminated by remote sensors, visual observations, and theoretical modeling.

(2) Methods have been refined for utilizing detailed data from Doppler radar and other sensors to retrieve fields of unseen microphysical parameters such as the electric field and densities of rain and hail. Application of a retrieval model to a well-observed storm in New Mexico provided accurate simulation of lightning flash rates.

(3) With the Cooperative Institute for Mesoscale Meteorological Studies, we applied a mesoscale model to data representative of conditions preceding severe local storms in the Great Plains. The pattern of low-level convergence and vertical shear of the horizontal wind that developed in the model is characteristic of tornado developments. We are accordingly optimistic regarding development of improved 6-12 hour forecasting methodologies for severe thunderstorms.

(4) Significant contributions to the national radar program (NEXRAD) included:

(a) Development of improved guidance for visual interpretation of contoured velocities as displayed on plan-position indicators.

(b) Improved numerical methods for processing Doppler data for identification and location of frontal boundaries, gust fronts, and tornado vortices, and for defining the vertical distribution of horizontal divergence.

(c) Ongoing engineering consultation and special studies.

(5) Contributions to safety of flight included:

(a) Improved description and understanding of the solitary-wave phenomenon, related to gust fronts.

(b) An example of attenuation as an impediment to effective use of 5-cm radars.

(c) Evaluation of criteria for siting NEXRAD radars for use at airports.

(d) Evaluation of the probability of lightning strikes to aircraft. Strikes at high altitudes are almost always triggered by the aircraft and are more likely during the stage of storm decay than during periods of storm intensification.

(6) A facility for acquiring polarization-diverse Doppler radar data at NSSL's Cimarron site has been completed. Theoretical studies and early data indicate significant prospects for such diverse results as improved point rainfall estimates, better discrimination among solid and liquid forms of precipitation, and better understanding of microphysical processes that regulate precipitation development.

(7) The Laboratory now has an active project involving profiler radars. The Wave Propagation Laboratory provided a 50-MHz radar with phased array antenna; it has been installed 30 km SSW of NSSL, and is maintained by students and staff of the University of Oklahoma. A 405-MHz system is being developed at NSSL for tests with a parabolic dish antenna, in order to evaluate the possibility that NEXRAD radars could be used as profilers for winds in clear air as well as in precipitation. Our project for controlling the antenna of the Norman Doppler radar by computer to track inexpensive balloons in clear air is also proceeding, and definitive tests of this technique for wind finding in fair weather are planned for FY 1986.

(8) Substantial new knowledge of lightning parameters has been obtained, and facilities for study of both cloud-to-ground and in-cloud lightning have been improved. Studies are focusing on critical differences between strikes that carry positive and negative charge to ground and between the conditions that favor one or the other.

(9) A theoretical study has shown how the radar beam of a phased array can be significantly narrowed, with resultant improved resolution of meteorological features; components are being assembled for a practical test of the idea.

(10) In a cooperative program with NASA and University of Oklahoma, airborne lidar has been shown to have remarkable capabilities for mapping the wind field in clear air in detail.

(11) As has been the case since its founding, NSSL shared storm data collected in Oklahoma with colleagues at far-flung institutions. We were a major participant in the ERL-sponsored PRE-STORM experiment; we installed and maintained approximately half of all the facilities used in

that experiment, and contributed improved processing and distribution of radiosonde data. We assisted the National Weather Service directly through evaluation of NWS radars in Alabama and Illinois, and through provision of Doppler radar and lightning data to the Weather Service Forecast Office in Oklahoma City. We now have a VAX 11/780 computer in the Laboratory to facilitate processing of data from our Doppler radars.

NSSL's historical antecedents in the former U.S. Weather Bureau and its former National Severe Storms Project are described in the NSSL Special Report prepared in 1976. From early emphasis on use of aircraft for storm investigations related to flight safety, the focus at NSSL has moved to theoretical and empirical studies based on data from a multitude of sensors for new insights into storm mechanics, and new applications to storm warning and prediction and safety of flight.

About one-fourth of NSSL's budget is devoted to maintenance and operation of comprehensive instrumentation for sensing meteorological parameters. Instrumentation includes two 10-cm Doppler radars on a 42-km baseline, a 50 MHz wind profiling radar, the tallest meteorologically instrumented tower in the United States, a network of solar-powered surface stations, and a broad range of sensors for mapping lightning processes in clouds, locating ground strike points of lightning, and measuring electric field parameters.

During 1985, arrangements were completed to construct a new building a few hundred feet from NSSL, this to accommodate most staff of the Weather Service Forecast Office to be moved from Oklahoma City, and the Operational Support Facility for NEXRAD, to be needed for the far-flung network of some 150 radars now projected for installation during the late 1980s and early 1990s. We at NSSL are looking forward to interesting and effective work with colleagues who will occupy this new building.

I have been Director of NSSL since its founding in 1964 and am grateful for the many opportunities that have been afforded by my position, and for associations with worthy colleagues. The challenges and opportunities appear to be at least as great today as they were 22 years ago! These will be addressed successfully by my successor and ongoing staff after my retirement about June 1, 1986.

METEOROLOGICAL RESEARCH GROUP

Peter S. Ray, Group Leader (through August 1985)
Rodger A. Brown, Acting Group Leader (since August 1985)

INTRODUCTION

The Meteorological Research Group seeks to improve thunderstorm forecast and warning capabilities by developing conceptual, numerical, and laboratory models of major thunderstorm phenomena and of the prestorm atmosphere. Analysis and interpretation of storm flow fields expand our understanding of external and internal forcing, thermodynamics, cloud physics, electrification, and cloud dynamics, which contribute to intense thunderstorms and their attendant phenomena. Subsets of the group objective are addressed by two projects: Modeling and Dynamics led by Carl E. Hane, and Storm Evolution and Analysis led by Rodger A. Brown (Edward A. Brandes, acting since September 1985).

RECENT ACCOMPLISHMENTS

Tornadic Storms

Theoretical studies of storm rotation, when combined with Doppler radar and storm intercept information, enhance understanding of tornadic thunderstorms. Davies-Jones (1984) established that veering of the storm-relative environmental winds with height (i.e., storm-relative streamwise vorticity in the environment) causes updrafts in supercell storms to rotate cyclonically on average; by the same token, downdrafts are caused to rotate anticyclonically. He also obtained from linear theory a formula for the correlation coefficient between vertical vorticity and vertical velocity in terms of storm motion, environmental winds, and the growth rate and horizontal scale of convection. A simple physical explanation is being documented in a popular article.

A model of Beltrami flow, in which vorticity is everywhere parallel to velocity, has been initialized to provide insights into the pressure field around a rotating updraft. As an exact solution of the Euler equations of motion, the Beltrami model serves as a test case for conceptual models that "define" main features of dynamic pressure fields around updrafts. The model also explains why the mesolow at the earth's surface is often observed to be several kilometers away from the circulation center in mesocyclones, and may help to explain the characteristic size and rotation rate of mesocyclones. Several results obtained by Davies-Jones (1984) using linear theory are also applicable when nonlinear effects are included.

Observational data also play a major role in our understanding of the generation and intensification of vertical vorticity within severe thunderstorms. Studies of several major tornadic storms during the past decade support recent numerical simulations showing that production of vertical vorticity begins at the very roots of an updraft as horizontal vorticity in low-altitude inflow regions is tilted toward the vertical. Then, as the flow passes through the updraft, the tilted vorticity and preexisting vertical vorticity are amplified by convergence to create the tornado parental circulation (mesocyclone). The low-altitude mesocyclone intensification that heralds tornadogenesis seems to result from interaction between spreading rainy downdraft air and inflow air from the storm's right flank. Vertical vorticity is amplified by surges of convergence in the region of interactions. Rear downdrafts, which develop at approximately the time of tornadogenesis, do not transport significant vorticity; rather, their divergent character reduces vertical vorticity. Rear downdraft formation reverses the horizontal gradient of the vertical wind across the low-altitude mesocyclone and increases vorticity generation by twisting within the mesocyclone, but the generation rate is less than half the amplification rate by convergence. Thus, tornadoes are most likely to be triggered by the vorticity amplification that follows from outflow-inflow interaction. During dissipation, updrafts and rainy downdrafts weaken, and rear downdraft air fills the mesocyclone. Vertical vorticity rapidly dissipates as air diverges near the ground, and the association between the mesocyclone and updrafts ends. These findings are summarized in the figure on the cover (Brandes, 1984).

The retrieval of pressure and buoyancy information from the basic three-dimensional wind field is improving our understanding of dynamic forcing within severe thunderstorms. For example, the structure and evolution of the Del City, Okla., tornadic storm of 20 May 1977 were clarified through an investigation into coevolving structure of velocity, pressure, and buoyancy. The pressure field near the storm updraft includes higher pressure on the upshear side and lower pressure on the downshear side. This orientation of pressure centers rotates with the shear vector with height (Hane and Ray, 1985). The buoyancy distribution in general shows warm updrafts and cool downdrafts, and a potential relation between low-level vertical vorticity production and horizontal buoyancy gradients.

On rare occasions, a tornadic storm that produces an unusually large and intense tornado is positioned close to an NSSL Doppler radar. In such situations, exceptional details about the radar reflectivity and Doppler velocity signatures in the vicinity of the tornado can be obtained. The storm that produced the violent (F4) Binger, Okla., tornado on 22 May 1981 was such a storm. During a portion of the tornado's lifetime, high pulse repetition frequency (PRF) measurements were made by NSSL's Norman Doppler radar; this special radar channel permits unambiguous velocities up to ±91 $m \cdot s^{-1}$ to be measured within the radar sampling volume. Analyses of the skirts of the Doppler velocity spectra revealed wind speeds of 90 $m \cdot s^{-1}$ within the tornado. Use of the normal PRF (±35 $m \cdot s^{-1}$) with the NSSL Doppler radars and the pulse pair processer does not permit examination of the Doppler velocity spectrum; instead, only the mean velocity in the sampling volume is available. However, a large and/or intense tornado produces a unique tornado vortex signature (TVS) among the mean Doppler velocity values as the radar scans past the tornado. The TVS associated with the Binger tornado had unprecedented vertical extent--extending from the ground to within about 1 km of storm top. Colocated with the TVS was a significant reflectivity minimum that became a weak echo hole at middle altitudes. The diameter of the weak echo region was about 750 m near cloud base and gradually increased to about 2 km at 9 km height. Calculations for microphysical retrieval (see Microphysical Processes) led to the speculation that low reflectivities in the narrow tube-like region were due to strong tangential velocities that prevented graupel from entering the tornado. This hypothesis is being tested with a finely resolving numerical model.

Direct observation of tornadoes is another means by which understanding of tornadic storms is achieved. A portable instrument, TOTO (TOtable Tornado Observatory), was first developed in the Wave Propagation Laboratory to make direct measurements of meteorological variables in tornadoes. Measurements of wind speed and direction, temperature, and pressure were made with this device near tornadoes and beneath a rotating wall cloud. Data from damage surveys and Doppler radar are used in conjunction with TOTO measurements to obtain estimates of wind speeds in and near tornadoes. On 29 April 1985 an NSSL intercept team (led by L. J. Wicker) successfully deployed TOTO in the path of a tornado for the first time. Subsequent damage surveys revealed that the tornado was of minor intensity (F0 classification) and that TOTO was located near the edge of the damage path. Wind speeds of 30 $m \cdot s^{-1}$ and a pressure drop of 1 mb in 1 s were recorded with the tornado, and a pressure fall of 5 mb in 2 min with the mesocyclone. However, results of wind tunnel tests and recent calibrations of TOTO sensors suggest some uncertainty in measurements of significant variations over such short periods.

Thunderstorm Evolution and Structure

Radar observations, both conventional and Doppler, are continuing to provide important information concerning the evolution and structure of convective systems. The mechanisms whereby intense convection was maintained on the leading edge of a large squall line occurring on 19 May 1977 were examined by Hane et al. (1985). Observations revealed that at certain locations along the line new convection formed in short shower lines that were perpendicular to the principal squall line (Fig. 1). Showers within the short lines, initiated by convergence not connected with outflow boundaries, sustained convection in the most intense portion of the squall line.

The characteristic lifetimes of particular thunderstorm features are important to operational meteorologists and to those engaged in aviation activities. Vasiloff et al. (1985), utilizing a data set obtained on 19 June 1980, determined reflectivity core growth rates of 4 to 5 dBZ min^{-1} and updraft growth rates of 3 to 7 $m \cdot s^{-1}$. Typical cells persisted 40 to 60 min. A related experiment, with important implications for scanning strategies with operational radars in NEXRAD, investigated the influence of data resolution on automated storm analysis and tracking algorithms. Results indicate that interlacing of consecutive volume scans (i.e., odd numbered tilt elevations from one data collection are mingled with even numbered tilt elevations from the next collection) produces a gain in the detectability and predictability of severe weather phenomena, because the collection interval for each scan is reduced significantly.

Other investigations of the structure and evolution of severe thunderstorms are continuing. A storm on 19 June 1980 slowly evolved from a multicellular state into a supercell storm (Vasiloff, principal investigator) owing to the formation of a large region of "background updraft" in which individual cells were represented by updraft perturbations. As the storm intensified, individual perturbations (updraft and reflectivity) became more difficult to identify. In the cell's reference frame, environmental vorticity was not significantly streamwise and, hence, individual updraft perturbations did not

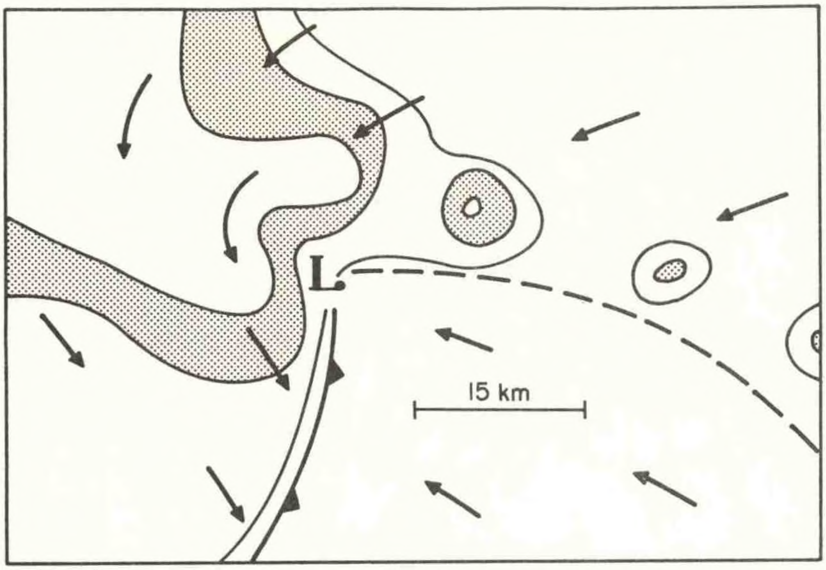


Figure 1. Low-level reflectivity and airflow over a region of the 19 May 1977 squall line. Solid contours with shading indicate values of reflectivity; arrows indicate direction of line-relative air motion. The cold frontal symbol marks the more pronounced portion of the gust front; the dashed line marks the axis of a region of enhanced convergence ahead of the squall line. The low pressure center exists as a consequence of the large cell to its west-northwest. Cells form in short lines along a confluence asymptote leading into the low center and eventually merge with the line proper, owing to different motion of cells and line. The region of high reflectivity in the line is thus maintained.

acquire strong rotation. However, the larger scale region of background updraft moved to the right of the individual cells and in this reference frame there was an appreciable streamwise component of vorticity. Thus, the supercell structure and the presence of mesocyclones in the 19 June storm were attributed to the development and motion of the background updraft region.

Scale interactions are prominently exposed in data sets collected on 26 April 1984 (Burgess, principal investigator). During the afternoon, isolated supercell storms formed and produced weak tornadoes; these were followed by nighttime formation of a continuous squall line. Violent tornadoes occurred when breaks developed within the line; it seems likely that an approaching shortwave trough aloft altered the mesoscale environment creating greater instability and a vertical wind shear profile more favorable for tornadoes.

A study of mesocyclone evolution, downbursts and the differential motion of mesocyclones occurring in the Lahoma and Orienta storms of 2 May 1979 has been completed (Brenda Johnson, principal investigator). As in many other cases, mesovortex formation and intensification seem tied to the tilting of horizontal vorticity and the subsequent amplification of tilted vorticity by convergence. Periodic regeneration of mesocyclones corresponded with updraft pulsations within background regions, while new mesocyclones developed as new

(a)

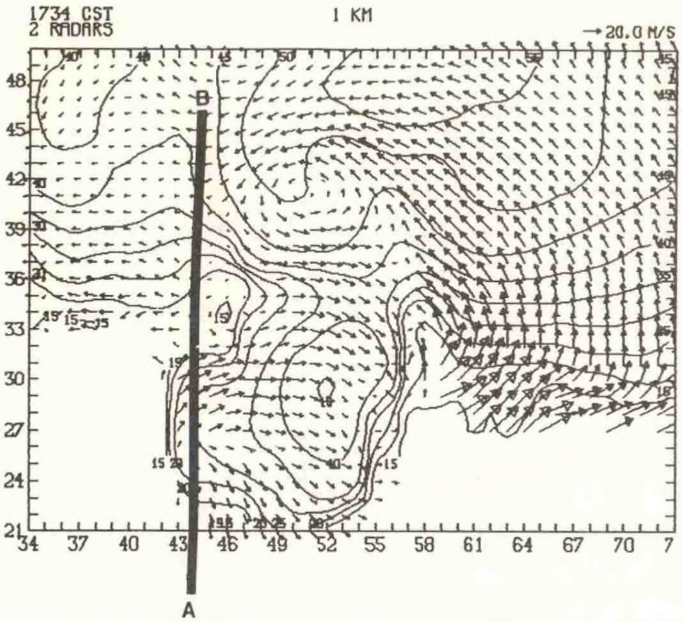
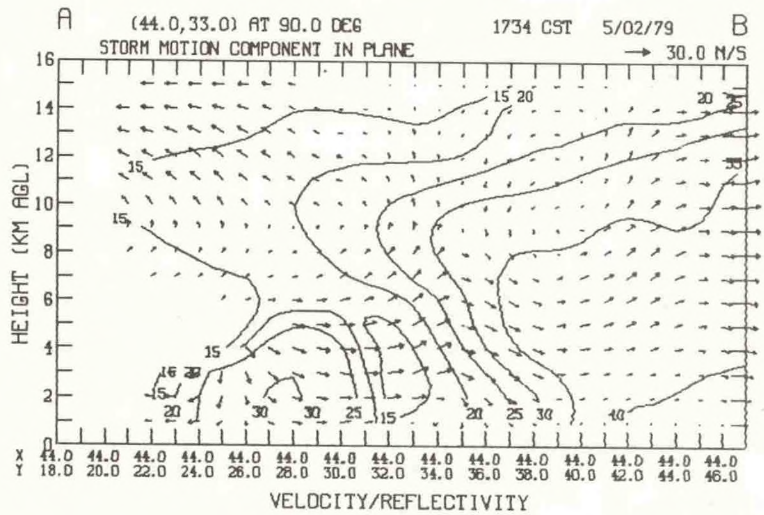


Figure 2. Ground-relative winds in (a) the horizontal plane and (b) a vertical plane denoted by A-B in (a). All winds correspond to 2 May 1979 at 1734 CST. Reflectivity (dBZ) is superimposed. Winds depict the Waukomis downburst (x,y: 44,28). This downburst is thought to have been enhanced by entrainment of dry and potentially cold environmental air into an area of weak reflectivities.

(b)



updrafts formed along gust fronts. Of two downbursts, one seemed to be triggered by heavy water loading (radar reflectivities >55 dBZ), whereas the second downburst involved weak reflectivity (<45 dBZ) but was probably enhanced by the entrainment of potentially cold environmental air at higher altitudes (Fig. 2). Principal mesocyclones within the two coexisting storms tended to approach and rotate cyclonically around each other. Observed rotation rates of 60-100° h^{-1} are in approximate agreement with computed values from a simple model for two interacting potential vortices.

Microphysical Processes in Storms

Documentation of numerical models for identifying microphysical processes in storms was completed (Ziegler, 1985). The work proceeds from description of the motion field by Doppler radar in three spatial dimensions and in time. Microphysical retrieval is applicable to studies of thunderstorm dynamics, microphysics, and electrification. Future efforts to initialize a dynamic cloud model with real data and to evaluate weather modification experiments will rely heavily on such a method.

A study of the sensitivity of microphysical output to the model representation of microphysical processes is currently being documented. Accuracy of the model output is most strongly dependent upon the formulations of warm cloud and hail processes and to the detail used to represent the hail size distribution.

Our microphysical retrieval model has been applied to several diverse types of deep moist convection. Relationships among the airflow, electrification, and cloud and precipitation development in an isolated mountain thunderstorm in New Mexico are being studied with single Doppler radar and sailplane data and a one-dimensional cloud model. Noninductive charge transfer accompanying collision and separation of ice crystals and riming graupel is calculated by the model. Total space charge, accumulated by the noninductive ice-ice mechanism plausibly explains the observed lightning flash rate in this storm. The graupel/ice collision rate and total charge separated per grid cell per minute resulting from model calculations are plotted with height and time in Fig. 3.

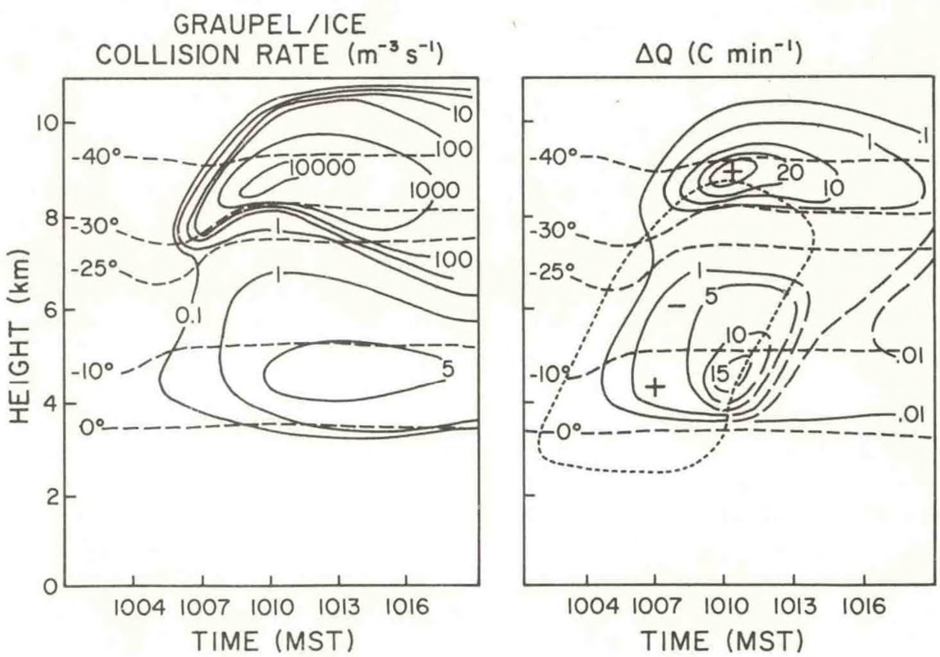


Figure 3. Time-height sections of graupel-ice crystal collision rates (left) and total charge separated in each cloud grid cell in 1-minute by the non-inductive graupel-ice mechanism (right). Contour values of collision rate and charging rate are noted. Selected ambient isotherms (°C) are indicated.

Diagnosis of the newly developed dynamic and microphysical retrieval models can be rigorously verified and extended through abundant in-situ aircraft measurements made in New Mexico during the summer of 1984. Preliminary analyses of storm morphology have begun, using highly resolving data from four Doppler radars, three aircraft, and a number of electric field and charge measurement instruments.

The thermal and microphysical structure of an African squall line has been analyzed using airflow defined by two Doppler radars and a two-dimensional version of NSSL's microphysical retrieval model. This study, in collaboration with French scientists at the Centre de Recherches en Physique de l'Environnement Terrestre et Planétaire, teaches more about squall line structure and allows contrasting diagnostic methods.

Mesoscale Modeling

Some forecasters have noted that weak frontal boundaries on the elevated terrain of the Texas Panhandle and western Kansas are favored sites for growth of disturbances. Growth of the disturbances seems to be synchronized with afternoon heating of high terrain; the synoptic depiction resembles a thermal depression located on the front. The net result is a backing of winds in the moist air eastward from the low center, and convergence northeast is focused by the disturbance. This northeastward location is thus a favorable area for severe thunderstorm development.

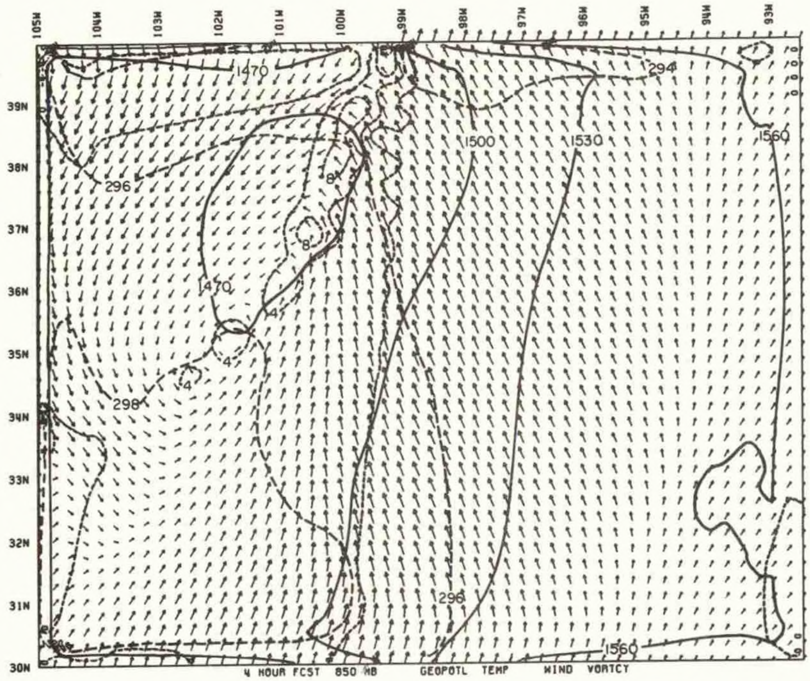
With the Cooperative Institute for Mesoscale Meteorological Studies, a mesoscale model has been formulated to address this and other problems. In our first comprehensive study, the model was initialized with a weak front and moderate southerly flow. The bottom (sloping) terrain was heated with a variable rate, decreasing eastward. The solution 4 hours into the simulation (shown at 850 mb in Fig. 4a) indicates development of a vortex, backing winds in the east, and convergent tendencies northeast of the low. An intriguing feature of this development is the tendency of the vertical wind shear in this area to exhibit large directional shears below 700 mb, characteristic of tornado proximity soundings. Vertical shear profiles resulting from model calculations at various times and locations are shown in Fig. 4b. The 850-mb fields at 8 hours (not shown) include increased vorticity values and falling geopotential tendencies south-southwest of the low shown in Fig. 4a.

Forecasts and Warnings

Much of NSSL's research related to improved forecasts and warnings anticipates the next-generation Doppler weather radar system (NEXRAD). The search for single Doppler signatures of certain weather phenomena continues. Fig. 5 simulates passage by a Doppler radar site of a cold front that separates uniform flows (Wood, principal investigator). Currently, wind and reflectivity fields from a numerical hurricane model are being used to construct Doppler radar signatures for these storms. We need to learn how changes in hurricane intensity are manifested in the radar observations.

A joint project (DOPLIGHT) with the National Weather Service Forecast Office at Oklahoma City completed its second year. Single Doppler velocity data with cloud-to-ground strike locations are transmitted in real time to the forecast office. An NWS forecaster coordinates the display selection from the

(a)



(b)

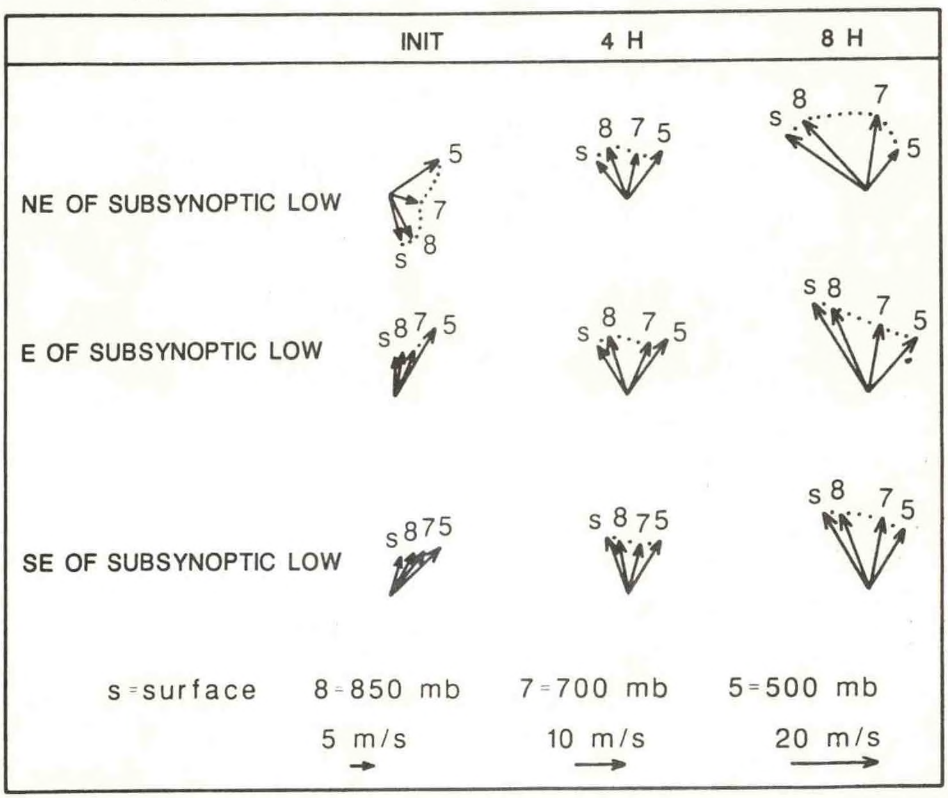


Figure 4. Results of mesoscale model calculations. (a) Wind field (vectors), geopotential (solid lines) temperature (K, dashed lines) and vorticity (in units of $10^{-5}s^{-1}$, dotted lines) at 850 mb 4 hours into the simulation. (b) Representation of the vertical wind shear at various times along longitude 100° west.

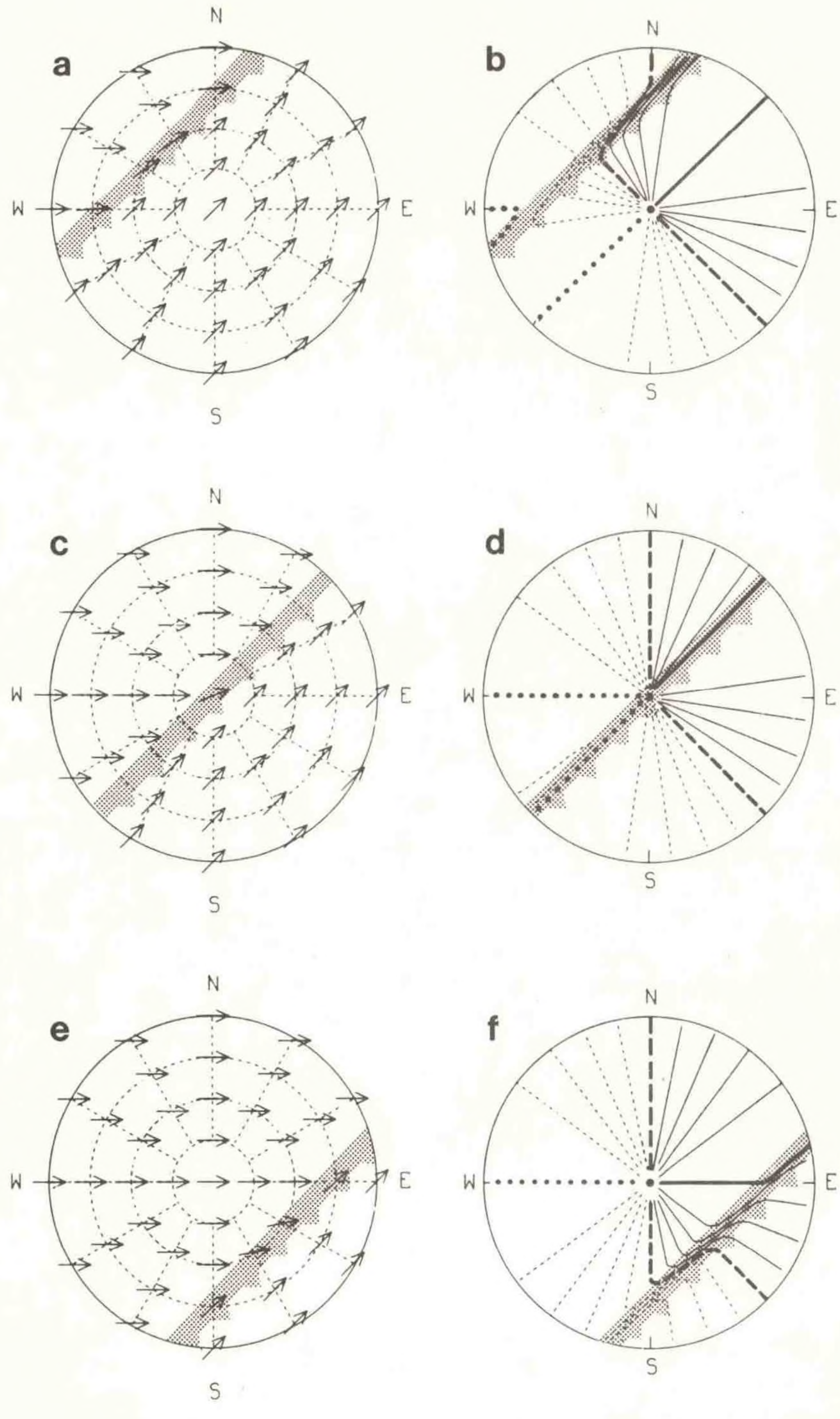


Figure 5. The left column represents simulated vector wind fields in the vicinity of a surface cold front (shown on radar display format). The right column (b,d,f) represents the corresponding single Doppler velocity patterns at zero elevation angle. Solid lines represent flow away from the radar; short dashes represent flow toward the radar; heavy long dashes represent zero Doppler velocity. Heavier solid and dotted lines indicate locations of maximum and minimum Doppler velocity values within the display. The front is indicated by light stippling.

NSSL radar site. The real-time Doppler velocity signatures are incorporated into the forecast office's weather warning function (Brown et al., 1985).

Attenuation of short radar waves can impede detection of severe weather phenomena. A comparison of reflectivity patterns at 5- and 10-cm wavelength for the 2 May 1979 data set (Brenda Johnson, principal investigator) illustrates the problems that can occur (Fig. 6). When the Orienta and Lahoma storms became radially aligned with respect to a 5-cm radar (located at x=0, y=0 km), signal attenuation exceeded 30 dB. The attenuation distorted the reflectivity structure of the Lahoma storm, and the expected association of mesocyclone and reflectivity maxima is not evident; i.e., the mesocyclone appeared in the weak reflectivity gradient on the left flank of the storm, not on the right flank as expected.

NSSL has been aiding the National Weather Service in evaluating "add-on" Doppler radars at Montgomery, Ala., and Marseilles, Ill. (Burgess, principal investigator). The Montgomery 5 cm radar seems effective for ranges <130 km. Although limited by a small velocity measurement interval and problems in velocity interpretation, local warning capability has been improved. The evaluation of the Marseilles 10-cm radar indicates an effective range of 150 km. Utility is limited by a wide beamwidth and low transmitter power. Donald Burgess also served on the NOAA Technical Evaluation Committee to review Off-the-Shelf Doppler Radars.

Data Acquisition and Processing

We constantly search for better data acquisition methods and improved techniques for analyzing data. The utility of surface observations in multiple-Doppler objective analysis schemes is related to radar range. Storms scanned by radars are typically 50 km or more distant. In this situation the observations are no lower than 0.25 km AGL with scanning at 0° elevation. This leaves the researcher with the choice of establishing the lowest level of the wind field analysis at the height of the lowest scan or using downward extrapolation to obtain the first analysis level at ground level. Downward extrapolation may suffer in accuracy since tall-tower data show that winds over large regions in the lowest half kilometer of a thunderstorm can vary significantly in the vertical, usually turning clockwise with height. Since vertical velocity determination requires accurate boundary conditions, a method of analysis has been developed (Ken Johnson, principal investigator) for drawing on both Doppler radar and surface data to produce a more representative surface wind field.

Airborne Doppler radar can collect data on target storms that are quite widely dispersed. However, the relatively long time required to sample an individual storm in detail, particularly with a single aircraft, and the amplification of statistical uncertainty in radial velocity estimates when Cartesian wind components are derived, suggests that errors in wind fields derived from airborne Doppler radar measurements would exceed those from a ground-based radar network that was well located to observe the same storm (Ray, principal investigator). Error distributions for two analysis methods (termed overdetermined and direct methods) have been applied to data collected on a storm induced by a sea breeze in western Florida on 28 July 1982. It

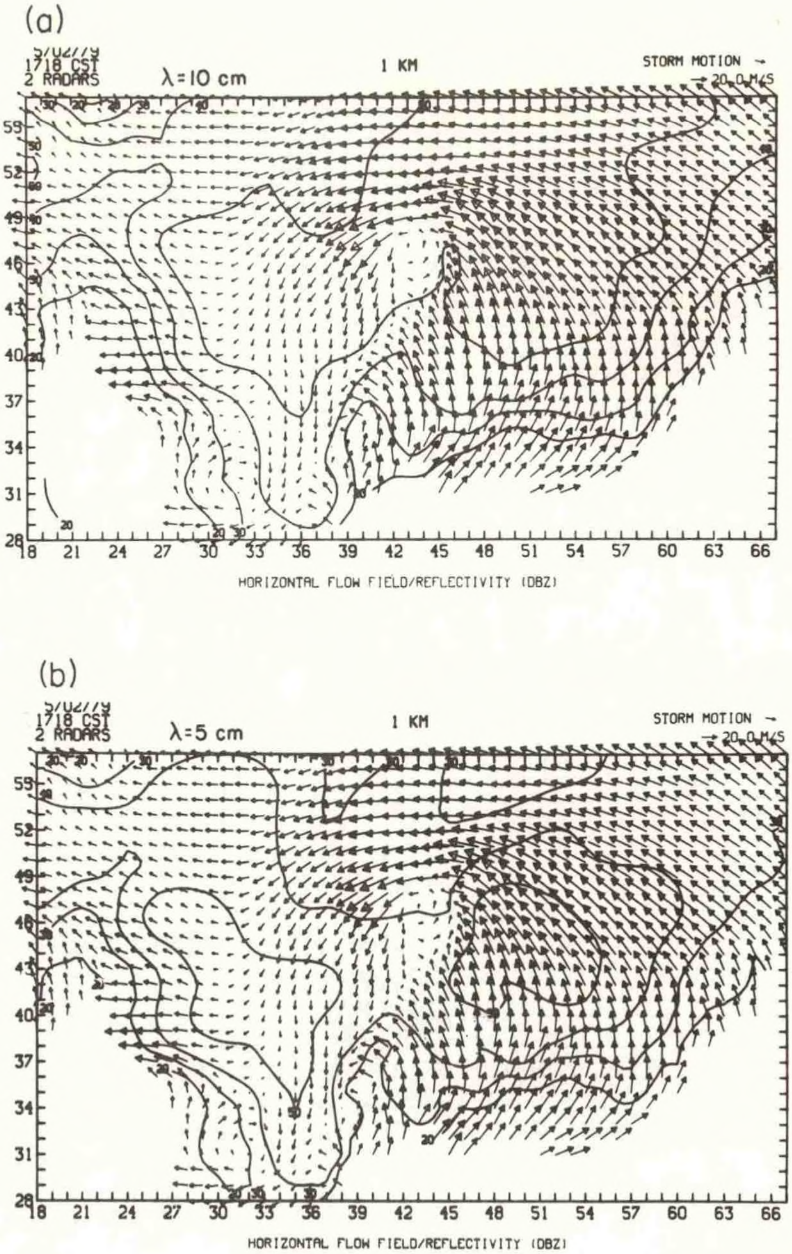


Figure 6. Reflectivity patterns from (a) NSSL's 10-cm Cimarron radar and (b) NCAR's CP-3 5-cm radar in the Lahoma (right) and Orienta (left) severe storms on 2 May 1979. Reflectivity contours are at 10-dBZ intervals, starting with 20 dBZ. The 5-cm Doppler radar was at (0,0), southwest of the storm complex. Wind vectors reflect the existence of the Lahoma mesocyclone in the center of each figure.

was gratifying to find that application of the direct solution not involving the continuity equation, and the overdetermined dual-Doppler method, which requires use of the continuity equation, produced similar fields. It is difficult to assess relative performance precisely, however, because the magnitudes of all errors are unknown and the response of each method to errors is different.

An extremely important component of the 1985 PRE-STORM Program was acquisition of rawinsonde data with 1.5-3 h time resolution from 12 supplemental sites and 15 National Weather Service sites. A routine was developed at NSSL to bring data from the supplemental sites to the PRE-STORM control center followed by processing the data in near-real time. The processed data were then transmitted to the national system via AFOS. Users of AFOS thus had access to upper-air data with unprecedented temporal and spatial resolution.

Objective analysis algorithms are being developed to read and analyze mesoscale rawinsonde data. The analysis package will be used to produce fields suitable for use in NSSL's version of the Warner-Anthes (Penn state-NCAR) mesoscale model.

MISCELLANEOUS

In severe wind storms and tornado situations, some structures survive while others are badly damaged or destroyed. In an engineering study (Burgess, coinvestigator), the effects of wind loads were examined on some common and upgraded roof connections. Preliminary results suggest that slight changes in connection strength cause large increases in structural integrity.

A recent journal article described an approximate solution to frontogenesis associated with a nondivergent vortex. Through a kinematic analysis, an exact analytic solution has been found to this problem (Davies-Jones, principal investigator).

EXPECTATIONS FY 1986

A number of studies will use data collected during the 1985 PRE-STORM Program

Data analysis to generate a statistical data base useful for developing algorithms for optimal network design.

A case study of scale interaction on 12 May 1985.

Extensive studies of cell-storm and storm-environment interaction for understanding mesoscale convective system morphology and evolution.

Mesoscale modeling experiments utilizing swarm release rawinsonde data as initial conditions for two excellent situations (10-11 May and 10-11 June 1985).

Other studies with individual days awaiting identification.

Analysis of the following storm cases will continue:

Thunderstorm Research International Project (TRIP) 1984 case.

22 May 1981 Binger storm microphysics and dynamics.

19 June 1980 reflectivity and electrical data.

Documentation of the following studies will be completed:

The sensitivity of microphysically retrieved variables to details of the microphysical formulation.

1982 Spring Program Summary

Compilation of mesocyclone statistics

Severe storms on 8 June 1974, 19 May 1977, and 6 June 1979

Training manual for interpretation of single-Doppler color displays

Book chapters on squall lines and rainbands and on dynamic and microphysical retrieval, and an encyclopedia article on severe thunderstorms

Among the new case studies to be initiated (other than PRE-STORM cases) are the following:

Microphysical retrieval/electrification on 19 June 1980

Dynamic retrieval on 19 May 1977

An initialization package will be developed, suitable for interfacing the objective analysis package with NSSL's mesoscale model.

Processing of rawinsonde data from all 27 PRE-STORM sites will be completed.

There will be a substantial effort to integrate observations with theoretical investigations and mesoscale numerical modeling.

Among specific topics to be examined are cyclogenesis on mesocyclone scales and larger multi-dimensional cloud modeling, and model initialization and verification studies.

Mesoscale modeling will continue with CIMMS. Another mesoscale model (Penn State-NCAR) will be transferred to the CDC 205, and the two models will be run on the heated terrain problem with real data.

DOPPLER RADAR AND STORM ELECTRICITY RESEARCH (DRASER)

Richard J. Doviak, Group Leader

Substantial facilities are available at NSSL to observe electrical and kinematical processes contemporaneously with precipitation phenomena. Major objectives of Doppler Radar and Storm Electricity Research (DRASER) include (1) determining relationships among processes of lightning, thermodynamics, and precipitation in thunderstorms in order to develop improved indicators of thunderstorm severity and hazards; (2) developing and refining remote-sensing techniques for locating and tracking storms and their attendant hazards; (3) defining lightning and kinematic characteristics of storms to aid design of appropriately robust aircraft and ground facilities, and models used in environmental studies; (4) providing ground truth and supportive data for development of new instrumentation and refinement of observational techniques.

These objectives are addressed with theoretical and observational studies. The Doppler Radar Group focuses its efforts on interpretation of prestorm and stormy weather phenomena, using Doppler radar as well as a multitude of other sensors. The Storm Electricity Group concentrates its analyses on data simultaneously obtained with Doppler radar and our many storm electricity sensors.

RECENT ACCOMPLISHMENTS

Studies of the Boundary Layer and Storm Initiation

Temperature profile updates: We are attempting to estimate changes in temperature and moisture profiles between rawinsonde releases, using velocity data from a single Doppler radar. The average horizontal wind at different altitudes in the vicinity of the radar site is estimated from sets of radial velocities measured around the station. Further processing yields the horizontal divergence and hence the distribution of vertical air velocity with height. Then, temperature and moisture changes due solely to the vertical components of air motion are computed directly from the vertical wind and initial temperature and moisture profiles. Tests performed on actual data are shown in Fig. 7. The predicted changes are in qualitative agreement with rawinsonde observations. In more advanced tests, diabatic heating, evaporation, and turbulent mixing are parameterized from net radiation, humidity near the ground, and horizontal winds. Finally, horizontal temperature advection is estimated from measured horizontal wind and horizontal temperature gradients at various heights. The temperature gradients are estimated by solving the general form of the thermal wind equation using the horizontal wind at different heights and assuming a value of vertical vorticity. The results of test cases indicate that vertical advection dominates the horizontal advection in affecting temperature and moisture changes over a few hours or less. The results indicate potential for thunderstorm prediction and warrant continued investigation.

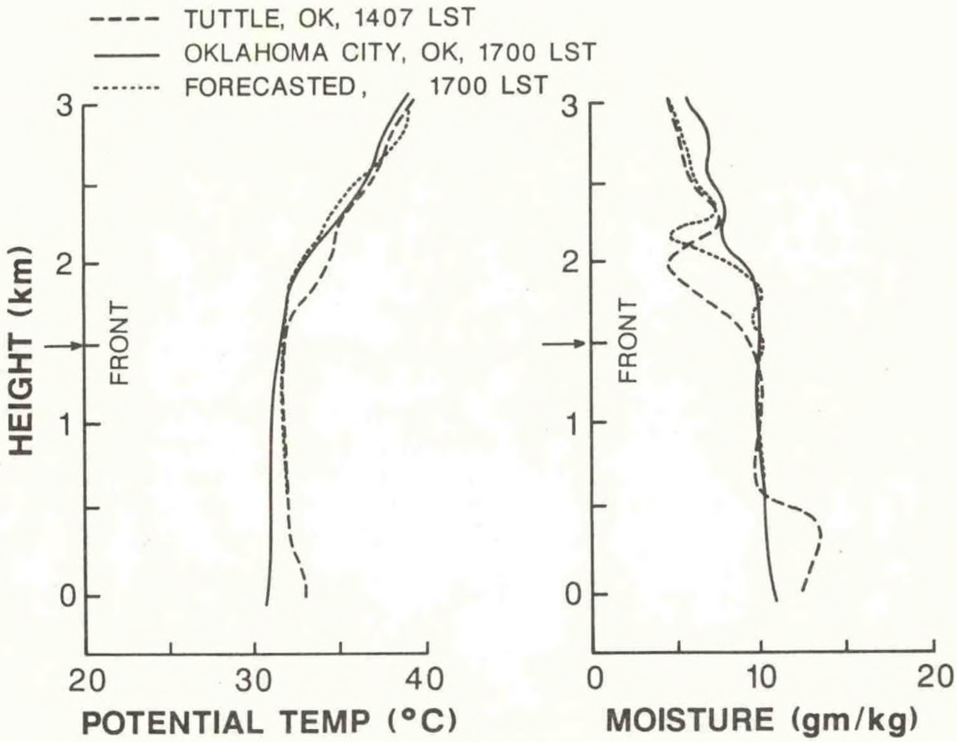


Figure 7. Initially (1407 LST) observed temperature and moisture profiles and Doppler data collected over a subsequent 3-hour period are used to estimate profiles at 1700 LST. The temperature profile observed 3 hours later at Oklahoma City shows significant cooling of the air at 2 km in agreement with that estimated. This cooling contributed to the initiation of thunderstorms.

Boundary layer kinematics: Divergence measured in a prestorm disturbed atmosphere with two Doppler radars, and divergence estimated by velocity-volume processing (VVP) from a single Doppler radar, show much better agreement when the radar data are filtered. This is because small-scale non-linearities that bias the VVP divergence are removed. Analysis of data gathered on 17 May 1981 revealed that convergence areas were detected near and ahead of the dry line.

An algorithm using single Doppler radar data with an assumption of uniform wind has been applied to narrow sectors (40° azimuth by 20 km range) of the boundary layer to derive the wind field in the vicinity of a front. The derived wind is consistent with rawinsonde wind data. Furthermore, the measured slope of the front is consistent with the divergence, deformation, and vertical air motion derived from VAD (velocity-azimuth display) analyses.

The turbulent structure of a convective boundary layer, deduced from ground-based Doppler radar data, shows that the wind, vertically averaged over the boundary layer, is insensitive to baroclinicity, in agreement with an hypothesis put forward by Arya and Wyngaard (Eilts et al., 1985). Furthermore, measured wind profiles and the equations of motion are used to derive the vertical profiles of momentum fluxes. Although these are a function of baroclinicity, the observed profiles compare well with those computed from a barotropic model (Fig. 8), and the slight shift of the observed profile to the right is in the correct sense for the observed baroclinicity (Doviak et al., 1985a).

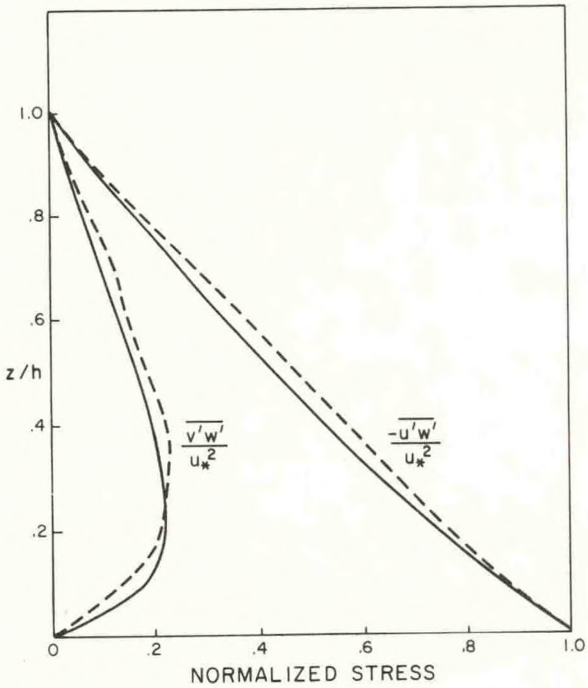


Figure 8. Momentum flux profiles derived from Doppler radar wind fields (dashed curve) compared with numerical model results for a barotropic, convective boundary layer. (From Wyngaard et al., 1974, "Modelling of the Atmospheric Boundary Layer", Advances in Geophysics, 18A, 193-211.

Boundary layer reflectivity factor: The reflectivity factor Z of the convective boundary layer observed on clear days and on the day during which a solar eclipse occurred reveals a dependence on incident solar radiation and ground wetness. Further, Z has a measured dependence on insolation that agrees with that deduced from theory (Fig. 9). Although the dependence on Bowen ratio (i.e., the ratio of sensible heat flux to latent heat flux) has not been rigorously tested, Z is higher during wet seasons, as expected from the theory.

A few sets of clear-air echo data have been collected using NSSL's 10-cm Doppler radar after cold-front passages to determine reflectivity factors in the wintertime boundary layer. Measured values of the structure constant were 10^{-14} to $10^{-15} m^{-2/3}$, which were also the values calculated from theory using rawinsonde data and eddy dissipation rates appropriate for turbulent breakdown of shear layers. However, on days (e.g., 27 May 1983) when surface heating generates significant fluxes of momentum and temperature, a different theory is required; its application gave reflectivity estimates in good agreement with observations.

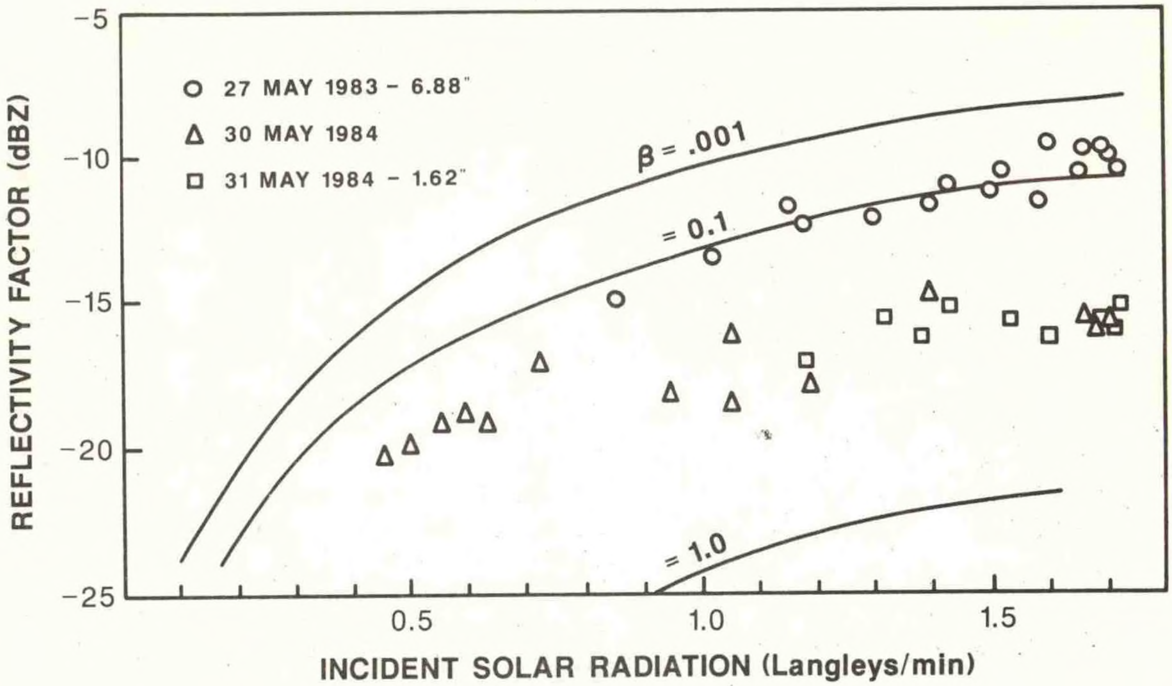


Figure 9. Radar reflectivity vs. insolation on three days. The Bowen ratio is indicated by the curves marked β. Rainfall totals at Oklahoma City are given in inches for May 1983 and 1984. During May 1983, 6.88 inches fell through 27 May, and there was none thereafter.

Measurement of Winds, Waves, and Turbulence

Intercomparisons: Two ground-based Doppler radars, an airborne Doppler lidar, a tall (444 m) instrumented tower, and a rawinsonde collected wind data in the quiescent planetary boundary layer (PBL) to allow, for the first time, comparison of wind fields measured by all these different sensors (Eilts et al., 1984). The vertical profile of wind measured by all sensors agreed to within a meter per second after corrections were made to account for temporal displacement in the measurements, the different spatial resolutions of the instruments, and drift of the inertial navigation system (Fig. 10).

Spectra of turbulence observed with the various sensors compared well in both magnitude and shape, suggesting that the lidar, radar, and in-situ tower instruments resolved similar structure in the PBL wind field. A peak at the 4-km wavelength, evident in spectra from all sensing systems, is attributed to horizontally symmetrical cells having a wavelength 4 times the inversion height in accord with theory.

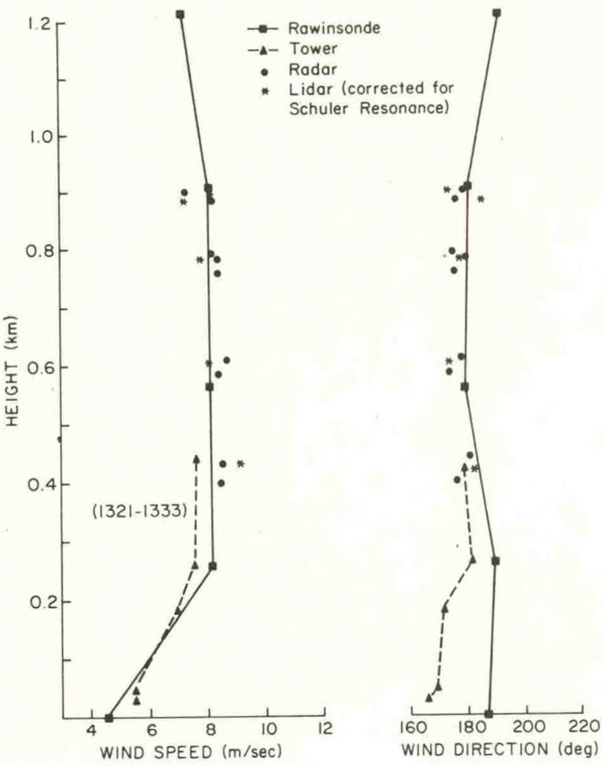


Figure 10. Wind profiles measured by Doppler lidar, Doppler radar, anemometers on a tower, and a rawinsonde. Because data were collected over a 2-hour period, they have been adjusted to remove a time trend relative to wind at 1330 CST.

Doppler lidar investigations of wind in stormy environments: The airborne Doppler lidar also made measurements in the vicinity of a thunderstorm and isolated cumulus congestus. Features of special interest seen in the derived wind fields are waves and vortices at the leading edge of a gust front marked by an arcus cloud formation, and well-defined wind shifts in cloudless regions (McCaul et al., 1985). The storm system, which contained the gust front vortices, moved eastward, intensified, and within 1 hour produced a damaging gust front tornado in Norman, Oklahoma.

Also seen by Doppler lidar were clear-air flows just below the base and sides of an isolated cumulus congestus circumnavigated by the aircraft (Doviak et al., 1985b). Analyses of winds above cloud base suggest that entrainment caused net convergence of environmental air into the cloud above its base (Fig. 11).

Wind Profiling: Advances in clear-air Doppler radar measurement have made practical the monitoring of radial velocities in the troposphere and lower stratosphere, and even the vector wind can be determined, with some assumptions. Because the objective of wind profiling is to monitor winds representative of larger scale atmospheric motions, an assumption of a time-invariant, spatially uniform wind field is commonly used. Then, the accuracy of the wind estimators depends on the error variance of the radial velocity, the departure from uniformity of the wind field, and the measurement geometry. Expressions for the variance and bias of some of these estimators have been derived when applied to a spatially linear wind field (Koscielny et al., 1984).

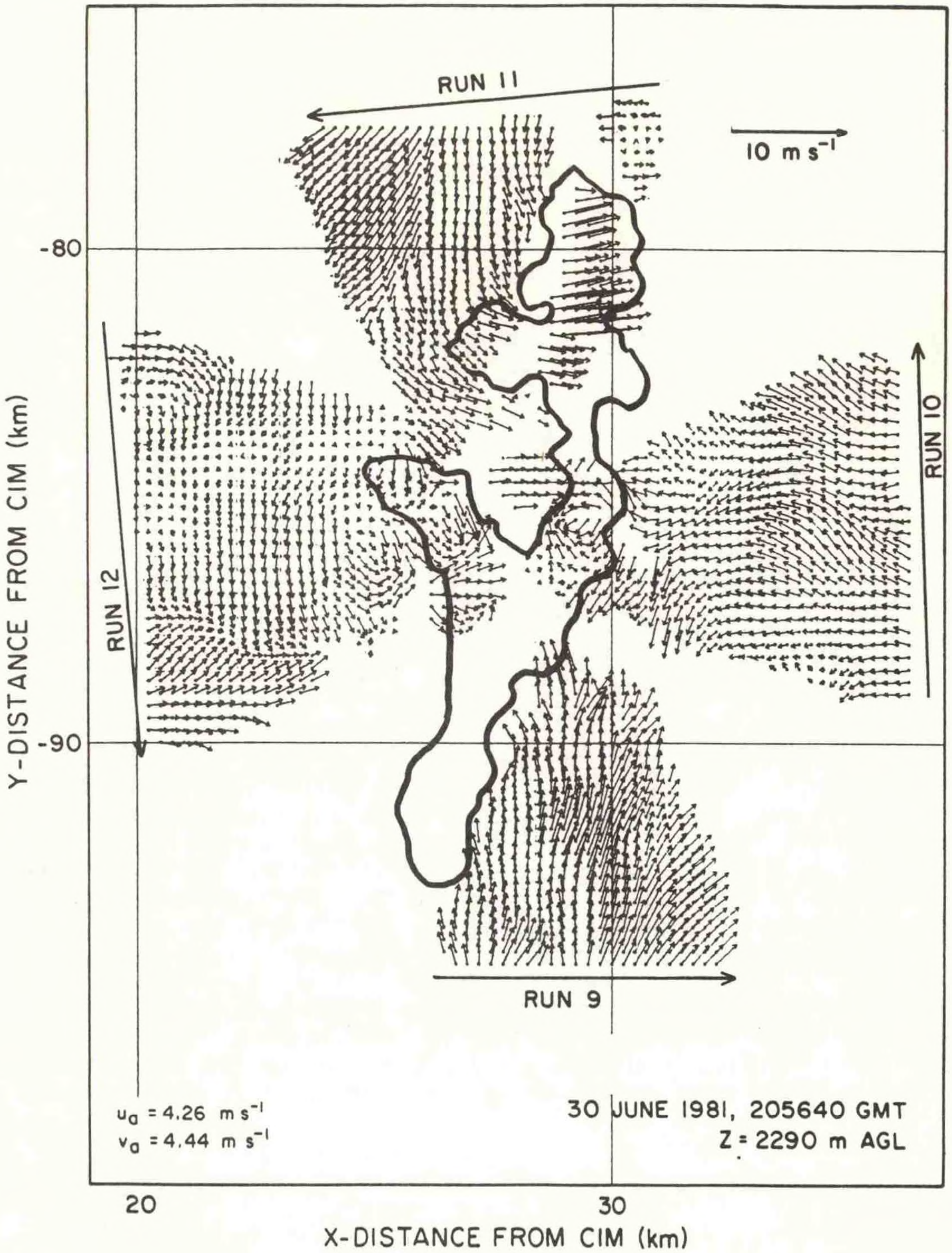


Figure 11. Perturbation horizontal wind fields at an altitude 1000 m above cloud base showing net convergence of environmental air attributed to entrainment. The cloud boundary (solid line) is where the 10- μm wavelength reflectivity gradient is strongest and delineates the cloud boundaries.

With the cooperation of the Wave Propagation Laboratory of ERL and the University of Oklahoma, NSSL installed a 50 MHz wind profiling radar at a site southwest of Washington, Okla., about 30 km south-southwest of NSSL. Observations began in mid-May, and the radar is making wind measurements continually. Wind fields observed with radar, and radiosonde data acquired at Oklahoma City 46 km away, show reasonable agreement; they also show some discrepancies that are being investigated further.

A parabolic reflector and positioner have been acquired from government surplus in order to assemble a 405-MHz radar that will be tested for its wind-profiling capabilities. We plan to make initial experiments in cooperation with WPL researchers who will be mating their transmitter and receiver to the assembled reflector antenna.

We have investigated how well Doppler velocities measured in storms can be used to estimate wind profiles in the nearby environment undisturbed by the storms. In limited data from 2 days there were approximately equal amounts of agreement and disagreement between environmental winds estimated from extra-storm winds measured with one or two radars, and those observed with a rawinsonde outside storms. However, estimated wind profile variance was not significantly different from that for profiles estimated from radar measurements in nonstormy environments. Additional study is warranted to determine quantitatively how well NEXRAD radar may sample synoptic-scale winds using velocities observed in storms.

A real-time VAD program was set up to support the DOPLOON project (intended to automate balloon tracking for determination of winds by Doppler radar). Our computer program needs to be refined further for improved acquisition and tracking of the target balloons. The small number of experiments so far do indicate that Doploon winds compare well with rawinsonde observations and that the method has considerable promise for routine use.

Turbulence: The turbulent energy budget in a severe storm has been computed and various terms of the turbulent kinetic energy equation have been evaluated (Brewster and Zrnic', 1984). Comparison of transverse and longitudinal spectra (across and along the wind, respectively) show that the former has larger power as expected from the theory of isotropic turbulence (Fig. 12) and that the inertial subrange of isotropic turbulence has an outer scale of about 2 or 3 km in the observed storm. The eddy dissipation rates computed from Doppler spectral width and those computed from spatial spectra of the resolution volume averaged mean velocity show excellent agreement (Zrnic' and Brewster, 1984 and 1985).

Solitary waves: The steady-state solitary wave solution of the Benjamin-Davis-Ono (BDO) equation in a two-layer deep fluid has been compared with observations (by Doppler radar and a 444-m-tall instrumented tower) of a boundary layer solitary wave (Doviak and Ge, 1984). A comparison of the observed wind and pressure perturbation fields with the theoretical results leads to the conclusion that the BDO theory explains most of the observed perturbations caused by this large-amplitude solitary wave (Fig. 13). Using the results of Maslowe and Redekopp, we have extended the theoretical solutions to the case observed here in which the upper layer has a weak, hydrostatically stable stratification. In this case, the extended theory shows that the solitary wave amplitude should decrease with time because of upward radiation of

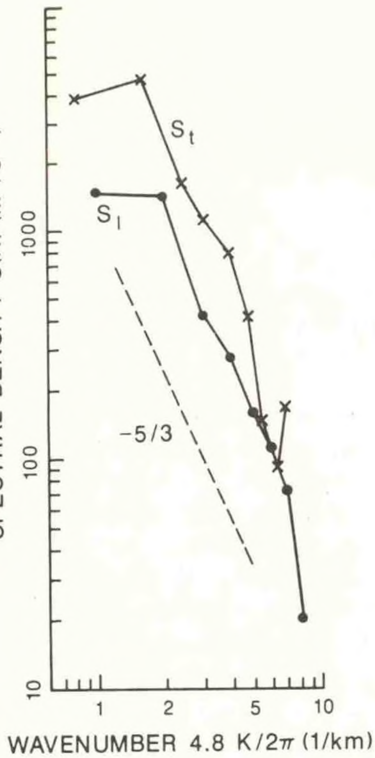


Figure 12. Longitudinal S_ℓ and transverse S_t spectra of vertical air velocities in a thunderstorm versus wave number K. For S_ℓ the wave number is directed along the vertical, and for S_t time-to-space conversion has been used to obtain K along the horizontal. On the average, the ratio of $S_t/S_\ell \geqslant 1.3$ in accord with theory.

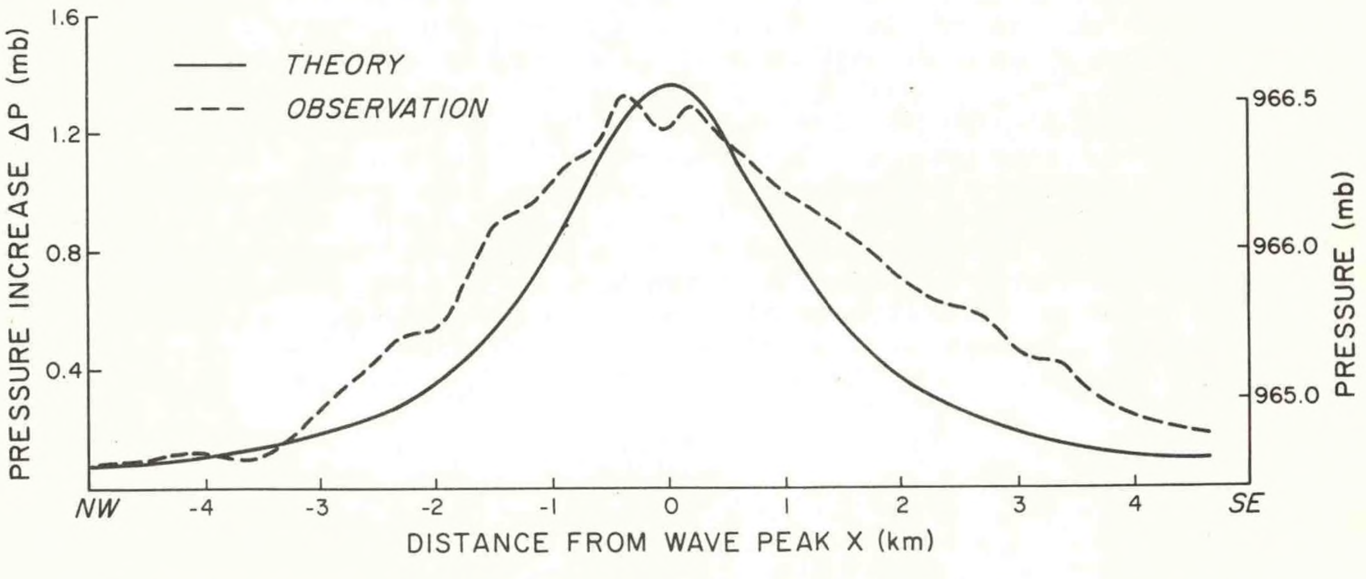


Figure 13. Theoretical and observed pressure perturbations caused by a thunderstorm-initiated solitary wave.

wave energy, a loss not present for a neutrally stratified upper troposphere. The theoretical results suggest attenuation rates about twice that observed. We have also initiated a joint research project with the Australian National University (ANU), and cooperative observations were made with ANU's microbarograph array and NSSL's Doppler radars and tall tower. Simultaneous data have been collected on at least two well-defined wave packets, which propagated through the network during the 1985 PRE-STORM period.

Aviation Related Studies

The Next Generation Weather Radar (NEXRAD) is slated to have an important role in the integrated and automated air traffic control system being planned by the Federal Aviation Administration. One major point of debate is the minimum rate at which weather data collected by NEXRAD must be updated so that no phenomena potentially hazardous to aviation go undetected. The methodology and results of a study to estimate the lifetimes of significant features in typical storm phenomena for situations other than takeoff or landing are examined. These results are of direct relevance in deciding on data update rates for NEXRAD. It is found that the storms studied contain no feature that might have been missed by a 5-min scan cycle, provided that concurrent reflectivity, radial velocity, and Doppler spectrum width data at several elevations are used in the detection of hazardous phenomena (Mahapatra and Zrnic', 1984).

The fields of the three principal Doppler moments (i.e., reflectivity, mean wind, and wind variability) have been related to weather events hazardous to safe flight. It is noted that detection of the hazard-causing phenomenon may be even more important than detection of the hazard itself (Doviak and Lee, 1985).

Siting of weather radars near airports: Weather radars are usually sited to survey as large an area as possible. However, in aviation applications fine resolution of low-altitude divergence and wind shear in regions of weak weather reflectivity may be required. This requirement can be most conveniently satisfied when the region surveyed is near the radar, but proximity exacerbates problems with ground clutter. Proper radar siting to take advantage of natural terrain and fabricated shields (clutter fences) can reduce ground clutter. Criteria have been developed that relate ground target illumination to antenna characteristics, shield heights, and the distance to the shield using both geometric optic and diffraction theory to estimate shield effectiveness (Doviak and Zrnic', 1985).

Downbursts: Downbursts in Oklahoma can be highly asymmetric: shear along the maximum shear axis can be more than 5 times the shear along the minimum shear axis. Furthermore, these downbursts are quite different from those observed around Denver, Colo., during JAWS. The majority of downbursts observed during JAWS were "dry"; i.e., little or no rain (<1/4 mm rain accumulation during the event) reached the surface. The downbursts were driven principally by evaporative cooling below cloud base, which occurred when precipitation fell into a deep, dry, well-mixed boundary layer. Lower cloud bases, and moister and slightly more stable boundary layers reduce the incidence of "dry" microbursts in the Oklahoma area. Most Oklahoma downbursts are associated with intense quasi-steady convective storms, and initiation mechanisms probably include low altitude melting of ice and evaporation of precipitation, precipitation loading at low-altitudes, and evaporational cooling at middle altitudes that accompanies entrainment of dry air.

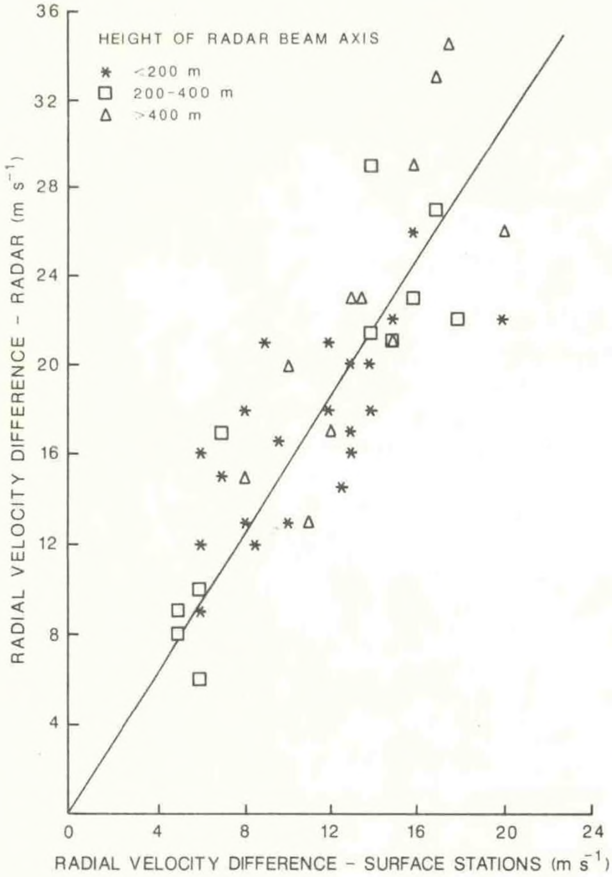


Figure 14. Velocity difference across gust fronts as measured by Doppler radar versus velocity difference measured at the surface by SAM stations. The code shows the approximate height of the Doppler radar observation. The solid line is a least-squares fit to the data, which shows that radar-measured horizontal shear is 60% higher on the average than surface-measured shear.

Shear: Comparison of surface-measured horizontal shear and that measured by Doppler radar was completed. For 41 comparisons of gust front shear, velocity differences measured across gust fronts by Doppler radar (at heights 50-600 m) averaged 1.6 times that measured at the surface (Fig. 14). Conclusions were that the Doppler radar is able to estimate shears below the radar beam and in fact may overestimate those shears.

Lightning strikes to aircraft: Analysis of data obtained during low-altitude storm penetrations with the NASA F106-B research airplane (Mazur et al., 1985a) provided the following results:

(1) The probability of direct strikes to the airplane (i.e., number of direct strikes divided by number of flashes within the radar's resolution volume containing the airplane) increases as storm cells decay and as the storm's lightning flash rates decrease (Fig. 15). This flash rate is estimated by the rate of lightning echoes observed along the beam in the penetrated storm.
(2) At low altitude within the storm cell the airplane can either trigger a strike to itself or be intercepted by a developing flash. High altitude strikes are nearly always triggered.
(3) Directions of channel development inferred from radar echoes from lightning agree with directions determined from actual television recordings of the same flashes from the airplane that show their propagation. Thus, a physically reasonable expectation is confirmed.

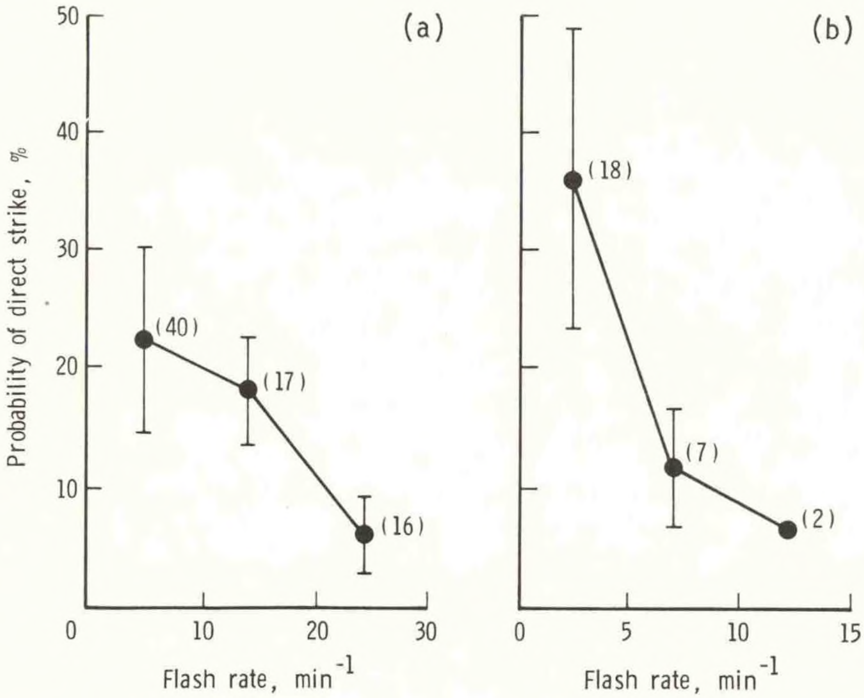


Figure 15. Lightning flash rate and probability of direct strike (PDS) to aircraft in a penetrated storm. (a) High-altitude flights, 1982-84 seasons, 73 penetrations, 108 strikes; (b) Low altitude flights, 1984 season, 27 penetrations, 27 strikes. Dots are the average PDS. The vertical bars are the 90% confidence intervals for the average PDS in each category. The actual number of penetrations is given in parentheses.

Airport terminal radar: The interservice NEXRAD Doppler weather radar, now under development and test, is expected to significantly aid FAA's projected aviation weather observation needs in the en route sector. However, questions have been raised about its adequacy for the highly dense and dynamic operations occurring in terminal areas. Constraints are associated with NEXRAD's basic design parameters as dictated by its multi-use role, and from its location as part of a national grid. There may be need for dedicated terminal area weather radars, especially at large and busy airports. For economy and faster implementation, it is desirable to use as much of NEXRAD hardware and software as possible in terminal area radars, and modify the operating parameters only to suit dedicated terminal area operation. An outline for such choice of parameters and a possible set has been presented (Mahapatra and Zrnic', 1985b).

Polarization Studies

A fast switch for polarization diversity was installed on NSSL's Cimarron Doppler radar, and first data collection began in the spring of 1985. Although detailed data analysis will not begin until FY 1986, we have been pursuing theoretical studies on several topics applicable to interpretation of our data and to enhance the measurement capabilities. Our theoretical investigations have produced the following conclusions:

(1) The acquisition time for differential reflectivity (Z_{DR}) can be substantially reduced by simultaneously sampling the vertical and horizontal electric fields (Sachidananda and Zrnic', 1985). Such a procedure does not compromise spectral moment estimation and allows scan rates of 3 rpm if correlation between simultaneously received horizontally and vertically polarized echoes is better than 0.995. A theoretical investigation of all the factors that contribute to the decorrelation established that this is indeed the case for rain media.

(2) A scheme for Z_{DR} measurement is suggested which uses alternate +45° and -45° polarized transmissions with simultaneous reception of horizontal and vertical signals to compensate for bias error due to propagation.

(3) A method for nearly eliminating the bias error due to receiver mismatch is suggested.

(4) A new method to estimate rainfall rate is based on differential phase ϕ_{DR}. It has been shown that the differential propagation phase constant versus rain rate, at high rates, is relatively insensitive to variations of the drop size distribution and thus can yield more accurate estimates than methods based on Z_{DR},R or Z,R relations (Fig. 16). Standard errors in ϕ_{DR} cause larger inaccuracies at low rain rate (<30 mm h^{-1}) than Z,R relations, thus limiting the method's usefulness to higher rain rates.

5) It is also shown that ϕ_{DR} can be used as a third remote measurable to determine a three-parameter drop size distribution.

Algorithms for the Next Generation Weather Radar (NEXRAD)

We have completed the development and testing of four NEXRAD algorithms:

(1) Uniform wind algorithm: This algorithm computes the azimuthal derivatives of radial velocity to estimate the transverse wind components. For a uniform wind, the relationship is exact. Application of this technique to Doppler data to estimate wind fields in the vicinity of frontal boundaries and in uniform wind situations showed good results. With the help of this algorithm, it will be possible to locate frontal boundaries with resolution much superior to that afforded by surface stations.

(2) NEXRAD Tornado Vortex Signature (TVS) algorithm: This is similar to the NEXRAD Mesocyclone algorithm. Its purpose is to identify regions of very high cyclonic shear associated with tornadoes. Testing on eight tornadic thunderstorm cases produced very promising results. The algorithm detected 84% of the actual number of TVS features, and there were no false alarms other than those caused by dealiasing problems. It has been observed that all violent tornadoes produce a TVS signature; thus our algorithm will enhance the tornado warning process.

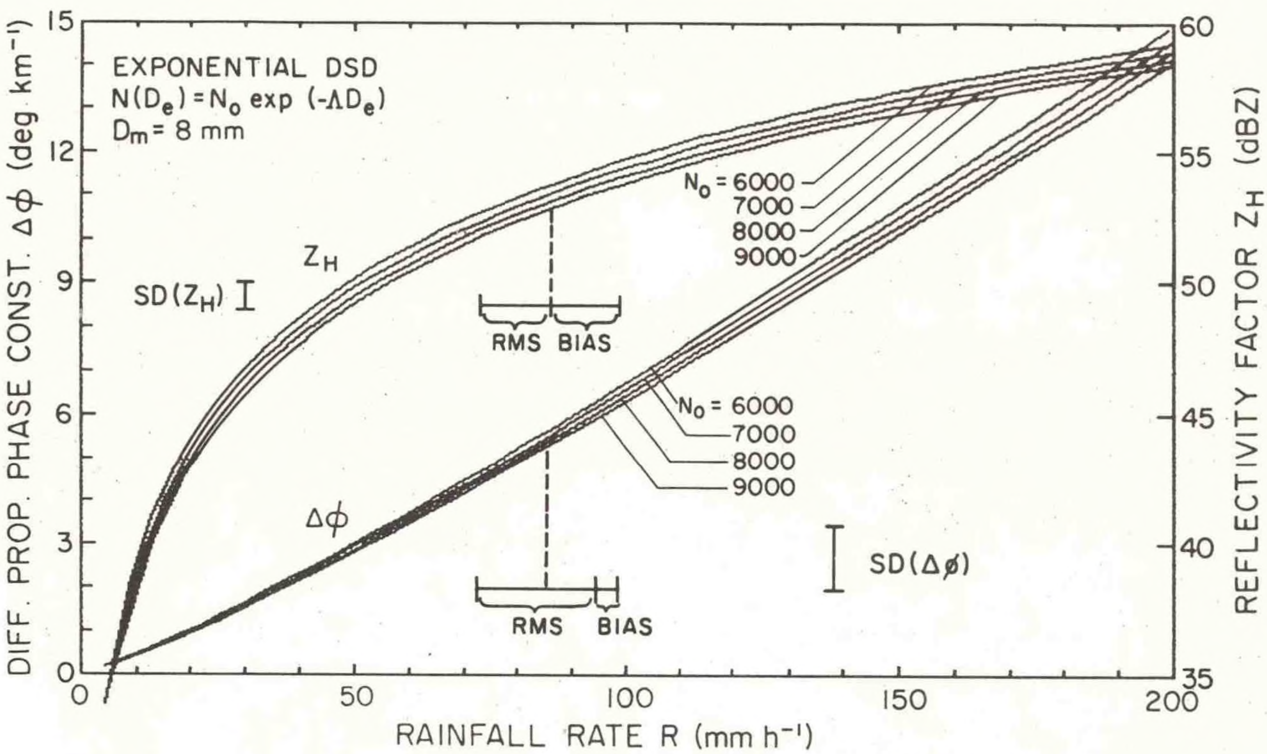


Figure 16. Rain rates from Z,R, and $\Delta\phi$,R relationships. The standard error of reflectivity $SD(Z_H)$ at horizontal polarization and the standard error of differential phase $SD(\Delta\phi)$ are for a dwell time of 50 ms, a pulse repetition time of 780 μs,, and a Doppler spectral width of 4 $m \cdot s^{-1}$. The bias error is caused by the uncertainty in N_o ($mm^{-1}m^{-3}$). At a rain rate of 65 mm/hr the accuracies of both methods are equal, but at higher rain rates the $\Delta\phi$,R method is superior.

(3) Divergence algorithm: This algorithm estimates parameters (e.g., diameter, mass flux, etc.) of a thunderstorm's updraft. Observed Doppler velocity data fields near the top of the storm appear to be consistent with those produced by a model of an axisymmetric updraft. Observations of the divergence evolution show that rapid increase in estimated divergence precedes a reflectivity buildup by 5 to 10 minutes.

(4) Gust front algorithm: This NEXRAD algorithm detects and tracks gust fronts (Uyeda and Zrnic', 1985). Shears along the radial and azimuthal directions are used to locate the gust front. Predicted gust front positions 15 minutes later than those observed at a reference time show good correspondence to the actual gust front location as determined both by Doppler radar and surface anemometers (Fig. 17).

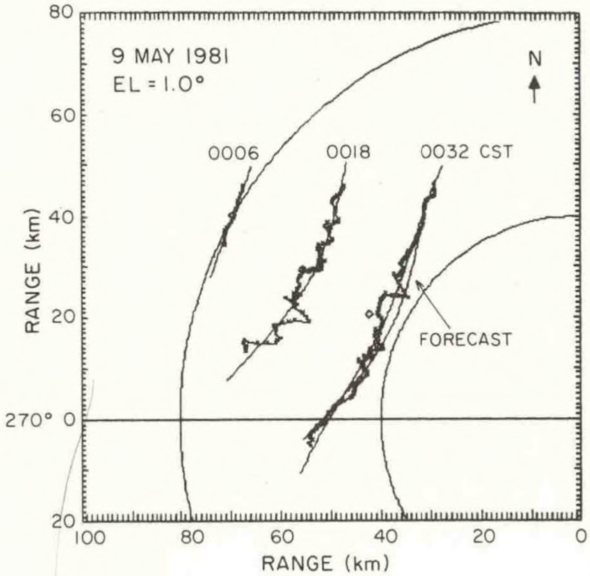


Figure 17. An automated algorithm plots the position (ragged line) of an advancing gust front and finds a smoothly fitted (in a least squares sense) line for the observed and predicted locations. Data from 0006 and 0018 are used to predict the gust front position at 0032. EL is the elevation angle of the radar beam at which data were acquired.

Lightning and Storm Studies

Positive Cloud-to-Ground Lightning and Synoptic Scale Weather: We analyzed synoptic-scale conditions for 13 May 1983, when an unusual number of positive cloud-to-ground (+CG) flashes occurred (MacGorman, 1984). Synoptic scale analyses were performed in cooperation with NASA/ Marshall Space Flight Center. Results indicate that the occurrence of +CG flashes does not appear uniquely related to sea level pressure tendencies, moisture convergence, or vertical temperature profiles, but may be linked to vertical shear in the horizontal wind (Rust et al., 1985b).

Continuing Currents in Intracloud Lightning Flashes: Analyzed data from our vertically pointing Doppler radar and the VHF lightning mapping system for about 70 intracloud flashes show lightning echoes generally having intensities stronger than those of precipitation (Rust and Mazur, 1984). Echoes from an intracloud flash are apparently a result of a current surge, perhaps a K change, that produces ionization detectable by radar. Evolution of the reflectivity of these flashes clearly shows thermal decay after the initial ionization. There is observational evidence that the thermal decay is slowed by a small continuous current in the intracloud channel, that follows an initial current surge. Continuous current in intracloud lightning has been inferred by others, but its presence was not known to be as frequent as our preliminary analysis indicates. There are practical implications for this finding in the area of aviation hazards.

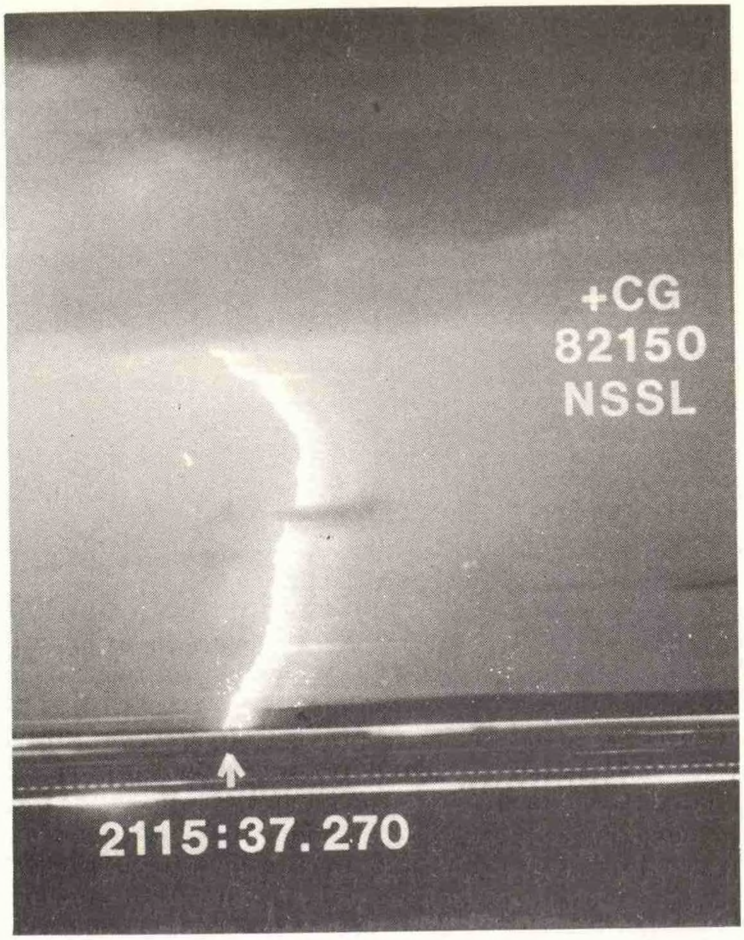
Lightning channels are observed to accelerate vertically immediately after their formation. It seems probable that this acceleration is a combined result of the earth's magnetic field and buoyancy acting on the hot plasma channel through which a current flows. The resulting velocity of the channel is due to this acceleration combined with the velocity of the air in which the channel is embedded (Mazur et al., 1985b).

Using lightning as a tracer, we infer vertical air velocities between -2.0 and 17.5 $m \cdot s^{-1}$. The observations thus far show that lightning is most frequent within updraft regions.

Other Storm Electricity Studies: In cooperation with NASA/Marshall Space Flight Center, we are analyzing the cloud-to-ground activity during periods of several mesoscale convective systems (Goodman and MacGorman, 1984). We have begun a study of the ratio of intracloud to cloud-to-ground lightning flash rates to determine its magnitude and to ascertain its relation to storm development. This information is also related to use of the cloud-to-ground data in National Weather Service operations.

We are in the final stage of preparation of an improved national lightning strike climatology for publication. We completed an analysis verifying that +CG flashes tend to have continuing current in the return stroke channel as shown in Fig. 18 (Rust et al., 1985a).

(a)



(b)

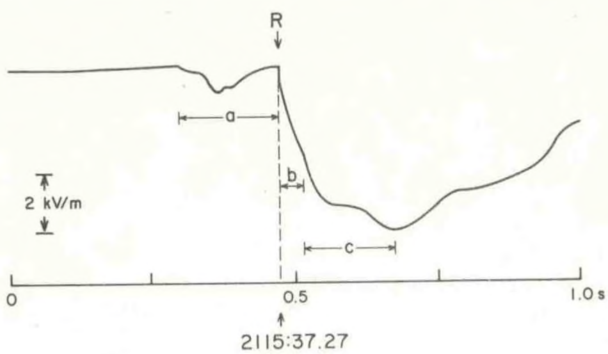


Figure 18. (a) Streak film photograph of +CG flash recorded at NSSL on 30 May 1982, at 2115:37 CST. Continuing current is evident from the continuous smearing of luminosity, lasting about 60 ms. (b) Electrostatic field change for the flash shown in (a). The total elapsed time is 1 s. The return stroke is labeled R and is at 2115:37.27 CST in agreement with the streak-film image. Interval a denotes the preliminary activity prior to the return stroke. Interval b is the confirmed continuing current, and c is additional continuing current, subsequent intracloud breakdown, or both.

The analysis of lightning activity in a multicell storm shows that (1) cells contain maximum lightning activity at the edge of the maximum reflectivity region, and (2) the growth and dissipation of the 40-50 dBZ reflectivity factor heights are correlated directly with lightning flash rates, indicating a close coupling between the convective and microphysical state of the cell and lightning production (Mazur et al., 1984).

Facility Upgrades and New Developments

Modification to our very high frequency (VHF) lightning mapping system was completed to allow mapping of the entire hemisphere continuously with data collected at rates of 16,000 lightning impulses per second This modification was tested and calibrated and then used to acquire data during the spring program.

For the PRE-STORM Program the coverage of our lightning ground strike locating network was expanded to Kansas and southern Nebraska, as well as contiguous parts of Arkansas, Missouri, and Colorado. Corrections for errors in lightning strike location have been identified for NSSL's Oklahoma network. Errors are caused by interference from electromagnetic scatter from nearby buildings and by propagation effects; therefore, they depend upon directions to lightning strikes as well as being site specific (Mach et al., 1984).

We combined the storm intercept programs of NSSL's Storm Electricity and Meteorology Research Groups. This proved to be a highly successful merger, and will be continued.

We completed design, fabrication, and initial data acquisition with a new instrument to measure the velocity of return strokes as they propagate between the ground and the cloud. The device uses optical sensing elements, placed behind a 35 mm camera lens system and coupled to high speed circuits, to record the optical waveform in eight narrow horizontal slits along the channel. We hope that our instrument will eventually replace the very expensive, cumbersome, and low-data-acquisition-rate camera systems now required to estimate return stroke velocity. Uses of the data will include determination of electric currents and other physical properties of the lightning channels. We hope to resolve the question raised several years ago by measurement of higher peak electric fields for return strokes in Florida than in Oklahoma. Such a difference, if not related to uncertainties in the data, is caused either by larger currents or faster return stroke velocities in the Florida storms.

We have found additional hardware (more memory, parallel interfaces) for the FPS AP120B array processor to facilitate real-time processing of Doppler velocity spectra. A program was written for the Perkin-Elmer computer to use its array processor to obtain Doppler spectra, and we have developed a program to facilitate processing of raw Doppler tapes. This program lists housekeeping, skips records, searches for a specified time, elevation angle, azimuth angle or step number, etc., so that the data can be inventoried and processed quickly.

A statistical classification approach to editing anomalous clear-air reflectivity data has been studied. Echo power and estimates of spectral width biased by receiver noise were selected for use as classification variables. The power and width space was divided into four regions for clutter, meteorological data, outliers, and noise. Boundaries for the regions were drawn by a mixture of theoretical and observational considerations. An application of the classification to prestorm data for 22 April 1981 showed good performance.

A method for whitening sidelobes of linear array antennas has been developed (Sachidananda et al., 1985a,b,c). It has a potential to reduce significantly the level of sidelobes without compromising the beamwidth. The method requires switching of a small number of elements (2 to 4) and uses an equal spacing between them.

Two techniques for resolving range and velocity ambiguities in Doppler weather radar data have been examined and compared (Zrnic' and Mahapatra, 1985). The staggered PRF method allows for automated velocity dealiasing whereas range overlaid echoes from targets in the first and second trip zones are incoherent with each other so they do not cause bias errors. The random phase method does not provide automated velocity dealiasing but can retrieve velocities in overlaid echoes better than that obtained with the staggered PRF method.

EXPECTATIONS FOR FY 1986

(1) In order to develop improved operational capabilities for forecasting the locations where storms develop and their intensity, we shall continue in-depth examinations of the prestorm radar data with other data sources and theory.

(2) To predict downdrafts and gust fronts, we will study their origin and evolution.

(3) We will study advanced techniques to reduce velocity and range ambiguities in Doppler radar.

(4) Wind-profiling capability of weather radars will be examined both theoretically and experimentally.

(5) NEXRAD algorithms for detection and tracking of hazardous weather will be improved.

(6) We will analyze our first polarization data obtained in Spring 1985, in order to determine the quality of rain rate estimates and the capability to remotely identify hydrometeor types (e.g., rain, hail) in storms.

(7) We will begin joint NSSL/Australian National University analysis of solitary wave data.

(8) The usefulness and accuracy of the 50 MHz radar wind profiler will be evaluated, and a 405-MHz radar wind profiler will be tested.

(9) The aspect dependency of Doppler spectrum width will be examined in depth.

(10) We will perform a side-by-side comparison of the two commercially available cloud-to-ground strike locating systems under funding from NWS.

(11) We will participate in the development of a National Plan for lightning data use and continue to address the need for and uses of a satellite-based lightning mapper system. Our involvement with the National Interagency Coordinating Group for Atmospheric Electricity Hazards will continue, through coordinated research and through vice-chairmanship of the 1986 International Conference of Ground and Static Electricity.

(12) We will replace the mobile storm electricity laboratory, which is no longer reliable, and increase the parameters that we record by adding meteorological sensors.

(13) We will expand the data base of the characteristics of positive cloud-to-ground flashes and examine their relationships with storm and environmental parameters.

(14) We will participate in the planning and data analysis of a multiagency program utilizing at least two instrumented airplanes to observe lightning strikes to aircraft and measure their hazard potential, and we will participate in STORM planning.

(15) Analyze lightning channel plasma properties from dual radar observations of lightning.

(16) Software to analyze ground strike data and VHF lightning mapping data will be further developed; PRE-STORM lightning ground strike data will be archived, and existing software will be converted so that the Gaithersburg computer can be utilized.

(17) Additional measurements of return stroke velocities will be acquired, capability of the NSSL lightning strike locating system for +CG detection will be evaluated, and we will examine CG lightning evolution in mesoscale convective systems.

COMPUTER AND ENGINEERING SUPPORT AND DEVELOPMENT

Dale Sirmans, Group Leader

The Computer and Engineering Support and Development Group develops techniques and equipment, maintains the NSSL observational facilities, and supports the observational programs associated with the meteorological research. The NSSL base facilities consist of two 10-cm meteorological Doppler radars, a WSR-57 (surveillance radar), a tall (444 m) tower, a 52-station surface network, an air traffic control facility (IFF) and air/ground communication, and equipment for measuring electrical phenomena in the atmosphere. The group also provides engineering support for the NEXRAD/JSPO Interim Operational Test Facility of the National Weather Service.

RECENT ACCOMPLISHMENTS

Computing and Data Processing

The NSSL VAX 11/780 was installed and became operational this year. It consists of 12 megabytes (Mb) of memory, 1778 Mb of disk storage, three magnetic tapes, and a RAMTEK color graphics workstation. The system is used for interactive editing of Doppler radar data, for editing and archiving other NSSL-collected data, and as a remote job entry link to the CDC 855/205 in Gaithersburg, Maryland.

A MICOM telecommunication system was installed which provides communication to the CDC 855/205 by means of two dedicated 9600-baud phone lines as well as a multiplexer and electronic switch for interconnection of all NSSL terminals to the VAX, the CDC/205, and the NSSL Perkin Elmer computer connected with the Norman Doppler radar.

NSSL supplied data sets to these users:

Lassen Research Manton, California	(R. Lee)
MIT Lincoln Laboratories Lexington, Massachusetts	(J. Evans)
NASA Goddard Space Flight Center Greenbelt, Maryland	(G. Heymsfield, R. Blackmer, I. Hakkarinon)
National Weather Service Weather Service Forecast Office Oklahoma City, Oklahoma	(D. Devore)
National Weather Service Techniques Development Laboratory Silver Spring, Maryland	(W. McGovern)

Purdue University
West Lafayette, Indiana (D. Klingle)

Texas Tech University
Lubbock, Texas (K. Mehta)

University of Oklahoma
Norman, Oklahoma (H. Bluestein, G. Byrd)

Facilities Engineering

Airborne Doppler Radar Evaluation: Representatives from the Sperry Corporation established a ground-based facility for Sperry's airborne Doppler radar developed for the commercial carrier market. Data from the system were compared with data from the NSSL Norman Doppler to evaluate system performance. This was the third airborne Doppler radar system evaluated at NSSL.

Data Transfer to Will Rogers WSFO: Transfer of quasi-real-time data from the Doppler radar at Norman to the National Weather Service Forecast Office at Will Rogers was done routinely during the PRE-STORM Program. These data proved useful to the duty forecaster and provided an opportunity for gradual technology transfer and examination of minimal Doppler radar products by the operations office.

Facilities Operation: Some NSSL facilities, particularly the Norman Doppler radar, were maintained operational from January into September in support of multiple programs: Winter Storm, during January through March; PRE-STORM from April through June, and Special Research during July and August. This schedule represented a substantial extension of the Laboratory's normal observational season.

Wind Measurement by Balloon Tracking with Radar: The in-house research program to examine the feasibility of upper-air wind measurement by balloon tracking with a NEXRAD-type radar continues. Experiments to determine balloon cross section and radar system performance were successful, and we are designing electronic circuits to facilitate automatic balloon tracking.

Acid Rain Measurement Program: The National Atmospheric Deposition Program site operation continues since its institution in 1983. Sample collection is both wet deposition (rainfall) and dry deposition (dust) at a local farm. Sample pre-analysis consisting of a pH and conductivity measurement is done at NSSL. Detailed composition analysis is done at the Illinois State Water Survey.

Facilities Development

CIM Radar Data Terminal: Long-needed improvements in the CIM radar real-time display and data recording were begun with the design and fabrication of a radar signal preprocessor and second-generation color display. Fabrication of the pre-processor and display terminal is complete, and system software is being written.

KTVY Tower Data Logger: An expanded data acquisition and recording terminal for the NSSL tall-tower facility was designed, built, and commissioned this year. Program demands in recent years have exceeded the capability of the original system placed in service in the late 1960s.

405-MHz Profiler: Work was begun on the establishment of a 405-MHz Profiler at NSSL. This is a joint program with WPL whereby NSSL is to build a steerable parabolic antenna system and WPL is to provide the Tx/Rx terminal. Goals are to evaluate the suitability of the 75-cm wavelength for central Oklahoma applications and the electrical performance of the parabolic antenna system.

Microwave Data Link: System engineering for a microwave data link between the NSSL, CIM, and NRO radars is complete, and hardware is scheduled for delivery in late 1985. Initially the system will be an L-band simplex link consisting of a transmitter at CIM, a repeater on the KTVY tower, and receiver at NRO. It will carry the full data from CIM and interface to a remote display terminal and to the Perkin-Elmer 3242 computer terminal at NRO. Among other things, it will provide NSSL with data needed to synthesize the observations from two Doppler radars in real time.

Radar Antenna Dual Polarization: Systems engineering for an antenna dual-polarization capability on the NSSL Doppler radar at Cimarron (CIM) completed and routine operations began with the PRE-STORM Program. Data for meteorological research, engineering evaluation, and propagation studies were acquired.

A block diagram of the system as now configured is shown in Fig. 19. The major engineering changes consist of the orthomode coupler and scalar feed to accommodate the two polarizations, the switchable ferrite circulator to steer the horizontal and vertical signals, and the waveform control for polarization sequence generation.

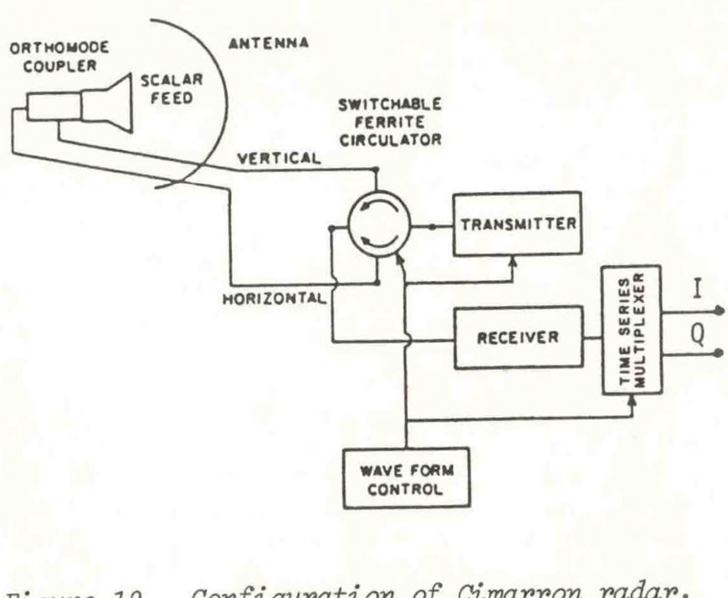


Figure 19. Configuration of Cimarron radar.

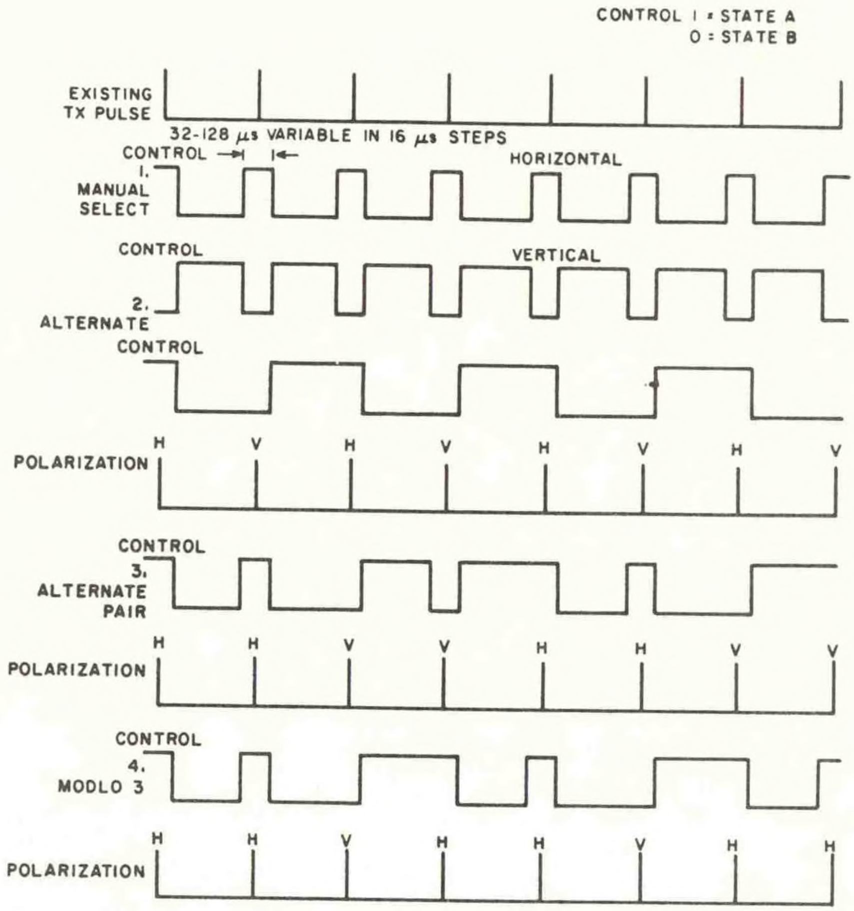


Figure 20. Dual-polarization waveform sequences.

The system can switch polarization at the PRF rate (actual time for switching is 6 μs) with five different polarization sequences as shown in Fig. 20. However, most data were taken with the alternate sequence. The orthomode coupler and scalar feed has isolation between the two polarizations of about 42 dB, but composite isolation is limited by the ferrite switch. The switch performance is shown in Fig. 21. At optimum power the switch delivers an isolation of 27.2 dB.

Primary illumination functions for the two polarizations are well matched, as seen in Fig. 22. The dual polarization primary illumination has a stronger taper (~15 dB) than original linear feed, resulting in a larger secondary 3-dB beam (0.88° compared with 0.81°) and lower sidelobe levels (first sidelobe of 24.5 dB compared with 22 dB). A typical secondary pattern is shown in Fig. 23.

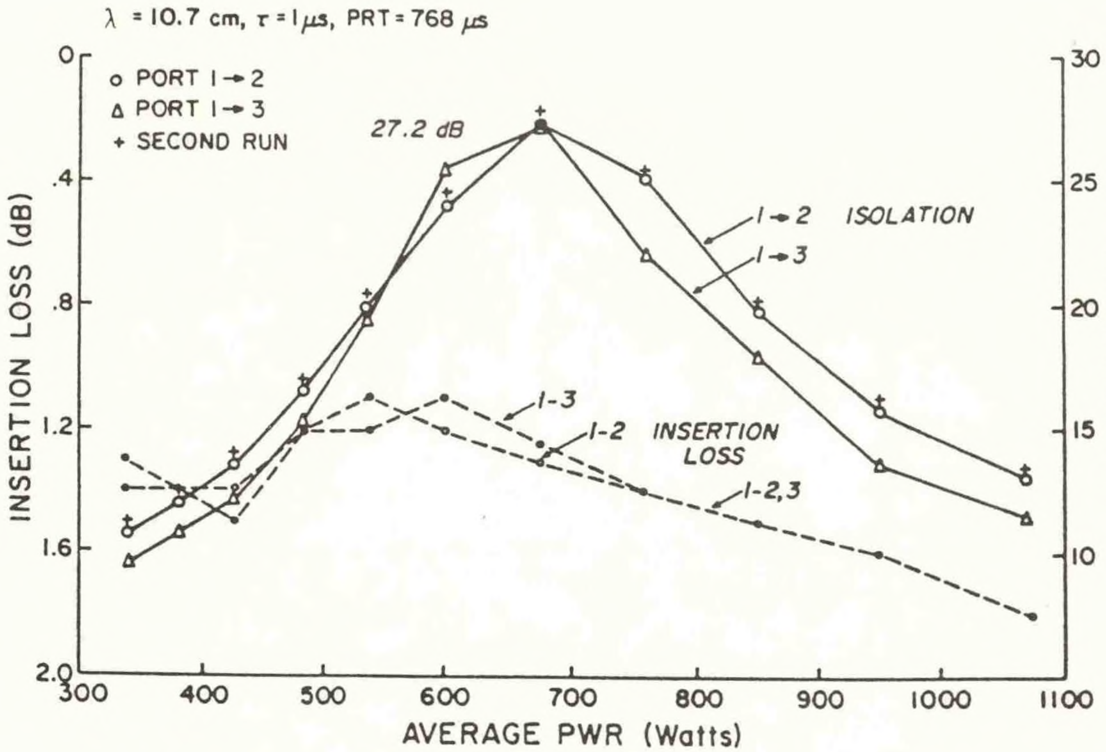


Figure 21. Ferrite switch isolation and insertion loss.

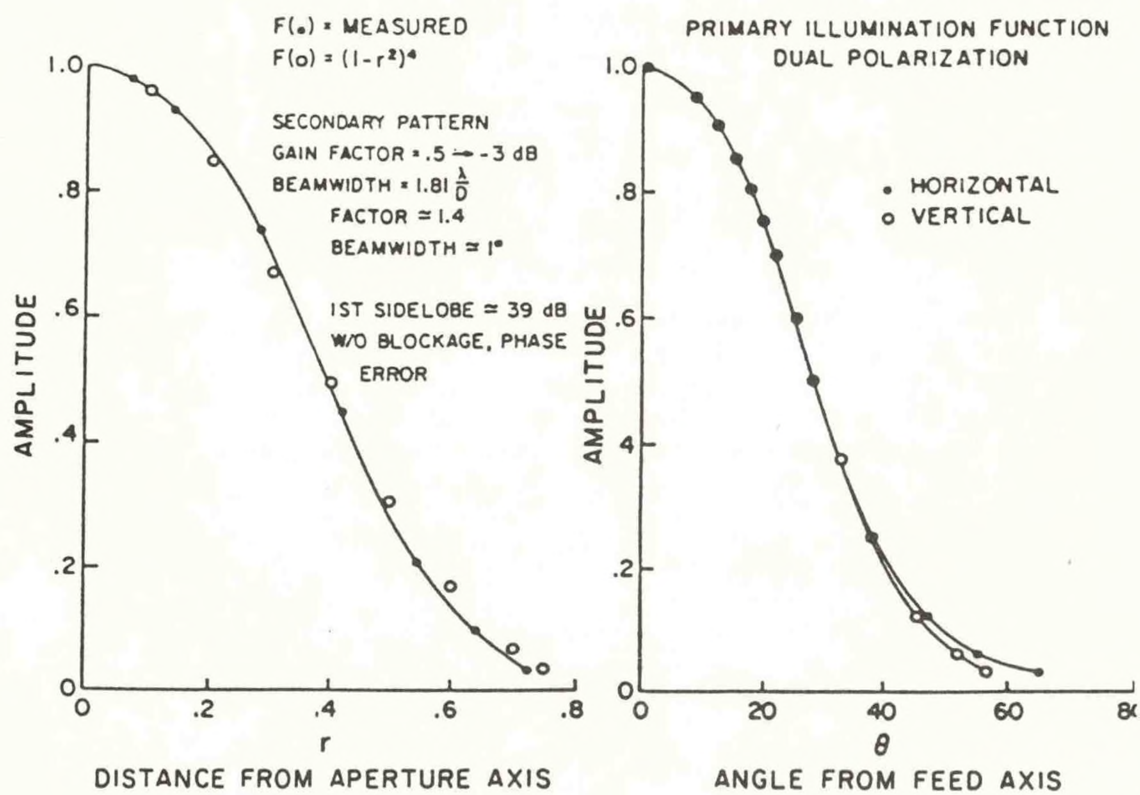


Figure 22. Antenna primary illumination.

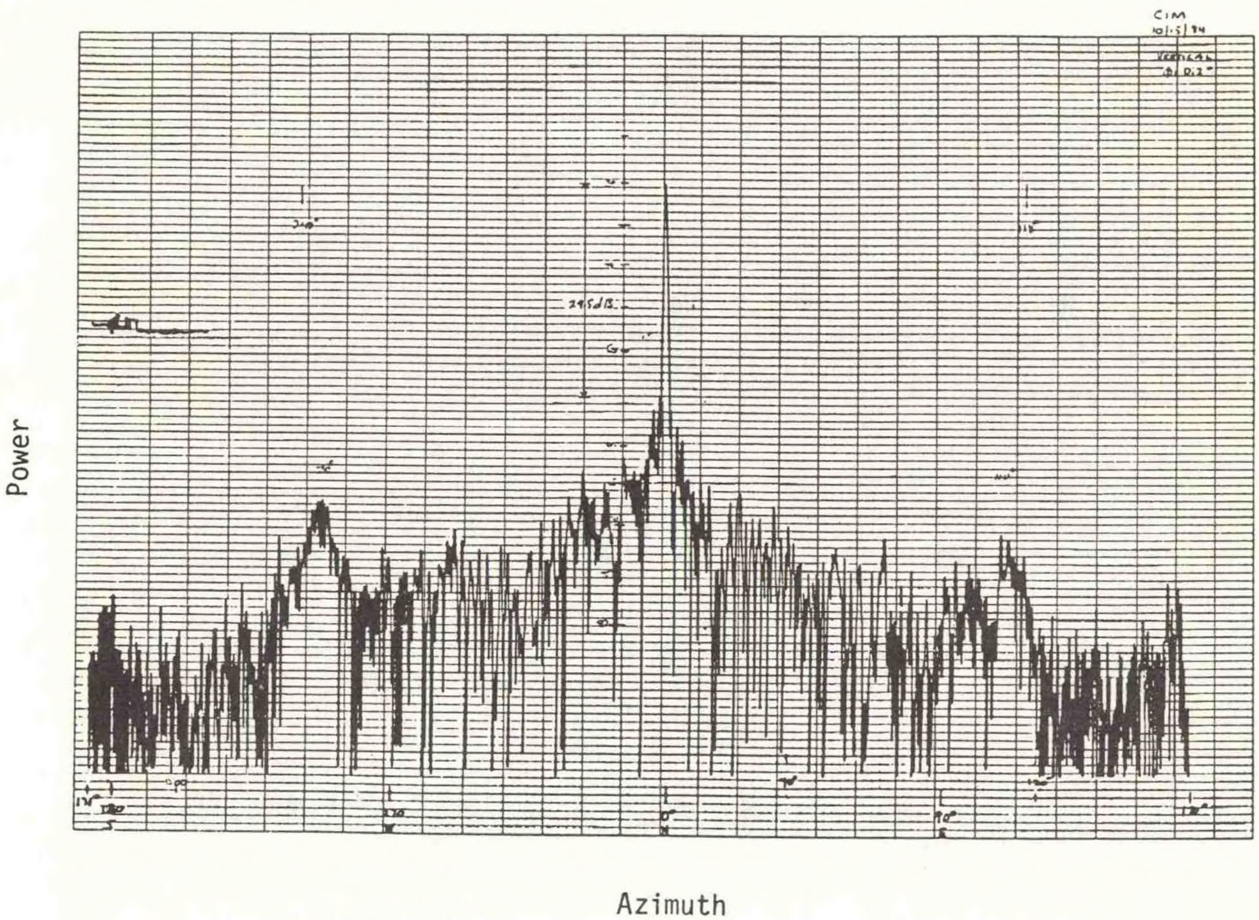


Figure 23. Antenna secondary pattern.

The data are recorded as complex video at the 16 time series gates. This results in a limited range of coverage but is sufficient for evaluation of meteorological utility. More important, it allows a comprehensive examination of signal statistics for information content and for development of signal-processing techniques.

EXPECTATIONS FOR FY 86

Computing and Data Processing

Upgrades to the VAX 11/780 will include the installation of a seven track tape to facilitate study of data acquired before 1986, and an electrostatic plotter and/or laser printer. Graphics software that is now operational on the CDC 750 will be converted for use on the CDC 205 and the NSSL VAX. New graphics software that uses the RAMTEK color graphics system will be designed to use unique features of the RAMTEK. Additional support will be given to scientists in the optimization of programs for use on the CDC 205.

Facilities Engineering

Radar Dual Polarization: During FY 1986 we will complete a study of dual-polarization signal statistics and an evaluation of meteorological utility. Initial examination of data has indicated that the technique has good potential for meteorological research, and we should proceed with the development of processing techniques and hardware needed to realize this potential.

Radar for Vertical Antenna: It is planned to design and fabricate a microwave transmitter and receiver to service a vertical antenna at the NRO radar site. Data will be recorded on a wideband analog recorder and processed through the NRO terminal. This will provide a vertical-looking radar capability without conflict with the NRO radar.

Fiber Optics Data Distribution System: NSSL has need of a high quality, wide-bandwidth data distribution system in and around the central Laboratory. It is planned to establish a data distribution network using fiber optics technology.

Microwave Data Link: The microwave portion of the CIM/NRO data link will be established in early FY 1986. The CIM radar interface is incorporated into the radar preprocessor and display terminal for this system and will be commissioned with this terminal in mid-FY 1986. Development of remote data processing for analysis and display at NRO will continue through FY 1986.

405 MHz Profiler: It is planned to complete a 405-MHz antenna terminal and to begin experimentation by mid-FY 1986. A preliminary evaluation of this system should be available by the end of FY 1986.

Cooperative Institute for Mesoscale Meteorological Studies

Y. Sasaki, Director, U. of Okla.;
and P. S. Ray, Associate Director, NSSL (through August 1985)

The Cooperative Institute for Mesoscale Meteorological Studies (CIMMS) is a joint venture of the University of Oklahoma (OU) and ERL through the National Severe Storms Laboratory. CIMMS received first funding in late FY 1978 and began major efforts during FY 1979. The program objectives and activities of CIMMS complement and supplement those of NSSL and the University through research conducted by Visiting Fellows, NOAA scientists, and University staff members and student appointees. The Council of Fellows, which helps formulate policy, includes OU faculty members, and members from NSSL hold adjunct professorial appointments at OU. The Advisory Council, which includes representatives from OU, NOAA, and outside organizations, meets annually.

During 1985, Drs. Robert Walko and Qin Xu were Postdoctoral Fellows; there were 4 Research Scientists, 2 Research Associates, and 11 graduate students. In addition to NOAA funding of approximately $500K, other agencies provided approximately $600K, and OU approximately $50K. M.S. degrees were awarded to two students employed by CIMMS.

During 1985, CIMMS was host to researchers from China, Taiwan, Japan, and France, who undertook studies in mesoscale meteorological modeling and development of optimization analysis in Doppler radar meteorology. CIMMS research associate Dr. John McGinley continued work on the Alpine Experiment (ALPEX) and satellite-based analysis techniques. Fellow Dr. Qin Xu received a grant from NSF to study extended theories of conditional symmetric instability and their application to problems associated with frontal rainbands. Fellow Dr. Robert Walko, also supported by an NSF grant, is working on turbulence statistics in laboratory-simulated tornado vortices. His group is obtaining a high-caliber flow visualization device capable of resolving fine structures in the flow trajectories, thus providing turbulent velocity correlation statistics useful in obtaining the frictional force in theoretical studies. A high-resolution 3-D numerical model is being developed in an attempt to simulate the turbulent flow. Laboratory flow measurements will help to verify the model.

CIMMS research results were reported in nine reports and five publications during FY 1985.

During April 1985, CIMMS was host to a symposium on NEXRAD, attended by more than 300 persons.

In October 1985, CIMMS will be host to the International Symposium on Variational Methods in Geosciences.

ADMINISTRATIVE GROUP

Loyce Tillman, Administrative Officer

The Administrative Management Group provides services related to communications, budget, procurement, project reporting, security, employee utilization, personnel administration, and library. The major responsibilities involve interaction with NSSL staff, with educational institutions and commercial concerns, and with administrators at ERL headquarters and in other agencies (such as FAA, NASA, NSF) and other components of NOAA.

Personnel

At the end of FY 1985 the NSSL total staff included 38 full-time, 5 part-time, and 8 intermittent employees.

The work of our staff continues to be supplemented by means of contracts with the University of Oklahoma, Applied Computer Systems, and the NEXRAD/Interim Operational Test Facility.

Land and Buildings

Leases on land and buildings used by NSSL during FY 1985 were renewed and entered into on 1 January 1983.

NSSL continues to occupy a two-story reinforced concrete and glass building leased from the University of Oklahoma. The building contains about 20,000 square feet and is situated on approximately 1.5 acres of land.

NSSL rents five other tracts of land from the University of Oklahoma:

(1) A warehouse containing 3,840 square feet of storage space.

(2) Ground space for the Doppler Radar Laboratory Building owned by NSSL, plus a tower supporting a rangefinder.

(3) Ground space across the street from NSSL, with the following facilities:

- (a) Small modulator building
- (b) WSR-57 radar atop a 20-meter tower
- (c) A second tower with UHF and VHF radio antenna
- (d) A third tower with IFF equipment (MPX-7 radar) to interrogate transponders aboard aircraft to determine aircraft position.

(4) Ground space (one-half acre south of and adjacent to the laboratory) occupied by a "benchmark" weather station. (This facility represents cooperation among NSSL, the University of Oklahoma, and the City of Norman, Oklahoma).

(5) Ground space used for placement of sensors to measure various parameters of storm electricity. Also located on the ground space is an 800-square-foot portable building used by NSSL personnel for observations and data acquisition.

Total cost for all the leases in items (1) through (5) is approximately $132.4K annually.

NSSL leases this additional space:

(6) One acre of land at Cimarron, Okla., about 45 km northwest of Norman, occupied by a second Doppler radar unit.

(7) Levels at the 457-meter KTVY (Television Systems, Inc.) tower, Oklahoma City, 40 km north of Norman. During most of FY 1984, wind and temperature sensors were operated at seven levels on the tower. Vertical wind data were obtained at the top and bottom, and digital data were obtained for pressure, rainfall, and solar radiation. An analog strip chart recorder and digital magnetic tape operate at the tower site, with simultaneous telephone-line telemetry of digital data for real-time displays at NSSL headquarters.

(8) Land for 28 network sites.

Total annual cost for items (6) through (8) above is approximately $30.4K.

<u>GRANTS AND CONTRACTS</u>

FY 1985

Grants and contracts administered by NSSL during FY 1985 are listed below. Other agencies are indicated in the first column where their funds were used to maintain the grant or contract.

Recipient organization, title of grant or contract, and prin. investigator	Number	NSSL Cognizant officer	Start date	Term date
Applied Computer Systems "Services for Facilities Management to Operate NSSL Computer Equipment"	NA84RAE05057 ($65,000)	Bumgarner	10/1/84	9/30/85
University of Oklahoma Cooperative Agreement "Cooperative Institute for Mesoscale Meteorological Studies" (Sasaki) CIMMS	NA85RAH05046 ($573,675)	Kessler	7/1/85	6/30/85
University of Washington 9/30/85 "Studies of Severe Convective Storms" (Houze)	NA85RAD00025 ($10,999)	Ray		10/1/84
University of Oklahoma 9/30/85 "Research on Severe Local Storms" (Golden) NASA	NA82RAH00003 ($17,223)	Rust		10/1/84
University of Oklahoma "Climatology of Precipitation Echoes" (Carr) NWS	NA85RAD05040 ($25,000)	Kessler	3/1/85	2/28/86
University of Oklahoma 2/28/86 "Install and Operate a 50-MHZ Profiler" (Walker) NSSL & WPL	NA85RAC05071 ($50,000)	Doviak		4/15/85

In addition to the above Grants and Contracts, $132.4K is disbursed annually for recurring services and maintenance agreements.

PUBLICATIONS AND REPORTS OF THE LABORATORY

FY 1985

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AS OF SEPTEMBER 30, 1985

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